ACOUSTIC DESIGN OF SWIMMING HALLS

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MASTER'S DISSERTATION

ACOUSTIC DESIGN OF SWIMMING HALLS

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Abstract

The Master thesis considers acoustic design of swimming halls. Focus is put into design solutions affecting the acoustic environment such as walls, absorbents and shape. The basis is gained from literature studies and new information achieved specific for the thesis.

Swimming halls are built in a certain way that makes a good acoustic environment hard to achieve. The construction consists of hard surfaces and with large volume which creates a loud environment with lot of echoes. The safety aspect may be harmed by this and it can also cause health problems.

The problem is that acoustic solutions are difficult to apply to swimming halls due to climate and function demands, for example the lower parts of the walls being exposed to water and contact. One problem is that acousticians are consulted at a later stage in the project where available solutions are more limited. The acoustic influence is getting more prioritized nowadays which is important in order to achieve a desired acoustic environment.

During the thesis persons with great expertise in areas regarding construction of swimming halls, both acousticians and other professionals, are interviewed. Visitors and employees in swimming halls have been consulted with questionnaires and the subjective part of acoustics is gained. Measurements in Hylliebadet in Malmö have been performed as well as simulations of a swimming hall in two versions. Parameters such as reverberation time, sound pressure level, speech intelligibility etc. are investigated as well as the subjective opinion on the acoustic environment in swimming halls.

The study presents results showing that the recommended reverberation time is achieved for new swimming halls with absorbents placed on the ceiling and on the walls. It also shows that the acoustic environment is improved by tilting a wall. The background noise is a part of the problem and to reduce this is an important aspect. The speech intelligibility is important for safety reasons and a sufficient level seems hard to achieve. The visitors are satisfied with the environment but the employees are exposed to a work environment that needs to be improved.

Solutions suggested are primarily an addition of absorbents, lower ceiling height and one tilted wall. Screens may be useful for educational purposes and water as a sound source should be further investigated. Drains for example causes high background noise and more quiet solutions would improve the acoustic environment and reduce the risk that visitors speak even louder, which creates even more sound.

The tools to achieve this are to include an acoustician in the early stage of the project. When acoustic solutions can be suggested before the design is determined the outcome is better and the cost lower. It also avoids the risk for later alterations. The team working with the swimming hall project should have experience from swimming halls and share this. Collaboration between acousticians and architects creates better solutions and reduces the risk for undesired compromises.

Sammanfattning

Det här examensarbetet behandlar den akustiska utformningen av simhallar. Fokus ligger på de lösningar som påverkar akustiken, så som väggar, absorbenter och utformningen. Grunden till arbetet är baserat på befintlig litteratur och ny information framtaget för arbetet.

Simhallar är en svår akustisk lokal där många hårda ytor och stora volymer försvårar. Detta ger en ljudmiljö med hög ljudnivå och långvariga reflektioner. Säkerhetsaspekten kan bli försämrad på grund av detta. Dessutom kan en dålig ljudmiljö leda till hälsorisker.

Problemet är att akustiska lösningar är svåra att applicera på simhallar, mycket på grund av klimatet och funktionskraven. Ett problem är att akustiker ofta tillfrågas i ett senare skede då utformningen redan är fastställd vilket begränsar möjligheterna. Akustiken blir mer och mer prioriterat och detta är viktigt för att uppnå en önskad ljudmiljö.

Under arbetes gång har kunniga personer tillfrågats och deras kunskap och erfarenhet är en viktig del av underlaget för slutsatsen. Detta gjordes via intervjuer. Även enkäter har använts där åsikter från besökare och anställda har kartlagts vilket inkluderar den subjektiva aspekten av akustik. Egna mätningar har utförts på Hylliebadet i Malmö och utformningen av simhallen har efterliknats och generaliserats för simuleringar. Två olika utformningar av simhall har simulerats för att undersöka skillnaden. Resultaten är grundläggande för slutsatsen. Parametrar som efterklangstid, ljudtrycksnivå, taluppfattbarhet med mera är undersökta tillsammans med den subjektiva upplevelsen av ljudmiljön i simhallar.

Studien presenterar resultat som visar på att de rekommenderade efterklangstiderna uppnås för nya simhallar med absorbenter i tak och på väggar. Att luta en vägg visar sig vara en förbättring. Bakgrundsnivån är en del av problemet och att reducera detta är en viktig del av lösningen för att uppnå god ljudmiljö. Taluppfattbarhet är viktigt för säkerhetsaspekten och resultaten visar att det är svårt att uppnå en tillräckligt god nivå. Besökarna är nöjda med ljudmiljön men de anställda är utsatta för en arbetsmiljö som behöver förbättring.

Föreslagna lösningar är framför allt absorbenter, låg takhöjd och en lutade vägg. Inlärningssituationen kan förbättras med avskärmning och vatten som ljudkälla bör studeras vidare. Skvalprännorna ger till exempel upphov till höga bakgrundsnivåer och tystare lösningar skulle förbättra ljudmiljön och reducera risken att besökarna höjer rösten för att överrösta och på så sätt ökar ljudnivån ytterligare.

Verktygen för att uppnå detta är att tillfråga en akustiker tidigt i projektet. När akustiska lösningar kan föreslås innan utformningen är bestämd kommer utfallet bli bättre och kostnaden lägre. Då undviks också risken för behov av senare åtgärder. De som arbetar med simhallsprojektet bör ha erfarenhet från tidigare simhallar och dela denna för bästa resultat. Samarbete mellan akustiker och arkitekter skapar bättre lösningar och minskar risken för att oönskade kompromisser uppstår.

Acknowledgments

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During the process with the thesis support and knowledge from LTH and ÅF Infrastructure has been highly appreciated. My supervisor Delphine Bard at LTH should have a big gratitude for guiding, input and support. I want to thank all the people at Sound and vibration at ÅF for helping me with the thesis with everything from measurement equipment and expertise to comradely support.

Furthermore, I want to thank all the persons I got the opportunity to meet and interview. I also want to express my gratitude to the employees at Hylliebadet and Kockums Fritid in Malmö for helping me execute my thesis and to the people who took the time to answer my questionnaires.

I also want to thank friends and family for their support.

Lund the 20th of May 2016

Malin Hall

List of terms

SPL	(dB)	Sound pressure level
T20, T30	(s)	Reverberation time
STI	(-)	Speech transmission index
S/N	(dB)	Signal to Noise
L_{eq}	(dB)	Equivalent sound pressure level
L_A	(dB)	A-weighted sound pressure level
L_C	(dB)	C-weighted sound pressure level
L_Z	(dB)	Z-weighted sound pressure level
F	(Hz)	Frequency
A	(-)	Absorption coefficient
Phon	(-)	Loudness

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Appendix:

1. Introduction

1.1. Background

Swimming halls are constructed for a very specific purpose. This leads to constructions with hard surfaces and large volumes which creates a noisy environment for visitors and employees (Socialstyrelsen, 2006). The sound waves bounces between walls, ceiling, floor and water surface since they are all hard surfaces. Absorbents are frequently used to improve the acoustic environment in buildings but due to the climate in swimming halls it isn't as simple as usual. The acoustic perspective is seldom a priority and is often consulted in a later phase.

The theoretical background of the study is published work about fundamental room acoustics and acoustics in large rooms. Theory about the ear and the health effects of sound on humans is also investigated along with acoustics in construction management. Besides that knowledge about connections between values from measurements and experienced acoustic environment will be used, for example reverberation time and speech intelligibility. Existing projects to study are provided by ÅF.

The acoustic environment affects the health of people and therefore work environment is an important issue to study (Arbetsmiljöverket, 2005). Health issues as tiredness as well as increased heart rate are caused by noise pollution. For employees the performance at work may be impaired. Another consequence of high sound pressure level is hearing damage.

Demands for acoustics in swimming halls are not specified and instead demands for other similar occupations are used. One problematic issue is the integration of acoustics in the project, which may occur in different phases of the building process. These are aspects that needs to be evaluated. A complete guide for acoustic environment in swimming halls seems to be missing and this thesis will be a contribution to the subject.

1.2. Problem formulation

The purpose of the study is to present possible improvements of the acoustic contribution in the design phase of swimming halls. The result will provide guidelines for future projects.

How should swimming halls be designed in order to have a good acoustic environment?

1.3. Aims and objectives

The purpose of the Master thesis is to investigate the current state of the acoustic environment in swimming halls, the acoustic part of the design phase and to detect possible improvements. Questions to be answered are what kind of parameters are important, what is experienced as good acoustics in swimming halls and how the design of the swimming hall effects the acoustic environment. The thesis will investigate the design of swimming halls in order to develop design guidelines and improvements.

Project aims:

- Analyze the acoustic part of the design phase of swimming halls
- Examine the design of swimming halls with measurements and simulations
- Detect connections between measurement values and experience
- Present possible improvements

1.4. Limitations

In order to reach useful conclusions with the available amount of time limitations are necessary. The study will examine the shape of swimming halls and the ability to effect the acoustic environment in the design phase. The structural design will not be considered and thereby measurements of airborne and structural borne sound between rooms will not be executed. Measurements and questionnaires performed in one swimming hall will provide values relatable to design and experience, but the study would be better with measurements of several swimming halls in order to compare different executions. Due to time limitations only one swimming hall is observed. The part of swimming halls that are considered are for example pools for exercise or education and adventure baths. Other spaces such as dressing rooms are excluded from the thesis. The main part of the thesis examines the acoustic environment and the acoustic part of the design phase in general and interviews are not limited to one swimming hall. Different absorbents and other materials are not observed at a detailed level.

1.5. Disposition of the study

The thesis is divided in chapter as following. The content and connections between topics are explained further down.

1.5.1. Chapters

1. Introduction
2. Theory
3. Guidelines
4. Methodology
5. Interviews
6. Measurements
7. Simulations
8. Discussion
9. Conclusion
10. References

Chapter 5, 6 and 7 are new information derived for the thesis. The result for each part is included in respective chapter and comparisons are done in the discussion. Further down the connections between the content in the thesis are explained as well as the chosen methodology is briefly introduced.

1.5.2. Content

The Master thesis consists of a wide spectrum of collected information related to acoustics. The focus is regarding to swimming halls but the literature is enclosing a greater region. The connections between the topics are illustrated in the figure 1 below.

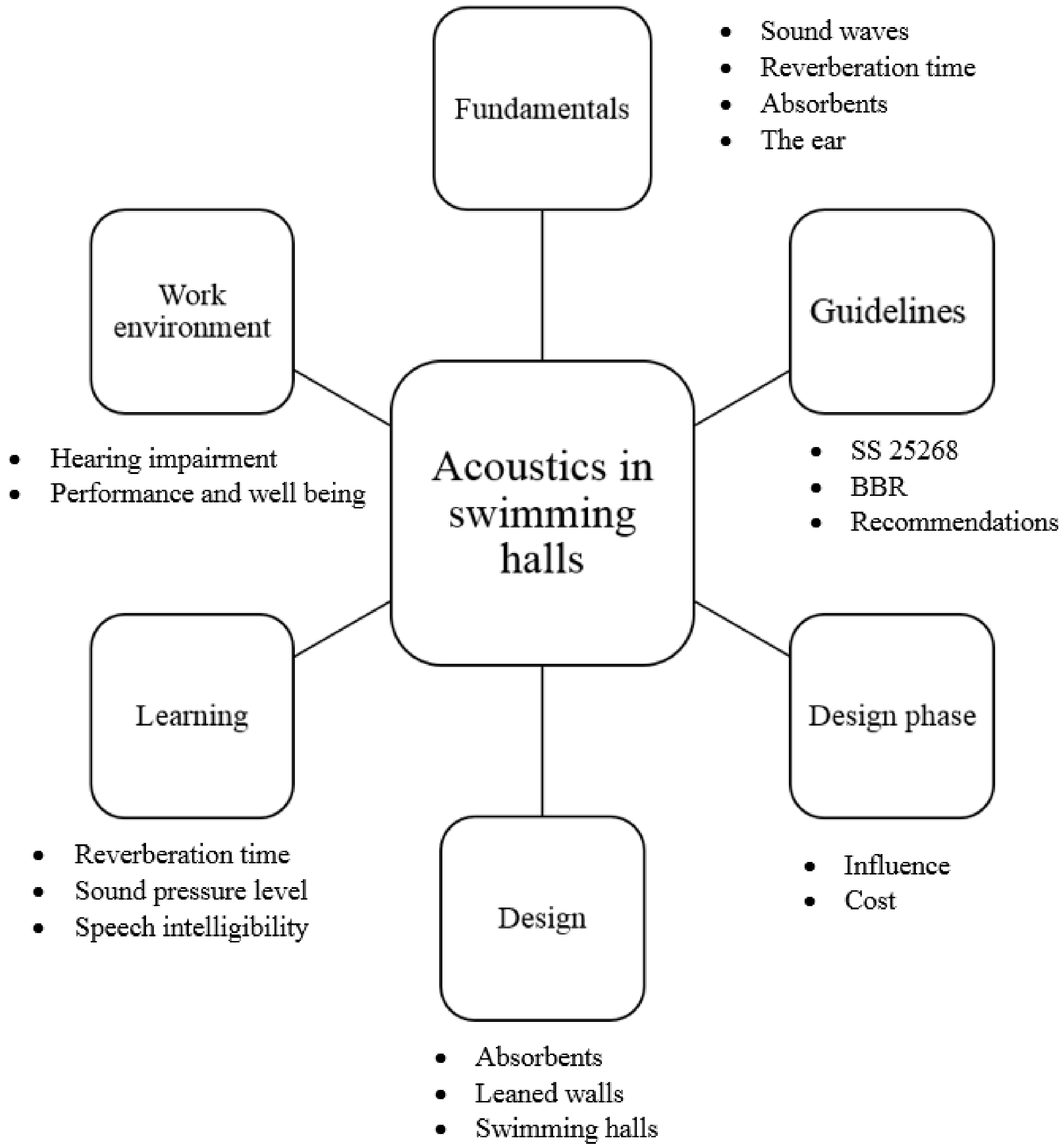


Figure 1: Flow chart describing the connection between the content of the thesis

Swimming halls are central in the thesis but the acoustics of swimming halls considers more than absorbents and measurements. The ear and hearing impairment are included in the thesis since it is a consequence of "bad" acoustics properties. Work environment is essential since high sound pressure levels will affect the employees. The visitors may also be affected but the greater consequences will harm the personnel and the theory of sound related to well-being and performance as well as the opinion of employees are important for the thesis.

Swimming halls are partly used for education purposes and this is taken into consideration. The sound environment effects the ability to learn and therefore is speech intelligibility etc. included in the thesis. Related to this is the safety aspect, where alarms and screams for help needs to be heard.

Fundamental acoustic theory is of course important in order to understand the way sound works and to explain the situation in swimming halls. Construction management is explained in order to emphasize the process, the roll of the acoustician and the consequences. The design phase is fundamental for the design of the room and evolves from the guidelines. The design is focused on absorbents and leaned walls. The outcome of the design phase is essential for the final swimming hall.

1.5.3. Methodology

In order to investigate the acoustic environment in swimming halls a literature study, measurements, questionnaire and interviews will be performed, more about this in Chapter 3. Measurements will be performed in one swimming hall. In order to investigate successful factors the measurements are supplemented with questionnaires for visitors and employees. Simulations of two versions of a similar swimming hall as for the measurements are executed.

Interviews: Interviews with more investigating questions for persons with sufficient knowledge and experience.

Questionnaire: Questions with multiple alternatives for visitors and employees in swimming halls.

Measurements: Reverberation time and sound pressure level are measured in one swimming hall. The sound pressure level is measured with and without activity.

Simulations: Design of a swimming hall in two ways is simulated in order to be compared to each other as well as to the measurements.

The questionnaire will detect connections between the acoustic experience in swimming halls and the result from the measurements. The interviews will show how the acoustic work is included in the development of swimming halls, give an explanation for the current situation and show where improvements can be done.

2. Theory

2.1. Fundamental acoustics

Fundamental acoustics theory is essential to explain in order to understand the way sound works. Regarding acoustics the theory of sound is necessary to know. Further down some basic theory of sound is introduced, for example characteristics, followed by common measures and the application in buildings.

2.1.1. Sound

The characteristics of sound such as content, movement and speed are introduced. Frequency is an essential definition explained in this chapter.

Sound waves

Sound is pressure variations in the air and is produced from example a vibrating surface (Ginn, 1978). The rapid fluctuations in the air are interpreted as sound in the human ear. The vibrations create waves that spreads through a media, for example air. The waves are propagating though the media by moved particles. One particle transfer momentum to the next particle and a moving wave is created. The sound waves are disturbed by obstacles (Åkerlöf, 2001). Small obstacles rarely affect the waves but large obstacles bends the waves which is called diffusing, see figure 2.

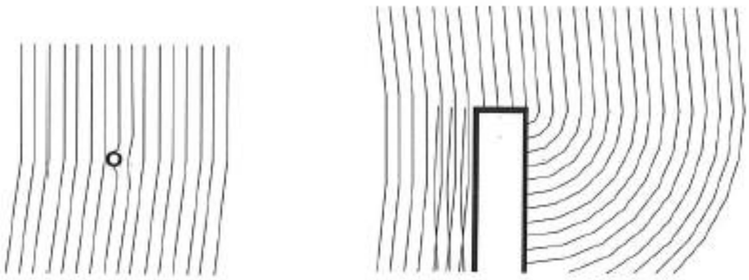


Figure 2: The waves reaction to small and big obstacles (Åkerlöf, 2001).

