Project number: 243827 FP7-ENV-2009-1

Project acronym: LC-IMPACT

Project title: Development and application of environmental Life Cycle Impact assessment Methods for improved sustainability Characterisation of Technologies.

Deliverable number: D3.11

Deliverable name: Recommended assessment framework, method and characterisation factors for noise impacts

Version: 1

WP number: 3

Lead beneficiary: CML

Nature: **R**[1]

Dissemination level: **PP**[2]

Delivery date Annex I: M41

Actual delivery date: 18/04/2013

Authors: Stefano Cucurachi, Reinout Heijungs, Philipp Preiss, Sandra Torras Ortiz, Katrin Ohlau

Comments: #

[1] Please indicate the nature of the deliverable using one of the following codes: **R** = Report, **P** = Prototype, **D** = Demonstrator, **O** = Other

[2] Please indicate the dissemination level using one of the following codes: **PU** = Public, **PP** = Restricted to other programme participants (incl. the Commission Services), **RE** = Restricted to a group specified by the consortium (incl. the Commission Services), **CO** = Confidential, only for members of the consortium (incl. the Commission Services)

Contents

Abstract

Noise is a serious stressor affecting the health of millions of citizens. It has been suggested that disturbance by noise is responsible for a substantial part of the DALY-score for human health. However, no recommended approach to address noise impacts was proposed by the ILCD reference handbook, nor characterisation factors and appropriate inventory data are available in databases. This report fills the gap of the absence of noise as an impact category in LCA and presents characterisation factors for noise impacts at a European level (i.e. EU27). The framework defined in deliverable 1 (chapter 1 below) are further analysed in deliverable 2 (chapter 2 below) and each of its parameters are explained and defined.

After the theoretical definition of the framework, two different parallel paths were followed for the definition and calculation of characterisation factors: characterisation factors in the form of spatially-defined maps and characterisation factors in the form of tabular values calculated from archetypal situations of emission. A total of 249 characterisation factors have been produced. The two different approaches may be combined and selected according to the amount of information available and the life cycle under study. The factors

produced are ready to be implemented in the available LCA databases and software. The framework proposed and used for calculations is flexible enough to be expanded to account for impacts on other target subjects than humans and to other continents than Europe.

Chapter 1 has been published in the International Journal of LCA (May 2012, Volume 17, Issue 4, pp 471-487) with the title “Towards a general framework for including noise impacts in LCA”. Chapter 2 is under review in the journal Science of the Total Environment.

1. Theoretical framework

Towards a general framework for including noise impacts in LCA

Stefano Cucurachi[1], Reinout Heijungs[1], Katrin Ohlau[2]

[1]*Institute of Environmental Sciences (CML), Leiden University, P.O. Box 9518 2300 RA Leiden, The Netherlands,*

[2] *Institute of Energy Economics and the Rational Use of Energy (IER), Department of Technology Assessment and Environment (TFU), Heßbrühlstraße 49a, 70565 Stuttgart, Germany*

E-mail contact: cucurachi@cml.leidenuniv.nl

1.1. Introduction

Within life cycle impact assessment (LCIA), the study of noise impacts is an underdeveloped field (ILCD 2010). The sheer nature of sound and noise has limited the possibility of developing a methodology usable for the evaluation of impacts determined by any source of noise and in principle expandable to the analysis of impacts on other species than humans. The dearth of data in other fields than transportation noise stimulated the focus of researchers on this only field. Ad-hoc methodologies developed solutions that are scarcely linked to the LCA practice commonly adopted for other pollutants and, in general, for impact assessment and which are based on the consideration of a specific traffic situation rather than on the evaluation of the noise emissions which are explicitly linked to activities in the life cycle of a specific functional unit. Fundamental concepts in LCA, such as system boundaries and functional unit, seem to fall into the background of the analysis. The proposed models lack the required flexibility to expand them from impacts on humans to other target subjects.

The intent of this paper is to propose a new framework for the evaluation of noise impacts (section 3), after briefly reviewing the literature in the field of LCA and noise and having assessed what the impacts of noise from an epidemiological perspective (section 2) are. While section 2 is based on existing reviewed knowledge, section 3 aims at assembling and expanding it to a new framework which may help towards the modelling and operalisation of noise impacts assessment for human health and possibly to the health of other species.

Basing on the approach taken in human and environmental risk assessment and the approaches commonly adopted in LCIA for other impact categories, the framework goes beyond the only consideration of transportation and road noise and aims at developing a comprehensive cause-effect chain methodology usable for the evaluation of any source of noise. Even though transportation noise can, in fact, represent a main source of noise impact in the life cycle of some products, in some others, e.g. construction works, it can represent a minor source of impact from noise. The proposed framework will be the skeleton for the future modelling activity which will be presented, together with the necessary developments in the field, in the research agenda section of this paper (section 4).

1.2. Fundamentals of sound and noise

1.2.1. Generation of a sound wave

If an object is moved at one place in a medium, e.g. air, there is an appreciable disturbance which travels through the medium, which we can refer to as vibration or sound. In the case of air as medium, a sudden movement of the object compresses the air causing a change of pressure which pushes on additional air, which in turn is compressed leading to extra pressure and to the propagation of the generated (sound) wave. To obtain a sound wave it is necessary that molecules moving from a region with higher density and higher pressure move, transmitting momentum to the ones at lower density and pressure in the adjacent region (see, for example, Feynman 1970 for a complete description). Audition is not static: something in the world has to happen to produce a sound, meaning that a sound source has to be involved in a physical action for the production of what is defined as a sound event or multiple types of sound events (Niessen, 2010). The recognition of a sound event by human listeners (auditory event) determines their cognitive representation of it (auditory episode) and therefore their reaction to it; when intolerable, unwanted, annoying or completely disruptive of the daily sonic experience of individuals, a sound becomes *noise*.

1.2.2. Sound, noise and noise impacts

Since ancient times sleep disturbance and annoyance were already considered main issues for the life of citizens (Ouis, 2001). Chariots in ancient Rome, for instance, were banned from night circulation, since their wheels clattered on paving stones (Goines and Hagler, 2007). Growing attention of research on noise impacts has emerged in the last century as a consequence of ever increasing levels of intensity of unwanted noise: in 1994 almost 170 million Europeans were found to be living in zones that did not provide acoustic comfort to residents (Miedema, 2007), requiring a close evaluation of the increasing magnitude of the presence and role of noise among ambient stressors.

In the 1960s, noise had already been identified as a health stressor and most of its public health impacts had been recognised (Ward and Fricke, 1969). They were later reviewed scientifically and confirmed in the 1970s to provide policy makers with recommendations (Health Council of the Netherlands, 1971; US EPA, 1974). Evidence has since then been found to corroborate the existence of a causal relationship between noise and specific effects on human beings, but also with respect to other forms of living creatures, affecting their ability to communicate when noise masks their communication sounds, e.g. birds or marine species, or also directly threatening their survival and reproduction (Brumm, 2004; Slabbekoorn et al. 2010).

The definition of noise as unpleasant, unwanted sound makes the evaluation of its perception quite subjective and less prone to a scientific and robust modelling of its health burdens, indicating the need to employ more than physical measures for operational purposes (Shepherd, 1974). Personal traits influence the reaction of people to noise as well as what is commonly defined as their subjective sensitivity to noise or attitude to noise in general (Stansfeld, 1992). A complete and literature-summarizing definition of noise sensitivity is found in Job (1999): “Noise sensitivity refers to the internal states (be they physiological, psychological [including attitudinal], or related to life style or activities conducted) of any individual which increase their degree of reactivity to noise in general”. It is then clearly indispensable to evaluate the subjective component of noise when evaluating its impacts on human health: some individuals can express more annoyance than their neighbours to a particular level of noise (Griffiths and Langdon, 1968; Bregman and Pearson, 1972; Stansfeld, 1992), some others high in trait anger might show stronger emotional reactions when disturbed by noise (Miedema ,2007). Moreover, the concept of soundmarks, i.e. sounds to which a certain community associate a specific feeling of recognition (Adams et al., 2006), and keynote sounds (Schafe, 1994), i.e. sounds heard by a particular society frequently enough to constitute the background against which any other sound is perceived, contributes to making the local situation where a sound event takes place fundamental to understand the relative impact of noise.

Scientific evidence confirms that it is clear that noise pollution is widespread and imposes long term consequences on health (Ising and Kruppa, 2004; Babisch, 2006). Following, in fact, the WHO (1947, 1994) definition of health as “a state of complete physical, mental and social wellbeing and not merely the absence of disease and infirmity” it is clearly understandable that noise impacts human health in manifold ways, which can be more easily detectable and linkable to the source as in the case of hearing loss but less evidently in causing other more subtle health effects. Moreover, it appears from the application of the available computational assessment models to case studies that not only is noise more directly perceived as disturbing by humans in comparison to chemical emissions or resource uses, but it objectively represents, for some processes in a life cycle, the most relevant of the health burdens. Considering, for instance, the overall health impacts of transportation within a life cycle it is possible to conclude that the impact from noise-related health burdens, evaluated using common metrics (see section 2.5), are of the same order of magnitude or higher than those that are attributable to other emissions (Doka, 2003; Muller-Wenk, 2004). It has to be noted that the assumption of linearity and the implication of averaging conditions could, however, have led to an overestimation bias and a misdjudgement of the overall health impacts due to noise (Franco et al., 2010)

1.2.3. Noise exposure and non-physiological effects on humans

Disturbance of activities, sleep, communication, and cognitive and emotional response usually lead to what is generally referred to as annoyance. Miedema (2007) defines this as a primary influence of noise and, as reported by Job (1999), it may include other more specific effects such as “apathy, frustration, depression, anger, exhaustion, agitation, withdrawal, and helplessness”. Annoyance is certainly the most well documented response to noise, seen as an avoidable source of harm.

Several effects on the sleeping activity have been associated with nocturnal noise. Physiological reactions lead to primary sleep disturbances, distressing the normal functioning of individuals during daytime and potentially disrupting personal circadian rhythm with consequential effects on health and well-being (Pirrera et al., 2010). A clear relationship has been found between transportation noise and altered aspects of the sleeping process and the quality of it, in terms, among others, of increased body motility (Williams et al., 1964), sleep stages redistribution (Pirrera et al., 2010) and self-reported sleep disturbance (Miedema, 2007).

In the context of verbal interactions of people, exceeding levels of noise cause frustration of communications, implying the necessity of raising the voice of the speaker to allow conversations and free speech, altering the social capabilities of individuals and leading to problems such as uncertainty, fatigue, lack of self-confidence, misunderstandings and stress reactions. Significant is the impact on vulnerable groups, "such as children, the elderly, and those not familiar with the spoken language" (Goines and Hagler, 2007).

Prolonged exposure to noise sources negatively affects processes which require attention and concentration. Experiments demonstrated a direct altering of memory and comprehension functions of individuals exposed to noise, especially sensitive subjects such as children (Clark and Stansfeld, 2007), with the manifestation of semantic errors, text comprehension errors, errors in the strategy selection for carrying out tasks, or reduction in connections between long-term memory and working memory (Hamilton et al., 1997; Enmarker, 2004).

1.2.4. Noise exposure and physiological response of humans

The direct exposure to continuous and loud sources of noise, especially if prolonged, and the synergic combination of the stressors previously described can lead to predictable physiological responses.

The direct exposure to noise leads to hearing impairment, caused by a mechanical damage to the ear or in some cases by the interference of noise with the basic functions of the auditory cells (Chen and Fechter, 1999). Hearing loss is dependent on a number of variables, such as type, duration, intensity, and frequency of the noise (Rao and Fechter, 2000); but to be considered are also other factors such as periods between noise exposures (Henselman et al., 1994), and of course the previously mentioned noise sensitivity and individual variability. Hearing impairment can be associated with abnormal loudness perception, distortion, and temporary or prolonged tinnitus (Berglund and Lindvall, 1995; Axelsson and Prasher, 2000).

The exposure to noise levels at or above 85 dB (e.g. the noise of a heavy truck traffic on a busy road) for a 8-hour-time-weighted average working day over a lifetime is associated to a hearing impairment at 4000 Hz of about 5-10 dB for most workers (Lusk et al., 1995). It is generally considered that a hearing impairment that exceeds 30 dB, averaged over 2000 and 4000 Hz at both ears, can constitute a social handicap (Passchier-Vermeer and Passchier, 2000). Noise-induced hearing loss is the most common occupational disease (NIOSH, 1996). Interesting is the example of construction workers, who usually do not only operate in a single working setting but move around job sites, being exposed not only to the noise coming from tools or equipment of their own, but also to the noise of those owned by the surrounding workers (Lusk et al., 1998).

The so-called leisure noise (usually exceeding 120 dB) has been closely studied epidemiologically and can be a cause of hearing impairment (Davis et al., 1998; Axelsson and Prasher, 1999), with young adults being the category of people mostly exposed, in environments such as clubs or discotheques. WHO (1995) recommends a maximum of 4 hrs of exposure, for a maximum of 4 times/year, to unprotected leisure noise levels exceeding 100 dB. 140 dB is identified as the threshold for pain; even the shortest exposure at levels greater than 165 dB can cause immediate acute cochlear damage (Berglund and Lindvall, 1995). Effects of somatic nature include stress-related cardiovascular disorders. It is important to underline how studies on this type of effects are complicated, because of the different sensibility, susceptibility and genetic predisposition of individuals to the impairment, and because of the difficulty in evaluating precisely past noise exposure of the subjects under study (Passchier-Vermeer and Passchier, 2000). The most complete studies available in the literature are generally focused on the exposure to traffic noise and aircraft noise with a dearth of data in the other fields of noise exposure, apart from limited studies in the field of occupational noise (Rai et al. 1981; Fogari et al. 2001).

In-bedroom and laboratory studies (Hofman et al., 1995) found that sound peaks due to transportation noise caused an increase in heart rates as a direct response to the stimulus in individuals living along highways with high traffic density. Sleep disturbance has been directly associated with collateral cardiovascular effects, including increased blood pressure, increased pulse amplitude, vasoconstriction, cardiac arrhythmias (Verrier et al., 1996), as well as increased use of sleep medication and cardiovascular medication (Franssen et al., 2004).

Babisch et al. (2005) and Babisch (2006, 2008) found evidence to support the hypothesis that chronic exposure to traffic noise increases the risk of myocardial infarction especially in male individuals with predisposition to high systolic and diastolic pressure in the range between 45 and 55 years of age, as confirmed by de Kluizenaar et al. (2007), but also in young adults aged 18–32 years (Chang et al. 2009). Less such evidence of association was found by Babisch and van Kamp (2009) in the case of aircraft noise. However, a Swedish study confirmed that hypertension was higher among people exposed to time-weighted energy-averaged aircraft noise levels of at least 55 dB(A) or maximum levels above 72 dB(A) around the Arlanda airport, in Stockholm (Stansfeld and Matheson, 2003).

Exposure to noise also activates the sympathetic and endocrine systems, intervening with the excretion of hormones. Increased levels of catecholamine were found in people exposed to road traffic noise as a response to stress levels (Babisch et al., 2001), but also in workers of a textile factory in Vietnam (Sudo et al., 1996). Irregular excretion of corticosteroids, adrenalin and nor-adrenalin (Slob et al., 1973) was found in laboratory tests on men as well as upon laboratory animals.

In the context of this article we are interested in analysing those effects that have been confirmed to have an impact on human health and which can be possibly modelled for their analysis in LCA and specifically in the life cycle impact assessment (LCIA) phase.

1.2.5. Sound and noise metrics and rating indices

The physical quantity which is of interest for the quantification of noise is sound pressure, defined as the incremental pressure due to the passage of the sound wave in the air, oscillating above and below ambient pressure (Ouis, 2001). Sound pressure level (Lp) is defined as:

$$Lp = 10\log\left(\frac{P^2}{P_{ref}^2}\right) = 20\log\left(\frac{P}{P_{ref}}\right) \tag{1}$$

where p is the sound pressure in Pa. The logarithmic unit is used to account for the large scale of the human sound pressure sensitivity and $P_{ref,}$ which is equal to $2*10^{-5}$ Pa, usually considered as the the lowest sound pressure detectable by the human ear (Lp = 0 dB). In other media (e.g. underwater) a different reference might be used. The sound pressure level is a dimensionless quantity (the logarithm of the ratio of two pressures), but the unit-like indication dB (decibel) is added to indicate the logarithmic scale. The multiplication by 10 is related to the choice for decibel instead of bel and it is then multiplied by a factor 2 following common properties of the logarithm function.

In subsequent elaborations, Lp has been refined to take into account the time-dependent character of noise, with differences of impact on human health and of response to noise identifiable with nocturnal and diurnal noise, and also to take into account the duration of the noise itself.

So-called A-weighting mode, expressed in dB(A), is the type of scale introduced to account for the subjective nature of noise exposure, which represents sound pressure levels at different frequencies comparable to that of the human hearing organ and its lower sensitivity to high and low frequencies (Passchier-Vermeer and Passchier, 2000). Together with the A-weighting mode a scale of octave bands frequencies or one-third octave-band frequencies is commonly selected, taking into account a specific range of frequencies, with a lower cut-off frequency and an upper cut-off frequency selected according to the specific objective of the measurement (e.g. target subject).

The Equivalent Continuous Sound Pressure Level (Leq) measures the A-weighted sound pressure level over a specified time of measurement T, which can be taken as 1, 8 (i.e., working day), 12, or 24hrs:

$$Leq = 20\log\left\{\left[\left(\frac{1}{T}\right)\int_0^T P_A(t)dt\right] / P_{ref}\right\} \tag{2}$$

where $P_A(t)$ represents the instantaneous A-weighted sound pressure in Pascal and T is a specified time interval. Penalties are introduced by other measures to account for exposures happening at specific times of a day. This is the case of Ldn, which represents the day-night level and accounts for an increased penalty of 10 dB(A) between 11PM-7AM. Similarly, Lden, the day-evening-night level, uses an analogous construction but sound levels during the evening, between 7PM-11PM, are increased by 5 dB(A), and those between 11PM-7AM are increased by 10 dB(A).

For single noise events the preferred measure is the sound exposure level (SEL), which is the equivalent sound level during an event (e.g. the overflight of a plane) normalised to a period of 1 second (Passchier-Vermeer and Passchier, 2000). In general, as established with the Directive on Assessment and Control of Environmental noise EC-2002/49 (EC, 2002), Lden proved to be a good indicator for long term effects and especially annoyance.

The study of noise levels, exposure and human health led to the definition of synthesis curves that quantify the exposure-response relationship of subjects exposed to variable levels of noise. Relations for which sufficient quantitative data are available typically regard transportation noise. Miedema and Vos (1998) integrated the results from 55 different datasets on noise and established summarizing functions to quantify the relationship between annoyance and the incidence of noise, developing a measure of the percentage of highly annoyed people (%HA) as a function of the Lden level. Criticism has been in the past raised (Probst, 2006) over the use of the %HA as a measure of the effect of noise on humans with the consideration that the metric provides a weak weighting of noise levels and does not reflect the perception of the local communities over the noise level experienced. However a position paper of the European Commission (EC, 2002) and a guide on good practices on noise exposure and effects by the European Environment Agency (2010) included the %HA as a suitable measure but considered also a larger number of endpoints with a dose-effect relationship. Noise-induced behavioural awakenings, chronic increase of motility, self-reported sleep disturbance, learning and memory difficulties and increased risk of hypertension were found to have sufficient evidence of dose-effect relations or of a threshold value.

Monetised estimates of health damages, also referred to as external costs or externalities (Navrud, 2002; ExternE, 1995), are commonly used to associate an economic value to the impact of a xenobiotic substance or a pollutant (e.g. noise) onto human health and quantify a loss in life quality in monetary units. Cost-benefit analysis represents a form of evaluation in which the health and non-health aspects of the exposure to a pollutant are evaluated in monetary terms. The procedure allows for an easier inclusion of non-health aspects for the evaluation of criteria such as well-being, personal life satisfaction, and productivity (de Hollander, 2004). These analyses include the willingness to pay (WTP) of households for a reduction of the noise level in a specific area, measured in euro per dB per household per year, and the willingness to accept (WTA), related to the acceptance level of individuals of the risk to which they are exposed, with the focus often oriented to evaluate productivity loss and health care use as a consequence of health impairment or non-health burdens (Krupnick and Portney, 1991; de Hollander et al., 1999).

Health adjusted years (HALYs) are generally the human health metrics used to transform any type of morbidity, including health issues from noise exposure, into an equivalent number of life years lost (Hofstetter and Hammitt, 2002). To the macro-category of HALYs belong quality adjusted life years (QALYs) and disability adjusted life years (DALYs). QALYs measure the actual health quality integrated over time, which usually requires variations and adjustments for the time preference of individuals or societes (Hofstetter and Hammitt, 2002; see Pliskin et al., 1980 for a theoretical basis of the measure). DALYs refer to the loss in health that an individual would be exposed to in the case of a morbidity compared to a hypothetical profile of perfect health which would have died at a standard expected age; they are the sum of years of life lost (YOLL) and the number of years lived with a disability (YLD).

