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Noise pollution and control in urban European environments

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The aim of this thesis was to provide an overview on the field of environmental acoustics, related noise control strategies and legislation, as well as computer modelling and measuring technologies.

As environmental engineers are employed in a variety of fields, a general understanding of acoustic principles and the field of environmental acoustics may be a field of interest for the aspiring environmental engineer. The field of environmental engineering would benefit from the inclusion of environmental acoustics or noise pollution, as it is closely related to air pollution in terms of its sources.

As acoustics is not a discipline in Metropolia UAS, an overview of the human hearing mechanism and the mechanisms of sound and sound propagation to provide adequate understanding of the underlying principles is given.

The thesis provides information about the legislation, regulations and concerns regarding environmental noise on a general level, as well as practical information on central documentation related to noise control processes. It was conducted as a literature review with consultation from specialists in the field of acoustic engineering and noise abatement.

Keywords	environmental noise, noise pollution, END, environmental acoustics

Tekijä Otsikko Sivumäärä Päivämäärä	Marikka Sand Melusaaste ja sen torjunta eurooppalaisessa kaupunkiympäristössä 24 sivua 30.4.2017
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Tämän insinöörityön tavoite on antaa yleiskuva ympäristöakustiikan alasta ja siihen liittyvistä meluntorjuntastrategioista ja -lainsäädännöstä, mallinnuksesta ja mittaustekniikasta.

Ympäristöinsinöörit työllistyvät monialaisesti, ja akustiikan periaatteiden ja ympäristöakustiikan tuntemus voi olla uusi, kiinnostava lähestymistapa ympäristötekniikkaan. Ympäristötekniikan alaa hyödyttäisi ympäristöakustiikan ja melusaasteen ottaminen kurssivalikoimaan. Melulla ja esimerkiksi pienhiukkaspäästöillä on yhteiset lähteet, minkä vuoksi ympäristömelun käsittely muiden ilmansaasteiden yhteydessä voisi olla luontevaa.

Akustiikkaa ei opeteta Metropolia AMK:ssa. Insinöörityön alussa annetaan yleiskatsaus kuulemisen mekanismeihin sekä ääniaaltojen syntyyn ja etenemiseen peruskäsitteiden ja konseptien selvittämiseksi.

Insinöörityö antaa yleistason tietoa lainsäädännöstä ja muista määräyksistä liittyen ympäristömeluun, sekä käytännön tietoa keskeisestä ympäristömeluprosesseihin liittyvästä dokumentoinnista. Työ pohjautuu alan kirjallisuuteen, ja siinä on konsultoitu akustiikan ja meluntorjunta-alan asiantuntijoita.

Asiasanat	Ympäristömelu, melusaaste, END, ympäristöakustiikka

Contents

1 Introduction

The ever-growing urbanisation, on a global as well as the European scale, poses several challenges to economic and environmental sustainability, as well as human wellbeing. Already early civilisations developed urban infrastructure to service people's need for travel, clean water, sanitation and energy. Roads can safely be assumed to be the first of these to develop, and even if their significance for societal development is obvious, the environmental impact of transport and traffic has also been identified as one of the major contributors to air pollution and global warming next to industrial activities. In addition to having adverse effects on the ecosystem, pollution poses a much more tangible problem to everyday life – nuisance and illness. (Advances in Ecological Sciences, 2001)

Traffic and industry emissions are not limited to particulate matter or toxic substances into air, soil and water bodies. Another form of pollution is noise pollution, which has also been accepted by the EU in its Environment Action Programme to 2020. (The European Parliament And The Council Of The European Union, 2013)

One may argue that environmental noise is not an environmental issue in the traditional sense, as it is not known whether exposure to sounds impacts the environment itself like for example industrial flue gas emissions. However, noise does affect human well-being and health, and environmental noise is essentially an unwanted emission of pressure waves through environmental media such as air and soil. The consensus now is that noise is an environmental issue, and this view is reflected in the fact that noise is considered an emission by legislation (YSL 2014/527 , 2014). In Finland (and for the most part in other EU countries as well), environmental noise regulation is governed by the Ministry of the Environment.

As environmental engineers are employed in a variety of fields, a general understanding of acoustic principles and the field of environmental acoustics may be a field of interest for the aspiring environmental engineer. The aim of this thesis is, to provide an overview on the field of environmental acoustics, related noise control legislation, as well as modelling and abatement technologies.

This thesis is a literature review, and, has been written with kind contributions from M. Sc. (Eng.) Heikki Helimäki of Helimäki Akustikot Oy, Helsinki and B.Sc. (Eng.) Ulaş Saygili of KSZ Ingenieurbüro GmbH, Berlin. Other acknowledgments go to Max Poppius, who showed me I understand Physics, my family for their unconditional support regardless of my frustration level, and Antti Tohka for pushing me the final distance.

2 Acoustics and environmental acoustics

The scientific discipline of acoustics is as varied as any academic field. In everyday situations, acoustics may be understood as the study of music or the study of sound traveling inside rooms. Acoustics is, however, a broad compilation of interlacing disciplines ranging from the arts to engineering, from seismography to psychology. The father of modern acoustics, Robert Bruce Lindsay, developed the Wheel of Acoustics to illustrate the many fields of study included in the topic of acoustics. It first appeared in the Journal of the Acoustics Society of America in 1964 (Brigham Young University - Acoustics Research Group, 2016):

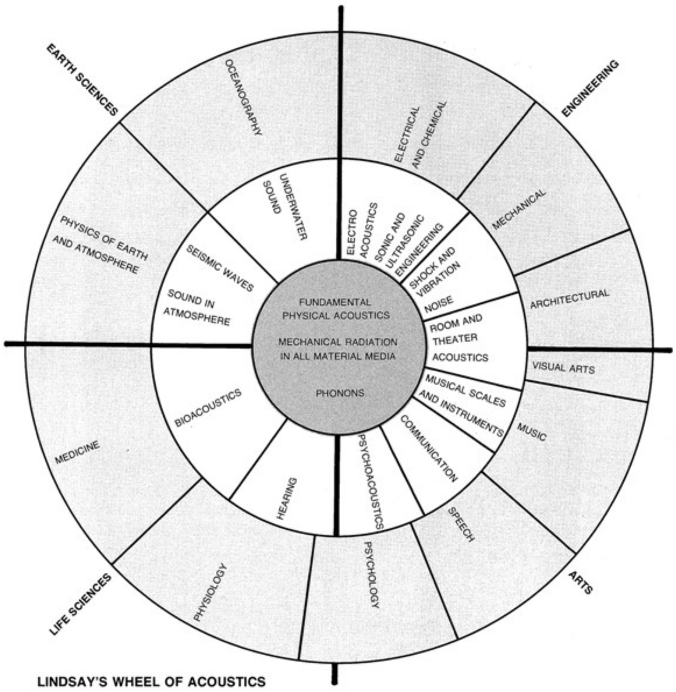

Figure 1 Lindsay's wheel of Acoustics *(Brigham Young University - Acoustics Research Group, 2016)*

Inspecting the wheel, we find there is no section labelled “environmental acoustics”. The academic disciplines concerned with environmental noise are varied. Presently, environmental acoustics is researched and studied for example under the disciplines of architecture, acoustic engineering, civil engineering or electrical engineering; also, private organisations as well as engineering offices conduct their own research and development in the field. There is thus no established discipline; the terms environmental acoustics, ecoacoustics, soundscape studies may be used interchangeably for this field.