Several different kinds of waves exists: plane wave, diverging wave, spherical wave, progressive wave and standing wave (Ginn, 1978). Plane waves are waves parallel to each other. Diverging wave is when sound from a source is growing and have a lower intensity with the distance. Spherical wave is sound from a source spreading in every direction. Progressive wave is when transfer of energy is in the direction of propagation. Standing wave consists of two or more waves emerging and constructs a wave with constant maximum and minimum, this can appear in instruments and in rooms.

Speed of sound

The speed of sound depends on the mass and elasticity of the medium, where the elasticity is determined by a constant multiplied with the atmospheric pressure, see formula 1 (Ginn, 1978).

$$c = \sqrt{\frac{1{,}4P_0}{\rho}} \quad (1)$$

P_0=atmospheric pressure

ρ =density of air

The speed of sound in air is 340 m/s (Socialstyrelsen, 2008). Sound is also spreading in other materials and higher density leads to higher speed of sound.

Wavelength

The wavelength, λ, is the length the wave moves during a complete wave motion and the distance between two successive pressure maxima or minima in a plane wave, see Figure 2figure 3 (Ginn, 1978). It is determined by the speed and frequency, se formula 2 below.

$$c = f\lambda \quad (2)$$

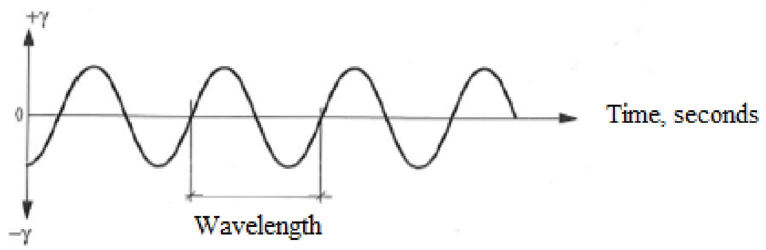


Figure 3: The wavelength for a clear tune (Åkerlöf, 2001).

The sound wave is affected by objects depending on the wavelength (Åkerlöf, 2001). High frequencies with smaller wavelengths are reflected on the object and a sound shadow is created behind the object. Sound waves with longer wavelengths is only a little disturbed and continues almost as before.

Frequency

Frequency is the number of waves per second (Åkerlöf, 2001). The frequency is given in the unit Hertz, Hz, and calculated as formula 3 below depending on the period time, T.

$$f = \frac{1}{T} \quad (3)$$

Sound often consists of several waves with different wavelengths (Åkerlöf, 2001). The audible area reaches from 20 Hz to 20 000 Hz which are wavelengths from 17 meters to 17 millimeters. Sound within the frequencies 20 to 200 Hz is low frequency sound (Socialstyrelsen, 2008). The length of the sound waves then vary between 17 meters and 1.7 meters and the long length makes it harder to reduce the sound waves. Low frequency sound travels longer due to this and may spread through boundaries such as walls more than higher frequencies.

Sound consists of tones with different frequencies (Socialstyrelsen, 2008). One clear tone consists only of one fundamental tone with one frequency. Noise is sound consisting of all frequencies in a random distribution of strength. Speech is a mix of tones and noise. Sound consisting of a large amount of low frequencies effects people more than sound without that. Consequences are tiredness, irritation, headache, disturbed sleep and difficulties with concentration.

Octave band

The frequency content in a sound is divided in octave band and third octave band (Bernström, 1987). Octave band is a distribution of frequencies and one octave band consists of three third octave band. The octave band is named with the middle frequency and the bands are called 125 octave band, 250 octave band and further on. Every middle frequency in the octave band is twice as high as the previous. The highest frequency in an octave band is twice as high as the lowest frequency. Sound calculations are often based on octave band while sound measurements are performed in both octave and third octave band. A value for the whole spectrum may be calculated in dB as well.

2.1.2. Measures

Sound can be measured in several ways. The most relevant measures for the acoustic environment in swimming halls, such as decibel and sound pressure level, are explained below.

Decibel

Units used for acoustical measurements are mostly sound pressure, sound intensity and sound power described in Pa, W/m^2 and W (Ginn, 1978). Besides this a logarithmic scale is used in order to include the wide range of audible intensities. One logarithmic scale is decibel, a relative measurement related to a reference pressure, power or intensity, see figure 5. The denotation r below is the power ratio corresponding one decibel.

$$Log_{10}r = 0{,}1 \quad (4)$$

Peak, average and rms

Sound pressure level and other measurements that varies in time might be measured at the peak, average or rms value (Ginn, 1978). Rms is the root mean square, it is connected to the energy content and is commonly used. The peak value is the maximum amplitude and the average is a mean value, see figure 4.

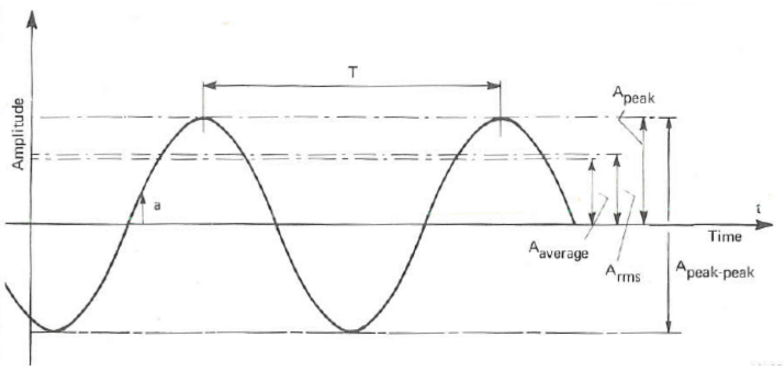


Figure 4: Relation between peak, average and rms of a sinusoidal signal (Ginn, 1978).

Sound pressure level

Sound pressure level, SPL, is calculated by the following formula.

$$SPL = 20log_{10}\left(\frac{p_{rms}}{p_0}\right) \quad (5)$$

Where p_{rms} is the root mean square pressure and p_0 the reference sound pressure level of 0.00002 Pa. The reference sound pressure level corresponds to the lowest sound that an average young adult can detect.

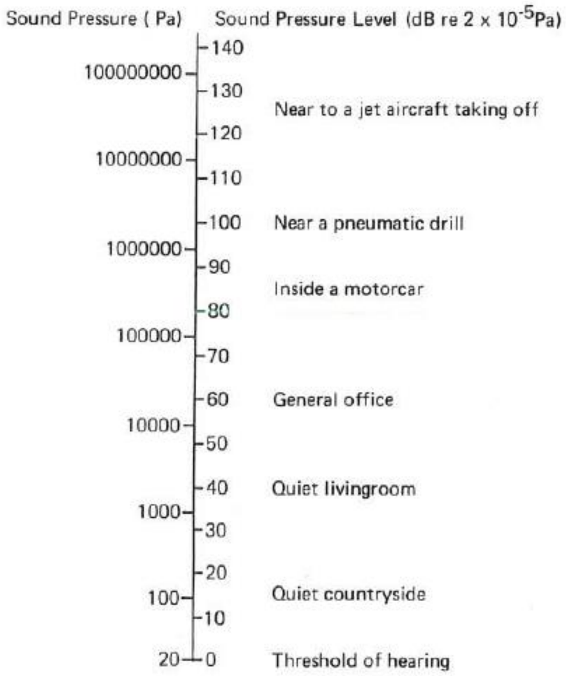


Figure 5: Listed examples of sound pressure levels (Ginn, 1978).

Sound pressure level is a common value to use for evaluating sound and two main values are used (Åkerlöf, 2001). The equivalent sound pressure level is the average value during a certain amount of time. The maximum level of sound is defined as the highest temporary sound pressure level during a certain amount of time.

2.1.3. Architectural acoustics

Sound is applied to buildings regarding the acoustic environment in a room. The sound situation is depending on sound sources, insulation and absorbents for example. In a swimming hall these are some parameters effecting the acoustic environment.

Sound sources

In architectural acoustics the variety of sound sources are large (Ginn, 1978). Loudspeakers, machines, the voice and musical instruments are examples of possible sources. This makes a difficulty due to the different behaviors of the sources. Two different ways to describe the sources are monopole and dipole. Monopole is one sound source that may spread the sound spherical from one point. This will create harmonic spherical waves if the medium is homogeneous and isotropic. Sound intensity is reduced with distance from the source since the area of sound energy is larger. Twice the distance will decrease the sound pressure level by 6 dB. One example of a situation when this occurs is a loudspeaker placed in a room with free space. A dipole or an acoustic doublet occurs when a source produces a sound spreading from two directions.

Sound insulation

Sound is able to spread between rooms in air or in the structure of the building (Ginn, 1978). Sources to airborne sounds are e.g. speech and loudspeakers. Structure borne noise is created by impact such as footsteps, slamming doors and some installations and travels through the structure. Impacts are also a source to airborne sound. In order to prevent sound transmission sound insulation is used. Airborne sound is spread between rooms by the separating boundary, e.g. wall, floor or ceiling, where some sound is absorbed and some sound propagates through. The airborne insulation is calculated with sound reduction index, R. Boundaries with larger value of R will create a better insulation and a lower sound pressure level at the other room.

$$R = 10log_{10}\left(\frac{W_1}{W_2}\right)\ dB\ (6)$$

W_1= sound power incident on the wall

W_2=sound power transmitted through the wall

For cases where the sound is diffuse and transmission is through the boundary calculations can be done as below.

$$R = L_1 - L_2 + 10log_{10}\left(\frac{S}{A}\right)\ dB\ (7)$$

Flanking transmission is sound transmitted through boundaries both direct and indirect, see figure 6 (Ginn, 1978). The figure shows possible paths, some through the separating wall and some waves travels other ways. Sound is also transmitted through air ducts, door leaks etc. Flanking transmission, R', is calculated below.

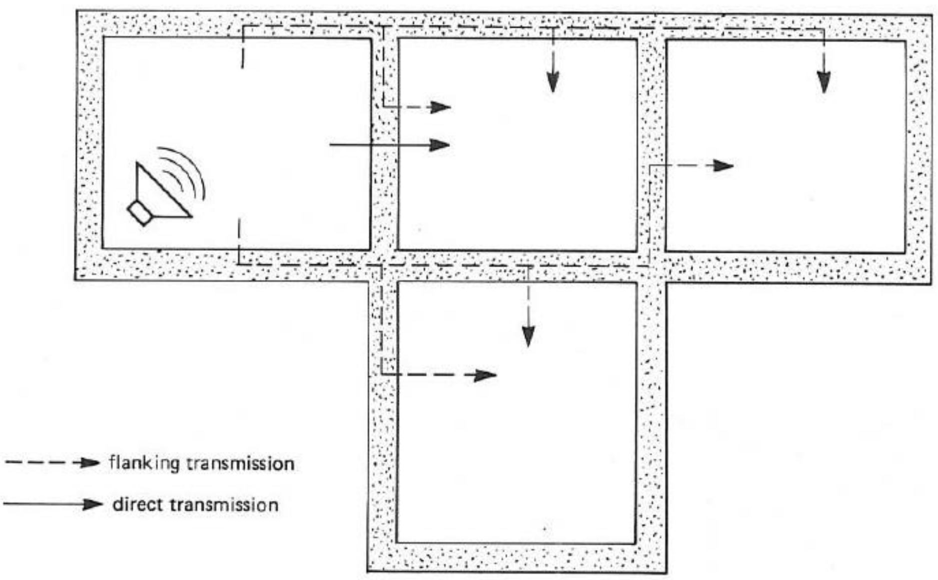


Figure 6: Transmission paths between rooms (Ginn, 1978).

$$R' = 10log_{10}\left(\frac{W_1}{W_3}\right)\ dB\ (8)$$

W_3=total sound power transmitted into the receiving room

Impact sound is prevented from spreading by impact sound insulation (Ginn, 1978). Vibrations in the structure transmits sound to the receiving room. The insulation, L_n, is calculated by the equation below.

$$L_n = L_i - 10log_{10}\left(\frac{A_0}{A}\right)\ dB\ (9)$$

L_n=normalized impact sound pressure level

L_i=impact sound pressure level

A_0=10 m^2 the reference absorption area

A =measured equivalent absorption area of the receiving room

Diffuse sound field

In a room the sound waves will spread from the source (Kinsler, 2000). When the waves collide with boundaries some waves are absorbed and the rest reflected back to the room. The reflections collide with another boundary and the new reflections are sent back. After a while this becomes a diffuse sound field where the energy density is constant. Reflections at the boundaries produce a sound energy distribution becoming more uniform with time.

Reverberation time

Reverberation time is defined as the time required for the sound pressure level to decrease 60 dB (Kinsler, 2000). With a continuous sound source two sound fields exists. The direct sound creates the direct sound field and the reflections creates the reverberation sound field.

Sabine's formula

The reverberation time can be calculated with Sabine reverberation formula (Ginn, 1978). The formula is derived from empirical studies of the relationship between the volume of a room and the amount of absorptive materials. The parameters are related to the reverberation time as below where T is reverberation time, V is volume and A is the total area of absorbents.

$$T = 0{,}161\frac{V}{A}\ (10)$$

The formula is adapted for room volumes less than 1000 m^3 and larger volumes are not accurate calculated with Sabine's formula (Saint-Gobain Ecophon AB, 2002).

Absorption coefficient

Absorption coefficient, α, is a dimensionless measure for a materials capacity to absorb sound waves (Saint-Gobain Ecophon AB, 2002). The value is decided from standardized measurements of a sample of the material in a reverberation chamber, see figure 7.

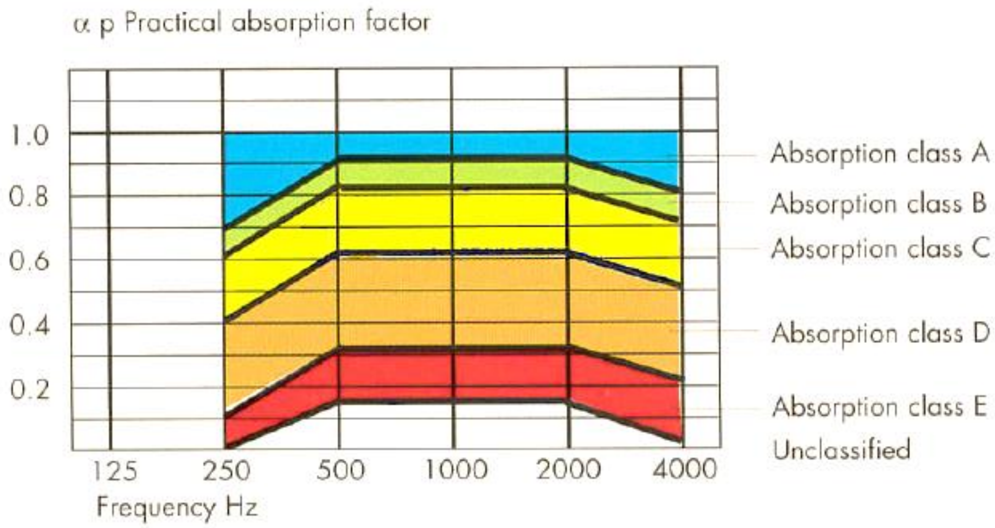


Figure 7: Absorbent classes (Saint-Gobain Ecophon AB, 2002).

The picture shows the distribution of absorbents (Saint-Gobain Ecophon AB, 2002). The ability to reduce sound is divided in absorption classes from A to E, where A is the best. The absorption coefficient is on the left axis and the absorption for each frequency from 250 Hz to 4000 Hz is shown on the x-axis. This is measured by the international standard EN ISO 354 and classified by the international standard EN ISO 11654.

2.1.4. Sound absorbents

Reflectors and absorbers are used in order to create a good acoustic environment (Ginn, 1978). All surfaces in a room absorbs sound. Hard surfaces such as tile absorbs little sound but soft, porous materials such as carpets absorbs far more sound. Sound absorbers have different characteristics and can be divided into categories: porous material, panel absorbers, cavity resonators and individual people and items of furniture (Kinsler, 2000). High frequencies are absorbed with porous materials, for example textiles and soft furniture, and low frequencies are best absorbed with thin sheets or openings (Rosenberg, 1992).

Porous absorbents

Porous absorbers are effective for reducing specific frequencies (Kinsler, 2000). The effect is small at the lower frequencies and increases with higher frequencies. The absorptivity increases with the thickness of the material. In order to decrease lower frequencies, the absorbent is placed a certain distance from the wall. Porous absorbents works due to friction and transforms some of the sound waves to heath energy (Saint-Gobain Ecophon AB, 2002). The rest of the sound energy is transmitted on the other side of the absorbent. Examples of porous absorbents are acoustic tiles and plasters, mineral wool, carpets and curtains.

Panel absorbents

Low frequencies are absorbed by panel absorbents, placed away from a solid backing (Kinsler, 2000). The panel vibrates and transforms some of the sound energy to heat energy. The effects increases with porous materials between the panel and backing. Gypsum and plywood boards are two examples of panel absorbers.

Cavity resonator

A box or similar object with room for air and connected to the room by a thin split works as an absorbent for frequencies close to the resonance (Kinsler, 2000). To create this panels or elements in for example wood with perforations are used. This absorbents are made of individual pieces where a few frequencies are absorbed or several absorbents with effectivity over more frequencies. In order to make this absorbents more effective porous absorbents might be used behind which makes more frequencies reduced (Saint-Gobain Ecophon AB, 2002).

People and furniture

Sound absorption per item of clothing on a person or on a furniture can be measured. Wooden furniture has some effect (Kinsler, 2000). Fabric works as porous absorbents but doesn't affect the reverberation time and speech intelligibility a lot since it concerns the higher frequencies, outside the speech use (Saint-Gobain Ecophon AB, 2002).

In order to reach the best room acoustic environment the free space, the ceiling, should be used (Saint-Gobain Ecophon AB, 2002). Sometimes addition of absorbents on the walls is necessary. Absorbents on the ceiling are partly protected from wear. Above the absorbents a space with air may be used in order to increase the absorbing effect, especially at the lower frequencies.

