Industrial Engineering and Ergonomics

Unit 7
Work Ecology
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Learning Targets

- Become familiar with the definition of noise and sound
- Obtain an overview of the physical and psychological evaluation categories of sound
- Have a basic idea of noise induced hearing damages
- Become familiar with technical, organizational and personal preventive measures for noise
- Learn basics for evaluating harmful hazardous work materials
- Learn classifications and effects of hazardous substances
- Be able to describe the taxonomy and the effects of hazardous substances
According to DIN EN ISO 6385 the influencing factors in work environments can be comprised of a physical, chemical, biological, organizational, social and cultural nature.

These factors can be categorized into the following groups: lighting, noise, mechanical vibration, radiation, climate and working/hazardous substances. The analysis and evaluation of the work environment with respect to these factors takes place according to the following pattern:

1. Basics of cause-effect relationships: The analysis of the environmental influences requires an initial knowledge of the laws of physics, chemistry and physiology.

2. Measurement: Familiarity with state variables and their interaction can answer the following question: Which quantitative specifications lead to a properly sized environment?

3. Quantifying: What has the greatest effect on health and well-being? These effects can result in personal damage, have psychological impacts, but can also influence health or working conditions.

4. Evaluation: If enough knowledge of the environmental loads is available to estimate hazards and operational demands, then set-points and limits for the work place can be determined.

5. Design advice: Arrangements should comply with the limits, or should generally serve to reduce any unnecessary stress and strain.
Noise-induced hearing loss is the highest recognized occupational illness. For this reason it is very important to be familiar with the causes, effects and protective measures. Noise can vary greatly in its sources; it can be caused by press equipment or transducers for instance. A workplace will be labeled as a noisy-workplace if any noise occurs in a duration or intensity that can be considered disturbing or damaging.

Noise is labeled as an audible mechanical wave propagating through elastic media. According to FASTL & ZWICKER (2007) the audible range of airborne sound lies between 20 Hz and 20,000 Hz. Lower frequencies are named “infrasonic”, while frequencies above the audible range are labeled “ultrasonic”.
In Germany there are about 2.5 – 3.5 million noisy workplaces. 5 million employees are exposed to noise greater than 85 dB(A).

During the last three years 10,000 new cases of noise induced hearing loss were indicated per year of which approximately 5,000 new cases were acknowledged for the first time while approximately 1,000 cases were indemnified for the first time.

Examples of noise at work are mining, road maintenance, textiles, packaging, printing presses, saws (chain, circular, metal, & stone), handheld power tools, turbines, assembly lines.
Sound waves propagate spherically in a compressible medium, whereby the speed of propagation $c$ is dependent on the density of the particular medium (under normal conditions, $c$ amounts to approximately 340 m/s in air, 1500 m/s in water, and 5960 m/s in steel). The sound particle velocity $v$ is to be distinguished from the speed of sound in terms of speed with which the material particles in the sound field oscillate. For the dispersion in firm bodies we speak of structure-borne sound instead of airborne sound. For noise protection at the workplace special attention must be paid to structure-borne sound. This is because oscillating solids stimulate the ambient air on their surface, which can amount to local resonance phenomena.
Sound propagation within the audible area is a matter of adiabatic compression or expansion. The waves phase velocity is the velocity of sound \( c_s \). The atmospheric pressure does not influence the velocity of sound, as an increase of pressure is accompanied by an increase of air density. The velocity of sound is contingent on the temperature \( T \). The right figure shows the spreading of sound waves in space with decreasing (left) and raising (right) temperature. With a decrease in temperature the velocity of sound at ground level is major and the sound waves are diverted upwards. The reverse effect can be observed with raising temperature. In this case the sound waves are diverted downwards.
Sinusoidal waves are labeled as pure tones and can be described on the basis of their pressure amplitudes and frequencies. The pressure amplitude produces the volume of the pure tone while the frequency generates the pitch. The sound pressure relates to the ambient pressure; it therefore gives account of the recurring air-pressure oscillations which are a consequence of an audible sound event. A complex tone is defined as a mixture of different frequencies, on condition that the frequencies exist in a harmonic relationship. In case this predefined ratio of frequency changes statistically the sound instance is then defined as noise.
The instantaneous sound pressure is measured in Pascal (1 Pa = 1 N/m²) and always refers to aberrations in the ambient pressure; that is to the dynamic ratio of air pressure. The pressure variations of a compressible sound transmission medium (usually air) are denoted as acoustic pressure, which occur with the propagation of sound waves. For reasons of the energetic contemplation, the effective sound pressure $p_{\text{eff}}$ is used as a parameter, which is defined by the averaging time $T = 1/f$. 
Sound pressure is for energetic considerations usually indicated as effective value $p_{\text{eff}}$. The effective sound pressure is the root-mean-square value of the instantaneous sound pressure at a point during a complete cycle $T$. It is also known as root-mean-square sound pressure. The index “eff” is usually omitted. The sound power $P$ [Watt] indicates an acoustic source’s average output power. Sound intensity $I$ is on an absorption area related to sound power.

