Universidade do Minho
Escola de Engenharia

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Contribution of the Evaluation Strategy and the Use of Hearing Protection for the Uncertainty Associated with Occupational Exposure to Noise

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Doctoral Thesis for PhD degree in
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Work performed under supervision of
Professor Doutor Pedro Miguel Ferreira Martins Arezes

March 2015

STATEMENT OF INTEGRITY

I hereby declare having conducted my thesis with integrity. I confirm that I have not used plagiarism or any form of falsification of results in the process of the thesis elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

University of Minho, ________________________________

Full name: Susana Raquel Pinto da Costa

Signature: ____

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Contribution of the evaluation strategy and the use of hearing protection for the uncertainty associated with occupational exposure to noise

Abstract

Noise induced hearing loss (NIHL) is in Europe, the most common occupational disease. The international standard ISO 9612:2009 specifies an engineering method for measuring the exposure to occupational noise and estimating noise exposure level. However, it does not acknowledge the use of individual Hearing Protection Devices (HPDs) in the expression of the associated uncertainty, despite the centrality of uncertainty to determine whether the worker is exposed to below the legal noise exposure level or surpassing it. Therefore, results obtained by applying the guidelines referred at the aforementioned document can be overestimated and consequently lead to a misclassification of exposure in epidemiological studies. Hence, although noise attenuation provided by hearing protection is not considered for the application of occupational noise exposure action values in noise exposure determination of the worker, it has to be taken into account when referring to exposure limit values. Currently, there are no studies that systematically compare and analyse the impact of their implementation at various levels, such as the accuracy of the results, the required equipment, the time spent and, above all, the uncertainty of measurement associated with the exposure calculation. The main objective of this thesis was to systematize the contribution of use of HPDs in the calculation of the uncertainty associated with the results obtained for occupational noise exposure, and considering the three measurement strategies defined in the standard. In order to accomplish this main goal, focus was on analysing probable predictors of the use of HPDs in occupational settings, and their effect on time of use of HPDs. It was expected that workers from the same company were more related than to employees from other companies. To account for that effect, two-level multilevel modelling was resorted to in the building of a model that explains the use of HPDs relating the several significant determinants. Results have shown that the most significant determinants in the use of HPDs are the benefits the workers recognize from wearing HPDs, their peers behaviour towards the use of HPDs, recognition of some level of self hearing impairment and, as a novelty to this knowledge niche, self-assessed forgetfulness regarding the use of HPDs.

Contributo da estratégia de avaliação e do uso de proteção auditiva para o modelo de estimativa da incerteza associada à exposição ocupacional ao ruído

Resumo

A doença profissional mais comum na Europa é a surdez originada pela exposição ao ruído ocupacional. A norma internacional ISO 9612: 2009 especifica um método de engenharia para medição e estimativa do nível de exposição ao ruído ocupacional. No entanto, não aborda o uso de protetores individuais auditivos (PIA) na expressão da incerteza associada, apesar da fulcralidade da incerteza para a determinação da exposição do trabalhador. Portanto, os resultados obtidos através da aplicação da norma supracitada podem ser subestimados levando, por conseguinte, a uma classificação errónea da exposição em estudos epidemiológicos. Atualmente, são poucos os estudos que sistematicamente comparem e analisem o impacto da execução da norma, a vários níveis, tais como a precisão dos resultados, os equipamentos necessários, o tempo gasto e, acima de tudo, a incerteza de medição associada ao cálculo de exposição. A relevância da obtenção de resultados tão exatos (no sentido de tão próximos quanto possível da realidade), pela computação de uma incerteza associada à exposição estimada num contexto de utilização de PIA, prende-se com o facto de, apesar de atenuação de ruído providenciada pelos protetores auditivos não ser considerada para aplicação dos valores de exposição ao ruído ocupacional na determinação da exposição ao ruído do trabalhador, tem que o ser quando referente a valores-limite de exposição. Reconhecendo esta lacuna, o principal objectivo desta tese foi o de sistematizar a contribuição do uso de protetores auditivos no cálculo da incerteza associada aos resultados obtidos para a exposição ao ruído ocupacional, considerando as três estratégias de medição referidas na norma. Para tal, o foco inicial desta tese foi a análise dos preditores prováveis da utilização de PIA e o seu impacto no tempo de utilização dos mesmos. Tomou-se como premissa que trabalhadores de uma mesma empresa estarão mais relacionados entre si do que com trabalhadores de outras empresas. Para simular esta relação, recorreu-se a modelação multinível, para construção de um modelo que explica o uso de PIA relacionando os diversos preditores significativos. Os resultados mostraram que os preditores mais importantes no uso de PIA são os benefícios que os trabalhadores reconhecem advir da utilização de PIA, a atitude dos seus pares relativamente à utilização de PIA, o

reconhecimento da existência de um certo nível de perda auditiva pessoal e, como novidade neste nicho de conhecimento, a autoavaliação do esquecimento em relação à utilização de PIA.

“ *Don’t only practice your art, but force your way into its secrets,*
for it and knowledge can raise men to the divine.”

\- Ludwig van Beethoven

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

AIC: Akaike's Information Criterion;

AICC: Hurvich and Tsai's Criterion;

ANOVA: Analysis of Variance;

BIC: Schwarz's Bayesian Criterion;

CAIC: Bozdogan's Criterion;

CCOSH: Canadian Centre for Occupational Health and Safety;

CDC: Centers for Disesase Control;

CI: Confidence Interval

dB: decibel;

df: degrees of freedom;

DV: dependent variable;

EB: Empirical-Bayes;

FDM: full-day measurement;

GUM: Guide to the Expression of Uncertainty in Measurement;

$\overline{H}$: mean of all variable H observations;

H_0: null hypothesis;

H_1: alternative hypothesis;

$\boldsymbol{H_k}$: kth observation of the variable;

HCP(s): Hearing Conservation Program(s)

HPD(s): hearing protection device(s);

HPM: Pender’s Health Promoting Model;

Hz: Hertz; cycles per second;

IEC: International Electrotechnical Commission;

INE: National Statistics Institute (Instituto Nacional de Estatística, Portugal);

ISO: International Organization for Standardization;

JBM: job-based measurement;

L_{Aeq}: A-weighted equivalent continuous sound level;

$L_{Aeq,8h}$: A-weighted equivalent continuous sound level normalised to an 8-hour workday;

$L_{Aeq,effective}$: effective equivalent level;

$L_{Aeq,T}$: A-weighted equivalent continuous sound level over a time period of T hours;

L_{eq}: equivalent continuous sound level;

$L_{EX,8h,effect}$: effective individual exposure to occupational noise;

$L_{EX,8h}$: Daily Exposure Level, is the sound exposure averaged over 8 hours;

$L_{EX,effective}$: effective equivalent exposure levels (when accounting for the use of HPDs);

LR: Likelihood ratio;

MIRE: microphone in real ear;

N: catalogued attenuation of the HPD;

NIHL: noise-induced hearing loss;

NIOSH: National Institute for Occupational Safety and Health;

NRR: Noise Reduction Rating

OSHA: Occupational Safety and Health Administration

P: Time percentage of use of HPDs (%HPD Use);

PPE: Personal protective equipment

R: “real” attenuation of the HPD;

$\boldsymbol{R_1^2}$: Intra-company variability:

$\boldsymbol{R_2^2}$: Between-company variability (level 2):

REAT: real-ear attenuation at threshold;

RRT: Round Robin Tests;

SD: Standard deviation;

SE: Standard error;

Sig.: Significance;

SPL: Sound Pressure Level

SPSS: Statistical Package for the Social Sciences;

t: t-test value;

TBM: task-based measurements;

U. S.: United States of America

VAS: visual-analogue scale;

WHO: World Health Organization;

-2LL: - 2 Log Likelihood, deviance;

%HPD Use: time of use of HPDs (in percentage).

SYMBOLS

$\boldsymbol{Y_{ik}}$: %HPD Use for worker *i* from the kth company;

$\boldsymbol{\gamma_{00}}$: intercept of the regression, average %HPD Use in the companies' population;

$\boldsymbol{\gamma_{p0}}$: average slope that relates the independent variable with variable p;

$\boldsymbol{X_{pik}}$: value of the x variable p for worker *i* of company *k*;

$\boldsymbol{\hat{\mu}}$: overall %HPD Use (across companies) estimator;

$\boldsymbol{u_{pk}}$: level 1 residual for variable $p;$

$\boldsymbol{\hat{\sigma}^2_{u_0}}$: between-company (level 2) variance in %HPD Use estimator;

$\boldsymbol{\hat{\sigma}^2_{e}}$: within-company between-workers (level 1) variance estimator;

$\boldsymbol{u_{0k}}$: level 1 residual;

$\boldsymbol{e_{ik}}$: level 2 residual;

$\boldsymbol{\beta_{0k}}$: mean Y for the kth company;

$\boldsymbol{\rho}$: variance partition coefficient.

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Part I

Research Problem and Literature Review

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Chapter 1. Addressing the Problem

Noise (derived from the Latin word nausea) is the undesirable, unwanted sound. It disturbs the homeostasis of human and animal life, having impact in both health and behaviour. Nevertheless, this physical agent and its impact on health are still, to this day, underestimated. Most likely because the effects are, in general, not immediate, and consequences are rampant and not considered by most as bearing a great magnitude of hazardousness. The results of the studies on the impact of noise and consequential hearing impairment on health are too enlightening for this hazard to continue to be overlooked. Hearing Protection Devices (HPDs) are devices that specifically protect the hearing from occupational exposure to noise, by decreasing the amount of noise that reaches the ear canal. This decrease (attenuation) varies according to the type of HPD used and how well it fits, and must reduce the workers' noise exposure to within the acceptable limits. There are several kinds of HPDs, differing on the way they are designed to be worn and on their operating mode. The choice on the HPD will depend on the characteristics of the work performed, but also on the worker himself, for even though HPDs have a nominal (advertised) attenuation, it has been proven that such attenuation is never achieved, due to several factors, one of which is the non-use of those devices by the workers.

1.1 Framework and motivation

Process industries are a major driving force in the Portuguese economy and its highest contribution is in the north of Portugal (INE, 2015; PORDATA, 2015).

Data shows that in Portugal, an average of companies of this nature, in the years 2010 to 2013, was above 70.000, employing over 600.000 employees, on average (PORDATA, 2015).

Rotors, gears, vibrating panels, turbulent fluid flow, impact processes, internal combustion engines, amongst several other sources, compound for the noise machines and industrial processes generate. These noise-generating mechanisms stem from the particularly noisy operations and equipment that make the industry, such as presses, drills, lathes, pneumatic equipment, milling machines, looms, pumps, compressors and transport vehicles (Gerges,Vedsmand & Lester, 2001).

Noise is, therefore, a ubiquitous occupational hazard in the occupational setting, issuing not only in metalwork, sawmills, carpentries, textile mills, as in many other blue-collar environments, but also in an office environment, even though with a more evident expression in the first one.

In many countries, noise-induced hearing loss (NIHL) is one of the most prevalent occupational disease. Workers from the manufacturing industries are the ones who suffer more occupational NIHL (WHO, 2011).

NIOSH (National Institute for Occupational Safety and Health) estimates that more than 22 million employees are exposed to dangerous occupational noise levels in the US, each year, and this number should ascend to the 500 million all over the world (Arezes & Miguel, 2002a; McReynolds, 2005; CDC, 2015). Statistics from the same institute reveal that 4 million workers perform each day in damaging noise environments, and 10 million people have a noise-related hearing loss caused be exposure to noise (CDC, 2015).

A study has been published this year, that aimed at estimating the incidence and prevalence of hearing loss for workers exposed to occupational noise (Masterson, Deddens, Themann, Bertke, & Calvert, 2015). Covering 30 years of results, across several industries, the study gathered the results of almost 2 million noise-exposed workers' audiograms, dating from 1981 to 2010, and concluded that the overall prevalence of hearing loss remained 20% over the three decades, for all industries (Masterson et al., 2015).

Moreover, the researchers found that there was a decrease in the incidence and risk of incident hearing loss over time, thus pointing to some progress in occupational hearing loss prevention efforts during these 30 years (Masterson et al., 2015). It was also found out that the sector that had the highest incidence of hearing loss during most time periods was the Construction sector (Masterson et al., 2015).

Even though risks of incident hearing loss generally lowered significantly during the study's time frame (2006-2010), the risk for incident hearing loss was found to remain high for workers in Healthcare and Social Assistance, and the prevalence was consistently high not only for Construction workers, but also for Mining workers (Masterson et al., 2015).

A study conducted by Arezes and Miguel (2002a) estimated that, in Portugal, the number of employees exposed to occupational noise in the years 1998, 2000 and 2001 had been around 780.000.

Notwithstanding the European Community efforts regarding health protection of employees facing occupational risk conditions, a study by Bragança and Matos (2004) revealed that the limit of personal daily exposure to occupational noise level was often exceeded in Portuguese industries. Leal and Fradique (2004) also concluded that the percentage of employees exposed to higher noise levels than those defined by the Portuguese legislation (Decreto-Lei n.° 182/2006, September 6th) was still high.

In a more recent study, Edelson *et al.* (2009) recognizing the contemporary relevance of this subject, also addressed the exposure to hazardous occupational noise levels in 2009, due to the high prevalence of incurable despite totally preventable NIHL among construction workers and so have several other researchers (Alberti, 1992; Goelzer, Hansen, & Sehrndt, 2001; Rabinowitz, 2000), which reflects the interest in this topic in the current scientific scenery.

For a better sense of the importance of this issue, it should be noted that NIHL can be permanent or temporary, depending on whether the is damage to the hair cells is irreversible or not. Permanent NIHL is a chronic, potentially debilitating, irreversible illness – even surgically – from which workers can be spared from by implementation of proper hearing conservation programs (Alberti, 1992; Edelson et al., 2009; Goelzer et al., 2001; Lusk, Hagerty, Gillespie, Caruso, 2002; Rabinowitz, 2000; Valoski, 1997).

The consequences of occupational noise exposure to the worker's health, performance and intercommunication have been the focus of studies of many researchers which, in turn, have also enhanced the importance of hearing conservation programs (Arezes & Miguel, 2002a; Concha-Barrientos et al., 2004; Dias et al., 2006; Kaczmarska et al., 2004; Kotarbinska & Kozlowski, 2005; McReynolds, 2005; Popescu, 2005).

1.2 The sense of hearing

Sound travels through air as a series of sinusoidal pressure waves. As the forwards and backwards oscillations of the prongs alternately compress and rarefy the surrounding air, the pressure varies sinusoidally. As the air molecules oscillate to and fro in the direction of propagation of the wave, a sequence of alternate waves of lower and higher pressure is formed (Davies, Blakeley, & Kidd, 2001).

The wavelength of a given sound wave is the distance, in metres, between corresponding points in the cycle and is inversely correlated with the frequency of the wave, which is the number of full cycles per second. The frequency of a pure tone is its pitch (Davies et al., 2001).

The amplitude of the wave, defined by the spread of movement of the individual molecules, is termed sound pressure, and is detected as the loudness (intensity) of the sound (Davies et al., 2001).

Since the “bel”, named after Alexander Graham Bell, $\log_{10}(p/p_0)$ is very large, a smaller unit is resorted to, the decibel. Moreover, in the usual sound intensity range for communication, the ear can barely distinguish an approximately 1-decibel change in sound intensity (Davies et al., 2001; Guyton & Hall, 2006).

A 10-time increase in sound energy is called 1 bel, and 0.1 bel is called 1 decibel. One decibel represents an actual increase in sound energy of 1.26 times (Guyton & Hall, 2006).

The decibel system can be used for comparing two energy signals from the same kind (e.g., sound, electrical, magnetic).

Given the ability of the ear to detect and discriminate extreme changes in sound intensities, the sound intensities are usually expressed in terms of the logarithm of their actual intensities (Guyton & Hall, 2006).

The variation of sound pressure is a form of physical energy and the rate of delivery of the energy (to the ear) is power. Sound pressure levels (SPL) measurements are distinguished from other measures that use the dB the notation by dB SPL.

The sound pressure (p) of any sound of interest can be compared to a standard sound (p_0), as a ratio, in decibels (dB):

Sound pressure level (in dB)= 2 x 10 x $\log_{10}(p/p_0)$ = 20 x $\log_{10}(p/p_0)$ (Davies et al., 2001).

For comparison of sound intensities, “2” is included in the equation for comparing the power of the sounds, which is proportional to the square of the signal amplitude, as the log of the square of a number is twice the log of that number. The recorded pressure of the sound of interest is p and p_0 is the reference pressure, which is is 20 µPa, in accordance with ISO 1683:2008 (or p_0=2 x 10^{-5} N/m^2).

This corresponds approximately to the average threshold for hearing within the most sensitive range of the auditory systems, which means that, for an intensity of recorded sound $p= p_0$, this would is 0 dB. 40 dB, for example, is a sound pressure 10 times greater (Davies et al., 2001).

The human ear responds to sound over a range of 120 dB, which is a multitudinous range in sound pressures.

The auditory system not only enables the detection of sounds from a very wide range of frequencies and intensities but also allows for highly detailed analysis of those sounds such as specific contents from the background noise and interpretation of both the signal content (for example speech) and the direction of its source (Davies et al., 2001).

The head is a natural barrier between the two ears. Because a sound source at one side produces a more intense stimulus to the ear nearest to it, besides arriving there sooner, a mechanism for sound localization based on intensity and differences in time of arrival of sound is provided (Alberti, 2001).

The ear, or organ of hearing, is conventionally subdivided into three parts: the external ear, the middle ear or tympanic cavity, and the internal ear or labyrinth (Gray, 2009).

The outer and middle ears amplify the sound signal, and this amplification is accomplished through a series of physics principles: first, the pinna has a fairly large surface area and funnels sound to the tympanic membrane, which is smaller. The surface of the tympanic membrane is, in turn, much larger than that of the stapes faceplate, yielding hydraulic amplification, where a small movement over a large area is converted to a larger movement of a smaller area. The ear canal, then, works as a resonating tube and amplifies sounds at between 3.000 Hz (cycles per second) and 4.000 Hz thus compounding to the sensitivity and susceptibility to damage of the ear at these frequencies (Alberti, 2001). Moreover, the ossicular chain works as a system of levers, which amplify the sound. On its passage from the exterior to the inner ear, sound is amplified by about 30 dB by the outer and middle ears (Alberti, 2001).

The inner ear then transduces vibration into nervous impulses, while it analyses the frequency (or pitch) and intensity (or loudness) of the sound (Alberti, 2001).

The first of this series of stimulus modifiers in the auditory apparatus starts in the external ear. It comprises the expanded portion named the auricula or pinna, and the external acoustic meatus. The auricula is an ovoid, high surfaced protrusion on the side of the head. Its lateral surface is irregularly concave, directed slightly forward, and its function is to collect the vibrations of the air by which sound is produced and funnel it to the tympanic membrane, through the external acoustic meatus (Gray, 2009).

The external acoustic meatus extends from the bottom of the auricula to the tympanic cavity, conducting the vibrations to the latter (Gray, 2009).

The middle ear or tympanic cavity (*Cavum Tympani*, Drum, Tympanum) is an irregular, laterally compressed space within the temporal bone. It is lined with mucous membrane and filled with air that comes from the nasopharynx through the pharyngotympanic tube. The middle ear features a chain of movable bones (ossicles) that connect its lateral and medial walls. These ossicles form a mechanical linkage between tympanic membrane and the oval window, a membrane-covered opening into the fluid-filled inner ear (Davies et al., 2001; Gray, 2009).

The ossicles are suspended by ligaments in a way that the combined malleus and incus act as a single lever, having its fulcrum approximately at the border of the tympanic membrane (Guyton & Hall, 2006).

The tympanic membrane (commonly called the eardrum) separates the tympanic cavity from the external acoustic meatus and the ossicles (malleus, incus and stapes) conduct sound from the tympanic membrane through the middle ear to the cochlea (the inner ear) (Davies et al., 2001; Gray, 2009).

The essential function of the middle ear is to transfer energy efficiently from relatively weak vibrations in the elastic, compressible air in the external acoustic meatus to the incompressible fluid around the delicate receptors in the cochlea (Gray, 2009).

There is, in fact, minimal loss in the conduction pathway, which is accomplished by the lever action of the ossicles and the mechanical advantage provided by the ratio between the large surface area of the tympanic membrane and the small area of the oval window, that serve as an impedance-matching device (Davies et al., 2001).

Nevertheless, sound waves can travel directly through the air of the middle ear and enter the cochlea at the oval window in the absence of the ossicular system and tympanic membrane. However, the sensitivity for hearing is lessened in (15 to 20) decibels, which is equivalent to a decreasing from a medium to a barely perceptible voice level (Guyton & Hall, 2006).

Sound waves cause the tympanic membrane to vibrate in phase with the alternating compressions and rarefactions of the sound pressure. Because the handle of the malleus is attached to the tympanic membrane, this vibration is transmitted to the malleus. Minute ligaments bound the malleus the incus, of which opposite end articulates with the stem of the stapes. Therefore, all ossicles oscillate in response to sound. The faceplate of the stapes lies against the membranous labyrinth of the cochlea in the opening of the oval window and its movement causes the oval window to move in and out (Davies et al., 2001; Guyton & Hall, 2006).

Movement of the oval window causes the cochlear fluid to be pushed on the other side of window whenever the tympanic membrane moves inward, and to pull backward on the fluid when the malleus moves outward (Guyton & Hall, 2006).

The internal ear, inner ear (*Auris Interna)* or labyrinth (due to the complexity of its shape) is the essential part of the organ of hearing, receiving the ultimate distribution of the auditory nerve. It is a cavity lying within the temporal bone, which contains the cochlea and the vestibular apparatus (Davies et al., 2001; Gray, 2009).

The cochlea is a hollow spiral structure of two and a half turns that may be divided into three fluid-filled compartments, the *scalae*, which are tubes coiled side by side (Davies et al., 2001; Gray, 2009; Guyton & Hall, 2006).

The scala tympani follows the outer contours of the cochlea and ends at the round window. At the centre of the spiral, the scala tympani is continuous with the inner compartment, the scala vestibuli. The scala vestibuli ends in the vestibule, an expanded region that links with the oval window. Both scala tympani and vestibule are filled with perilymph and the scala media (cochlear duct), which is a membrane-bound compartment filled with endolymph, separates them. The scala vestibuli and scala media are separated from each other by Reissner's membrane (also called the vestibular membrane). The scala tympani and scala media are separated from each other by the basilar membrane (Davies et al., 2001; Gray, 2009; Guyton & Hall, 2006).

The organ of Corti, which is the sense organ itself, lies along the basilar membrane within the scala media. It is a complex organ that comprises a structural frame (the rods of Corti), several supportive cells and two groups of electromechanically sensitive cells, hair cells (outer and inner hair cells). These hair cells are receptive end organs that generate nerve impulses in response to sound vibrations, for they are innervated by different cell axons, whose cell bodies lie in the spiral ganglion, and which project to the brainstem as part of the auditory nerve whilst being also innerved by motor, efferent nerves Davies et al., 2001; Gray, 2009; Guyton & Hall, 2006).

Because the cochlea is embedded in a bony cavity, vibrations of the entire skull can cause fluid vibrations in the cochlea itself, a phenomenon known as bone conduction. Therefore, under appropriate conditions, it is possible to hear the sound from a tuning fork or an electronic vibrator by placing it on any bony protuberance of the skull, being more evident if placed on the mastoid process near the ear (Guyton & Hall, 2006).

The range of hearing of a healthy ear is approximately 10 octaves from somewhere in between 16 Hz and 32 Hz to somewhere in between 16.000 Hz and 20.000 Hz. However, the sound range depends to a great extent on loudness. With increasing age, this frequency range is usually shortened to 50 Hz to 8.000 Hz or less (age-related hearing loss – presbycusis) (Alberti, 2001; Davies et al., 2001; Guyton & Hall, 2006).

It should be noted, however, that the auditory system is not equally sensitive over the whole range of this range; the sensitivity is low at the extremes but highly increases above 128 Hz up to about 4.000 Hz when it again becomes rapidly decreases. Higher and lower frequencies (regarding this range) are less easily detected, therefore sounds with frequencies outside this range have to be louder in order to have the same perceived loudness for the subject listening to them. The predominant frequencies of speech coincide with the greatest sensitivity of the system (Alberti, 2001; Davies et al., 2001).

1.3 Recognition of hearing loss as an occupational disease

It all started with Fosboke, who first cited occupational hearing loss in the medical literature in 1831, when referring to “blacksmiths’ deafness” with concomitant tinnitus, in the medical literature (Fosboke, 1831).

Half a century elapsed when Holt referred to it as “boiler-maker’s deafness,” because he based his findings on 40 men from the steam-boiler shops in Portland, Maine (Holt, 1882). By that time, hearing loss was clearly identified, but the scientific knowledge on the mechanism was scarce. For Holt, it was the constant vibration of the joints of the ossicles that caused ankylosis, especially of the stapes. There were no efficient mechanisms of prevention, and Holt reported workers unsuccessfully trying to block noise by covering of their ears with cotton wool and pads. Complaints about interference with hearing and itchiness are traceable to that time.

Hearing conservation interest arose only in a serious and sustained manner, though, only after World War II, when soldiers returned home with hearing loss. Only in the late 1940s/early 1950s, the industrial hearing conservation programs (HCPs) came into existence, and some of the first reported programs were established in the aviation and metals industries (Gerges et al., 2001).

By the late 1960s, the United States of America (U. S.) government published noise regulations (U.S. DOL, 1969) that became more prominent and widely applied with the promulgation of the Occupational Safety and Health Act of 1970 and with the enactment of the noise standard in 1971 (OSHA, 1971). Ten years later, OSHA published the hearing conservation amendment (OSHA, 1981 and 1983), which detailed the specifics of an occupational hearing conservation program, only insinuated at in the original 1971 standard.

Nowadays, several authors have stressed consequences of exposure to occupational noise to the workers’ health, performance and intercommunication, and demonstrated the importance of hearing conservation programs (Arezes & Miguel, 2002a; Concha-Barrientos, Campbell-Lendrum, Steenland, & others, 2004; Dias, Cordeiro, & Gonçalves, 2006; Kaczmarska, Mikulski, & Smagowska, 2004; Kotarbinska & Kozlowski, 2005; McReynolds, 2005; Popescu, 2005).

1.4 Hearing Conservation Programs (HCPs)

Implementation of HCPs aims to prevent occupational NIHL. Occupational hearing loss is recognized as a health problem, so the Occupational Safety and Health Administration (OSHA) has published regulations that specify minimum requirements that employers shall meet. Complying with the OSHA regulations, however, is not the same as being successful in preventing occupational hearing loss, as revealed by many ineffective HCPs (Royster & Royster, 1998).

A traumatic noise exposure may cause an immediate hearing loss in some cases. Short exposures can also cause hearing damage. Take, for example, a chain saw, which has the sound intensity of about 109 dB; without proper hearing protection, running the chain saw for only 2 minutes can cause hearing loss (NIOSH, 2007a).

Usually, though, occupational hearing losses occur gradually, and so workers are not aware of their hearing loss. On one hand, because the first 10 years of exposure is when the rate of hearing loss growth is highest, hearing loss prevention is especially important for new workers. On the other hand, because of the spreading of hearing loss spreads into the frequencies most needed to understand speech with continued exposure, preventing occupational hearing loss is also important for workers in their mid and late careers (NIOSH, 2010).

Some programs are bound to fail because of how the HCP is conducted: whenever there is lack of communication and coordination between plant personnel involved in the HCP and between on-site personnel and corporate headquarters, when decisions are made resorting to information that is not accurate or sufficient, because proper training to the use of HPDs is not provided to the workers, because HPDs available in stock are simply not adequate, the over-reliance of decision makers on noise reduction ratings when selecting the HPDs, because there is no financial or time availability to fit and train each worker singly, because companies fail to use the audiometric monitoring results to educate and motivate employees and to evaluate the effectiveness of the program (Royster & Royster, 1998).

Ineffective HCPs have no return of invested time or resources. Effective HCPs, on the other hand, are cost-effective and bring several benefits to the employer:

- productivity, efficiency and versatility of workers are higher if their communication abilities are not impaired;
- accident rates are reduced;
- stress and fatigue related to noise exposure decrease, also adding to the increase in productivity and efficiency;
- employee relations improve;
- job turnover lowers;
- the company's prestige increases and is perceived as a desirable employer;
- monetary losses from workers' compensation claims and insurance premiums are lessened (Royster & Royster, 1998).

NIHL prevention is the greatest benefit workers get from HCPs. Hearing loss reduces the quality of life of the impaired subject. Many jobs require adequate hearing, which is why hearing loss may decrease employment potential. Social lives are enjoyed over pleasurable interpersonal communication with family and friends, bringing sense of belonging. Appreciation of music and sounds of nature are compromised in the event of hearing impairment. Good hearing is, thus, invaluable. Several times, non-occupational hearing losses and potentially treatable ear conditions are detected through the annual audiograms, which constitutes a health screening benefit (Royster & Royster, 1998).

A successful hearing loss prevention program is composed by noise exposure monitoring, application of engineering and administrative controls, audiometric evaluation, use of HPDs (whenever compulsory), education and motivation of workers, traceability (record keeping), evaluation of the program, and program audit (CDC, 2011).

Insight of the character of the noise source is of paramount importance when conducting HCPs, as it is essential for the selection of the most appropriate measuring instrumentation to assess the exposure of workers to occupational noise.

1.5 Types of noise

According to ISO 12001:1996, depending on the temporal variations in sound pressure level, noise can be classified as steady, non-steady or impulsive.

Steady noise is a noise with negligible, small fluctuations of sound pressure level within the period of observation. It remains within 5 dB for a long time (ISO 12001:1996).

Non-steady noise is characterized by the significant shifting of its sound pressure levels during the period of observation. This type of noise can be divided into intermittent noise and fluctuating noise (ISO 12001:1996).

If the level of the noise changes continuously and to a great extent during the period of observation, it is a fluctuating noise. On the contrary, if the level of the noise abruptly drops to the level of the background noise several times during the period of observation, during which the level remains at a constant value different from that of the ambient during, at lest, 1 second, then the noise is intermittent (ISO 12001:1996).

Impulsive noise is characterized by of a series of bursts of sound energy, each burst during less of less than 1 second. In the impulsive noise consists of a single burst of sound energy or a series of bursts with intervals larger than 0,2 s between the individual bursts it is designated an isolated burst of sound energy. If a series of noise bursts of comparable amplitude with intervals shorter than 0,2 s between the individual bursts take place, then it is a quasi-impulsive noise (ISO 12001:1996).

Sound can also be characterized by its frequency spectrum. Tonal noise (which can be continuous or fluctuating) is characterised by discrete high or low frequency. It is more annoying than broadband noise, which is characterised by a frequency spectrum where there is constant energy over all frequencies. Narrow band noise is characterised by confining energy to a discrete frequency (Hansen, 2001).

Sound that occurs at frequencies below 20 Hz is called infrasound, whereas ultrasound denominates sound that is characterized by frequencies above 20,000 Hz (Hansen, 2001).

1.6 Measuring noise exposure

When reporting the exposure of workers to occupational noise, the noise level in dB (A) is expressed, which means that the noise has been measured using the filter specified as the A network, being referred to as the "A-weighted level". Its widely use to evaluate occupational exposure has to do with its good correlation with hearing damage, even though the "C" weighting better describes the loudness of industrial noise (Hansen, 2001).

It is common that industrial noise fluctuates. In order for these variations to be translated into a concrete value of exposure, the equivalent continuous sound level (L_{eq}) was defined, which is the steady sound pressure level, that, over a given period of time, has the same total energy as the actual fluctuating noise (ISO 1999:2013).

The A-weighted equivalent continuous sound level is denoted L_{Aeq}. The A-weighted equivalent continuous sound level normalised to an 8-hour workday (which can also be referred to as daily noise exposure level) is denoted $L_{Aeq,8h}$, and the A-weighted equivalent continuous sound level over a time period of T hours is denoted $L_{Aeq,T}$ (ISO 1999:2013).