Both cost-based and health-adjusted life years find methodological objections (Diener et al., 1998) in the literature, which usually include the consideration of the limited reliability of questionnaire-based surveys and the consideration of health as an economic good (de Hollander and Melse, 2004), as well as the substantial uncertainty related to the measures even though found to be less than one order of magnitude (Burmaster and Anderson, 1994). Equity principles and morale often come into the argument of one choice to be made over the other or to exclude both of them on the basis of various reasons. For the context of this article a detailed exemplification of the pros and cons of the methodologies described is not considered beneficial towards the improvement of the state-of-science in the field of LCA and noise, since both measures provide a useful framework for the explicit evaluation and comparison of health impairments associated with environmental exposures (de Hollander and Melse, 2004).

1.3. Sound and noise in LCA

1.3.1. The current situation

Compliance to the ISO standards is often seen as a fundamental measure of quality for LCA studies. ISO 14’040 (2006) and ISO 14’044 (2006), together with the setting of the standards for LCA, specified the feature and the phases of the analysis, including the description of the life cycle inventory (LCI) and of the life cycle impact assessment (LCIA) phases. The addition of the effects on human health due to exposure to noise, also according to the ISO standard requirements, should – whenever possible – be assessed in the LCIA phase and data regarding noise included in LCI. Nevertheless, in the words of Franco et al., (2010) “several methodological shortcomings still hinder the inclusion of transport noise as an established impact category within life cycle assessment” and “earlier attempts […] yielded valuable results […], but these were of limited use in the context of everyday LCA practice”. This remark highlights two main aspects of how research in the field of noise and LCA has progressed.

The investigation of possible ways of incorporating the evaluation of noise into LCA has considered primarily and almost exclusively “transport noise” (or traffic noise as it is often referred to) losing the focal point that noise effects in LCA need to relate to the functional unit, which is the transport and not the traffic situation (Althaus et al., 2009a). The two terms, “traffic” and “transport”, seem to overlap in the literature, while a distinction should be made to stick to the process causing the noise and not to the situation in which the event takes place. It is necessary to evaluate for each specific life cycle under investigation what sources of noise is preponderant and develop a method that could be applicable to any noise situation relevant to the LCA practice.

The second element emerging from the words of Franco et al. (2010) is the limited use in the everyday LCA practice of the results so far available in the field, still not allowing for a revision of already available LCA analyses. Characterization factors of the impact category noise are still not included in the main LCIA systems and few studies have developed models and software of limited use in common practice and that do not yet provide application to upscaled and larger systems at a European and World level (LC-IMPACT, 2010), nor do LCI databases which do not include data on noise. Back in 1993, Fava et al. already concluded that "a few processes – blasting minerals, for example – require attention, and certain products – for example, gasoline-powered lawn mowers, leaf blowers, edging tools [...] should be included in an LCA if feasible".

Althaus et al. (2009a) reviewed the methodology and state-of-science for the integration of traffic noise in LCA. Strengths and weaknesses of 66 LCA case studies were studied and combined with data regarding the study of LCA and traffic noise to define a set of requirements, thus a "profile for noise inclusion methods for LCA" (see p.564, Althaus et al., 2009b). Even though the profile was seemingly not directly referring to a specific type of noise, but generally to "noise inclusion", the list is specific to the traffic/transportation noise inclusion in LCA. Five different methodologies were analysed in detail to check for their coherence with the explained requirements, covering the whole spectrum of methods available in the field of study of traffic noise and LCA: CML guide for LCA (Guinée et al., 2001); Ecobilan method (Lafleche and Sacchetto, 1997); Danish LCA guide method (Nielsen and Laursen, 2005); Swiss EPA method (Muller-Wenk, 2002, 2004); Swiss FEDRO method (Doka, 2003). Among these methods, only the CML guide for LCA seems to focus on the consideration of the physical nature of sound/noise, and on the construction of an indicator that could be used for any stationary source of noise. Althaus et al. (2009b) also propose a framework, which is consistent with the requirement profile individuated and based on the Swiss EPA method. The method is adequate for the consideration of "generic and specific road transport" and, following Muller-Wenk's method (2004), focuses on the consideration of additional noise emissions due to additional vehicles, based on the official Swiss emission model SonRoad (Heutschi, 2004b). The proposal allows for a specific consideration of various vehicles, contexts and traffic situations in terms of space, time, speed and volume, but it does not take into account noise from mixed transportation (Lam et al. 2009). Percentage of highly annoyed individuals (%HA or frequently disturbed or instantaneously disturbed) and DALYs are the measures commonly used in the methods for the evaluation of impacts on human health at various levels of noise.

On the same lines moved Franco et al. (2010), who expanded on the work of Muller-Wenk by incorporating state-of-the-art noise emission models of the series of "improved methods for the assessment of the generic impact of noise in the environment" (IMAGINE, 2005, 2007a, 2007b).

In the above mentioned methodologies, background is dealt with (or not as in Guinée et al., 1992 and Doka, 2003) in various manners and commonly the background situation defines a baseline condition and starting point from which developing the calculations. The Danish LCA guide method (Nielsen and Laursen, 2005) explicitly considers the impact of noise on humans as a function of the part of the noise exceeding the background noise level (Althaus et al., 2009). Muller-Wenk (2002, 2004) evaluates the background noise situation through the use of data calculated by available computer models using pre-existent traffic intensities and ground properties at specific locations. Franco et al (2010) take background noise into account and incorporate it in their developed methodology by comparing the impacts of various specific traffic scenarios with or without (i.e. with the sole consideration of the background noise level) the consideration of a specific traffic flow. Lafleche and Sacchetto (1997) consider calculated or measured noise levels along roads as their starting point for the calculation of the area affected by a noise level above a defined threshold (Althaus et al., 2009a).

On the impact side, the impact of noise on human health is quantified in terms of the number of annoyed people, using solely annoyance as a comprehensive indicator of impact and Lden as a descriptor of noise levels.

The methods presented in the review by Althaus et al. (2009a) and the work by Franco et al. (2010) represent the full spectrum of methods currently available in the field of LCA and noise.

One approach needs to be highlighted. Meijer et al. (2006) describe how the LCA of dwellings could incorporate health effects of traffic, not as part of the life cycle of these dwellings (so not relating to the transport for the materials of the house), but for other life cycles, which just happen to have impacts for the residents of these dwellings.

1.3.2. Requirements for the assessment of noise in LCA

Ensuring the wide applicability of a noise evaluation models in LCA (Althaus et al., 2009b) means that we should allow for the consideration of any type of noise which is proved to cause harm to human health. We can translate this into the following fundamental requirements:

1. Consideration of generic and specific sources of noise in LCA
2. Separate treatment of different routes of noise emission within a LCA analysis
3. Accounting for noise emissions from activities in different geographic contexts and evaluation of differences in noise-treatment policies
4. Accounting for different temporal and spatial contexts of noise emission and impact on human health
5. Accounting for all the activities in the life cycle which can be associated with a noise emission, with particular attention to cases of noise levels above a given threshold
6. Extendibility to other target organisms

The first requirement ensures the accuracy of data included in LCA studies, with the focus placed on considering any source of noise. Separate treatment of emission routes ensures that all the possible routes of noise emission, deriving from the transportation of a product from A to B or from the laying of the groundwork of a building, are considered in a complete LCA. Different noise levels from activities have also to be considered among the characteristics and configuration of the context where the emission takes place. Spatial differentiation is fundamental in the context of noise in order to have a clear view of the measures in place at different locations (e.g. noise barriers) to protect citizens from being exposed to a source of noise and to account for the vicinity of the listener to the source when a noise event takes place. The temporal importance of the evaluation of noise levels has already been stressed in the previous sections, given the increased level in annoyance and stress levels verifiable in the occasion of a nocturnal noise event. Requirement 5 confirms the necessity of treating noise emissions as any other emissions in the life cycle. The flexibility (requirement 6) highlights what has been considered as a lack of already developed noise assessments available in the literature: in the future it should be possible to investigate, provided specific modelling adjustments, the impacts of noise on other organisms than humans.

The approach commonly in use in the context of LCA for chemical emissions can then be expanded to evaluate noise impacts, following the above-described requirements. In the procedure below, this parallel is described in detail using a multi-step approach, which takes into account the reviewed epidemiology of noise, the LCA and noise work previously analysed, and the theory described in the previous section of this paper.

1.3.3. Noise compared to emissions into the environment

For a comprehension of noise in the context of emissions it is fundamental to investigate useful areas of commonalities with, and distinction from, toxic compounds.

Given the physical nature of sound, noise obeys to the law of radiation, meaning that its intensity decreases as the distance from the source increases, with an effect localized in the immediate vicinity of the source itself, soon disappearing after the sound is produced (Muller-Wenk, 2002). On the contrary, typical distances between an emission source of a compound and its location of deposition can amount to several hundreds of kilometres (Potting et al. 1998). Phenomena that are typical of other compounds, in fact, such as dispersion, dilution, accumulation/bio-accumulation, sedimentation and deposition, adsorption or degradation assume different characteristics in the case of noise. Moreover, besides the energy content of a specific sound emitted by a source, it is essential to ponder other important pieces of information, such as the frequency structure, the volume over time, and site-specific factors (e.g. presence of sensitive groups or keynote sounds) that can influence the impact and the magnitude of it. For toxic releases, the emission compartment is quite important. For noise, we can restrict the discussion to air in the case of human health impacts, although a further refinement of the air compartment into urban and rural will be made, and an additional temporal specification (e.g., day, night) will be introduced. For a future extension to aquatic organisms (Anderson et al., 2011), we may need to include other compartments as well.

The LCA framework introduces a major break between inventory analysis and impact assessment. Inventory analysis looks at the elementary flows (or stressors or environmental interventions), i.e. the physical things taken from or introduced into the environment. It does so first on a per-unit-process basis, and later on aggregates them across the life cycle.

In the context of toxics, the emission in kg per type of pollutant (phenol, benzene, etc.) per compartment (air, water, etc.) is what is specified here. Additional descriptors may then be needed (e.g., distinguishing Cr(III) and Cr(VI), or rural and urban emissions). In the context of noise, the physical intervention is the sound level (e.g., in dB, or in energy units), with a possible addition of other descriptors (day or night, rural or urban, high or low frequency, etc.).

The impact assessment takes the inventory results as a starting point. Typical methods for the assessment of human toxicity in impact assessment are based on a causality chain (Udo de Haes et al., 2002), used to depict the changes in the quality of a natural environment. In principle, the same type of chain can be applied to the evaluation of noise impacts.

Four phases are considered in human toxicology as parts of a full causality chain. As correctly suggested by Muller-Wenk (2002, 2004), the same scheme can be adapted for the use in the context of the evaluation of noise emissions:

- **Fate analysis** refers to the change in concentration of a specific pollutant caused by a given emission. In the context of noise impact evaluation, the purpose of the analysis is to determine the increase of sound pressure levels if one or more processes in the life cycle determine noise production.

- **Exposure analysis** investigates the number of individuals (humans or other target subjects) affected by the change in concentration identified in the fate analysis. An increase in the sound pressure levels identified in the fate analysis has an impact on a quantifiable number of individuals.

- **Effect analysis** shows the effect of the increased concentration of a pollutant if humans (or other target subjects) are exposed to it for a given time lapse. The increase in the concentration of sound emissions (i.e. the marginal increase of sound levels above the background level) has various impacts on humans (or other target subjects), both psychologically and physiologically (see section 2), that are quantified at this stage of the analysis.

- **Damage analysis** describes the total measurable damage represented by the health effects considered in the previous analysis. The damages caused by the exposure to the noise sources/ noisy processes in the life cycle are in this phase evaluated to identify what type of diseases are identifiable on humans (or other target subjects).

1.4. General framework for sound emissions and noise impacts

1.4.1. Method overview

The framework here presented builds upon the considerations and the information commented in the previous sections. The breakdown of the various parts of the model starts by proposing a way in which sound can be dealt with in an inventory analysis, overcoming the issues of the common use of the logarithmic unit dB. A methodological proposal follows, which provides a theoretical way of calculating characterisation factors for the impact category *noise*, using a fate and effect factor (Pennington et al., 2004).

The methodology is based on the consideration of the variation of background sound levels at the emission compartment as a consequence of the presence of one -or more- sound emitting sources in the life cycle, which consequently determines a variation in the effect on humans at the exposure compartment where the sound propagates.

1.4.2. The inventory part for sound

The first question to address regards attaching sound to a unit process, in such a way that an aggregation across the life cycle can provide a starting point for the impact assessment. Even though sound is usually measured in dB, the sound pressure level is obviously not the right quantity to present, as it does not allow for an aggregation over the life cycle. Moreover, it lacks the aspect of duration of the sound.

Heijungs et al. (1992) stressed the necessity of translating a sound from dB into an additive scale and of incorporating the duration of the relative sound emission into an aggregate measure, and proposed the use of Pascals-squared-seconds. Similarly, in the field of occupational noise exposure, Drott and Bruce (2011) propose to use the Pascals-squared-seconds, or *pasques*. Pasques is an additive measure of sound exposure, therefore not suitable for the inventory of sound in a life cycle.

In common practice, a unit process is usually represented in number per unit output. This means that all data are related to that reference. When dealing with a permanently running steelworks which produces 500 kg/hr steel and needs 600 kg/hr iron, one typically converts the output of steel to 1 kg, thereby the input of iron is changed from 600 kg/hr into 1.2 kg of iron. It must be observed that not only the numerical value changes, but the unit also changes from a flow (kg/hr) into an amount (kg). If the process emits 10 kg/hr of a pollutant, this converts into 0.02 kg, and when it covers 800 m^2, this converts into 1.6 m^2*hr. If the process in question produces a sound output of a certain frequency (say, 1 kHz) of 90 dB, it does not make sense to convert this into 90/500 = 0.18 dB*hr. Rather, the sound power level of the source must be calculated and then converted to a quantity that can be added.

The sound power level calculated in dB is obtained by applying the following Eq. (3):

$$Lw = 10\log\left(\frac{W}{W_0}\right) \qquad (3)$$

where Lw is the sound power level in decibels, and W is the sound power in watt, produced by the source referred to a reference sound power (W_{ref}) of 1 picowatt (10^{-12} watt; ISO 1996), which is normally considered as the lowest sound discernible by a person with a good hearing.

Thus, by back transforming the value of the sound power level in dB to the sound power, or more precisely to its energy per unit of time, it is possible to obtain an addable quantity. This proceeds by:

$$W = W_{ref} \times 10^{Lw/10} \tag{4}$$

The analysis of the sound power of a process commonly requires, with the intent of reducing the calculation and time efforts, and given the wide variety of frequencies the human ear is subject to (i.e. from about 20 Hz to 20 kHz), the selection of a scale of frequencies, from f_n to f_{n+1}, determining a set of values of W and Lw to be contemporaneously evaluated (e.g. $W_{fn...fn+1}$). A scale of octave bands, meaning a frequency band with each progressive band having double the bandwidth of the previous, is usually considered handy for the analysis of the sound power level and in general of noise levels. The centre frequencies assigned for the bands covering the full range of human hearing are commonly the frequencies from 63 Hz to 8KHz (ISO 1996), which can be conveniently numbered from 1 to 8. The assignment of frequencies to octave bands thus proceeds according to Table 1.1.

Table 1.1. Definition of the octave bands (Ford 1970)

Octave band (i)	Centre frequency [Hz = s^{-1}]	Frequency range [Hz = s^{-1}]
1	63	44-88
2	125	88-177
3	250	177-354
4	500	354-707
5	1000	707-1414
6	2000	1414-2828
7	4000	2828-5656
8	8000	5656-11312

Thus, back to the previous example, the steelworks produces energy per unit of time of 0.001 J/s at, for instance, 1 kHz, so in octave band 5. Applying the conversion to the per-kg of steel, and then expressing it in joule further transforms this into:

$$\begin{aligned}
&(0.001\ J/s)/(500\ kg/hr) = \\
&= (0.001\ J/s)/(500\ kg\ /\ 3600\ s) = \\
&= ((0.001\ J)*3600)/(500\ kg) = \\
&= ((0.001/500)*3600)\ J = 7.20*10^{-3}\ J
\end{aligned}$$

Normal LCI routines are further applicable to scale these numbers to the functional unit, and to aggregate them for every unit process across the entire life cycle. This can be done for different categories of sound, e.g., for sound of high frequency during the night in an urban location, for sound of medium frequency during the evening in a forest, etc.

Thus, the inventory table (Table 1.2) contains sound items defined for the scale of eight frequency bands selected, expressed in J. Following the usual conventions in LCI, one can symbolise these by m_1, m_2, etc., where m_i indicates the emitted amount of type i, or alternatively by $m_{1,1}$, $m_{1,2}$, $m_{2,1}$, etc., where the first subscript refers to the type of emission (benzene, day-time frequency noise, etc.) and the second subscripts to the emission compartment (e.g. air, sea water, etc.), or further specify the sound items classifying the attributes considered (e.g. day, night, rural, etc., as in the example in Table 1.2).

Table 1.2. Example of an inventory table including also sound energy emissions in J per octave-band centre frequencies for a hypothetical life cycle

Symbol	Name (i)	Specification (c)	Amount	Unit
m_1	SO_2	high population density air	23	kg
m_2	SO_2	low population density air	10	kg
m_3	Cr III	fresh water	0.5	kg
m_4	Octave 1	urban, day	$8.33*10^{-3}$	J
m_5	Octave 2	urban, day	$7.20*10^{-3}$	J
…				
m_8	Octave 5	urban, day	$7.20*10^{-3}$	J
…				
m_{11}	Octave1	rural, day	$5.50*10^{-3}$	J
m_{12}	Octave2	rural, day	$5.30*10^{-3}$	J
…	…			
m_{19}	Octave 1	rural, night	$3.20*10^{-3}$	J
…				

1.4.3. The characterization factor

The characterization factor (CF) for the assessment of noise emissions can be calculated using a fate and effect factor, Eq. (1), according to the classical LCIA characterization scheme (Pennington et al. 2004), as in Eq. (5):

$$CF_{i,c} = \sum_{f} \left(FF_{i,c,f} \times EF_{i,f} \right) \qquad (5)$$

where FF is the fate factor and EF the effect factor, i is the inventory item in compartment c, and f the final compartment after the fate step, where the target(s) is assumed to be exposed. Thus the fate factor FF models how inventory item i moves from compartment c to compartment f and the effect factor EF how serious the effect is for the population living at f and exposed to i.

Below, we elaborate the two steps of fate and effect for the conceptual sound-noise model.

1.4.4. The fate factor

In the context of toxics, the fate factor for a substance i is defined as the factor that measures how a change of continuous release to compartment c ($\Phi_{i,c}$) will result in a change of the steady-state concentration in compartment f ($C_{i,f}$):

$$FF_{i,c,f} = \frac{\partial C_{i,f}}{\partial \Phi_{i,c}} \qquad (6)$$

Multi-media fate models, such as EUSES (Vermeire et al., 1997), contain expression for $C_{i,f}(\Phi_{i,c})$. The fate factors will embody aspects of fugacity (how willing is a chemical to move from one compartment to another one) and degradability (how stable is a chemical in a specific compartment).

In the noise context, the development of theoretical models for the measurement of sound propagation from sources to receivers at various distance, impedances and contour characteristics (Boulanger et al., 1997; IMAGINE, 2005,2007a, 2007b), and that of methods aiming at evaluating the attenuation of noise with distance (Delany et al., 1976), together with the specialist production in sound propagation manuals (see for instance Ford 1970) are a consolidated science of acoustics. For the purpose of LCA, ISO 9613-2 (ISO, 1996) provides a more flexible and practical engineering method that can be used for predicting the long term average sound pressure level under defined conditions from a source of known sound power emission. Any source is defined as a point source or as an assembly of point sources, moving or stationary, making the standard suitable for overcoming methodological limitations in assessing noise impacts in LCA and able to follow the requirements defined (section 3.2). At this stage of the development, the ISO 9613-2 standard allows for the development of a generic structure that is able to encompass any situation of emission and propagation, being it determined by a single source or by an assembly of point sources each with directivity or propagation properties and in principle contributing to the overall sound emission. The model will be in the future supported, for the determination and calculation of specific variables and components (see Table 1.3), by findings of the international project IMAGINE (2007a, 2007b).

We propose, therefore, to use the long-term average sound pressure level (Lp) per octave-band i, as specified by ISO 9613-2, as a basis for the modelling of fate, adapting the notation when needed for disambiguation purposes. For the quantification of the Lp, in dB, we follow the procedure suggested by the ISO 9613-2 standard. We start by calculating the equivalent continuous octave-band sound pressure level at the final compartment f from Eq. (7):

$$Lp_{i,f} = Lw_{i,c} + D_{i,c,f} - A_{i,c,f} \tag{7}$$

Here, $Lw_{i,c}$ is the sound power level as described in Eq. (3). $D_{i,c,f}$ is the directivity correction, in decibels, that describes to what extent a deviation of sound pressure level occurs in a specified direction from the source of sound power level $Lw_{i,c}$. The directivity correction D is 0 dB for an omnidirectional sound emitting source. $A_{i,c,f}$ in Eq. (7) is the octave-band specific attenuation, in decibels, occurring during the propagation of sound from source to receiver and it is given by the contemporary consideration of several attenuation factors, which include geometrical divergence, atmospheric absorption, meteorological variation, presence of barriers, miscellaneous other effects, etc. The methodology can be adapted to be used for any generic source of sound, including that generated by transportation, with the introduction of transportation means-specific attenuation and propagation parameters. Given that Lp is expressed in dB a conversion will be needed to have the sound pressure expressed in pascal and therefore comparable with the sound power emission (W) gathered in the inventory phase. Recalling the definition of sound pressure level as presented in section 2.5, in Eq. (1), and that of sound power level in Eq. (3) we obtain:

$$\begin{aligned} P_{i,f} &= P_{ref} \times 10^{Lp_{i,f}/20} = \\ &= P_{ref} \times 10^{\left(Lw_{i,c} + D_{i,c,f} - A_{1,c,f}\right)/20} = \\ &= P_{ref} \times 10^{\left(Lw_{i,c}\right)/20} \times 10^{\left(D_{i,c,f} - A_{1,c,f}\right)/20} = \\ &= P_{ref} \times \sqrt{\frac{W_{i,c}}{W_{ref}}} \times 10^{\left(D_{i,c,f} - A_{1,c,f}\right)/20} = \\ &= \frac{P_{ref}}{\sqrt{W_{ref}}} \times \sqrt{W_{i,c}} \times 10^{\left(D_{i,c,f} - A_{1,c,f}\right)/20} \end{aligned} \tag{8}$$

Here $P_{i,f}$ is the sound pressure, in pascal, in octave band i at compartment f relative to a reference sound pressure, P_{ref}, of $2*10^{-5}$ pascal (ISO 1996), while $W_{i,c}$ is the sound power, in watt, in octave band i at compartment c. The factors $D_{i,c,f}$ and $A_{i,c,f}$ thus serve to translate how much sound power from a source at c reaches a target at f.