Human perception for acoustic stimuli inside the ear features an approximately logarithmic course. The auditory threshold lies at a frequency of 1,000 Hz (1 kHz) at approximately 20 $\mu$Pa, also $2 \cdot 10^{-5}$ Pa. The pain threshold lies at approx. $2 \cdot 10^2$ Pa.

If the aim was to capture the whole dynamic of the lower and upper hearing threshold via an equidistant system of units, quite “bulky” values would be the result. For this reason in acoustic measurement logarithmic dimensions, which are denoted as acoustic levels, are used.

Accordingly, the noise level $L_p$ is calculated as logarithmic proportion of the squared (effective) acoustic pressure to the squared reference sound pressure of 20 mPa (→ hearing threshold) in Bel [B]. Levels are usually indicated in tenth Bel that is decibel [dB].

The smallest for human’s discriminable sound pressure difference is 1 dB. Analogically the assessment levels for sound power and sound intensity need to be calculated. Sound intensity level, sound power level and sound pressure level are the same, whether they disperse in even or spherical waves far field.
This figure shows typical sound pressure levels using examples of familiar noise sources in our environment. When there are several effective acoustic sources at the same time the logarithmic scale must be considered. In carrying out an assessment it is not possible to add several sound pressure levels algebraically due to the logarithmic scale. Instead, the levels must be combined on an energy basis: the sound pressure levels are not added; instead the individual acoustic power levels are added.

For estimation it is useful to know that doubling the emitted sound power of an acoustic source leads to a 3dB increase in the sound pressure level.
The ear can be divided into three parts:

- Outer ear (pinna and auditory canal)
- Middle ear (typanic canal and ossicle)
- Inner ear (cochlea and semicircular canals of the equilibrium organ)

The human pinna, with exception of the earlobe, consists of cartilage; it collects incoming acoustic waves.

The eardrum lies at the end of the auditory canal (outer auditory canal). The eardrum membrane oscillates from incoming acoustic waves and transfers these oscillations to the 3 ossicles in the middle ear (malleus, incus, stapes).

Function: Sound on the eardrum is transferred across ossicles onto the cochlea, which is filled with fluid. The sound wave travels up the scala vestibuli and back down the scala tympani. At the round window the pressure equalization takes place. Hairs (cilia) of different rows of hair on the basilar membrane in the cochlea are moved depending on the frequency of the sound. They hereby activate stimulus effect channels (small ion channels). The approximately 20,000 sensory cells with hair (cilia) and their embedding on the basilar membrane as well as the tectorial membrane comprise the Corti organ. It is there that sound energy is transformed into electrical energy. The acoustic nerves guide the stimulus effect and channels it to the brain cortex, which we then hear.
Sound pressure levels based on "equal-loudness-contours" (DIN ISO 226) document the spectral sensitivity of the human ear. The sensitivity of the human ear is particularly great in those frequency ranges in which human languages are transmitted. This can be easily read off from the accompanying diagram.

The ear is optimized for languages!

The dB-scale does not display exact hearing sensitivity, as this is dependent on frequency. The ear is less sensitive at the lower and upper levels of the hearing threshold in the frequency domain (20 Hz and approximately 20 kHz, see range of audible sound on slide 7-6); at 4000 Hz sensitivity is at a maximum. Therefore, the sound pressure level must be much higher at the hearing thresholds than at the sensitivity maximum if an equally strong perception is to occur.