2.2. The hearing system

The ear and the hearing system is a central theoretical part of acoustics and therefore introduced in this chapter. The ear is fundamental for the relationship between sound and health consequences, presented later on.

2.2.1. The ear

The ear consists of three parts: the outer, middle and inner ear (Kinsler, 2000). The ear together with the nervous system acts as a frequency analyzer and is one of the most delicate mechanical structures in the human body. The ear is illustrated in figure 8. The pinna directs the sound into the auditory canal, a tube about 2.8 cm long, leading to the eardrum. The middle ear consists of three ossicles (bones). The malleus (hammer), the stapes (stirrup) and the incus (anvil) are the three components and are placed in an air-filled space. The inner ear is connected to the middle ear by the oval window and contains a liquid. The area between the eardrum and the oval window acts as a broadly resonant coupler to the liquid. The inner ear consists of three parts: the vestibule, semicircular canals and cochlea. The semicircular canals only contributes a sense of balance, but the cochlea, with the shape of a snail shell, containing cilia (small hairs) sending electrical impulses to the brain. When sound pressure reaches the eardrum it transforms into vibrations that are forwarded to the cochlea through the middle ear (Ando, 1998). The stapes drives the fluid in the cochlea which creates a traveling wave. The vibrations put the fluid in motion and the membrane in the cochlea translates it with receptors of around 15000 hair cells. These are nerve cells and transmits the message to the brain where it is interpreted.

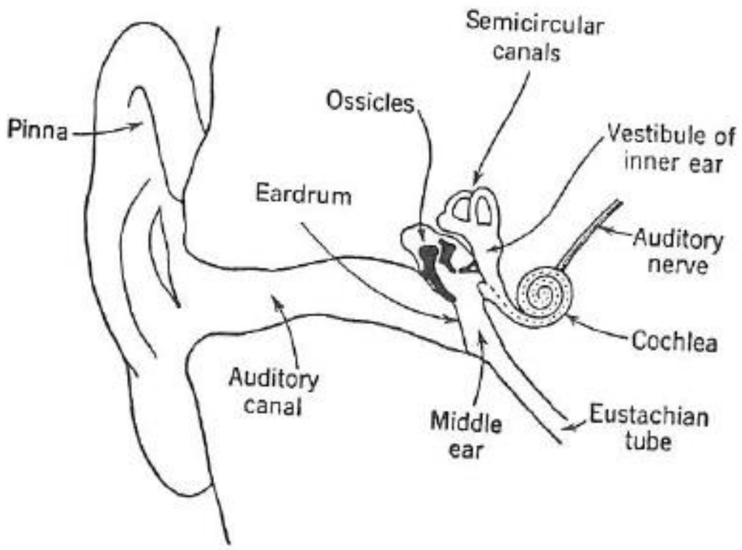


Figure 8: The ear (Kinley, 2000).

2.2.2. Capacity

The acoustic environment in a room is subjective and depends on the ability of the human ear (Ginn, 1978). The ear can be compared to an extremely sensitive microphone and is, in cooperation with the brain, a frequency analyzer capable to distinguish tones. The range of sound pressure is wide, from 0.00001 Pa to over 100 Pa. The most sensitive range is between 1000 and 5000 Hz. The minimum intensity level perceptible by the ear is called the threshold of hearing, as shown in figure 9. The threshold depends on the frequency, decreasing with increasing frequency. The upper threshold is the threshold of feeling, where a tickling or feeling occurs within the ear. The threshold of feeling is not as dependent of the frequency as the threshold of hearing, and the threshold of feeling is therefore more even in the figure. Between the thresholds areas of speech and music can be framed. The threshold of hearing is different for each person, and is therefore a reason for the perceived acoustic experience in a room.

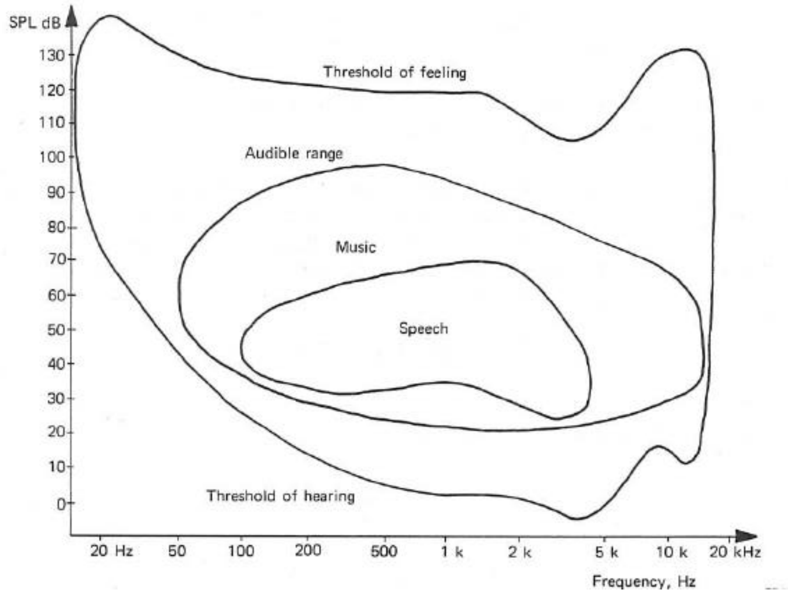


Figure 9: Audible range of frequencies and sound pressure levels (Ginn, 1978).

Sound is subjective and one parameter to explain this is loudness (Ginn, 1978). Loudness is a non-linear function of frequency and sound intensity, for example is a higher frequency hearable at lower sound pressure level than lower frequency, illustrated in figure 10. The figure below is created from subjective experiments where the curves represent equal loudness of sound intensity and frequency. Phon is the unit for loudness and the loudness level of each curve is illustrated.

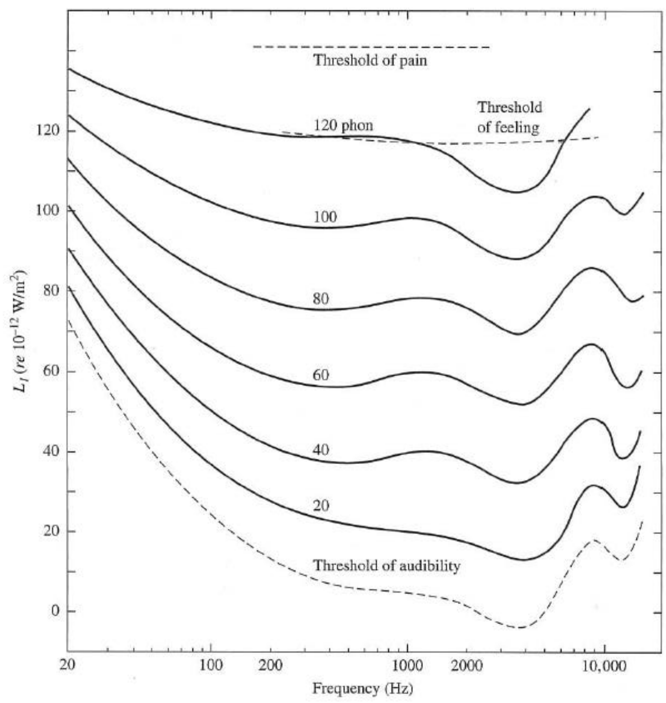


Figure 10: Equal loudness contours. L is sound pressure level (Kinsler, 2000).

2.2.3. Hearing damage

Damaged hearing capacity is common and results in reduced sensitivity for high frequencies (Bernström, 1987). In figure 9 the area of hearing will be decreased and the threshold of hearing and the threshold of feeling will be closer to each other. In order to protect the ear from damage there is the acoustic reflex (Kinsler, 2000). For high intensities the muscles of the ossicles change the tension and reduces the amplitude of motion of the stapes. The inner ear is thereby protected from damage. Sound for a shorter period of time might reduce the hearing temporary and when the source of the sound is removed the hearing recovers, called a temporary threshold shift (TTS). Sound with high intensity and longer duration can cause permanent threshold shift (PTS) and the threshold of hearing will not go back to original capacity. At this stage the hair cells in the inner ear are permanently damaged. Hearing loss is caused by high intensity sounds, and hearing impairment means a loss in ability to understand speech. Two different kinds of hearing loss reasons exist. Trauma is a high intensity sound that immediately causes a hearing damage on for example eardrum, ossicles or hair cells. Chronic is lower sound levels than trauma levels but repeated and is able to damage the hair cells after a period of time.

2.2.4. Risk for hearing damage

Powerful sound during a shorter period of time might result in temporary reduced hearing (Arbetsmiljöverket, 2005). Most times the ability to hear recovers but after exposure of powerful sound during a longer period of time the ear might get permanently damaged. Higher sound pressure level needs a shorter period of time in order to be dangerous. In order to judge the harm of a sound the principle of same energy level is used (Socialstyrelsen, 2008). An increase of sound pressure level of 3 dB gives the double effect and half the amount of time is needed before a hearing damage may occur. For example, a sound pressure level of 85 dB may proceed for 8 hours while 88 dB only for 4 hours. This varies between people and damages may occur earlier for some people. With A-weighted sound level the maximum level before risk for damage is 85 dB during a longer period of time (Arbetsmiljöverket, 2005). Even at 75-80 dB there is a risk for more sensitive people.

2.2.5. Consequences

The consequences of hearing damages are for example tinnitus, overly sensitive hearing and reduced hearing ability (Socialstyrelsen, 2008). Tinnitus is a lingering ringing sound in the ear occurring from a hearing damage. It can be temporary or permanent and is a symptom of e.g. a hearing damage, not a disease itself. According to Socialstyrelsen (2008) about 15 % of the Swedish people suffers from tinnitus, and 100 000 of them has severe problems. Four out of five with tinnitus also suffers from reduced hearing ability. There is no cure but some possible treatment to linger the troubles. Reduced hearing is one of the consequences of hearing damage. Reduced hearing is the most common work disease over the whole world. Reduced hearing increases the ability to perceive speech and may lead to social inconvenience etc. Overly sensitive hearing is another consequence where sound with a high sound pressure level is experienced as agonizing.

2.2.6. Weighted system

The characteristics of the ear effects the ability to experience sound (Kinsler, 2000). In order to adapt measurements to the ear different weighted sound levels exists. Most adapted to the way of hearing is the A-weighted sound level. C-weighted sound level is relatively flat whit a lower level at higher frequencies and is also commonly used, see figure 11.

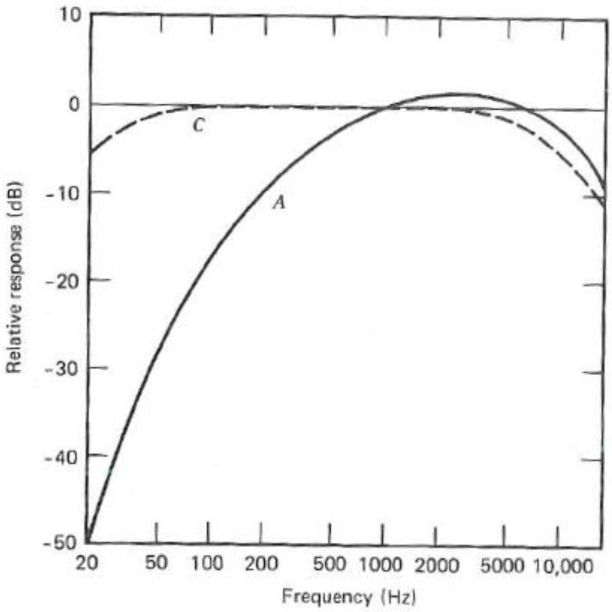


Figure 11: Filter characteristics for A and C-weighted sound pressure levels (Ginn, 1978).

2.3. Environmental acoustics

Acoustics related to the environment people are in are relevant. Sound is subjective and may be experienced as desired or disturbing. The reasons behind this is explained in this chapter.

2.3.1. The character of the sound

Sound can be disturbing, depending on the character of the sound (Bernström, 1987). Clear tones are more disturbing than noise and short impulses are more disturbing than constant sound. Sound is subjective and the sources we like are less disturbing than sources we can't control by our self. Other factors are time of the day, occupation, environment etc. The characteristics of the sound effects the consequences (Arbetsmiljöverket, 2005). Sound pressure level, frequency and durability will determine the outcome. Increasing sound pressure level, tones and varying sound are more disturbing than the opposites. Low frequencies are known to be tiring. The variation of sound is also effecting the experience of it (Socialstyrelsen, 2008). Sound variation over time is divided into continuously, intermittent and impulses. Continuously sound has only small variations of the sound pressure level over a certain amount of time. One example of a continuously sound is a fan. This is often measured in equivalent sound pressure level. Intermittent sound varies in level all the time and one example is an engine that starts and stops all the time. Impulses are short and sudden sounds. The characteristics is presented by distribution of frequencies etc. The level of disturbance is depending on the individual person since the experience of sound is subjective (Arbetsmiljöverket, 2005). Noise covers speech and noisy environments might obstruct speech and therefore be disturbing. In noisy environment people might increase the level of speech and both increase the current sound pressure level and be wearisome for the person.

2.3.2. Noise

Arbetsmiljöverket (2005) defines noise as undesirable sound, both dangerous and disturbing sound. Noise is interpreted as unwanted sound but physically it's the same as sound (Socialstyrelsen, 2008). The difference is due to the experience where noise is categorized as undesired sound. It's common to make a connection between noise and sound pressure level (Dyrssen, 2014). Noise is often described as high sound level but even more important is the fact that it is undesired sound, regardless the level. High sound pressure level at a club is not experienced as disturbing by most of the visitors. When a sound interrupts our focus it is experienced as disturbing, and thereby as noise. The acoustic expectation is important for the experience of the sound, whether it is desired or not and if it is expected will affect the attitude to it. Noise can be disturbing in both a psychological and physiological way (Arbetsmiljöverket, 2005). The noise might be related to a feeling or an experience, for example tiredness and irritation, as psychological effects. Additional physiological consequences may appear, such as increased heart rate and increased level of stress hormones, see figure 12. According to the World Health Organization (1999) noise is a health issue and will probably continue as a problem in the next century. To prevent consequences, it is important to have strategic actions and control the noise level.

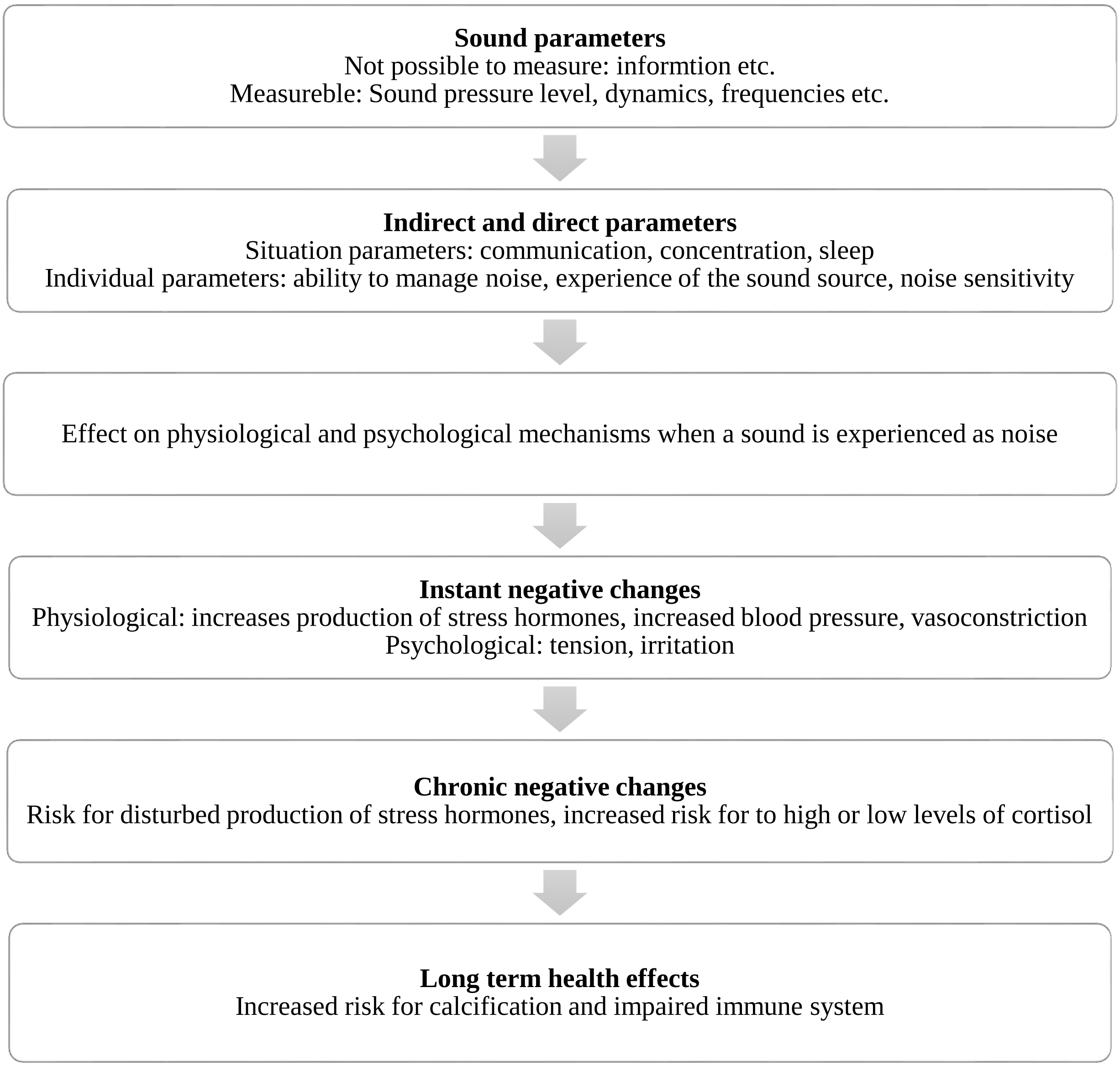


Figure 12: The effect on health from sound exposure (Saint-Gobain Ecophon AB, 2002).