3 Physics of Sound

An exhaustive definition of sound is

> a periodic disturbance in the pressure or density of a fluid or in the elastic strain of a solid, produced by a vibrating object. It has a velocity in air at sea level at 0°C of 332 metres per second (743 miles per hour) and travels as longitudinal waves.
> (HarperCollins Publishers Limited , 2016)

In more simple terms, a vibrating sound source compresses and expands the air around it, generating pressure fluctuations, which will form a spherical wave field radiating from it - much like a spherical version of the wave circles a droplet of water forms on impact with a water surface. Sound is, essentially, the part of total pressure which fluctuates relative to air pressure. This fluctuation is termed sound pressure p. (Filippi, et al., 1999)

3.1 Sound waves

Sound waves are mechanical, which means they need a medium to propagate. Sound will not travel through a vacuum, as it needs the particles of the medium to interact, in order for the energy from the initiating force to be transferred. Sound waves are longitudinal or compression waves, which describes the fact that the direction of the energy propagation is parallel to the direction of the medium particles.

3.1.1 Periodic vs. aperiodic signals

Sound pressure fluctuations are perceived relative to time. Sounds can be categorised into different classes with respect to time, namely periodic and aperiodic. Sound is periodic, if it manifests itself in a repeating wave pattern. Aperiodic sound fluctuates in a non-uniform pattern over time. Periodic waves oscillate, that is they move in a regular pattern above and below a base line. This is called harmonic motion, and is described with the harmonic oscillator function

$$x(t) = X\cos(\omega t + \alpha) \quad (1)$$

where

- t is time
- X is the amplitude (wave height) and
- ω is the angular frequency (angular speed $\frac{rad}{s}$), and
- α is the phase (position of a point in time).

Simple periodic signals can be added generating beats, an aperiodic signal or a more complex periodic signal. The result is determined by the frequencies and phases of these; adding two harmonic signals with the same frequency but different phases produce another harmonic signal, adding two harmonic signals with different frequencies will result in beats or complex periodic signals, or an aperiodic signal.

On the basis of this, the urban sound environment, including all man-made and natural emissions, can be viewed as being aperiodic in nature. While the emission of a single vehicle, like a running car engine, generates a periodic wave pattern, or a single emission like an explosion generates a sound impulse (Figure 2), the entirety of sounds forming the urban soundscape produce an aperiodic, and when viewed on a large scale even chaotic, pattern.

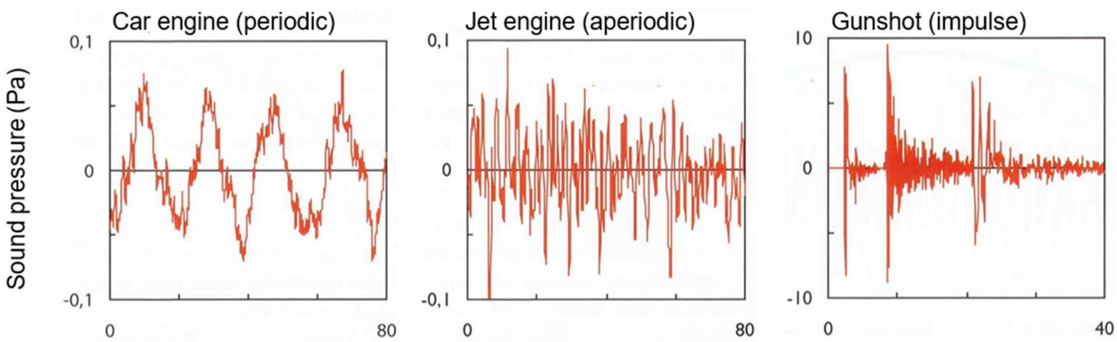

Figure 2. Wave patterns of different sound classes (Lahti, 2003)

3.1.2 Wave motion

In addition to time, (sound) waves also move in space. Three-dimensional waves are described with a second-order linear PDE. The Wave Equation

$$c^2\nabla^2\varphi - \frac{\partial^2\varphi}{\partial t^2} = 0 \qquad (2)$$

models the movement of a wave with respect to time and space, where

- c is the speed at which the wave propagates in a medium,
- φ is sound pressure,
- t is time and
- $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2} + \frac{\partial^2}{\partial y^2}$ in Cartesian coordinates. (3)

Moving waves can have the property free vs. forced. Free waves are initiated by a disturbance (a released force) in the medium, and will propagate freely through the medium. The motion of forced waves is also maintained by the force creating the disturbance. Another classification for waves is progressive vs. standing. Progressive waves propagate in one (positive or negative) direction. A standing wave is generated, when two progressive waves with opposing directions are combined resulting in a wave that appears to be static with regards to direction (but not time). (Reynolds, 1981)

3.2 Acoustic properties

The *loudness* or *amplitude* of a sound wave is a quantity describing as how quiet or loud the sound is perceived, i.e. the magnitude of the sound pressure. It is therefore measured in Newtons per square meter $\frac{N}{m^2}$ or, more commonly, Pascal. A higher amplitude indicates a louder sound, a lower amplitude a quieter sound. *Attenuation* describes the loss of strength a soundwave experiences traveling through a medium. *Pitch* describes the *frequency f* of a sound wave. It is measured in Hertz Hz, which is the unit for cycles per second q2. In terms of hearing, a higher frequency denotes a higher sound, a lower frequency a lower sound. Sounds which exceed or fall below the frequencies humans can perceive are called ultrasound and infrasound, respectively. *Bandwidth* describes he spectrum of frequencies contained in a sound. *Timbre* describes the tone or “colour” of a sound. Several sounds having the same pitch and loudness can still be distinguishable from each other by their timbre. A common example of this are different instruments playing the same note with the same volume. When recorded, each will produce a unique wave pattern. (Reynolds, 1981)