The unit of loudness was introduced in consideration of this frequency dependency and defined in the following manner. The loudness in Phons is equal to the sound pressure level [dB] of a 1000 Hz tone perceived to be identically loud. Consequently the determination of loudness is always a comparison measurement. Curves of equal loudness (see slide) are obtained by making such comparison measurements throughout the entire acoustic range. Each curve indicates how the sound pressure level $L$ must be changed as a function of the frequency so that it evokes the associated constant loudness along the entire acoustic range. Through subjective hearing comparisons it was established that for acoustic sensations to even begin, considerably higher levels must exist in frequencies above 8000 Hz, and especially in frequencies lower than 250 Hz.
The diagram shows how the metallic membrane mounted over the condenser plate receives the sound pressure waves, which then begins to oscillate. The oscillations cause changes in the capacitance, which then produce an electric signal that is proportional to the original sound.

The voltage signal is measured from the discharging resistor, which is electronically amplified for further processing.

All sound pressure level measuring instruments have to be tested in accordance with DIN 61672.
Since the human loudness perception is dependent on the frequency of the sound waves, the equal-loudness contours (slide 7-13) must be considered through a suitable filtering of the measured sound pressure level [dB].

Various absorption filters are available for this. The important A-filter, used for noise assessment in the workplace, leads to an amplification of the sound pressure level in the frequency range of 1000-6000 Hz in which sounds perceived by humans are especially disturbing. This is due to the low level of the auditory threshold in the frequency domain (frequency contingent). Adequate statements about the subjectively perceived loudness of the noise (A-weighted sound pressure level) can be made by using this filter.

The C-filter is mostly used for the measurement of peak pressure levels (DIN EN 61 672).
According to DIN EN 61672 – 1, three different time weightings are standardized: F (fast, time constant 125 ms), S (slow, time constant 1 s) and in the appendix C (informative) I (impulse, time constant for increasing level 35 ms, time constant for decreasing level 1.5 s).

When set to "S", this results in a highly curbed variation in time on the shown or recorded sound pressure level. The level runs much faster in the setting "F". The setting of "I" is characterized by rapid increases in individual sound events and a subsequent relatively slow drop. This review was originally intended to allow for better interpretation of impulsive sound events. According to the appendix C of DIN EN 61672-1, it is not suitable for this purpose.

In addition to the above time periods, the time weighting “peak” is defined; a very short time constant is used when levels rise and this level is stored. The peak level in the entire history is therefore shown.

To identify the level specified the used time constant can be found in the index, e.g. $L_i$ impulse rating. In addition, whenever a frequency rating is used it also is indicated in the index (e.g. $L_{Cpeak}$ at C-rating and time rating "peak").
Perform a spectral analysis in one-third or octave steps, so that the ear exhibits an approximated logarithmic sensitivity.

Octave Band
An interval in the audible frequency range whose upper frequency is twice that of the lower (e.g. 25 Hz : 50 Hz).

One-Third Octave Band
Region of a 1/3 octave with a frequency proportion of $1 : 2^{1/3}$.

The spectral composition curve of the sound waves was largely neglected in previous energetic considerations. Spectral analyses are done in order to examine sound pressure levels and their distribution in the frequency domain. In examinations of noise, spectral analyses are conducted in one third or octave steps because the ear approximately shows logarithmic sensitivity in these frequency ranges as well. An octave is a frequency range whose initial and final frequency are represented by the $1 : 2$ proportion, e.g. 25 Hz : 50 Hz. A third is the range of a third octave, which means the frequency proportion is $1 : 2^{1/3}$. 
The 'daily personal noise exposure' is a measurement of the average noise energy a person is exposed to during a typical work day. It is directly related to the risk of hearing damage. The following noise exposures would all result in a daily personal noise exposure $L_{Ar}$ of 85 dB(A):

- 85 dB(A) for eight hours,
- 88 dB(A) for four hours,
- 91 dB(A) for two hours,
- 85 dB(A) for four hours plus 91 dB(A) for one hour.

In the same way, continuous exposure to 88 dB(A) for eight hours would give a daily personal noise exposure of 85 dB(A), whereas exposure to 85 dB(A) for just four hours would give a daily personal noise exposure of 82 dB(A).