2.3.3. Work-related diseases

Work-related diseases are caused by short or long term exposure to a harmful source (Arbetsmiljöverket, 2015). Inconvenience may occur after a few years and is both physical and psychological. According to a study from Arbetsmiljöverket (2015) of work-related diseases in Sweden year 2014, 15 percent of the reported cases are caused by physical causes, noise being the most common. The result is impaired hearing and tinnitus and three out of four cases are men. Employees in swimming halls are not mentioned in the report but are comparable with elementary school teachers, employees at restaurants and culture work. At restaurants work-related diseases is reported 72 times during 2014, 3 out of this is caused by noise and the same numbers for culture and service work is 60 cases and 5 caused by noise. Elementary school teachers is probably one of the most comparable profession and 77 out of 116 cases is caused by noise.

Percentage exposed to noise at least 25 percent of the working time according to Arbetsmiljöverket (2014) is around 30 percent for men and 15 percent for women. This is based on a survey but also compared to measurements, for example of sound pressure level. The survey describes noise as too high sound pressure level to be able to speak normally. The professions with most exposure to noise are for men building constructor, machine operator, farming and metal worker and for women machine operator, pre-school teacher, high school teacher and employees at restaurants. Teacher is comparable with employees at swimming halls, as mentioned above, and this points to a high level of noise exposure.

2.3.4. Health consequences

Community noise is a health issue. According to Mats Nilsson (2013) in a study of children following are possible outcomes from noise exposure: decreased hearing, tinnitus, sleeping difficulties, impaired learning and high stress levels. The amount of persons with hearing damage is increasing with age and is more common for men than women. Vulnerable groups for reduced speech intelligibility are children, elderly, people with hearing damage or people not used to the spoken languages (World Health Organization, 1999). Decreased speech intelligibility can cause problems with concentration, fatigue, decreased working capacity and stress reactions as well as reduced self-confidence etc. Noise from installations for example seldom causes hearing damages but can reduce the ability to concentrate and decrease speech intelligibility (Nilsson, 2013). Locals such as schools and preschools needs to have a good acoustic environment in order to help the users (World Health Organization, 1999). Speech intelligibility and disturbing noise are essential acoustic questions for this kind of rooms.

The sound pressure level effects the speech intelligibility. Table 1: Speech intelligibility for different sound pressure levels Arbetsmiljöverket (2005).Table 1 shows the connection between A-weighted sound pressure level and the ability to understand speech according to Arbetsmiljöverket (Arbetsmiljöverket, 2005).

Table 1: Speech intelligibility for different sound pressure levels Arbetsmiljöverket (2005).

dB(A)	Speech intelligibility
70	Loud conversations can barely be heard at the distance of 1 meter for persons with adequate hearing
55	Environment fulfills average demands for conversations with normal voice level at close distance to the speaker
50	As above but at 5-10 meters
40	Environment fulfills average demands for speech intelligibility at close distance even for elderly and people with impaired hearing as well as in foreign languages
35	As above but at 5-10 meters

Longer reverberant time increases echoes from speech and covers following sound (Arbetsmiljöverket, 2005). This will be disturbing in normal rooms when the reverberant time exceeds 0.8 s but in large rooms speech intelligibility is often hard to achieve. Noise and echoes will perhaps cover important messages and therefore be a risk. At a worksite noise from the occupancy is less disturbing than extraneous noise. Noise might lead to tiredness and stress symptoms which will lead to decreased performance. High sound pressure level during a longer period of time can lead to immediate tiredness.

Places with high sound pressure levels are e.g. sport activities, cafeterias in school buildings and sports halls (Nilsson, 2013). Children are often exposed to this kind of places and are also a vulnerable group. Noise can also occur from the people's activities. A high level of background noise, from example air ducts and reflections, will increase the sound pressure level and also increase the sound from the activities since people will try to be louder than the masking background noise. Reflections from the walls, floor and ceiling will delay the sound and mask speech for example. The increased noise level both raises the listener's threshold of hearing and masks the information (Kinsler, 2000). In order to compensate for this people tend to move closer, talk louder and use electronic devices.

2.4. Speech intelligibility

One essential value for the acoustic environment in swimming halls is speech intelligibility, explained in this chapter.

2.4.1. Theory of speech intelligibility

Speech intelligibility is the ability to hear speech in a room (Bernström, 1987). The speech intelligibility is not the same at every point in the room. The speech intelligibility is often subjective but there is also ways to measure this. If the speech intelligibility isn't good this can be due to a lot of factors. The design of the room may cause too high or too low absorption, too high level of absorption reduces speech at greater distance and too low level of absorption is decreasing the speech intelligibility. Also a high level of background noise can mask speech and late reflections and echoes makes it harder. Speech is often within 100-6000 Hz, and with the most important energy between 300 and 3000 Hz (World Health Organization, 1999). Higher level of masking background noise and at higher amount of the high energy frequencies will reduce the percentage heard by the listener. Signals such as fire alarms may also be masked by background noise. With an interfering sound pressure level from background noise people will raise their voice and increase the sound pressure level. In quiet surroundings the sound pressure level at 1 m between speaker and listener is about 45-50 dB(A), but with a noisy background shouting at 30 dB(A) higher is a possible outcome. Background noise reduces the speech intelligibility but most word can often still be heard but causes greater strain of the listener. Reverberation time over 1 s leads to loss in speech discrimination. In an ordinary classroom the sound pressure level might be 65-70 dB(A) due to talking and moving of furniture etc. (Saint-Gobain Ecophon AB, 2002). In order to be heard in this environment at least 10-15 dB(A) must be added to the speech and that results in screaming. By this, noise increases even more noise.

A long reverberation time results in decreased speech intelligibility when sound from one word still travels when the next word is heard (Saint-Gobain Ecophon AB, 2002). Our ability to hear sound is effected by the relation between the sound pressure level of speech and the sound pressure level of background noise. Factors affecting the speech intelligibility are the geometry of the room, the acoustic characteristics of the room's surfaces, the voice of the speaker and the hearing capacity of the listener.

2.4.2. Measurements methods

Speech intelligibility measurements the effectiveness or adequacy of communication (Brüel & Kjaer, 2013). The level of understanding is often measured as a percentage of words, sentences or phonemes. The percentage understood by the listener is the amount of speech intelligibility. Physical measurements are performed with a small loudspeaker or similar sound source and a microphone placed at the listener's position. In order to measure the speech intelligibility several methods exist, where STI, RASTI and STIPA are the most common. They are all performed as mentioned and RASTI and STIPA are simplified versions of STI.

Speech intelligibility is effected by several parameters (Brüel & Kjaer, 2013). These are the reasons to why the signal that is heard is never the same as the original source. The parameters are listed below.

- Level of background noise
- Distance from the speaker to listener
- Loudness of the speech (signal strength)
- Voice spectrum of the speech
- Amount of reverberation (echoes)

In order to determine the speech intelligibility the background noise and the acoustics preferences of the room are the most essential parameters. The parameters are illustrated below, see figure 13 and 14.

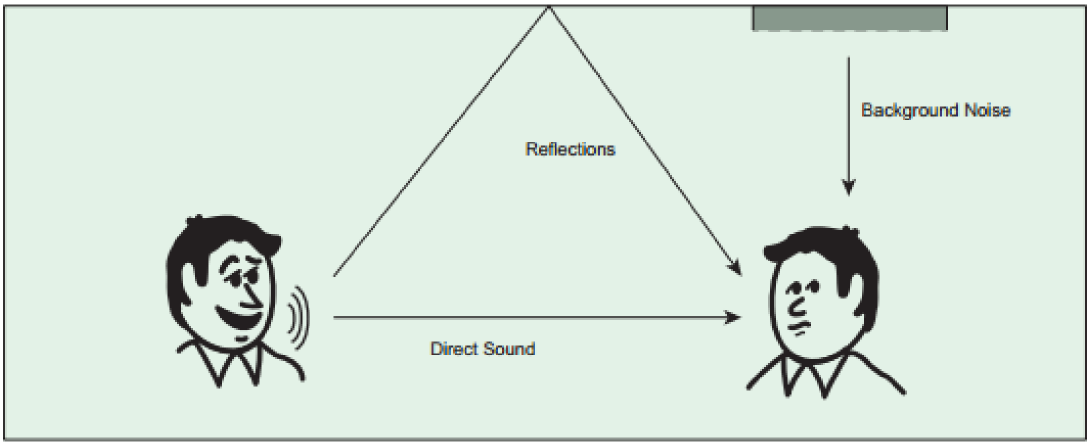


Figure 13: Illustration of speech intelligibility in a conversation (Brüel & Kjaer, 2013).

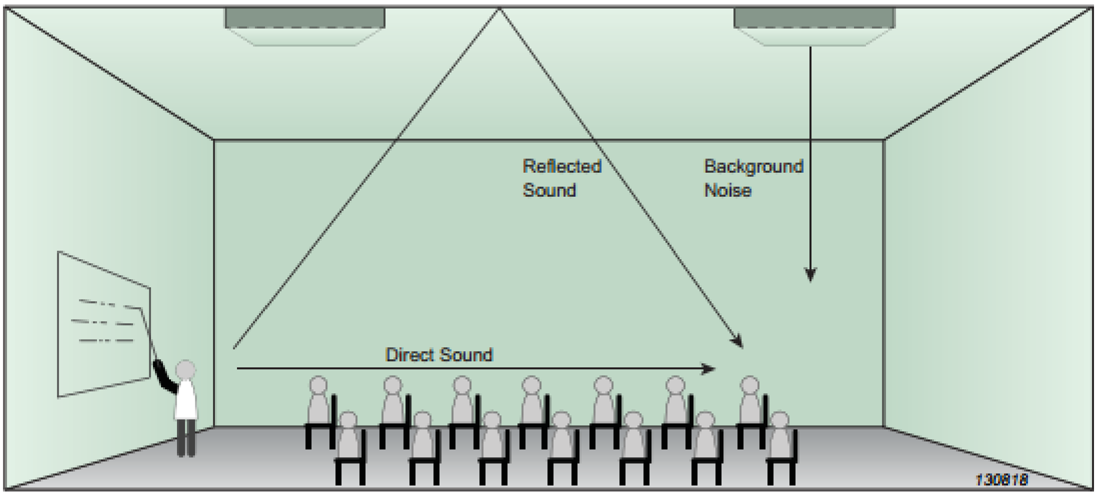


Figure 14: Illustration of speech intelligibility in an educational situation (Brüel & Kjaer, 2013).

2.4.3. STI

STI is measured over seven octave bands from 125 Hz to 8000 Hz (Brüel & Kjaer, 2013). The result is a weighted value and is within the limits of 0 and 1, see table 2.

Table 2: Relation between STI and speech intelligibility (Brüel & Kjaer, 2013).

STI	0.00-0.30	0.30-0.45	0.45-0.60	0.60-0.75	0.75-1.00
Speech Intelligibility	Bad	Poor	Fair	Good	Excellent

A value of 0.75 of the scale from 0 to 1 with STI is necessary for a good level of speech intelligibility in a classroom (Saint-Gobain Ecophon AB, 2002). In order to achieve this, the reverberation time should be 0.5 seconds or less and the background noise doesn't exceed 30 dB(A) and 45 dB(C). A value above 0.8 is seldom exceeded in reality (Brüel & Kjaer, 2013).

2.4.4. Other methods

RASTI (Rapid Speech Transmission Index) measure the speech intelligibility in an objectively way (Saint-Gobain Ecophon AB, 2002). As mentioned, a loudspeaker is placed at the position of the speaker and emits sound while a microphone is collecting the sound at the position of the listener at two frequencies, 500 and 2000 Hz. STI is measured in the same way but at more frequencies. RASTI was developed in order to shorten the measurement period (Brüel & Kjaer, 2013). For this method the background noise must be smooth in time and frequency, echoes must be avoided and the reverberation time cannot be strongly frequency dependent. STIPA is a measure method similar to STI but simplified in order to shorten the measurement performance time, such as RASTI. Other methods are AI (Articulation Index) and %ALcons (Articulation Loss of Consonants) for example (Saint-Gobain Ecophon AB, 2002). The % ALC value varies from 0 to 100, where 0 is excellent. The value is corresponding to the reception of the listener (Brüel & Kjaer, 2013).

2.4.5. Signal to Noise

According to Robert Ljung (Ljung, 2010) the two acoustical parameters most effecting the speech intelligible except for the absolute speech level is signal-to-noise and reverberation time. Signal-to-noise, S/N, is a measurement of the signal's strength in relation to the noise from surrounding sources. A low S/N is decreasing the ability to hear speech. The background noise could be noise from installations or noise from people's activities. The speech intelligibility uses cognitive resources and makes it harder to understand and remember the information. The signal to noise ratio should be at least 15 dB(A) in order to achieve full sentence intelligibility (Brüel & Kjaer, 2013). The SNR is a logarithmic ratio of the signal level and the noise level compared to each other. Since a value of STI seldom is reach over 0.8, the SNR value above 15 dB(A) is a useful demand to achieve.

2.4.6. EDT, Early Decay Time

EDT, Early Decay Time, measures the reverberation time (Brüel & Kjaer, 2013). For this method the initial and highest level part of the decaying energy is crucial. The value is given by the decay from 0 to 10 dB below the initial level and then calculated for the time to reach 60 dB less sound pressure level.

2.4.7. Speech and room design

Speech contains vowels and consonants, the vowels are generally louder and more audible (Ljung, 2010). Same as for reading, only consonants are understandable but only vowels are not, applies for speaking. The human speech is mostly between 100 Hz and 8000 Hz, vowels being in the lower frequency range. Rooms designed for learning should have reflections reaching the audience all the way through the room (Ljung, 2010). Too much reflections will decrease the speech intelligibility and make the teaching harder. Reflections reaching the listener 35-40 ms after the direct sound improves the speech intelligibility. Later reflections will instead mask the speech. By this, information may be lost. Longer reverberation time masks the consonants more than vowels which decreases the understandability. A phenomena called

"Upward spread of masking" means that low frequency sound mask high frequency sounds better than the opposite. Since vowels often are lower frequencies these are less reduced than consonants, and thereby also decreases the ability to understand speech. Unfavorable acoustic environments with high background noise level strains the working memory.

Table 3: Average vocal effort and sound level (Brüel & Kjaer, 2013).

Vocal effort	**dB(A)**
Whispering	32
Soft	37
Relaxed	42
Normal (private)	47
Normal (public)	52
Raised	57
Loud	62
Very loud	67
Shouting	72
Max. shout	77

Vowels and consonants are not at the same energy level and the average level of consonants is 10-12 dB lower than vowels, see Table 3 (Brüel & Kjaer, 2013). Consonants are more important than vowels in order to understand speech. Consonants contains most of the information and separated syllables and words from one another.

2.4.8. Learning

The environment in learning situations is essential to the result (Saint-Gobain Ecophon AB, 2002). Temperature may cause a decreased quality and to high temperature might be compensated by raised vocal level. Sound, climate, air quality, ergonomic, light and lightning are examples of factors contributing to the indoor environment. All of these considered as a wholeness at the beginning of the design phase of a building will improve the result. The speech intelligibility decreases with noise from ventilations, speech, traffic, steps, move of furniture etc. Noise effects assignments that requires a lot of concentration more than other assignments.

2.5. Construction management

In order to relate the importance of the design phase to the outcome of swimming hall projects the theory of construction management is essential. Another important aspect regarding this topic is cost effectiveness and influence throughout the process which are fundamental aspects for achieving a successful result.

2.5.1. The building process

The building process exists of the initial planning, the execution and the follow-up of a project (Saint-Gobain Ecophon AB, 2002). The main activities are planning, design, construction and maintenance, see figure 15. The process includes a lot of different professionals, for example designers. The designers such as architects, engineers, acousticians and other specialists are consults and are working with the planning and the design of the project. A consult is an expert on a specific topic, for example installation and electrical. The consults contribute with special knowledge and are important for the shape and functions of the building. The consults interpret the demands ordered by the client. Client is a person, an organization, a company or similar that starts the building project (Nordstrand, 2009). Client makes decisions about the design, solutions, quality and environmental demands for example. Municipalities are the client of schools, pre-schools, sports facilities etc. These are non-profit buildings. In the initial investigation demands should be specified and a factor of success is to define these according to required quality and to fulfill environmental standards (Saint-Gobain Ecophon AB, 2002). One example of this is to plan for educational buildings away from noisy surroundings. The consults, for example in acoustics, are included in the design phase of the building process (Nordstrand, 2009).

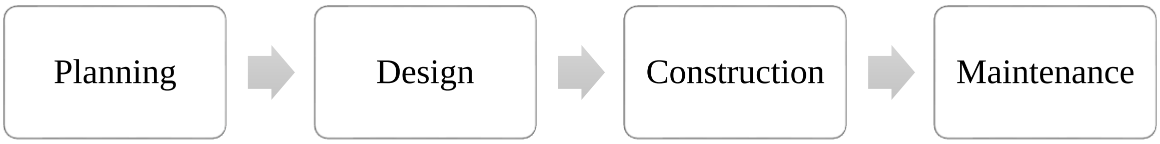


Figure 15: The building process illustrated in the main steps.