3.3 Sound propagation in ambient air

As discussed, sound is the disturbance of energy propagating in a medium. We have described a sound wave as a longitudinal wave and wave motion being three-dimensional. Outdoors, sound will, if not hindered, radiate from the source as spherical waves. Any obstacles in the path of a sound wave will affect its path. These obstacles are for example atmospheric changes (e.g. air temperature and density), altering terrain or man-made structures like houses or sound barriers. The challenge with analysing and modelling outdoor sound propagation is that the sound sources tend to be complex in nature, that is to say, nonpoint sources. The use of empirical data is amended with theoretical research to generate more reliable forecasting models. When assessing the expected noise level in a certain target area, the sound pressure levels of all sources and the attenuating impact of all obstacles are evaluated, and the result is calculated for the observation point. (Hansen, 2005)

The sound pressure level at this observation point (L_p) can be described with the expression

$$L_p = L_w - K + DI_M - A_E \quad (4)$$

where

- L_w is the sound power level,
- K is the geometrical spreading factor,
- DI_M is the directivity index and
- A_E is the excess attenuation factor.

Sound Power Level describes the rate at which sound travels per unit time and has the unit Watt (=power). The *Geometrical Spreading Factor* is a descriptor of the spherical radiation distance of the sound. The *Directivity Index* describes the variation of sound intensity with regards to its direction, i.e. as sound travels it is hindered by obstacles, and therefore has a stronger intensity in some directions than others. Attenuation is described as the amount of sound retained by forces or factors influencing its path. The measure of it is dB. The excess attenuation factor combines the attenuation of five different effects: Air Absorption, Barrier shielding, forest/foliage attenuation, ground effects and meteorological effects. *Air absorption* describes the attenuation caused by air temperature and relative humidity for different frequencies. *Barrier shielding* described the attenuation from barriers, houses and equipment (industrial facilities). These barriers refract and reflect sound before it reaches the observation point. *Forest attenuation* describes the amount of sound absorbed by vegetation such as forests or other areas of dense foliage. The *Ground Effect* describes the increase in noise due to ground material. The baseline is soft ground (any natural surface) with no effect, and a small increase is attributed to harder materials such as asphalt. The main *Meteorological Effects* influencing the propagation of sound are winds and temperature, which influence the curvature of the sound path. (Hansen, 2005)

4 The human auditory system

Hearing is a crucial sense for human interaction and the understanding of our environment. What we hear influences us psychologically, even though we may not fully be aware of it before sound becomes noise, or, when other major senses such as sight is impaired, our auditory sense becomes our main connection to our surroundings. This chapter will now briefly illustrate how the human auditory system receives these pressure waves, and how they are transmitted to and processed by the brain.

4.1 Anatomy of the ear

Figure 3 shows an illustration of the human ear. The outermost part of the ear (the ear lobe) is called the pinna. In humans, its main function is to help determine the direction of the sound source. The pinna modifies the sound spectrum, and the direction from which the sound approaches influences how this modification (or filtering) changes the perception of the sound in question. The sound waves are then carried through the ear canal to the middle ear. (Plack, 2014)

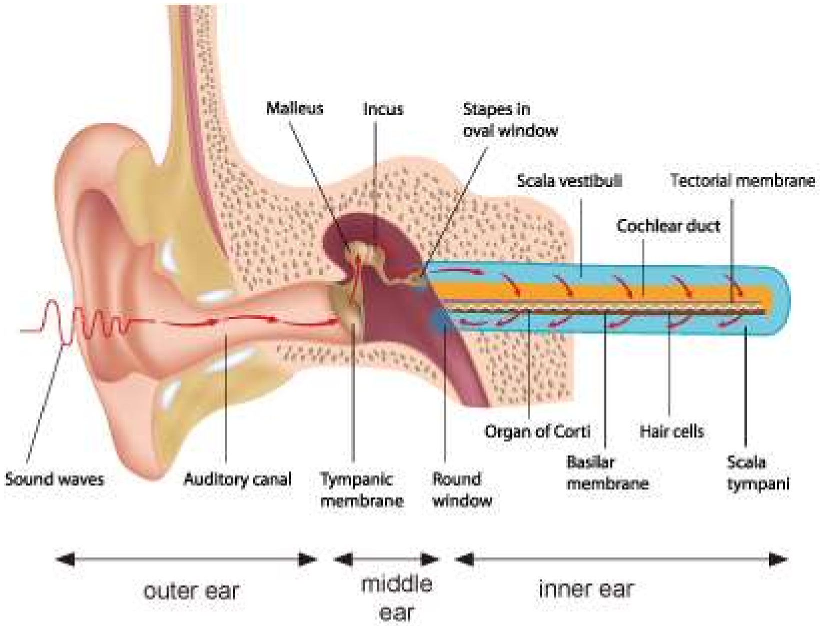

Figure 3 The Anatomy of the human ear. (Yamaha Corporation,2016)

The middle ear hosts the *tympanic membrane* (ear drum) and the *ossicles* (hearing bones). The tympanic membrane reacts to the sound waves by vibrating, and this vibration is transmitted by the ossicles to the inner ear. In the inner ear lies the *cochlea*, the transducer or “microphone” of the ear. Here the pressure variations are translated into electrical signals, neural impulses, which travel through the auditory nerve comprising of a variety of fibres and neurons with different functions. (Plack, 2014)

4.2 Central auditory system

From the auditory nerve, sounds (now transduced into nerve impulses) travel to the brain stem, where the signals from both ears are merged, and different brainstem nuclei process different sound frequencies. From here, the signals are transmitted into the thalamus (midbrain), which acts as a junction for all sensory input. Finally, the auditory cortex (located on both sides of the brain in the temporal lobe) receives the signal. Like the neurons in the brainstem, these neurons are, again, arranged *tonotopically*, meaning different cells process different frequencies. The cells in the auditory cortex perform a complex analysis of all the individual features of the signal. After the signal is processed, it can be identified by the brain as a certain sound (i.e. speech, music, noise), added to other sensory information and/or associated with prior experiences to become a sensation. (Plack, 2014)

4.3 Hearing range

In the previous chapter, we established sound to be pressure waves moving in a fluid, in our case, air. The fluctuations perceivable to human hearing are very small. Consider the magnitude of air pressure $1\ atm = 100\ kPa$. The lowest audible sound, or sound threshold, is $20\ \mu Pa = 2 * 10^{-9}\ atm$, and even traffic noise on a very busy street only measures around $100\ mPa = 10^{-6} atm.$ (Lahti, 2003)