A-weighted average level $L_{pAm}(T')$ with $T = \text{total assessment time (8h)}$, $L_{Ai} = \text{assessed sound pressure level in part time interval } t_i$. 

The rating level $L_{Ar}$ is equivalent to the daily noise exposure level $L_{Ex, 8h}$ according to 2003/10/EG.

The A-weighted average level $L_{pAm}(T)$ [dB(A)] (also equivalent continuous sound level $L_{pAeq}$)

An assessment time of 8 hours is usually used to estimate the weighted average level over a shift. This is called the rating level $L_{Ar}$.

$$L_{pAm}(T) = L_{pAeq} = 10 \cdot \log \left[ \frac{1}{T} \sum_{i=1}^{n} \frac{t_i \cdot 10^{-L_{pAm}/10}}{10} \right] \text{[dB(A)]}$$

$$L_{Ar} = L_{pAm}(T = 8h) \text{[dB(A)]}$$

The rating level $L_{Ar}$ is equivalent to the daily noise exposure level $L_{Ex, 8h}$ according to 2003/10/EG.
In addition to the effects on hearing (aural effects), noise can also have extra-aural effects such as: psychonerval effects, which can result in a lack of attention, loss of concentration, etc. To produce these effects, the sound pressure level is not decisive but rather the person’s disposition to the sound event and its informational content. In an office, for example, even low noise levels (40-45 dB) cause a disturbance when sound containing information (conversations of other people) are noticed; equally loud, continuous background noises (hum of an air conditioner) are no longer noticed after a certain amount of time due to adaptation.

Vegetative-hormonal effects, such as blood pressure increase, increased gastric juice production or sleep disturbances can already occur at a sound pressure level larger than 45 dB(A).

Noise in the workplace increases the risk of an accident when:

- attention is interrupted
- communication abilities are limited, and
- warning signals or sounds indicating danger are covered up.
The figure shows an audiogram of a person suffering from geriatric hearing loss. It also contains an audiogram of a person suffering from noise-induced hearing loss. These audiograms illustrate the shift of a person’s auditory threshold compared to the normal threshold dependent on the frequency. The noise damage is frequently seen (here too) through the loss of hearing ability at around 4 kHz. This hearing loss is also called the C5 dip. The first signs of noise-induced hearing damage can be detected early on (before the affected individuals notice it themselves) with the help of audiometry.

A Noise Induced Permanent Threshold Shift (NIPTS) is noticed at around 4 kHz and with further exposure, hearing loss gradually spreads over wider frequency range.
If the forces acting on the cutter can be distributed over a larger amount of time, instead of an instantaneous action, a significant noise reduction can usually be achieved.
Another aspect of noise control is the layout of the purchased machinery. Evaluating the location of machinery through analytical evaluations or simulation is much cheaper and easier than physically moving the equipment later. Simple guidelines to follow are: keep machines, processes and work areas of approximately equal noise levels together and separate noisy and quiet areas by buffer zones with intermediate noise levels.
Personal hearing protectors offer the last possibility to prevent noise induced hearing loss. There are three types of hearing protectors available: Ear Muffs / Ear Plugs / Canal Caps.

<table>
<thead>
<tr>
<th>$L_{Ar}$</th>
<th>Measures</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ lower action limits</td>
<td>$L_{ex,8h} = 80$ dB(A)</td>
<td>• Hand out personal ear protection equipment</td>
</tr>
<tr>
<td></td>
<td>$L_{peak} = 135$ dB(C)</td>
<td>• Employer obligation to provide information/instruction</td>
</tr>
<tr>
<td></td>
<td>$P_{peak} = 112$ Pa</td>
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| ≥ upper action limits | $L_{ex,8h} = 85$ dB(A) | • Personal ear protection equipment must be worn according to UVV Noise |
| | $L_{peak} = 137$ dB(C) | • Obligatory to denote areas as noise intensive |
| | $P_{peak} = 140$ Pa | • Preventive medical precautions (hearing tests) required |
| | | • Setting up of noise reduction programs |

The protective measures should be appropriate for the considered exposure limits.