The fate factor is now defined as the marginal increase of the sound pressure at f due to a marginal increase of the sound power at c, evaluated at the background level $W_{i,c}=Wamb_{i,c}$:

$$FF_{i,c,f} = \left(\frac{\partial P_{i,f}}{\partial W_{i,c}}\right)_{W_{i,c}=Wamb_{i,c}} = \tag{9}$$
$$= \frac{P_{ref}}{\sqrt{W_{ref}}} \times \frac{1}{2\sqrt{Wamb_{i,c}}} \times 10^{\left(D_{i,c,f}-A_{i,c,f}\right)/20}$$

The fate factor is measured at c given the ambient condition before the functional unit under investigation is introduced into the system, therefore the fate factor reflects the marginal increase in the total ambient sound power at c.

As P_{ref} and W_{ref} are given, this reduces to

$$FF_{i,c,f} = \frac{C_{ref}}{\sqrt{Wamb_{i,c}}} \times 10^{\left(D_{i,c,f}-A_{i,c,f}\right)/20} \tag{10}$$

where C_{ref} is 20 Pa*$W^{-1/2}$. The unit of the fate factor is Pa/W: it brings about the conversion of a source sound power in W to a target sound pressure in Pa. Therefore a sound power "emitted" by a generic source in the life cycle at compartment c (e.g. rural day), being it a machine, a truck, a train, etc. or a combination of them is diffused into air and propagates through the medium and reaches compartment f, attenuated by the direction of emission from the source and by a series of attenuation factors (e.g. meteorological, physical, etc.) which determine a variation of sound pressure at f. It has to be noticed that the fate factor is a function of the sound power $Wamb_{i,c}$. This is not the case for the linear multi-media models that are used for toxicity assessment, but it is not strange in itself. Toxicity models in LCA often employ a non-linear dose-response relation for the effect factor (Huijbregts et al., 2011), but not for the fate factor. We should understand the $Wamb_{i,c}$ as the background level to which a marginal change is added. So, it is not case-dependent, but it obviously depends on the compartment (location) of emission c, and on the octave band i. Background levels of sound pressure may be obtained from noise maps, where noise exposure data by different noise sources and noise assessment data at a European level have been collected for most European countries (EEA-ETC LUSI, 2010).

1.4.5. The effect factor

In LCIA, the effect model transforms the results of the exposure step (the dose) into a measure of impact. For toxics, a usual way to do so is to divide the dose for a chemical by a critical level, say the EC50 or HC5, of that chemical. In that way, different types of chemical are “normalized”. This can be interpreted as a conversion step transforming the dose into an “effective” dose, where the intrinsic harmfulness of the chemical is used to establish the relative weight of a chemical.

For the effect step in the noise model, we do a similar thing. The effect of the exposure to noise depends on three aspects:

- the aspect of the frequency-dependency of perception by humans;
- the aspect of the time of the day of the exposure;
- the aspect of the number of humans that are exposed in the target area.

Because the effect indicator we develop corrects the sound levels at a target location into “effective” sound levels, the unit of the category indicator results will still be pascal-like, so looking like an exposure indicator, but in fact representing an effect indicator.

Following the specifications above, the sound pressure level in octave band i at compartment f, $Lp_{i,f}$, is perceived differently for different octave bands. The A-weighting provides standardized weighting factors for this (Fletcher and Munson 1933; ANSI 2001).The A-scale weighting factors for octave band i is denoted as α_i, and is added to $Lp_{i,f}$ to obtain the frequency-corrected sound pressure level $Lpf_{i,f}$, (for which the “unit” dB(A) is typically used):

$$Lpf = Lp_{i,f} + \alpha_i . \tag{11}$$

To account for the fact that sound emissions influence the life of individuals differently according to the time of the day the emission takes place, the value of $Lpf_{i,f}$ is further corrected by a penalty that is zero for daytime and non-zero in the evening and at night (Ouis 2001; see section 2.5 of this article). Thus, Eq. (11) transforms as:

$$Lpft_{i,f} = Lp_{i,f} + \alpha_i + \beta_f \tag{12}$$

where β_f represents the time weighting of the sound. For the frequency-and time-corrected pressure, Pft, back transforming the dB into pascal applying the definition of sound pressure level, we thus obtain

$$\begin{aligned} Pft_{i,f} &= P_{ref} \times 10^{Lpft_{i,f}/20} = \\ &= P_{ref} \times 10^{(Lp_{i,f}+\alpha_i+\beta_f)/20} = \\ &= P_{ref} \times 10^{(Lp_{i,f})/20} \times 10^{(\alpha_i+\beta_f)/20} \end{aligned} \tag{13}$$

The third aspect of the number of targets is introduced by multiplying the total value of Pft at f by the number of people living in compartment f, N_f:

$$PP = \sum_f \left(N_f \times \sum_i Pft_{i,f} \right) \tag{14}$$

where PP is interpreted as the person-pressure of sound, which is measured in person-Pa.

The effect factor is introduced as the marginal change in person-pressure due to a marginal change in the sound pressure of octave band i at compartment f:

$$EF_{i,f} = \frac{\partial PP}{\partial P_{i,f}}. \tag{15}$$

As the complete formula for "dose-response" is

$$PP = \sum_f \left(N_f \times \sum_i \left(P_{ref} \times 10^{(Lp_{i,f})/20} \times 10^{(\alpha_i + \beta_f)/20} \right) \right) \tag{16}$$

the effect factor becomes

$$EF_{i,f} = N_f \times 10^{(\alpha_i + \beta_f)/20}. \tag{17}$$

The effect factor is thus strikingly simple: it contains just the A-scale weighting for octave band i (α_i), the day/night weighting (β_f) and the number of people living in compartment f (N_f). The unit of the effect factor is *person*, thus it represents, given the population at f, the number of people that are exposed to a variation in sound pressure at compartment f corrected according to the sensitivity to the frequency composition of the emission and the time of the day of the exposure.

1.4.6. The midpoint characterization factor and its use in LCIA

For midpoint characterization, the usual structure applies. The characterization factor is

$$CF_{i,c} = \frac{C_{ref}}{\sqrt{Wamb_{i,c}}} \times \sum_f 10^{(D_{i,c,f} - A_{i,c,f})/20} \times N_f \times 10^{(\alpha_i + \beta_f)/20} \tag{18}$$

The summation over the emission compartment *f* allows for the evaluation of the total impact of the sound emission on the target subjects living at *f*. The compartment can be spatially identified and defined as urban, rural or off-shore, or, with a finer grain of definition, further divided to incorporate a higher level of detail.
The unit of the characterization factor is person-Pa/W. It is applied in an LCA by means of

$$HN = \sum_i \sum_c CF_{i,c} \times m_{i,c} \tag{19}$$

where HN represents the noise impact to humans. As the sound emission $m_{i,c}$ is measured in J, the impact NH has the unit person-Pa/W*J = person-Pa*s. It can be interpreted as the number of people that are exposed to a certain sound pressure for a certain period of time.

The characterization factor looks complicated, so let us see what is needed to tabulate lists of such factors, as has been done for established impact categories, like global warming and toxicity. We need to specify the archetypical emission and exposure compartments c and f. For instance, one could choose here to define three spatial and three temporal situations: urban, rural and off-shore, and day, evening and night. For the frequencies i, we already chose for the eight frequency bands of Table 1. Six sets of numbers have to be listed; see Table 1.3.

Table 1.3. Values and possible sources for the parameters of the characterization factor

Parameter	Value	Source
α_i	{-26.2, -16.1, -8.6, -3.2, 0.0, 1.2, 1.0, 1.1} [dB]	ANSI, 2001
β_f	{0, 5, 10} [dB]	Ouis, 2001
N_f	to be elaborated	Gridded population of the world, CIESIN, 2011
$A_{i,c,f}$	to be elaborated	ISO9613-2(ISO, 1996) IMAGINE (2007a; 2007b)
$D_{i,c,f}$	to be elaborated	ISO9613-2(ISO, 1996) IMAGINE (2007a;2007b)
$Wamb_{i,c}$	to be elaborated	Noise maps, EEA-ETC LUSI 2010

Some of the data present in Table 3 requires the combination and gathering of various sources of information. Some of the data in question is usually available in the form of GIS maps with a variable level of grid mesh. This is the case of the number of people living at the exposure compartment, N_f, and of the background noise levels, $Wamb_{i,c}$ available in the form of noise maps. The values of $A_{i,c,f}$ and $D_{i,c,f}$ depend on the location of emission and exposure and can be derived from the application of the ISO9613-2 and of the findings of the IMAGINE project (2007a, 2007b) to the archetypical compartments to be developed.

With a choice of three spatial and three temporal compartments and eight octave bands, there are no more than 72 characterization factors. In this way, applying the characterization step requires a simple and concise recipe.

1.5. Noise impact model development and future research agenda

The structural framework presented in section 3 represents the first step of a development process which will culminate in the creation of a working mathematical model, together with its elaboration and application to case studies, which will possibly allow for the determination of a *noise footprint* of a life cycle. The flexibility of the framework structure will allow for its expansion and adaptation for the incorporation of previous work and new contributions in the field, with particular attention to results obtained by international EU projects which have obtained significant results in proposing suitable methods for the measurement of sound propagation from various sources. The proposed model allows for the measurement of the sound emission from a single sound-emitting source or multiple sources present at the emission compartment. However, as in the case of models dealing with the combined emission of chemicals, the summation of multiple sources can lead to an extremely high noise *concentration* in the studied environment. At this stage of development, the model does not discriminate between possible synergistic, antagonistic, or interference effects of the emitting sources, but logarithmically treats their impacts.

The overall uncertainty of the model has not been tackled in this contribution, although it is of fundamental importance to deal with uncertainty in any LCA contribution. Given the complexity and the extension of such analysis, we reserve to conduct it in our follow up research. The use of techniques such as global or local sensitivity analysis (Heijungs and Huijbregts, 2004; Saltelli et al., 1999) can help to perfect the model performance and applicability. The study of the impact of the variation of the model input, considered the methodological, temporal and geographical variability of the model, will ensure to study how uncertainty of the input propagates to the variance of the model output and will allow to propose accurate characterisation factors for noise impacts. Similarly, the risk of underestimation of the impact, which applies to all data systems, will be taken into account in the characterization of noise. In the case of noise measurement, average values could portray a modelled system which in reality has a much higher impact on the health of the exposed population. Blast noises, for instance, which are common in the mining or construction sectors, are the result of sudden emissions which follow moment of silence. Therefore, averaging a value over time could underestimate the effective proportion of the impact.

For the noise impact on humans, in contrast to many traditional impact categories, we have not introduced a dimensionless potential, like the global warming potential (relative to CO_2 to air) and the human toxicity potential (relative to, e.g., dichlorobenzene to air). For reasons of consistency, it would be reasonable to do the same and reformulate the characterization as

$$HNP_{i,c} = \frac{CF_{i,c}}{CF_{ref_i,ref_c}} \tag{20}$$

where HNP represents the human noise potential, related to a unit of sound emission in a predefined reference octave band and in a predefined reference compartment, for instance 1 kHz at urban day-time. The result of the characterization would in that case not be expressed in person-Pa*s, but in J-equivalent of the reference sound, just as the GWP yields a result in kg-equivalent of CO_2.

Our idea at this moment is not to use the dimensionless potential for noise, but to use the (admittedly abstract) person-Pa/W for the characterization factors and the person-Pa*s for the characterization results, while having J as unit for the inventory. Furthermore, in order to develop a methodological solution for the quantification of noise impacts, it is fundamental to gather information about the background or ambient condition of the area where the sound event takes place. The importance of the specific location of exposure has been stressed in section 2.2, where auditory cognition concepts as soundmarks and keynote sounds have also been defined. Key elements of the location of emission (e.g. time of day) have to be defined to incorporate the subjective impact of noise in the analysis . The characterization factor developed allows for the evaluation of location-specific features of the emission. LCA tries to measure marginal changes, on a background situation subject to environmental interventions, even in circumstances in which they are relatively small and diminishing with increasing distance from the source (Verones et al., 2010). In our framework the fate factor is calculated considering that the emission compartment is already sonically perturbed and that the increase of pressure at exposure compartment is dependent on the increase of power at the emission compartment. As for the effect on humans, corrections have been applied to the sound pressure calculation to make it as adherent as possible to the human perception of sound/noise as identified in common epidemiological practise.

The calculation of the CF for noise impacts on human subjects allows for a midpoint characterization, though a possible extension of the framework from midpoint to endpoint level could be applied, with specificities to be further investigated with respect to the relationship between DALYs and the morbidities highlighted in the sections 2.3 and 2.4 of this article.

WHO (2011) selected (among the outcomes earlier reported) cardiovascular disorders, cognitive impairment, sleep disturbance, tinnitus and annoyance as consequences of noise to focus research on, giving details on appropriate measures and indexes to be used case by case and with detail of DALY estimates when possible. Estimated DALYs for western European countries were respectively: 60000 years for ischaemic heart disease, 45000 years for cognitive impairment of children, 903000 years for sleep disturbance, 21000 years for tinnitus and 587000 years for annoyance. All impacts in total ranged between 1.0 and 1.6 million DALYs. WHO data should be further analysed in details. If DALYs caused by environmental noise are compared with those from other pollutants, it is important to take into account the approximations and assumptions made in the calculation process. There are, in fact, several uncertainties, limitations and challenges which have to be taken into account for the selection of health effects. Unfortunately, the quality and the quantity of the evidence and data are not the same across the different health outcomes and derived from a limited pool of studies. Possible confounding factors should be taken into account in the analysis. These include age, gender, smoking, obesity, alcohol use, socioeconomic status, occupation, education, family status, military service, hereditary disease, use of medication, medical status, race and ethnicity, physical activity, noisy leisure activities, stress-reducing activities, diet and nutrition, housing condition and residential status (WHO 2011). Other stressors like air pollution and chemicals might be considered in the context of combined exposure with noise. A further point to consider with respect to variability is that psychoacoustical variations (see, for example, Moore 1989) should be taken into account for the analysis to be as much as possible reflective of the effective perception of noise by humans, and should possibly be included in future expansions of the framework.

A-weighting and temporal corrections, in fact, do not fully cover the complete range of variations of human perception and relative response to a sonic event. Events with similar sonic features and similar sources that produce them can be perceived differently by different individuals and determine different stimuli and sensations (e.g. at equal contour conditions, a modern and fast train is pleasant, while an old and ugly one is unpleasant). The extent to which this is feasible is at this stage not clear.

As described in section 2.5 of this chapter, dose-effect curves for a generic noise health effect supported by quantitative data are commonly available for effects attributable to Lp determined by transportation noise. Curves can be re-set and converted to Pa and variation of dose-effect relationships calculated per variation of sound pressures in Pa. Further research, also taking into account the precautions mentioned, is needed for other sources than transport related ones.

Given the stochastic nature of noise effects on humans, meaning that we have statistical evidence of the existence of some effects but we lack a deterministic link between severity/effect and exposure (Bare et al., 2002), uncertain estimates need to be made to move to an endpoint level. Potting, in Bare et al. (2002), suggests that a combination of "the spatial differentiated or site-dependent midpoint modelling with the site-generic endpoint modelling" would be desirable. In the context of noise the midpoint could then be translated, bearing in mind the introduction of extra uncertainty into the system, into an endpoint, requiring the calculation of a damage factor for human health, by using the DALY scale and a convenient health damage model.

Given the number of people, N, living at compartment f we can evaluate through PP the number of people who are exposed to a sound pressure in pascal. Individuals will be exposed to a different noise-related morbidity to which a year of life lost, or a fraction of it, can be associated. The morbidity could be intended as a statistically defined function linking the person-pascal at compartment f to the disability adjusted years given the composition of the population. At this stage the damage factor is just touched on and will be further developed in our future work (see Chapter 2).

Advancements in the modelling of noise impacts still require the development of research in some key fields. On the inventory side, there is a lack of sound emission data for unit processes outside the highly analysed transportation field. At a midpoint level impacts can already be highlighted through the framework , but dose-response curves need to be re-set. Furthermore, research should be oriented towards translating new epidemiological findings, where possible, into dose-response relationships, in turn translatable, if necessary, into the DALY scale. For the expansion of research to the evaluation of the impacts of noise on the quality of eco-systems and other subjects than humans, it would be necessary to incorporate in the analysis epidemiological data on ecosystems, which has not been systematically organised yet, in order to stress similarities and singularities of impacts on humans and impacts on ecosystems. As reported in section 2, on-going studies are already investigating the field with interesting results that could be incorporated in the model. In principle, the framework provided could be adapted with minor changes (e.g. different frequency correction) to non-human populations, providing the basis for future work in the field of LCA and noise impacts on the survival of ecosystems.

Acknowledgments for chapter 1

We would like to warmly thank Prof. Dr. Geert de Snoo from the Institute of Environmental Sciences – CML of the University of Leiden and Dr. Ralph Rosenbaum from the Technical University of Denmark for the helpful and detailed comments provided. Sincere thanks to the reviewers who thoroughly checked the logic and the mathematics of the model and helped us to improve the paper.

1.6. References

Adams M et al (2006) Sustainable Soundscapes: Noise Policy and the Urban Experience. Urban Stud 43(13): 2385-2398

Althaus HJ, De Haan P, Scholz RW (2009a) A methodological framework for consistent context-sensitive integration of noise effects from road transports in LCA. Part 1. Requirement profile and state-of-science. Int J Life Cycle Assess 1:218-220

Althaus HJ, De Haan P, Scholz RW (2009b) A methodological framework for consistent context-sensitive integration of noise effects from road transports in LCA. Part 2. Analysis of existing methods and proposition of a new framework for consistent, context-sensitive LCI modelling of road transport noise emission. Int J Life Cycle Assess 14:560-570

Anderson PA, Berzins IK, Fogarty F, Hamlin HJ, Guillette LJJ (2011) Sound, stress, and seahorses: The consequences of a noisy environment to animal health. Aquac 311(1-4):129-138

ANSI 2001 ANSI/ASA S1.42-2001 (R2011)-American National Standard - Design Response of Weighting Networks for Acoustical Measurements. ANSI, New York

Axelsson A, Prasher D (2000) Tinnitus induced by occupational and leisure noise. Noise Health 8: 47-54

Babisch W (2006) Transportation Noise and Cardiovascular Risk. Review and Synthesis of Epidemiological Studies, Dose-effect Curve and Risk Estimation. UBA [Federal Environmental Agency] Report

Babisch W (2008) Road traffic noise and cardiovascular risk. Noise Health 10 (38): 27-33

Babisch W, van Kamp I (2009) Exposure-response relationship of the association between aircraft noise and the risk of hypertension. Noise Health11(44):161-168

Babisch W, Fromme H, Beyer A, Ising H (2001) Increased catecholamine levels in urine in subjects exposed to road traffic noise. The role of stress hormones in noise research. Environ Int 26: 475-481

Babisch WF, Beule B, Schust M,Kersten N, Ising H (2005) Traffic noise and risk of myocardial infarction. Epidemiol 16: 33-40

Bare JC, Norris GA, Pennington DW, McKone T (2002) TRACI-the tool for the reduction and assessment of chemical and other environmental impacts. J Ind Ecol 6: 49-78

Berglund B, Lindvall T (1995) Community noise. Document prepared for the World Health Organization Archives of the Center for Sensory Research, 2(1). Centre for Sensory Research, Stockholm

Boulanger B, Watters-Fuller T, Attenborough K, Li KM (1997) Models and measurements of sound propagation from a point source over mixed impedance ground. J Acoust Soc Am 102:1432-1442

Bregman HL, Pearson RG (1972) Development of a Noise Annoyance Sensitivity Scale. National Aeronautics and Space Administration, Springfield

Brumm H (2004) The impact of environmental noise on song amplitude in a territorial bird. J Anim Ecol 73, 434-440

Burmaster DE, Anderson PD (1994) Principles of good practice for the use of Monte Carlo techniques in Human Health and Ecological Risk Assessments. Risk Anal 14:477-481

Chang TY, Su TC, Lin SY, Jain RM, Chan CC (2007) Effects of Occupational Noise Exposure on 24-Hour Ambulatory Vascular Properties in Male Workers. Environ Health Perspect 115:1660-1664

Chen GD, McWilliams ML, Fechter LD (1999) Intermittent noise induced hearing loss and the influence of carbon monoxide. Hear Res 138:181-191

Clark C, Stansfeld SA (2007) The effect of transportation noise on health & cognitive development: A review of recent evidence. Int J Comp Psychol 20(2):145-158

De Hollander AEM (2004) Assessing and evaluating the health impact of environmental exposures. PhD Thesis, Utrecht University

de Hollander AEM, Melse JM, Lebrte E, Kramers PGN (1999) An aggregate public health indicator to represent the impact of multiple environmental exposures. Epidemiol 10: 606-617

de Kluizenaar Y, Gansevoort RT, Miedema HM, et al. (2007) Hypertensionandroad traffic noise exposure. J Occup Environ Med 49:484-492

Delany ME, Harland DG, Hood RA, Scholes WE (1976) The prediction of noise levels L10 due to road traffic. J Sound Vib 48(3):305-325

Diener E, Sapyta JJ, Suh EM (1998) Subjective well-being is essential to well-being. PsycholI 9:33-37

Doka G (2003) Ergänzung der GewichtungsmethodefürÖkobilanzen Umweltbelastungspunkte'97 zu Mobilitäts-UBP'97. Doka Ökobilanzen, Zurich, Switzerland

Drott ES, Bruce RD (2011) A different look at noise exposure, hearing loss, and time limits. Hearing Review 18(5):34-36

EEA-ETC LUSI (2010) Noise Observation and Information Service for Europe maintained by the European Environment Agency (EEA) and the European Topic Centre on Land Use and Spatial Information (ETC LUSI) . European Commission, EU

Enmarker I (2004) The effects of meaningful irrelevant speech and road traffic noise on teachers' attention, episodic and semantic memory. Scandi J Psychol 45:393-405

European Commission (2002) Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise. Off J Eur Comm, EU. Available at: http://ec.europa.eu/environment/noise/directive.htm .