2.5.2. Design phase

The design phase is complex. New buildings has a lot of opportunities to choose from, but renovations are limited (Nordstrand, 2009). During the process a large number of people are involved and need to collaborate. Time and cost are decided early and the project needs to be adapted to that. In project with a lot of possibilities the work of the architect is essential. In order to find the best solutions for the specific project a lot of parameters needs to be taken in consideration. The design work is a team work with all different kinds of consults together with the architect and client. During the design phase communication is important and all solutions that needs to be used by every different type of consult must be known by all participants. For example, collisions are avoided by communication. One way to work with this is three dimensions’ models where collisions are visual. During the process decisions are made and the project progresses.

The design phase can be divided into three parts (Nordstrand, 2009). From an initial planning program, the design of the building is decided and results in the first drafts with suggested design. Next step is the structural system, installations etc. The consults, except for the architect, usually joins the project in this phase. Last of all is a detailed design of the building. This is presented in writing and drafts which constitutes the project documentation. This stages forms the building and the consults has a big impact of the result.

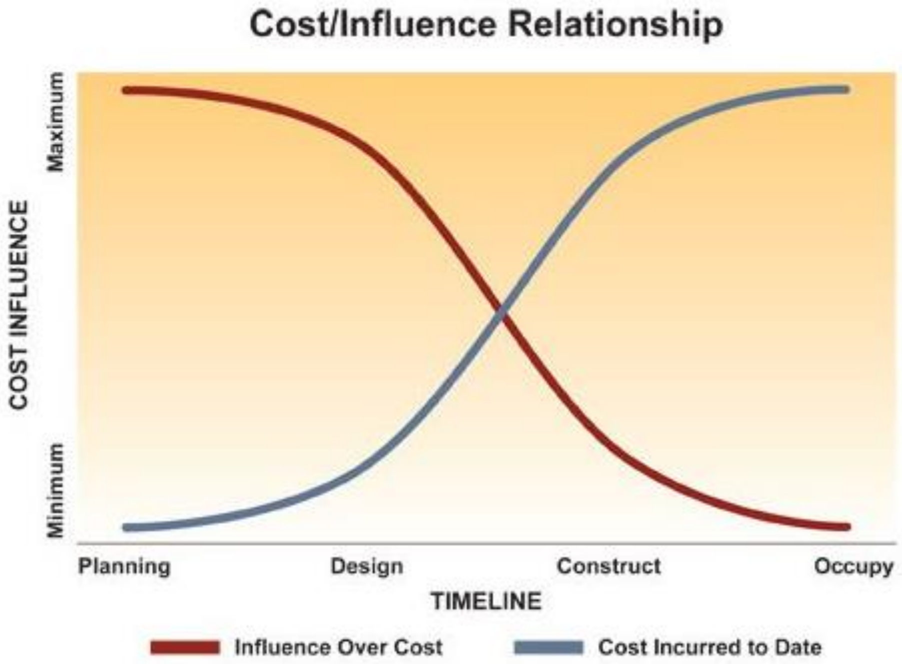


Figure 16: Collaboration between influence and cost during the duration of a project (Sakonnet Associates , 2016).

2.5.3. Influence and cost

Society, demands and environmental decisions effects the building process. In order to achieve a good result and a high quality with a low cost as much as possible should be decided in the early stage of the building process, this is illustrated in figure 16 (Saint-Gobain Ecophon AB, 2002). Arrangements later in the process in more complicated and often expensive. In order to achieve as large cost effective process as possible the acoustic questions needs to be maintained at an early stage of the planning (Åkerlöf, 2001). The cost will increase a lot if the questions are addressed during production and solutions made during maintenance may cost 10-100 times as much as if the acoustics would have been addressed in the early stages. After the building is delivered complains may occur on the acoustic environment and solutions to manage this are very expensive.

2.6. Room acoustics

Acoustics effects the experience in a room and may be used in order to create desired situations. This chapter addresses the use of acoustics in buildings. Acoustics in locations such as swimming halls are also introduced.

2.6.1. Acoustic room design

Acoustic design in rooms are used for several purposes, e.g. increase speech intelligibility, make it easy to hear music, tune down the sound from the general noise level and mask the disturbing sound from speech and occupation (Bernström, 1987). The shape of the room affects the acoustic environment. Examples of this are size, shape, surfaces as well as size and placement of absorbents. Definition of room acoustics according to (Ginn, 1978):

"Consider a sound source which is situated in a room. Sound waves will propagate away from the source until they encounter one of the room's boundaries where, in general, some of the sound energy will be reflected back into the room, some will be absorbed and some will be transmitted through the boundary. The complex sound field produced by the multitude of reflections and the behavior of this sound field as the sound energy in the room is allowed to build up and decay constitutes the acoustics of the room."

Sound waves are reflected from surfaces in rooms, figure 17 (Ginn, 1978). The first reflecting wave and possibly the second reflecting wave can be taken in consideration when designing a room. Sound waves ends in the reverberant sound field in general after the first two reflections.

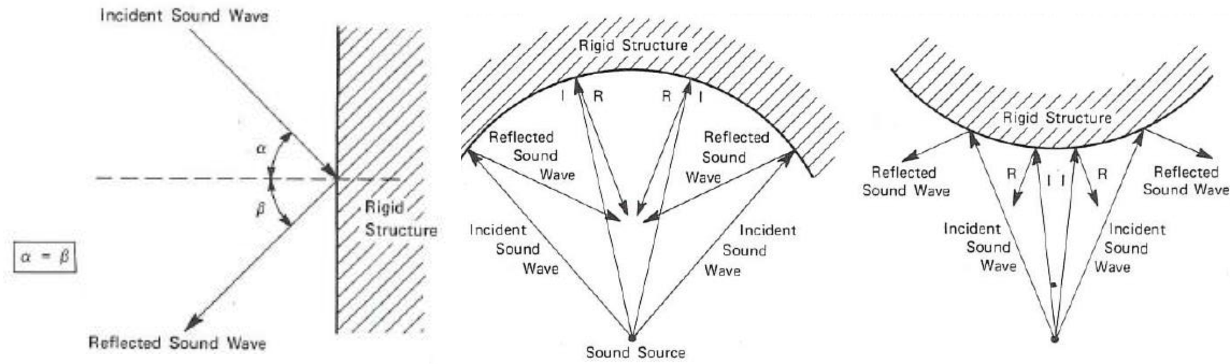


Figure 17: Laws of reflection (Ginn, 1978).

2.6.2. Growth and decay of sound in a room

Sound will grow and decay in a room (Ginn, 1978). The sound intensity at a point will increase due to reflections from walls, floors and ceilings until an equilibrium is achieved. The equilibrium means that the energy absorbed by the room is equal to the energy radiated by the sound source. When the sound source is terminated the sound is not immediately gone. The sound fades gradually and the decay is determined by the amount of absorbents in the room, the decay is known as reverberation time. Figure 18 shows the connection between sound pressure decay over time, linear and logarithmical scale. The amount of absorptions is proportional to the sound intensity and makes the growth and decay of sound pressure an exponential function.

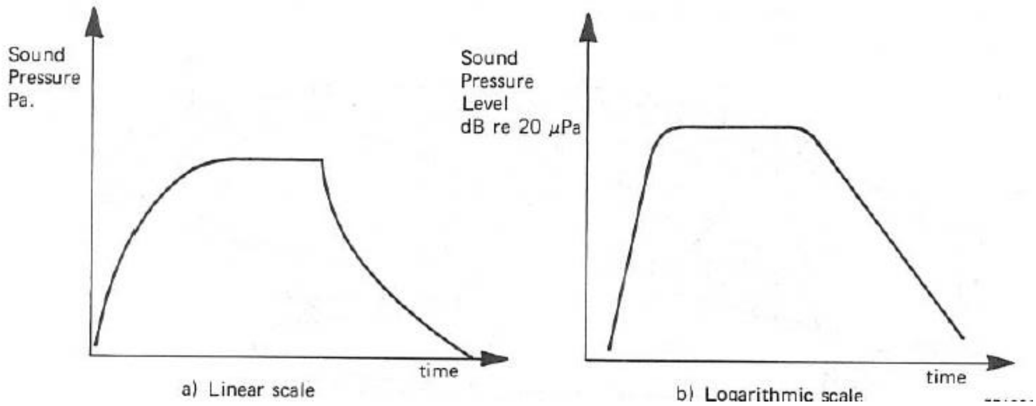


Figure 18: Growth and decay of sound in a reverberant room (Ginn, 1978).

2.6.3. Principles for design of rooms and auditoria

The volume of the room is a crucial factor for the acoustic result (Ginn, 1978). Reverberation time is an essential design factor but the subjective part is making it even harder. Perfect reverberation time may vary between persons but some guidelines for different types of rooms exist, see figure 19. In general, for speech the reverberation time should be as short as possible and for concert and church music it should be long. By measurement the reverberation time and the volume in rooms considered having good acoustics a relationship can be detected, see figure 19. The curves are a guideline and due to different opinions of good acoustical environment there is a big variety to consider. The expectations on the room are also effecting the experience of the acoustics (Åkerlöf, 2001). For example, libraries are expected to be quiet and in churches long reverberation time is expected even if the acoustic environment would be improved with more absorbing surfaces.

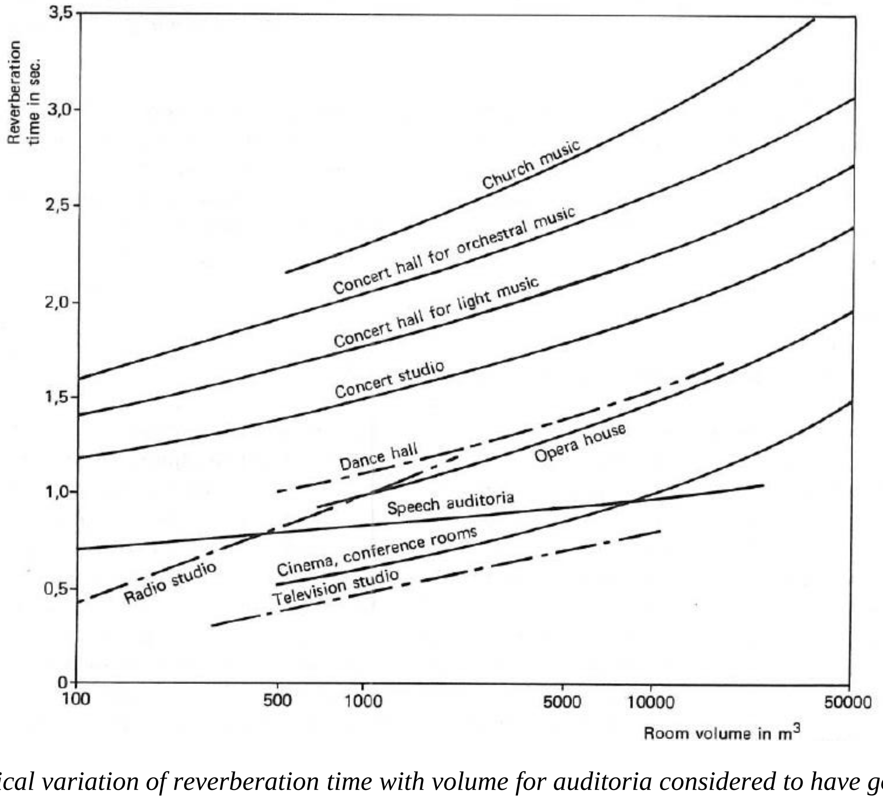


Figure 19: Typical variation of reverberation time with volume for auditoria considered to have good acoustical properties (Ginn, 1978).

Except for the reverberation time there are other factors to consider (Ginn, 1978). The size and shape of the room as well as the placing of absorbents and sources are effecting the acoustic environment. The size may create echoes, dead spots and flutter. Echo is sound reflections later than 0.05 seconds after the sound is sent, perceived as later reflections and thereby disturbing. Dead spots are places in a room where sound only reaches after it has passed a particularly absorbing surface. Flutter emerges from parallel hard surfaces where the sound will bounce between the surfaces, decaying slowly and therefore create noise.

2.6.4. Design of room for speech

Rooms designed for specific purposes can be shaped for a good acoustic environment (Ginn, 1978). For speech the speaker needs to be heard clearly by everyone. Factors effecting the ability to interpreted speech are background sound level, reverberation time and the shape of the room. Noise from the background may mask the speech and should therefore be kept under 30 dB. Reverberation time should be in a specific interval in order to make a good acoustic environment. Too long reverberation time will mask following speech due to slow decay time. Too short reverberation time isn’t good either since reflections are necessary to spread the sound enough. The shape of the room should avoid echoes, dead spots and flutter. The amount of absorbents are connected to the volume of the room and the desired reverberation time. For rooms made for music it is harder to get a good acoustic environment since it is very subjective. Often aesthetics and other criterions are effecting the shape as well.

2.6.5. Room design

The purpose of room acoustic design is to create a good acoustic environment adapted to the disposal of the room (Rosenberg, 1992). For rooms with several using areas a perfect acoustic environment is hard to achieve. In order to know if the acoustic environment is good a definition of the function of the room is necessary. It is important to know if people in small groups are talking to each other or if there will be for example lectures. The first example can be called non-communicative and the second communicative. For the non-communicative room the demands are easy to define. The room needs to be toned down in order to allow talks in smaller groups. In other words, a short reverberant time is desired. Example of non-communicative room are entrance halls, restaurants and corridors. For the communicative room is it more difficult, and different types of purposes demands different acoustic environment. The volume of the room is a crucial factor, for a speaker it gets harder to be heard with a greater volume. The sound waves are reflected when it reaches surfaces. Early reflections help us receive the information but later reflections creates echoes. Early reflections reach the ear of the listener within 50 milliseconds. More and stronger early reflections creates a clearer speech. Later reflections are better for music events. The architectural design of the room affects the acoustic environment, for example a low ceiling results in less late reflections. The source of the sound is crucial, a source placed in the middle of the room is generally a bad acoustic solution.

2.6.6. Shape

The acoustic environment in a room is depending on the shape of the room (Dyrssen, 2014). The dimensions, materials, boundaries and openings are effecting the acoustic outcome. Besides this, the individual expectations and attitudes are essential for the experience of the room. Social and cultural reasons for spending time in the particular room are soft value factors that also contributes to the result. Sound can be a way to identify a room with lingering sound that creates a specific acoustic environment for the room. By this we can recognize a room by the way it sounds.

2.6.7. Sound isolation

Noise from the outside should be minimized in favor for the acoustic environment (Rosenberg, 1992). Sound isolation is important in order to achieve the desired acoustic environment within a building (Kinsler, 2000). Otherwise noise from outside will disturb and impair. Noise from inside the building, for example air conditioners, should be considered in the design and contribute to a low background sound pressure level. Noise from the occupation affects speech intelligibility and is reduced by for example absorbents, i.e. low reverberation time (Rosenberg, 1992). The acoustic environment is depending on the design and flexible solutions expands the possibilities. Curtains, screens and temporary absorbents are some examples.

2.6.8. Design phase

The acoustic conscious of an architect can improve the acoustic environment in several ways (Dyrssen, 2014). It will increase the insight of the room boundaries and transitions as well as the sound directions and changes in a room and by that increase choices related to acoustics. The materials, shapes and surfaces affects the way the sound will react and knowledge about this will improve the acoustic environment. The social perspective may be involved as well. The way people acts in the room and the way the acoustic environment responds, for example if its tunes down, enhances or clarifies, will affect the experience. In addition, choice or colours, visual expression etc. might be related to the sound experience. Aspects to consider while designing a room from the acoustic point of view are what kind of opportunities that exists, such as noise, sounds and activities. More specific opportunities are masking effects, special qualities, social functions, listening requirements and accessibility requirements. An important aspect is the persons the room is supposed to be designed for.

2.6.9. Sport halls

Sports halls should be designed with short reverberation time and reduce sound at a large distance, increase speech intelligibility at short distance, low noise level and have no reflections or echoes (Bernström, 1987). In order to be able to give instructions and have education a good speech intelligibility at short distance is necessary as well as the background noise needs to be reduced. To achieve this the room should be designed with a small volume, low ceiling height, absorbents on ceiling and walls, absorbents close to noisy installations and have no big hard surfaces. This solution is difficult to apply to swimming halls due to function demands and climate.

2.6.10. Swimming halls

Swimming and water activities creates high sound pressure level at the same time as communication and instructions are an important part of the activities (Saint-Gobain Ecophon AB, 2002). Safety is also an important aspect to consider while designing swimming halls. Large spaces make people talk to each other from greater distance which tend to raise to level of speech in order to be heard above other conversations. This increase the sound pressure level even more. Hard surfaces create a disturbing increase of sound pressure level and sound distribution. In swimming halls, sound is allowed to travel far and one sound source disturbs a lot of people. Hard floors create a high level of structural sound from steps. Figure 20 shows an example of a swimming hall.

Figure 20: Example of a swimming hall (Liljewalls, 2016).

The construction and inventory of swimming halls may cause sound to bounce on the surfaces due to lack of absorbing effect (Socialstyrelsen, 2006). Disturbing sound pressure level may occur close to activities and when the swimming halls is frequently used. There is no limit value for noise in swimming halls for the visitors. Employees should not be exposed to an equivalent sound pressure level of 85 dB L_{eq8h} for daily activity (Arbetsmiljöverket, 2005). In order to achieve the demands for reverberation time according to Swedish Standard suggested solution is an absorbing ceiling with sound absorbing class A (Saint-Gobain Ecophon AB, 2002). In order to avoid echoes between hard surfaces some hard walls also should be covered with absorbents. The surfaces should be durable and in swimming halls resist moisture. More about the Swedish Standard in chapter 3. Guidelines.

2.7. Reference projects

Three existing projects are used to detect current work and knowledge.

2.7.1. Introduction

Existing projects are synoptically studied as a part of the empirical basis. All projects are renovations where the purpose is to suggest sound standard sketches. In all cases the design is determined and handed as fundamental information. Standard SS 25268 is used and sound class C is aimed for. The three projects are listed below. The construction design is not included in the thesis and focus is at absorbents and design.