The main reason for treating noise as an environmental pollutant is the fact that exposure to noise has been associated with a variety of diseases. A recent report by WHO Europe presents a conservative estimate of the impact of noise in disability-adjusted life-years (DALYs) to be between 1 – 1.6 million each year. The health risks include cardiovascular disease (hypertension, ischaemic heart disease), cognitive impairment of children (impairment of for example learning and decision-making), tinnitus (“ringing ears”), sleep disturbance and annoyance. (World Health Organization WHO, 2011)

Although it is accepted that noise does have adverse effects on human wellbeing, and that for the most part increasing noise levels do also increase said effect, there is no consensus about the exact dose-response ratio, especially with regards to individual diseases. (1996-1:2003, 2003) For this reason, the European Noise Directive END recommends using “estimated noise annoyance” as an evaluation basis for noise exposure and impact. (EU, 2002)

5 Noise control strategies

The fact that the adverse effects of noise have been shown, does unfortunately not provide a straight-forward, universally applicable definition or mathematical model of noise. The impact of noise is dependent not only on how much the annoying sound exceeds the background noise level, but also on what activities and what part of a person’s circadian rhythm it is intruding on. In simple terms, a sound disturbing our sleep is generally perceived more readily as noise, and has a more severe effect on our well-being, as the same sound in the background of our daily commute to work, where we may not even register it. The definition of noise is therefore the ambiguous “unwanted sound”, and the measure used is sound pressure level, for which limits have been set with respect to time and location. (Cowan, 1994)

Outi Ampuja (Ampuja, 2008) outlines the challenges of environmental noise control with regards to urban planning as being firstly the lack of a coordinating body assessing for example the effects of new infrastructure such as remote shopping centres, high cost and relative inefficiency of measures like noise control barricades, as well as the growing number of all types of transport vehicles and work machines.

In modern society, a certain level of tolerance towards noise is expected of people as a sound- and noiseless environment is simply not possible. We are confronted by sound in occupational surroundings, traffic, in our homes and the venues of our leisure activities. Strategies for noise control depend not only on the type of place and the criteria for acceptability established for these, but also on the sound source. A point source, like an industrial facility, offers more numerous strategies than nonpoint sources such as traffic. The starting point for any noise control procedures is the determination of acceptable noise levels and, based on these, the establishment of limit values and, subsequently, best practice and technology guidelines. (Hansen, 2005)

Preferably, noise control strategies should be in place before new facilities or infrastructure are constructed. Applying measures to combat existing problems is always more costly and challenging. As with all challenges an ever-evolving system (in this case, our society) faces, development and improvements have more often than not be applied to an existing condition. The first requirement of a feasible noise control strategy is the establishment of the target state, in this case, a set of regulations defining the acceptable levels of noise safe for the population. Considering the many uncontrollable factors affecting the propagation of outdoor sound, these must be set at a minimum safe level to allow for, for example, the fluctuation of atmospheric conditions. (Hansen, 2005)

As noise pollution is a complicated subject, the establishment of said noise limits, although a complex process in itself, is not the only thing to be considered. Many times, the psychological aspects of noise abatement can have an equally large impact on human wellbeing as the actual physical reduction of dB levels. Take for example the planting of rows of trees between main traffic arteries and housing; the actual reduction in sound pressure levels is negligible, but the absence of the visual connection to the noise source may still increase the feeling of wellbeing and reduce stress levels in the population. (García, 2001) (Hansen, 2005)

5.1 Sound source modification

The most effective means of controlling the impact of noise is to reduce its generation. In terms of urban noise control, this would mean the development and use of more quiet vehicles, or the reduction of speed limits. This can be achieved by modifying the engines as well as the cooling and exhaust systems of cars (both passenger and mass transport) to operate in a more favourable frequency range and shielding the sounds emanating from it. The emergence of electric or hybrid cars is not only a progress in terms of noise abatement, but other environmental emission issues as well. In air traffic, this has already yielded significant improvement, as is evident from for example the Finavia noise impact survey discussed later in this thesis. When reducing the noise emissions from industrial sites, the development of quieter machinery and processes also serves the reduction of occupational noise and its impact on the workers. Using noise insulation in buildings and planning operations to take place at times when the negative effect is reduced are simple, if not always cost-effective strategies. (García, 2001)

5.2 Transmission path control

The control measures applied to the sound path are the area of engineering arguably the most relevant to an environmental engineer, as many different fields of research and design are key players in a successful outcome. Controlling the transmission path of noise means applying measures to the immediate environment around the sound source to achieve a reduction in sound pressure levels. On a larger scale, this means including noise assessment in the zoning phase, the design phase and the building phase of city planning. Designating areas for more noisy activities, by planning buffer zones and directing traffic away from sensitive areas, noise control management is done pre-emptively. (García, 2001)

Existing infrastructure may require modification with increasing population and noise-generating activities. This concerns mostly road and rail traffic. In addition to operational noise from vehicles, the boundary noise generated from the interaction of wheels and road/rail surface contributes to traffic noise. Developing surface as well as wheel materials which reduce noise is a complex process, as the research results regarding the characteristics influencing noise levels are dispersed. However, in both road and rail traffic, the connection between resistance (friction) and noise is evident. Creating a combination of reduced friction and safe travel is one of the challenges faced in material engineering. (García, 2001)

Isolating or reflecting road and rail traffic noise is the most commonly used noise abatement strategy today. Acoustical barriers are viewed as an integral part of the design itself. These barriers are vertical constructions of various materials; and they not only serve the purpose of attenuating sound, but they also have the aforementioned psychological and aesthetic function. Generally, vegetation is not considered a very effective barrier against sounds except for very high frequencies, but the value of green areas in urban areas for wellbeing is recognised. The main requirements for acoustical barriers are ease of construction and maintenance, sufficient mass for sound attenuation and safety to the surroundings. (García, 2001)

Sound barriers are also employed around airfields to reduce the noise from ground operations. However, the main strategy for limiting air traffic noise nuisance is operational control both for ground and flight operations. Air traffic is limited to dedicated airfields with regulated noise assessment procedures, and flight routing is planned with consideration to people living in the immediate area around the airfields. Take-offs and landings are limited to certain numbers per amount of time, and day- and night-time restrictions apply. Maintenance runs of aircraft engines and other equipment is limited to certain areas and times. Again, all of this must be done with close attention to air travel safety. (García, 2001)

5.3 Sound receiver modification

In terms of noise control in urban areas, the final solution to reduce noise impact is the modification of the residential and occupational buildings themselves. However, this is the most ineffective and problematic strategy. Sound travels into buildings both through the air and the structure itself. The choice of materials and structures for walls, windows, floors and doors with better insulating capabilities can help reducing air- and structure noise inside buildings. These will also reduce noise generated by the occupants and their daily activities. When planning and constructing new buildings, considering the orientation with respect to sound sources, and using building shapes which in themselves have a deflecting or refracting effect should be considered. (García, 2001)