1.7 The economic toll

In 2010, NIOSH placed approximately 13% of the U.S. workforce, which accounts for approximately 16 million people, on the manufacturing sector (NIOSH, 2010).

That year, occupational hearing loss was appointed as the most commonly recorded occupational illness in manufacturing (17.700 cases out of 59.100 cases), accounting for 1 in 9 recordable illnesses. Over 72% of these cases occurred among workers in manufacturing. To grasp the full meaning of these numbers, one must keep in mind that, for the case to be OSHA-recordable, the worker's hearing loss must be determined to be work-related and severe to a degree where the worker has become hearing impaired. This means that many other workers would present measurable occupational hearing loss even though not having become hearing impaired to that moment (NIOSH, 2010).

Data from 2014 shows that, in the U. S. alone, around 22 million workers were exposed to hazardous levels of occupational noise, and an additional 9 million are exposed to ototoxic chemicals (CDC, 2014). These numbers translate to yearly compensations for workers' hearing loss disability of about 242 million dollars (CDC, 2014).

It seems reasonable to wonder whether, given the still, nowadays, high prevalence of NIHL (the most direct consequence of exposure to occupational noise in workers of trades that present hazardous levels of noise), occupational hygiene is being effective in its purpose. And whether the money that is being spent would not be more wisely spent in proper, effective HCPs.

1.8 Other effects of noise exposure

It is well known that noise is among the most common hazards of occupational exposure and workers subject to noise can suffer several levels of hearing disabilities (Sbihi, Teschke, Macnab, & Davies, 2009).

Withal, occupational noise exposure has also been identified as a stressor, influencing physiological processes, associated with hypertension and other heart conditions, and other illnesses as well as stress and experience mental fatigue, irritability and discomfort (Lusk et al.,, 2002; Neitzel, Somers & Seixas, 2006; Rabinowitz, 2000; Stansfeld, 2003; Tabachnick, 1994).

More recently, a study by Lin et al (2011) revealed worrying results when it was able to link hearing loss and dementia. In fact, they found that hearing loss was independently associated with all-cause dementia following a log linear distribution, i.e., the risk of all-cause dementia increased log linearly with hearing loss severity.

These disorders are known as non-auditory effects, which are divided into two categories – physiological effects and performance effects, and include contraction of the muscles in the presence of loud noise, changes in the respiratory rhythm, in the heart beat pattern and in the diameter of the blood vessels, especially in the skin, annoyance, stress, and impaired verbal communication (Van Dijk, 1986; CCOSH, 2007).

These findings should be a caveat to workers who ignore the real effects of noise exposure preferring, inclusively, to expose themselves greatly in order to sooner deafen and quickly cease to feel the discomfort that say they feel from the noise and/or hearing protection devices (HPDs).

Unprotected workers in high-noise environments are also proved to be less productive, more prone to lost-time accidents, and to experience more problems than those with lower noise exposures (Berger, 2000).

The causal relation between work-related accidents with both noise exposure in the workplace and NIHL has been established by several studies.

Early in the 70s, the specialized international literature indicated that workers exposed to intense occupational noise had a risk two to three times more likely to crash when compared to non-exposed workers (Melamed, et al., 2004).

Picard, Girard, Simard, Larocque, Leroux and Turcotte (2008) studied the association of work-related accidents with noise exposure in the workplace and NIHL and concluded that, overall, 12.2% of the accidents considered were owed to a combination of noise exposure in the workplace (≥90 dBA) and NIHL.

A study conducted by Cantley, Galusha, Cullen, Dixon-Ernst, Tessier-Sherman, Slade, Rabinowitz and Neitzel (2014) revealed that workers with a history of tinnitus in conjunction with high-frequency hearing loss sustain a 25% increased acute injury risk whereas low frequency hearing loss was associated with minor, less serious, injury risk.

It is no wonder noisy industries register higher absenteeism rates. However, it is yet to be known if the latter is a consequence of psychological aversion to noise or if it results from physiological consequences of noise stress (CCOSH, 2007).

1.9 Protecting from the hazard

When a risk is identified, the sequence of interventions should begin in the emitting source, following acting on the general environment and, lastly, on the worker himself. Thus, risk monitoring should start in the elimination (when possible) or reduction of the risk.

Some authors, like Matos (2004), analyse noise exposure risk and recommend noise minimization and elimination procedures. These measures are based on a simple concept of eliminating the source of hazardousness or, in its impossibility, replacement of these sources with others less hazardous. Collective protection measures should follow. This means that, if the risks are not liable to be reduced or extinguished, measures should be taken in order to protect all workers from them, simultaneously protecting more that one worker through circumscription (encapsulation of the source of noise). Worker withdrawal or remoteness from the emission source is the action that follows and, finally, individual protection of worker.

The first two measures cited before are more desirable because they produce more efficient results. Also, if efficiency is achieved in this stage, no other sequential measures are necessary. These measures consist of constructive measures (engineering measures), acting on production processes, equipment and facilities and should be integrated at the design stage or project (Cabral & Veiga, 2009).

The following two situations are reserved to cases in which, even with a control of the process, the risk of exposure can not be eliminated, nor mitigated to a safe level.

In this case, action must be taken towards the worker's protection, whether by relocating him further from the risk source or reduction of the time he is exposed to it (organisational measures, as, for example, jobs rotation).

When neither of these strategies can be enforced in the context of a company, employers and workers have to cooperate in setting a safe and sound workplace environment, thus ensuring the most protection for workers (OSHA, 2003).

Figure 1 illustrates the pyramid of the desirable sequence of actions to be taken in order to break the chain of propagation of the risk (which is desirable as early as possible, top to bottom).

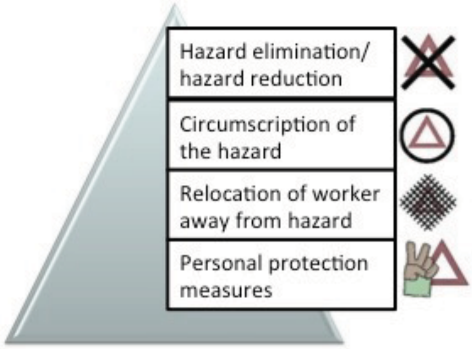

Figure 1. Pyramid of risk propagation prevention actions.

1.10 Personal Protective Equipment (PPE)

Personal protective equipment (PPE) is any equipment specifically designed to protect workers from the occupational risks that jeopardize their health or safety. In the US alone, it is estimated that 20 million workers use PPE on a regular basis (CDC, 2012).

Council Directive 89/686/EEC of 21 December 1989 defines PPE as "any device or appliance designed to be worn or held by an individual for protection against one or more health and safety hazards".

In the Portuguese legal framework, according to Decreto-Lei n.° 348/93, of October 1, which transposes into law internal Council Directive 89/656/EEC of 30 November on the minimum safety and health of workers in the use of Personal Protective Equipment, PPE stands for all equipment, and any addition or accessory designed to be used by the worker to protect himself from risks to his health and safety, not covering:

- ordinary work clothes and uniforms not designed to protect the safety and health of workers;
- relief and rescue service equipment;
- personal protective equipment for military, police and people of law enforcement services;
- personal protective equipment used in road transport;
- sports equipment;
- self-defence or deterrent equipment;
- portable devices for detecting and signalling risks and nuisances.

The hazards the workers are exposed to arise from the contact with biological, chemical, physical (e.g., noise, radiation, vibrations) and other workplace hazards. Depending on the characteristics of the hazard and the part(s) of the body to protect, different PPE are resorted to. Earplugs and earmuffs, gloves, hard hats, safety glasses and shoes are examples of PPE (Miguel, 2005; OSHA 2003).

Also because the PPE require a higher effort of the worker in carrying out its tasks, should only be considered as a last resort or as a temporary measure until more effective risk control techniques can be used (Miguel, 2005; OSHA, 2003).

Employers are responsible for providing workers appropriate PPE and training in its use and care after performing a "hazard assessment" of the workplace, through identification and control of physical and health risks (OSHA, 2003).

Efficacy of the PPE depends on its integrity, proper use and fit, which is why it is important that workers attend training sessions on how to correctly wear, store and maintain the PPE, discarding it and replacing it whenever a defect is detected (OSHA, 2003).

It is paramount that the right PPE is chosen, for it does not minimize the hazard nor does it guarantee abiding or total protection for the worker. In order to ensure the required level of protection, the choice of the PPE must consider:

- the type of risk the worker is exposed to and the level of protection required,
- the environment conditions he works in, making possible the simultaneous use of different PPE if so required, and efficiency maintenance in the presence of other hazards,
- the part(s) of the body that need(s) protection and,
- the characteristics of the worker himself (Miguel, 2005; OSHA 2003).

Participation of workers in choosing their own protective equipment, in addition to being a factor for accession to the solution, decreases the possibility of maladjustment of PPE to the physical characteristics of each (Miguel, 2005).

The fitting of the PPE defines whether the worker is safely protected or hazardously exposed (OSHA 2003).

Since the effective use of PPE depends on the adaptation of the worker to the PPE, these must encourage the worker use by being lightweight and fit comfortably, adapting to the ergonomic requirements and the health of employees;. They must also be robust and of safe design and construction homologated (conform to the rules for the design and manufacture of safety and health), provide effective protection against the risks for which they were manufactured without entailing by itself increased risk (Miguel, 2005; OSHA, 2003).

Portaria n.° 1131/93, of 4 November defines procedures that the manufacturer must observe to obtain a declaration of conformity of the PPE. The EC type-examination is the procedure by which an approved inspection body ascertains and certifies that a PPE model satisfies the legal provisions relating to it.

When purchasing equipment, one has to check if it has a visible, legible and indelible CE marking. Moreover, it has to be accompanied by an EC Declaration of Conformity and an information manual in native language.

This applies to all activities and processes carried out in an Organization and also stakeholders carrying out any activity the risk assessment determines the use of PPE.

The technical description of PPE and the activities and business sectors for which they may be necessary, appear in Portaria n.º 988/93 of 6 October. The Directive 89/686/EEC of the Council of 30 November divides the PPE in three categories according to the degree of risk in which they are used:

a) Category I - minimal risk. Examples: gardening or dishwashing gloves; sunglasses, clothing and footwear for use in adverse weather conditions;

b) Class II - moderate risk. Examples: crash helmets; visors and goggles; clothing, footwear and gloves for situations of some risk; protective earphones;

c) Category III - equipment that protect from hazardous conditions that may seriously and irreversibly affect health. Examples: protective equipment against extreme heat (> 100° C); protective equipment against extreme cold (<-50° C); protective equipment against electrical hazards; protective equipment against chemical and radiation exposure; protective equipment against falls from heights.

The procedures that the manufacturer must observe to obtain a declaration of conformity of the PPE are defined, in the Portuguese legal framework, in Portaria n.º 1131/93, of 4 November. The EC type-examination is the procedure by which an approved inspection body ascertains and certifies that a PPE model satisfies the legal provisions relating to it.

To test a new PPE workers must be selected with an as far as possible objective criterion of assessment. The final decision on the use of PPE should be made based on careful analysis of the job (Miguel, 2005).

In sum, the company is required to provide workers the appropriate gratuitous PPE according to the risk(s) associated with their tasks, in perfect condition and operation in the following situations:

- whenever collective protection measures are not technically feasible, or do not offer complete protection against the occupational hazards the worker is exposed to;
- while collective protection measures are being implemented;
- to meet emergency situations.

To this end, the Company must:

- purchase the right PPE adequate to the worker activity;
- provide workers only homologated PPE;
- train the employee for the PPE proper use;
- make PPE use compulsory;
- replace the PPE immediately when damaged or lost (Royster & Royster, 1998; Worksafe, 2012; Worksafe, 2014).

But the obligations are not confined to companies and its workers, as the manufacturer is bound to:

- be certified for the manufacture of PPE;
- indicate the classification, description and specification of the PPE;
- indicate the purpose for which it is intended;
- provide a sample of the PPE, stamped with the manufacturer's name and reference number;
- hold the certificate of registration issued by one of the specialized agencies (Decreto-Lei n.° 130/2013).

The PPEs that specifically protect the hearing from occupational exposure to noise are the Hearing Protection Devices (HPDs).

1.11 Hearing Protection Devices (HPDs)

HPDs protect the hearing by decreasing the amount of noise that reaches the ear canal. This decrease is called attenuation, and varies according to the type of HPD used and how well it fits. HPDs must reduce the workers' noise exposure to within the acceptable limits (OSHA, 2003).

Hearing protection can increase the worker's ability to hear his equipment or others' voices because it filters the background noise. Some earmuffs may help even hearing-impaired workers communicate better in noisy backgrounds, through amplification circuits (NIOSH, 2007a).

The relevance of the use of HPDs is further aggravated by the role of the devices in the prevention of, besides NIHL, non-auditory disorders, rendering more positive health outcomes and constituting an important predictor of the decrease of blood pressure (Lusk et al., 2002).

It is not an easy task to determine whether the worker needs HPDs. Exposure to excessive noise is defined by:

- the loudness of the noise, which is measured in decibels (dB),
- the duration of exposure of the worker to the noise;
- the mobility of the worker between areas with different noise levels;
- the noise being generated by one or several sources (OSHA, 2003).

According to how HPDs are worn, these devices can be grouped in three types:

- earmuffs, that protect against noise by covering the outer ear sealing pressing against the head, thus providing an acoustic barrier;
- earplugs, which consist of plugs to be inserted into the outer ear canal in order to prevent the propagation of airborne sound to the middle ear, sealing the ear canal;
- semi-aural or canal caps, that typically seal the opening of the ear canal, are composed by earplugs connected by a headband (CDC, 2013).

Earmuffs

Generally easy to fit and convenient to put on and take off, there are many models of earmuffs available, designed to fit most workers. Earmuffs are made of a rigid external material internally coated with a flexible material. The adaptation to the ear should be of total coverage of the outer ear. Muffs can be of more subtle dimensions or larger dimensions to hold extra materials for use in extreme noise. They can also have embedded electronic components that aid communication, block impulsive noises, and/or transmit radio emissions (CDC, 2013; Miguel, 2005; NIOSH, 2007b).

Earplugs

Earplugs are inserted into the external auditory canal and aim to reduce the intensity of pressure variations that reach the eardrum. These devices can be expandable or (pre-)molded.

Expandable plugs are made of a formable material that expands and adapts to the shape of the ear canal, aiming to reduce the intensity of pressure variations that reach the eardrum. This material can be cotton, wax or plastic impregnated cotton, silicone rubber, plastics or fiberglass wool. When properly inserted, expandable plugs work as well as most molded earplugs. By rolling the expandable plugs into a thin, unwrinkled cylinder, a smooth tube is obtained; thin enough so that about half the length fits easily into the ear canal. Not every earplug fits every ear though, workers with small ear canals have difficulty rolling typical plugs small enough to make them fit, which is why a few manufacturers offer a small size expandable plug (CDC, 2013; Miguel, 2005; NIOSH, 2007b; OSHA 2003).

If the worker can't get at least half of the plug into the ear canal, or if it can't expand enough to stay firmly seated, a different size is needed (NIOSH, 2007b).

Because people are not exactly symmetric, it may occur that a worker needs a different size plug for each ear, for the plugs should seal the ear canal without bringing discomfort. Therefore, workers should try different sizes before choosing (CDC, 2013; OSHA, 2003).

Pre-molded or molded plugs are individually fitted by a professional and can be disposable or reusable. Reusable plugs are silicone-, plastic- or rubber-made plugs, made in several sizes (for small, medium or large ear canals) or as "one-size-fits-most" (CDC, 2013; OSHA, 2003).

Each pre-molded plug may have slightly different fitting instructions according to the number of flanges and the shape of the tip, but it essentially is inserted by reaching over the head with one hand to pull up on the ear and using the other hand to then insert the plug with a gentle rocking motion until the ear canal is sealed. After each use, these reusable plugs should be cleaned. (CDC, 2013; NIOSH, 2007b; OSHA, 2003).

Canal caps

Canal caps consist of tips that resemble earplugs, joint by a flexible plastic or metal band, form canal caps. The tip may be formable or pre-molded. Some bands can be worn over the head, behind the neck or under the chin. Models with jointed bands increase the ability to properly seal the earplug (CDC, 2013).

The pressure exerted by bands is sometimes considered uncomfortable and not all tips adequately block all types of noise. Generally, the canal caps tips that resemble stand-alone earplugs seem to block the most noise (CDC, 2013).

There are also special types of HPDs, such as helmets with integrated circumaural, caps or muffs with communication, electronic amplification or with active noise reducing digital circuits (Gerges et al., 2001).

According to the operating mode, HPDs may be grouped into:

a) Conventional HPDs; in which passive means are used to get attenuation, i.e. without the use of any additional mechanisms. These devices have higher efficiency with regard to the degree of speech intelligibility, which is superior when compared to the active protection equipment;

b) Level-dependent attenuation HPDs: earplugs or earmuffs that protect against intermittent or impulsive noise, allowing communication in silent periods. These may be active or passive devices. Active devices contain a microphone and amplifier system that transmits the external noise to the headphones placed inside the protectors, attenuating noise levels per frequency band or amplitude of the sound spectrum. One example is a device that only transmits sounds in the range of conversational frequencies. Passive devices usually incorporate an acoustic filter, which allows the transmission of low sound pressure levels by attenuating the high sound pressure levels;

c) Protection with uniform or flat attenuation: HPDs that evenly attenuate the sound pressure levels across the spectrum. These devices are mediocre whilst advantageous in that they minimize the distortion normally caused by HPDs;

d) HPDs with active noise reduction (ANR): ANR is a technique that uses sound waves overlapping to reduce the noise intensity felt by the worker, through an embedded electronic system that produces counter-phase waves, exerting destructive interference of waves of equal sound pressure level. These are more efficient at low frequencies, unlike conventional HPDs;

e) Communication HPDs: usually earmuffs, these devices allow the transmission of messages or the perception of important signals for performing different tasks;

f) Anti-noise helmets: allow to advantageously reduce the transmission of air acoustic waves to the skull (Miguel, 2005; Rudzyn, & Fisher, 2012).

Combined protection (dual hearing protection)

Double hearing protection means wearing earmuffs and earplugs simultaneously. When there is exposure to high sound pressure levels at multiple frequencies, it is common to combine earmuffs and earplugs in order to achieve greater attenuation than the HPDs could provide by themselves. The attenuation rendered by the combined use is not the sum of the values of the two HPDs due to noise transmission by bone conduction, which occurs above 2 KHz.

A study by Berger (1984) showed that the attenuation achieved by dual hearing protection is significantly lower than the algebraic sum of each device attenuation value, instead resulting in a gain in attenuation of, at least, 5 dB than either device alone, at individual frequencies. Berger attributed that difference to the mechanical coupling of the two devices through the body tissues and sealed air between them, and to the bone conduction phenomenon. Through bone conduction, energy that should be blocked by the HPDs finds alternative flanking sound paths through the tissues and bones of the skull, thus bypassing the HPDs and reaching the inner ear. Findings from that study still prevail and reveal that, at frequencies below 2 KHz, the performance of the combined protection is strongly influenced by the selected earplug, whereas that frequency up, combined protection is only limited by the flanking bone conduction pathways to the inner ear.

Miscellaneous devices

New devices that are hybrids of the traditional types of HPDs have emerged as the manufacturers' answer to the comments and requests of HPDs users. Plugs that essentially are a foam tip on a stem have been designed to meet the workers that appreciate the comfort of foam plugs, refuse to roll them in dirty environments. These plugs are inserted like pre-molded plugs (CDC, 2013).

Lighter earmuffs are being developed, composed of high-tech materials to reduce weight and bulk, yet effectively block noise. In the near future there may be plugs that allow two-way communication (CDC, 2013).

No specific brand of HPDs is the best obvious choice, several factors have to be considered besides noise attenuation when deciding upon the most suitable HPDs (according to each specific context) from the panoply of HPDs and HPDs' characteristics available: cost, durability, chemical stability, safety, wearer acceptability and hygiene (Gerges et al., 2001).

The characteristics of the workers themselves also have to be taken into account. For example, facial hair, long hair, glasses, earrings and facial movements such as chewing gum all break the seal of the earmuff cushions around the ear, thus hindering the accomplishment of good protection through earmuffs and reverting to the choice of plugs or caps. The working environment is, not infrequently, also important when selecting appropriate HPDs. In some environments workers consider the earmuffs are heavy and hot (CDC, 2013; NIOSH, 2007b; OSHA 2003).

Verbeek, Kateman, Morata, Dreschler and Mischke (2012) reveal that, for high frequency impulse noise, earplugs are a good option, particularly earplugs made of porous material, for they allow a good degree of intelligibility at the level of conversation.

So, the best HPD is the one that is comfortable and convenient and that the worker will wear whenever in an environment with hazardous noise (CDC, 2013).

Even though the recourse to HPDs (else praised by several authors for their importance in the worker's health) is not, by far, the best choice of a strategy to prevent NIHL, but the last stronghold to protect the hearing of workers exposed to occupational noise when all other protective measures, including legal measures of protection, are neither efficient nor enforceable in a given context, in general, HPDs are preferred to technical and engineering controls, since the latter pose more laborious and onerous measures (Arezes & Miguel, 2005; Riko & Alberti, 1983).

Therefore, HPDs are still, to this day, the preferred measure by the companies' decision-makers to prevent workers' NIHL regardless of their constraints, very much so like over three decades ago (Seixas, Neitzel, Stover, Sheppard et al., 2010; Malchaire & Piette, 1997; Riko & Alberti, 1983).

Apparently simple to solve, the NIHL problem has perpetuated in the occupational settings, due to the low rates of use of HPDs (McCullagh, 2002).

Considering the aforementioned, it seems righteous to assume that, perhaps, despite all the trust placed in HPDs' performance, these devices are not effectively protecting workers from hearing disorders (Malchaire & Piette, 1997).

In fact, it is well known that the HPDs' potential for effective protection is not fully achieved unless these devices are worn during the total amount of time they are needed, in other words, when hearing protection is advisable, prevention of NIHL relies on the use of HPDs during the total amount of time when exposed to high-noise levels (Brady, 1999).

In order to clarify this argument, one shall take, for example, a HPD with catalogued attenuation of 26 dB that is only worn 75% of the time. Resorting to the equation of the effective attenuation of a HPD presented by Arezes and Miguel (2002b) and Barbara et al. (1995), an effective attenuation of 6 dB is obtained, which is far less than the advertised 26 dB. If the time of use of the HPD is maintained at 75%, but the HPD is exchanged for one with a nominal (catalogued) attenuation of 18 dB, effective attenuation is still 6 dB. This means that in this case, to be more significant, unaccounted for factors would have to introduce, by themselves, a decrease of more than 8 dB to the catalogued attenuation.

For a better sense of the strictness of these statements, let us look at Table 1, that shows the maximum protection provided by that HPD to the worker. Failing to wear the HPD for only five minutes (which does not appear as much in an eight hour journey) will result in a protection of only 20 dB, which may not be enough to comply with the safe legal levels of exposure.

It is now clear that, in fact, protection afforded by HPDs depends on the period the devices are worn (Arezes & Miguel, 2006; Barbara, Soudry, & Pringalle, 1995; Neitzel & Seixas, 2005) that is, when workers fit HPDs correctly, which sometimes is not the case (Casali & Park, 1990).

And even when removed or displaced for small amounts of time, protection can be significantly affected (Arezes & Miguel, 2005; Else, 1982 cited by Riko,1983).

Given the role of HPDs in hearing protection against exposure to occupational noise, it is important to evaluate the "real" attenuation provided by HPDs worn by workers exposed to occupational noise, in order to have more meaningful data available, so that noise exposure is clarified and better NIHL prevention strategies are developed (Neitzel, Somers, & Seixas, 2006).

This brings to front the need to assess whether workers use the hearing protection devices available for them and if not, why.

Table 1. Maximum protection afforded by non-continuous use of an HPD with catalogued attenuation of 26 dB.

Percent time used	Maximum Protection
50%	3 dB
60%	4 dB
70%	5 dB
75%	6 dB
80%	7 dB
90%	10 dB
95%	13 dB
98%	17 dB
99%	20 dB

Also, it is of great importance to assess the HPDs' periods of use, or non-use, by workers. As put by Berger and Gauger "In terms of measured protection we often worry about inaccuracies of 2 or 3 dB, yet simply failing to wear a 25-dB HPD for 20 minutes out of an 8-hour shift will reduce the delivered protection by twice that amount" (Berger, 2000 cited by Berger and Gauger, 2004).

Although the amount of publications devoted to occupational noise mitigation reflects the interest and development of this specific matter, a part of this issue is in the need of more research, namely, the behaviour of the worker towards HPDs (Arezes & Miguel, 2005).

However, as noted by Berger (2003) some studies show that tests to the attenuation provided by hearing protection devices in laboratory are very unreliable, which hinders the task of assigning HPDs for workers, as it means that the attenuation labelled on the devices does not match the actual attenuation.

Casali and Park (1990) had also alerted to the fact that spectral attenuation data and, consequently, noise reduction rating (NRR) overestimated actual attenuation values. Therefore, attenuation of a given HPD is usually computed by affecting the laboratory-determined NRR of the HPD with a derating factor (Neitzel, Somers & Seixas, 2006).

Even though this practice acknowledges the fact that catalogued attenuation of a HPD differs from its “real” attenuation, other factors must be accounted for, like the user-fit variability (Neitzel, Somers & Seixas, 2006).

Adding to that, and despite their importance, workers are not yet sufficiently familiar with HPDs, having little training and motivation for their use (Neitzel & Seixas, 2005).

This problem is further compounded by factors such as possible discomfort and availability of various sizes, making the choice of which HPD would be more adequate and distribution of HPDs by several workers of a company even more complex.

Aware of this difficulty, and more than a decade before the latter study, Damongeot (1994) made a presentation of several types of HPDs according to their classification followed by recommendations as to when they should be chosen and also when to avoid them, based on noise exposure type, nature of the noise, environment conditions, nature of the task, other individual protective equipment and human factors.

Berger, Franks, & Lindgren (1996) also reviewed several field studies of hearing protection attenuation, reporting subject participation in field studies to be of one of two genres: candid selection or scheduled testing. On the first one, subjects know their work is under investigation, on the other one, they do not. The researchers mentioned two main methods to measure real-world attenuation, real-ear attenuation at threshold (REAT) and microphone in real ear (MIRE). They also referred the need to better define field performance possibilities, enhancing the importance of HPDs’ use to the prevention of NIHL.

It is still, to this day, a subject of much interest and controversy in this scientific field.

Voix and Laville (2009) also addressed the issue of exact attenuation determination. They stated that there are two approaches for the determination of the attenuation: either by modelling or measurement. They argued that in the first case, authors who have tried to model a novel earplug that includes a passive acoustical filter did not regard sound transmission through the rest of the earplug, thus failing to predict the exact attenuation of the plug. On the other approach, authors explained that the available attenuation measurement methods were too time demanding or too delicate to be done in an individual-fit basis.

Although one recognizes the relevance of these studies, a question arises: “How important is determining the exact attenuation of a HPD if its efficiency is far more dependent on the time they are worn?”. In other words, if one establishes a relationship between percentage of time used and “real” (or, as some authors call it, “exact”) attenuation, given the catalogued attenuation, will other factors unable to be accounted for so far, introduce significant changes in results previously obtained?

A standard published by ISO in 2009 (revised in 2014), the ISO 9612:2009 “Acoustics - Determination of occupational noise exposure – Engineering Method”, specifies an engineering method for occupational noise exposure measurement and noise exposure level estimation. This document was thought and materialized by the acoustical community, health and safety practitioners and industrial users, with the aim of achieving a normalized document to be followed by different countries, in which the same methods would be applied, therefore rendering results which could be compared (Ausselineau and Gaulupeau, 2010).

In an attempt to meet the local measuring habits and cultures, this standard turned out to describe three different occupational noise measurement strategies: task-based measurement (TBM), job-based measurement (JBM) and full-day measurement (FDM). Several industrial actors deemed the standard too strict in what concerns the requirements regarding measurement time, making its regular application very unpractical and extremely costly, even more so when it is only intended to assess if either a worker is overexposed or not, questioning the feasibility and reasonability of the standard (Ausselineau and Gaulupeau, 2010).

Costa and Arezes (2012a) stressed that the standard does not acknowledge the use of individual HPDs in the expression of the associated uncertainty in any of the three strategies. Now, consideration of the measurement uncertainty can determine the difference between the worker being exposed to below the legal noise exposure level or surpassing it (Costa & Arezes, 2012a).

Therefore, results obtained by applying the aforementioned document can be overestimated and consequently lead to a misclassification of exposure in epidemiological studies (Sbihi et al., 2009).

Hence, although noise attenuation provided by hearing protection is not considered for the application of occupational noise exposure action values in noise exposure determination of the employee, it has to be taken into account when referring to exposure limit values.

Regarding ISO 9612:2009, it is important to remember that there is a need to test and compare the three strategies outlined, since it seems that there are no published peer-review studies in this domain (Costa and Arezes, 2012b).

Arezes, Mateus and Bernardo (2012) persued a comparison between the three strategies proposed by the ISO 9612:2009. The authors had tried to establish that comparison earlier, but failed to do it in a systematic manner, keeping the need for a structured and well planned comparison in order to better understand its applicability, as well as to realize the contribution of hearing protection (Mateus, Arezes, & Bernardo, 2010).

1.12 Further legal and normative framework

In Europe, the European Committee for Standardization, Technical Committee 159, Hearing Protectors (CEN/TC 159) is responsible for the standardization of HPDs and the acoustical test methods are established by the International Organisation for Standardisation, Technical Committee 43, Acoustics, Sub-Committee 1, Noise (ISO/TC 43/SC1).

Safety requirements and testing of HPDs are defined in the standards EN 352-1:2002 (earmuffs), EN 352-2:2002 (earplugs), EN 352-3:2002 (earmuffs attached to an industrial safety helmet) and EN 352-4:2001 (level-dependent earmuffs), EN 352-5:2002 (active noise reduction earmuffs, EN 352-6:2002 (earmuffs with electrical audio input), EN 352-7:2002 (level-dependent ear-plugs) and prEN 352-11 (two-way communication earmuffs). Standard EN 458:2004 is a guide document containing the recommendations on the selection, use, care in the use and maintenance of HPDs. Standards EN 13819-1:2002 and EN 13819-2:2002 respectively establish the physical test methods and the acoustic test methods for HPDs.

The basic requirements for the design, manufacture and use of hearing protectors against the harmful effects of noise are detailed in Directive 89/686/EEC on Personal Protective Equipment of 21 December 1989. Directive 2003/10/EEC of 6 February 2003 defines the minimum health and safety requirements for workers regarding noise exposure.

Other relevant standards are summarised in Table 2.

Table 2. Relevant standards addressing HPDs and acoustics.

NP EN 21683:1997	Acoustics. Preferred reference quantities for acoustic levels.
NP EN 24869-1:1994	Acoustics. Sound Attenuation of Hearing Protectors – Part 1: Subjective Method of Measurement
NP 3498:1988	Measurement of the Sound Attenuation of Hearing Protectors. Subjective Method.
NP 2239:1986	Acoustics. Audiometers.
NP3225-1:1986	Acoustics. Vocabulary. Part 1–General Definitions.
NP 3225-2:1986	Acoustics. Vocabulary. Part 2 – Sound Propagation.
NP 3225-3:1986	Acoustics. Vocabulary Parte 3 – Hearing.
NP 3496:1988	Acoustics. Sound level meters.
NP 1732:1981	Acoustics. Evaluation of conversation intelligibility distances in noisy environment.
NP 4397:2008	Occupational Health and Safety Management Systems. Requirements
ISO/CD 7029	Acoustics - Statistical distribution of hearing thresholds related to age and gender

Lei n.° 102/2009 of September 10 regulates the legal framework for the protection of safety and health at work. Yet, January 28, 2014, Lei n.° 3/2014 was published, which is in effect since last February 27, 2014. This document came undertaking the second amendment of the legal framework of the promotion of safety and health at work, approved by Lei no. 102/2009 of 10 September, first amended by Lei n.° 42/2012 of August 28.