European Commission (2002) Position Paper On Dose Response Relationships Between Transportation Noise And Annoyance. Off J Eur Comm, EU

European Environment Agency – EEA (2010) Technical Report N.11/2010. Good practice guide on noise exposure and potential health effects. available online at: http://www.eea.europa.eu/publications/good-practice-guide-on-noise

ExternE (1995) Externalities of Energy, European Commission EUR 16520 EN, Volume 1-6 Available at: htrp://www.ExrernE.irc.es

Feynman R, Leighton RB, Sands M (1966) The Feynman Lectures on Physics, Volume I and II. Addison-Wesley, Reading

Fletcher H, Munson WA (1933) Loudness, its definition, measurement and calculation. J AcoustSoc Am 5: 82-108

Fogari R, Zoppi A, Corradi L, Marasi G, Vanasia A, Zanchetti A (2001)Transient but not sustained blood pressure increments by occupational noise. An ambulatory blood pressure measurement study. J Hypertens 19:1021-1027

Ford RD (1970) Introduction to Acoustics. Elsevier Publishing Ltd, New York City, USA

Franco V, Garraín D, Vidal R (2010) Methodological proposals for improved assessments of the impact of traffic noise upon human health. Int J Life Cycle Assess 15(8):869-882

Franssen EAM, van Wiechen CMAG, Nagelkerke NJD, Lebret E (2004) Aircraft noise around a large international airport and its impact on general health and medication use. Occup Environ Med 61:405-413

Goines L, Hagler L (2007) Noise pollution: a modern plague. South Med J 100:287-294

Griffiths ID, Langdon FJ (1968) Subjective response to road traffic noise. J Sound Vib 8:16-32

Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, van Oers L, Wegener Sleesewijk A, Suh S, Udo de Haes HA, de Brujin H, van Duin R, Huijbregts MAJ, Lindeijer EW, Roorda AAH, van der Ven BL, Weidema BP (2001) Life cycle assessment: an operational guide to the ISO Standards. Final Report, May 2001, Ministry of Housing, Spatial Planning and Environment (VROM) and Centrum voorMilieukunde (CML), Rijksuniversiteit, Den Haag and Leiden

Hamilton P, Hockey GRJ, Rejman M (1997) The place of the concept of activation in human information processing theory: an integrative approach. Erlbaum, Hillsdale, NJ

Health Council of the Netherlands (1971) Committee on Noise Annoyance and Noise Abatement. Geluidhinder [Noise Annoyance]. The Hague

Henselman LW, Henderson D, Subraminiam M, Sallustio V (1994) The effect of 'conditioning' exposures on hearing loss from impulse noise. Hearing Res 78: 1-10

Heutschi K (2004a) SonRoad: New Swiss road traffic noise model. Acta Acustica united with Acustica 90:548-554

Hofman WF, Kumar A, Tulen JHM (1995) Cardiac reactivity to traffic noise during sleep in man. J Sound Vib 179:577-589

Hofstetter P, Hammitt JK (2002) Selecting human health metrics for environmental decision-support tools. Risk Anal 22(5):963-981

Huijbregts MA, Hellweg S, Hertwich E (2011) Do we need a paradigm shift in life cycle impact assessment?. Environ SciTechnol 45(9):3833-4

Heijungs R, Huijbregts MAJ (2004) A review of approaches to treat uncertainty in LCA. p.332-339. In Pahl Wostl C, Schmidt S, Rizzoli AE, Jakeman AJ. Complexity and Integrated Resources Management.

Transactions of the 2nd Biennial Meeting of the International Environmental Modelling and Software Society, Volume 1. iEMSs (ISBN 88-900787-1-5), Osnabruck. 2004, 1533 pp.

International Life Cycle Data System (ILCD) Handbook (2010) available online at http://lct.jrc.ec.europa.eu/assessment/assessment/projects

IMAGINE (2005) WP6: IMAGINE railway noise source model, default source data and measurement protocol. IMAGINE (Improved methods for the assessment of the generic impact of noise in the environment) Project. TNO Technical Report, Delft, The Netherlands

IMAGINE (2007a) Guidelines for the use of traffic models for noise mapping and noise action planning. Deliverable 7 of the IMAGINE (Improved methods for the assessment of the generic impact of noise in the environment) Project. TNO Technical Report, Delft, The Netherlands

IMAGINE (2007b) The noise emission model for European road traffic. Deliverable 11 of the IMAGINE (Improved methods for the assessment of the generic impact of noise in the environment) Project. Available at: http://www.imagine-project.org

Ising H, Kruppa B (2004) Health effects caused by noise: evidence in the literature from the past 25 years. Noise Health 6: 5-13

ISO 14040 (2006) Environmental management: life cycle assessment- principles and framework, Second ed. ISO, Geneva.

ISO 14044 (2006) Environmental management: life cycle assessment- requirements and guidelines. Second ed. Geneva.

ISO 9613-2 (1996) Acoustics - attenuation of sound during propagation outdoors - part 2: A general method of calculation. ISO, Geneva

Job RFS (1999) Noise sensitivity as a factor influencing human reaction to noise. Noise Health 3: 57-68

Krupnick AJ, Portney PR (1991) Controlling urban air pollution: a benefit-cost assessment. Science 1991: 252: 522-8

Lafleche V, Sacchetto F (1997) Noise assessment in LCA-a methodology attempt: a case study with various means of transport on a set trip. Int J Life Cycle Assess 2:111-115

Lam K-C, Chan P-K, Chan T-C, Au W-H, Hui W-C (2009) Annoyance response to mixed transportation noise in Hong Kong. ApplAcoust 70:1-10

Lancastershire City Council (2007) Technical appendixes volume 3. Operational Noise Model Inputs. www.leics.gov.uk/downloaddatabasefile?file=2823 Accessed: 28 April 2011

LC-IMPACT (2010) Improved Life Cycle Impact Assessment methods (LCIA) for better sustainability assessment of technologies. Project Report, EU. Available at: http://www.lc-impact.eu/

Lusk SL, Ronis DL, Baer LM (1995) A comparison of multiple indicators: Observations, supervisor report, and self-report as measures of workers' hearing protection use. Éval Health Prof 18:51-63

Meijer A, Huijbregts MA, Hertwich E, Reijnders L (2006) Special Issue Honouring Helias A . Udo de Haes: Including Human Health Damages due to Road Traffic in Life Cycle Assessment of Dwellings. Int J Life Cycle Assess 2006:1(1)

Miedema HME (2007) Annoyance caused by environmental noise: elements for evidence-based noise policies. J Soc Issues 63(1):41-57

Miedema HME, Vos H (1998) Exposure-response relationships for transportation noise. J AcoustSoc Am 104:3432-3445

Moore BCJ (1989) An introduction to the psychology of hearing. Academic Press, London

Müller-Wenk R (2002) Attribution to road traffic of the impact of noise on health. Environmental series no. 339. Swiss Agency for Environment, Forest and Landscape (SAEFL), Bern

Müller-Wenk R (2004) A method to include in LCA road traffic noise and its health effects. Int J Life Cycle Assess 9:76-85

Navrud S (2002) The State of the Art on Economic Valuation of Noise. Report prepared for the European Commission, DG Environment. April 14th 2002. Available at: http://europa.eu.int/comm/environment/noise/

Nielsen PH, Laursen JE (2005) Integration of external noise nuisance from road and rail transportation in lifecycle assessment. Danish Environmental Protection Agency, Copenhagen

Niessen ME (2010) Context-based sound event recognition. PhD Thesis, Rijksuniversiteit Groningen

Ouis D (2001) Annoyance From Road Traffic Noise: a Review. J Environ Psychol 21(1):101-120

Passchier-Vermeer W, Passchier WF (2000) Noise exposure and public health. Environ Health Perspect 108(6):123-131

Pennington DW, Chomkhamsri K, Pant R, Wolf M, Bidoglio G, Kögler K, Misiga P, Sponar M, Lorz B, Sonnemann G, Masoni P, Wang H, Ling L, Castanho C, Soon C, Fieschi M, Filareto A, Hauschild M (2010) ILCD Handbook Public Consultation Workshop. International Reference Life Cycle Data System (ILCD). Int J Life Cycle Assess 15(3):231-237

Pennington DW, Potting J, Finnveden G, Lindeijer EW, Jolliet O, Rydberg T, Rebitzer G (2004) Life cycle assessment (Part 2): Current impact assessment practise. Environ Int 30: 721-739

Pirrera S, de Valck EK, Cluydts R (2010) Nocturnal road traffic noise: A review on its assessment and consequences on sleep and health. Environ Int 36:492-498

Pliskin JS, Shepard DS, Weinstein MC (1980) Utility functions for life years and health status. Oper Res 28(1):206-224

Potting J, Schöpp W, Blok K, Hauschild M (1998) Site-Dependent Life-Cycle Impact Assessment of Acidification. J Ind Ecol 2: 63-87

Probst W (2006) Noise perception and scoring of noise Exposure. The 13th international congress on sound and vibration. Vienna.

Rai RM, Singh AP, Upadhyay TN, Patil SKB, Nayar HS (1981) Biochemical effects of chronic exposure to noise in man. Int Arch Occup Environ Health 48: 331-337

Rao D, Fechter LD (2000) Protective effects of phenyl-Ntert-butylnitrone (PBN) on the potentiation of NIHL by CO. Toxicol Appl Pharmacol 167 (2):125-131

Saltelli A, Tarantola S, Chan KPS (1999) A quantitative Model-Independent Method for Global Sensitivity Analysis of Model Output. Technometrics 41 (1): 39-56

Schafer RM (1994) The Soundscape: Our Sonic Environment and the Tuning of the World. Destiny Books, Rochester

Shepherd, M (1974) Pollution and mental health, with particular reference to the problem of noise. Psych Clin 7:226-236

Slabbekoorn H, Bouton N, van Opzeeland I, Cours A, Ten Cate C, Popper AN (2010) A noisy spring: the impact of globally rising underwater sound levelsonfish. Trends Ecol Evol 25:419-427

Slob A, Wink A, Radder JJ (1973) The effect of acute noise exposure on the excretion of corticosteroids, adrenaline and noradrenalin in man. Int Arch Arbeitsmed 31: 225-235

Stansfeld SA (1993) Noise, noise sensitivity, and psychiatric disorder: epidemiological and psychophysiological studies. Psychol Med, MonogrSuppl 22:1-44

Stansfeld SA, Matheson MP (2003) Noise pollution: non-auditory effects on health. Br Med Bull 68:243-57

Sudo A, Nguyen AL, Jonai H, Matsuda S, Villanueva MB, Sotoyama M, Nguyen TC, Le VT, Hoang MH, Nguyen DT, et al (1996) Effects of earplugs on catecholamine and cortisol excretion in noise-exposed textile workers. Ind Health 34:279-286

U.S. EPA (1974) Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety. EPA/ONAC 550/9-74-004.Washington

Udo de Haes H, Lindeijer E (2002) The Conceptual Structure of Life-Cycle Impact Assessment. In Life-Cycle Impact Assessment: Striving Towards Best Practice, Society of Environmental Toxicology and Chemistry Press: Pensacola FL, pp 209 -225

Vermeire TG, Jager DT, Bussian B, et al (1997) European Union System for Evaluation of Substances (EUSES): Principles and structure. Chemosphere 34:1823-36

Verones F, Hanafiah MM, Pfister S, Huijbregts MAJ, Pelletier GJ, Koehler A (2010) Characterization Factors for Thermal Pollution in Freshwater Aquatic Environments. Environ Sci Technol 44 (24): 9364-9369

Verrier RL, Muller JE, Hobson JA (1996) Sleep, dreams, and sudden death: the case for sleep as an autonomic stress test for the heart. Cardiovas Res 31:181-211

Ward WD, Fricke JE (1969) Noise as a public health hazard. Am Speech Hear Assoc Report No. 4

WHO (1947) The chronicle of the WHO, Vol. 1. World Health Organization, Geneva

WHO (1994) Assessing human health risks of chemicals. Derivation of guidance values for health based exposure limits. World Health Organization, Geneva

WHO (2011) Burden of disease from environmental noise - Quantification of healthy life years lost in Europe. World Health Organization, Copenhagen

Williams HL, Hammack JT, Daly RL, Dement WC, Lubin A (1964) Responses to auditory stimulation, sleep loss and the EEG stages of sleep. Electroencephalogr Clin Neurophysiol 16: 269-79

2. Recommended assessment framework, method and characterisation factors for noise impacts. Characterisation factors for life cycle impact assessment of sound emissions

Stefano Cucurachi[1], Reinout Heijungs[1]

[1]*Institute of Environmental Sciences (CML), Leiden University, P.O. Box 9518 2300 RA Leiden, The Netherlands,*

E-mail contact: cucurachi@cml.leidenuniv.nl

2.1. Introduction

2.2. Scope

The aim of this chapter is to operationalize the model presented in chapter 1 and published in Cucurachi et al. (2012), to implement these factors and to use them for the calculation of characterization factors for noise impacts. The environmental mechanisms involved in the propagation and attenuation of sound emission, and the relative noise impact are complex, non-linear and highly dependent upon local circumstances .The acoustic phenomena and parameters which are relevant in the proposed framework are, in fact, strictly related to a particular topography and to specific local conditions. To reach a greater accuracy, propagation of sound is usually calculated either taking a fully empirical approach, or assuming specific conditions of propagation (e.g. a flat area with short grass). In an ideal world, LCA should be able to portray any possible context of (sound) emission and to account for the effects of those emissions on the target subjects. In practice, sound levels need to be predicted for different heights above the ground, for various types of foliage (e.g. tree belts), for walls, houses, etc. For a fully-empirical local noise assessment, this can be done. In LCA, however, a life cycle typically spans thousands of locations, so a site-specific assessment is not feasible. This puts the modeller to face a situation in which one has to choose between the use of highly specific spatially-defined data, or a situation in which it is necessary to assume representative conditions for the archetypal compartments of emission. Even though the level of accuracy may be greater when location-specific data is considered, spatially-defined variables are not uncertainty-free, nor is the amount of information available to practitioners sufficient to use them to describe the specific life cycle under consideration.

2.3. Research focus

The method described in the following sections is based on the established standards of propagation of sound from a stationary of moving sources, such as ISO 9613-1, ISO 9613-2

(ISO, 1993a; ISO, 1996a), as well as on the recommended approach for the calculation of sound emission and propagation at a European level (European Commission, 2012). Data was processed and scaled to allow for the calculation of characterization factors for noise both in the form of ready-to-be-used maps at a European scale, and in the form of archetypal dimensions of emissions. The special case of indoor "occupational" sound emissions was defined only as an archetypal situation of emission. It was decided to use spatially-defined parameters (i.e. GIS map or raster data) to compile characterization factors in the form of maps in a spatially-defined context. The outcome of this process was used to define archetypal situations of emissions, which used central nominal values for calculations. The use of spatially-defined CFs allowed for the selection of central values in the most appropriate range. In total, 217 CFs were produced for the archetypal situations.

This contribution fills the gap of the absence of noise as an impact category in LCA and presents CFs for noise impacts at a European level (i.e. EU27), which can be used by practitioners, provided the inventory (i.e., sound emission) data are available. The factors produced are, in fact, ready to be implemented in the available LCIA databases and software. The framework proposed and used for calculations is flexible enough to be expanded to account for impacts on other target subjects than humans and to other continents than Europe.

2.4. Elaboration of the framework

2.4.1. Definition of spatial parameters and archetypal situations of emission

The environmental mechanisms involved in the propagation and attenuation of sound emissions, and the relative noise impacts are typically complex, non-linear and highly dependent upon local circumstances. In order to operationalize the impact assessment model described in Cucurachi et al. (2012) and presented in chapter 1, a series of input parameters, constants and variables are introduced by this contribution and is detailed in the next sections (see Table 1).

Table 2.1. Parameters and variables used in the model

Input parameter [a]	Description [b]	Unit/Expression [c]
Lw	Background sound power level	dB
T	Temperature	°C
Rh	Relative humidity	%
P	Local pressure	Pa
h	Height of propagation	m
d	Distance from source to receiver	m

S	Surface of propagation	m^2
Nf	Population	number [d]
ρ	Population density	number
Wamb	Background Sound Power	W
Pr	Attenuation factor for protective measures	dB
ψ	Rate of use of protective measures	%
αm	Room absorption parameter	number
C_{ref}	Ratio of conversion factors	number
D	Directivity of sound propagation	dB
C	Constant transformation factor dB to Watt	W
P_{ref}	Reference ambient pressure	Pa
P_{rel}	Relative pressure	number
Kelvin	Conversion factor from °C to°K	number
T_{ref}	Reference ambient temperature	°C
T_{kel}	Local temperature in Kelvin	°K
T_{rel}	Relative temperature	number
T_{01}	Triple-point isotherm temperature	°K
H	Molar concentration of water vapour	number
fro	Nitrogen relaxation frequency as in ISO 9613-1	Hz
frn	Oxygen Relaxation Frequency as in ISO 9613-1	Hz
αatm	Attenuation factor due to atmospheric conditions	dB/m
rc	Sound absorbing characteristics of a room	m^2
R	Sound absorbing characteristics of a room	dB
α	Frequency penalty	dB
β	Time penalty	dB
Aatm	Attenuation due to atmospheric conditions	dB
Adiv	Attenuation due to divergence	dB
Aground	Attenuation due to ground conditions	dB
Apr	Attenuation due to the use of protective measures	dB
Aextra	Attenuation due to other factors	dB

The parameters defined in Cucurachi et al. (2012) were firstly spatially-defined in raster maps (see Supplementary Information 2, available in electronic format), which were meaningfully combined to obtain spatially-explicit CFs for EU27 (Eurostat, 2007) using ArcGIS 10 (ESRI, 2011).

The following dimensions were defined:

- octave: 63 Hz (44 to 88 Hz), 125 Hz (88 to 177 Hz), 250 Hz (177 to 354 Hz), 500 Hz (354 to 707 Hz), 1000 Hz (707 to 1414 Hz), 2000 (1414 to 2828 Hz), 4000 Hz (2828 to 5656 Hz), 8000 Hz (5656 to 11312 Hz);

- time: day (7 am to 7 pm), evening (7 pm to 11 pm), night (11 pm to 7 am), and unspecified.

CFs in the spatial format were calculated using ArcGIS 10 (ESRI, 2011). A total of 32 CFs were produced. The resulting raster maps are provided as Supplementary Information 2 to this contribution available in electronic format.

Single parameters were obtained from various sources (see Table 2.2), and adapted for the calculations described in the next sections.

Table 2.2. Specific parameters and resolution used in the spatial context

Parameter	Source of the data	Spatial resolution
Ambient sound level [dB]	EASA, 2009	10 km
Temperature [ºC]	Hijmans, 2005	1 km ca.
Relative humidity at 2 metres [%]	Saha et al., 2010	38 km ca.
Ambient pressure [kPa]	ISO, 1993a; 1996a	Set to 10 km
Average propagation height [m]	This report	Set to 10 km
Distance [m]	This report	Set to 10 km
Number of exposed subjects [number]	EASA, 2009	10 km
Elevation [m]	Jarvis et al., 2008	30 m

The ETRS89 Lambert Azimuthal Equal Area (Annoni et al., 2003) was defined for all raster layers and a cell size of 10 kilometres was selected in line with the available data. Given the different provenience of all sources, processing tools in ArcGIS were used to obtain raster maps with the suitable level of spatial definition. Map algebra (Burrough et al., 1998) was, then, used to implement the calculations defined in section 2.3. For those parameters whose value would not change at different locations, a constant raster was defined and used as an input for calculations.