6 Measuring noise

We have established sound being pressure fluctuation and being measured in units of pressure, such as Pascal (Pa). However, sound pressure levels are reported on a log scale. The unit of sound pressure level L is decibel (dB). Decibels are derived from sound pressure p and reference pressure p_0, which is set at 0 dB = 20µPa (human hearing threshold):

$$L_p = 20 \log \frac{p}{p_0} \qquad (5)$$

The use of a log scale has two reasons: firstly, the human hearing operates logarithmically, which warrants the use of an equivalent scale; secondly, the log scale facilitates expressing the huge variations in naturally occurring sound pressure levels. (Lahti, 2003)

Earlier, we established the measure of loudness as describing the perceived strength of a sound. This is a subjective measure, and its relation to the measurable quantity of sound pressure level is not a simple one. Loudness depends on the frequency of the sound, on the sound pressure level, as well as the bandwidth of the signals. To accommodate for all the different aspects of human hearing, a frequency weighted unit for sound pressure level has been established as the reference unit for sound and noise. A transfer function is applied to physical sound measurements to produce a measure called *A-weighted sound pressure level* ($dB(A)$ or), which is an approximation of the human ears response to noise, as it weights frequencies more perceivable to the human ear. (Hansen, 2005)

In noise control documentation, the A-weighted equivalent continuous noise level

$$L_{Aeq,T} = 10 * log\left[\frac{1}{T}\int_0^T 10^{L_A(t)/10}\right]dt \qquad (6)$$

describes the sound pressure level over time as a single value, an average of the squared A-weighted noise over a certain time period. (Hansen, 2005)

For noise control purposes, especially in densely populated urban environments, a distinction between peak-time noise levels and other times is of importance. The ISO 1996 standard defines three time periods (day, evening, night), which are used in noise control regulations such as the European Noise Directive, which can be found in Table 1 on page 18.

6.1 Measurement technology

Environmental noise monitoring systems can be either portable devices or semi-permanent to permanent installations. Not unlike any other type of physical measuring system, these systems consist of some sensor/sensors, a logging and/or communication device, and a user interface. With the help of the meters' data logging features, sound pressure level data can then be analysed and visualised for example with the help of modelling software.

6.1.1 Sound level meters

The most common measuring devices for environmental noise assessment are sound level meters. They can be used both for point-source measurements (such as the immediate surroundings of an industrial facility) or longer-term monitoring (road noise level measurements). A sound level meter consists of a microphone, from which the signal is led to a set of filters and amplifiers, which may be setup to for example remove meteorological disturbance. These meters either report instantaneous sound pressure levels, or they can accumulate sound pressure level information over longer periods of time (integrating sound meters). (Cowan, 1994) (MIP Electronics Oy, 2017)

6.1.2 Spectrum analysers

When the sound pressure level measurements from sound level meters are not sufficient, spectrum analysers may be used to collect information on the frequency distribution of the source. FFT (fast Fourier transform) or narrow band and octave band analysers record sound pressure levels, but they can split the signal onto separate bands, thus making it possible to distinguish between point sources (i.e. separating wind turbine noise from traffic noise). (Cowan, 1994) (Noise News, 2017)

6.1.3 Acoustical cameras

The latest innovation in noise assessment technology are acoustical cameras. They are visually similar to parabolic antennae, i.e. disc-shaped devices with several hundred built-in microphones. With this technology, single sources are even more easily identified in a multi-source soundscape. Acoustical cameras have proven to be especially useful when investigating noise generated by wind turbines. The acoustical camera allows for the identification of for example blade damage, tower resonance and tonal noise, a special kind of single-frequency sound arising under certain circumstances in propeller-type devices. (NORSONIC, 2017) (MIP Electronics Oy, 2017)

6.1.4 Annoyance survey

In addition to loudness, pitch and timbre, which have essentially been quantified and are thus measurable, sounds are also interpreted by our brain in terms of the emotional responses they evoke. The study of behavioural responses to auditory stimuli is called *psychoacoustics*. Psychoacoustic experiments may include participants to for example evaluate the loudness, pleasantness or direction of a sound on a simplified scale (ranks or classes). (Plack, 2014)

When we recall the definition of noise to be “unwanted sound”, we must understand that noise as a concept also includes the above mentioned qualitative aspect. Where sound pressure level, frequency and duration are physical quantities which can be measured rather easily with modern technology, the question of unwantedness is more abstract. When assessing the impact of noise, this qualitative dimension is measured by questioning the people about their exposure and sensitivity to noise, as well as their perception of their own level of annoyance. Combining the physically-based exposure information from SPL and frequency measurements with the response information from the survey, an exposure-response relationship can be calculated to estimate the burden on health from environmental noise. (World Health Organization WHO, 2011)

6.2 Modelling and software

As described earlier, noise maps are a visualisation of the distribution of sound pressure levels in a specified area for a specified time period. EU member states are legally bound to produce their strategic noise maps as part of the noise abatement agreements signed by them. In addition to this, noise maps are generated for for example zoning purposes or as part of building permit acquisition. These maps are generated with the help of sound modelling software.

Sound modelling software programs utilise input data not only to visualise an existing or past situation, but they are also capable of producing projections for optimisation purposes by modifying the input parameters. The two most commonly used programs in Finland and Europe are CadnaA and SoundPlan. Of these, CAdnaA is part of a suite including tools for modeling air pollutant emissions. The programs produce visual representations or the measurements and projections, which can be interpreted not only by the planning engineer, but also the technically less experienced official or member of the public (Figure 4):