Portaria n.° 702/80 of September 22 approves the General Safety Regulation and Hygiene at Work in industrial undertakings, altering the first document issuing this matter, Portaria n.° 53/71 of February 3. The latter was the first document to legislate on general working conditions and noise exposure in particular. These documents address the obligations of companies and workers referring, inclusively, the use of PPE, but they are very vague and not greatly legally binding on the issue of noise exposure, only recommending that the noise exposure limit values do not exceed those indicated in Portuguese standards. In fact, at the dates of entry into effect of these documents, there were no other legal documents that established obligatorily for limit values for noise exposure levels, or use of HPDs. That only happened with the (revoked in the meantime) Decreto-Lei n.° 251/87 of June 24, that approved the General Regulation on Noise. This document was later on amended by the Decreto-Lei n.° 292/89, of September 2 (revoked by Decreto-Lei n.° 292/2000 of November 14).

Five years later, Decreto-Lei n.° 72/92 of April 28 established the general framework for protection of workers against the risks arising from exposure to occupational noise, to be applied to all business establishments and services, including public administration. This now revoked act was regulated by Decreto Regulamentar n.° 9/92 of April 28, and transposed into national law the Directive n.° 86/188/EEC of the Council of 12 May, 1986, on the protection of workers from the risks related to exposure to noise at work, pressing the alteration and specification of Decreto-Lei n.° 251/87 of June 24. Decreto Regulamentar n.° 9/92 of April 28 was revoked by Decreto-Lei n.° 182/2006 of September 6.

Portaria n.° 987/93 establishes the minimum requirements of health and safety in the workplace, under the Decreto-Lei n.° 347/93, of October 1, which transposes into internal law the provisions of Directive n.° 89/654/EEC of the Council of 30 November.

Decreto-Lei n.° 292/2000 of November 14, approved the legal regime on noise pollution, also called "General Noise Regulations", by revising the General Noise Regulation approved by Decreto-Lei n.° 251/87, of 24 June, amended by Decreto-Lei n.° 292/89 of September 2. Decreto-Lei n.° 292/2000 was later amended by Decreto-Lei n.° 259/2002 of November 23, and finally revoked by Decreto-Lei n.° 9/2007 of January 17, the document that approves the General Regulation of Noise.

In the year preceding the new General Regulation of Noise, Decreto-Lei n.° 182/2006 of September 6 was published. This document transposes into national law Directive 2003/10/EC of the European Parliament and of the Council, of February 6, on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise).

Decreto Regulamentar n.° 76/2007 of 17 July amends the Decreto Regulamentar n.° 6/2001, of 5 May, approving the list of occupational diseases and their encoded content, and republishes it. In this document, hearing loss by cochlear damage is identified as an occupational disease caused by noise. O Decreto Regulamentar n.° 6/2001 of May 5 approves the list of occupational diseases and their encoded content.

Lei n.º 98/2009 of 4 September regulates the repair system of work accidents and occupational diseases, including professional rehabilitation and reintegration, in accordance with Article 284 of the Labour Code, approved by Lei n.º 7/2009 of 12 February.

The Directive 2003/10/EC of the European Parliament and of the Council of February 6, on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise) is transposed into national legislation by Lei n.º 182/2006 of September 6.

Decreto-Lei n.º 352/2007 of 23 October, approving the national table of disabilities, including an otorhinolaryngology section, defines the concept of professional deafness, distinguishing it from subjective concepts and assessing the effects of noise as sonotraumatic to the cochlea, differentiating between traumatic and non-traumatic injuries, classifying the latter as ear fatigue, reversible and without sequel. It also considers noise with Leq 85 dB (A) as the alarm quota for the prevention within the hygiene and safety and occupational medicine, being that only the noise with Leq 87 dB (A) is considered harmful to the cochlea.

International standard ISO 1999:2013 specifies a method for calculating the expected noise-induced permanent threshold shift in the hearing threshold due to noise exposure. This document provides the basis for calculating hearing disability according to several calculations when the hearing threshold levels exceed a certain value at commonly measured audiometric frequencies, or combinations of frequencies.

The measure of exposure to noise for a population at risk is the noise exposure level normalised to a nominal 8 h working day, $L_{EX,8h}$, for a given number of years of exposure. Use of ISO 1999:2013 for sound pressures exceeding 200 Pa (140 dB relative to 20 µPa) is recognized as extrapolation.

The NP ISO 1996:2011, parts 1 and 2, entitled "Description, Measurement and Evaluation of Environmental Noise" replaced the NP series 1730: 1996 on 30 June 2011. Its overall objective is to contribute to the international harmonization of methods of description, measurement and evaluation of the resulting ambient noise from all sources.

According to the General Regulation of Noise, the noise tests necessary to verify the legislation have to be carried out by bodies accredited under the National Quality System. Accreditation is conducted in accordance with the NP EN ISO / IEC 17025: 2005 - "General Competence Requirements for Testing and Calibration Laboratories".

The technical equipment necessary to carry out noise tests are, compulsorily, object of metrological control under Decreto-Lei n.° 291/90 of 20 September.

Before the 1990s, it was thought that infrasound exposures were rare and, even if they could occur, they were believed not likely to be dangerous to a person's hearing or health, at levels found in industry directly (Johnson, Papadopoulos, Watfa, & Takala, 2001).

As complaints of workers dealing with ultrasound equipment began to increase, they were commonly attributed to sound generated as sub-harmonics of the original sound source which caused, for example, work pieces to vibrate. Researchers started to wonder whether the frequency range of audible sound was real or resulted from inappropriate technical means to shape audiometric tests for frequencies called infra- and ultrasound. Even though scientific evidence points to the existence of hearing threshold levels outside both ends of the approximate range of hearing (20 Hz to 20 kHz), it is not sufficient to define occupational exposure levels, because in practice the extra-aural effects of infrasound to cause body vibrations cannot be suppressed nor can the general impact of ultrasound on the complete hearing organ, which generates a vague sensation. Still, an effort has been made over the years, that resulted in standards that define boundaries between the different kinds of sound (ISO 7196) that outline measurement purposes (IEC 1012) and in recommendations containing occupational exposure levels for ultrasound, of which the ACGIH (1999a) is an example.

1.13 Issuing uncertainty

It seems reasonable to assume that assessment of the percentage of HPDs' use is a more important issue to be enlightened regarding the achievement of the “real” attenuation of HPDs.

According to Neitzel and Seixas (2005), relying on HPDs' attenuation alone for protection towards high noise levels is dangerous, as protection also depends on the time HPDs are worn. That is, even when workers properly fit a HPD, effective protection of the HPD suffers a heavy decrease with increasing time of non-use.

Hence, one of the objectives of this work is to encounter an expression that given a set of parameters (that might be work-related, HPDs' intrinsic characteristics or others found to be relevant during the study) estimates the workers' percentage of HPDs' use.

In order to accomplish this goal and based on previous works referred throughout this document, this study will be based on the cross-analysis of results attained from direct observation of workers and questionnaire completion, followed by modelling of HPDs' use (Arezes and Miguel, 2005; Sbihi et al, 2009).

It is thus important to assess the behaviour of workers towards the use of HPDs, according to the type of HPD worn, by examining the HPDs' utilization profile, in order to obtain more reliable attenuation data. But the kind of data obtained, explaining workers' behaviour, may be somewhat imprecise and, if so, fuzzy logic may have to be used, as fuzzy approach is useful when dealing quantitatively with imprecision (Varela, Barbosa, & Costa, 2013).

For the last two decades, fuzzy logic has been applied in a wide range of science fields such as engineering, management and medicine. The researchers' tendency to use this methodology relates to its ability of translating qualities to mathematics.

In the primordial paper of Zadeh (1965) explaining fuzzy sets, the author explained the need to create these fuzzy sets (that he defined as "a 'class' with a continuum of grades of membership"), arisen from the fact that, in the real physical world, classes of objects are not defined with precise criteria of membership.

The need to resort to fuzzy sets to explain the real world has been shared by several other researchers, as this paper has since been cited by 35107 other works.

Fuzzy logic relies on a set of if-then rules, i.e., considering a given system under study, in which several variables operate, fuzzy logic explains each relationship between the independent variables and dependent variables as an "if-then" rule (Zadeh, 1965). The first part of the rule, the "if" part is bound to a specific region of an input space and the consequence part of the rule, the "then" part presents a local model that best engages the data in the corresponding region (Zadeh, 1965).

When all relationships are built and explained as a set of "if-then" rules, a linguistic model is set out. Afterwards, operations among membership functions related to the fuzzy sets are performed, allowing the transformation of the rules into mathematics. In fuzzy logic, membership takes a number between 0 and 1, and expresses the degree to which variables relate (Aluclu, Dalgic & Toprak, 2008; Karwowski, Gaweda, Marras, Davis, Zurada & Rodrick, 2006; Zadeh, 1965).

Thus, fuzzy sets cast the first stone to the building of a framework that enables an unconstrained manner of handling problems in which the genesis of imprecision is not the presence of random variables but, and more importantly, the lack of sharply defined criteria of class membership.

Indeed, the term “fuzzy” derives from the smooth boundaries of the fuzzy sets forming the input space. In fact, these smooth boundaries allow partial memberships between regions and overlapping (Aluclu et al., 2008; Karwowski et al., 2006; Zadeh, 1965).

Contrary to what may seem, fuzzy logic is often used in everyday language. Every time one expresses a thought using vague sentences that are better understood than when exact terms are used, fuzzy logic is being applied. For instance, when using soap, instructions are to rinse with water abundantly after use. This sentence makes more sense than “rinse with 3 litres of water after use”, for it is assumed that common sense is enough for people to know how much is “abundantly”.

This means we are naturally used to operating with fuzzy data and to making decisions based on imprecise information.

The role of fuzzy logic theory is to enable computational models of real systems to act on both fuzzy and statistical uncertainties, just as we do (Bezdek, 1993). For this reason, fuzzy logic theory is a very desirable tool for professionals who, on a daily basis, deal with people: their performance towards a given environment, likes and dislikes, emotions and their impact in human behaviour.

It is not hard to imagine that scientific disciplines bound to occupational matters benefit greatly from fuzzy logic theories.

Several authors have resorted to fuzzy logic theory in order to handle uncertainty (D’Errico, 2009; Giniotis, Grattan, Rybokas, & Kulvietiene, 2004; Mauris, Lasserre, & Foulloy, 2001; Wirandi & Lauber, 2006).

Grassi, Gamberini, Mora and Rimini (2009) resorted to fuzzy logic in a study where they proposed a new methodology for risk assessment, inserting factors that accounted for effects of human behaviour and environment on risk level, besides injury magnitude and occurrence probability of an accident. They stated that use of fuzzy logic theory gave origin to both an evaluation process they found more coherent and a rank of hazardous activities they thought adequate. One of the reasons the authors chose to integrate a fuzzy-based solution technique in the model they proposed was to enable the analyst to preserve coherence in his evaluation by making judgments resorting to fuzzy linguistic terms. The other one was to allow handling the evaluation's uncertainty.

Ability to handle uncertainty and to deal quantitatively with imprecision, added to lower number of variables required, reduction of human error and the possibility to chose, from a multitude of solutions, the most adequate for a given problem, are pointed by researchers as the main advantages of the fuzzy methodology.

In short, fuzzy logic has disseminated, been adapted and used in all its strands in a range of science fields. It is no wonder it has great impact in occupational health and safety domain also, in particular the risk prevention domain, as the quantification of behaviours, preferences and sensations are major issues in this theme.

The bulk of scientific work that has profited from the use of fuzzy logic really represents the boost of knowledge the suiting of its rules has allowed and the great breakthroughs made thenceforth.

Fuzzy logic also has been used in regression analysis (Ramli, Watada, & Pedrycz, 2011).

The uncertainty given by the three different measurements can also be tested, in order to confirm and quantify the associated reliability, as done by Ognedal and Turunen-Rise (2004), who compared an inter-laboratory method for measurement of noise in working environments. In order to do so, the 3 measurement strategies (TBM, JBM and FDM) shall be applied to all work stations selected (by different teams of research), so that all measurements can be done under the same conditions, using the predefined equipment, that is, the simultaneous use of sound level meter and dosimeter.

Having all measurements done under the same conditions, using the predefined equipment will, expectedly, grant a statistical basis for describing the variation of noise throughout the day and/or weeks (Voss, 2005).

The standard conditions, under which measurements will be applied for all employees and/or groups of employees, may ensure greater reliability and greater accuracy in results and by decreasing the subsequent error.

Resembling previous works, results shall be statistically treated in a daily and weekly basis, so as to put together a significant set of data on the indicators to be used and per workstation (Kaczmarska, Mikulski & Smagowska, 2004).

A systematic methodology may test the accuracy (trueness and precision), repeatability and reproducibility of the three measurement strategies, much like what has been done by Castellote and Andrade (2006), who used the ISO 5725-2:1994 to compare methods for determining chloride transport parameters in concrete.

In order to perform occupational noise measurements, practitioners and researchers need more than just a table indicating which one(s) to use given the work situation, but rather information regarding each strategy's accuracy, reproducibility and repeatability.

For a full comparison, it is also important to obtain data (exposure values) regarding the time needed to complete each measurement strategy.

One important issue is also uncertainty and its formulation, which must also be tested.

RRT are considered by most of the authors as an important external quality tool used to determine and/or verify the accuracy of measuring methods, enabling to determine a level of agreement between different methodologies. Also, these tests may help clarify other sources of uncertainty not yet acknowledged and sort systematic errors.

RRT are also widely used by authors when intending to provide precision data according to ISO/IEC 17043 (02-2010) - Conformity assessment – General requirements for proficiency testing.

1.14 Thesis Organisation

This thesis comprises three major parts: Problem and Literature Review, Developed Work and Conclusions and Future Perspectives.

The first part – Research Problem and Literature Review – consists of the discovered gaps and conjuncture that led to the need for the search of a resolution for the detected problem (Chapter 1. Addressing the problem) and focuses on what have been found and done so far in the scientific niches that address these issues and that can, somehow, provide an early pathway for achieving the goal of answering the research question (Chapter 2. Literature review). Several scientific approaches are described, so as to gather as much reliable information as possible and, from there, choose the best fitting options.

The research approach, methodology, results and discussion are brought together by Part II – Developed Work. Chapter 3 presents the research problem that motivates the research goals and conceptualisation of the structure of research. All methods and strategies (whether novelties or adaptations) designed to achieve the thesis goals are detailed in Chapter 4. Chapter 5 clarifies all results obtained by the implementation of the preceded sections.

Finally, the main conclusions drawn from the results obtained and some questions raised about future work to be developed are issued in Part III – Main Findings. The outputs that emerged from this research are set out in annex 2.

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Chapter 2. Literature Review

The most direct consequence of exposure to occupational noise is NIHL and, given the high prevalence of NIHL in workers whose workplaces present hazardous levels of noise, occupational hygiene does not appear to be effective in its purpose given that, in 2007 alone, approximately 23 thousand cases were reported of occupational hearing loss valued as hearing impairment (CDC, 2015). Unfortunately, these assertions are found to be true to this day, leading to the idea that new research and action directions may have to be considered.

2.1 Introduction

Although the amount of publications devoted to occupational noise mitigation reflects the interest and development of this specific matter, a part of this issue is in the need of more research, namely, the behaviour of the worker towards HPDs (Arezes & Miguel, 2005).

As of January 2015, over one thousand seven hundred records were found with keywords “occupational noise attenuation”, and over 1.200 records under the keywords “hearing protection devices attenuation”, on Elsevier database alone (Science Direct, 2015).

On what concerns to occupational health and safety, assessing occupational risks, exposure to hazards and workers’ health status are routine to health and safety practitioners.

The boosters are the researchers who want to ‘think ahead’, inspired by the ability to predict. Once the researcher has figured out what the key issues involving a certain context are, holding knowledge on the variables and their effect in a desirable result, the disclosure of the systematization of the problem will provide readily available solutions to cases that resemble the one studied.

Moreover, the identification of those key factors, also known as predictors, determinants, indicators will allow for the construction of models that will theorize the problematic to a wider range of problems of the occupational settings.

The most obvious advantage for researchers focused in occupational settings matters, is the attainment of particular traits of human behaviour (objectives, activities, likes and dislikes) in advance (Zukerman & Albrecht, 2001).

The search for an explanation of this phenomenon has motivated several researches, providing a bulk of information regarding the determinants of HPDs use. Once the practitioner grasps the key issues surrounding the use of HPDs, he will be able to deliver a prompt solution provided by the disclosure of the systematization of the problem.

Several authors have addressed the HPDs’ use issue among workers exposed to occupational noise, either by determining or by evaluating putative determinants for its use (Arezes & Miguel, 2005; Edelson, Neitzel, Meischke, Daniell, Sheppard, Stover, & Seixas, 2009; Lusk, Ronis, Kazanis, Eakin, Hong, & Raymond, 2003; Melamed, Rabinowitz, Feiner, Weisberg, & Ribak, 1996; Ronis, Hong, & Lusk, 2006; Sbihi, Teschke, Macnab, & Davies, 2009, 2010).

By revealing a pattern of use of HPDs in the working environment, also the task of sorting and distribution of HPDs can be facilitated. Once a pattern of use of HPDs is unveiled, a novel stage on occupational noise exposure assessment can be reached, one that not only acknowledges the use of HPDs, but also includes their contribution to the uncertainty related to the occupational noise exposure level assessed, a part of the main objective of this study.

2.2 Identification and collection of predictors of the use of HPDs

Predictors are a variety of agents that exist in the occupational context and arise as factors that may be the cause of a demeanour (Arezes & Miguel, 2012; Edelson et al., 2009; Griffin, Neitzel, Daniell, & Seixas, 2009; Kushnir, Avin, Neck, Sviatochevski, Polak, & Peretz, 2006; Lusk, Eakin, Kazanis, & McCullagh, 2004; Sbihi et al., 2009), that originate an insight (Alayrac, Marquis-Favre, Viollon, Morel, & Le Nost, 2010), or that have influence on exposure (Abel, Kunov, Pichora-Fuller, & Alberti, 1985; Burstyn, Kromhout, & Boffetta, 2000a, Burstyn, Kromhout, Kauppinen, Heikkilä, & Boffetta, 2000b; Cavallari, Osborn, Snawder, Kriech, Olsen, Herrick, & Mcclean 2012a, b).

The search and determination of predictors has stimulated the work of many researchers in many science disciplines. It has driven the development of several successful models in the occupational matters and with great acceptability among the scientific community. These in turn, provide anticipated knowledge and, hence, make more effective the health and safety practitioners actions, by diminishing the time needed for assessments and by providing a bulk of early information (Costa & Arezes, 2013).

Arezes and Miguel (2002) found that catalogued (N) and effective/real attenuations (R) were significantly different, in a study where they also found that more comfortable, lower catalogued attenuation HPDs were more likely to be worn by workers (hence more efficient) than less comfortable, higher catalogued attenuation ones, meaning that high HPD’s efficiency can only be obtained if an adequate balance between factors that influence its use is met.

In a later study by the same authors (Arezes & Miguel, 2005), self-efficacy was found to be the main predictor of the use of HPDs. Moreover, individual risk perception was found to be an important predictor of the use of HPDs by workers, alongside with contextual factors.

Nevertheless, the same study results showed that even though HPDs were needed in all workplaces studied, some workers were not aware of the risk they faced, as they did not find their workplace to be dangerous enough for using HPDs. Some of the reasons given by the workers to explain non-use of HPDs were the delay to begin their work shift and interference with communication, pressure in the head, headache and itching, among other comfort issues (Arezes & Miguel, 2005).

Berger (1991) had earlier advised for the fact that the type of HPD could influence the use of the devices, alerting to the barriers workers presented to its use, some of them already mentioned earlier in this document, adding to sound distortion. He emphasized the fact that different types of HPDs present distinct characteristics that must be exploited in order to make better decisions in the choice of adequate HPDs, avoiding overprotection as much as overexposure.

Tabachnick (1994) stated that, when considering buying a HPD, the most important factors to account for were comfort and likeliness to use.

Over 30 years ago, Riko and Alberti (1983) had already explained the rationale for the wearer of the HPD to have a say on the choice of the device, since he is the one who knows whether he is likely to wear it or not.

In Arezes and Miguel (2006), authors convey the need for conception of new motivation tools for the use of HPDs and advise special care towards specific groups identified in the study; like older, higher professional experience and lower educational background workers.

Later on, the authors reiterate the importance of risk perception as a major predictor of HPDs' use, asserting both risk perception and out-come value for hearing preservation as being the most significant determinants of HPDs' use. The contextual level's importance is also restated, with the disclosure of company's safety climate as an important predictor (Arezes & Miguel, 2008).

Edelson et al. (2009) share this finding in a study where they resorted to a questionnaire survey and a validated combination of activity logs with simultaneous dosimetry measurements to assess HPDs' use. They found that HPDs were used for less than half the time they were needed (in average) and reported site, trade and perception that the use of HPDs is not time consuming as important determinants of their use. Plus, they concluded that management support for safe work practices and training were factors that positively influenced the use of HPDs.

On the reverse of the coin, Tabachnick (1994) states that a characteristic of earmuffs people typically cannot adapt to is the difficulty in locating a sound origin.

Sbihi et al. (2009), on the other hand, developed a hierarchical model to predict HPDs' use and concluded that the latter is associated with noise exposure, age and specific jobs and departments.

Afterwards, the authors used their model to account for HPDs' use in retrospective noise exposure assessment, and found that the difference before adjustment for HPDs' use and after was significant, revealing a 4 times increased noise exposure and hearing loss slope, after the adjustment (Sbihi et al., 2010).

That same year, Seixas, Neitzel, Stover, Sheppard, Daniell, Edelson, and Meischke (2010) performed a study where a novelty was introduced, a personal noise level indicator with real-time feedback of the individual's noise exposure level. Results pointed to a positive effect of this device on the use of HPDs, and a survey revealed that workers found it useful.

To sum up, the predictors of the use of HPDs have been identified and include: individual risk perception, subjective opinion on the company's safety climate, individual judgment on comfort, noise annoyance, education, age, trade group, seniority, perceived barriers to the use of HPDs and self-efficacy in their use, acknowledged value of the use of HPDs and deriving benefits, gender, ethnicity, dysfunctional thinking patterns and self-perceived susceptibility to hearing loss (Costa & Arezes, 2013).

2.3 Contribution of the Pender's Health Promoting Model (HPM)

Grounded on social learning theory, the Pender's Health Promotion Model (HPM) is a tool of problem systematization, developed as a means to explain workers health-promoting behaviours, by establishing factors of different natures supposed to influence the actions of workers.

The evolution of the HPM has been cyclic throughout the years, as it has suffered several revisions, having several other researchers contributed actively to its evolvement, also adjusting it to other frameworks. Consequently, so has evolved the discovery of the determinants of the use of HPDs (Lusk & Kelemen,1993; Lusk, Ronis, & Hogan, 1997; Lusk, Ronis, & Kerr, 1995; Ronis et al., 2006).

The HPM can be briefly described as lying on two spheres in order to assess major determinants of health behaviours: the first one includes the individual characteristics and experiences of the subject, where prior related demeanour, biological, psychological and sociocultural factors establish whether the worker is prone to behave in a certain way; the second sphere is based on behaviour-specific cognitions and affect, regarding perceived benefits of action, perceived barriers to action, perceived self-efficacy, activity-related affect, interpersonal influences of peers, family and providers, situational influences (such as options, demand characteristics and aesthetics), commitment to a plan of action and immediate competing demands and preferences), believed to fundamentally shape the subject's behaviour (Pender, Murdaugh & Parsons, 2011).

Lusk and colleagues have intensively dedicated their research to the study of the implementation of the HPM, testing it for several occasions and contexts.

In 1993, Lusk and Kelemen placed the burden of the workers' hearing health in their active decision of consistently using HPDs, rather than focusing on reducing noise exposure (as had several previous studies). Therefore, they started by carrying out a preliminary study to prepare for testing HPM as a causal model.

Results from that research showed that the workers' reported use of HPDs was statistically significant and positively correlated with the perceptions of the subjects regarding namely: the stemming benefits and self-efficacy of the use of HPDs; value of outcomes in what concerns to keeping out noise and wellbeing improvement; and health-promoting behaviours in the areas of self-actualization and stress management. Also, perceptions of barriers for the use of HPDs were also accounted for, and found to be statistically significant and negatively related to use. The authors concluded that the knowledge of the predictors of HPDs' use does indeed help nurses in implementing interventions by increasing use and decreasing hearing losses (Lusk & Kelemen, 1993).

In 1997, Lusk and colleagues tested the HPM as a causal model of the use of hearing protection by construction workers and their results agreed with the 1996 revised version of the HPM. The authors stated that the best predictors for the use of HPDs were the behaviour-specific predictors, such as perceived barriers to use of hearing protection and that the results obtained supported the use of the HPM to predict the use of HPDs (Lusk, Ronis & Baer, 1997).

By 1999, Lusk Hong, Ronis, Eakin, Kerr and Early tested the effectiveness of a theory-based intervention to increase the use of HPDs among midwestern construction workers and a national group of plumber/pipefitter trainers and resorted to the 1987 version of the HPM to establish the conceptual basis for development of the training program.

In fact, they concluded that the intervention was successful in increasing the use of HPDs, although the use of HPDs did not reach the desired 100% of the time needed, and no significant effects on intention to use HPDs in the future were found (Lusk et al, 1999).

This shows that, to a certain level, the HPM covered some key determinants of the use of HPDs, even though some seem to have been overlooked. This comes in line with what has been stated earlier in the introduction, denouncing the need for improvement of the initial model (Lusk et al, 1999).

McCullagh, Lusk and Ronis (2002) aimed at identifying the factors affecting the farmer's use of HPDs by using the HPM. Thus, through a logistic regression analysis, the authors found that interpersonal support, barriers and situational influences were statistically significant predictors of the use of HPDs, rightly predicting seventy eight percent of the cases studied by them. The fact that the model was able to predict the large majority of the cases studied can be explained by the recourse of authors to the revised version of the HPM (1996). On the other hand, failing to correctly predict the twenty two percent of other cases, was explained in part by the authors as being a consequence of the non-probability convenience sampling approach, which afforded a biased study.

For the purpose of explaining Mexican American workers' hearing protection use, Kerr and colleagues (2002) used the HPM. As a result, they identified cognitive-perceptual factors that directly affected the use of HPDs: clinical definition of health, perceived benefits and barriers to the use of HPDs, self-efficacy in their use and perceived health status; and a modifying factor that, although does not directly affect the use of HPDs, explains additional variance: situational factors (Kerr, Lusk & Ronis, 2002).

In 2007, Kerr and colleagues tested the effectiveness of two different strategies: computer-based tailoring and targeting to promote use of hearing protection (Kerr, Savik, Monsen & Lusk, 2007).

To account for gender differences in blue collar workers' use of HPDs, Lusk et al. (1997) resorted to the HPM to develop a structural equation model of self-reported use of HPDs by male and female blue collar workers. The authors concluded that the global results of use were not significantly different between genders and also that self-efficacy and barriers to the use of HPDs were the two best predictors of the use of HPDs for both genders.

Also based on the HPM, in 2009, Edelson and colleagues identified the predictors of the use of HPDs among construction workers by resorting to the components of the revised HPM and to safety climate factors to evaluate likely predictors. Five of the HPM components were found to be important predictors of the use of HPDs at the individual level, namely: belief that wearing HPDs is not time consuming, belief that wearing HPDs is not uncomfortable, belief that preventing hearing loss is important, belief that wearing HPDs eases hearing and self-efficacy (Edelson et al., 2009)

These findings are in accordance to what Berg and Hiselius (2000) found in a study, where they observed the reluctance of hearing-impaired members of the workforce to wear HPDs due to the feeling of isolation from necessary communication (adding to the difficulty to hear machine sounds). The authors mention the occurrence of NIHL in these conventional wearers of HPDs in the frequency range where speech intelligibility is most critical, adding to the fact that their HPDs also attenuate the most in that range, leading to a poor adherence to hearing protection programs and aggravating their NIHL. They conclude that, because workers wearing uniform-attenuation HPDs are more conscientious participants in hearing protection programs, this type of HPD is more efficient in providing protection for them.

Another reason commonly presented to justify non-use of HPDs is the impairment it implies on warning sounds' detection ability. This, if nothing else, is ironic, since NIHL can in fact jeopardize individual safety and performance at work (Reilly, Rosenman, & Kalinowski, 1998).

In 2010, Kim and colleagues objectified the identification of factors that influence the use of HPDs amidst workers exposed to noise using the HPM. The researchers found that social modelling and perceived benefits were important predictors of the use of HPDs (Kim, Jeong & Hong, 2010).

Based on the HPM, Seixas and colleagues were able to develop a multi-component intervention to promote hearing protection use (Seixas et al., 2010).

The model presented by Nola Pender in 1987 has been a propeller of the knowledge of the HPDs' usage predictors and the latter reciprocate by feeding the loop with information to improve and enhance the HPM.

The contribution of HPM to studies dedicated to occupational matters is evident. It provides the authors the ability to predict the performance of a worker, given a certain work setting and grants health and safety practitioners prompt answers to otherwise complex problems and knowledge beforehand.

2.4 Issuing the ISO 9612:2009 (now 9612:2014)

Costa and Arezes (2012) give some clues regarding what to look for when comparing the three measurement strategies presented in ISO 9612:2009, namely the performance of each strategy in terms of repeatability, accuracy and reproducibility. The authors also state that applicability of the methods will only be established once they have been sufficiently tested, thus highlighting the need for the performance of systematic testing to the strategies, preferably by different research teams.

Seixas, Sheppard and Neitzel (2003) had already compared TBM estimates with FDM, concluding that TBM measurements are important for exposures in which task time varies significantly, but also carry a substantial degree of error when a task has great inter-individual and variability within the different shifts. They also stated that there is a need to improve the prediction to task-associated exposure.

Taking into account the study developed by Ognedal and Turunen-Rise (2004), some key points are easily foreseen. For instance, what is the performance of each strategy in terms of repeatability? What can one expect while choosing one strategy over another?

Questions need be answered so that the researcher is fully advised when opting for specific strategy.

The comparison between the three strategies regarding accuracy, repeatability and reproducibility could be established by means of Round Robin Tests (RRT), used by several authors (Castellote & Andrade, 2006; Jaeschke, Audibert, Caneghem, Humphreys, Janssen-van Rosmalen & Pellei, 1990; Oasmaa & Meier, 2005; Ognedal & Turunen-Rise, 2004; Tang & Sørensen, 2001) as an important instrument of external quality control used to determine and/or verify the accuracy of measuring methods, enabling to determine a level of agreement between different methodologies.

Another question that arises is: “How does the familiarity/experience of the researcher influence the result and how does it reflect on the expanded uncertainty?”.

In the study by Ognedal and Turunen-Rise, conclusions state that, even though researchers had the guidelines of the engineering method, a significant percentage of researchers did not fulfil its requirements. Some of them did not even report the result in a correct manner (Ognedal & Turunen-Rise, 2004).

It is thus important that the 3 strategies proposed by ISO 9612:2009 are applied by several different teams with different backgrounds, in order to evaluate how well researchers reproduce what is prescribed in the method, and if that’s not the case (resembling the 2004 study by Ognedal and Turunen-Rise) it is important to evaluate why. In the latter study, some researchers commented that the text needed be re-written, since they found it not to be very explicit (Ognedal & Turunen-Rise, 2004).

Another issue that deserves much attention is the uncertainty issue.

To Antunes (2004), there is a growing need for studies that allow for acoustic tests to evaluate "reproducibility values and subsequent return of the measurement uncertainty associated value, according to the ISO guide to the measurement uncertainty of expression (GUM)".