2.7.2. Projects

Sollentuna sim- och sporthall
Vallentunasimhall och gym
Farsta Sim- och idrottshall

2.7.3. Solutions

The three projects have similar conditions. The design is consequently determined, that limits the possibilities for acoustic solutions. All three has similar solutions, mostly absorbents since adapted shaping isn't possible. The suggestions for absorbents are similar for the projects, summarized below.

Absorbents

The two first mentioned projects have suspended ceiling with absorbent class A/Ah for the whole ceiling area suggested, see 2.1.8 theory. For one of those swimming halls the existing absorbents in the ceiling is calculated and is not completely fulfilling class A. The existing ceiling is perforated plate and this decreases the absorption for high frequencies a bit in comparison with absorbent without perforated plate. The last one suggests absorbents of mineral wool in class A or perforated plate with at least 30 % open area and mineral wool behind. The second alternative gives an experience of a sound reminding of a can. At least absorbent of class B should be used for 70 % of the available wall area, suggested for one project. For a wall separating two rooms with swimming pools the area above glass should be provided with absorbents on both sides in the suggestion.

Other aspects

One project accentuates that an existing problem in an educational swimming pool room is that the sound pressure level is mainly caused by sound from the drain as well as from a loud ventilation fan, and that these two needs to be altered in order to achieve a good acoustic environment. Interesting aspects in the projects are as following:

"In the following, suggestions of sound demands are presented in consideration of room acoustics, sound isolation and installation noise in order to achieve a, for the existing space, good acoustic environment. The demands in the standard concerns only new constructions."

"For description of room acoustical qualities a large number of parameters are available. Out of these the reverberation time is the most common and at the same time easiest to subjectively experience. In the proposal of sound standard the amount of absorbents and sound class is also given."

3. Guidelines

3.1. Demands

Acoustic planning needs guidelines in order to reach a sufficient standard. Demands from Swedish Standard and BBR for acoustics in swimming halls are presented below. Values for reverberation time and sound pressure level are received.

Swedish Standard

In the Swedish Standard SS 25268 ”Acoustics - Sound classification of spaces in buildings - Institutional premises, rooms for education, preschools and leisure-time centers, rooms for office work and hotels” demands for different kinds of spaces are presented (Swedish Standards Institute, 2007). The standard is also used for the design of swimming halls. Demands for reverberation time for swimming halls are presented, see table 4, but otherwise demands for schools are used.

Table 4: Summary of demands from the Swedish Standard 25268:2007.

Space / Sound class	**A**	**B**	**C**	**D**
Higher level of education	1.2	1.5	**1.5**	2.0
Schools and pre-schools	1.0	1.2	**1.2**	2.0

Table 4 is a summary of demands for reverberation time in seconds from the Swedish Standard 25268:2007 for educational spaces, first higher education and then schools and pre-schools. The demands are for large spaces for sports, for example sports hall and swimming hall.

The table above shows that a reverberation time of 1.2 s for elementary schools and 1.5 s for high school is the longest reverberation time accepted for swimming halls in order to achieve the demands of BBR. The background sound pressure level from installations is attached in appendix for high schools, which is almost the same demands as for elementary schools. The reverberation time is measured with T20 where the decay of 60 dB is evaluated from -5 dB to -25 dB (Swedish Standards Institute, 2007). The Swedish standard 025268 recommends a reverberation time of 1.0 or 1.2 seconds for swimming halls depending on the choice of quality level (Saint-Gobain Ecophon AB, 2002). This is for frequencies from 250 to 4000 Hz but 125 Hz is allowed to be 20 percentages higher. For volumes above 1500 m^3 an increased reverberation time should be expected.

The standard contains guidelines for the design of spaces (Swedish Standards Institute, 2007). Where speech intelligibility is important absorbents needs to be placed at more surfaces than the roof when there are parallel surfaces. In that case, at least one of the opposite surfaces needs to have absorbents or be heavy diffusing surfaces. At the height of the ear of the users of the space is a preferred height to place absorbents. In a large space with a high ceiling height and weak diffusing environment it is necessary to apply a sound diffusing or absorbing design of several plane surfaces. The amount of absorbents should be distributed at roof and at least one of two parallel surfaces. Spaces with a high contribution to the sound pressure level, such as cafeteria and playroom, needs arrangements to reduce the sound source and should be designed with a maximum amount of absorbents on several of the room's boundaries. The increased amount of absorbents will contribute to a lower sound pressure level.

BBR

Boverkets byggregler, BBR, (Boverket, 2015) provides demands and general advices regarding acoustics in buildings but also refers to The Swedish Standard SS 25268. Sound class C is enough to reach the demands of BBR. The constitution states that buildings with locals such as preschools, schools and office work spaces should be designed in order to limit disturbing noise. This will avoid inconvenience and health issues for the users. Installations and elevators in the building should be design to prevent noise, both from the object itself and from outside. This should be done in consideration with the occupation so that it won't be disturbing for people in the building. Reverberation time should be chosen in consideration with the use of the space.

3.2. Certification

Projects today are often designed with environmental certifications. Several certifications are used, for example EU GreenBuilding, BREEAM, LEED and Miljöbyggnad (Sweden Green Building Council, 2016). Miljöbyggnad is commonly used in Sweden and demands for the acoustic environment are included, see extract in Table 5 and complete information in appendix 1. Miljöbyggnad considers structural sound, airborne sound, sound from installations and sound from the outside, but not reverberation time. For a higher value the acoustic parameters, two for silver and all for gold, needs to exceed class C and swimming halls are already difficult in an acoustic perspective.

Table 5: Demands for acoustic environment in all kinds of new buildings for the levels Bronze, Silver and Gold (Sweden Green Building Council, 2016). Sound classes according to SS 25267 or SS 25268.

Demand	Bronze	Silver	Gold
Acoustic environment	Sound class C for the four parameters	At least two out of the four parameters fulfills Sound class B	At least Sound class B on all four parameters

BREEAM uses a system with points, and demands for acoustics exists where more points are distributed for class B for example. The total amount of points for the project decides the certification, and therefore acoustic demands are not necessary to use if other parameters may fulfill the necessary points together.

3.3. Target values for sound pressure level

Folkhälsomyndigheten gives some target values of maximum sound pressure level in order to avoid hearing damages and inconvenience. The highest sound pressure level recommended for areas where children and adults are staying is L_{Amax} 110 dB and L_{Aeq} 97 dB (Folkhälsomyndigheten, 2014B). Target values for noise levels are presented below in Table 6 and are recommendations to avoid inconvenience, followed by target values for low frequency sound in Table 7 (Folkhälsomyndigheten, 2014A).

Table 6: Noise (Folkhälsomyndigheten, 2014A).

Maximal sound pressure level L_{Amax}	45 dB
Equivalent sound pressure level L_{Aeq}	30 dB
Sound with hearable tones L_{Aeq}	25 dB
Sound from music systems L_{Aeq}	25 dB

Table 7: Low frequency sound (Folkhälsomyndigheten, 2014A).

f (Hz)	SPL (dB)
31.5	56
40	49
50	43
63	42
80	40
100	38
125	36
160	34
200	32

4. Methodology

4.1. Description

The research is conducted with the methodologies described below. In order to reach satisfying information a literature study, interviews, questionnaires, measurements and simulations are performed. More about the motivation further down in the chapter.

4.1.1. Literature study

New research needs to take existing published material into consideration (Merrian, 1994). The purpose of the research is to contribute with new knowledge and therefore useful existing information needs to be considered. A literature search summarizes the available information about a subject and the purpose is to show the “state of the art”, which means the current situation. This is a basis for improvements of the area and continued research. All published materials are usable for research (Ejvegård, 2009). Key words are important to use in the search of relevant information. The search for information is done at databases, libraries etc. and documents, publications and books are examples of information sources. A whole essay may be collected literature since the research is rapidly increasing and overviews are more important nowadays. Documents not produced for research is a source reflecting the reality and is useful for qualitative studies (Merrian, 1994). They contain phenomena about the pre-defined problems and provides an empirical basis.

4.1.2. Case studies

Research can be done in a lot of different ways, for example case studies where the methodology consists of interviews, questionnaires, focus groups, document analysis etc. (Gibson, 2009). A case study can involve a person, an institution or other categories. The design of the research contains a few fundamental steps: specify questions, choosing sites and participants and deciding how to analyze the data. Case studies examines one or several cases about a particular problem (Merrian, 1994). Case studies are anchored in reality and gives a holistic statement of the phenomena.

Two examples of approaches are non-experimental studies and experiments (Gibson, 2009). Non-experimental studies consists of one or several cases studied in detailed and compared to each other when several cases are used. The data is sampled from both quantitative and qualitative research. The result is a description or an explanation of a phenomenon (Merrian, 1994). The result is analyzed qualitatively. Experiments are examining a phenomenon with a broad use of data collecting; interviews, questionnaire and observations (Gibson, 2009). The purpose is to study the relationship between cause and effect (Merrian, 1994).

4.1.3. Qualitative and quantitative methods

In order to collect opinions, knowledge and information qualitative and quantitative methods can be applied. Qualitative research is a flexible method and results in a lot of data reflecting the design of the research (Gibson, 2009). The researcher affects the outcome of the qualitative research when constructing the research, called reflexivity. The purpose of the methods is according to the author:

“Analysis involves deciding what counts as variables in the first place, on making sense of any relations that may be found between variables, and on relating statistical findings to research questions and concepts”.

Interviews and questionnaires study a few pre-defined variables with a great number of search units (Merrian, 1994). Variables are chosen from theory and models. This may produce quantitative results. Interviews can be used for qualitative research as well (Holme & Solvang, 1997). Quantitative methods produce results in numbers and qualitative methods are expressed in writing (Merrian, 1994).

4.2. Questionnaire and interviews

In order to find out the opinion, idea and knowledge of people questionnaires and interviews may be used (Ejvegård, 2009). Interviews are verbal and questionnaires are written. A questionnaire consists of several printed questions handed out to a number of persons in order to collect opinions. Interviews may be used to evaluate the expert’s knowledge and experience. Different kinds of questions may be used for interviews, structural and non-structural, but for questionnaires only structural questions are used. Structural questions are pre-defined, both the content and formulation. It can be open or closed answers, where closed is constructed with different options to choose from. Participants should not be totally transparent (Gibson, 2009). A certain visibility is necessary. Sometimes the participant’s wants anonymity and pseudonyms can be used, but often the identity or a lot of information of the participant is necessary for the analysis. Anonymity can be hard to achieve because a lot of information can be essential and it can be difficult for the researcher to know what kind of information that is easy to recognize. The purpose of interviews and questionnaires is to create data of a specific topic and the participant’s insight in this particular subject.

4.2.1. Interviews

Interviews are executed with one expert at a time (Ejvegård, 2009). These often take a lot of time and the people should be chosen with consideration. The selection of respondents is important (Holme & Solvang, 1997). The selection is systematically and not randomly from chosen criteria. The respondents need to contain sufficient knowledge of the subject in order to contribute to enlarged information content in the research. One problem that may appear is that experts may bring a mispresented picture of the matter and may be very persuasive. The method demands a lot of effort from the researcher, who needs to be involved in the subject. The identities should not be disclosed without consent and the report should be written so that answers may not be apparently belonging to someone (Ejvegård, 2009). In order to do this several interviews are necessary. It is important for the researcher to know the purpose of the study in order to get relevant answers and ask the important questions. Interviews can be performed in different ways. Structured interviews consist of questions that are asked to all the participants in the same sequence (Gibson, 2009). The questions are predefined and carefully developed to be precise and relevant for the research. Semi-structured are adapted after the outcome of the conversation. It contains several predefined questions but can be asked without order and with a different emphasis and formulation. The questions need to be asked at appropriate times and the researcher have to be able to listen to the answers and adapt the following questions. Unstructured interviews has no predefined questions and the interview will develop subsequently.

4.2.2. Questionnaire

Easier, cheaper and less time demanding than interviews are questionnaires (Ejvegård, 2009). This will collect opinions from a large number of people in writing. Response rate and response loss is essential to address. Response loss is when people hand the questionnaire back unanswered or when answers to questions are missing. The number of answered questionnaires must be large in comparison to the asked crowed, with 80 percent being an appropriate limit. Questionnaires with at least 40 answers are meaningful to process statistical. The same questions are asked to everyone and the answers are easy to compile. The questionnaire should not be too large and he questions must be easy to interpret. Questions cannot be guided in this case either. Closed answers must exclude each other in order to be possible to answer correctly. Closed answers are easy to process statistical. Questions with open answers are useful to detect missing parts or get valuable comments. Questions regarding opinions should always have an odd number of answers in order to have an answer without any statement, an answer for "neither". A problem with questionnaires is that for example the scale from bad to good may be interpreted different to people.

4.2.3. Reliability and validity

Reliability of a measurement method is important in order to judge the usefulness (Ejvegård, 2009). Reliability of questionnaires is depending on how the questions are asked and how they may be interpreted. In order to evaluate the reliability of the questionnaire is to see if contradictions within one answer occur. Contradictions indicate low level of reliability.

Validity considers if the method is measuring the pre-defined question (Ejvegård, 2009). The measurements can be created from by pre-defined criteria and if these aren't sufficient the result may be deceptive. Questionnaires are difficult to test for this. If there is a reference to the measurements results comparison may be performed. Reliability is necessary in order to be able to achieve validity, but sufficient reliability isn't always providing validity.

4.2.4. Analyze

The data is translated in order to represent the results (Gibson, 2009). In this process decisions about relevance and analyzing discernment is done by the researcher. The result represents the processed data. The aim of the result is to present an analytic focus of the data. Analysis of the data is performed to find similarities, differences and themes. Three basic studies are commonality, differences and relationships. Commonality is defined as similarities that can be categorized, differences are the contrast in the data and relationships are relations between different variables and phenomena. A relation might be defined as a hypothesis in the study.

4.3. Motivation

Literature is collected mainly from the University of Lund's library and database. Keywords such as fundamental acoustics, room acoustics and swimming halls where used. The literature is critically chosen. During the literature search the absence of published work within the chosen subject was obvious. The presented literature is used to explain important parts of the subject in order to complete the thesis as well as to be a basis for problem formulation, choice of method and analyzes.

The chosen method is experimental case studies consisting of interviews, questionnaires, measurements and simulations. The interviews treat the subject widely in order to collect the existing knowledge within the subject. Since there isn't a lot published work about this topic it was necessary to examine current knowledge and work procedure. Measurements and simulations on a specific case were performed as well and together all these parts creates new information. Smaller studies on existing documents of swimming hall projects were performed as a cross case study in order to increase the knowledge of the state of the art.

The existing knowledge base, work procedure and view of the acoustic part in the design phase of swimming halls was visualized by the interviews. This contributes to the thesis with a qualitative analyze. The selection of respondents was focused on the involvement in swimming hall projects and the knowledge. In order to find answers to the problem a broad view was desired. Respondents are chosen to present several sides of the involved persons in the projects. Out of the asked persons the majority are acousticians with great experience in the subject, as well as entrepreneurs, architects and other experts are included. This is necessary since the acoustician's focuses on sound and to only ask them will probably bring a misleading view of the current situation. The collaboration between the different parties is also of interest and in order to examine this all views must be represented.

The interviews were performed one by one, either in person or by phone. Four standardized questions were used in order to compare the answers. They were asked in the same way and they are structural questions. Other questions asked were semi-structural, pre-defined in order to suit the specific expert but asked depending on the outcome of the interview. Some persons talked a lot on their own and some interviews consisted of many pre-defined questions. The interviews were successfully performed. As many interviewed experts as possible was desired but since interviews are very time consuming the total number of people is limited although sufficient to bring a lot of knowledge to the study. Overall the collected information is a large amount and circumstantial to analyze.

Questionnaires are performed in order to collect the opinion of the visitors. Since the experience of the sound environment is subjective the opinion of a larger number of people is of interest. The target group was chosen to represent the experience of a visit to a swimming hall and questionnaires were handed out to leaving visitors at particular occasions. This limits the number of respondents but every questionnaire is answered by a relevant person with the experience still in mind. On occasion was at an exercise swimming pool during calm hours and the other one at a large swimming hall with several pools as well as adventure baths during rush hours. The purpose is to find themes and relations between variables and the experience. The questionnaire was handed out to as many visitors as possible and only a few declined. The asked persons were limited by age, where children were not asked.

The questions are handed out on a questionnaire, see appendix 2. The questionnaire consists of pre-defined closed questions with alternatives where the "neither" is included where needed. At the end one open question exists in order to give the respondents an opportunity to give comments. The questionnaire was available in Swedish and English. Overall the questionnaires went well. Out of the target group many people answered and the total amount is enough to process statistically. The questionnaire consisted of both front and back and in some cases the back was missed. The first English questionnaires handed out seemed to be in too advanced language, this was altered for the second round.

The questionnaires yield results that are possible to do quantitative analyzes on. This is used in the thesis in order to represent the experience of the sound environment in order to fulfill two purposes.

1. Map the subjective attitude to the experience of sound environment.
2. Compare to the actual sound environment and measured values

The first purpose is used to see the opinion among people. For example, if the sound environment affects the experience and if the sound environment affects the choice of swimming halls. The second purpose is to be able to compare the environment in a particular swimming hall to the experience. In the swimming hall measurements were performed and the answers in the questionnaires are related to the measurement values. The first one was not measured but the situation is known to be calmer.

Employees at the swimming hall where the measurements were performed were handed a small questionnaire with open questions. These were performed as a sample of the experience of the people working in the swimming halls. They were able to answer the questions anonymously without influence from the researcher. These are analyzed qualitatively.