The results obtained were used to elaborate archetypal situations of emissions, i.e. urban, suburban, rural, industrial and indoor.. Statistical data was used for the definition and differentiation of parameters amongst the defined dimensions. In all the cases when it was not possible to find suitable statistical support, the data available in a map format and spatially-defined was analysed and provided a sufficient basis, upon which to develop calculations. The sources of the data are reported in Table 2.3. The parameters used for the protective measures and the rate of use of protective measures were defined only for the case of indoor emissions.

Table 2.3. Specific parameters and sources used in the archetypal context

Parameter	Source of the data (elaboration from)
Ambient sound level [dB]	EASA, 2009;King et al., 2012
Temperature [ºC]	Hijmans et al., 2005
Humidity [%]	Saha et al., 2010
Ambient pressure [kPa]	ISO, 1993a
Average propagation height [m]	This report
Distance [m]	This report
Population density [people/km^2]	Eurostat, 2012; Analysis of spatially-defined data in the spatial context
Reference area [km^2]	Eurostat, 2007; Analysis of spatially-defined data in the spatial context
Number of exposed subjects	Eurostat, 2007; Analysis of spatially-defined data in the spatial context
Use of protective measures	Concha-Barrientos et al., 2004
Rate of use of protective measures	Concha-Barrientos et al., 2004

Parameters and constants were combined together in a spread-sheet compiled using Microsoft Excel (see Supporting Information). Figure 2.1 shows the interactions among variables as they were taken into account in the spread-sheet model.

The following dimensions were defined for this context:

- octave: 63 Hz (44 to 88 Hz), 125 Hz (88 to 177 Hz), 250 Hz (177 to 354 Hz), 500 Hz (354 to 707 Hz), 1000 Hz (707 to 1414 Hz), 2000 (1414 to 2828 Hz), 4000 Hz (2828 to 5656 Hz), 8000 Hz (5656 to 11312 Hz);
- location: urban area, suburban (i.e. residential) area with no nearby traffic concern, rural area with no nearby traffic, industrial or commercial area, indoor, and unspecified;
- time: day, evening, night, and unspecified.

Section 3 and the Supplementary Information (see Supplementary Information 1 and 2, available in electronic format) provide the full set of results for the defined dimensions in both spatial and archetypal contexts.

2.5. Noise impact assessment framework

Most sounds emitted by a source are complex, and fluctuate in amplitude and frequency content. The relationships between sound energy level and frequency are required for the meaningful analysis of a sound spectrum. Cucurachi et al. (2012) proposed to analyse the sound emitted by a source according to the one-third octave bands centre frequencies in which its spectrum can be split into. The distinction among frequencies allows to depict and follow the ability of our hearing system to perceive the frequency composition of a sound, but also allows to be as much as possible able to accommodate any context of emission. If certain centre-frequency bands are dominant for a specific source, or limited information is available, selected centre-frequency bands may be chosen instead of others (e.g. 63 hertz to 500 hertz, instead of 2000 hertz to 8000 hertz). Similarly, if the model would have to be expanded for the consideration of impacts on other target systems than humans, the centre-frequency ranges of interest may not be the same. No differentiation among sources was proposed in Cucurachi et al. (2012), but it was recommended to differentiate the emissions at the inventory level according to frequency of emission (e.g. 63 Hz), the location (e.g. rural and urban), and the time of the day (i.e. day, evening, and night) of the sound emission. The characterization of the frequency, the time, and the location of the sound emission are also crucial in the later impact assessment of the relative noise perceived by the target subjects. Therefore, the sound emission is not only spatially differentiated as is common for many impact categories, but also temporally and physically differentiated. The collection of information at the inventory phase can provide a better characterisation of sound, thus potentially a better quantification of the relative noise impacts. At the inventory level, Cucurachi et al. (2012) prescribe to take into account the sound power level of each source and to convert it into sound energy, using the physical properties of sound. International standards (e.g. ISO 9613-2; ISO, 1996a) and reports (e.g. WHO, 2001) provide suitable and readily usable information to calculate the sound power level of any source, being it static or mobile. An accurate reference is the CNOSSOS reference report (European Commission, 2012) provides indications on how to calculate the sound power emission of any type of source, discriminating among noise caused by the so-called road traffic (e.g. light motor vehicles, medium motor vehicles, etc.), railway traffic, air traffic, and industrial sources.

Following ISO9614-1 (ISO, 1993b), in CNOSSOS the sound power level is defined as "in-situ" or in "semi-free field". Sound power includes eventual effects of reflections and other specifications in the immediate vicinity of the source (e.g. the surface under the source). The parameters are specified per class of sources and also for combinations of similar sources (e.g. traffic conditions). Sound power level (in decibel, dB) can be back-transformed to the relative sound power using the reference value of 10-12 watt (W), and then the relative sound energy to be reported in the inventory table can be calculated by applying the methodology reported by Cucurachi et al. (2012). Here, it is specified that the time a source is active in a life cycle can be calculated based on the production rate of the system (i.e. kg/s) and the relative output (i.e. kg). If the system under study has to produce e.g. 1 kg paper, and the relative production rate is, e.g., 500 kg paper/hour, in that case the time to be used for the conversion of a sound power in W to a sound energy in joule (J) would be 7.2 second (i.e. J = W * s).

2.5.1. The fate factor for outdoor sound emissions

In Cucurachi et al. (2012) the fate factor was defined as in Eq. (21):

$$\mathbf{FF_{i,c,f}} = \frac{\mathbf{C_{ref}}}{\sqrt{\mathbf{Wamb_{c,f}}}} \times \mathbf{10}^{(\mathbf{D_{c,f}} - \mathbf{A_{i,c,f}})/20} \qquad (21)$$

and measured in Pa/W. The expression defines the conversion of a source sound power in watt (W) to a target sound pressure in pascal (Pa). The fate factor reflects a marginal increase in the total ambient sound power of octave-band i at time c, and at location f due to the fact that a functional unit was introduced into the system, evaluated at the background level $Wamb_{c,f}$. In the model, the ambient sound power is not differentiated per frequency band. This assumption flows from the lack of data that is at the moment available in the literature. Ideally, also the background sound power should be differentiated per frequency band, given that also the frequency composition of the background conditions would also influence the perception and impacts of the sound emissions.

The formula includes the following parameters: Cref (20 $Pa*W^{-1/2}$) is the ratio between the constant reference values Pref (20 µPa) and Wref (10−12 W); Wamb refers to the background sound level at a target location measured in W, at a specific time of the day. For lack of data, Wamb has not been defined per octave band i; instead the total Wamb has been taken.

D is the directivity correction, in dB, that describes to what extent a deviation of sound pressure level occurs in a specified direction from the source of sound power level $Lw_{i,c,f}$. It is independent of the frequency of emission.

A is the combination of octave-band specific attenuations, in dB, occurring during the propagation of sound from source to receiver and it is given by the contemporary consideration of several attenuation factors, which include geometrical divergence, atmospheric absorption, meteorological variation, and miscellaneous other effects.

In order to operationalize the model, the variables will be described in the following sections.

2.5.1.1. Background sound environment

The degree to which environmental noise affects humans (and other species) depends on the ambient background conditions of the soundscape they are used to, as well as to a certain extent to the sensitivity of each individual to sound changes above the background. Human activities generate sound at growing intensities with growing population levels (US-EPA, 1974; Stewart et al. 1999). Sound emissions are usually quantified in terms of a pressure level in dB or scaled to the sensitivity to sound of the human hearing system (in dBA). Both quantities are called sound pressure level. The background sound environment of a specific location may be also measured by its sound power level. Availability of data in both cases is limited. We use the sound power to indicate the physical natural quantity (i.e. measured in W), while sound power level here denotes the sound power ratio (in dB) referred to a reference quantity of 1 pW.

In a study by Sintef (2007) day-evening-night equivalents of sound pressure background level were obtained as a function of the population density at a given location. The result gives an approximation of the actual sound levels, which may underestimate the noise levels, especially in urban contexts (EASA, 2009). The BANOERAC report (EASA, 2009) measured actual sound pressure levels in a number of locations representative of various settings (e.g. urban residential area, rural area, etc.). Data was compared with previous findings and updated with some corrections for extreme situations. The model incorporated the effects of the road network and urban noise, included a minimum threshold for quiet rural areas, and analysed data from the available strategic noise maps developed by EU member states (EASA, 2009). The study reports sound pressure level using the measure L95, in dBA, for day, evening, and night. L95 defines the sound pressure level exceeded for 95% of the time at a given location (i.e. only in 5% of the time the sound pressure level was less than L95). Background sound pressure levels, as calculated by BANOERAC, may be defined as the sound pressure level at a location from a number of more or less identifiable sound sources when the direct sound from prominent sources is excluded (EASA, 2009). In the context of acoustic ecology it would be defined as the reference soundscape of a specific location. Using a more appropriate LCA terminology, the background sound pressure level may be defined as the background sound as a location which was not yet perturbed by the functional unit under study, whose sound power has been inventoried in the LCI table. L95 represents a sound pressure level, in dBA, which may be transformed to a sound power, in W. We are, in fact, interested in the sound power of the environment under study. In other terms, we assume that the environment where the emission takes place is itself a source of sound emission with a certain sound power. This “theoretical” source is a composition of sources already perturbing the environment before the functional unit is active in it. The value of the background sound power is in reality different across different centre-frequency ranges, as it was the sound power inventoried in the LCI. Due to the limited availability of data, we considered the value of the background sound environment as equal across all centre-frequency bands. For the details of the calculation of the L95 value we refer to the full BANOERAC report (EASA, 2009).

2.5.1.2. From Sound pressure level to Sound power

In real situations, the relation between sound pressure level and sound power level or normal sound intensity level is very complicated. In practical terms, it is possible to consider an approximation of the ideal case of free field emissions, for which sound power is explicitly related to the sound pressure. Any correction factors for other influences (e.g. reflection, meteorological influence) was here neglected but considered in the calculation of attenuations (see section 46). Thus, the sound power level, Lw, over the propagation surface can be expressed as:

$$\mathrm{Lw} = \mathrm{Lp_{avg}} + 10\log\left(\frac{\mathrm{S}}{\mathrm{S_0}}\right) + 10\log\left(\frac{\mathrm{P_{ref}^2 S}}{\rho c \mathrm{W_{ref}}}\right), \qquad (22)$$

where Lp_{avg} is the averaged sound pressure level in dB, S is the total surface of propagation in m2, S0 is the reference surface of 1 m^2, Pref is the reference sound pressure (101325 Pa), ρ is the volumetric mass of air (1.16 kg/m3), and c is the speed of sound (343.2 m/s). The expression is based on the equivalence of sound intensity and average sound pressure. It means that a sound source will radiate different sound powers in different environments. Assuming the approximation in free field conditions, the right term of the expression goes to zero when the reference values of sound pressure and sound power are put into the equation, and the last term vanishes when ρc = 400 kg/ m2*s. This is the case if we assume a temperature of 20 ◦C with an ambient pressure of 1 atm (Bies and Hansen, 1996; WHO, 2001). Therefore, Lw can be rewritten for an omnidirectional source in a free field condition as:

$$\mathbf{Lw} = \mathbf{Lp_{avg}} + \mathbf{10\log}\left(\frac{\mathbf{S}}{\mathbf{S_0}}\right) = \mathbf{Lp_{avg}} + \mathbf{10\log}\left(\mathbf{4\pi d^2}\right), \qquad (23)$$

where d represents the distance from the source to the target in m, if spherical spreading is assumed. Lpavg can be considered, in our case, as equivalent to the L95, the background sound pressure level calculated at each location under consideration (i.e. for day, evening and night), and the expression generalised as:

$$\mathbf{Lwamb_{c,f}} = \mathbf{L95amb_{c,f}} + \mathbf{10\log}\left(\mathbf{4\pi d^2}\right). \qquad (24)$$

We took for the SC L95ambf,c (with c = day, evening, night, or unspecified) as the value of each cell of the BANOERAC output map. Therefore, the propagation surface at each point was calculated as a function of each square grid of 10 km of side. Therefore, Lwamb,c,f reduces to:

$$\mathbf{Lwamb_{c,f}} = \mathbf{L95amb_{c,f}} + \mathbf{10\log(100)} = \mathbf{L95amb_{c,f}} + \mathbf{20}. \qquad (25)$$

The value in dB was then back-converted to a value in watt by using the reference Wref. We, then, obtained:

$$\mathbf{Wamb_{c,f}} = \mathbf{W_{ref}} \times \mathbf{10^{(L95amb_{c,f}+20)/10}}. \qquad (26)$$

To our knowledge BANOERAC is the only project which focused on developing background sound data for Europe in a systematic way. Several methodologies are available in the literature to improve measurements of background sound levels. In the case sufficient data would be available for a specific location or test area, specific techniques have been applied and provided solid results (e.g. land use regression used Xie et al., 2011).
For the archetypal situation of emission, Lwamb was calculated considering that the average sound pressure level at a specific location is a function of its population density. Once again free field conditions were assumed, and Lwamb was calculated applying the formula earlier presented with the addition of a factor related to the surface under consideration:

$$\mathbf{Lwamb_{c,f}} = \mathbf{18} + \mathbf{\log_{10}(\rho)} + \mathbf{10\log}\left(\frac{\mathbf{S}}{\mathbf{S_0}}\right), \qquad (27)$$

where the second term to the right of the expression refers to the spherical propagation of sound for a certain surface under consideration. The results of the spatial analysis and the BANOERAC report were used as a support to control the calculations and to improve their adherence to real data. For example, in the case of industrial sound emissions the approximation based on population would underestimate sound power levels. The value of Lwamb was, then, adjusted (e.g. by a factor 2) according to the type of context and considering that in the case of industrial sound emissions sound power levels are also a function of the amount of machines that are used and goods that are moved (WHO, 2001).

The value of Wamb was then calculated by:

$$\mathbf{Wamb_{c,f}} = \mathbf{W_{ref}} \times \mathbf{10^{(Lwamb_{c,f})/10}} . \quad (28)$$

2.5.1.3. Directivity ($D_{c,f}$)

The approximation of free-field conditions, which was suitable for the calculation of sound power levels and sound power, does not explain all the conditions that in reality affect the propagation of sound. The presence of the directional sound radiation properties of a source were considered by introducing directivity factor D, which describes the angular dependence of the sound intensity (ISO, 1996a). Theoretically, a simple point source radiates uniformly in all directions (i.e. it is an omnidirectional source). In real conditions, the radiation of sound from a typical source is directional, and it is greater in some directions than in others (Smith et al., 1996; Bies and Hansen, 1996; WHO, 2001). D is often expressed as a directivity index (in dB), calculated as a ratio between the intensity Iθ in a specific direction and angular orientation (θ) and the mean intensity (Bies and Hansen, 1996):

$$\mathbf{D_{\theta}} = \frac{\mathbf{I_{\theta}}}{\mathbf{I_{avg}}} . \quad (29)$$

Alternatively, the directivity can be expressed as a dimensionless value which varies according to the position to the ground of the emitting source (see Table 2.4).

Table 2.4. Directivity factor and directivity index in representative situations

Dimension conditions	Directivity factor, Q	Directivity Index DI (dB)
Free space	1	0
Centred in a large flat surface	2	3
Centred at the edge formed by the junction of two large flat surfaces	4	6
At the corner formed by the junction of three large flat surfaces	8	9

Directivity indicates how much sound will be directed towards a specific area compared to all the sound energy being generated by a source and it is independent of the frequency of emission (WHO, 2001), therefore it helps to quantify how much of the sound pressure will reach the exposed targets. We considered the case of an omnidirectional source placed on the ground, which can be approximated to a D value of 2 (or 3) dB, which means that sound radiates in a hemispherical pattern from a source placed on the ground. A value of 1 dB may be used for source in air (e.g. airplane).

2.5.1.4. Attenuations (Ai,c,f)

Following the definition of the ISO standard 9613-2 (ISO, 1996a), Cucurachi et al. (2012) introduced attenuation factors to account for the dissipation of sound through the medium (i.e. air in this case) from a source sound power to a sound pressure at the receiver compartment. Attenuations can be defined as:

$$\mathbf{A_{i,c,f}} = \mathbf{Aatm_{i,c,f}} + \mathbf{Adiv_{i.c.f}} + \mathbf{Aground_{i,c,f}} + [\ldots]\ \mathbf{Aextra_{i,c,f}}\ , \qquad (10)$$

where each factor A represents a type of attenuation, in dB, and depends on the frequency, time and location of emission. Other attenuations (i.e. Aextra in the equation) may be considered if enough data is available for the specific context or life cycle under investigation, or to account for specific effects which are of importance in the case at hand. Other possible attenuations are described in the CNOSSOS report (European Commission, 2012). The case of attenuations by barriers was not considered at this stage, due to the lack of data on the presence of barriers in different European contexts.

Atmospheric conditions. Attenuation due to atmospheric absorption ($Aatm_{i,c,f}$)

Scientific literature has widely dealt with attenuation of sound due to specific atmospheric conditions (see for instance, Harris, 1966; Delany and Bazley, 1970; Piercy et al., 1977; Salomons et al., 2011). The calculation of attenuation may be relatively straightforward for specific cases when full knowledge of the emission compartment and of the exposure compartments is available. However, meteorological data may be either difficult to be obtained or can be scarcely representative of the effective temporal and spatial variation of parameters. Maher (2007) states that precipitations (e.g. rain, snow, or fog) do not usually cause a significant effect upon sound levels. However, these phenomena may affect humidity, wind and temperature gradients, which in turn do effect the propagation of sound, and their effect can be determined locally, both in downwind and upwind conditions (Rasmussen, 1985; Nijs and Wapenaar, 1990).

CNOSSOS (European Commission, 2012) prescribes to account for the attenuations due to meteorological effects when the in-situ sound power is calculated. In the development of the characterization model here proposed, the calculation of atmospheric attenuations (e.g. temperature) was not considered at the stage of the calculation of the sound power (i.e. at the LCI phase), but was embedded in the calculation of the characterization factors following the defined LCIA model.

The attenuation from the source to the receiver due to the atmospheric absorption (Aatm) is a function of the distance that sound waves travel and it is given by:

$$\mathbf{Aatm_{i,c,f}} = \boldsymbol{\alpha}\mathbf{atm_{i,c,f}} \times \mathbf{d}, \qquad (11)$$

where $\alpha atm_{i,c,f}$ is the atmospheric attenuation coefficient in dB/m at each octave-band centre frequency for each frequency band, as defined by ISO 9613-1 (ISO, 1993a).

In the spatial analysis of data, at each location the specific meteorological condition of exposure were considered and the relative parameters calculated as raster maps in a GIS environment. The value of αatm was calculated for the one-third-octave band standard frequencies (ISO, 1993a), from the combination of location-specific temperature (yearly average at the ground) and relative humidity (annual average at 2 m from the ground). The calculation of the αatm parameter is detailed in Appendix A of this contribution.

Attenuation due to geometrical divergence (Adiv)

Sound power is attenuated at increasing distances from the emitting source. The attenuation relative to the distance from source to receiver, Adiv in dB, was calculated as described in the ISO9613-2 reference standard (ISO, 1996a):

$$\mathbf{Adiv = 20\ log\left(\frac{d}{d_{ref}}\right) + 11}, \quad (12)$$

where d represents the distance in m from source to receiver, and dref is the reference distance of 1 m. For the calculation of the characterization factors, d can be differently defined according to the archetypal situation of emission. For instance, it can be assumed that in an urban situation of emission the distance from source to receiver may be less than that associated to rural and far field conditions.
For the spatial case, the distance d was assumed as an average value of 50 metres (i.e. all exposed targets are at least at a distance of 50 metres from the sound-emitting source). In the archetypal contexts, distance was considered as varying according to the specific characteristics of each defined dimension and compartment.

Attenuation due to the ground effects (Aground)

Sound waves may also be absorbed by the ground in between the source and the receiver. Attenuations due to ground effects are mainly the result of the interference between the ground characteristics between source and receiver and their ability to interact with the propagation of the sound wave (European Commission, 2012). The magnitude of the attenuation depends on the porosity or permeability of the ground surface (Rasmussen, 1981; Attenborough, 1982; de Jong et al., 1983; Reed et al., 2010). Surfaces which are hard or smooth (e.g. pavement) absorb little sound, whereas soft or porous ones (e.g. grass) can absorb sound substantially (Reed et al., 2010). The vegetation at a specific location also contributes to the modification of waves, as a function of their structure, extent and density (Fang and Ling, 2003; Reed et al., 2010).

The acoustic absorption of ground is represented by a dimensionless G coefficient, defined between 0 and 1 (ISO, 1996a), which is independent of the defined frequency range (see Table 5). Following the definition of archetypal compartments, a G value was assigned to each of them. If the distance between the source and the receiver is limited, attenuations due to the in-between ground can be neglected.