Uncertainty assessments are patent in ISO 9612, but one can question whether the formulation is accurate since, once again, the strategies have not been enough tested, and there are still no comparable values to make assessments from. Different background team testing would also allow checking if overlapping of result exists and, consequently, if the formulation of uncertainty is correct.

Nevertheless, the main question and most important of all, still has no answer, not until this issue is taken into practice. That question is whether the methods are applicable or not, and the answer can only be given when these are sufficiently tested.

2.5 Contributions of Multilevel Modelling

Social and behavioural research often addresses problems that investigate the relationships between individuals and the larger context they live in, such as families, schools, or neighbourhoods, having a hierarchical or clustered structure (Field, 2009; Godlstein, 2011, Greenland, 2000; Hox, 2010, 2013).

The need to combine, in a statistically proper manner, variables defined at the individual and the group level, originated the emergence of multilevel models and dedicated software.

Decades of published examples and methodological studies proving the superiority of the multilevel perspective granted its widespread acceptance in the social sciences (Greenland, 2000).

Despite the greater complexity of the multilevel perspective, and the increased mental effort it demands to be understood and built, because the real world data are often hierarchical, it is not surprising that in the social, medical and biological sciences, multilevel structures are the norm (Field, 2009; Godlstein, 2011; Greenland, 2000; Hox, 2013).

Multilevel modelling designates models for relationships between variables defined at different levels of a hierarchical data set, which is often considered a multistage sample from a hierarchically structured population (Hox, 2013).

The major benefit of the hierarchical approach is the unification and clarification of the meaning of the apparently discrepant frequentist (classical) and Bayesian analysis, because it renders superior methods to both the frequentist and Bayesian methods (Greenland, 2000).

Multilevel modelling has been patent in many researches over the last 50 years. Bayesian, Empirical-Bayes (EB), Stein, penalized likelihood, mixed-model, ridge, random-coefficient regression, and variance-components analysis are all special cases of hierarchical regression (Greenland, 2000). Other special cases include conventional estimation methods (e.g., least squares and maximum likelihood) in which there is only one level in the underlying model (Greenland, 2000).

Educational and sociological research in the 1980s addressed these models, and, in the beginning of the 1990s, they were outlined in monographs (Raudenbush & Bryk, 2002; Goldstein, 1987).

Raudenbush and Bryk (1986) named their multilevel regression model “hierarchical linear model”, whereas De Leeuw & Kreft (1986) named it “random coefficient model”. Longford (1987) addresses his model as “variance component model” and Littell, Milliken, Stroup, & Wolfinger (1996) referred to their model as “mixed-effects” or “mixed” model. Although these models are not the same, all acknowledge a hierarchical data structure, with one outcome measured at the lowest level, and explanatory variables at all existing levels.

In hierarchical structures some variables are clustered or nested within other variables, i.e., the individuals and the social groups are conceptualised as a hierarchical system of individuals nested within groups, with individuals and groups defined at separate levels of the hierarchical system. Systems can be observed at different hierarchical levels, and variables may be defined at each level. Variables can be measured directly at their own natural level, e.g., at the school level one may measure school size and denomination, and at the children level, one may measure intelligence and school success (Field, 2009; Greenland, 2000; Hox, 2010).

Common applications are individuals within groups, repeated measures within individuals, longitudinal modelling, growth curve research (where a series of several distinct observations are viewed as nested within individuals), meta-analysis (where the subjects are nested within different studies) and cluster randomized trials.

The multilevel regression model is a direct extension of single-level multiple regression and multilevel structural equation models, which includes multilevel path and factor analysis. Examples include persons nested within geographical areas or institutions (e.g. schools or employers), and repeated observations over time on individuals (Hox, 2010; 2013).

The organisation of such data in hierarchies is not by chance and must not be neglected. When individuals form groups or clusters, it might be expected that two randomly selected individuals from the same group will tend to be more alike than two individuals selected from different groups (e.g., similarly high capable students grouped in highly selective schools (Goldstein, 2011)).

The premise is that individuals interact with the social contexts they are inserted in, under influence of the social groups or contexts to which they belong, which are, in turn, modulated by the individuals who make up that group.

In animal and human studies of inheritance, for instance, there is a natural hierarchy where offspring are grouped within families. Descendants from the same parents tend to be more similar in their physical and mental characteristics than individuals chosen at random from the population at large. Nevertheless, groups may arise for reasons less strongly associated with the characteristics of individuals, such as allocation of children in schools (Goldstein, 2011; Hox, 2010).

The moment groupings are set, even if their setting is effectively random, they will tend to become differentiated, and this differentiation causes that group and its members to both influence and be influenced by the group membership. Neglecting this relationship risks overlooking the importance of group effects, rendering invalid many of the traditional statistical analysis techniques used for studying data relationships (Goldstein, 2011).

The sampling procedure often occurs in two stages: first, a sample of companies is taken, and next a sample of workers within each company is taken. In real research, though, the researcher may have a convenience sample at either level, or may decide not to sample workers but to study all available workers in the sample of companies (Hox, 2010).

Taking the most referred example in literature – children learning – and since the lowest level (level 1) is usually defined by the individuals, in a two-level structure where the level 2 units are the schools, the children may be the level 1 units clustered within schools. Children learn in classes and characteristics of their class (e.g., teacher features and ability of other children in the class), most likely affect the children's educational attainment. Because of these (class) effects, test scores for children in the same class are expected to be more similar than scores for children from different classes (Goldstein, 2011; Hox, 2010).

When these dependencies are expected to occur, there is a need to analyse data with a hierarchical structure through multilevel models, for an analysis that overlooks the hierarchical structure is an analysis that treats each school completely separately by fitting a different regression model within each one. This approach is appropriate if the focus is in making inferences about those schools only. However, if schools are seen as a (random) sample from a population of schools and there is an intention to infer about the variation between schools in general, then a full multilevel approach is necessary (Goldstein, 2011).

Multilevel analysis of individuals within groups does not assume that the group sizes are equal and multilevel analysis of repeated measures within individuals does not assume that all individuals have the same number of measures (Hox, 2013).

Multilevel regression models are essentially a multilevel version of the familiar multiple regression model and the multiple regression model has been proved to be very versatile (Cohen and Cohen, 1983; Pedhazur, 1997).

Through the dummy coding of categorical variables, it can be used for analysis of variance (ANOVA)-type of models as well as the more usual multiple regression models. Since the multilevel regression model is an extension of the classical multiple regression model, it also contributes to addressing a wide range of research problems (Hox, 2010).

Like in logistic regression, the test of the overall fit of a multilevel model is assessed resorting to a chi-square likelihood ratio test and the SPSS software reports the - 2 Log Likelihood. The smaller this value, the better (Field, 2009).

SPSS provides four adjusted versions of the Log Likelihood value. All can be interpreted as the Log Likelihood. None of them are intrinsically interpretable. Still, they are all useful as a tool for comparing the models. The value of Akaike's Information Criterion (AIC), Hurvich and Tsai's Criterion (AICC), Schwarz's Bayesian Criterion (BIC) and Bozdogan's Criterion (CAIC) can all be compared to their equivalent values in other models. Better fitting models present smaller values (Field, 2009).

Building the multilevel model should start with a basic model in which all parameters are fixed, introducing after the random coefficients as appropriate and exploring confounding variables (Raudenbush & Bryk, 2002).

By doing this, one is able to compare the fit of the model as one makes parameters random, or as new variables are added. The comparison of models is accomplished by subtracting the Log Likelihood value of the new model from the old model Log Likelihood value (Field, 2009).

Even though multilevel analysis was originally intended for continuous normally distributed data, there are recent extensions to non-normal data (Hox, 2013).

One of the major advantages of the multilevel approach is overcoming the problem of always having to assume, when analysis of covariance is used, that the relationship between the covariate and the outcome is the same across the different groups that make up the predictor variable. In multilevel models this variability in regression slopes can be explicitly modelled (Field, 2009).

When using independent ANOVA one has to assume that the different cases of data are independent. Now, multilevel models are specifically designed to allow modelling these relationships between cases. Multilevel models expect missing data. So, one way of dealing with some type of ANOVA or regression with missing data is resorting to multilevel modelling (Field, 2009).

An analysis that explicitly models the manner in which workers are grouped within companies has several advantages:

- it provides data analysts statistically efficient estimates of regression coefficients;
- the use of clustering information provides correct standard errors, confidence intervals and significance tests, which are generally more conservative than the traditional ones obtained by overlooking the presence of clustering;
- by permitting the use of covariates measured at any of the levels of a hierarchy, it allows the researchers to explore the extent to which companies differ for different workers, and whether some factors are better at explaining the variation for the former workers than for the latter (Goldstein, 2011).

Most limitations of multilevel modelling, however, are in fact limitations of all modelling methods, which compounds to the reason why many authors claim generality and superiority of multilevel modelling to established methods (Greenland, 2000).

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Part II

Developed Work

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Chapter 3. Research Approach

For years, health and safety practitioners and researchers have debated the paradigm of the use of HPDs. Several scientific approaches have been resorted to in several occupational settings. The huge amount of publications devoted to occupational noise mitigation mirrors the relevancy of this issue, but the decades of research also reveal that this subject not only evolves through time, it is far from being completely understood. This section aims at gathering the information from the previous chapters and integrating it in this thesis framework. The balance between what has been proposed and the actual pathway taken to overcome the constraints faced during the development of the thesis is also presented.

3.1 Research question

The main research question of this work is: "What is the equation that delivers the uncertainty related to the personal exposure to occupational noise, to be resorted to whether the strategy used to measure the workers' exposure and the type of HPD worn?".

Other research questions to be answered first are:

1. "Which are the factors that influence the time of HPDs' use?" (causal type of question) followed by;
2. "What is the equation that relates the percentage of time of use of HPDs (dependent variable, *DV*) and the factors that influence their use (independent variables)?" (relational type of question).

3.2 Conceptualisation

At this stage, the balance between what you could theoretically be done and what was feasible to do, given the necessary equipment, available time, and intervening agents and actors of this research, was made.

Supported in the HPM, the conceptualization of the research model is based on the factors that influence the use of HPDs. As can be seen in Figure 2, it is assumed that a number of modifying factors will modulate the cognitive-perceptual factors of the worker, thus influencing the use of HPDs. Each of these factors is patent in the questionnaire the workers have answered in the form of question(s), bringing together all the identified predictors.

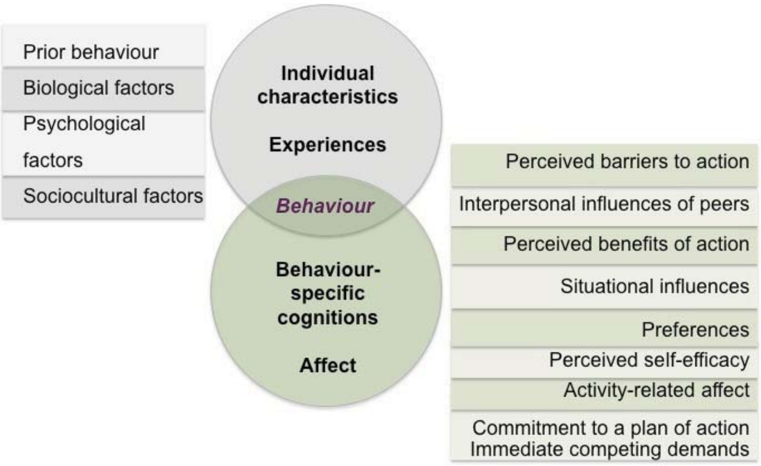

Figure 2. Conceptualization of the model of research (adapted from Lusk, Ronis and Hogan, 1997; and Pender et al., 2011).

One way of building a robust model that expresses the use of HPDs as a function of the predictors considered by the several researchers that dedicated their research to this subject, is to collect as much as possible studies that focus on this matter, so as to obtain a sufficient number of data that allows building a feasible model.

The bulk of data needed to entail the construction of that model based on the results presented by other researchers alone is massive.

The greatest part of the papers subject to this topic returned results which data were considered of low quality to follow this path (Costa & Arezes, 2012, 2013), due to not having all the three characteristics necessary for them to be the basis of a study where the most reliable results possible and the more stringent data available are of paramount importance.

The triad of features patent in a research that ensures that the data are quality data are:

- the methodology of assessment;
- the “raw” results obtained (previous to statistical analysis and corrections);
- and the corresponding measurement uncertainty (Costa & Arezes, 2012).

Since the purpose of these data is being the foundations of a strategy for dealing with an associated uncertainty, there is no interest in adding more sources of uncertainty.

Not enough reliable papers with traceability of data were available and it was not possible to assemble the necessary data volume from the existing literature to follow this strategy. The research approach started, hence, by building from the root the tools to gather the necessary data for construction of the model, supported by the existent literature.

A questionnaire was built and validated. The validation of the questionnaire was accomplished using workers from a company that did not enter the implementation phase of the final questionnaire.

The validated questionnaire was, afterwards, completed by workers whose use of HPDs is compulsory, spread by four different companies, during the visits to the companies’ stage. RRT was discarded at this stage, as were the comparison between the measurement strategies detailed in ISO 9612:2009 and the modelling of the use of HPDs according to the type of HPDs worn. Motivations are developed further on.

The research approach was grounded on other available strategies to meet the objectives of this thesis, answering the proposed research question.

Because questionnaires followed by structured observation to analyse statistically (quantitatively) the data obtained are going to be used, research choice is multi-method quantitative study (Saunders et al., 2007).

Advantages of quantitative research include: testing hypothesis before data are collected; generalizing research findings when the data are based on random samples of sufficient size; providing precise, quantitative, numerical data; obtaining data that permit quantitative predictions; allowing the construction of a situation that eliminates the confounding influence of many variables, permitting the construction of more credible cause-effect relationships, all very interesting in the present work and harmonised with this work's objectives.

Hypothesis that the percentage of time of HPDs' use is a function of several factors will be tested, hence following a deductive reasoning, using multilevel (hierarchical) analysis.

Figure 3 summarizes the research methodology approach of this work, the research "onion".

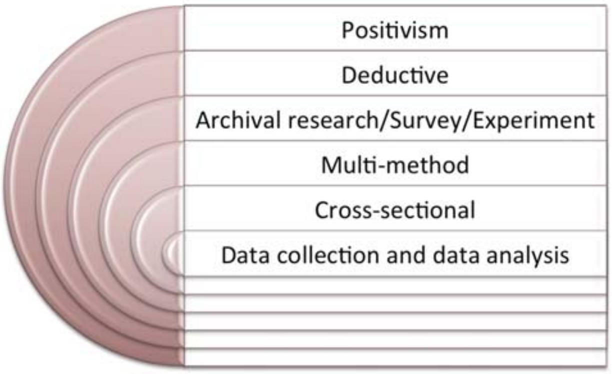

Figure 3. The research "onion".

3.3 Research goals

The main objective of this thesis is the study of the impact on the calculation of the uncertainty related to personal exposure to occupational noise, resulting from the use of hearing protection equipment and the strategy to measure personal occupational exposure to noise.

For this primary objective, several other more specific objectives will be met, namely:

- Conduction of a survey using a questionnaire addressed to workers;

- Assessment of workers' behaviour towards the use of HPD;
- Construction of a mathematical model that explains the percentage time of use as a function of the HPDs' use predictors;
- Proposal of a methodology for estimating the uncertainty related to personal exposure to occupational noise based on HPDs' use and the strategy used for the measurement of personal exposure to occupational noise, in order to overcome one of the detected shortcomings of the standard.

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Chapter 4. Methodology

Literature review provided an array of methods and strategies to chose from in order to pursue the attainment of the aims of this thesis. Some of the initially considered (potential) strategies were discarded by virtue of the type of data obtained, feasibility of implementation of the strategies applied in the field and other constraints. All methods and strategies proven to fit this research approach are detailed in this Chapter.

4.1 Research methodology

In order to obtain a model that translates the uncertainty related to the personal effective exposure to occupational noise, through an equation that represents the time of use of HPDs (in percentage) as a function of *n* predictors, the methodology of the research was carefully planned, in order to avoid missing some crucial steps, which might have led to an unsound research.

Respect for the methodology procedures structure was crucial in attaining the needed reliable elements for the subsequential tasks. Therefore, and based on Quivy and Campenhoudt (2008), the research was organized in 8 sequential steps (Figure 4).

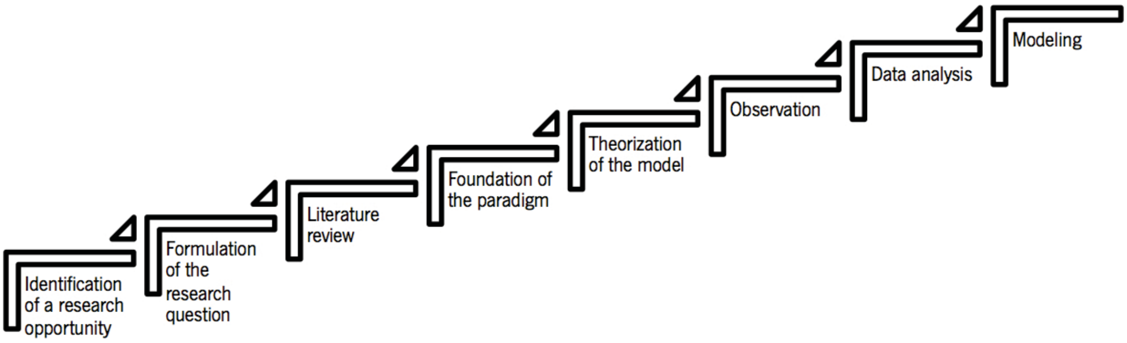

Figure 4. Research methodology steps.

These steps, in turn, consisted of task(s). The tasks (and subtasks) performed during the execution of this thesis were:

1. Literature review
2. Identification and collection of predictors of the use of HPDs and factors that antagonize the use of HPDs
3. Establishment of contacts with companies
4. Discrimination of material needed for subsequent tasks
    4.1. Selection of industries where the use of HPDs is compulsory
    4.2. Visiting the companies
    4.3. Assessment of the workers' exposure to occupational noise
    4.4. Gathering of the data obtained
    4.5. Definition of the study sample
    4.6. Population's characterisation
5. Data acquisition
    5.1. Questionnaire definition

   - 5.1.1. Investigation of questionnaire construction methodologies
   - 5.1.2. Construction of the questionnaires
   - 5.1.3. Validation of the questionnaires
   - 5.1.4. Distribution of questionnaires to workers observed

6. Variables description and statistical procedures
7. Identification of the predictors of the time of use of HPDs
8. Development of a methodology to assess the relationship between predictors for the use of HPDs and percentage of time worn (utilization profile of the HPDs)
9. Assessment of the contribution of the use of HPDs to the uncertainty associated to the individual exposure to occupational noise
10. Assessment of uncertainty related to the effective personal exposure to occupational noise.

This thesis entailed an extensive literature review, from which the reported HPDs' use predictors were taken.

Search focused mainly in attitudes towards the use of HPDs, but a smaller part of the search was dedicated to study behaviour in general and attitudes regarding consumers' choice in order to disclose other possible explicators of the use of HPDs, emerging, as hypothesis, the hedonic (non-task-related) quality aspects of the HPDs (Hassenzahl, 2001).

Also, from literature review, information was gathered and a subsequential analysis was made regarding all relevant documents to the subject of this thesis, assembling all methodologies detailed by other researchers and identifying their gaps, paths that unsuccessful and, therefore, unworthy of consideration, and improvement opportunities.

Some methodologies were discarded and the remaining were evaluated in terms of applicability and relevant contributions to this investigation.

The several available methodologies for analysing the data were retrieved and compared in terms of advantages, fitness of use and feasibility.

From Chapter 2 - Literature review, there are 16 theoretical predictors of the use of HPDs (shown in Figure 5).

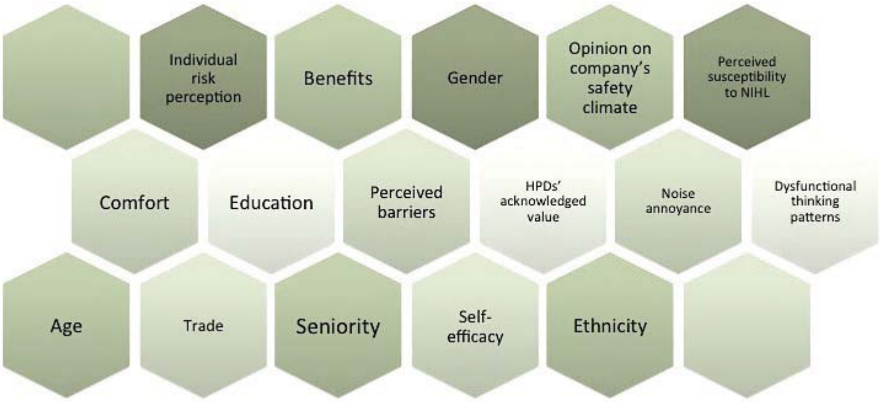

Figure 5. Theoretical predictors of the use of HPDs.

Over five hundred subjects from eight companies were targeted to participate in the study through convenience sampling. Four companies participated in this study.

Sites were chosen based on existence of workers whose use of HPDs was compulsory, proximity to the research centre facilities and openness to cooperate with the University. Two of the companies are medium size companies, one is a small company and one is a multinational company.

Research staff provided an overview of the study procedures and protocols at scheduled meetings. All participants enrolled in a voluntary and informed-basis.

Visits were conducted in the companies with other two fellow researchers. At the meetings, the methodology of the research was clarified and usually, it was then when limitations to what could be done were imposed by the companies. The researchers were not allowed to film in any of the companies' precincts, so all observations would have to be recorded by hand, on data sheets.

Noise exposure measurements were carried out in several workstations. These measurements, although having involved the expenditure of several hours both in its preparation (for all working tools were properly prepared and validated) and in their implementation, were discarded due to lack of conditions for holding stringent, reliable results. It so happened that, although having a cooperation agreement with the companies concerned been entered, it was not fully honoured by the other parties, either because workers did not comply whenever their cooperation was necessary, either because the production directors and supervisors did not allow the abidance of researchers enough time on the premises for measurements to be done according to standard 9612. Thus, in order to circumvent this problem, only workers whose use of HPDs was mandatory, were selected in companies that later collaborated on the study.

Data sheets were, then, created to record the use of HPDs. The use of HPDs was recorded from every shift of each company by two of the researchers (two independent samples) with, at least, 3 repetitions, compounding for thousands of records. The sampling of the workers' use of HPDs was done randomly taking care, however, to cover all shifts. Workers were taken by surprise with the presence of the researchers, who claimed to merely be interested in measuring the noise emitted by the machines or even to perform an assessment of the environment conditions.

So that the workers' behaviour were not immediately conditioned by the presence of researchers, these were accompanied by sound level meters and environmental meter equipment and even simulated the execution measurements of noise emissions from machinery and of thermal environment.

The researcher would record a circle (O) in the record sheet if the worker was wearing his HPDs, and a cross (X) if the worker was not wearing his HPDs.

Even though the time spent on one of the companies alone was about 17 h, per worker, per day, during three different non-consecutive days, those records were later sidelined because of concerns related to the types of results obtained, that girdled the usage rates to 0%, 33%, 66% and 100%.

However, this was not a fruitless effort, for the observation of workers in their real-work context and relationships and exchange of ideas that were developed with shift responsible and production directors gave rise to the speculation that the use of the devices depends also on the work paradigm, besides the many factors that have been pointed out as being responsible for the use/non-use of HPDs by workers. In addition, the researchers agreed that it contributed to greater confidence of the workers at the time responding to the questionnaires, having some even confided in relation to their peer relationships, hierarchy and even their view on their importance in the eyes the company and opinion on HPDs available to them.

All these informations were valued and integrated into the questionnaire.

HPD use data were collected from each subject through a survey designed to collect current HPD use and possible predictors of the use of HPDs, pooling the several studies and meanwhile obtained information.

The questionnaire final form was optimized following Hill and Hill (2008) organization and procedures (see annex 1). Attending on the book premises, the questionnaire was divided in four main sections:

1 – Demographic information and individual characteristics;

2 – Self-assessment of the use of HPDs;

3 – Behaviour-specific cognitions items;

4 – Open question and observations.

The building of the questionnaire was made so that it contained the three characteristics that make up for a good questionnaire:

- Discrimination: which is achieved when people with different scores on a questionnaire differ in the construct of interest.
- Validity: when items designed to measure something do it effectively. Validity includes content validity – representativity of the questions (sampling adequacy of items, ensuring the questions cover the full range of the construct); criterion validity – when the questionnaire measures what it is supposed to measure; and factorial validity: inferred when items cluster into meaningful groups – is assessed through factor analysis (a factor is composed of items that correlate highly with it).
- Reliability: when the same questionnaire provides the same results given the same conditions. Before being reliable, a questionnaire must first be valid. Cronbach's alpha is the most common measure of scale reliability. As a rough guide, an acceptable value for Cronbach's alpha is 0.8, while values substantially smaller indicate an unreliable scale (Field, 2009).

Based on the study by Costa and Arezes (2013), the questionnaire was built compiling items and constructs to render the following information:

- age,
- gender,
- trade,

- seniority at the company,
- level of education,
- self-assessed percentage of HPD use (%HPD Use),
- health importance to self,
- individual risk perception,
- subjective opinion on the company's safety climate,
- HPDs' comfort and noise annoyance,
- health status (self-assessed hearing status and tinnitus),
- perceived barriers to the use of HPDs,
- self-efficacy in the use of HPDs,
- acknowledged value of the use of HPDs and deriving benefits,
- susceptibility to hearing loss,
- hearing-conservation related knowledge,
- workplace environment evaluation,
- relations with peers and hierarchies,
- and HPDs' hedonic qualities.

The self-assessed percentage of HPD use on time of use was made through a visual analogue scale (VAS) adapted from the study by Arezes and Miguel (2012). According to Lusk, Hong, Ronis, Eakin, Kerr and Early (1999) and Seixas, Neitzel, Stover, Sheppard, Daniell, Edelson, and Meischke (2010), self-assessed use of HPDs is a reliable measure of the use of HPDs.

Survey items regarding acknowledged value and attitudes towards HPDs were based on a revised HPM (Pender, Murdaugh, & Parsons, 2011).

In addition to these items, record was taken regarding the working situation of each worker, whether temporary or effective and, by suggestion of some of the production engineers, the working shift was also registered.

At this point, the fuzzy approach was discarded. Since the focus of this thesis is on uncertainty, the way that would introduce more uncertainty, more specifically in the fuzzification and defuzzification processes, was deprecated. The pathway with more scientific support was, hence, chosen, the one supported by the several existing scientific studies previously presented, using methodologies already tested and proven suitable for this study.

Response to each item were on a 5-point Likert scale, except for the evaluation of noise at the workplace, that was in a 3-point scale (“No noise”, “Noisy”, “Very Noisy”). Items were analysed in their native scales. “Don’t know” and blank responses were coded missing.

The scoring of eleven negatively worded construct items was reversed in order to match the scale of other items.

The cohesiveness of the items in each construct was tested using Cronbach’s α. Construct items with low cohesiveness ($\alpha<0.6$) were analysed separately. In those cases, the item with the greatest association with %HPD Use from each non-cohesive construct was used to represent that construct in multilevel modelling.

Given that subjects were analysed within companies, the possibility emerged that answers from subjects working in the same company would be more alike than from subjects from different companies.

Evidence was found of Company effects on %HPD Use, and so the multilevel analysis was reverted to.

Therefore, it is an assumption in this study, that the observations are not independent, but clustered by one grouping variable (Company), i.e., as a step-wise procedure designed to explore and analyse data from complex structure populations, multilevel analysis was performed allowing for Company effects, in order to correctly model correlated error.

Hence, the modelling of the time of HPDs use (in percentage) consisted of an iterative process, in which assumptions are made regarding wearers of HPDs, by which the determinants of the use of HPDs would compound for the model that explains the use of HPDs.

The data structure in the population in multilevel research is hierarchical, and the sample data are a sample from this hierarchical population. In this research, the population consists of companies and workers within these companies.

When understood as a hierarchical structure, units identified as the lowest level of the structure are atomic units.

These are commonly individuals (in this case, blue-collar workers). Workers are then grouped into *higher-level* units, in this case, companies (Figure 6). By convention it is said that workers are at level 1 and companies are at level 2 of the structure. This is, therefore, a study that is based in a level-two multilevel hierarchical structure, in which workers are nested within companies.

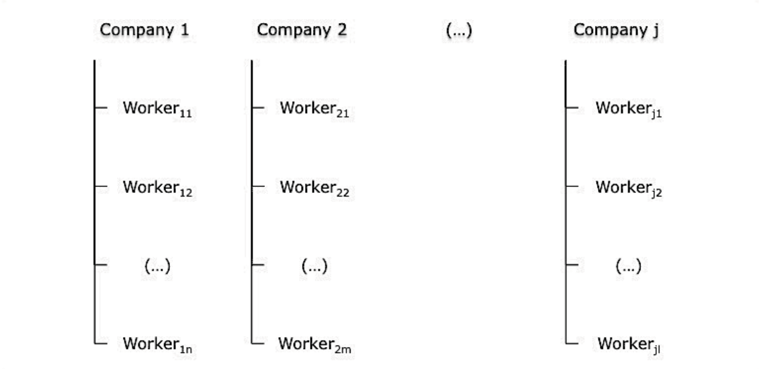

Figure 6. Unit diagram of a two-level nested structure: workers within companies.

The two-level regression model is given by Equation 1.

$$Y_{ik} = \gamma_{00} + \gamma_{p0}X_{pik} + \gamma_{0q}W_{qk} + \gamma_{pq}W_{qk}X_{pik} + u_{pk}X_{pik} + u_{0k} + e_{ik}\ (1) \qquad \text{Eq. (1)}$$

$where\ \gamma_{00} + u_{0k} = \beta_{0k}$, which represents the mean Y for kth company;

γ_{00} represents the intercept of the regression and;

u_{0k} and e_{ik} are the level 1 and level 2 residuals, respectively.

In this case, the %HPD Use for worker *i* from the kth company (Y_{ik}) is interpreted as resulting for the %HPD Use of the company the subject is nested in and the residuals (e_{ik}). It is assumed that the errors are normally distributed, with a mean of 0 and variance σ_e^2 constant through companies.

In the Company level (level 2), the mean percentage for each company (β_{ok}) is interpreted as a combination between the average %HPD Use in the companies' population (γ_{00}) and the random variation (u_{0k}) around the average. $\beta_{0k} = \gamma_{00} + u_{ok}$

It is assumed that the random component u_{0k} has a mean of zero and variance σ_{u0}^2. The combined model (Equation 2) is obtained:

$$Y_{ik} = \gamma_{00} + u_{0k} + e_{ik} \qquad \text{Eq. (2)}$$

which corresponds to the ANOVA model with a random effects factor.

For construction of the model, SPSS 22.0 (Statistical Package for the Social Sciences) software was resorted to.

The computation of the uncertainty associated to the use of HPDs was based on Equation 3 (from Arezes & Miguel, 2002 and Barbara, Soudry, & Pringalle, 1995) where the HPD's real attenuation (R) is a function of percentage of time use of HPD (P) and N, the catalogued (nominal) attenuation of the HPD.

$$R = 10log\frac{100}{100 - P\left(1 - 10^{-\frac{N}{10}}\right)} \quad dB \qquad \text{Eq. (3)}$$

Uncertainty is given by the error propagation on the effective individual exposure to occupational noise (L_{Aeq}) computation (Equation 4), where the "real" attenuation of the HPD (R) is subtracted to the results obtained through noise exposure measurements, the daily exposure level ($L_{EX,8h}$).

$$L_{Aeq,effect.} = L_{EX,8h} - R \quad dB \qquad \text{Eq. (4)}$$

For the sake of quality, results must always be presented as a triad, consisting of the assessment methodology, the "raw" results obtained (previous to statistical analysis and corrections) and the corresponding uncertainty (Costa and Arezes, 2012).

It is a strong belief that the hurdles and constraints encountered while pursuing the objectives of this work contributed to building a more efficient, clear and rigorous path, that led to an optimized result, with better usability, and flexibility in application.