5. Interviews and questionnaires

5.1. Interviews

In order to collect sufficient information interviews have been conducted. Circumstantial interviews with professionals are presented below and questionnaires with visitors and employees in the swimming hall are presented further down in 5.2.

5.1.1. Execution

In order to investigate the current work and view on acoustics in swimming halls eleven people with great experience of the topic was interviewed. The group exists of persons involved in swimming halls in Sweden, from developers and entrepreneurs to architects and acousticians. The largest group consist of acousticians, five out of eleven respondents. All respondents possess necessary knowledge and expertise of the field. Four identical questions were asked to everyone in order to compare the opinions, listed below. Two exceptions were made, one respondent had a different knowledge base and the questions was not relevant and one respondent focused on experience from working on a particular project since the standard questions were already asked to a colleague of the respondent. Otherwise the interviews were performed similar and the standard questions asked in the same way, as structural questions. Other questions asked were written ahead and based on the knowledge of the particular person, then asked depending on the outcomes, as semi-structural interviews. The interviews were performed one at the time on a meeting in person or by phone.

The 4 standard questions:

How do you work in order to achieve a good acoustical environment in swimming halls?
What kind of solutions are used?

What kind of compromises regarding other demands comes up at the design phase of swimming halls?

How prioritized would you say acoustics are general at the early design phase of swimming halls?

What are the general factors of success in a swimming hall?

5.1.2. Overview standard questions

The four standard questions are summarized one by one. The summarize represent the answers given to the specific question during the interviews. The answers are represented quantitatively.

Question 1

How do you work in order to achieve a good acoustical environment in swimming halls?
What kind of solutions are used?

Summary

Calculations, models and sometimes measurements are the used methods. The most common solutions are absorbents in the ceiling, partly on the walls and inclined walls. Absorbents in the ceiling are used every time according to the respondents. Wall absorbents are used in varied extent. Inclined walls are an acoustic solution effecting the fundamental design. The answers are more detailed described below.

Methods
In order to achieve a good acoustic environment in swimming halls methods as calculations, models and measurements are applied. One respondent says that for existing swimming halls in need to be altered, measurements regarding reverberation time are performed and then a sufficient amount absorbent is calculated, while new swimming halls should be calculated from the beginning. The second statement is also mentioned by other respondents who say that a planning with calculations of amount of absorbents is used to receive the desired reverberation time, and that models are made in a software. The acoustic solutions are then determined from the calculations. Measurements may be performed in order to control the results but are not always performed.

Ceiling absorbents
Absorbents in the ceiling are used to absorb sound and reduce reflections. Absorbents in the ceiling are always a solution to achieve a desired acoustic environment in swimming halls and are directly mentioned by seven of the nine respondents that answered this question.

Wall absorbents
Wall absorbents are mentioned as a solution by six of the nine asked people. Common wall absorbents are both soft and wooden hard absorbents, and it is important to cover them from damage. Soft absorbents are hung high on the wall, usually at 3 meters height, and hard absorbents may be placed lower, down to 60 centimeters above the floor. Since people may reach these absorbents they need to be resistant. These absorbents usually have a durable outer layer and an absorbent behind. The attachment to the wall is crucial to avoid moisture problems.

Inclined walls
Inclined walls are used to make the sound waves reach the ceiling absorbents earlier and thereby reduce the reflections, as a more efficient solution. Most common is to tilt one wall, usually the one that is easiest and cheapest to angle. Inclined walls aren't always appreciated by the architect, according to one acoustician, and one way to compensate for this is to use absorbents lower down on the wall instead of tilting the wall. Another example, mentioned by two respondents, of a compromise are walls that are impossible to use absorbents on, for example if it is glass, holds equipment or needs to be easily cleaned, then to tilt the wall is a solution. Inclined glass walls have been proven to be a successful solution according to one respondent. Wall absorbents was in one example tilted in order to make up for lack of total cover of absorbents in the ceiling. Inclined walls are mentioned as a used solution by six of the nine respondents and all of these three solutions seems to be applied as standard solutions in swimming hall projects today.

Question 2
What kind of compromises regarding other demands comes up at the design phase of swimming halls?

Summary
Moisture, cost and aesthetics are the main compromises in relation to acoustics. Moisture is an issue expressed by five, cost by two and design by six out of nine. Moisture is necessary to consider, especially with the climate in a swimming hall. Cost is often a factor but it seems that swimming halls are project where acoustic solutions are prioritized and cost is not a big

obstacle. Compromises may occur in the choice of material and absorbents but according to the respondents this is not a main issue. Aesthetics and design seems to be the biggest issue, partly because the design may be decided before the acoustician comes in and partly because acoustic solutions affects the design vision. Acoustic solutions are often invisible and without a distinct purpose for the visitors, and therefore may create confusing visuals. The architects have design as an issue, and problems may be a more boring design and to find different designs for each swimming hall when the solutions are similar. Moisture is a divided issue, five respondents say that it is an issue and important to consider and one thinks that it is not interfering since absorbents is made to resist moisture etc., and the three others doesn't mention moisture as a compromise.

Other compromises expressed are resistance and hygiene, mentioned by five respectively one. Resistance as in durable hard absorbents as well as a sustainable building. Hygiene puts demands on surfaces and makes it harder to apply acoustic solutions. Compromises with the construction solutions occurs according to one respondent since it is crucial to build a sealed building. This is especially crucial with inclined walls. In order to success with this easy solutions and easy connections are preferable, and easy connections are mentioned by two. Glass is mentioned as a problem by four respondents, for example the difficulty to lean glass walls and that rooms with a lot of glass surfaces creates high sound pressure levels.

Question 3

How prioritized would you say acoustics are general at the early design phase of swimming halls?

Summary

The respondents has different views about the priority. The opinions vary from that it is very prioritized to that acousticians are involved too late. Out of nine respondents five says that it is very prioritized and considered initially. One says mediocre and one says that it is getting more and more prioritized. One respondent say that it depends on the project team and another respondent thinks that the acousticians are involved too late and that the consequence of that is expensive arrangements afterwards.

The respondents who thinks that it is very prioritized says that there is a consciousness about the risk for bad acoustic environment in swimming halls, the loud working environment and that alterations later on are expensive. Also classification, such as Miljöbyggnad, puts demands on the acoustics. One of the other respondents says that acoustics isn't a main issue with new constructions. Two of these respondents says that the acousticians are involved in the initial phase. Acoustic solutions are crucial for the design, for example inclined walls, and therefore it is necessary to discuss this at an early stage in order to avoid problems further on. Two respondents express an issue with architects who prioritizes design or think they have enough experience to re-use solutions. One respondent says that it varies a lot between teams and where persons with experience from swimming halls are involved the result is better. The respondent that thinks acousticians comes in too late says that the solutions could be improved otherwise and that the acoustic environment is crucial also for safety reasons. The common opinion is that acousticians must be involved initially.

Question 4
What are the factors of success in a swimming hall?

Summary
The fourth standard question is a general question where all the different professionals got an opportunity to focus on desired factors, not only acoustics aspects. The answers are therefore scattered and a lot of different aspects are presented. By the acousticians four out of five has the acoustic environment as an aspect. Three of them connects that to wellbeing, and those two aspects are the factors of success. The other two also mentions the logistical planning, the prestige in swimming halls that will make it a better building and that the result is better if architects and acousticians develop the solutions together. Acoustic solutions should contribute to the design and not be an obstacle. The architects mentions attraction, good maintenance and that every user should feel included. Other respondents state the importance of initial studies and analyzes of other swimming halls, include the opinions from performers and use experienced persons during construction. Several of the mentioned respondent mentions wellbeing, including all users, teaching the municipality to swim, a successful layout and room planning, and attraction. One respondent says that experience and knowledge among the involved persons during the project is crucial for a successful result due to the complexity of swimming halls.

5.1.3. Miscellaneous
The interviews resulted in a large amount of information. The part above presents the standard questions common for all respondents. Moreover, information about a lot of topics were collected. The most relevant parameters regarding the acoustic environment in swimming halls are presented below.

Collaboration between architects and acousticians
One aspect mentioned by several respondents is the collaboration between architects and acousticians. Two respondents say that it is important for the acoustician to work together with the architect and together create solutions. Acoustic solutions should in order to be successful contribute to the architectural experience, and not the opposite. According to one respondent there are cases when the architects has a vision about the design from the beginning, and then the acousticians needs to implement this and make suitable solutions. The architects view is that it is possible to make good compromises. It is important for them to combine demands with the visual. Undesired acoustic solutions may be compromised by add more absorbents at another place or tilt another part for example. For the architect it also is a difficulty to work with acoustic solutions in order to find new aesthetical appealing solutions for each project.

Safety
The safety in swimming halls should be a big acoustic discussion. In this thesis this is outside the margins but reflections about this are still made. The respondents say that it is a safety risk with high sound pressure levels. Evacuation and to hear teachers and children from a distance is obstructed.

Work environment
The acoustic environment is effecting the working environment. The employees at swimming halls may suffer from the consequences. The opinion from the respondents is that it is an environment with high sound pressure level and due to this it is an exhausting working environment. Other aspects are impulse sounds from whistle blows or shouting children, as well as the high temperature and moisture level. Two respondents say that the discussion about

working environment increases the prioritizing of acoustics and that the discussion is included in the design phase. One respondent says that the sound pressure level will be too high without sufficient acoustic planning and thereby effect the work environment badly. On the other hand, one respondent says that it is not widely discussed now but is a growing topic.

Experience

The importance of experience also became a discussion with the respondents. Five respondents say that it is important and three of those five claims it to be fundamental in order to success. Experience is important because the more involved you are in a project, the more you know about good solutions etc. according to one respondent. Swimming halls seems to be a challenging project to do for the first time but experience in the project team and shared knowledge is a key to handle that, but that it might be hard to collect the knowledge without support. Since the client often is a municipality, with few swimming hall projects during a long time, lack of experience is likely to be a problem. This can be handled by a good relationship between the client and entrepreneur so that they will take part of the knowledge. One way to achieve this are partnering projects. Experienced consults in different areas are of great importance.

Education

Educational spaces should enhance consonants and diminish vowels in order to increase the speech intelligibility. Office spaces should be made the opposite way since you don’t want to hear each other. In order to achieve a good educational room, the vowels should be reduced, since it is harder to increase the energy in consonants in speech. Signal-to-noise will affect the speech intelligibility and C50 are a measures of that. The Lombard effect is important in educational areas, and means that people will speak 10 dB higher than the background noise. In swimming halls, the background noise should be reduced in order to reduce the speech sound pressure level. According to three respondents speech intelligibility is an important factor in swimming halls. It will affect the educational situations. Another respondent thinks that the environments might be loud but that education often is working well, depending on the teacher. In educational situations screens seems to be a desired solution according to several respondents. One respondent says that the sight is crucial for guards and that sufficient passages is necessary which may limit the possible use of screens.

Suggested solutions

During the interviews a lot of different sound related aspects came up. This is summarized below and will show a general view of the important aspects of acoustics related to swimming halls.

The most desired solution seems to vary between the respondents, where four respondents gave strict answers during discussion. Two respondents mention that it is more effective to tilt a wall than to use a lot of absorbents. Another respondent says that it is better to absorb than to diffuse and one respondent prefers high frequency absorbents instead of inclined walls, except from glass walls where diffusing is the only option. According to one respondent diffusion is important in swimming halls due to the limited possibility to use absorbents. Overall it seems that most respondents prefer to use an inclined wall when possible. Inclined walls are used only for acoustical reasons. According to one respondent diffusion is important to create a desirable acoustic environment since it makes the sound softer. Not only the sound pressure level is important, if the sound is intrusive or pleasant makes a difference.

In general, the purpose is to alter hard parallel surfaces, either by absorbents or by tilting a wall. The most common solution seems to be one inclined wall and one or more walls with absorbents. The ceiling is always covered in absorbents and the mission is to as quick as possible bring the reflections to the ceiling. Successful solutions are, according to one respondent, hard absorbents, diffusing surfaces and to hide the low frequency absorbents in the ceiling. One respondent says that absorbent should be maximized where possible and two respondents says that the swimming hall never will be too sound absorbing.

The angled of inclined walls was discussed more deeply with two respondents with great knowledge. The angel needs to be at least 3-4 degrees to be sufficient. More degrees will provide a better result. 5 and 7 degrees seems to be common and the interval stretches up to 10 degrees, although the trend might be moving towards the lower angles. Two inclined walls opposite each other will need less inclination but according to all the respondents the most used solution is to tilt one wall. According to one respondent problems may occur with inclined walls due to accessibility demands where passage can’t be too narrow and fixed installation areas for example.

A debated topic during the interviews is the use of glass. As mentioned before several respondents experienced glass as a problem, due to the contribution to a worse acoustic environment and the difficulties with tilting it. One respondent had an example where a glass wall was exchanged during the design phase in favour for the acoustic environment. One respondent says that one way to reach a good acoustic environment as well as energy performance is to reduce the glass areas. The same respondent also says that large glass walls has been a tradition in Sweden and maybe it is time to re-evaluate the use of glass walls in Swedish swimming halls.

A lot of other aspects are also affecting the acoustic environment. One large sound source in swimming halls is the water, particularly the drains by the pool edge. These generates a high background level and people will raise their voice to be heard. Solutions to reduce this sound source are existing, for example plastic or tilted drains, according to one respondent. One respondent say that an improvement would be to include an acoustician while designing the things that creates large volumes, for example attractions in adventure baths. Vegetation is commonly used in adventure baths and according to two respondents it makes a difference. Vegetation isn’t directly effecting the acoustic environment but helps to diffuse the sound and also experienced as soothing. One important aspect to consider while designing the construction mentioned by two respondents is crosstalk, when sound escapes through installation etc., between rooms.

Opinions regarding demands

The reverberation time is related to the room volume. High ceiling height creates longer reverberation time and may be a problem in swimming halls according to several respondents. According to one respondent reverberation time is the measure most effecting the experience of the sound in every type of building, not only swimming halls. The reverberation time seems to be a target instead of a demand due to the limitations of acoustic solutions. The desired values are 1.5 in large rooms and lower, 1.2 or less, in smaller room and adventure baths. One example according to one respondent when the reverberation time was higher than desired where when walls couldn’t be as inclined as desired by the acoustician and the room is large with high ceiling height. In adventure baths the interior design makes it hard to calculate the reverberation time in advance with walls, levels, bridges etc. One way to address the acoustic aspect within the design according to two respondents is to use rounded figures that sends the sound upwards. It is also important to avoid plane surfaces reflection the sound waves back and forth.

The regulation used for designing swimming halls is SS 025268. The demands are directed to school locals and is not adapted to swimming halls. The overall view is that the regulation is a support for the acoustician but experience is more important. One respondent thinks that the regulation isn't working at all and that other aspects than reverberation time is important, such as impulse sounds from screams etc., but the regulations may be used for supporting the acoustician. Two respondents say that improvements of the standard isn't necessary since swimming halls is such a special type of building and experience is sufficient. Besides experience visits to other swimming halls seems to be a useful source to make a successful swimming hall.

Environmental certification is an aspect mentioned by three respondents. Two respondents say that it limits the possible solutions. One example of a problem that occurs is that structural sound needs to be altered in order to achieve the higher demand but it won't affect the acoustic environment a lot and will provide a less sustainable solution. One respondent mention that it is making the acoustic environment more prioritized in the design phase.

Design phase

The design phase holds a lot of decisions creating the final result. All respondents think that it is important to consider acoustics from the very beginning. Following are some quotes about this, translated from Swedish.

"In the initial phase a lot of decisions are made, things appearing later on creates problems. If the (acoustic) demands isn't considered from the beginning, it will be problems afterwards."

"Make as much acoustic work as possible as early as possible"

"Unspecific demands in documents creates problems later on where they are harder to solve and more compromises are needed. It is better to have the problems at an early phase, in order to be able to work together"

All quotes can be applied to the design phase of all projects and empathizes the importance of early solutions. One respondent says that acoustics is considered already during the sketching in swimming hall projects and a design that will work with acoustic demands needs to be chosen. One way to work with acoustic demands at an early stage is to do study visits and map the sound sources in swimming halls. According to one respondent it is important to write descriptions about the acoustic environment in the different locations in words before values in order to reach the client. Another respondent says that experienced persons should explain the difficulties with acoustics to the client and be clear about what they want to create. One respondent says that the acoustician needs to be included in the initial phase and look at what can be done and how to do it. Experienced people will provide solutions proven to work and the solutions should be included from the start.

One aspect that occurred during interviews is that acoustic solutions isn't the factor of success for architects. Acoustic solutions aren't placing the architects in architectural magazines or winning a competition. Acoustic solutions are, according to the respondents, invisible. As mentioned before, acoustic solutions should contribute to the design and not decrease the visuals. The solutions aren’t always logical to the viewer, an example of this is inclined walls that may seem strange for the visitors and therefore disturbing the architectural entirety.

5.2. Questionnaire visitors

Questionnaires was handed out to visitors in swimming halls in order to detect the subjective aspect of the subject. The result is analyzed statistically and compared to measurement values.

5.2.1. Execution

The questionnaire consists of closed questions and one open question for comments. The detailed responses from the questionnaires are attached in appendix 2, followed by the questionnaire in both Swedish and English versions.

Occasions

The questionnaires was handed out at two occasions. The first occasion was at an exercise swimming pool divided in two sessions of about two hours each. The first one was during daytime when it was calm and without children. The later one was during an event with low music, candles and without splashing sounds etc. The second occasion was at a large swimming hall at the time it usually is as busiest. The questionnaires were handed out during 2.5 h and at the same time as measurements of sound pressure level was executed. The target group was people leaving the swimming hall and at both times the position was nearby the exit from the swimming hall.