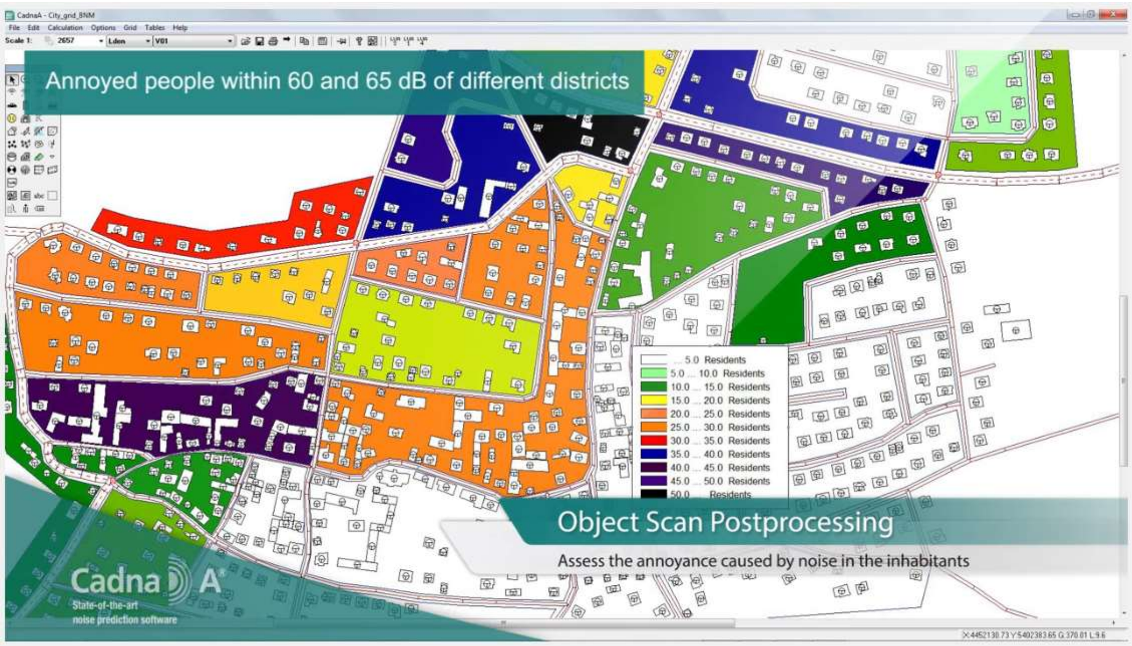

Figure 4 Screen shot of the CadnaA demo video by DataKustik

7 Noise control measures in the EU

7.1 European Noise Directive - END

The European Commission has, already in the 1996 Future Noise Policy green paper (Commission of the European Communities, 1996), stated environmental noise to be a major environmental issue in Europe. Consequently, different EU directives cover specific noise emission types, mainly from vehicles. The aim of Directive 2002/49/EC relating to the assessment and management of environmental noise, or **END**, is to further develop and wrap together existing environmental noise control measures regarding traffic and infrastructure, industrial emissions and machinery not only for the immediate future, but also for future generations.

The END builds partly on the ISO 1996 standard published by the International Organization for Standardization ISO in 1996 (amended 2003). The aim of ISO 1996 is to harmonize assessment and measurement principles, as well as provide estimates on how certain noise levels will impact the population of affected areas. These outlines will help governments and organizations in developing noise control measures as well as set national noise limits. The three-part standard related to environmental noise comprises information about and instructions for basic quantities and procedures, acquisition of data pertinent to land use and application to noise limits.

Under END, Member States must adopt a variety of practices regarding the assessment and control of environmental noise, and reports of each must be submitted to the European Commission. The European Environment Agency **EEA**, the EU's coordinating body for environmental affairs, stores all submitted reports in the European Environment Information and Observation Network **Eionet**. (EEA, 2012)

The END requires member states to produce **Strategic Noise Maps** of key affected areas, as well as **Noise Action Plans** to bring noise levels down to an accepted level. With the help of Strategic Noise Mapping measured levels are visualized and reported, and Action Plans set up control and mitigation strategies to secure acceptable noise levels in the mapped areas. The directive specifies two main noise indicators and two supplementary indicators to be used in environmental noise assessment and regulation: L_{den}, which is a measure of annoyance, and L_{night}, which is a measure of sleep disturbance. In addition to these, member states may use their own supplementary indicators where demanded by special situations. Noise levels are to be reported for defined areas (such as residential areas, quiet areas) with regards to these indicators.

As the purpose is to harmonise practices across the EU, a detailed set of instructions or methodological framework called the **CNOSSOS-EU** for producing the Strategic

Noise Maps has been developed by EU expert authorities. CNOSSOS-EU supplements the END Annexes. These established indicators, measuring systems (i.e. the above mentioned specific units and criteria), as well as limit values should be used when collecting and reporting environmental noise data from road traffic, railway traffic, aircraft and industrial noise.

7.2 Common Noise Assessment Methods in Europe (CNOSSOS-EU)

In earlier chapters, we have discussed the complexity of the concept of environmental noise, which generates the issue of choosing suitable assessment methods. This question has been evident already when establishing noise-related EU legislation, which – like all EU legislation – can be viewed as a “best practice scenario” based on existing legislation of member states. Therefore, END contains an article giving EU authorities the possibility to define and demand certain procedures from member states for producing their reports.

Since mapping practices vary across member states, the results of the first END-based proved the necessity for a common framework. Thus, a special technical committee (CNOSSOS-EU Technical Committee) was set up under the Noise Regulatory Committee, comprising members nominated by each member state. In co-operation with an extensive group of contributors of experts, other relevant committees and authorities (such as the WHO European Centre for Environment and Health and the European Environment Agency) the methodological framework called **C**ommon **NO**ise A**SS**essment Meth**O**d**S** in **EU**rope was developed during 2009 - 2012, and must be adopted by Member states by 31 December 2018.

The CNOSSOS-EU framework is designed to help member states produce more consistent and comparable data from noise mapping. Presenting and making these results available in a commonly understandable format can improve both the planning and execution of actions for environmental noise mitigation demanded by END, as well as people’s understanding and awareness on environmental noise exposure issues.

CNOSSOS-EU defines – in much detail - noise indicators, parameters and frequency ranges for different noise sources and for example vehicle types, reference traffic and meteorological conditions and corrections to be used for them (e.g. to account for increased noise from studded tyres). It also includes a quality assurance section, as well as a guidelines section to ensure the correct use of the framework, as well as a revision of the ENDRM reporting mechanism. (EC Joint Research Centre, 2012)

7.3 Strategic Noise Mapping

EU member states must produce their Strategic Noise Maps in five-year intervals. Environmental noise is mapped for urban agglomerations (> 250 000 inhabitants), for major roads (> 6 000 000 vehicle passages/a), major railways (> 60 000 train passages/a) and major airports, more detailed ones also showing ports, industrial sites and other major noise sources. They show the existing and/or predicted noise data in 5 dB ranges of L_{den} and L_{night} (or $L_{evening}$ where appropriate) at an assessment height of 4 metres, any exceedances of set noise limits, as well as the amount of different types of buildings and people exposed.