4.2 References

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Chapter 5. Results and Discussion

This Chapter presents all relevant results. These results were achieved by implementing the strategies and methodologies detailed in Chapter 4. Because the final results were obtained through an iterative process, it only makes sense to discuss them while presenting them. Many of the results obtained by the application of methodologies which have proved fruitless, or whose results have not been good enough, are not included in this section, even though they were the natural steps to take towards the aimed ouctome and the important role they played in achieving the final, liable and rigorous results.

5.1 Descriptive statistics report

Researchers managed to collect questionnaires from three hundred and one respondents. Eighty-seven percent of the subjects were male, with an average and standard deviation age of (41 ± 12) years. The average seniority was (201 ± 10) months.

Figure 7 shows the mean age of workers by Company, where it seems that ages do not vary substantially between companies.

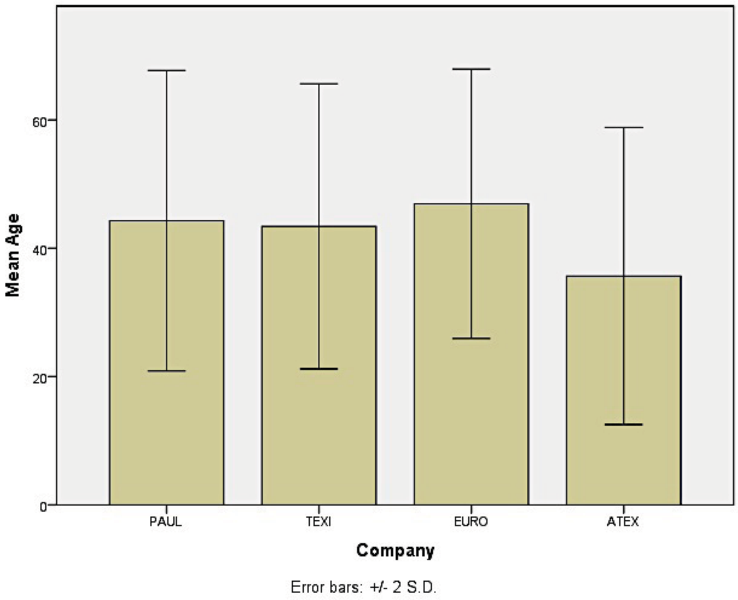

Figure 7. Mean age of workers by Company.

Figure 8 presents the mean percentage of HPD use regarding the workers' gender, by Company. The ATEX company shows the higher rates of use of HPDs, but influence of gender is unclear. It might be possible that gender is not a determining factor in the use of HPDs, but more information is necessary.

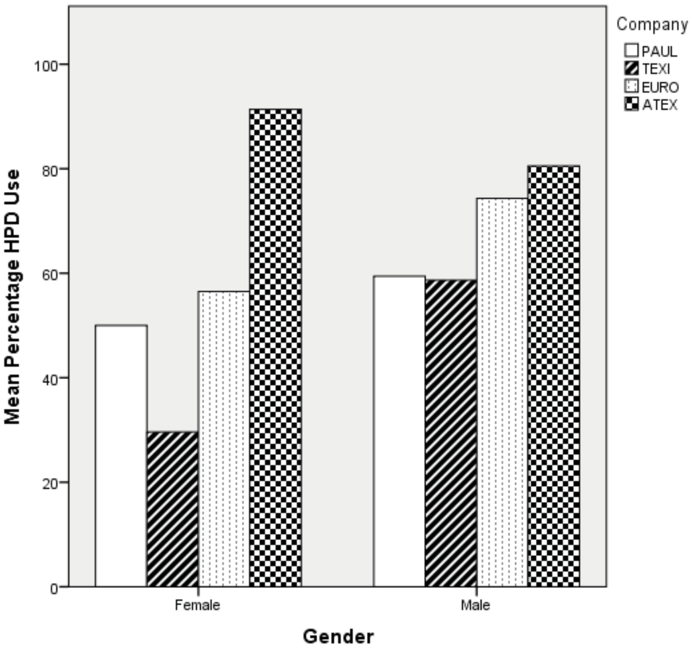

Figure 8. Mean percentage of HPD use regarding the workers' gender, by Company.

Figure 9 shows the mean percentage use of HPDs regarding the workers' gender and overlapping of 95% confidence intervals (CI) can be observed, pointing to no significant differences between genders in the use of HPDs. Accordingly, this result echoes results from previous research (Lusk, Ronis, & Baer, 1997).

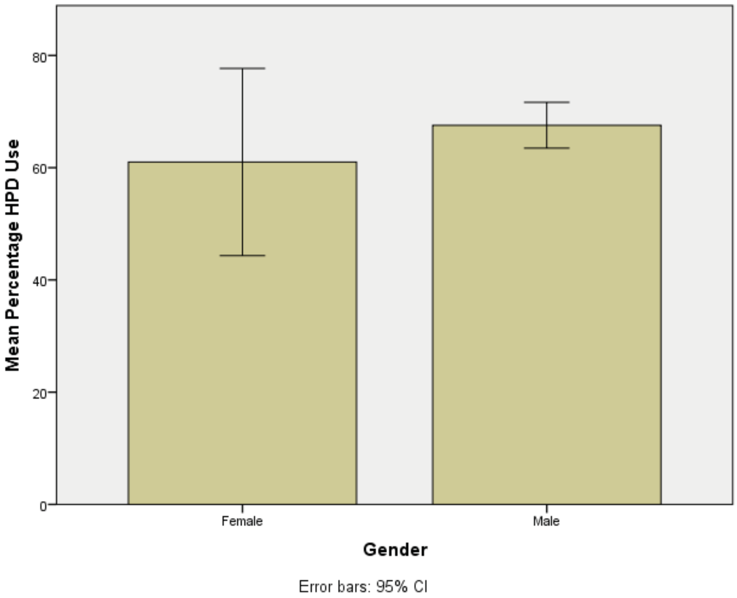

Figure 9. Mean percentage use of HPDs regarding the workers' gender with overlapping 95% CI.

Ninety-four percent of the subjects were contract workers. No significant differences in the HPD use rates appear to exist, either, regarding the type of contract workers celebrated with companies, for Figure 10 shows overlapping 95% CI for both types of contracts, against what has been hypothesised in the beginning of this study.

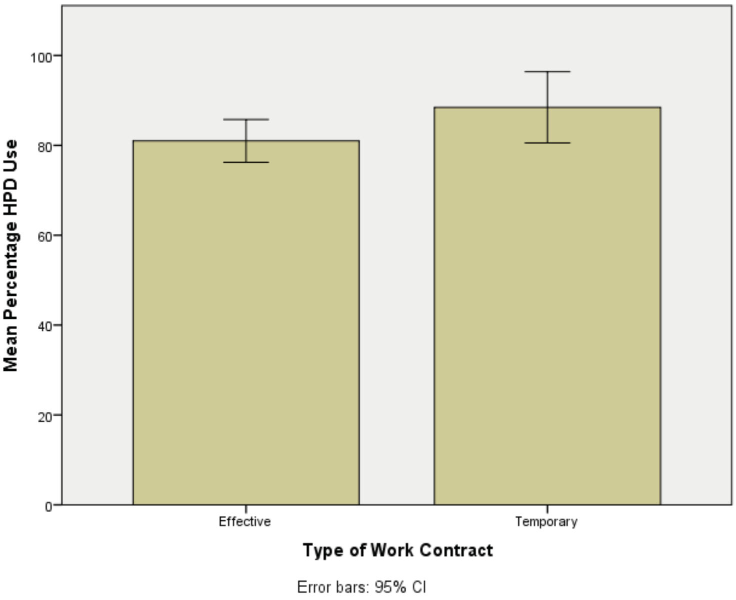

Figure 10. Mean percentage use of HPDs regarding the type of contract workers celebrated with companies with overlapping 95% CI.

Elementary School has been completed by twenty-four percent of subjects and twenty-three percent of subjects completed ninth grade, whereas twenty percent of subjects completed High School and only one percent were at least, undergraduate.

The answers of the respondents to the first item “In your job, how important are the aspects that can influence your health?” are summarised in Figure 11.

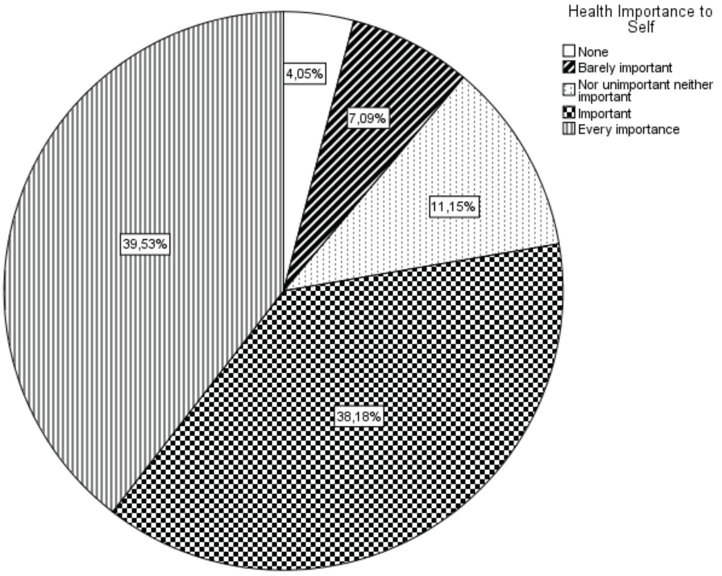

Figure 11. Summary of item "In your job, how important are the aspects that can influence your health?" answers.

Figure 11 shows that work-related aspects that may influence one's health were classified as, at least, important by seventy-seven percent of respondents.

Deafness prevention was declared to be important to over ninety-five percent of the subjects (Figure 12).

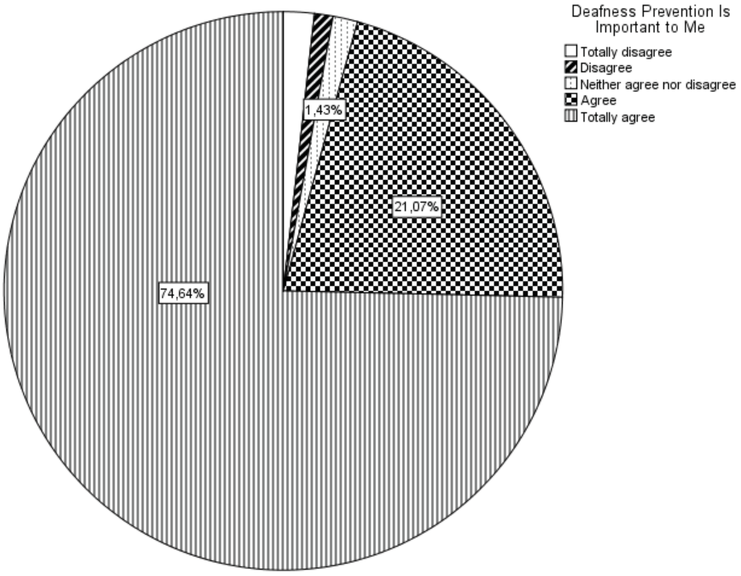

Figure 12. Summary of item "Deafness prevention is important to me." answers.

When asked whether they knew where their HPDs were, only eighty-seven percent of respondents declared to know where they were (Figure 13). Although it may strike as a high percentage, one must keep in mind that the use of HPDs was compulsory to all respondents.

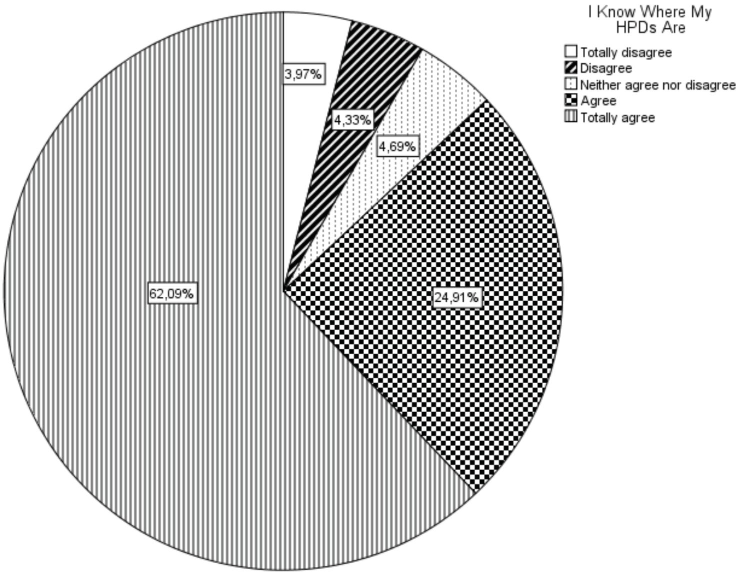

Figure 13. Summary of item “I know where my HPDs are.” answers.

Over seventy-nine percent workers declared being satisfied with their jobs, as can be observed in Figure 14.

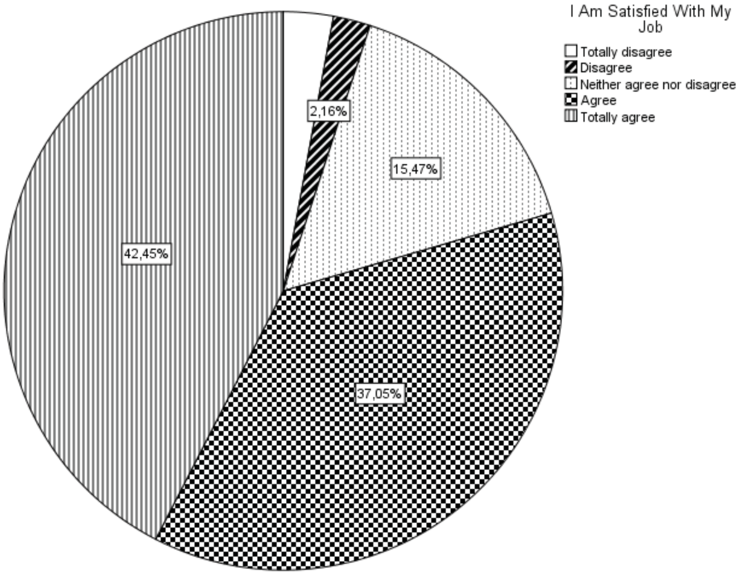

Figure 14. Summary of item “I am satisfied with my job.” answers.

The percentage of respondents that recognized having had training regarding HPDs were under forty (Figure 15).

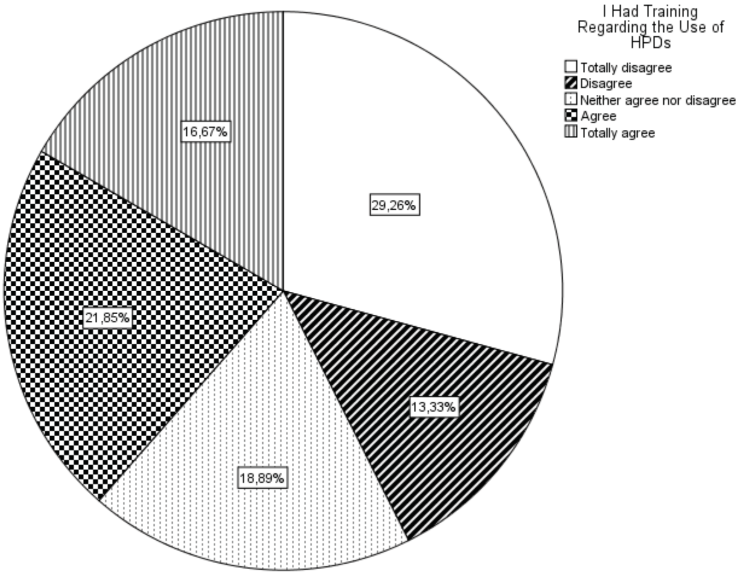

Figure 15. Summary of item “I had training regarding the use of my HPDs.” answers.

Over eighty-five percent of respondents declared their working site was, at least, “Noisy” (almost seventy percent classified their workplace as “Very Noisy”), as can be seen in Figure 16.

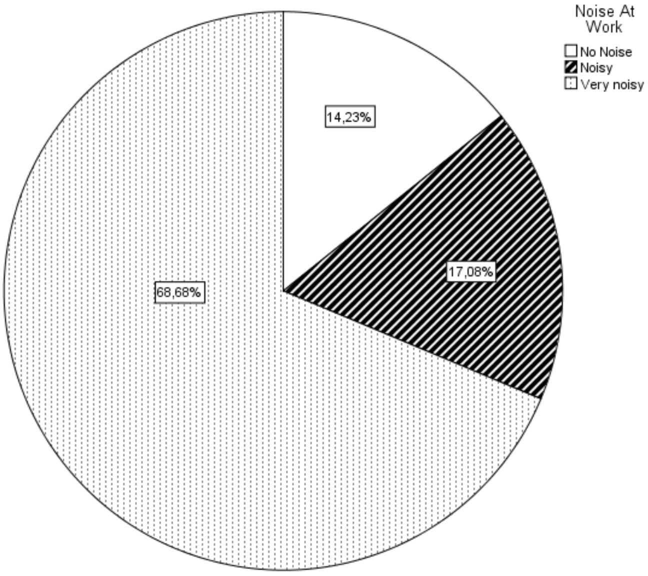

Figure 16. Summary of item “Noise at work.” answers.

Less than a quarter of the respondents declared they knew their last exposure to noise results Figure 17)

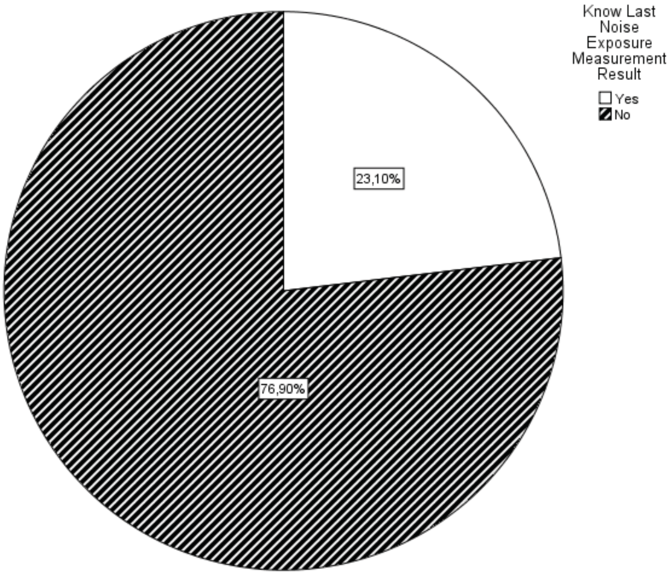

Figure 17. Summary of item “I know my last noise exposure measurement results.” answers.

Almost nineteen percent of respondents admitted to having hearing problems (Figure 18).

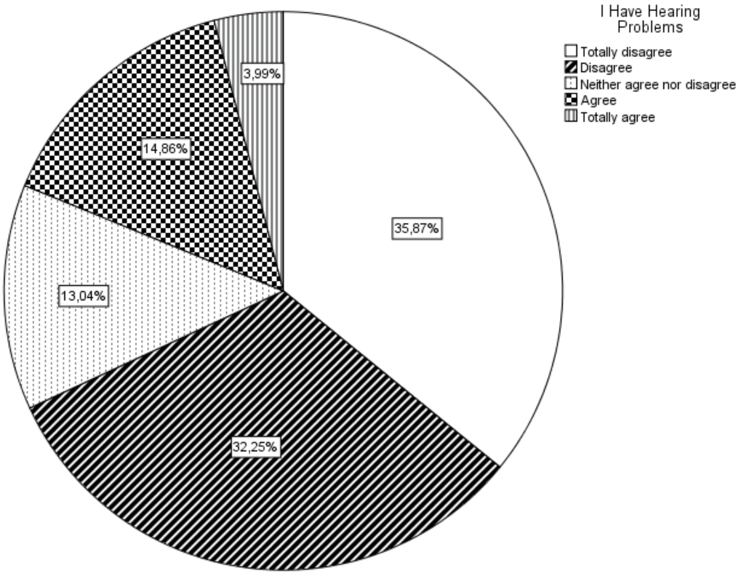

Figure 18. Summary of item “I have hearing problems.” answers.

Of the total respondents, almost thirty-nine percent reported having experienced tinnitus at least sometimes (Figure 19).

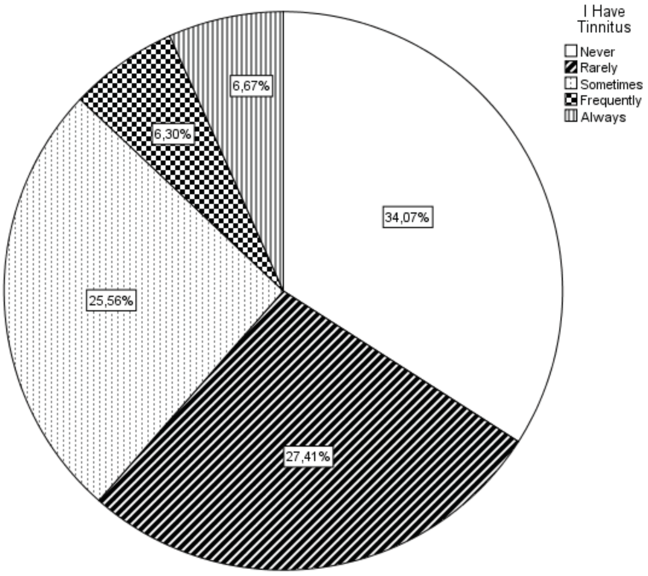

Figure 19. Summary of item “I have tinnitus.” answers.

About thirty percent of subjects admitted to, at least sometimes, relieving HPDs, moving them away from the ears, as can be observed in Figure 20.

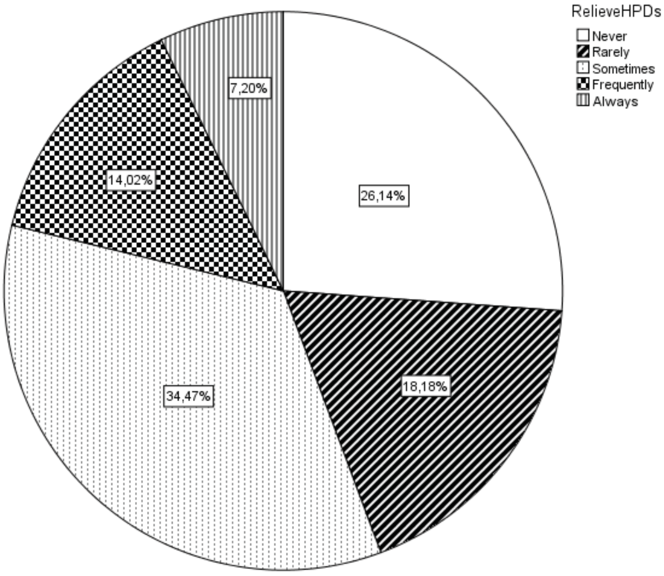

Figure 20. Summary of item “I relieve my HPDs, moving them away from my head.” answers.

Almost ninety percent of the respondents believed their HPDs were adequate (Figure 21).

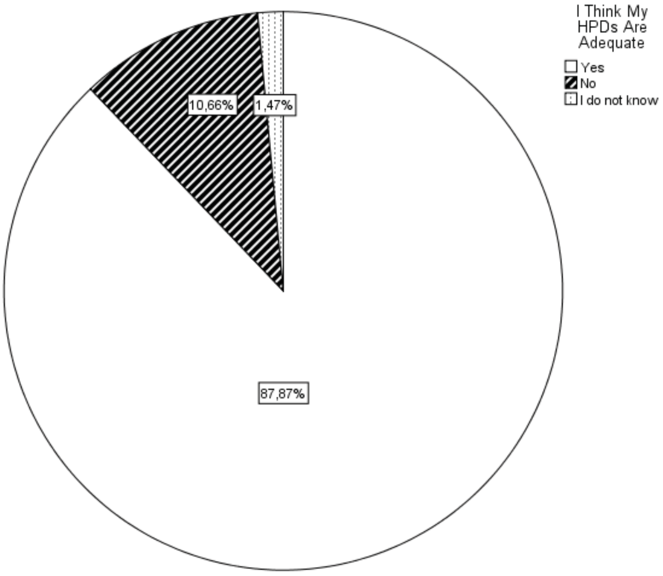

Figure 21. Summary of item "I think my HPDs are adequate." answers.

Over ninety percent of the respondents declared they knew when they had to wear HPDs (Figure 22).

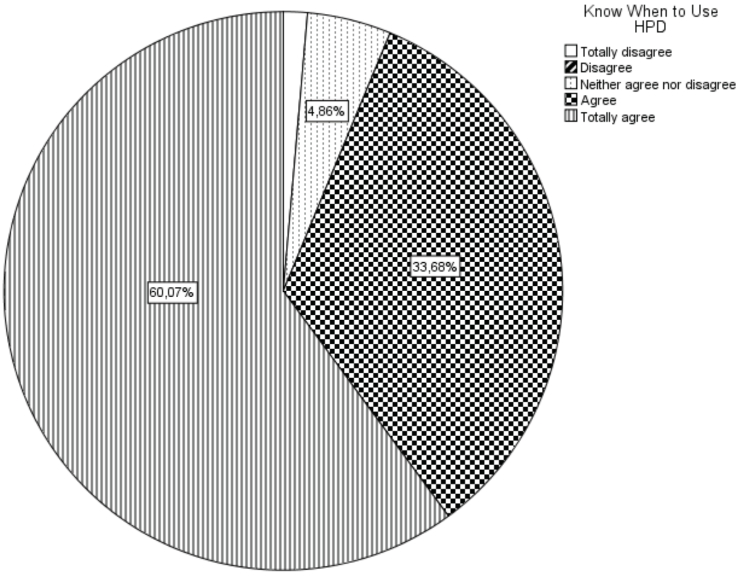

Figure 22. Summary of item "I know when to use my HPDs." answers.

The percentage of workers that declared knowing how to properly fit HPDs is very similar to the percentage of workers who declared knowing when to used them, as can be observed in Figure 23.

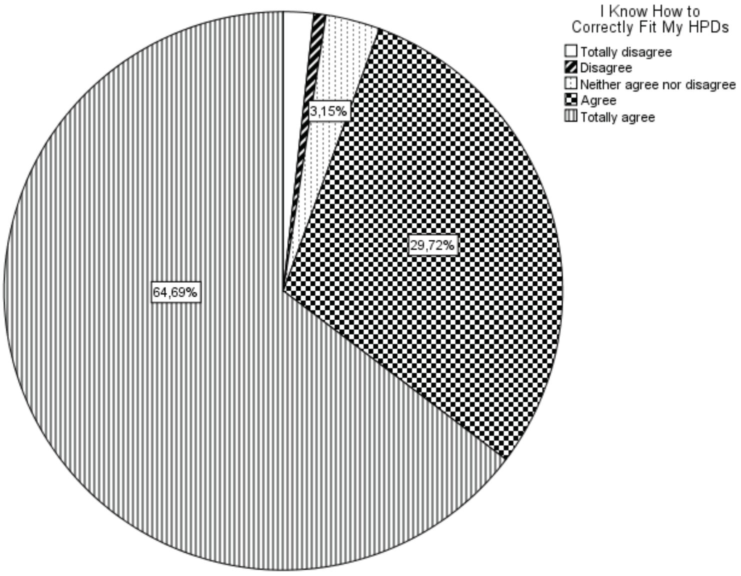

Figure 23. Summary of item “I know how to correctly fit my HPDs.” answers.

A little over thirty percent of the workers admitted to forgetting to use their HPDs, at least, sometimes (Figure 24).

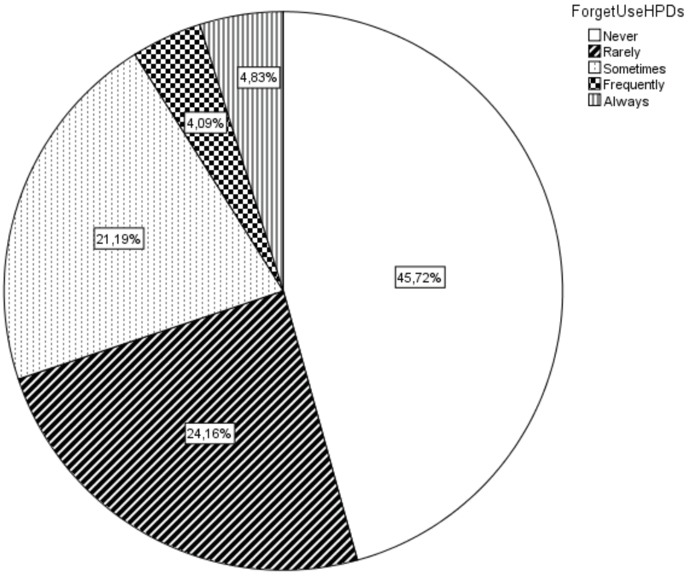

Figure 24. Summary of item “I Forget to wear my HPDs.” answers.

Apparently, the time required for using HPDs is not an issue for the workers, since the vast majority of them does not see in it a compromise of time (Figure 25).

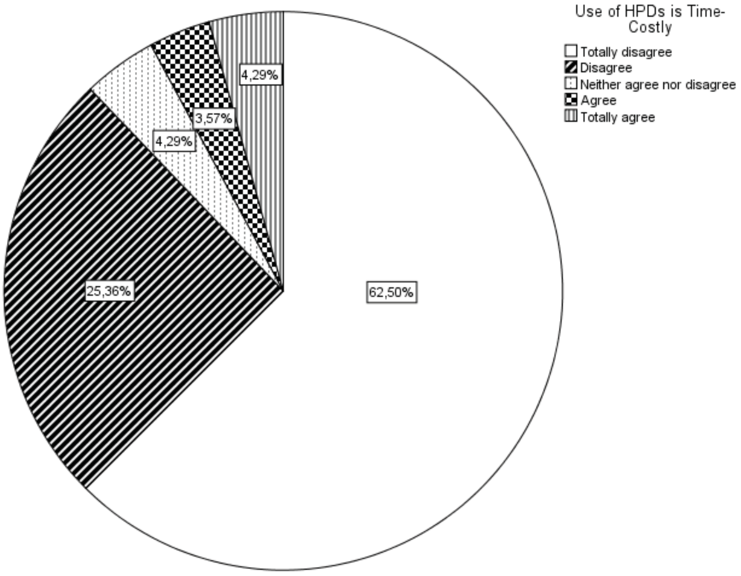

Figure 25. Summary of item “Using HPDs is time-costly.” answers.

Neither an issue seem to be any limitations imposed by the use of HPDs to the execution of their work. By looking at Figure 26, only about eight percent of respondents seem to feel that HPDs, in some way, limitate their work.

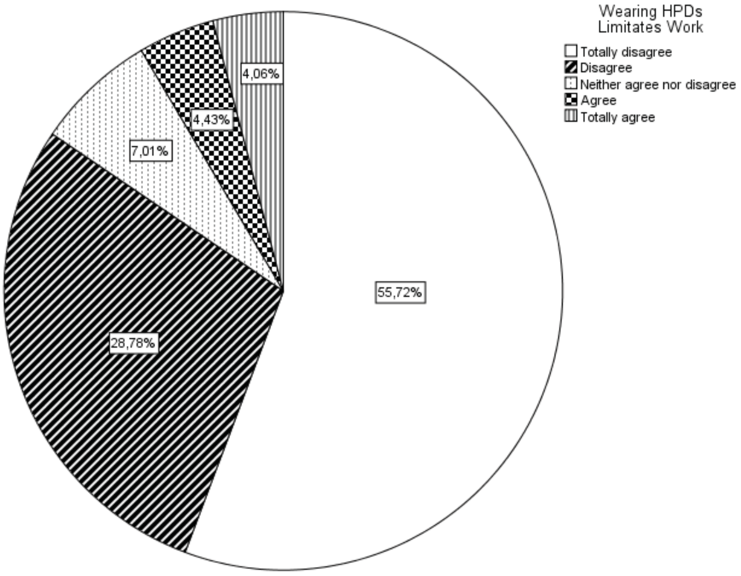

Figure 26. Summary of item “Wearing HPDs limitates my work.” answers.