Table 1.5. Definition of the G coefficient (European Commission, 2012)

Description	Attenuation of sound propagation [kPa * s/m2]	G value
Very soft (snow or moss-like)	12.5	1
Soft forest floor (short, dense heather like or thick moss)	31.5	1
Uncompact, loos ground (turf, grass, loose soil)	80	1
Normal uncompact ground (forest floors, pasture field)	200	1
Compacted field and gravel (compacted lawns, park area)	500	0.7
Compacted dense ground (gravel road, parking lot)	2000	0.3
Hard surfaces (asphalt, concrete)	20000	0
Very hard and dense surfaces (dense, asphalt, concrete, water)	200000	0
Definition of value for the archetypal compartments		G value
urban area		0
suburban		0.7
rural		1
industrial		0.3
Indoor		0
Unspecified		0

As suggested by Reed et al. (2012), it was possible to associate for the calculation of the spatially-defined CFs a value of G to different types of land cover, using data from the CORINE database (Bossard et al., 2000). The latest available version of the database was used. Land cover data with a spatial definition of 250 m was resampled using the majority principle (i.e. data aggregated to the required spatial size according to the “most popular” values within the 10 km2 area) in ArcGIS 10 (ESRI, 2011), in order to adhere to the 10 km2 reference which was selected. G values were then assigned to each cell to allow the calculations (Table 2.5).
For the archetypal dimensions of emission, G values were defined following the definition of CNOSSOS (European Commission, 2012) and are reported in Table 2.4. The full calculation process of Aground is provided in Appendix B of this contribution.

2.5.2. The effect factor for outdoor sound emissions

The effect factor was defined by Cucurachi et al. (2012) as:

$$\mathbf{EF_{i,c,f} = N_{c,f} \times 10^{(\alpha_i+\beta_c)/20}} \quad (13)$$

The unit of the effect factor is person. Nf represents the population size at the exposure compartment f at a certain time of the day c, αi is the penalty (in dB) to be added to account for the A-level scale (ISO, 1996a), βc represents the weighting of the sound emission (in dB) for the time of the day the emission took place.

2.5.2.1. Population density (Nf)

The number of inhabitants at a specific location of exposure is an important parameter for the estimation of the exposure to noise. In the context of strategic noise mapping, CNOSSOS (European Commission, 2012) prescribes to use the number of people residing in a building for the calculation of people exposed to noise. Unfortunately, data on this parameter is not always available and the exposure of people living at that specific location was characterised by the population size of that specific location, as provided by BANOERAC (EASA, 2009). If enough information is available, the population size can be substituted by the number of inhabitants of each dwelling at the location under consideration, calculated as a function of the physical characteristics of the building(s) taken into consideration (e.g. the floor space, volume, number of floors, etc.) or calculated following specific national default values (European Commission, 2012).

For the spatial case, Nf was defined as the population size of each cell of 10 km square as provided in BANOERAC (EASA, 2009). In the archetypal case, population sizewas defined based on the definition of the archetypal compartments of emission and based on the study of representative cases in the SC.

2.5.2.2. Other parameters (α_i, β_c)

The A-scale weighting for octave band i (α_i), was added to the calculation to account for the sensitivity of the human hearing system to specific frequency ranges (ISO, 1996a), and was defined by an additional value in dB to be added to each centre-band frequency (Cucurachi et al., 2012).

The day/evening/night weighting (β_c) was added to account for the extra annoyance to emission in the evening or at night. The value of βc has been quantified as an additional 5 dB emission for the evening emissions, an additional 10 dB for night emissions, and an additional 7.5 dB for unspecified emissions.

The values of αi and βc were varied according to the definition of the reference archetypal conditions.

2.5.2.3. Indoor/localised occupational sound emissions

This section refers to the definition of an indoor/localised occupational compartment of sound emissions (indoor compartment, from now on). It refers to the exposure to sound emissions which take place in an indoor environment (e.g. a print shop, a production line in a factory) or to sound emissions which are localised to a specific site (e.g. a construction site). The sound emissions here considered can be defined as “occupational”. Therefore, they are specifically oriented at investigating the effects of sound emissions (and noise) on, e.g., operators of plants, builders, musicians and, in general, all the categories of workers operating with equipment which produces a sound energy of constant or variable intensity and which are subject to serious health burdens (Concha-Barrientos et al., 2004; Stewart et al., 2011).

2.5.3. Indoor case of emission. Variation of parameters

We extended the fate factor described in Cucurachi et al. (2012) to the indoor compartment with the introduction of a term R, which represent the refraction of sound indoor.. The fate factor may be written as:

$$\mathbf{FF_{i,c,f}} = \frac{\mathbf{C_{ref}}}{\sqrt{\mathbf{Wamb_{c,f}}}} \times \mathbf{10}^{\left[\mathbf{D_{c,f}}+\mathbf{R_{i,f}}-\mathbf{A_{i,c,f}}\right]}. \qquad (14)$$

The unit of the fate factor is Pa/W and maintains the exact same meaning as described in section 3. R represents the reverberant component of sound in a space (i.e. room or localised site), measured in dB. It expresses the acoustic properties of a room (or site), as a function of its specific absorption properties and its surface (Schroeder, 2007).

2.5.3.1. Indoor sound background (Wamb)

The parameter Wamb refers in the case of the indoor compartment to the ambient conditions of the site under study before the functional unit is active to perturb that environment. Data on the sound power level of working environments can be obtained by direct on-site measurement or from the literature in applied acoustics. The same assumptions made in section 2.3.2 were considered. The value of background sound power was corrected (e.g. multiplied by a factor 3) to account for the extra sound power due to the presence in the indoor working environment of extra sources of sound emissions (e.g. air-conditioning systems, piped music; see WHO, 2001).

2.5.3.2. Attenuations (A)

All the sound-emitting sources in the environment under study were assumed to be placed at an average distance of 1 metre from the receivers. At such a distance, Aground was not applicable. Adiv, due to the distance from source to receiver, and Aatm, due to local atmospheric conditions, were accounted for in the calculations in the form introduced in the previous sections (see section 2.3.4). An extra attenuation is here considered, Apri,f, which is expressed as:

$$\mathbf{Apr_{i,f}} = (\mathbf{Pr} \times \boldsymbol{\psi}). \tag{15}$$

It regards the potential attenuation of sound emissions at different octaves in a specific location, due to the fact that personnel may be wearing protective measures (i.e. the value Pr in dB), taking into account also ψ, a factor, between 0 and 1, which represents the rate of usage of protective measures in a specific industry or sector.

2.5.3.3. Reverberant component of sound propagation (R)

The sound absorbing characteristic of a room, rc, was calculated applying the following formula (WHO, 2001):

$$\mathbf{rc} = \frac{\mathbf{S \times \alpha_m}}{(\mathbf{1 - \alpha_m})} \tag{16}$$

where αm is the average absorption of the environment site, and S the surface of the study site in m2 (sometimes referred to as m2 sabines). Typical values of αm vary between 0.05 (i.e. large room) and 0.8 (i.e. environment with sound absorbing tiles). An open-air localised area can be assumed to have little absorbance (i.e. αm = 0.01). To obtain a quantity in dB that could be added to the other attenuation parameters, a factor R was re-calculated according to the formula:

$$\mathbf{R_{i,f}} = \mathbf{10 \log_{10} \frac{rc}{rc_{ref}}}, \tag{17}$$

where rcref is a reference value of 1 m2. In all cases in which accurate information is available for the composition of the working site under study, values of rc and R may be quantified with higher accuracy following the relative standards (e.g. ISO 11690-1 and ISO 14257; ISO, 1996b, 2001).A value of αm of 0.05 was assumed as constant for day, evening and night and unspecified indoor emissions.

2.5.3.4. The effect factor for indoor or localised occupational sound emissions

The effect factor defined by Cucurachi et al. (2012) and reported in section 3 still holds for the indoor compartment of emissions. In this case, the main difference is the interpretation of the day/evening/night penalty βc. In the indoor compartment, in fact, it does not refer to the sleep disturbance of individuals, since they are at work and typically not asleep. The penalty here refers to the disruption of the regular biological clock as determined by evening and night working hours (WHO, 2001). The value of Nf reported in the formula for the effect factor (see section 2.3.4) in the indoor case represents the number of workers exposed to the sound emission.

2.6. Characterisation factors and sensitivity analysis

2.6.1. Definition and quantification of CFs for noise impacts on humans.

The CFs for midpoint noise impacts were defined in Cucurachi et al. (2012) according to the classical LCIA characterisation scheme (Pennington et al. 2004), as shown in Eq. 18:

$$\mathbf{CF_{i,c,f}} = \sum_{\mathbf{f}} \left(\mathbf{FF_{i,c,f}} \times \mathbf{EF_{i,c,f}}\right), \tag{18}$$

thus, the CF for each of the defined spatial and archetypal situations of emission were calculated by multiplying the FF and the EF at a certain centre-frequency (i), time (c), and location (f). The quantity which expresses the CF is person-Pa/W, which would correspond to s*m-3 using the SI standard units (Heijungs, 2005). If we consider that a sound emission, mi,c,f, is inventoried in units of sound energy (in J), the noise impact on humans (HN) can be expressed by the quantity person-Pa*s, or using the SI unit kg/m*s.
A total of 248 CFs was calculated for the defined archetypal and spatial contexts. These CFs are representative of a vast array of possible conditions of emission, but, obviously do not cover them all. Some of the relevant input parameters are highly specific and localised. To support also the needs of a practitioner that would have complete information on all sound emissions in a life cycle, we introduced in the system an extra CF, in order to leave the user the possibility of defining a "user-defined" context of emission. If enough information is available, one could directly input the location-specific parameters into the model, and have a customised characterisation factor as a result. According to the information available, the practitioner may choose to use 10-by-10 km maps and/or archetypes for different phases of a life cycle, or, alternatively, define site-specific customised conditions. The calculation sheet for the development of localised user-defined CFs is provided in the Supplementary Material 3, available in electronic format.

2.6.2. Characterisation factors under archetypal conditions

The fixed parameters reported in Table 6, allowed for the calculation of all the archetypal CFs, and are representative of the full set of dimensions defined in section 2.1. The case of either unspecified frequency ranges, or unspecified time, or unspecified space, and all possible permutations of the three cases also needed to be defined. In some cases it was decided to take a regular mean or a weighted (i.e. with a probability index) value of parameters across dimensions. Given the impossibility of averaging several values of the background sound power level across different dimensions, due to the logarithmic scale used for the measurement of the parameters, a pessimistic approach was considered and the maximum value in all cases was selected. The underlying assumption is that the protection of the health of the target should be paramount also at the modelling phase, thus the background levels shall be in all cases the worst among day, evening and night conditions.

The following assumptions were made:

- Unspecified frequency: in this case, the central 1000 Hz frequency was selected for the calculations as it is the central frequency range for which no extra penalty has to be added in the calculation of sound emissions in dBA (ISO, 1996a). This frequency band is central in the sound spectrum and provides a sufficient representation of a sound, if unspecified. Input parameters for time and place did not change.
- Unspecified time: an average value of 7.5 decibel was considered for the penalty β for day, evening and night emissions. For the calculation of the other parameters, values were dimensioned according to the probability of emissions taking place during different parts of the day. It was decided to adopt a pessimistic view over reality, and therefore the highest probability-weight was attached to "night-parameters", then to "evening parameters", and a lower weight was assigned to "day- parameters". The maximum background sound power level was chosen. It was, in fact, decided to adopt a pessimistic view on input parameters for frequency and place remained equal.
- Unspecified place: the values of the system parameters were averaged across the four different outdoor places of emissions, differentiated per day, evening and night, with unaltered values for the frequency. The maximum background sound power level was chosen.
- Unspecified time and place: the values of the system parameters were averaged, without any additional weight, across places and times of sound emission considering the 12 different outdoor contexts of emissions. Emissions across places and time were assumed to be equally probable. Emissions taking place indoor were excluded from the calculations, in light of the definition given of the indoor compartment in section 2.3.8. The maximum background sound power level was chosen across the 12 different outdoor contexts.
- Unspecified frequency and time: the values of the system parameters were averaged across day, evening and night for each of the defined places of emission. The maximum background sound power level across day, evening, and night was chosen.
- Unspecified frequency and unspecified space: the central 1000 Hz frequency was selected for the frequency, together with an average of all day, all evening and all night values respectively. The maximum background sound power level of all day, all evening and all night values, respectively, was chosen.
- Unspecified frequency, unspecified time and unspecified space: the central 1000 Hz frequency was selected for the frequency, and the values of all other parameters were averaged across 12 outdoor possible combinations of dimensions. The maximum sound power level across all the possible outdoor combinations was chosen.

Table 2.6. Parameters defined for the archetypal case

place	time	Wamb [dB]	T [°C]	Rh [%]	P [Pa]	h [m]	d [m]	ρ[person/m2]	S [m2]	Nf [people]	Pr [dB]	ψ	αm
urban	day	77	20	30	101325	3	10	200	20	4000	-	-	-
urban	evening	82	16	60	101325	3	10	375	20	7500	-	-	-
urban	night	84	12.8	60	101325	3	10	450	20	9000	-	-	-
urban	unspecified	84	15.2	54	101325	3	10	377.5	20	7550	-	-	-
suburban	day	69	20	30	101325	3	10	66.7	30	2000	-	-	-
suburban	evening	75	16	60	101325	3	10	133.4	30	4000	-	-	-
suburban	night	75	12.8	60	101325	3	10	133.4	30	4000	-	-	-
suburban	unspecified	75	15.2	54	101325	3	10	120	30	3600	-	-	-
rural	day	62	20	40	101325	3	100	50	10	500	-	-	-
rural	evening	68	16	70	101325	3	100	100	10	1000	-	-	-
rural	night	68	12.8	70	101325	3	100	100	10	1000	-	-	-
rural	unspecified	68	15.2	64	101325	3	100	90	10	900	-	-	-
industrial	day	84	20	30	101325	3	10	66.7	30	2000	-	-	-
industrial	evening	82	16	60	101325	3	10	50	30	1500	-	-	-
industrial	night	78	12.8	60	101325	3	10	33.4	30	1000	-	-	-
industrial	unspecified	84	15.2	54	101325	3	10	45	30	1350	-	-	-
indoor	day	63	25	40	101325	3	1	0.033333	300	10	5	0.3	0.05
indoor	evening	61	25	40	101325	3	1	0.026667	300	8	5	0.3	0.05
indoor	night	58	25	40	101325	3	1	0.02	300	6	5	0.3	0.05
indoor	unspecified	63	25	40	101325	-	1	0.024667	300	10	5	0.,3	0.05
unspecified	day	84	20	32.5	101325	3	32.5	94.5	22.5	2125	-	-	-
unspecified	evening	82	16	62.5	101325	3	32.5	155.6	22.5	3500	-	-	-
unspecified	night	84	12.8	62.5	101325	3	32.5	166.7	22.5	3750	-	-	-
unspecified	unspecified	84	15.2	52.5	101325	3	32.5	138.9	22.5	3125	-	-	-

SEVENTH FRAMEWORK PROGRAMME

The results of the calculations of the CFs for the 248 possible combinations of the dimensions of sound emissions are reported in the Supplementary Information 2 to this contribution.

If we focus on sound emissions at the central frequency of 1000 Hz (in Figure 2.1), it is possible to notice that the highest impact relates to emissions taking place indoor, and at night, while those taking place during the day in a rural area are the least impacting. The case of unspecified emissions at an unspecified time scores lower than emissions taking place during the day.

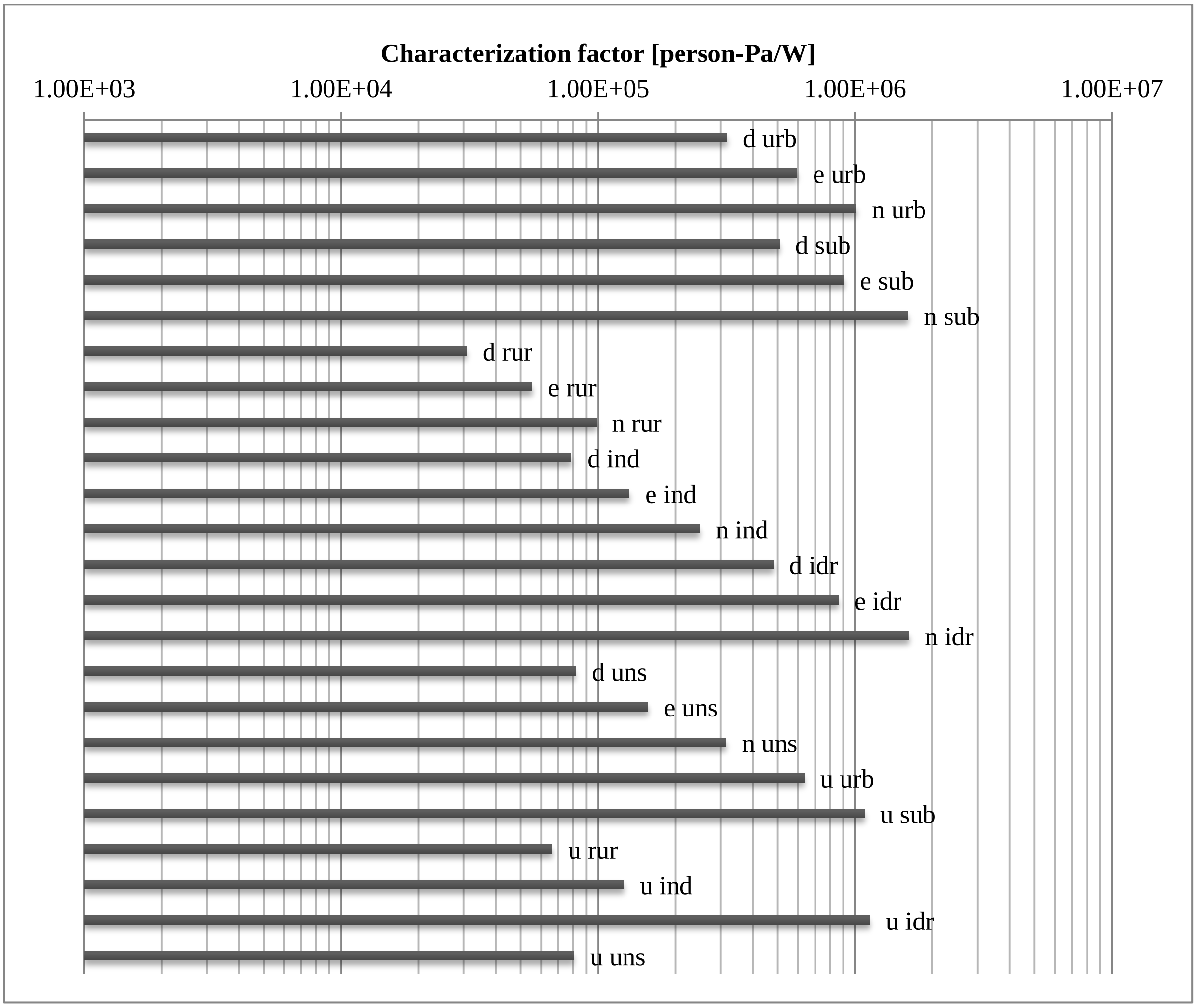

Figure 2.1. Characterisation factor (in person-Pa/W) at 1000 Hz. In the figure: urb=urban; sub=suburban; rur=rural; ind=industrial; idr=indoor; u=unspecified; d=day; e=evening; n=night

The trends reported for the lowest available octave band of 63 Hz follow a similar trend as described above for emissions at 1000 Hz (see Table 2.2).

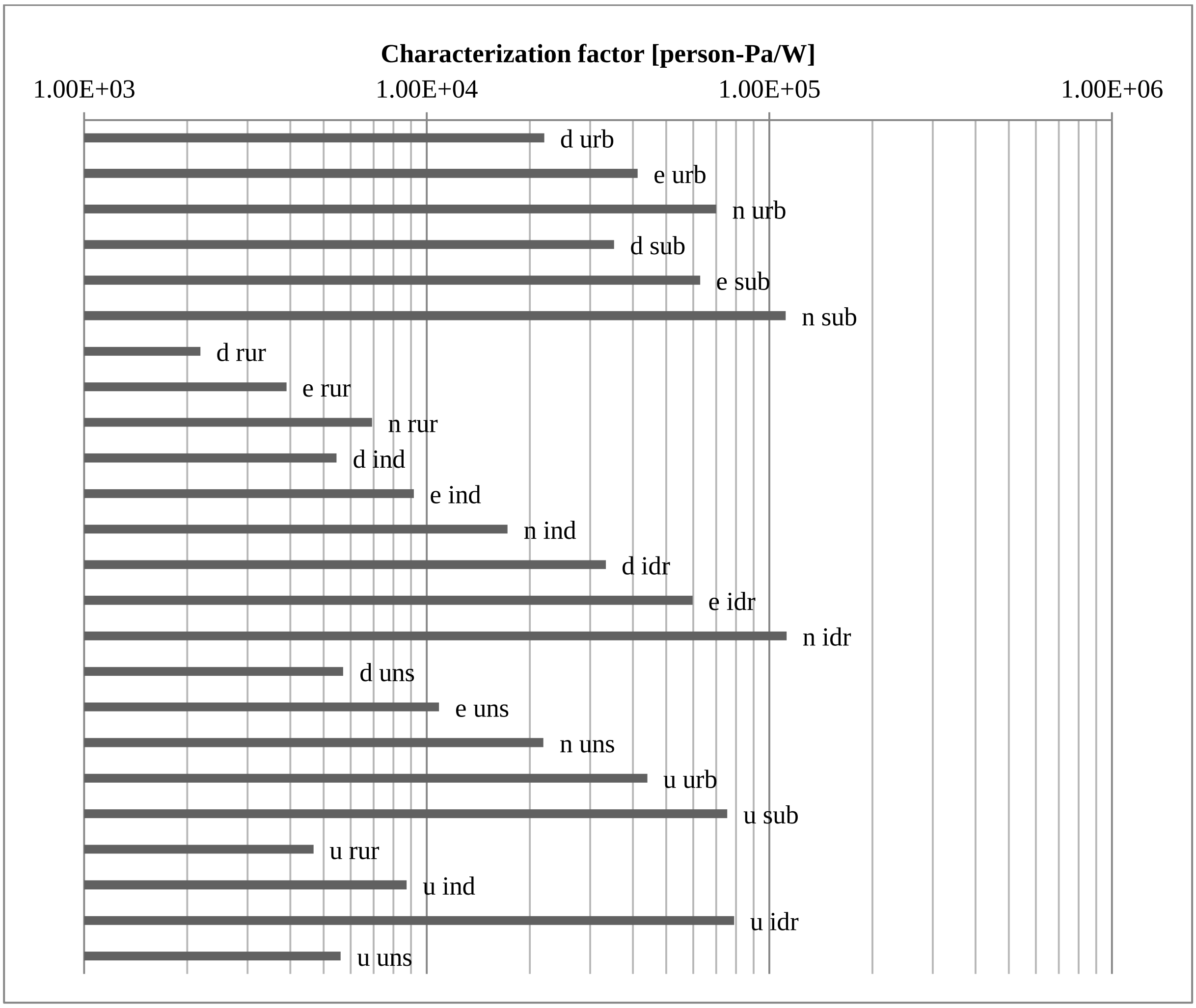

Figure 2.2. Characterisation factor (in person-Pa/W) at 63 Hz. In the figure: urb=urban; sub=suburban; rur=rural; ind=industrial; idr=indoor; u=unspecified; d=day; e=evening; n=night

At urban location and at day time the CFs change at varying frequencies (Figure 2.3), and the highest impact results at 2000 Hz.