Table 1 Noise indicators

Short name	**Long name**	**Definition**
L_{den}	Day-evening-night noise indicator	$L_{den} = 10 * log\left[\frac{12}{24}10^{L_{day}/10} + \frac{4}{24}10^{(L_{evening}+5)/10} + \frac{8}{24}10^{(L_{night}+10)/10}\right]$
L_{Aeq}	Equivalent A-weighted continuous noise level	$L_{Aeq,T} = 10 * log\left[\frac{1}{T}\int_0^T 10^{L_A(t)/10}\right]dt$
L_{day}	Day-noise indicator	Time-dependent measure of L_{Aeq} from 07.00 to 19.00 local time
$L_{evening}$	Evening-noise indicator	Time-dependent measure of L_{Aeq} from 19.00 to 23.00 local time
L_{night}	Night-time noise indicator	Time-dependent measure of L_{Aeq} from 23.00 to 07.00 local time

Of these, L_{den} and L_{night} are the most commonly used in the noise mapping process. They correspond to the day and night-time reference values and are measured as L_{Aeq}, which means that the sound pressure is equalised to one reference or average level even though the source may generate varying sound levels over time (as described in the ISO acoustics standards, see chapters X and Y). In addition to these, the END lists several special indicators which can be used for, for example, extra protection evaluation, specific quiet areas or seasonal noises. These are presented in common statistical formats such as plots and tables.

Strategic noise maps are produced both as official reports for the European Commission and the citizens of any given member state. They act as a general source of information for the people, but also form the basis of the second noise control tool EU member states must produce, the Noise Action Plans.

7.4 Noise Action Plans

After completion of the Strategic Noise Mapping, the designated local authorities must draw up a so-called noise action plan, which is a detailed management plan for any noise issues arising from the maps. The noise action plans include a summary of the noise map data, as well as plans for their mitigation and control. The plan must cover the five-year period until the next noise mapping is due, including target scenarios, planned actions, regulatory measures and/or incentives, budgets, responsible authorities plus long-term strategies exceeding the five-year reporting period.

Member states are free to choose the format of the plans, and they do vary significantly from country to country. For illustration purposes, we have compared three Noise Action Plans from the similar-sized European cities Helsinki, Stuttgart and Dublin. These cities were chosen because they are similar in size and population density, they all have a variety of public transport, an airport, industrial and residential areas as well as a metropolitan area reaching beyond the major city centres (Table 2).

Table 2 Basic statistics of selected cities (Wikipedia, 2017)

Functional Urban Area	**Population in millions**	**Pop. density per km^2**	**Area km^2**	**Air passengers millions/p.a. 2016**	**Country level GDP PPP per capita 2015**
Helsinki	1.5	412	2 970	17.2	40 601
Stuttgart	2.7	730	3700	10.6	47 268
Dublin	1.3	4 600	115	27.9	54 654

However, all three are also different enough to provide food for thought in terms of comparing chosen solutions in noise control (note especially the reverse population density/area ratio for Dublin). All of them are in member states of the EU, which eliminates legislative restrictions for implementation of noise prevention and control solutions as much as possible. The area to be considered, call it the system of the assessment, is the statistical unit Functional Urban Area (a city and its commuting area) as defined by Eurostat (Eurostat, 2017).

7.4.1 Case: Helsinki 2013 - 2018

The current Noise Action Plan for 2013 – 2018 (Liikennevirasto, liikennejärjestelmätoimiala, 2013) is based on 10 major noise assessments from 2012 and five additional surveys from different authorities. The plan covers a geographical area around 2455 km of roads and railways. The L_{den} exposure of over 55 dB affects 476 180 Finns, 285 700 are exposed to L_{night} levels of over 50 dB. The plan lists 58 areas which are most urgently in need of noise abatement (exposure levels of over 65/60 dB or otherwise especially susceptible areas) An investment of 154 million euros will reduce the number of L_{den} affected people by 7.8%, and the number of L_{night} affected people by 7.1%.

The plan has two approaches: preventing exposure by designing new traffic routes or restoration of existing ones, so that noise levels are equal or even lower than before, or more integrated land use planning and zoning activities, and mitigating existing exposure by constructing sound barriers along heavily trafficked roads, and, if feasible, using road surface materials which generate less noise.

The challenge with mitigating structures such as the proposed sound barriers is, that, like any other man-made structure, they will deteriorate over time. Either the ground will give way and lower the barrier so sound can travel above it, or parts may have to be replaced. The oldest barriers may have to be replaced entirely, as they may for example not fulfil modern sound absorption requirements. The plan estimates the maintenance cost of the current sound barrier network to be at approximately 2 million euros per year. Also, when replacing barrier units, the material cannot be reused but must be landfilled, which poses both economic and environmental strain.

The Helsinki-Vantaa airport is not included in the Helsinki Noise Action Plan, as it is located inside Vantaa borders. However, a separate noise assessment plan is composed for the area; the latest one having been published this year (2017). An example of the noise maps is shown in Figure 5. According to this plan, even though take-offs and landings have increased in numbers, the constant modernisation of aircraft have resulted in a steady decrease of air traffic noise. As air traffic noise is subject to changes due to weather conditions (e.g. wind directions), mitigation must mainly happen with traffic time restrictions as well as the fleet modernisation.

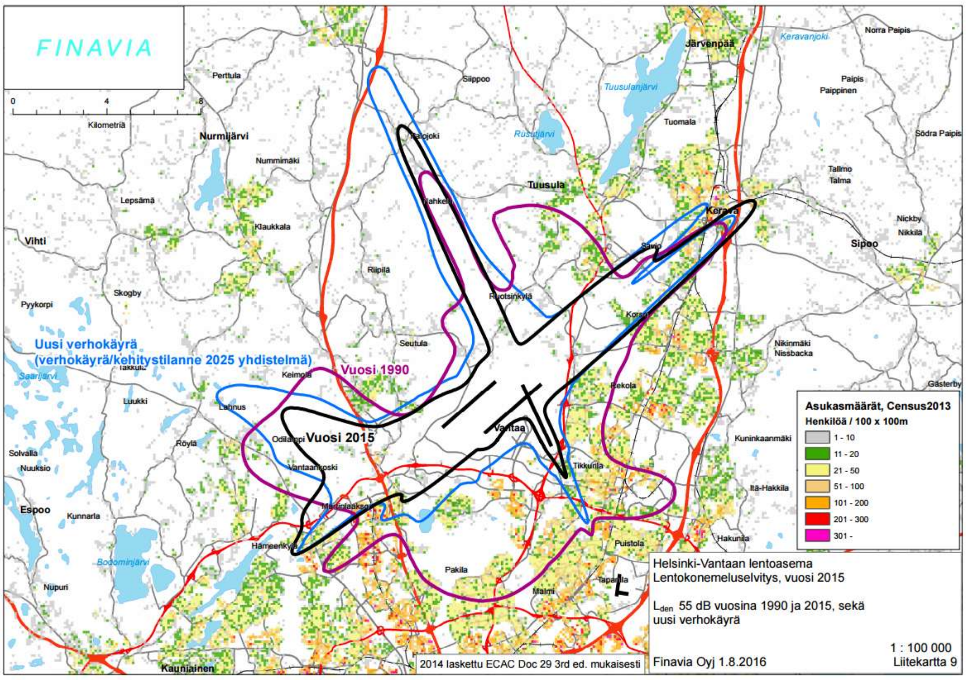

Figure 5 An example of sound pressure range representation from the Helsinki airport noise impact report (Finavia Oyj, 2016)