Comfort, on the other hand, is a subject that already has some expressiveness within the respondents. Over twenty percent of the workers declared that HPDs are uncomfortable (Figure 27).

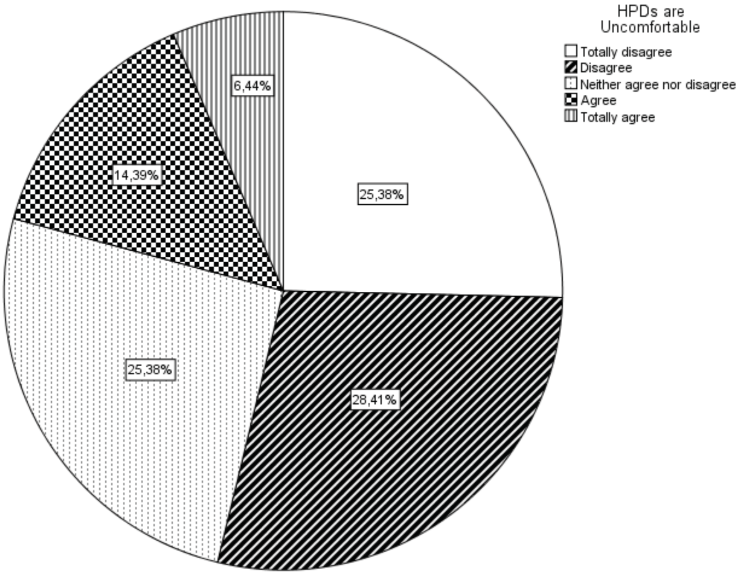

Figure 27. Summary of item “HPDs are uncomfortable.” answers.

The complex notion of comfort was tried to be unravelled through some more specific items that specifically affirmed the use of hearing protectors as a cause of:

- pain;
- heavy heat;
- sweating;
- feeling isolated;
- difficulty in hearing alarms;
- difficulty in hearing the machines;
- looking ridiculous and;
- being mocked.

Under thirteen percent of the respondents agreed that HPDs hurt (Figure 28).

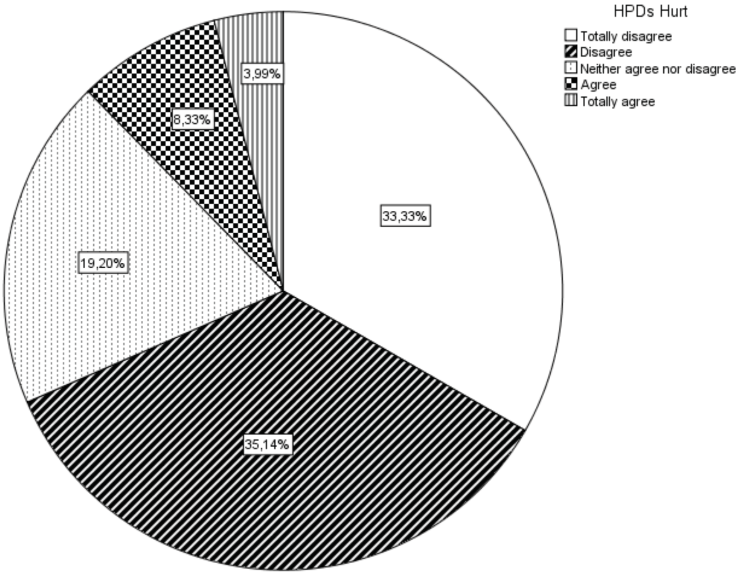

Figure 28. Summary of item “HPDs hurt.” answers.

Over twenty percent of respondents agreed that HPDs made them sweat (Figure 29).

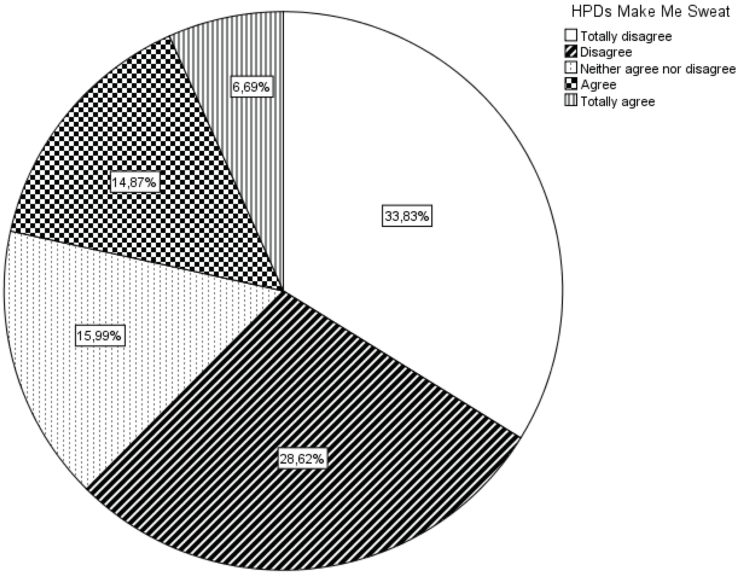

Figure 29. Summary of item “HPDs make me sweat.” answers.

About eighteen percent of the workers stated that wearing HPDs hindered hearing alarms (Figure 30).

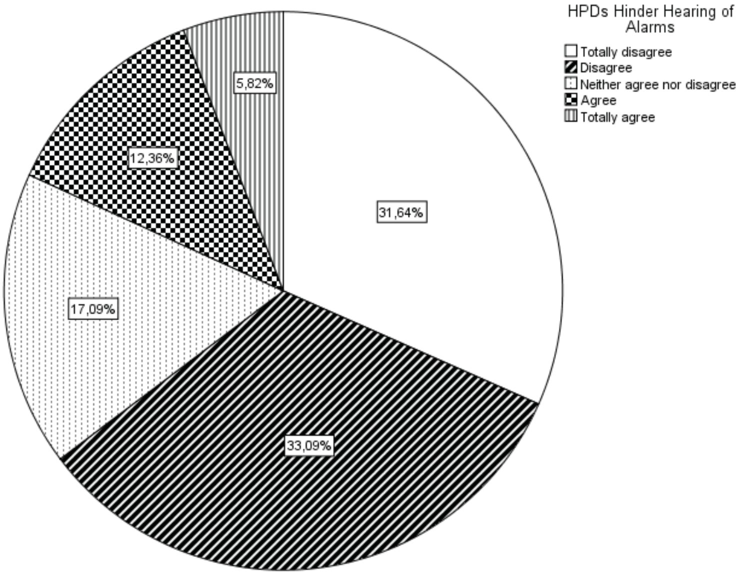

Figure 30. Summary of item "HPDs hinder hearing alarms." answers.

Figure 31 shows that, for over twenty percent of respondents, wearing HPDs makes listening to the machines, harder.

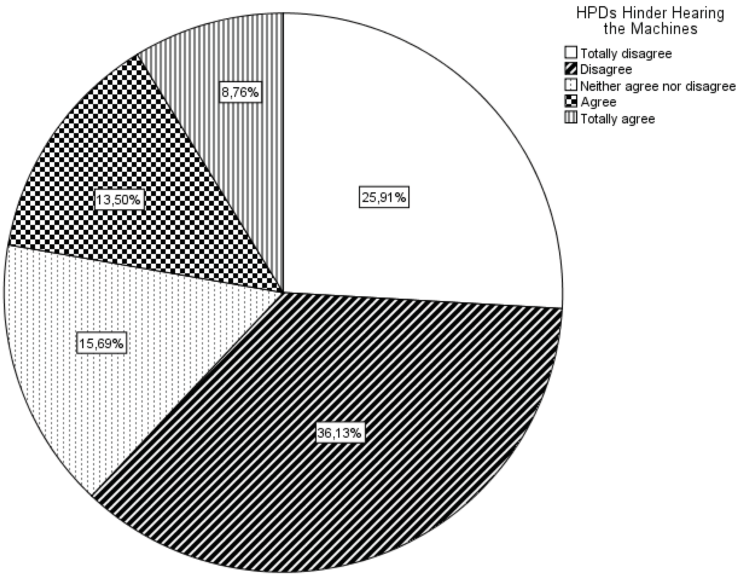

Figure 31. Summary of item "HPDs hinder hearing the machines." answers.

A little over eight percent of the respondents agreed that wearing HPDs made them feel ridiculous (Figure 32).

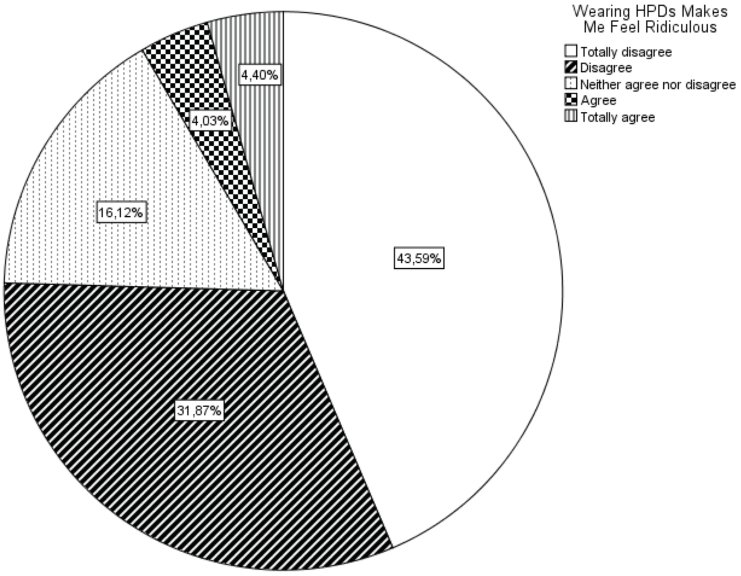

Figure 32. Summary of item “Wearing HPDs makes me feel ridiculous.” answers.

Under six percent of the workers declared to having been teased for wearing HPDs, as Figure 33 shows. Even though it is a relatively small percentage, it is still worrying that some workers feel derided by their peers in the discharge of rules that ensure their welfare and safety.

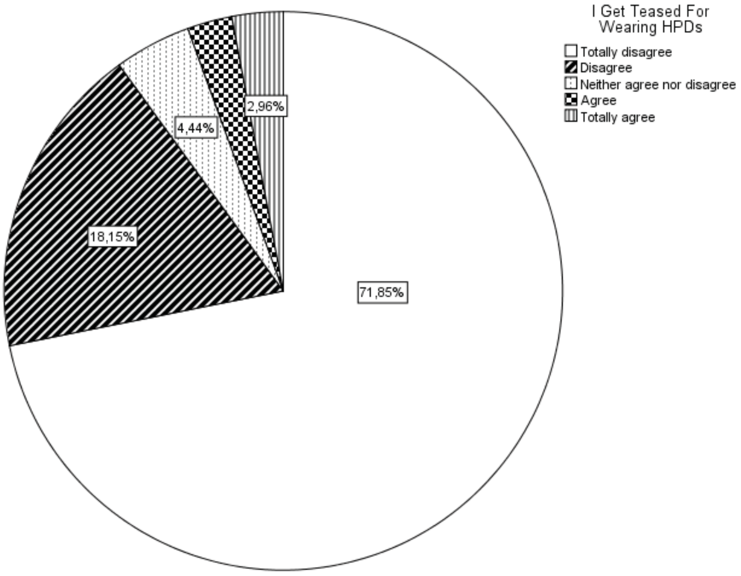

Figure 33. Summary of item “I get teased for wearing HPDs.” answers.

About thirty-two percent of the respondents declared HPDs made them feel, at least sometimes, isolated (Figure 34).

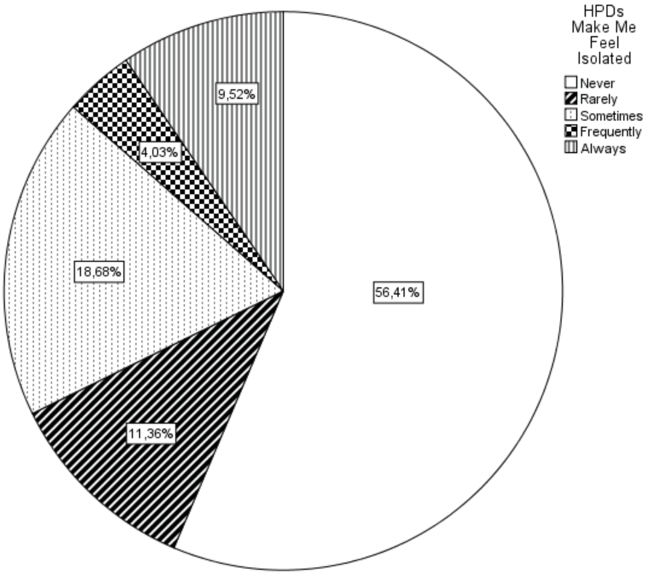

Figure 34. Summary of item “HPDs make me feel isolated.” answers.

A little over twenty percent of the respondents agreed to a deriving benefit from the use of HPDs, which is easing of listening to their co-workers (Figure 35).

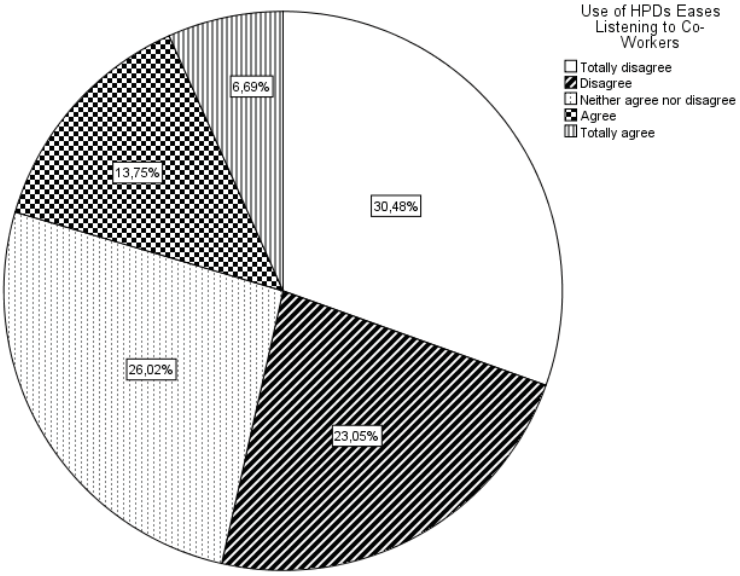

Figure 35. Summary of item “Use of HPDs eases listening to co-workers.” answers.

Another benefit tested was the avoidance of headaches. Over forty percent of the respondents agreed that, lacking to wear HPDs causes them to have headaches (Figure 36).

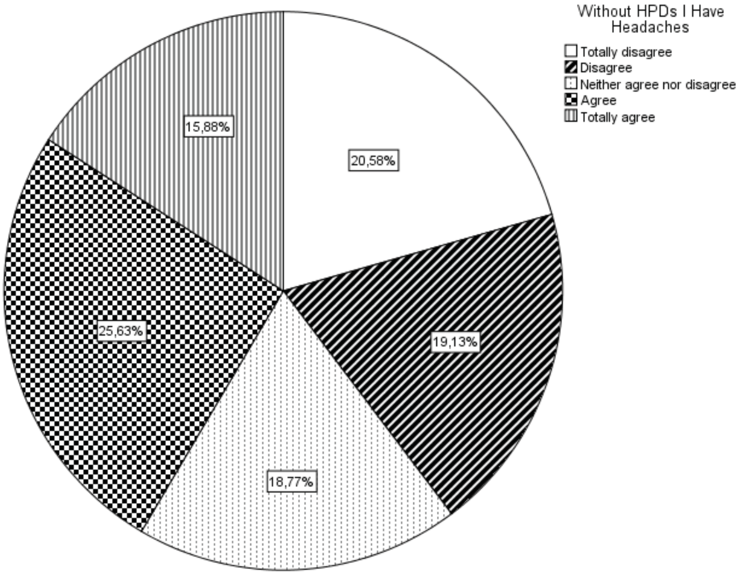

Figure 36. Summary of item “Without HPDs I have headaches.” answers.

All in all, almost fifty-five percent of the respondents agreed that wearing HPDs made them feel more comfortable, as shown in Figure 37.

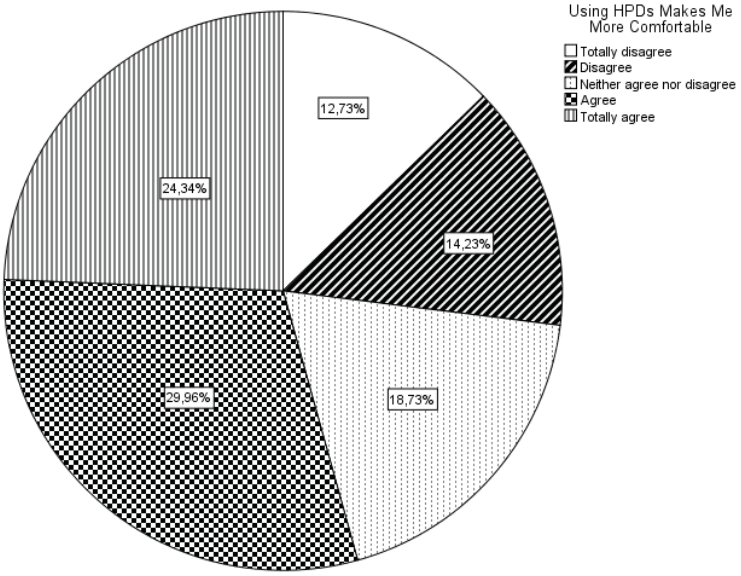

Figure 37. Summary of item “Using HPDs makes me more comfortable.” answers.

Knowledge of noise and its effects were also tested.

Regarding the damage potential of noise, workers were asked to what level they agreed with the statement: “High noise levels of noise can cause deafness”. As can be seen on Figure 38, about ninety-three percent of the respondents agreed to this sentence be true.

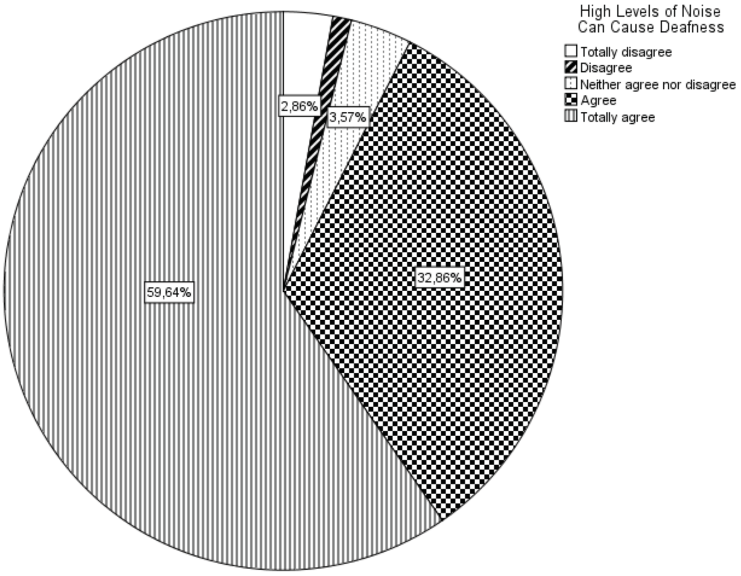

Figure 38. Summary of item “High levels of noise can cause deafness.” answers.

A little lower, though, is their knowledge on the NIHL protective potential of HPDs. Under eighty-five percent of the respondents agreed HPDs could protect them from deafness derived from exposure to occupational noise (Figure 39).

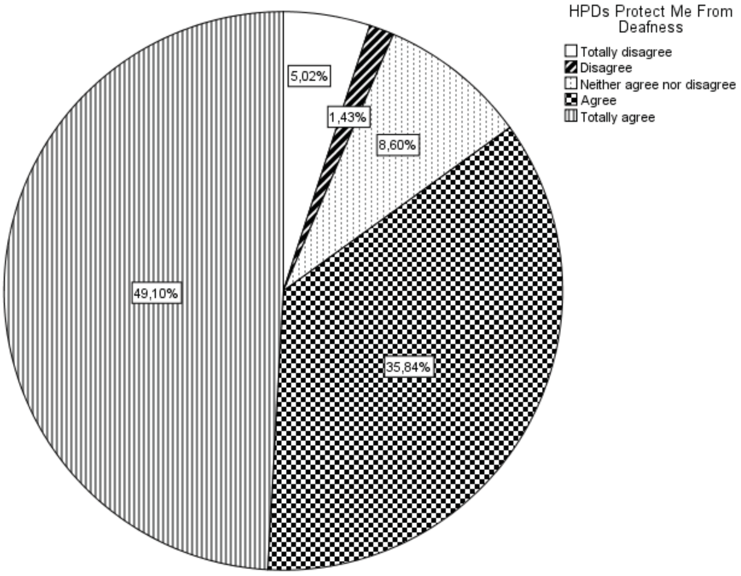

Figure 39. Summary of item “HPDs protect me from deafness.” answers.

The effects of the peers and the hierarchy was further studied, by inclusion of questions such as: “I wear HPDs because my boss tells me to”. Almost thirty percent of the respondents declared that, at least sometimes, they wear HPDs because their supervisors obligate them (Figure 40).

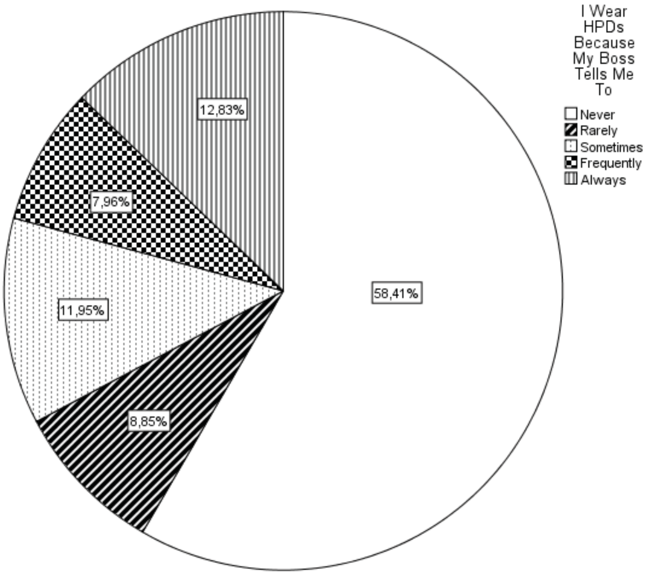

Figure 40. Summary of item “I wear HPDs because my boss tells me to.” answers.

The example set by the supervisor was another item. Almost half of the respondents agreed that their supervisor set a good example regarding the use of HPDs. About a quarter of the respondents declared that their supervisor was not a good example concerning the use of HPDs. The “neither agree nor disagree” score, though, has a striking percentage, which can result from some embarrassment of workers in a potential placement of their supervisor at stake (Figure 41).

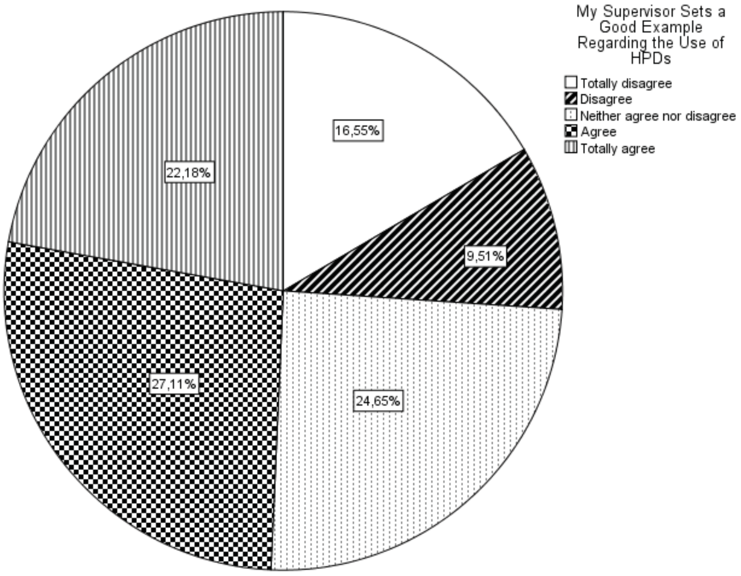

Figure 41. Summary of item “My supervisor sets a good example regarding the use of HPDs.” answers.

In relation to any pressure from any fines that the company may be subject to due to worker non-compliance, Figure 42 shows that over forty percent of the respondents wear, at least sometimes, their HPDs, because if they do not, their company may have to pay a fine.

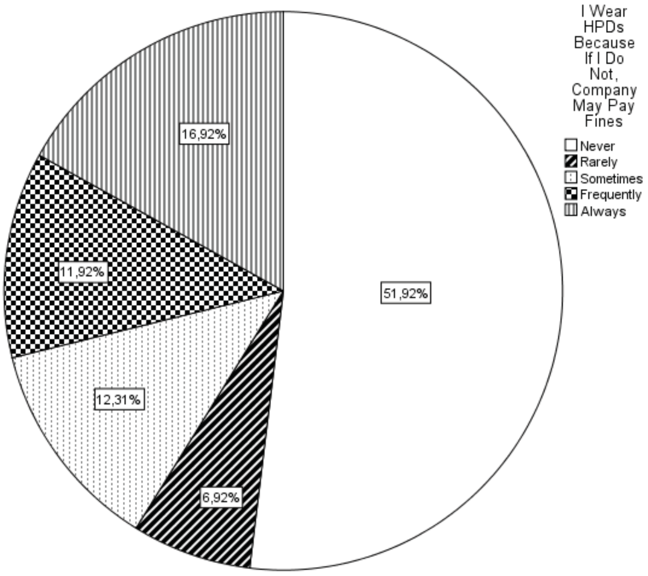

Figure 42. Summary of item “I wear HPDs because if I do not, my company may pay a fine.” answers.

The peers behaviour towards the use of HPDs does not seem to have an impact in the use of those devices, as only about eight percent of respondents agreed that they wear HPDs because their co-workers wear them (Figure 43).

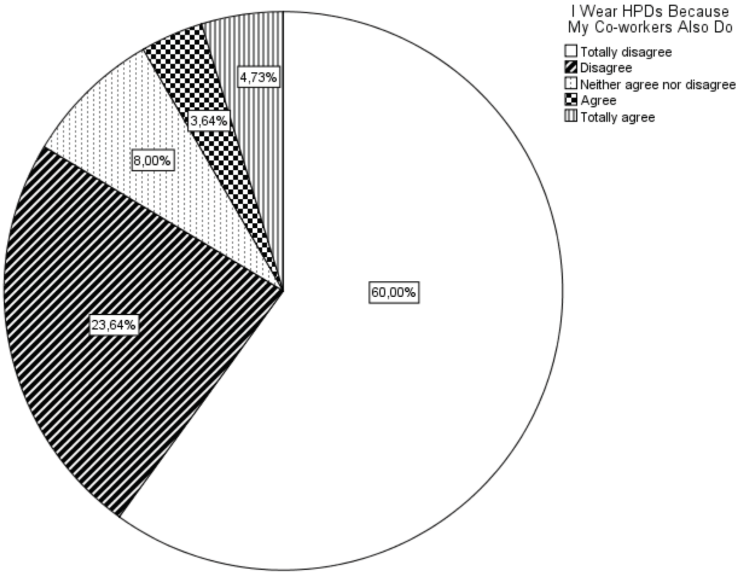

Figure 43. Summary of item “I wear HPDs because my co-workers also do.” answers.

Filter questions performed well, with significant relationship between self-assessed %HPD Use and “*I always wear HPDs when I am supposed to*”, $\tau = .44, p(one - tailed) < .01$ and self-assessed %HPD Use and *“%HPD Use relatively to co-workers*”, $\tau = .32, p(one - tailed) < .01$. Variable “I forget to wear HPDs” was recoded as a means to test concomitance with self-assessed %HPD Use, and significant correlation between the two variables was proved ($\tau = .46, p(one - tailed) < .01$). These results show that the workers were honest in the completion of the questionnaires, answering questions carefully and not in a random fashion. In line with the existing literature, it seems safe to assume that the self-assessment of hearing protection use corresponds to their real use of HPDs.

The burden of the use of HPDs has been discussed earlier (Arezes & Miguel, 2005; CDC, 2013; Damongeot, 1994; NIOSH, 2007b; OSHA 2003).

So, it was intended to study whether the use of HPDs in sites deemed excessively hot or humid by workers was lower, due to the extra burden these imputed to work, so items were included that allowed the workers to classify their working environment.

Figure 44 shows that over forty-three percent of the respondents deemed their working environment too hot.

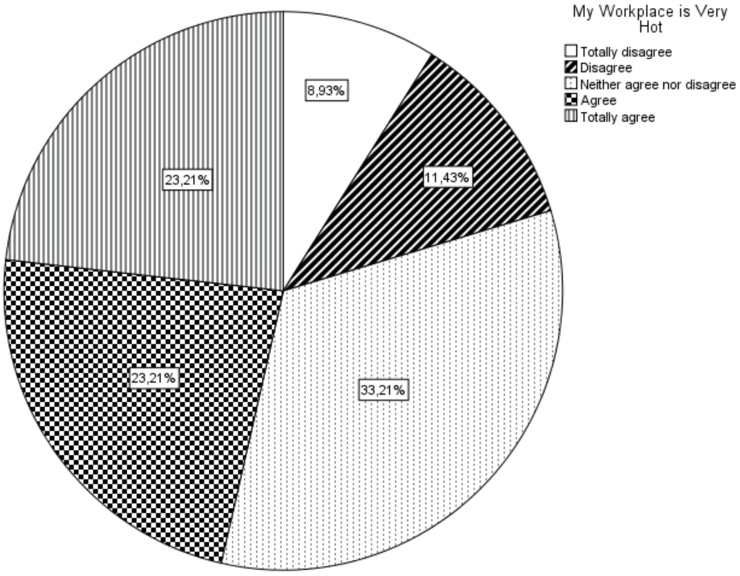

Figure 44. Summary of item "My workplace is very hot." answers.

By looking at Figure 45, it is possible to see that almost seventeen percent of the respondents declared their working environment was very humid.

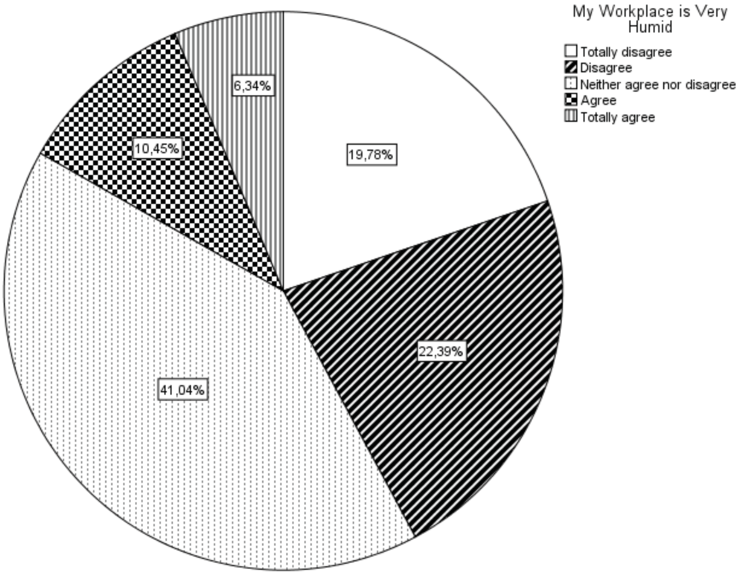

Figure 45. Summary of item "My workplace is very humid." answers.

Given the low expression of these results, it is possible that the environmental conditions of the workplace do not affect the rate of use of HPDs.

Table 3 shows that the average %HPD Use (from 0% to 100%) is not the same in across companies: ATEX company has the highest average %HPD Use (81.85%) whereas TEXI company has the lowest average %HPD Use (55.83%). This means that %HPD Use may be related to the company.