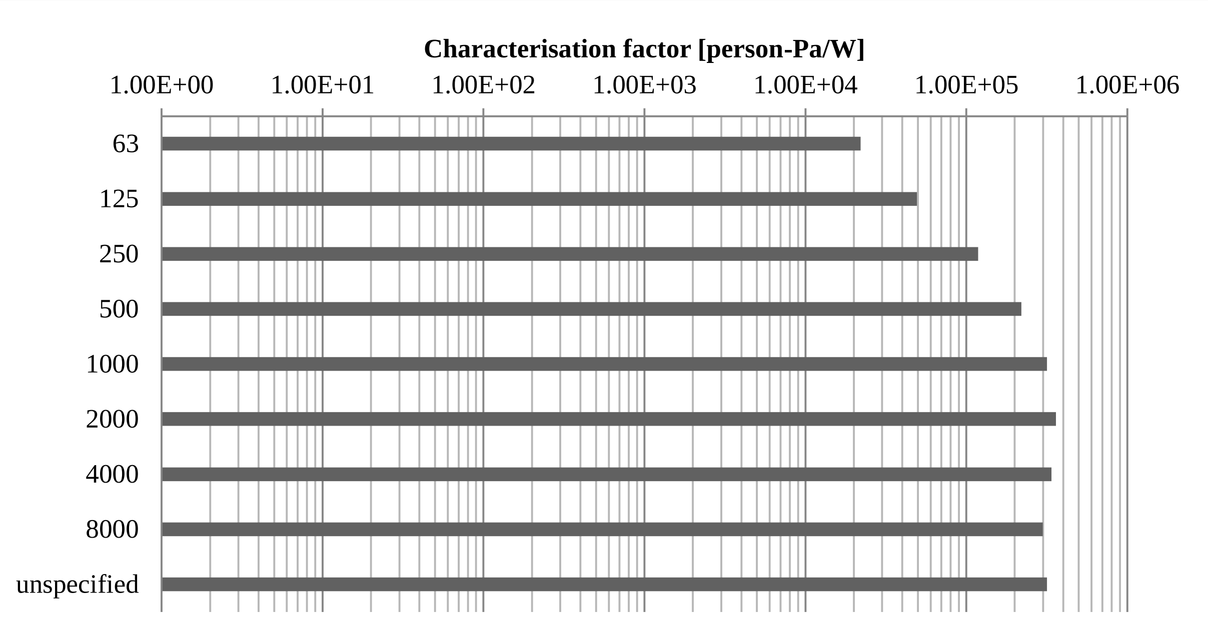

Figure 3. Characterisation factor (in person-Pa/W) in a urban area during day time at eight centre-octaves and unspecified frequency

2.6.3. Maps of characterisation factors for EU27

In the spatial context, 32 maps of CFs with a 10 km2 grid were produced (see Supplementary Information 1). They refer to emissions taking place in EU27. Raster data was collected and analysed for all the defined parameters. CFs are provided for eight centre-frequencies (i.e. from 63Hz to 8000 Hz) for day, evening, night and unspecified time. In this case, the value of Wamb for the unspecified case was calculated as a mean of the Wamb value for day, evening, and night.

For the case of unspecified frequency of emission, we recommend to consider the use of the CFs calculated at the central frequency of 1000 Hz.

We will focus the analysis on emissions at a 63 Hz and compare those taking place during day, evening, night or during an unspecified time (Figure 2.4). Following the colouring scale, the least affected areas are shown in green, while the most affected are represented in dark red. From the comparison of the maps it is clear that metropolitan areas are the most sound-intensive locations, no matter the time of the emission.

Areas around bigger cities (e.g. Great London area) are the ones which show the highest values of CFs. Areas with CFs values close to zero, or equal to zero, correspond to areas where attenuations are so dominant to attenuate any effect of the sound emission. The model adopted shows to be sensitive in changes in emissions at different centre-frequency ranges. The mean for CFs at 63 Hz during day time is 1757.05 person-Pa/W, with a standard deviation of 2634.63 person-Pa/W. CFs for emissions taking place at night have the highest impact, with an average of 7098.74 persona-Pa/W and a standard deviation of 9134.29 person-Pa/W. During the evening the CFs at 63 Hz have a mean of 2070.34 person-Pa/W and a standard deviation of 2827.88 person-Pa/W. In the case of unspecified time of emission, a mean of 2650.87 person-Pa/W was calculated, with a standard deviation of 3632.74 person-Pa/W.

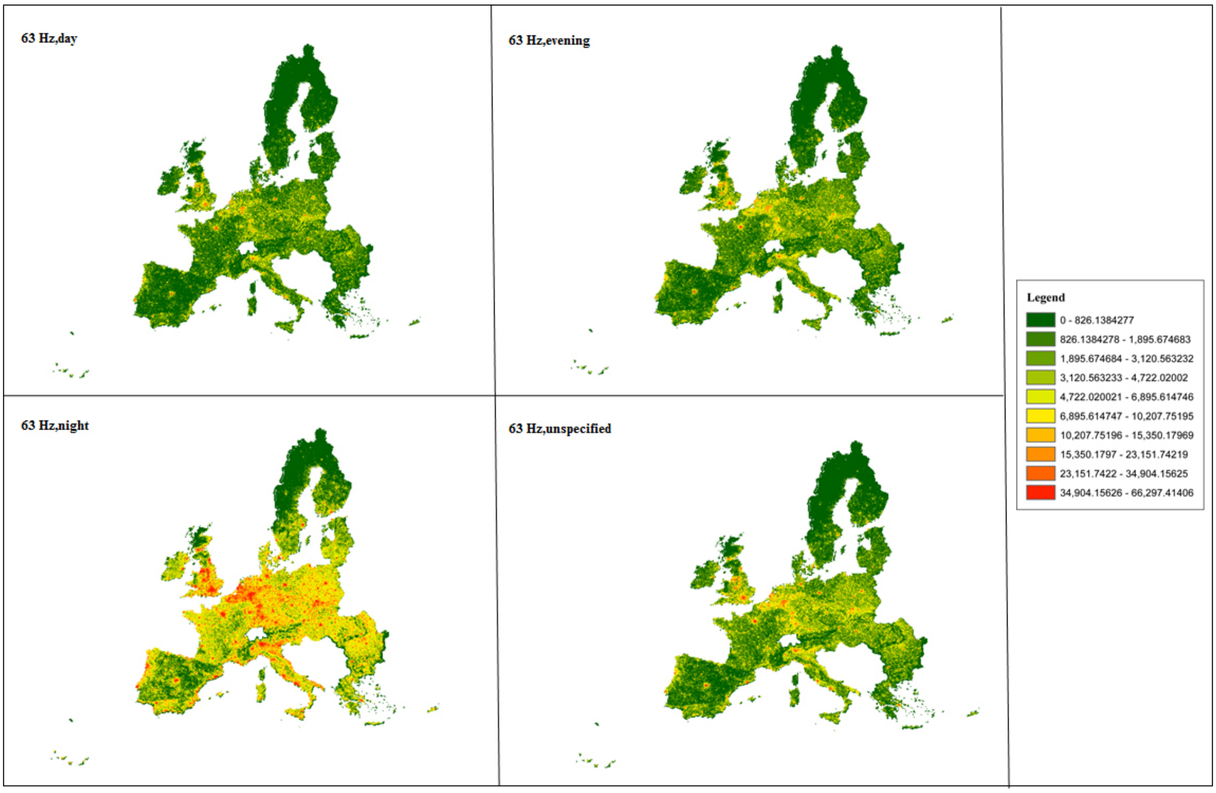

Figure 2.4. Characterisation factor in map at 63 hertz for day, evening, night and unspecified time, at 63 Hz for EU27

At the same frequency, 63 Hz, CFs for day and evening have in all cases a lower value than CFs for night and unspecified time. In Figure 2.5 the difference is shown graphically. The highest differences are visible (in red) around areas with higher population density and higher background sound levels.

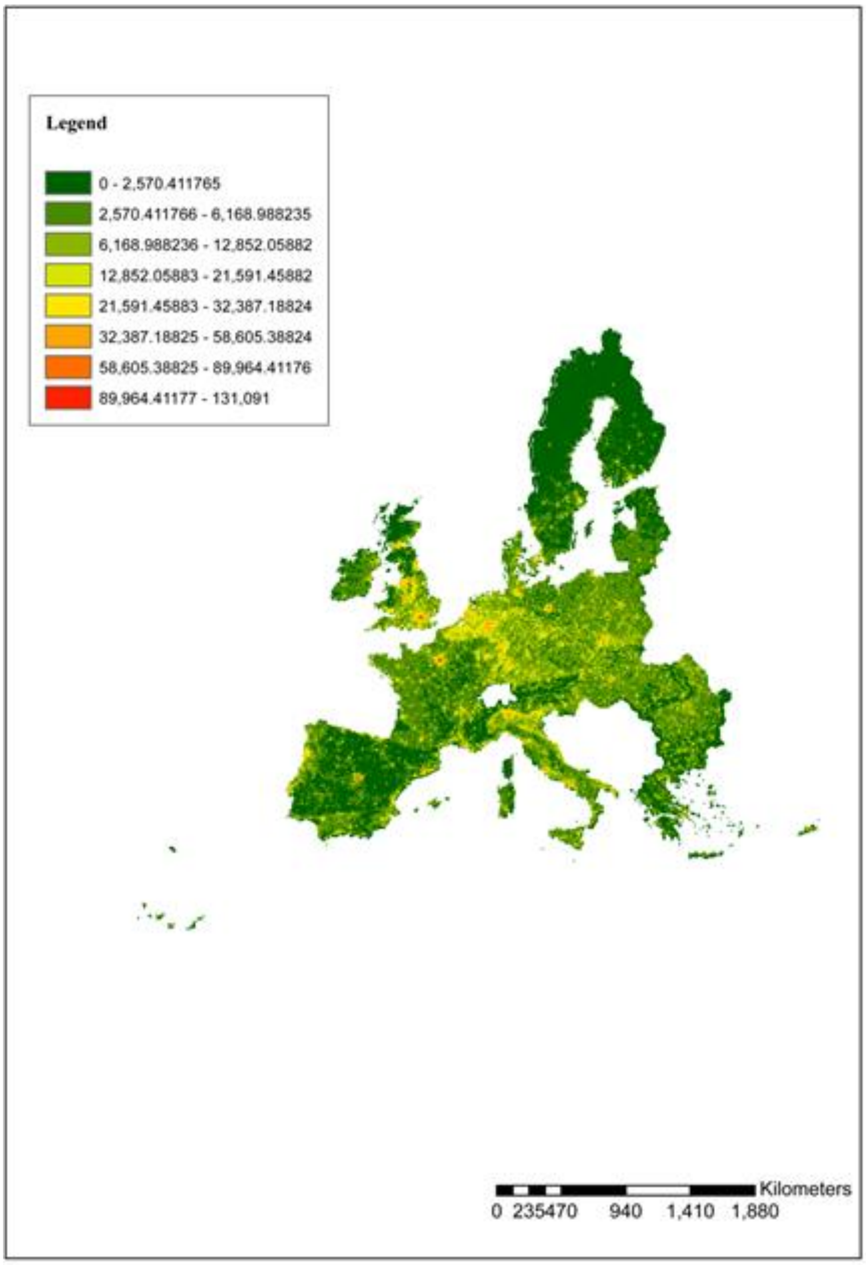

Figure 2.5. Difference between Characterisation factors at 63 Hz night and CF at 63 Hz unspecified

2.6.4. Global sensitivity analysis applied to the noise impact model

For the calculation of CFs, in both the archetypal and the spatial cases, it was necessary to fix factors to a central value, either using data from the literature or extrapolating data from the spatial analysis. We are conscious that this decision introduces extra uncertainty into the overall model. While it can be accepted that uncertainty is an intrinsic feature of complex models (Couclelis, 2003), it does not exclude that much can be done to manage and resolve uncertainties where possible. As stated before in this report, also spatial calculations are also the results of assumptions and of the extension of characteristics defined for a specific area to a greater or smaller area of reference. Therefore, they are also uncertain.

We decided to corroborate the proposed model and calculations by applying global sensitivity analysis (i.e. considering at once the full range of input factors). For each parameter a sample distribution was chosen as shown in below (

Table 2.7). We used Monte Carlo method (Caflisch, 1998) with quasi-random sampling to calculate a 1000 samples of each of the thirteen uncertain input factors considered in the noise LCIA model. The sampling technique was selected considering to avoid clusters and gaps, which may occur in samples generated randomly (Saltelli et al., 2008). The quasi-random samples are random in the sense that are distributed uniformly across the entire sample space, but the selection algorithm keeps the newly selected points away from the already selected ones, thus avoiding the phenomenon of discrepancy (i.e. the lumpiness of a sequence of points in a multidimensional space; Saltelli et al., 2008).

Table 2.7. Description of uncertain input factors

Statistical definition of parameters				
Parameter [unit]	Symbol	Distribution	Mean a or left bound b or discrete values c	Standard deviation a or right bound b or discrete values c
Ambient sound power level [dB]	Lw	Lognormal	0	1
Frequency [Hz]	fm	Discrete (equiprobable)	[63;125;250;500;1000;2000;4000;8000]	[0.1;0.1;0.15;0.15;0.15;0.15;0.1;0.1]
Temperature [deg]	T	Uniform	0	25
Relative Humidity [%]	Rh	Uniform	10	90
Pressure [kPa]	P	Uniform	10	101325
Average propagation height [m]	h	LogUniform	2	8
Distance [m]	d	LogUniform	5	50
Reference area [km2]	S	LogUniform	5	30
Number of people	Nf	Normal	1000	300
Directivity [dB]	D	Discrete	[3;6;9]	[0.7;0.15;0.15]
Frequency penalty [dB]	α	Discrete	[-26.2;-16.1;-8.6;-3.2;0;1.2;1;1.1]	[0.1;0.1;0.15;0.15;0.15;0.15;0.1;0.1]
Time penalty [dB]	β	Triangular d	[0;5;10]	-
Ground	G	Uniform	0	1

composition coefficient				

Sensitivity analysis was conducted and the noise impact framework was implemented in the software SIMLAB (Saltelli et al., 2004). The variance-based method extended Fourier amplitude sensitivity testing (eFAST, Saltelli et al., 2002, 2008 pp.164-166) was used to study how the variance of the output of the proposed model would depend on the uncertain input factors (Saltelli et al., 2008). Variance-based methods are based on the decomposition of the variance of a model output as V(Y) = V[E(Y|Xj)] + E[V(Y|Xj)], for any generic input variable Xj (Tarantola et al. 2002). eFAST provides for every input variable both the first-order sensitivity index (Sj, i.e. the direct contribution to variance of each parameter) and the total-order sensitivity index of each input parameter (STj, i.e. the sum of all the sensitivity indices, including all the interaction effects, involving that parameter). Table 8 shows the first and total order indices for the noise impact model calculated using eFAST. Each of the first order indices, Sj, indicates by how much the output variance could be reduced if any input Xj could be fixed to a nominal value (Saltelli et al. 2008), thus is equal to V[E(Y|Xj)] / V(Y). The total sensitivity index, STj, is a measure of the overall effect of an factor Xj on the output, including also all the interactions. It corresponds to the expected variance that is left when all factors are fixed (Saltelli et al. 2008); thus, STj = V[E(Y|X-j)] / V(Y), where X-j indicates that all factors are considered but Xj (Tarantola et al. 2002). The calculation of the STj allows to identify noninfluential factors in a model, rather than prioritizing the most influential ones.

Table 2.8. First and total order sensitivity indices

	First order indices (Sj)			Total order indices (STj)		
Input variable (Xj)/Model output (Y)	EF	FF	CF	EF	FF	CF
Lw	0.06	0.07	0.10	0.44	0.66	0.82
Freq	0.09	0.07	0.11	0.79	0.65	0.88
T	0.08	0.07	0.07	0.69	0.66	0.66
P	0.04	0.05	0.09	0.41	0.76	0.75
Rh	0.08	0.08	0.07	0.75	0.71	0.69
h	0.07	0.07	0.07	0.62	0.63	0.63
d	0.06	0.11	0.11	0.55	0.89	0.89
S	0.08	0.07	0.04	0.72	0.64	0.58
Nf	0.04	0.07	0.06	0.40	0.64	0.57
D	0.07	0.11	0.11	0.60	0.89	0.89
α	0.10	0.09	0.09	0.81	0.80	0.76
β	0.32	0.09	0.12	0.91	0.80	0.89
G	0.03	0.09	0.09	0.39	0.76	0.74

The indices were calculated both for the final CFs but also for EF and FF. For the EF, the penalty β has the highest S index. For instance, the result would suggest that the size of the penalty matters in the overall result, therefore the model is sensitive to the extra values in dB added to day, evening and night emissions. The distance from source to receiver, d, and the directivity of sound, D, contribute to most of the variance of the FF. Therefore, the uncertainty of the attenuation factor included in the model could be reduced if the actual distance and direction of propagation of sound were known. For the CF, also the background sound conditions, Lw, together with the frequency of emissions appear to be the most relevant values.

The sum of the first-order indices does not add to 1, which confirms that the model is non-additive and highly non-linear (Saltelli et al., 2008). The STi (Table 3.3) confirm that higher-order interactions are present and need to be taken into account for the complete understatement of the model. As Saltelli et al. (1997) propose, a set of input parameters with total sensitivity index greater than 0.8 can be regarded as `very important', between 0.5 and 0.8 as `important', and between 0.5 and 0.3 as `unimportant', and less than 0.3 `irrelevant'. In the case of our model, interactions highlight how all the included parameters are important, because of the higher order interactions between them. The distance d from the source to the receiver is still the most influential value, together with the directivity index D and the penalty β (i.e. STi=0.89). The frequency of the sound emission comes right after with a ST of 0.88.

2.7. Conclusions, future agenda and potential expansion of the model

This contribution proposes CFs which are immediately usable for the calculation of the impact of noise on humans at a midpoint level for any sound-emitting source, or combination of emitting sources. The methodology can be also applied with minor adjustments (e.g. frequency of interest, number of exposed subjects) to other target systems than human beings. The provided CFs can be implemented in any of the available LCA databases for impact assessment systems.

The calculations are based on the assumptions that the level of detail of CFs may be more or less of interest for practitioners and researchers, according to the amount of information that is available to them in a specific case. In total, 248 potential CFs were calculated (i.e. 32 spatial and 216 archetypal). Most life cycles will require the use of multiple CFs and even the combination of both spatial and non-spatial factors, based on the amount of data that is available and on the complexity of the system under study. The additional possibility of using user-defined values as input is allowed for the expansion of contexts of emissions and its adaptation to the specific needs.

The CFs are applicable to life-cycle aggregated sound emissions, measured in joule. The procedure for obtaining these frequency-, time-, and location-specific data from dB that belong to individual unit processes has been described by Cucurachi et al. (2012). The standard databases with process data for LCA do not contain noise emissions, thus more investigations are needed at the inventory level to use the characterization factors as elaborated in the present work. The literature provides already enough information to analyse specific cases, such as the proposed CNOSSOS report (European Commission, 2012).We will demonstrate the use of the CFs in a future case study, nevertheless.