The threshold values are the maximum daily noise exposure level $L_{ex,8h} = 87$ dB(A), the peak noise level $L_{peak} = 140$ dB(C) and the maximum sound pressure $P_{peak} = 200$ Pa.
Definition of airborne hazardous substances:

- Aerosols: disperse distributions of solid or liquid substances in gases
- Dusts: disperse distributions of solid substances in gases, created by mechanical processes or stirring up
- Fog: finely distributed fluid substances in gas, particularly in air
- Smokes: disperse distributions of the finest solid substances in gas, created through thermal or chemical processes
- Gases: elementary or molecular substances
- Vapors: gaseous substances that are in an equilibrium with their fluid/solid phases
German Chemicals Act (Chemikaliengesetz, ChemG):

- Protection of humans and the environment against hazardous impact of dangerous substances and preparations
- Before the stage of commercialization, any influences the new chemical substances might have on humans and the environment must be determined

German Ordinance on Hazardous Substances (Gefahrstoffverordnung, GefStoffV)

- It is the producer’s commitment, to pack and mark hazardous substances and preparations orderly
- It is also the contractor’s commitment to protect employees who deal with hazardous substances and preparations:
  - Duty to investigate (hazardous materials / substitutes)
  - Monitoring obligation (workspace analysis for according to TRGS 402: Limits)
  - Labeling
  - Information and consultation of works and staff councils or employees
  - Creation of standard operating procedures
For each kind of hazardous substance, there is a ‘work place limit’ which stands for the maximum amount for the time weighted average concentration of a substance allowed in the air at a workplace in relation to the reference time period. It indicates at which concentration of a substance certain acute or chronically damaging effects on the general health are not to be expected (§3 Abs. 6 GefStoffV). In addition to the hazardous effect criteria of the substance, the summary should also include the practical conditions of the working process.

Historically, the critical values are drafted as a shift average of 8 hours a day, 5 days a week during ones career. In reality, values show large variations; thus quick exposure spikes can occur. Therefore, in order to prevent damage to health, there is a top limit to the variations of the average value.
The classical MAK-values are no longer relevant in a formally legal way. At the moment, unless AGW-values are defined in a more actual way, the AGW-values refer to the old MAK-values. The MAK-values describe the maximum allowable concentration of working materials such as gas, steam or vapors in the workplace air. MAK takes into account the current state of knowledge about the substances, and also considers repeated and long-term exposures over an 8-hour workday. However, the compliance of an average workweek of 40 hours should not adversely affect the health of the employees. As a rule, the MAK-values are integrated over time periods which could be a work day or shift.

The MAK-values usually (but not always) account for the fact that the different sensitivities of employees are contingent to various factors such as age, constitution, nutritional condition and climate. Compliance to the MAK-values does not protect against any occurrence of allergy sicknesses among employees. Nor does it safeguard unborn children from teratogenic substances (normally deviant).

MAK-values/AGW are revised every year by the Senate Commission for the Assessment of Harmful Work Materials by the German Research Foundation, and are published in different locations (ex. as TRGS).
Since January 1st 2005, the new hazardous material regulations of biological-workplace tolerance-values (BAT values) have been replaced by the biological limit values (BGW). The old BAT-values can still be applicable as indicatory and orientation values until the conversion of the regulation has completely occurred. The biological limit is a limit that defines the toxicological-occupational health derived concentrations of a substance, its metabolic or stress indicators in the corresponding biological material, and so that the general health of an employee will not be impaired (§ 3 Abs. 7 GefStoffV).

Biological limits can be defined as concentrations, generation- or emission-rates (amount/time values). As with the workplace limits (AGW), the material contamination over an 8 hour workday or a 40 hour workweek is used as the standard. Biological limits are intended for a singular healthy individual. The effect-characteristics of the biological material are considered for blood and/or urine. The occupational health and toxicological founded criteria are also decisive for the protective measures. Biological limits are generally only valid for the exposure of single materials (TRGS 903).
Substitute a less harmful material: e.g. Water-based cleaning compounds instead of organic based or solvents with higher dose thresholds.