Table 3. Descriptive Statistics for HPD use (in % of the duration of the shift).

Company	N	Mean	SD	Coefficient of Variation
PAUL	17	58.88	29.234	**49.6%**
TEXI	132	55.83	36.738	**65.8%**
EURO	15	71.93	17.240	**24.0%**
ATEX	97	81.85	21.396	**26.1%**
Total	**261**	**66.62**	**32.692**	**49.1%**

Figure 46 shows the mean percentage of HPD use regarding the workers' shift, by Company. Overall, as noticed before, ATEX company shows the higher rates of use of HPDs, while TEXI company lies at the opposite position, with the lowest utilization rates. Regarding the time of day, the use of HPDs is uncertain, for it varies depending on the company. For that reason, it seems that this will not be a determining factor in the HPDs utilization rate, contrary to what was hypothesised at the beginning of this study.

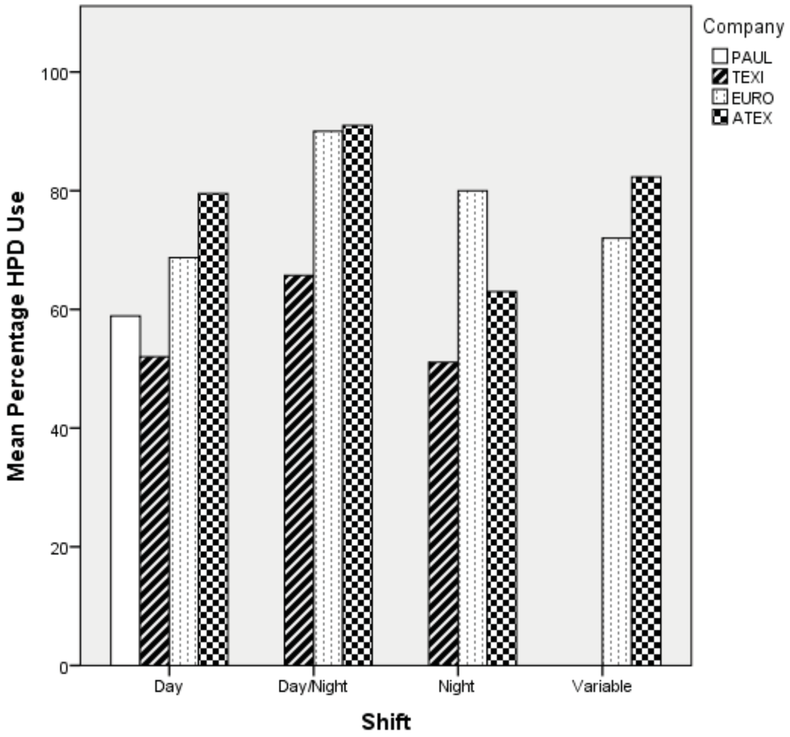

Figure 46. Mean percentage of HPD use regarding the workers' shift, by Company.

Tables 4 and 5 provide information to check whether the proposed model is capable of representing the variability observed in the data given that the model fit is best as these statistics are smaller.

Table 4. Information Criteria before Company effects (*DV*: %HPD Use).

-2 Log Likelihood	2559.962
Akaike's Information Criterion (AIC)	2563.962
Hurvich and Tsai's Criterion (AICC)	2564.009
Bozdogan's Criterion (CAIC)	2573.091
Schwarz's Bayesian Criterion (BIC)	2571.091

In other words, Tables 4 and 5 can be used to assess the overall fit of the model.

Table 5. Information Criteria considering Company effects (*DV*: %HPD Use).

-2 Log Likelihood	2531.117
Akaike's Information Criterion (AIC)	2537.117
Hurvich and Tsai's Criterion (AICC)	2537.211
Bozdogan's Criterion (CAIC)	2550.811
Schwarz's Bayesian Criterion (BIC)	2547.811

The first value that allows for assessment of the overall fit of the model is *deviance* ($-2LL$). The others are modifications to $-2LL$ that increment its value through some function of the number of parameters.

In this study, the Likelihood Ratio (*LR*) method was used.

These information criteria values are not direct interpretation criteria, but they are useful to compare alternative models whenever subsequent models include all terms from the previous model. The difference between $-2LL$ from two different models follows a *chi-squared* distribution, with as many degrees of freedom (df) as number of parameters by which the two compared models differ, thus obtaining the gain of adding the effects in which the models differ.

The strategy based on the alteration in *deviance* is more reliable for small samples than the direct test offered by the SPSS, the Wald Z test, because the *LR* is less conservative than the Wald Z test, which can sometimes fail to reject H_0.

This means that the regression coefficients of some variables can present descriptive *p-values* in the Wald test >.05 (non-significant) pointing to the exclusion of that variable from the model, while such an exclusion would not be allowed when resorting to the *LR* test.

Hence, the Wald test is a good test to start sorting the variables initially, in univariate analyses, rendering at that point, the variables that are ought to be part of the multivariate analyses. Once the plot of variables for the multivariate models is complete, the exclusion criteria should be based on the *LR*.

The Estimates of Fixed Effects (Table 6) provides the regression coefficient of each effect and its confidence interval, where the direction of the coefficients reveals if the relationship between the predictor and the dependent variable (*DV*) is positive or negative.

Table 6 indicates the estimated value of the *intercept*, this estimate represents the populational average of the 4 companies in the dependent variable (*DV*) %HPD Use.

The overall %HPD Use (across companies) is estimated as $\hat{\mu} = 67.29$. The mean for company k is estimated as $67.29 + \hat{u}_{0k}$, where $\hat{u}_{0k}$ is the company residual which will be estimated. A company with $\hat{u}_{0k} > 0$ has a %HPD Use that is higher than average, while $\hat{u}_{0k} < 0$ for a below-average company.

Table 6 also presents the *standard error*, *degrees of freedom* and *p-value*, allowing to test for the null hypothesis (H_0) that the parameter is zero:

$$H_0: \gamma_{00} = 0$$

$$H_1: \gamma_{00} > 0$$

In this case, as $p - value = 0 < 0.001$, it can be concluded that, for an error probability of 0.1%, $\%HPD\ Use > 0$, as expected, since negative percentages are nonsensical.

Table 6. Estimates of Fixed Effects for Company effects (*DV*: %HPD Use).

Parameter	Estimate	SE	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	67.286	5.800	4.646	11.601	<.001	52.028	82.545

Estimates of Covariance Parameters (Table 7) presents the estimates of the parameters associated to the random effects of the model.

Between-company (level 2) variance in %HPD Use is estimated as $\hat{\sigma}_{u_0}^2 = 105.851$, and shows how much the *DV* varies between companies.

Within-company between-workers (level 1) variance is estimated as $\hat{\sigma}_e^2 = 926.807$, and shows how much the *DV* varies within each company. The total variance is $105.851 + 926.807 = 1032.658$.

From Table 7, the variance partition coefficient (ρ) is $\frac{105.851}{926.807} = 0.114$, which indicates that about 11% of the variance in %HPD Use can be assigned to differences between companies.

Table 7. Estimates of Covariance Parameters for Company effects (*DV*: %HPD Use).

Parameter		Estimate	SE	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		926.807	81.637	11.353	<.001	779.851	1101.455
Intercept [subject = Company]	Variance	105.854	85.507	1.238	.216	21.732	515.588

5.2 Computing the uncertainty related to the effective exposure to occupational noise

This section comprises all the steps that allowed for computing the effective exposure of workers to occupational noise, based on the determined predictors, through the modelling of the use of HPDs. It starts with the first objective, the modelling of the use of HPDs, to which follows the computation of the real attenuation of the HPD (R), and ending in the primordial objective, the computation of the uncertainty related to the effective exposure to occupational noise, accounting for the use of HPDs.

5.2.1 Modelling the use of HPDs

All sequential steps of the multilevel analysis are presented in this section, whilst the results obtained are discussed.

The multilevel analysis ends with the construction of a model that explains the *DV* (%HPD Use), based on the meanwhile discovered significant predictors. It congregates the testing of Company effects and sequential inclusion of variables in the model: inclusion of level 1 variable *Benefits*, inclusion of level 1 variable *Interpersonal*, inclusion of level 1 variable *Hearing Problems*, inclusion of level 1 variable *Seniority* and inclusion of level 2 variable *Location.*

5.2.1.1 Testing for Company effects

To test for the significance of Company effects, a *LR* test comparing the null multilevel model with a null single-level model was carried-out.

This step is extremely important for the generalization of the results to be obtained. Otherwise, companies whose employees participated in this study would have to be treated as a variable themselves, and the results could not be generalized to any other company (Goldstein, 2011; Greenland, 2000).

In fact, other researchers have used other methods to treat their results and, failing to use multilevel analysis retrieved results that, contrary to what is postulated, cannot be generalized to companies other than those that have been used by them. Further, the use of another methodology than multilevel analysis, makes this variable "companies" become a confounding variable, camouflaging other variables, these rather, the ones that directly affect the use of HPDs.

To fit the null single-level model, the random between-company effect was removed.

Looking at Table 7, all information needed to test whether Company effect is null:

$$H_0\colon \sigma_\beta^2 = 0$$

$$H_1\colon \sigma_\beta^2 > 0$$

To test this hypothesis, Wald statistics was resorted to. This test has a $p - value = .216 > .05$, so the null hypothesis that population variance of factor Company is zero, cannot be rejected, and the %HPD Use may not differ from company to company.

Nevertheless, it is necessary to bear in mind that the Wald Z test is a very conservative test.

The covariance parameters were estimated assuming the factor Company is independent from residuals.

For that reason, the *LR* test statistic is a much more reliable test for the present data structure, and is computed as LR – the difference in the – 2 Log Likelihood values for the two models (view Table 4 and Table 5):

$LR = 2559.962 - 2531.117 = 28.845$ on 1 d.f. (because there is only parameter difference between the models, one model includes $\hat{\sigma}_u^2$, the other does not).

Bearing in mind that the 5% point of a *chi-squared* distribution on 1 d.f. is 3.84, there is overwhelming evidence of Company effects on % HPD Use.

The multilevel model with Company effects will, hence, be reverted to.

Company 1 has an estimated residual of -5.55, which was ranked second, i.e., two places from the bottom. For this company, %HPD Use is estimated of 67.29 – 5.55 = 61.74%.

In contrast, the percentage from company 4 (ranked fourth, the highest) is estimated as 67.29 + 13.35 = 80.64%.

Company 3 has an estimated residual of 2.93, ranking third, with a %HPD Use estimated as 67.29 + 2.93 = 70.22%.

Finally, company 2 ranked first, with a residual estimated of -10.74, which means that the estimated %HPD Use for company 2 is 67.29 – 10.74 = 56.55%.

The null model is, thus, obtained (Equation 5):

$$Y_{ik} = 67.29 + u_{0k} + e_{ik} \qquad \text{Eq. (5)}$$

Where:

$Y_{ik} - dependent\ variable\ for\ element\ i\ from\ level\ 1\ and\ element\ k\ from\ level\ 2;$

$u_{0k} - random\ error\ for\ each\ level\ 2\ element;$

$e_{ik} - level\ 1\ random\ error.$

5.2.1.2 Adding level 1 variable *Benefits*

Inclusion of a level 1 variable is needed in order to study variability in level 1, i.e., differences between workers from the same company.

For that purpose, construct *Benefits* will be added to the model to assess whether this construct is related to the %HPD Use. If so, this construct can enlight, at least in part, what the differences observed between workers from the same company are due to. This construct is a categorical variable, computed from items “If I do not wear HPDs I get the headaches” and “HPDs make me more comfortable”.

By including this construct to level 1, the model in that level will be (Equation 6):

$$Y_{ik} = \beta_{0k} + \beta_{1k}x_{ik} + e_{ik} \qquad \text{Eq. (6)}$$

The level 2 term remains $\beta_{0k} = \gamma_{00} + u_{ok}$ and term $\beta_{1k} = \gamma_{10}$ is the same in every company, for only two level 1 variables are related.

The combined model is obtained (Equation 7):

$$Y_{ik} = \gamma_{00} + \gamma_{10}x_{ik} + u_{0k} + e_{ik} \qquad \text{Eq. (7)}$$

Coefficient γ_{10} represents the average slope that relates %HPD Use with the construct *Benefits*.

The results obtained by adding a new construct to the model, are presented in Tables 7, 8 and 9.

The *LR* test statistic for a comparison of these models is $LR = 2531.117 - 1844.648 = 686.469$ on 1 d.f , for the -2 LL is now 1844.648.

Comparing with the results for the null model, the addition of *Benefits* has reduced the amount of variance at both the Company and the worker level.

The between-company variance has decreased from 105.851 to 47.760, and the within-company variance has shrunk from 926.807 to 633.355. Given that *-2LL* has decreased, it can be concluded that the quality of the model has improved.

Table 8 indicates whether the predictor that has been added significantly predicts the outcome. In this case, predictor *Benefits* significantly predicts %HPD Use ($p - value < .001$).

The intercept ($\hat{\gamma}_{00} = 32.04$) is an estimate of the %HPD Use, in the population of companies.

The coefficient associated to the construct *Benefits* ($\hat{\gamma}_{10} = 12.11$) indicates that workers with a score that one point higher in that construct will use the HPDs $(12.11 + u_{1k})$% more.

Table 8. Estimates of Fixed Effects after including *Benefits* (*DV*: %HPD Use).

Parameter	Estimate	SE	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	32.039	6.405	22.075	5.002	<.001	18.759	45.319
Benefits	12.112	1.549	197.256	7.822	<.001	9.059	15.166

Table 9 presents the estimates of the covariance parameters.

Estimation of variability between companies ($\hat{\sigma}_{u_0}^2$) and residual variance ($\hat{\sigma}_e^2$) have both dropped in relation to the null model.

Intra-company variability is $R_1^2 = \frac{926{,}807-633.355}{926.807} = 0.317$.

Between-company variability (level 2) is $R_2^2 = \frac{926{,}807-47.760}{926.807} = 0.948$, which means that about 95% of the differences observed between companies (diferences in %HPD Use) are diferences attributable to *Benefits*.

ρ is now: $\rho = \frac{\hat{\sigma}_{u_0}^2}{\hat{\sigma}_{u_0}^2+\hat{\sigma}_e^2} = \frac{47.760}{47.760+633.355} = 0.070 = 7\%$.

This means that, after adding the effect attributable to *Benefits*, 7% of the total variance (variance of the *DV*) is still due to differences between %HPD Use of companies.

Table 9. Estimates of Covariance Parameters after including *Benefits* (*DV*: %HPD Use).

Parameter		Estimate	SE	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		633.355	64.240	9.859	<.001	519.172	772.651
Intercept [subject = Company]	**Variance**	47.760	46.500	1.027	.304	7.084	321.967

The combined model is now (Equation 8):

$$Y_{ik} = 32.04 + 12.11 Benefits + u_{0k} + e_{ik} \qquad \text{Eq. (8)}$$

5.2.1.3 Adding level 1 variable *Interpersonal*

As a level 1 variable, this construct is expected to relate to %HPD Use. This way, it could help better explain differences observed between workers from the same company. This construct is a categorical variable, computed from the items “I wear HPDs because my co-workers also wear them” and “I get teased for wearing HPDs by my co-workers”.

By including this level 1 construct, the model obtained is (Equation 9):

$$Y_{ik} = \beta_{0k} + \beta_{1k} x_{ik} + \beta_{2k} w_{ik} + e_{ik} \qquad \text{Eq. (9)}$$

While level 2 term remains the same, the resulting combined model is (Equation 10):

$$Y_{ik} = \gamma_{00} + \gamma_{10} x_{ik} + \gamma_{20} w_{ik} + u_0 + e_{ik} \qquad \text{Eq. (10)}$$

Coefficient γ_{20} represents the average slope that relates %HPD Use with construct *Interpersonal*. Table 10 presents the results of adding the second construct and it can be observed that the *intercept* has changed, now estimated as $\hat{\gamma}_{00} = 40.07$.

Table 10. Estimates of Fixed Effects after including *Interpersonal* (*DV*: %HPD Use).

Parameter	Estimate	SE	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	40.067	6.960	34.678	5.757	<.001	25.934	54.201
Benefits	12.227	1.523	197.347	8.027	<.001	9.223	15.230
Interpersonal	-5.500	2.100	194.853	-2.619	.010	-9.641	-1.358

The coefficient associated to the construct *Benefits* has slightly changed to $\hat{\gamma}_{10} = 12.23$ and the coefficient associated to the construct *Interpersonal* is $\hat{\gamma}_{20} = -5.50$, indicating that a worker with a one point higher score on *Interpersonal* construct than another worker from the same company wears, in average, his HPDs $(5.5 + u_{2k})\%$ less.

Estimation of variability between companies and residual variance have both decreased.

Intra-company variability is now $R_1^2 = \frac{926.807-612.655}{926.807} = 0.339.$

Between-company variability (level 2) is $R_2^2 = \frac{926.807-43.560}{926.807} = 0.953.$

The combined model has now changed to (Equation 11):

$$Y_{ik} = 40.07 + 12.23 Benefits - 5.50 Interpersonal + u_{0k} + e_{ik} \qquad \text{Eq. (11)}$$

Table 11 provides the parameters to compute ρ, which is now: $\rho = \frac{\hat{\sigma}_{u_0}^2}{\hat{\sigma}_{u_0}^2 + \hat{\sigma}_e^2} = \frac{43.560}{43.560+612.655} = 0.066 = 6.6\%.$

Table 11. Estimates of Covariance Parameters after including *Interpersonal* (*DV*: %HPD Use).

Parameter		Estimate	SE	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		612.655	62.128	9.861	<.001	502.224	747.368
Intercept [subject = Company]	Variance	43.568	42.617	1.022	.307	6.406	296.339

This means that, after adding the effects of *Benefits* and *Interpersonal*, 6.6% of the total variance (variance of the *DV*) is still due to differences between %HPD Use of companies.

5.2.1.4 Adding level 1 variable *Hearing Problems*

Variable *Hearing Problems* is a dichotomous variable that indicates whether a worker suffers from hearing impairment (value 1) or does not suffer from hearing impairment (value 0).

Also a level 1 variable, this construct is expected to relate to %HPD Use.

By including the level 1 construct, the model is (Equation 12):

$$Y_{ik} = \beta_{0k} + \beta_{1k}x_{ik} + \beta_{2k}w_{ik} + \beta_{3k}z_{ik} + e_{ik} \quad \text{Eq. (12)}$$

Coefficient γ_{30} represents the average slope that relates %HPD Use with variable *Hearing Problems*.

Level 2 terms remains the same, and so the resulting combined model becomes (Equation 13):

$$Y_{ik} = \gamma_{00} + \gamma_{10}x_{ik} + \gamma_{20}w_{ik} + \gamma_{30}z_{ik} + u_0 + e_{ik} \quad \text{Eq. (13)}$$

Adding the third independent variable (Table 12) has, again, altered the *intercept*, that is now $\hat{\gamma}_{00} = 47.32$.

Table 12. Estimates of Fixed Effects after including *Hearing Problems* (*DV*: %HPD Use).

Parameter	Estimate	SE	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	47.320	7.840	53.517	6.036	<.001	31.599	63.041
Benefits	12.283	1.509	197.281	8.141	<.001	9.308	15.259
Interpersonal	-6.079	2.100	194.988	-2.894	.004	-9.641	-1.358
[HearingProblems=0]	-8.586	4.371	196.355	-1.964	.051	-10.221	-1.937
[HearingProblems=1]	0[b]	0	.	.	.	.	.

b. this parameter has been set to zero because it is redundant.

The coefficient associated to the construct *Benefits* has slightly changed to $\hat{\gamma}_{10} = 12.28$.

The coefficient associated to the construct *Interpersonal* is now $\hat{\gamma}_{20} = -6.08$ and the coefficient associated to the variable *Hearing Problems* is $\hat{\gamma}_{30} = -8.59$.

Therefore, %HPD Use in workers with some kind of hearing impairment is $(8.59 + u_{3k})\%$ smaller than in workers with no hearing impairment.

The combined model is now (Equation 14)

$$Y_{ik} = 47.32 + 12.28 Benefits - 6.08 Interpersonal - 8.59 Hearing_{Problems} + u_{0k} + e_{ik} \qquad \text{Eq. (14)}$$

Estimation of variability between companies has decreased and the residual variance has slightly increased (Table 13).

The intra-company variability is $R_1^2 = \frac{926.807 - 600.680}{926.807} = 0.352.$

Between-company variability (level 2) is now $R_2^2 = \frac{926.807 - 44.111}{926.807} = 0.952.$

Table 13. Estimates of Covariance Parameters after including *Hearing Problems* (*DV*: %HPD Use).

Parameter		Estimate	SE	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		600.680	60.900	9.863	<.001	492.431	732.726
Intercept [subject = Company]	**Variance**	44.111	42.205	1.045	.296	6.763	287.715

ρ is now: $\rho = \frac{\hat{\sigma}_{u_0}^2}{\hat{\sigma}_{u_0}^2 + \hat{\sigma}_e^2} = \frac{44.111}{44.111 + 600.680} = 0.068 = 6.8\%.$

After adding the effects due to *Benefits*, *Interpersonal* and *Hearing Problems*, 6.8% of the total variance (variance of the *DV*) is still owed to differences between %HPD Use of companies.

5.2.1.5 Adding level 1 variable *Forget to Wear HPDs*

Variable *Forget to Wear HPDs* is a categorical variable that indicates how often a worker forgets to use HPDs (Never=1, Rarely=2, Sometimes=3, Frequently=4 and Always=5).

By including the level 1 construct, the model is the one described in Equation 15.

$$Y_{ik} = \beta_{0k} + \beta_{1k}x_{ik} + \beta_{2k}w_{ik} + \beta_{3k}z_{ik} + \beta_{4k}v_{ik} + e_{ik} \qquad \text{Eq. (15)}$$

Coefficient γ_{40} represents the average slope that relates %HPD Use with variable *Forget to Wear HPDs*.

Level 2 term remains the unstirred, so the resulting combined model is (Equation 16):

$$Y_{ik} = \gamma_{00} + \gamma_{10}x_{ik} + \gamma_{20}w_{ik} + \gamma_{30}z_{ik} + \gamma_{40}v_{ik} + u_0 + e_{ik} \qquad \text{Eq. (16)}$$

Adding the fourth independent variable (Table 14) has dramatically altered the intercept, that is now $\hat{\gamma}_{00} = 22.71$.

Table 14. Estimates of Fixed Effects after including *Forget to Wear HPDs* (*DV*: %HPD Use).

Parameter	Estimate	SE	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	22.707	10.029	154.941	2.264	.025	2.896	42.519
Benefits	8.434	1.545	196.580	5.459	<.001	5.387	11.480
Interpersonal	-5.099	1.974	195.394	-2.583	.011	-8.992	-1.205
[HearingProblems=0]	-8.540	4.054	196.667	-2.106	.036	-16.536	-.544
[HearingProblems=1]	0^b	0	.	.	.	.	.
[ForgetWearHPDs=1]	44.236	8.754	195.967	5.053	<.001	26.971	61.501
[ForgetWearHPDs=2]	37.468	8.959	196.286	4.182	<.001	19.800	55.137
[ForgetWearHPDs=3]	25.060	8.968	196.199	2.794	.006	7.374	42.747
[ForgetWearHPDs=4]	16.634	11.783	196.953	1.412	.160	-6.604	39.872
[ForgetWearHPDs=5]	0^b	0	.	.	.	.	.

b. this parameter has been set to zero because it is redundant.

The coefficient associated to the construct *Benefits* has decreased to $\hat{\gamma}_{10} = 8.43$, the coefficient associated to the construct *Interpersonal* is now $\hat{\gamma}_{20} = -5.10$ and the coefficient associated to the variable *Hearing Problems* is $\hat{\gamma}_{30} = -8.54$.

Coefficients associated to *Forget to Wear HPDs* show that never forgetting to wear HPDs maximizes %HPD Use (as would be expected).

The coefficients relative to "*Forget to Wear HPDs* = 1", "*Forget to Wear HPDs* = 2", "*Forget to Wear HPDs* = 3" and "*Forget to Wear HPDs* = 4" have a fixed component, representing contrasts with the reference "*Forget to Wear HPDs* = 5" (Always) on average, and a Company-specific component.

For example, after accounting for *Benefits*, *Interpersonal* and *Hearing Problems*, workers who never forget to wear HPDs (*Forget to Wear HPDs* = 1) working in company *k* are expected to have a %HPD Use that is $(44.24 + \hat{\mathrm{u}}_{4\mathrm{k}})\%$ higher than workers who always forget to wear HPDs in the same company.

It should be noted, however, that relationship between *Forget to Wear HPDs* and % HPD Use is not significant for the fourth category (Frequently), which means that, for a worker who frequently forgets to wear HPDS (*Forget to Wear HPDs* = 4) this relationship is not significant ($p - value = .160 > .05$).

The combined model is now (Equation 17):

$$\begin{aligned} Y_{ik} = 22.71 + 8.43 Benefits - 5.10 Interpersonal - 8.54 Hearing_{Problems} \\ + \hat{\gamma}_{30} Forget_{Wear_{HPDs}} + u_{0k} + e_{ik} \end{aligned} \qquad \text{Eq. (17)}$$

Estimation of variability between companies has decreased and the residual variance has slightly increased (Table 15).

Table 15. Estimates of Covariance Parameters after including *Forget to Wear HPDs* (*DV*: %HPD Use).

Parameter		Estimate	SE	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		511.404	51.803	9.872	<.001	419.316	623.717
Intercept [subject = Company]	Variance	23.249	24.421	.952	.341	2.967	182.182

Intra-company variability: $R_1^2 = \frac{926.807-511.404}{926.807} = 0.448.$

Between-company variability (level 2): $R_2^2 = \frac{926.807-23.250}{926.807} = 0.975.$

ρ is now: $\rho = \frac{\hat{\sigma}_{u_0}^2}{\hat{\sigma}_{u_0}^2+\hat{\sigma}_e^2} = \frac{23.250}{23.250+511.404} = 0.043 = 4.3\%.$

This result means that, after accounting for the effects of *Benefits*, *Interpersonal*, *Hearing Problems* and *Forget to Wear HPDs*, 4.3% of the total variance (variance of the *DV*) is still due to differences between %HPD Use of companies.

5.2.1.6 Adding level 1 variable *Seniority*

Variable *Seniority* is a continuous variable that indicates the time (in months) the worker has been working in the company. Also a level 1 variable, it is included as a means to determine if the time a worker has been working in a company is related to %HPD Use.

By including this level 1 variable, the model is (Equation 18):

$$Y_{ik} = \beta_{0k} + \beta_{1k}x_{ik} + \beta_{2k}w_{ik} + \beta_{3k}z_{ik} + \beta_{4k}v_{ik} + \beta_{5k}g_{ik} + e_{ik} \qquad \text{Eq. (18)}$$

Coefficient γ_{50} represents the average slope that relates %HPD Use with variable *Seniority*.

Level 2 term remains the same, hence the resulting combined model (Equation 19):

$$Y_{ik} = \gamma_{00} + \gamma_{10}x_{ik} + \gamma_{20}w_{ik} + \gamma_{30}z_{ik} + \gamma_{40}v_{ik} + \gamma_{50}g_{ik} + u_0 + e_{ik} \qquad \text{Eq. (19)}$$

The intercept is now $\hat{\gamma}_{00} = 30.20$, as a result of addition of the fifth independent variable to the model (Table 16).

The coefficient associated to the construct *Benefits* has slightly decreased to $\hat{\gamma}_{10} = 7.96$ and the coefficient associated to the construct *Interpersonal* is now $\hat{\gamma}_{20} = -4.83$.

The variable *Hearing Problems* coefficient associated to is $\hat{\gamma}_{30} = -9.92$ and the coefficients associated to *Forget to Wear HPDs* have all also decreased.

The coefficient related to *Seniority*, $\hat{\gamma}_{50} = .020,$ which signifies that %HPD Use decreases .02% for each month the worker has been in company k. *Seniority* appears not to be a significant contribution to assess %HPD Use ($p - value = .83 > .05$).

Table 16. Estimates of Fixed Effects after including *Seniority* (*DV*: %HPD Use).

Parameter	Estimate	SE	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	30.202	10.821	166.872	2.791	.006	8.838	51.566
Benefits	7.960	1.559	196.346	5.107	<.001	4.886	11.034
Interpersonal	-4.8311	1.9676	195.479	-2.455	.015	-8.7117	-.9506
[HearingProblems=0]	-9.9230	4.1037	196.012	-2.418	.017	-18.0161	-1.8299
[HearingProblems=1]	0^b	0	.	.	.	.	.
[ForgetWearHPDs=1]	42.189	8.782	195.597	4.804	<.001	24.869	59.509
[ForgetWearHPDs=2]	36.206	8.931	196.371	4.054	<.001	18.594	53.818
[ForgetWearHPDs=3]	23.553	8.949	196.679	2.632	.009	5.906	41.201
[ForgetWearHPDs=4]	17.563	11.716	196.786	1.499	.135	-5.543	40.669
[ForgetWearHPDs=5]	0^b	0	.	.	.	.	.
Seniority	-.020	,011	197.083	-1.745	.083	-.042	.003

b. this parameter has been set to zero because it is redundant.

Estimation of variability between companies and the residual variance have both decreased (Table 17).

Table 17. Estimates of Covariance Parameters after including *Seniority* (*DV*: %HPD Use).

Parameter		Estimate	SE	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		504.910	51.153	9.871	<.001	413.980	615.814
Intercept [subject = Company]	**Variance**	18.805	21.396	.879	.379	2.022	174.883

Intra-company variability: $R_1^2 = \frac{926.807-504.910}{926.807} = 0.455.$

Between-company variability (level 2): $R_2^2 = \frac{926.807-18.805}{926.807} = 0.980.$

ρ is now: $\rho = \frac{\hat{\sigma}_{u_0}^2}{\hat{\sigma}_{u_0}^2+\hat{\sigma}_e^2} = \frac{18.805}{18.805+504.910} = 0.036 = 3.6\%$. Therefore, after weighing the effects of *Benefits*, *Interpersonal*, *Hearing Problems*, *Forget to Wear HPDs* and *Seniority*, 3.6% of the total variance (variance of the DV) is still due to differences between %HPD Use of companies.

This variable will not be included in the model, though, given it also does not contribute to a significant improvement of the model ($-2LL = 1801.004 - 1798.018 = 2.986$).

5.2.1.7 Adding level 2 variable *Location*

Location is a dichotomous variable that indicates whether the Company is located at a rural or urban site. Variable *Location* takes the value 1 for “urban” and the value 2 for “rural”.

It is a level 2 variable, also known as a contextual variable, by which it is intended to study variability of level 2, i.e., explain the differences in %HPD Use between companies.

By including the level 2 variable, the level 1 model is maintained as (Equation 20):

$$Y_{ik} = \beta_{0k} + \beta_{1k}x_{ik} + \beta_{2k}w_{ik} + \beta_{3k}z_{ik} + \beta_{4k}v_{ik} + \beta_{5k}g_{ik} + e_{ik} \qquad \text{Eq. (20)}$$

The level 2 model, however, will now be (Equation 21):

$$\beta_{0k} = \gamma_{00} + \gamma_{01}h_k + u_{0k} \qquad \text{Eq. (21)}$$

where H_k is the kth observation of the variable and $\overline{H}$ is the mean of all variable H observations.

The resulting combined model (Equation 22):

$$Y_{ik} = \gamma_{00} + \gamma_{10}x_{ik} + \gamma_{20}w_{ik} + \gamma_{30}z_{ik} + \gamma_{40}v_{ik} + \gamma_{50}g_{ik} + \gamma_{01}h_k + u_{0k} + e_{ik} \qquad \text{Eq. (22)}$$

Coefficient γ_{01} represents the average slope that relates %HPD Use with *Location*.

The intercept is now estimated as $\hat{\gamma}_{00} = 27.96$, as a result of addition of the fifth independent variable to the model (Table 18).