The CFs provided are in person-pascal/watt, or s*m-3. The measure provides a midpoint characterisation factor for the impact of noise on humans. The quantification of the amount of DALYs that are associated to the quantity expressed by the midpoint CFs may be used to provide a measure of the noise impacts at an endpoint level. The calculation of the DALYs associated with noise has been extrapolated in past studies by the study of data from surveys on noise annoyance and level of disturbances (Miedema and Vos, 1998; Muller Wenk, 2004; WHO, 2011). Itsubo and Inaba (2008) developed a damage function for noise impacts associating to a sound energy emission in joule the corresponding value in DALYs. We intend to go towards this direction, making also use of the results available in the literature of the impacts of noise on health (see for instance, Fyhri and Klæboe, 2009; Pirrera et al., 2010). The conversion of person-pascal/watt in the DALY scale is under development and is based on the conversion of curves from the decibel unit to the natural physical units of reference.

The result of the global sensitivity analysis allowed for a better comprehension of the model structure when parameters are independent. The first order and total order sensitivity indices, that we calculated, already provide an idea of the areas where investments may be made to reduce uncertainty. We saw, in fact, that it is risky to fix some values to a central value without carefully thinking over their contribution to the variance of the output and the high-order interactions between a parameter and the others. The results provide a good basis on which to expand the analysis of the framework and by which to improve data collection. The limited availability of data (e.g. only one trustable source for background sound levels) and the highly localised nature of the impacts may pose a challenge to the collection of information for some of the parameters. As stated in Borgonovo et al. (2012), without a proper sensitivity analysis one is exposed to the so-called black-box effect, namely the risk of not fully understanding the behaviour of the model on which analyses and decisions are based. The use of global sensitivity analysis techniques should become standard practice also in the LCIA development. Several applications of sensitivity analysis techniques have, in fact, improved the understanding and the performance of complex environmental systems (see, for instance, Fassó et al. 2003, and Borgonovo et al. 2012). As it was shown in the case of noise, the development of spatially-explicit CFs does not statim reduce uncertainties. In our case, the lack of data did not allow us to go to a finer resolution than 10 km2. In order to evaluate also the right scale of spatial definition for the development of maps of CFs, a global sensitivity analysis should be conducted. The application of sensitivity analysis to environmental risks and impacts may have to handle a large set of input data, especially in the case of spatially and temporally variable systems. Techniques have been developed to overcome such issues through the use of meta-models (Marrell et al. 2011). In this context, a Gaussian process model as developed by Marrell et al. (2011) can and should be used to calculate sensitivity indices (or index maps) and process uncertainties also in the case of high dimensional output of a model, as are typically characterisation maps in LCIA.

Acknowledgements for chapter 2

The authors would like to thank Sandra Torras Ortiz from the University of Stuttgart, in Germany, for the valuable contribution in the gathering of part of the GIS data, and Nicolas

Davin from Naturalis-Biodiversity Center, in Leiden, The Netherlands, for the precious tips and hints on data handling in GIS. Warm thanks also go to Willem Franken from EASA, who permitted to fully access the documentation of the BANOERAC project, and to dr. Enrico Benetto and dr. Olivier Baume from the CRP Henry Tudor in Luxembourg, who provided important comments for the improvement of this contribution.

2.8. Appendix

Appendix 2A – Calculation of the factor αatm based on ISO9613-1 (ISO, 1993)

ISO9613-1 was followed for the calculation of the attenuation factor αatm. In both the spatial and archetypal cases, following the analytic equations in ISO 9613-1 (ISO, 1993), the molar concentration of water vapour (in %) was calculated for any given temperature and pressure from the formula:

$$\mathbf{H} = \mathbf{Rh} \times (\mathbf{P_{sat}}/\mathbf{P_{ref}})/(\mathbf{P_{atm}}/\mathbf{P_{ref}}), \tag{2A.1}$$

where Patm is the atmospheric pressure in Pa, Prel the relative pressure pressure in Pa, and Psat is the saturation water pressure in Pa, and Rh is the relative humidity in % at a specific location. In the spatial context, the local ambient air pressure was calculated as a factor of the elevation (Jarvis et al., 2008). In the archetypal contexts of emission, ambient pressure was considered at a nominal atmospheric pressure of 101325 Pa and the other meteorological parameters were modelled as static over time, and uniform meteorological conditions at specific locations (i.e. archetypal compartments) were considered for the calculations.

The ratio (Psat/Prel) is given by the following formula provided in the ISO 9613-1 (ISO, 1993):

$$(\mathbf{P_{sat}}/\mathbf{P_{rel}}) = \mathbf{10}^{\left(-6.8346\times(T_{01}/T)^{1.261}+4.6151\right)}, \tag{2A.2}$$

where T is the temperature at the specific location under study in kelvin and T01 is the triple-point isotherm temperature of 273.16 K (i.e. + 0.01 ºC). The calculation of the molar concentration of water vapour, h, allows for the calculation of two relaxation frequencies, frO and frN, in Hz, which can be calculated from:

$$\mathbf{fro} = \frac{\mathbf{P_{atm}}}{\mathbf{P_{rel}}}\left(\mathbf{24} + \mathbf{4.04} \times \mathbf{10^4 H}\frac{\mathbf{0.02+H}}{\mathbf{0.391+H}}\right) \tag{2A.3}$$

and

$$\mathbf{frn} = \frac{P_{atm}}{P_{rel}}\left(\frac{T}{T_{ref}}\right)^{-1/2} \times \left(9 + 280H\, e^{\left\{-4.170\left[\left(\frac{T}{T_{ref}}\right)^{-1/3}-1\right]\right\}}\right), \qquad (2A.\ 4)$$

where Tref is the reference temperature of 293.325 K and T is the temperature measured at the location under consideration (in K). The relaxation frequencies allow for the calculation of the value of α according to the equation from ISO9613-1 (ISO, 1993; section 6.2 and Annex B; fm is the frequency band under study):

$$\propto \mathbf{atm} = 8.686 fm^2 \left(\left[1.84 \times 10^{-11}\left(\frac{P_{atm}}{P_{rel}}\right)\left(\frac{T}{T_{rel}}\right)^{\frac{1}{2}}\right] + \left(\frac{T}{T_{rel}}\right)^{-\frac{5}{2}} \times \left\{\begin{matrix} 0.01275\left[e^{\left(\frac{-2239.1}{T}\right)}\right]\left[f_{rO} + \left(\frac{fm^2}{f_{rO}}\right)\right]^{-1} \\ +0.1068\left[e^{\left(\frac{-3352.0}{T}\right)}\right]\left[f_{rN} + \left(\frac{fm^2}{f_{rN}}\right)\right]^{-1} \end{matrix}\right\}\right). \qquad (2A.\ 5)$$

Appendix 2B - Calculation of the attenuation Aground based on the CNOSSOS reference report (European Commission, 2012)

The value of $Aground_{i,c,f}$ in homogenous conditions was calculated as in:

$$\mathbf{Aground}_{i,c,f} = \max\left(-10\log\left[\begin{matrix} 4 \times \frac{k^2}{d^2} \times \left(z_s^2 - \sqrt{\frac{2C_f}{k}}(z_s) + \frac{C_f}{k}\right) \\ \times \left(z_r^2 - \sqrt{\frac{2C_f}{k}} z_r + \frac{C_f}{k}\right) \end{matrix}\right], \mathbf{Aground, min}_{i,c,f}\right), \qquad (2B.\ 1)$$

where k represents the ratio between the nominal centre frequency band (in Hz) and the celerity of sound in air (i.e. taken as 340 m/s); d is the distance in m from source to receiver; zs is the height of the source in m, which was approximated to 1 m for all calculations (i.e. source close to the ground); zr is the height of the receiver in m, which was approximated to 2 m for all calculations (i.e. receiver 1 m above emitting source); Cf is a factor of the absorption of ground at increasing distances and of the speed of sound (i.e. 343.2 m/s). Aground, mini,c,f represents the lower bound of Aground and takes into account the fact that when the source and the receiver are far apart, the first reflection source side is no longer on an artificial surface but on the natural land (European Commission, 2012). The lower bound of the equation is calculated as in:

$$\mathbf{A}_{ground,min} = -3(1 - G) \cdot \qquad (2B.\ 2)$$

As specified in the CNOSSOS report, the value of k (in m) can be calculated as:

$$\mathbf{k} = \frac{2\pi \times fm}{c}, \qquad (2B.\ 3)$$

where fm is the nominal centre frequency, in Hz, c is the speed of sound in air (i.e. 340 m/s). The value of Cf is defined by:

$$C_f = d\,\frac{1+3wde^{-\sqrt{wd}}}{1+wd}, \qquad (2B.\ 4)$$

and w is given by:

$$w = 0.0185\,\frac{fm^{2.5}G^{2.6}}{fm^{1.5}G^{2.6}+1.3\times10^{3}fm^{0.75}G^{1.3}+1.16\times10^{6}}. \qquad (2B.\ 5)$$

In all cases where the value of G was zero, the attenuations Aground was considered as equal to 3 dB (European Commission, 2012).

2.9. References

Annoni A., Luzet C., Gubler E., 2003. Map Projections for Europe. Institute for environment and sustainability. Available at: http://mapref.org/LinkedDocuments/MapProjectionsForEurope-EUR-20120.pdf. Accessed on the: 28-06-2012.

Attenborough K., 1982. Acoustical characteristics of porous materials. Phys. Rep. 82(3):179-227.

Bies D.A., Hansen C.H., 1996. Engineering noise control: theory and practice. 2nd edition, E. & F.N. Spon, London..

Borgonovo E., Castaings W., Tarantola S., 2012. Model emulation and moment-independent sensitivity analysis: An application to environmental modelling. Environ. Model. Softw. 34, 105-115.

Bossard M., Feranec J., Otahel J., 2000. CORINE land cover technical guide- Addendum 2000. Eur. Environ. Agency. Tech. Rep. 40.

Burrough P.A., McDonnell R.A., 1998. Principles of Geographical Information Systems. Oxford University Press, Oxford, UK.

Caflisch R. E.,1998. Monte Carlo and quasi-Monte Carlo methods. Acta Numerica. 7. Cambridge University Press. pp. 1–49.

Concha-Barrientos M., Campbell-Lendrum D., Steenland K., 2004. Occupational noise. Assessing the burden of disease from work-related hearing impairment at national and local levels. World Health Organization, Geneva.

Couclelis H., 2003. The certainty of uncertainty: GIS and the limits of geographic knowledge. Trans. in GIS 7:165–75.

Crosetto M., Tarantola S., Saltelli A., 2000. Sensitivity and uncertainty analysis in spatial modeling based on GIS. Agr. Ecosyst. Environ. 81:71–79.

Cucurachi S., Heijungs R., Ohlau K., 2012. Towards a general framework for including noise impacts in LCA. Int. J. Life Cycle Ass. 4(17):471-487.

de Jong B.A., Moerkerken A., van der Toorn J.D., 1983. Propagation of sound over grassland and over an earth barrier. J. Sound Vib. 86(1):23-46.

Delany M.E., Bazley E.N., 1970. Acoustical Properties of Fibrous Absorbent Materials. Appl.Acoust. 3: 105.

EASA – Environmental Aviation Safety Agency, 2009. Background Noise Level And Noise Level From En Route Aircraft Final Report. Available online at: http://www.easa.europa.eu/rulemaking/studies-and-research-activities.php. Accessed on the: 05-06-2012.

ESRI, 2011. ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute. Computer Software.

European Commission,2002. Position Paper On Dose Response Relationships Between Transportation Noise And Annoyance. Off. J. Eur. Comm., EU.

European Commission, 2012. Common NOise ASSessment MethOdS in EU (CNOSSOS-EU) Available online at: http://circa.europa.eu/Public/irc/env/noisedir/library?l=/material_mapping/cnossoseu/cnossoseu_technical/kick-off_15-16nov2010/cnossos-eu_9nov2010pdf/_EN_1.0_&a=d . Accessed on: August 2012.

Eurostat, 2007. Euroindicators. Available online at: http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home/. Accessed on the: 21-08-2012.

Fang C., Ling D., 2003. Investigation of the noise reduction provided by tree belts.Landscape and Urban Plann. 63:187-195.

Fassó A., Esposito A., Porcu E., Reverberi A. P., Veglió F., 2003. Statistical sensitivity analysis of packed column reactors for contaminated wastewater. Environmetrics 14:743–759.

Fyhri A., Klæboe, R., 2009. Road traffic noise, sensitivity, annoyance and self-reported health—A structural equation model exercise. Environ. Int. 35(1): 91-97.

Harris C.M., 1966. Absorption of sound in air versus humidity and temperature. J. Acoust. Soc. Am. 40: 148-159.

Heijungs R., Guinee J.B., Huppes G., et al., 1992. Environmental life cycle assessment of products. I. Guide, October 1992. II. Backgrounds, October 1992. CML, Leiden, 226 pp.

Heijungs R., 2005. On the Use of Units in LCA (4 pp). Int. J. Life Cycle Assess. 10(3): 173-176.

Hijmans R.J., Cameron S.E., Parra J.L., Jones P.G., Jarvis A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climatol. 25:1965-1978.

ILCD - International Reference Life Cycle Data System Handbook - General guide for Life Cycle Assessment - Detailed Guidance, 2010. European Commission, Joint Research Centre, Institute for Environment and Sustainability. Publications Office of the European Union, Luxemburg.

ISO, 1993a. ISO 9613-1: International standard: Acoustics - attenuation of sound during propagation outdoors - part 1: Calculation of the absorption of sound by the atmosphere. ISO, Geneva.

ISO, 1993b. ISO 9614-1: International standard: Acoustics - Determination of sound power levels of noise sources using sound intensity - part 1: Measurement at discrete points. ISO, Geneva.

ISO, 1996a. ISO 9613-2: International standard: Acoustics - attenuation of sound during propagation outdoors - part 2: A general method of calculation. ISO, Geneva

ISO, 1996b. ISO 11690-1: International standard: Acoustics – Recommended practice for the design of low-noise workplaces containing machinery. ISO, Geneva.

ISO, 2000. ISO 14040: Environmental Management – Life Cycle Assessment– Principles and Framework. ISO, Geneva.

ISO, 2001. ISO 14257: International standard: Acoustics – Measurement and parametric description of spatial sound distribution curves in workrooms for evaluation of their acoustical performance. ISO, Geneva.

Itsubo R. N., Inaba A., 2008. Noise Impact Assessment in LCA : Damage Function of Road Transport Noise in Japan. Available online in Japanese at: http://www.aist-riss.jp/main/modules/groups_alca/content0005.html?ml_lang=en. Accessed on the: 18-05-2012.

Jarvis A., Reuter H.I., Nelson A., Guevara E., 2008, Hole-filled seamless SRTM data V4, International Centre for Tropical Agriculture CIAT. Available online at: http://srtm.csi.cgiar.org. Accessed on the: 21-08-2012.

Kleijnen J.P.C., 1987. Statistical Tools for Simulation Practitioners. Marcel Dekker, New York, Usa.

LC-IMPACT, 2011. Deliverable D3.1. Available online at: http://www.lc-impact.eu/downloads. Accessed on the: 21-08-2012.

Maher R.C., 2007. Acoustical Characterization of Gunshots. Conference proceedings SAFE 11-13 April, Washington D.C., USA.

Marrel A., Iooss B., Jullien M., Laurent B., Volkova E., 2011. Global sensitivity analysis for models with spatially dependent outputs. Environmetrics 22(3): 383-397.

Miedema H., Oudshoorn C., 2001. Annoyance from transportation noise: Relationships with metrics DNL and DENL and their confidence intervals. Environ. Health 109(4).

Miedema H.M.E., Vos H., 1998. Exposure-response relationships for transportation noise. J. Acoust. Soc. Am. 104:3432-3445.

Müller-Wenk R., 2004. A method to include in LCA road traffic noise and its health effects. Int. J. Life Cycle Assess. 9:76-85.

Nelson D.I., Nelson R.Y., Concha-Barrientos M., Fingerhut M., 2005, The global burden of occupational noise-induced hearing loss. Am. J. Ind. Med. 48:446–458.

Nijs L., Wapenaar C.P.A., 1990. The influence of wind and temperature gradients on sound propagation, calculated with the two-way wave equation. J. Acoust. Soc. Amer. 87.

Pennington D.W., Potting J., Finnveden G., Lindeijer E., Jolliet O., Rydberg T., Rebitzer G., 2004. Life cycle assessment Part 2: Current impact assessment practice. Environ. Int., 30(5): 721-739.

Piercy J.E., Embleton T.F.W., Suthrland L.C., 1977. Review of noise propagation in the atmosphere. J. Acoust. Soc. Am. 61: 1403-1418.

Pirrera S., De Valck E., Cluydts R., 2010. Nocturnal road traffic noise: A review on its assessment and consequences on sleep and health. Environ. Int. 36(5): 492-498.

Rasmussen K.B., 1985. On the effect of terrain profile on sound propagation outdoors, J. Sound Vib. 98(1):35-44.

Rebitzer G., Ekvall T., Frischknecht R., HunkelerD., Norris G., Rydberg, T., et al., 2004. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environment international, 30(5): 701-720.

Reed S.E., Boggs J.L., Mann J.P., 2012. A GIS tool for modeling anthropogenic noise propagation in natural ecosystems. Environ. Model. Softw. 37:1-5.

Saha S., et al. 2010: The NCEP Climate Forecast System Reanalysis. Bull. Amer. Meteor. Soc. 91, 1015–1057.

Salomons E., van Maercke D., Defrance J., de Roo F., 2011. The Harmonoise sound propagation model. Acta Acust. Acust. 97:62–74.

Saltelli A., Chan K. S., Tarantola S., 1997. Sensitivity analysis of model output: an improvement of the FAST method. Joint Research Center.

Saltelli A., Ratto M., Andres T., Campolongo F., Cariboni J., Gatelli D., Tarantola, S., 2008. Global sensitivity analysis: the primer. Wiley-Interscience, USA.

Schroeder M., 2007., Springer Handbook of Acoustics. Springer, New York, USA.

Sharma A., Vijay R., Sandar V.K., Sohony R.A., Gupta A. 2010. Development of noise simulation model for stationary and mobile sources: A GIS-based approach. Environ. Model. Assess. 15(3): 189-197.

SINTEF, 2008. Background noise levels in Europe. Available online at: http://www.sintef.no/home/Information-and-Communication-Technology-ICT/Acoustics/Environmental-acoustics/Noise-mitigation-programs/. Accessed on the: 10-09-2011.

Smith B.J., Peters R.J., Owen S., 1996. Acoustics and noise control. 2nd edition, Addison-Wesley.

Stewart C.M., Russel W.A., Luz G.A., 1999. Can population density be used to determine ambient noise levels? Forum Acusticum, Berlin, Germany.

Stewart J., McManus F., Rodgers N., Weedon V., Bronzaft A., 2011. Why noise matters: a worldwide perspective on the problems, policies and solutions. Abington, Oxon, UK, Routledge.

Tarantola S., Giglioli N., Jesinghaus J., Saltelli A., 2002. Can global sensitivity analysis steer the implementation of models for environmental assessments and decision-making?. Stoc. Env. Res. Risk A. 16: 63-76.

US EPA, 1974. Population Distribution of the United States as a function of outdoor noise level, Report 550/9-74-009.

WHO, 2001. Occupational exposure to noise evaluation, prevention and control. Edited by Berenice Goelzer, Colin H. Hansen and Gustav A. Sehrndt. Available online at: http://www.who.int/occupational_health/publications/occupnoise/en/index.html . Accessed on: 29 11 2012. World Health Organization, Copenhagen.

WHO, 2011. Burden of disease from environmental noise - Quantification of healthy life years lost in Europe. World Health Organization, Copenhagen.

Xie D., Liu Y., Chen J., 2011. Mapping Urban Environmental Noise: A Land Use Regression Method. Environ. Scien. Tech. 45(17):7358-7364.

List of abbreviations and symbols

Abbreviation/symbol	Description [unit]
D	Distance [metre]
Aatm	Atmospheric attenuation [decibel]
AC	Archetypal context
Adiv	Geometrical divergence [decibel]
Aextra	Attenuation due to other factors [decibel]
Aground	Ground attenuation [decibel]
C	Cref [pascal/watt]
CF	Characterisation factor [number of people-pascal/watt]
D	Directivity [decibel]
EF	Effect factor [number of people]
F	Centre-frequency [hertz]
FF	Fate factor [pascal/watt]
Frn	Nitrogen relaxation frequency [hertz]
Fro	Oxygen Relaxation Frequency [hertz]
H	Average propagation height [metre]
H	Molecular concentration water vapour
Int1	Int1 (intermediate calculation as in ISO 9613-1)
Int2	Int2 (intermediate calculation as in ISO 9613-1)
Int3	Int3 (intermediate calculation as in ISO 9613-1)
LCI	Life Cycle Inventory
Lw	Background sound power level [decibel]
Nf	Number of exposed subjects
P	Ambient pressure [kilo-pascal]
P_Sat_over_P_ref	Saturation vapour pressure/reference pressure
Pr	Usage of protective measures [decibel]
Pref	Reference pressure [kilo-pascal]
Prel	Relative pressure
Rh	Humidity [%]
S	Site surface [square meters]
SC	Spatial context
R	Reverberant component of sound propagation [decibel]
T	Temperature [degree centigrade]
T01	Triple point isotherm temperature [Kelvin]
Tkel	Measured ambient temperature [kelvin]
Tref	Temperature at 20C [kelvin]
Trel	Relative temperature
Wamb	Background sound power [watt]
A	Correction for human sensitivity [decibel]
α atmospheric	Atmospheric attenuation factor [decibel/metre]
Am	Room absorption parameter
B	Correction for time of the day [decibel]
P	Population density [people/kilometre square]
Φ	Rate of use of protective measures