Enclose the process: Capture of substances and vapor before they are dispersed. Three guidelines: a) physically enclosure of process or equipment
b) remove air movement from the enclosure
c) minimize the distance from an external hood to the source

Enclosure of the poison cabinet

Order of fighting against harmful substances:
1. Avoid them
2. Technical measures
3. Organizational measures
4. Personal security measures and behavior instructions/requirements
We live in an era of new technology and more complex production systems, where fluctuations in global economics, customer requirements and trade agreements affect a work organization’s relationships. Industries are facing new challenges in the establishment and maintenance of a healthy and safe work environment.

Screen of potential employees: Restrict development of people who are more sensitive than others (pregnant women, those with allergies,...)

Training of supervisors, engineers and workers: Employers have to inform their employees about chemicals and train them in safe use.

Reduction of exposure time: This also decreases recovery time. Not all work time must necessarily be exposure time.
Examples are:
Aprons, leggings, gloves, respirators to protect lungs, earmuffs and earplugs, safety glasses, helmets, hairnets

Problems:
Protective clothing is the last line of defence. Much protective clothing decreases the comfort or performance of the person, causing temptation not to use protective clothing.
Questions to examine your success in learning

✓ What is sound? What is noise?
✓ How can be sound categorized?
✓ What measurement categories are used to assess the sound level?
✓ What can be described by the equal loudness contours?
✓ Which types of noise induced hearing damages are caused by noise?
✓ What are the critical factors influencing the severity of hazardous substances in the human body?
✓ What technical, organizational and personal preventive measures do you know of when it comes to hazardous substances?
Literaturverzeichnis

- VDI Richtlinie 3720 (1982) Lärmmarsch konstruieren. VDI, Düsseldorf
Carcinogenic dust causes cancer (for example arsenic, beryllium, hexavalent chromate, nickel).

Toxic dust damages the viscera via toxic effects (for example lead, zinc, cadmium, manganese). It is mainly the total dust concentration that is considered for evaluation.

Caustic dust causes damage by forming bases and acids which destroy tissue (for example lime, chrome, cadmium, manganese, vanadium).

Radio active dust damages via ionizing radiation.

Allergy inducing dust damages via acute and chronic inflammation of lungs and skin. For example: allergic bronchial tubes asthma and inflammation of the skin via chromates (for example in the dust of concrete, nickel or tropical wood).

Inert dust are not toxic and do not cause specific health damages (for example ferric-, magnesium oxide). For these dusts the “general dust limit value” is relevant, which fixes a maximum of fine dust of 6 mg/m³. The maximum is necessary as these dusts can disturb the functioning of the lungs due to occlusion of alveoli.

Smokes are defined as distributions of the finest solid substances in a gas, especially air. They emerge via thermal and/or chemical processes. The primary particle of smokes normally have a diffusion-equivalent-diameter smaller than 0.5 mm. In contrast to most of the dusts, with smokes you also have to care about chemical-irritative and/or chemical-toxic effects. You have to pay special attention to the fact that the smoke that emerges while welding varnished components contains a lead, zinc, chrome and phosphorus combination, and the smoke which emerges while soldering contains heavy metals.
Fogs are finely distributed liquid substances in gases, particularly in air. Particular attention should be paid to oil mist caused by metal working. According to current scientific standards, the levels found in workshops are not harmful as long as the oils do not contain toxic additives. During metal working, however, carcinogenic nitrosamines were discovered in the oil mist and allergic skin reactions have been observed as a consequence.

Gases are elemental or molecular substances that are, under normal air conditions, very distant from their dew point, and are therefore not present as solids or liquids.

Vapors are gaseous substances that result from evaporation or vaporization and that remain balanced in their viscous as well as their solid phase. Organic solvents have a low boiling point and can thus often be found as vapors. The often used chlorinated hydrocarbons, such as tetrachlormethane CCl₄, trichloethane CCl₂-CHCl, tetrachlorehene (perchloethylene) CCl₂-CCl₂, 1,1,1-trichloethane CCl₃-CCl₃ and dichloromethane (methylene chloride) CH₂Cl₂ produce strong vapors and cause dizziness, light-headedness and intoxication quite easily. Chronic consequences are a lack of concentration, alcohol intolerance and severe liver and kidney damage. Halogenated hydrocarbons work as a contact poison in liquid form and are highly poisonous if orally ingested.