Table 18. Estimates of Fixed Effects after including *Location* (*DV*: %HPD Use).

Parameter	Estimate	SE	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	27.956	12.978	84.581	2.154	.034	2.150	53.762
Benefits	7.995	1.562	195.686	5.118	<.001	4.914	11.075
Interpersonal	-4.824	1.967	195.534	-2.452	.015	-8.704	-.945
[HearingProblems=0]	-9.913	4.102	196.065	-2.416	.017	-18.004	-1.823
[HearingProblems=1]	0^b	0	.	.	.	.	.
[ForgetWearHPDs=1]	42.049	8.790	195.290	4.784	<.001	24.714	59.384
[ForgetWearHPDs=2]	36.075	8.937	196.210	4.037	<.001	18.450	53.701
[ForgetWearHPDs=3]	23.563	8.946	196.690	2.634	.009	5.921	41,205
[ForgetWearHPDs=4]	17.770	11.731	196.203	1.515	.131	-5.365	40.905
[ForgetWearHPDs=5]	0^b	0	.	.	.	.	.
SeniorityCompany	-.020	.011	197.996	-1.698	.091	-.041	.003
[Location=1]	2.541	8.099	10.005	.314	.760	-15.502	20.585
[Location=2]	0^b	0	.	.	.	.	.

b. this parameter has been set to zero because it is redundant.

The coefficient associated to the construct *Benefits* has slightly increased to $\hat{\gamma}_{10} = 8.00$, the coefficients associated to the construct *Interpersonal* and the variable *Hearing Problems* have both slightly decreased to $\hat{\gamma}_{20} = -4.82$ and $\hat{\gamma}_{30} = -9.91$, respectively.

Coefficients associated to *Forget to Wear HPDs* almost did not change, with very slight decreases. The coefficient associated with seniority is now $\hat{\gamma}_{50} = .019$, almost unchanged also.

The coefficient associated with the level 2 variable Location is $\hat{\gamma}_{01} = 2.54$, which would mean that companies located in urban areas have a %HPD Use $(2.45 + u_{0k})\%$ higher than companies in rural locations, in average.

The *p-value* associated with this coefficient is, however too high for the relation between *Location* and %HPD Use to be significant ($p - value = .76 > .05$), as it can be seen on Table 19.

Because of the aforementioned and, also, because the inclusion of this variables does not produce a better quality model than the previous $(-2LL = 1798{,}018 - 1797{,}920 = 0{,}098)$, this variable will not be included in the model.

Table 19. Estimates of Fixed Effects after including *Location* (*DV*: %HPD Use).

Parameter	Estimate	SE	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	27.956	12.978	84.581	2.154	.034	2.150	53.762
Benefits	7.995	1.562	195.686	5.118	<.001	4.914	11.075
Interpersonal	-4.824	1.967	195.534	-2.452	.015	-8.704	-.945
[HearingProblems=0]	-9.913	4.102	196.065	-2.416	.017	-18.004	-1.822
[HearingProblems=1]	0[b]	0	.	.	.	.	.
[ForgetWearHPDs=1]	42.049	8.790	195.290	4.784	<.001	24.714	59.384
[ForgetWearHPDs=2]	36.075	8.937	196.210	4.037	<.001	18.450	53.700
[ForgetWearHPDs=3]	23.563	8.946	196.690	2.634	.009	5.921	41.205
[ForgetWearHPDs=4]	17.770	11.731	196.203	1.515	.131	-5.365	40.905
[ForgetWearHPDs=5]	0[b]	0	.	.	.	.	.
SeniorityCompany	-.019	.0113	197.996	-1.698	.091	-.042	.003
[Location=1]	2.541	8.099	10.005	.314	.760	-15.502	20.585
[Location=2]	0[b]	0	.	.	.	.	.

b. This parameter is set to zero because it is redundant.

Type III Tests of Fixed Effects output shows whether the predictors significantly predict the outcome. After all determinants were included in the multilevel model, of the total determinants included in the multivariate analysis, only four have proven of interest to model the use of HPDs (Table 19 and Table 20): *Benefits* and *Interpersonal* constructs, items "*I Forget to wear HPDs*" and "*I have hearing problems*", with significant values on Type III Tests of Fixed Effects $(p - value < .05)$.

Table 20. Type III Tests of Fixed Effects after including *Location* (*DV*: %HPD Use).

Source	Numerator df	Denominator df	Z	Sig.
Intercept	1	92.116	38.452	<.001
Benefits	1	195.686	26.190	<.001
Interpersonal	1	195.534	6.014	.015
HearingProblems	1	196.065	5.839	.017
ForgetWearHPDs	4	196.464	7.930	<.001
SeniorityCompany	1	197.996	2.883	.091
Location	1	10.005	.098	.760

Essays for modelling different slopes across companies (allowing both the intercept and the slopes to vary randomly across companies) – random slope models – were also performed, but results indicated that changes introduced by determinants in %HPD Use are the same for all companies, i.e., the slope of the regression line is fixed across companies.

Other researchers have conducted similar studies, whose results are included and compared in an earlier paper of Costa and Arezes (2013).

Yet, besides not having covered the same determinants, exacerbates the fact that they have not used multilevel modelling, assuming uncorrelated error, thus computing wrong standard errors for prediction parameters.

It is often a violated assumption that also leads to misinterpretations of the predictor variables' effects, both in magnitude and direction (Goldstein, 2011).

Thus, it is not surprising that the obtained results differ from previous published studies.

All predictors hypothesized, including (adding to the ones in the model) age, self-efficacy in the use of HPDs, gender, seniority at the Company, education, health importance to self, individual risk perception, subjective opinion on the Company's safety climate, perceived barriers to the use of HPDs, acknowledged value of the use of HPDs, susceptibility to hearing loss, hearing-conservation related knowledge, workplace environment evaluation, working shift, type of contract with the Company (permanent or temporary) and HPDs' hedonic qualities were part of the primary model.

For the purpose of parsimony, the results obtained are not shown in detail in the present thesis, for all showed non-significant effects in %HPD Use (all $p - values > .05$).

The model that best fits the relationship between the studied predictor and the %HPD Use is, therefore (Equation 23, see also Table 19):

$$\begin{aligned}\%\mathrm{HPD\ Use} = \gamma_{00} \\ + \gamma_{10} Benefits + \gamma_{20} Interpersonal + \gamma_{30} Hearing\ Problems \\ + \gamma_{40} Forget\ to\ Wear\ HPDs + u_0 + e_{ik}\end{aligned} \qquad \text{Eq. (23)}$$

This model corroborates what the early descriptive analysis seemed to point out, so far as that gender, type of contract that the employee has with the company, the work shift, any limitation that the use of HPDs imposes to the execution of work and the loss time that its use may entail, are not factors that significantly influence the use of HPDs.

5.2.2 Computation of the real attenuation of the HPD (R)

For calculating the uncertainty associated to the use of HPDs, P – percentage of time the HPD is worn – is substituted by Equation 23 in Equation 3, where the independent variable R - the real attenuation of the HPD - is a function of P and N (catalogued attenuation of the HPD), yielding Equation 24:

$$\boldsymbol{R} = 10log \frac{100}{100 - (\gamma_{00} + \gamma_{10} Benefits + \gamma_{20} Interpersonal + \gamma_{30} Hearing\ Problems + \gamma_{40} Forget\ to\ Wear\ HPDs + u_0 + e_{ik})\left(1 - 10^{-\frac{N}{10}}\right)}\ dB \qquad \text{Eq. (24)}$$

5.2.3 Computation of the uncertainty related to the effective exposure to occupational noise, accounting for the use of HPDs

The uncertainty related to the effective equivalent exposure levels (when accounting for the use of HPDs, $L_{EX,effective}$) is given by the error propagation on the effective individual exposure to occupational noise calculation (Equation 25), where R – real attenuation provided by the HPD - is subtracted to the results obtained through noise exposure measurements – daily exposure levels ($L_{EX,8h}$).

$$\boldsymbol{L_{EX,effective}} = L_{EX,8h} - 10log\frac{100}{100 - (\gamma_{00} + \gamma_{10}Benefits + \gamma_{20}Interpersonal + \gamma_{30}Hearing\ Problems + \gamma_{40}Forget\ to\ Wear\ HPDs + u_0 + e_{ik})\left(1 - 10^{-\frac{N}{10}}\right)}\ dB(A) \qquad \text{Eq. (25)}$$

It should be noted that, when the duration of the exposure (t_e) is the same as the reference duration of the exposure (t_0, which, by the Portuguese legislation is 8 hours), the effective daily exposure level ($L_{EX,8h,effective}$) equals the effective equivalent level ($L_{Aeq,effective}$).

If the duration of exposure does not coincide with the reference duration of exposure, $L_{EX,8h,effective}$ can be computed by Equation 26.

$$\boldsymbol{L_{EX,8h,effective}} = L_{\boldsymbol{Aeq,effective}} + 10log\frac{t_e}{t_0}\ dB(A) \qquad \text{Eq. (26)}$$

5.3 Testing the model

Twenty-two questionnaires that were not used in the multilevel analysis for the construction of the model, for failing to have the self-assessed use of HPDs answered, were used to test the model.

This test was based in the items and the constructs and integrate the model, obviously, but also in one of the filter-questions: “I always wear my HPDs when I have to”. Taking inspiration on several fuzzy logic-based studies (Al-Humaidi & Tan, 2011; Mogharreban & Dilalla, 2006). Answers to this question, on a 5-point Likert scale, were converted to intervals of %HPD Use, in the following manner: score 1 (“Never”) in the Likert scale corresponded to [1; 20] %Use of HPDs; score 2 (“Rarely”) corresponded to [21; 40] %Use of HPDs; score 3 (“Sometimes”) corresponded to [41; 60] %Use of HPDs; score 4 (“Frequently”) corresponded to [61; 80] %Use of HPDs and score 5 (“Always”) corresponded to [81; 100] %Use of HPDs. The ranges were chosen for the sake of maintaining the amplitude of the intervals all equal, while discarding the 0% in favour of the 100%, by virtue that the 100% appeared in the results obtained and the 0% did not.

By looking at Table 21, it can be concluded that the model was able to correctly predict twelve of the twenty-two cases studied, which accounts for over half of the cases.

Table 21. Results of the test to the model.

Case	Y (%HPD Use)	Answer to the item "I always wear my HPDs when I have to"	Corresponding HPD Use range (%)
1	77	5	[81-100]
2	55	4	[61-80]
3	69	4	[61-80]
4	55	5	[81-100]
5	51	3	[41-60]
6	92	5	[81-100]
7	81	5	[81-100]
8	50	1	[1-20]
9	78	4	[61-80]
10	59	1	[1-20]
11	50	1	[1-20]
12	100	5	[81-100]
13	97	3	[41-60]
14	75	5	[81-100]
15	83	4	[61-80]
16	84	5	[81-100]
17	83	5	[81-100]
18	82	5	[81-100]
19	100	5	[81-100]
20	91	4	[61-80]
21	66	4	[61-80]
22	100	5	[81-100]

It may appear as though this is an unsatisfying success rate, but looking closer at the results, one can see that, of the remaining 10 cases, the model computed a %Use of HPDs that was only lower in 4% and 6% than the self-assessed %HPD Use in three of the cases. By the principle of selection of the most conservative strategies, in which the route that considers the greatest possible exposure of workers is chosen, this is a good result.

Of the seven cases left, the model computed a %Use of HPDs that was actually higher than the ranges of the self-assessed use. This may be due to a higher awareness and sensitivity of the workers, regarding the use of HPDs, which causes these workers to penalize their % Use of HPDs more harshly than what, perhaps, translates into reality.

Notwithstanding, it should be noted that one of the %HPD Use computed was only higher by 3% that the self-assessed %HPD Use in one of the cases. Again, if this result were rounded to the tens, it would fall into the ranges of the self-assessed use.

In the remainder 6 cases, the difference between the computed %HPD Use and the workers self-assessed use of HPDs was higher (the %HPD Use retrieved by the model is more than 25% less the lower limits of the ranges comprised by the self-assessed use of HPDs in 5 of the cases). These results may reflect the embarrassment of the workers to show a low use of HPDs, even though the questionnaires were anonymous. Let us not forget that these were questionnaires in which the VAS was not filled, which may be due to several reasons (not realizing where to place the self-assessment in the scale, problems in interpreting the scale), but these 6 may be cases where workers did not feel comfortable disclosing their true use.

These are the type of cases that highlight the need for a questionnaire that, through indirect questions, which make reference to behaviours that do not come as compromising, relationships with colleagues and hierarchies and even recognition (or not) of some benefits, can reveal the true use of HPDs by these workers.

Therefore, it seems reasonable to assume that the use of a completely anonymous questionnaire based only on items that comprise the model (ergo, with no request of self-assessment use of HPDs) will bring optimized, highly accurate, results.

Regarding what has been said earlier, respecting the amount of money that is spent in Health and Safety promoting measures and in compensations for NIHL (CDC, 2014) this study has the potential to represent a million dollar-worthy tool.

Furthermore, as Berger stated, worrying about 2 or 3 dB innacuracies can no longer be the pathway to be taken, not when the non-use of HPDs grants even more significative innacuracies (Berger, 2000 cited by Berger and Gauger, 2004).

Therefore, this tool represents a profit for employers, to the extent that the share capital of the companies destined to the implementation and improvement of Health and Safety at Work will be better conducted to the most efficient measures, first, because it will allow companies to invest in the HPDs in which its employees adhere better and, moreover, because the efficiency of the measures taken will be higher, so the less will be expended in subsequent rewards for hearing diseases and impairment acquired in the occupational environment.

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Part III

Main Findings

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Chapter 6. Conclusions and Future Perspectives

Noise is, indeed, an ubiquitous hazard and the exposure of workers to high levels of noise is, still, staggering high. The efforts made by the international agencies and institutes are proven insufficient as the noise-related complaints remain, the compensations add up to millionaire values and results of audiograms show, in an era in which the health and safety at work takes, more than a concern, numerous legal bonds and much is spent on promoting health and safety at work. The conclusion to be drawn is that, in truth, the resources are not being expended efficiently.It was, in fact, necessary to change direction of research in order to obtain results closer to reality. A new approach provided more efficient results in the explanation of the reasons that underlie the time of use of HPDs, which is demonstrably low. A very advantageous methodology was achieved also, which addresses the need for standardization of the results globally, and that overcomes a, so far, neglected need, which was the computing of the uncertainty related to the individual exposure to occupational noise of workers worldwide.

6.1 Conclusions

Unfortunately, at the end of this research, it is concluded that noise is still, nowadays, an underestimated hazard. Either because the effects of the exposure to this physical agent are not, usually, immediate or because the causal relation between exposure to noise and its consequences are not, most of the times, recognized, therefore not being considered by most as having a great magnitude of hazardousness, workers are still exposed to dangerous levels of occupational noise, not making an efficient effort to minimize their exposure, through, for example, maximizing the time of use of their HPDs.

It is noticeable the lack of training of the majority of the workers regarding the use of HPDs and their effectiveness. Some believe that wearing them will put them in danger, by hindering the hearing of warning alarms. Several are unaware of the real consequences of being exposed to noise. The implications of removing the devices for short periods or misfitting them to the ear on the effectiveness of the HPDs are also ignored by several workers. There were even cases where the workers wanted to be deafened by exposure so that noise would no longer trouble them.

Besides the predictors that integrate the model, all the other hypothesized predictors, such as: age, self-efficacy in the use of HPDs, gender, seniority at the company, education, health importance to self, individual risk perception, subjective opinion on the company’s safety climate, perceived barriers to the use of HPDs, acknowledged value of the use of HPDs, susceptibility to hearing loss, hearing-conservation related knowledge, workplace environment evaluation, working shift, type of contract with the company (permanent or temporary) and HPDs’ hedonic qualities were part of the primary model, neither having significant influence in the use of HPDs.

Among all determinants that were essayed as being part of the model that intends to explain what leads workers to wear less or more their HPDs, only three revealed having a significant impact in the use of HPDs.

These results are not, in general, in line with the existent literature, but it is understandable, since new determinants were added to the previous known and also, because the methodology used (multilevel modelling) allowed for unveiling what could be confounding variables in previous studies.

Results from this research allow the conclusion that workers that acknowledge benefits in wearing HPDs will tend to use them longer.

Peers also play an important role in the use of HPDs, as seen in the results obtained for the Interpersonal construct.

Workers that assume having hearing problems will, in average, wear their HPDs longer (perhaps because are more sensitized to the problem and feel the repercussions) than workers who do not recognize having hearing problems.

Finally, recognizing to forgetting to wear HPDs is also a significant predictor of the use of HPDs.

Completion of a very simple, reader-friendly, and prompt questionnaire, will render employers a very close idea of how much their employees are wearing their HPDs and provide health and safety practitioners a closer estimation of the real exposure of workers to occupational noise.

The multilevel approach proved to be the strategy that best fitted the model that expresses the use of HPDs as a function of the predictors, and most limitations of this approach to modelling are in fact limitations of all modelling methods.

The main objective of this research was to provide the uncertainty that must be disclosed when assessing the effective exposure to occupational noise, in order for that assessment to be reliable and interpreted. Through a stepwise procedure that recognizes the hierarchical structure of workers within companies, thus acknowledging the similarities between workers from the same companies, discriminating between workers from different companies, computation of the uncertainty related to the effective personal exposure to occupational noise was made possible and optimized.

The main advantage of this methodology is its transversality – because the dependent variable is a standardized outcome, it may be used not only to compute the uncertainty related to the personal exposure to occupational noise assessed by all three strategies presented in ISO 9612, accounting for the use of HPDs, but also through implementation of different guides and through subsequent revised versions, meeting the vision and ambition of the acoustical society, as well as health and safety practitioners and industry actors.

Another advantage of these findings is that this model, like the HPM, is amenable to evolve, suffering revisions for encompassing the evolution of knowledge and changing of the working paradigms that occur naturally over time.

This study has the potential to represent a million dollar-worthy tool, considering the capital that is spent in Health and Safety promoting measures and in compensations for NIHL.

Also, this study fulfils the need for a way of addressing the more heavy and relevant inaccuracies, which come from to the non-use of HPDs.

Therefore, this tool represents profit for the companies, as it will allow them to invest in the HPDs in which its workers adhere better and, moreover, as it will prompt efficiency of the measures taken to increase, the less will be expended in subsequent rewards for hearing diseases and impairment acquired in the occupational environment.

6.2 Future perspectives

As were idealized from the beginning, Round Robin tests would be a great way of testing this model through implementation in different settings worldwide and comparison of the results obtained.

On one hand, because workers are susceptible to sensitization activities, and because (as stated before) this is an issue that is constantly evolving, one major concern while conducting this this study was that, what is true today, may not remain truthful in the future.

Even though this may seem a somewhat frustrating affirmation, given that an engineering study always has the intention of creating some tool, some knowledge that endures in time, one has to keep in mind that this study has also a social sciences part, which is the behaviour, and behaviour always has to be expected to develop, to undergo changes. For that reason, the greatest achievement of this work is that it is, by himself, amenable to mutate without major changes. Like the HPM, it stands as a robust tool, strongly based on theory, but with enough flexibility to accommodate any changes that may possibly arise.

From this viewpoint, it is then a tool which will remain over time: the theoretical basis is there, as it regards all possible variables, or behaviour modulators.

Nevertheless, given it is an iterative process, the magnitude of the number of variables renders a very time-consuming and laborious operation. It would be very profitable to create a user-friendly software, where health and safety practitioners would upload the data from the questionnaires and it would run the iterations automatically and provide the optimized result for each case.

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Annexes

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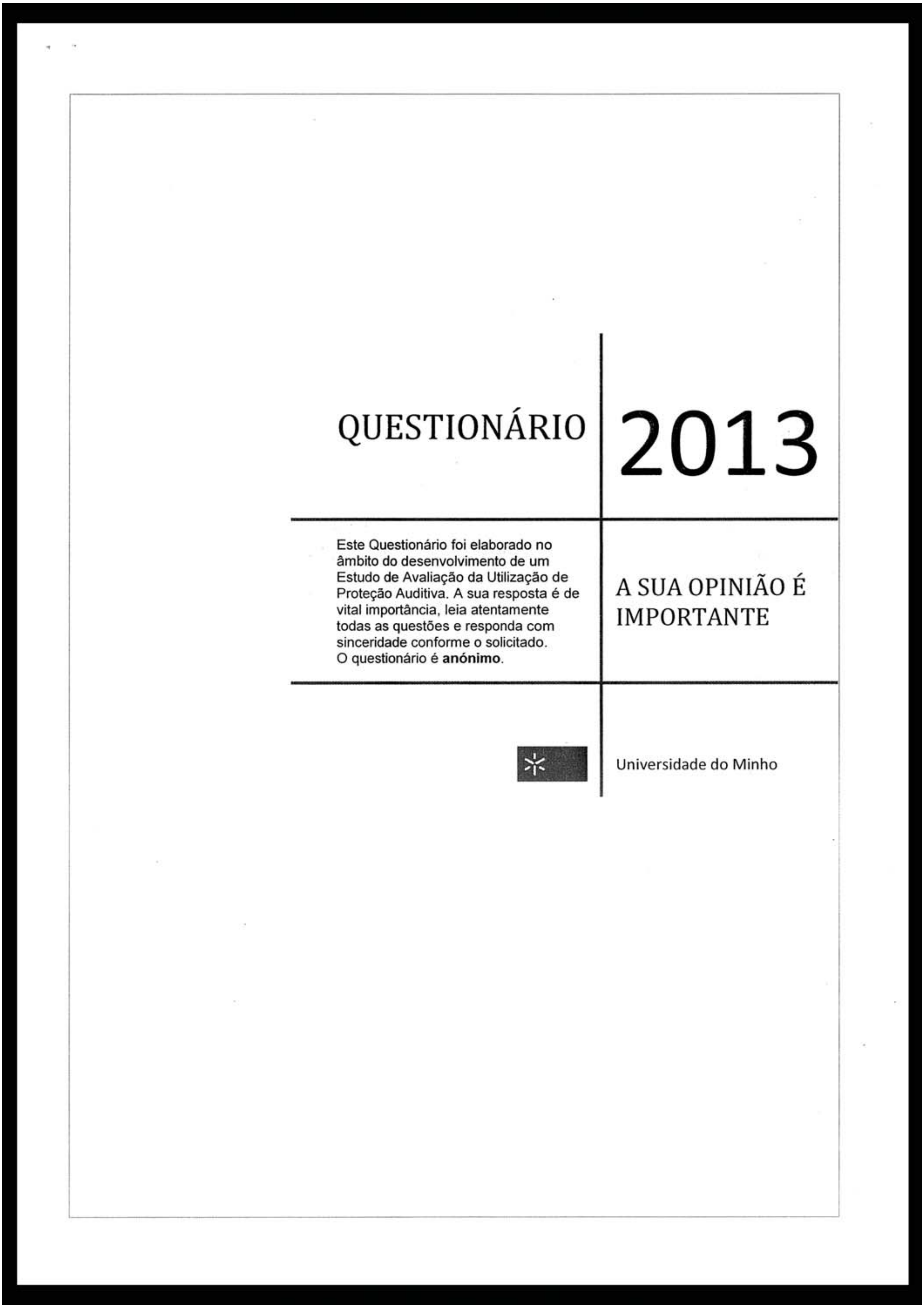
Annex 1

Questionnaire



QUESTIONÁRIO 2013

Este Questionário foi elaborado no âmbito do desenvolvimento de um Estudo de Avaliação da Utilização de Proteção Auditiva. A sua resposta é de vital importância, leia atentamente todas as questões e responda com sinceridade conforme o solicitado.
O questionário é **anónimo**.

A SUA OPINIÃO É IMPORTANTE

Universidade do Minho

Refª:
Empresa:
CAE:

Caracterização do Trabalhador

1. Idade: ____________ anos **2.** Género: Feminino ○ Masculino ○

3. Profissão/Função na empresa: ______________________________

4. Turno de Trabalho: ______________________________

5. Escolaridade (Especifique, como por exemplo: 4º ano, 9º ano, 11º ano, outra): ______________________________

6. Há quanto tempo trabalha na empresa? ________ anos ___________ meses

7. Durante esse tempo na empresa, exerceu sempre a mesma atividade? Sim ○ Não ○

7.1. Se **não**, indique quais as funções anteriores: ______________________________

8. No seu trabalho, que importância dá aos aspetos que possam influenciar a sua saúde?
Nenhuma ○ Pouca ○ Nem Pouca Nem Muita ○ Muita ○ Toda ○

Análise do Trabalhador

9. Sabe qual foi o resultado da última medição de ruído feita ao seu posto de trabalho? Sim ○ _____ dB(A) Não sei ○

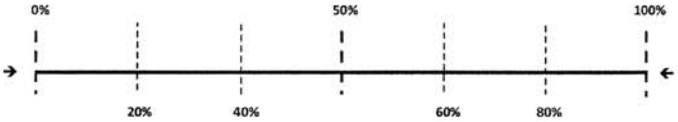
10. A empresa colocou à sua disposição protetores auditivos? Sim ○ Não ○

Se respondeu que **"NÃO"**...Termine o Questionário
Se respondeu que **"SIM" prossiga para a pergunta 11**

11. No seu trabalho, deve utilizar proteção auditiva durante todo o tempo do turno de trabalho? Sim ○ Não ○

12. Do tempo **do seu turno** em que **deveria usar proteção auditiva**, qual a percentagem de tempo em que realmente usa o protetor? (Marque com X, **na linha preta abaixo**, a percentagem de tempo em que utiliza o protetor auditivo)

Marque um X nesta linha



13. Classifique as seguintes afirmações, dando a sua opinião em relação a cada uma delas. Utilize a escala de 1 a 5 (**1** – "**Discordo** Totalmente" e **5** - "**Concordo** Totalmente")

	Discordo Totalmente 1	Discordo 2	Nem Discordo Nem Concordo 3	Concordo 4	Concordo Totalmente 5
Proteção auditiva					
Sei quando devo utilizar proteção auditiva.	○	○	○	○	○
Sei como se coloca corretamente os protetores auditivos.	○	○	○	○	○
Conforto					
Usar os protetores auditivos obriga a perder muito tempo.	○	○	○	○	○
Os protetores auditivos limitam o meu trabalho.	○	○	○	○	○
Usar protetores auditivos faz com que seja mais fácil ouvir os meus colegas.	○	○	○	○	○
Se não usar protetores auditivos, fico com dores de cabeça.	○	○	○	○	○
Uso protetores auditivos porque me fazem sentir mais confortável.	○	○	○	○	○
Os protetores auditivos são desconfortáveis.	○	○	○	○	○
Os protetores auditivos fazem-me suar.	○	○	○	○	○
Os protetores auditivos magoam.	○	○	○	○	○
Perceção					
Os protetores auditivos impedem-me de ouvir alarmes.	○	○	○	○	○
Os protetores auditivos dificultam-me ouvir a(s) máquina(s).	○	○	○	○	○
Qualidades do protetor					
Quando uso protetores auditivos sinto-me ridículo.	○	○	○	○	○
Acho que os protetores auditivos ficam-me bem.	○	○	○	○	○
Risco					
Os protetores auditivos protegem-me de ficar surdo por causa do ruído.	○	○	○	○	○
Se um trabalhador estiver exposto a ruído elevado pode perder capacidade de ouvir.	○	○	○	○	○
Satisfação no trabalho					
Estou satisfeito com o meu trabalho.	○	○	○	○	○
Audição					
Tenho problemas de audição.	○	○	○	○	○
Prevenir a surdez é muito importante para mim.	○	○	○	○	○

Recorde a escala de **1** a **5** (**1** "Discordo Totalmente" e **5** "Concordo Totalmente")					
	1	**2**	**3**	**4**	**5**
Hierarquia					
O meu responsável é um bom exemplo no que respeita aos protetores auditivos.	○	○	○	○	○
Pares					
Uso protetores auditivos porque os meus colegas também usam.	○	○	○	○	○
Os meus colegas gozam comigo quando eu uso protetores auditivos.	○	○	○	○	○
Formação					
Tive formação sobre protetores auditivos.	○	○	○	○	○
Classificação local de trabalho					
O meu local de trabalho é muito quente.	○	○	○	○	○
O meu local de trabalho é muito húmido.	○	○	○	○	○
Outros					
Sei onde estão os meus protetores auditivos.	○	○	○	○	○

14. Como classifica o seu ambiente de trabalho relativamente ao ruído? (Marque com um X)

Sem ruído ○ Com ruído ○ Muito ruidoso ○

15. Há quanto tempo utiliza protetor auditivo? _________anos _________meses

16. Utilizou sempre o mesmo tipo de protetor auditivo? Sim ○ Não ○

17. Acha que o seu protetor auditivo é o mais adequado para si? Sim ○ Não ○ Se **não**, indique o motivo:_____________________________

18. Em relação aos seus colegas, o tempo em que utiliza os protetores auditivos, é:

Muito Inferior ○ Inferior ○ Igual ○ Superior ○ Muito Superior ○

19. Dê a sua opinião em relação a cada uma das seguintes afirmações. Utilize a escala de 1 a 5 (**1** – Nunca; **2** – Raramente; **3** – Às Vezes; **4** – Frequentemente e; **5** – Sempre.)

	Nunca **1**	Raramente **2**	Às Vezes **3**	Frequentemente **4**	Sempre **5**
Sinto dificuldade em colocar corretamente os protetores auditivos.	○	○	○	○	○
Uso os protetores auditivos sempre que tenho de os usar.	○	○	○	○	○
Alivio os protetores auditivos, afastando-os das orelhas.	○	○	○	○	○
Sinto um zumbido nos ouvidos.	○	○	○	○	○
Esqueço-me de colocar os protetores auditivos.	○	○	○	○	○
Usar protetores auditivos faz-me sentir isolado.	○	○	○	○	○
Uso protetores auditivos porque senão, a empresa pode ser multada.	○	○	○	○	○
Uso protetores auditivos porque o meu chefe manda.	○	○	○	○	○
Uso protetores auditivos por outra razão (Escreva):_____					

Sugestão

Para melhorar a utilização dos protetores auditivos, o que gostaria de mudar? (Utilize o espaço seguinte para escrever):

Annex 2

Published papers, communications and posters

Costa, S., & Arezes, P. (2012b). Comparison between occupational noise measurement strategies: why is it important?. *Work: A Journal of Prevention, Assessment and Rehabilitation*, *41*, 2971-2973.

Costa, S., & Arezes, P. M. (2013). On the nature of hearing protection devices usage prediction. *Occupational Safety and Hygiene*, 453.

Costa, S., & Arezes, P. M. (2013). The influence of shift work in the use of hearing protection devices. *Frontiers of Discontinuous Numerical Methods and Practical Simulations in Engineering and Disaster Prevention*, 453.

Varela, M. L. R., Barbosa, R., & Costa, S. (2013). P2P Web Service Based System for Supporting Decision-Making in Cellular Manufacturing Scheduling. In *Computational Intelligence and Decision Making* (pp. 155-165). Springer Netherlands.

Costa, S., & Arezes, P. (2012a). A retrospective reflection/investigation on occupational noise exposure. Proceedings from SHO 2012: The International Symposium on Occupational Health and Hygiene, Guimarães, Portugal.

Costa, S. & Arezes, P. (2012) "Fuzzy logic theory applications on the Occupational risk prevention domain", 10th International Conference on Occupational Risk Prevention, ORP2012, Bilbao, Spain, 2012.

Costa, S., & Arezes, P. (2013). "Pender's health promotion model's contribution to occupational health and safety.", International Conference on Occupational Risk Prevention, Santiago, Chile.

Costa, S., Loureiro, I. F., & Leão, C.P. (2013). Bringing Awareness to Hygiene and Safety Issues to the Young Stratum of Society, in 2013 1st International Conference of the Portuguese Society for Engineering Education (CISPEE), Oct 31-Nov 1, ISEP, Porto, Portugal, 4pp. ISBN: 978-1-4799-1221-6.