7.4.2 Case: Stuttgart 2009

In Stuttgart, the current Noise Action Plan (Landeshauptstadt Stuttgart, Amt für Umweltschutz, Stadtklimatologie, 2009) addresses areas which are exposed to L_{den} values of over 65 dB and L_{night} values of over 55dB. When limits exceed 70/60 dB, mitigation needs are considered urgent. Unlike the Helsinki Plan, it includes an assessment of air traffic noise.

Stuttgart lists several possibilities for reduction of road traffic noise; the emphasis inside agglomeration areas is on improving public transport as well as bicycle and pedestrian routes. Also, restrictions on the use of roads at certain times or by heavier vehicle types is proposed, as well as designating heavily trafficked roads for one-way traffic only. Also, construction of noise barriers or covering roads entirely as well as quiet road surfacing are suggested. As for rail traffic, several options exist ranging from widening curve radius, renewing the fleet, lowering sped limits and covering parts of the track are an option. Route network planning is an important issue for mitigation, as is zoning.

7.4.3 Case: Dublin 2013 – 2018

The Dublin Agglomeration Noise Action Plan (Dún Laoghaire - Rathdown County Council, 2013) is a continuation of their previous plan from 2008 – 2013. It addresses four major areas, namely noise reduction and prevention for road traffic and for rail traffic, the planning process and the protection of quiet areas. The area covered in the plan is surrounding 3950 km of road and rail routes as well as the airport.

The Dublin approach comes from the quality of life of locals. It emphasises the environments effect on human wellbeing as much as social and economic factors. From the previous plan, significant reductions in noise exposures have already been achieved: for example, L_{den} exposure over 55 dB has been reduced from 94% of population to 55%, and the exposure to L_{den} levels of over 70 dB has reduced by half.

In terms of traffic noise reduction, public transport and cycling are endorsed, as well as reduction of driving speed and optimisation of traffic light cycles. Night-time traffic is suggested to be reduced, as is traffic in noise sensitive areas.

Airport noise is now controlled through a flight traffic monitoring system, which allows matching of noise complaints to flight patterns; this in turn can help developing mitigating processes. All in all, only 0.02 % of the population are exposed to disturbing night-time noise from air travel.

7.5 Environmental permits and noise assessments

In addition to the country level plans and assessment, single facilities, such as industrial plants, or venues, such as outdoor concerts, need to register their activity with the environmental authorities when planning activities that will exceed the baseline noise limits for the area type. The documentation is available to the public via the local environmental authorities, which in Finland are the Regional State Administrative Agencies. (Aluehallintovirasto, 2017)

Depending on the nature and duration of the activity, a notification or permit is needed. If the activity is temporary, such as a one-time outdoor event, the organiser needs to notify the environmental authorities, who upon inspecting the notification may require further information or measures to ensure public safety. (YSL 2014/527 , 2014)

When planning permanent activities, deviations from noise limits are subject to an environmental permit. The permit will state the allowed deviations for these noise limits, and the applicant must produce a noise assessment suitable for the type of activity planned. Assessments and permits must be also produced for all activities amending any established activities. Mitigation of the impact must be ensured by using best available technology (BAT) and consulting the appropriate reference documentation (BREF) for each industry.

7.6 EU reporting tools for environmental noise assessment documents

While the CNOSSOS-EU framework describes the technical implementation of noise assessment, the results also need to be reported in a way that allows the governing authorities to supervise that deadlines are met and obligations are fulfilled. To help Member States in this endeavour, a harmonised method of communicating the results was developed by the EEA, i.e. the Electronic Noise Data Reporting Mechanism or **ENDRM**.

ENDRM was launched to be used already in the first Noise Mapping round in 2007, and has been improved based on the experiences collected during this period. It provides among other tools reporting templates, data flow structures, content specifications and timelines to ensure Member States are compliant with END requirements.

ENDRM was developed to simplify reporting by reduction of repetition, selecting best-suited formats for each data type, ensuring consistent use of the same formats for each reporting round, as well as matching these reports with reporting approaches already in use inside the EEA/EC. ENDRM reports are available to the public through the European environment information and observation network **Eionet** through the Reportnet infrastructure. At present, a collaboration initiative known as Shared Environmental Information System **SEIS**, is under development to serve as an interconnected fully electronic reporting and information retrieval system.

8 Conclusions

Considering the concepts of environmental noise, noise abatement and noise mitigation, psychoacoustics may prove to be an interesting field of research. The current principle of setting noise level limits relies purely on sound pressure levels. However, although high sound pressure levels (like an explosion or prolonged exposure) may cause physical damage to the hearing organs, the perceived noise which causes the most harm as cognitive impairment or annoyance is not adequately described by decibels, as there are many elements such as sharpness (frequency) or fluctuation, which contribute to the perceived nuisance but cannot easily be incorporated in computer models. Soundscape research (also: acoustic ecology, ecoacoustics) attempts to describe the interaction between people, sounds and the environment. New, more integrated models and intelligent measuring principles are being developed for environmental noise assessment, but are yet at an early stage. (Genuit & Fiebig, 2006)

For environmental engineers, the most interesting prospects arise from the possibilities of joint modelling and abatement design of both noise and air pollutant emissions. Over the last years, research has been conducted around the globe to find spatial and temporal correlations between these emissions. Modelling software can already be applied to both emissions. As the main contributors for both are traffic and industry, environmental impact assessments for both zoning and construction purposes would benefit greatly from a combined process, as both emissions are required to be estimated in an EIA. An environmental engineer familiar with noise pollution issues in addition to other, more traditional pollution issues will be an asset on the current job market.

The aim of this thesis was to show the significance of the field of environmental acoustics to environmental engineers, and to give insight in the theories and practicalities relating to it. Although these were presented, the thesis would have benefitted greatly from the planned participation in an actual noise survey, which, unfortunately, had to be omitted due to organisational challenges.

Rock ‘n’ Roll ain’t noise pollution.

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