Kockums Fritid
Friday 26/2
Occasion 1: 14.15-17.00
Occasion 2: 18.30-20.30

Hylliebadet
Sunday 24/4
Occasion 3: 14.10-16.40

The total number of filled out questionnaires is 133, where the different occasions contributes with 43, 43 and 47 each. The question with least amount of answers is at 126 due to missed questions on the back, so in general all questions are well represented. The total amount is analyzed as a general opinion as well as the different occasions are used to find a connection between variables and experience. The amount of answers is enough to statistically analyze it together as well as separated. Out of the target groups the majority was asked to fill out the form, some was missed due to full occupation and only a few people declined in both cases. The amount of answers is well representing the opinion of the visitors during the chosen time.

Observations

During the occasions observations of the swimming halls was performed. The first occasion was describing as calm by the respondents and the visitors was there for exercise and hardly any children where present. At the second occasion the main sources are the water and children shouting and the sound pressure level reaches high levels, see Chapter 6. Measurements.

5.2.2. Response

The responses are presented below. First as a summary of the response to all of the questions. The summary is followed by graphics for three chosen questions and further down each question is presented one by one.

Summary

The majority had a good experience and the respondents are assumed to be positive to the swimming hall. The majority also rated the acoustic environment as good, especially in the calmer swimming hall. About the effect of the acoustic environment the opinions are scattered, but the trend is increasing along the scale and the majority thinks that it does affects. Communication is rated well and the aesthetics is also appreciated. The two swimming halls are rated to be better than other swimming halls in general, as well as many people also answered “don’t know”. The opinion of if the acoustic environment affects the choice of swimming hall is scattered, 40 % on each side and 20 % is neutral. Tiredness is very seldom experienced as a consequence of a visit in a swimming hall by the respondents. This is comparable to the opinion of the employees.

The total distribution of responses for the three occasions and total value for the most interesting questions are included below in figures 21-23. Occasion 3 is related to performed measurements.

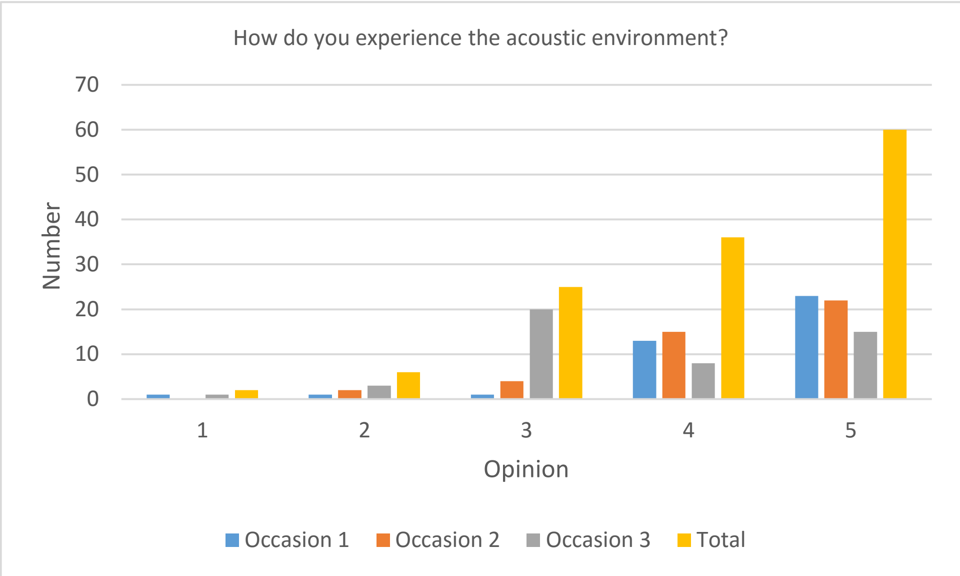


Figure 21: Response rate question 1

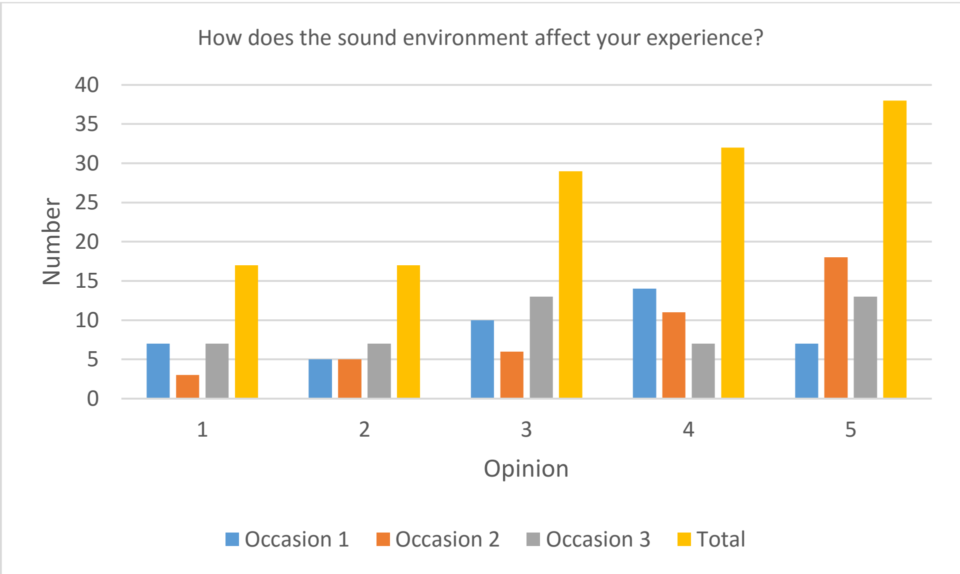


Figure 22: Response rate question 2

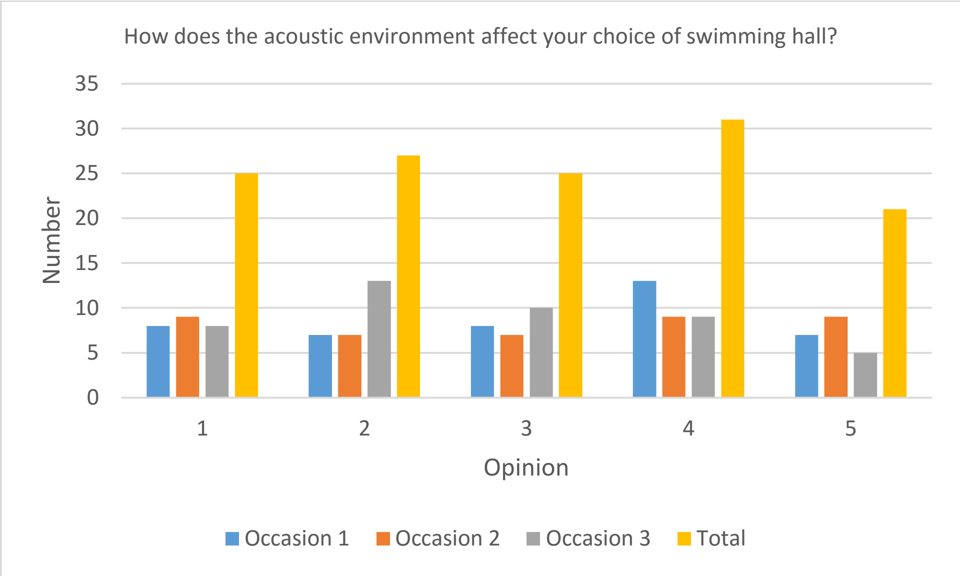


Figure 23: Response rate question 3

Detailed overview

How satisfied are you with your experience in the swimming hall today?

Overall the respondents are satisfied with their visit. Only one person rates the experience below 3 and is thereby unsatisfied, 16 are neutral and 55 respectively 61 rates the experience high, out of 133 total. In general 87 % of the respondents are positive to the visit.

How do you experience the acoustic environment?

The majority rates the acoustic environment as good or very good, in total 74 %, see figure 21. The two swimming halls are both rated well, 89 % and 53 % (where 42 % is neutral). The acoustic environment is rated higher in the smaller, calmer, swimming hall.

In order to see if the sound environment is related to the general experience of the visit a comparison can be done. This can be compared to next question, if the sound affects the experience. The two questions above collaborates at 70 % for positive sides on both matters, which means that out of the people answering the questionnaire 70 % are satisfied with the experience and are also experiencing the acoustic environment as good.

How does the sound environment affect your experience?

The answers to this question is increasing from 13 % to 29 %, see figure 22. The opinions are scattered, some doesn't think it affects and some think it does. It points to the assumption that it is very subjective. In total the part on the upper side of the scale is 53 %. In total 43 % of all respondents thinks that the factor above affects and also judges the acoustic environment as good.

How do you experience the ability to talk?

Communication is overall rated as well, 72 % of the responses are on the upper grades. This might be related to conversations over a short distance but points to that the ability to carry a conversation isn't harmed by the acoustic environment. This is not easy to relate to safety aspects.

How do you experience the ability to have oversight over for example kids?

The answer rate on this question is too low to judge. It is excluded from the attached detailed response as well.

How do you experience the look of the swimming hall on the inside?

In general, both swimming halls are rated as appealing. Most answers are at level 3 and 4 on the scale.

How do you experience the sound level in this swimming hall compared to other swimming halls?

Both swimming halls are rated as better than other swimming halls in general, as well as the number on "don’t know" is quit high, which may depend on that people often visit the closest swimming hall.

How does the acoustic environment effect your choice of swimming hall?

This question addresses the subjective relation to the effect of acoustic environment and the answers are scattered, see figure 23. It is the same amount of answers on both positive and negative side on the scale. Both sides have 40 % representation and 20 % is unaffected. This strengthen the theory that it is very subjective.

This question is relatable to if the acoustic environment affects the experience. Out of the respondents 30 % thinks that both the statement above and that the acoustic environment affects the experience much or a lot. This may show contradictions which makes the questionnaire less reliable but the low collaboration seems to depend on the scattered view of the affect the acoustic environment has on the choice of swimming hall. A lot of people are probably choosing swimming hall by distance and attraction regardless of the acoustic environment.

How often do you experience mental tiredness, headache etc. after a visit in a swimming hall?

The general opinion is that it seldom arises, 72 % thinks that it seldom or never happens. The target group is visiting during a shorter period of time.

5.3. Questionnaire employees

Questionnaires are also handed out to the employees in swimming halls. These are analyzed qualitatively and compared to measurement values.

5.3.1. Execution

A small questionnaire was handed out to the employees at Hylliebadet at the same time as measurements and questionnaires to visitors was performed, Sunday 24th of April around 3 o'clock. The questionnaire consisted of four questions and was handed out to seven randomly chosen persons as a cluster sample. The purpose is to receive an overview of the work environment.

5.3.2. Response

The collected opinions are summarized for each question below.

How do you experience the sound environment in the swimming hall?

Everyone claims that the sound pressure level is high. One says that it varies a lot depending on the amount of visitors and another says that it is low most days but very high at weekends. Ear plugs are necessary according to two of the asked employees. Two persons describes the sound environment as noisy and one mention screaming, loud talking and music as sound sources contributing to the high sound pressure level.

How does the sound environment affect your work performance?

All seven consulted employees say that the acoustic environment affects the work performance negative in one or other ways. Two mentions tiredness and headache. One person says that the sound environment makes it harder to focus on the work assignments, one says that it impairs the ability to keep attention and one says that it is hard to hear colleagues in the radio. According to one person the sound environment together with the other strenuous work environment aspects such as heath, moisture and poor air quality, are strongly affecting the desired length of time spent in the swimming pool area.

Are there any aspects where the sound pressure level is an obstacle? For example safety, education, communication

Communication is mentioned by everyone and safety by four out of seven. According to several persons the safety is at risk because of the reduced ability to communicate, for example to hear difference between play and panic or to hear colleagues if there is an accident or similar. The communication may suffer when you can't be sure that the verbal communication reaches the receiver, says one person.

Do you feel mental tiredness, headache or similar after a work pass?

The homogenous answer to the question is yes. Everyone experience tiredness and headache after a shift in the swimming hall, but two of them suffers from headaches less often. According to one person, shorter exposure in the environment is improving the consequences and two claims that ear plugs are helping.

6. Measurements

6.1. Execution

Measurements were performed in a Swimming hall in Malmö, Hylliebadet. This is a new swimming hall opened in 2015. Since the study focused on the larger rooms in the swimming halls the measurements were performed in the space with 50 meter long pool, in a space with a smaller pool and in the adventure bath, see figure 24. Measurements of reverberation time and background noise were performed before the swimming hall opened for the day. Sound pressure level during activity was performed during daytime. Those measurements were performed at the time of the week when most people usually visit the swimming hall in order to receive the maximum values. The measurements were performed according to the Swedish Standard SS-EN ISO 3382-2:2008 and SS-EN 16032.

STI is an interesting value to measure but in this thesis it was not performed. Several values are important in order to evaluate a room, especially as complex as swimming halls. Only reverberation time and sound pressure level is not enough to make a statement about the swimming hall in general but it is a good value for discussion. The purpose of the measurements is to have a basis for analysis of relevant values for the acoustic environment and to be able to compare these with the subjective opinion.

6.1.1. Swimming pools

The measurements were mainly performed in two rooms, referred to as the large and small swimming pool, see figure 24 and 25. The large swimming pool is a 50 meter long pool for exercise and practice with a small platform for audience along one of the long walls. The small pool is an educational pool and surrounded only by an edge to walk on. A sketch further down shows the position and below are pictures from the measurement occasion. Both rooms were empty and quiet, except from water noise. The pictures are taken during the measurements on the 22th of April around 6 o'clock in the morning. The sound pressure level is also measured in the adventure bath since it is possible that the volume is at the highest there but since the design is very specific for this swimming hall the other locations are better as references.

One wall is a façade and has windows on a part of the wall. Several acoustic solutions are used, for example are the walls made of perforated sheets, some of the yellow parts on the pictures, and absorbents on some parts. The ceiling is completely covered by absorbents. The wall between the two rooms is mostly made of glass. All walls are straight in vertical direction, but a bit irregular in horizontal direction, as shown on the sketch.

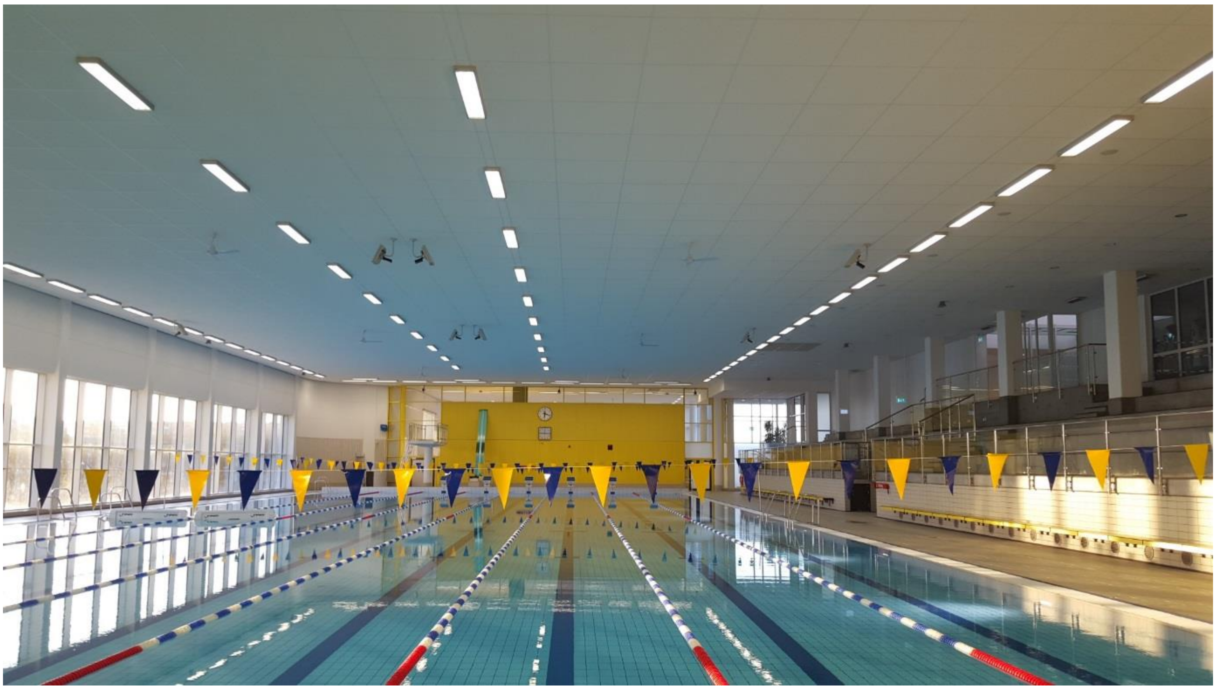


Figure 24: Large swimming pool

Figure 25: Small swimming pool

6.1.2. Equipment

The measurements are performed with a Sound Level Meter Type 2270 from Brüel & Kjaer. The sound pressure level is measured with the Sound Level Meter but measurements for reverberation time were performed with more equipment as well. An omnidirectional loudspeaker and a power amplifier are connected to the Sound Level Meter, see figure 26. Reverberation time can be measured in several ways. The room can be acoustically excited by various sources of sound, in this case a loudspeaker since the volume is large and the lower frequencies are important.

Figure 26: Measurement arrangement

6.1.3. Measurement positions

Measurements were performed in two positions in each room, see figure 27. At point one, red dot, reverberation time and background noise 1 was performed, see table 8. At point 2, yellow dot, background noise 2 was performed. In the small swimming pool reverberation time was measured at point 3, blue dot, and background at point 4, green dot. Sound pressure level during activity was measured twice during daytime at point 1, 3 and 5 (black dot). The measurements are listed in Table 8: Measurementstable 8.

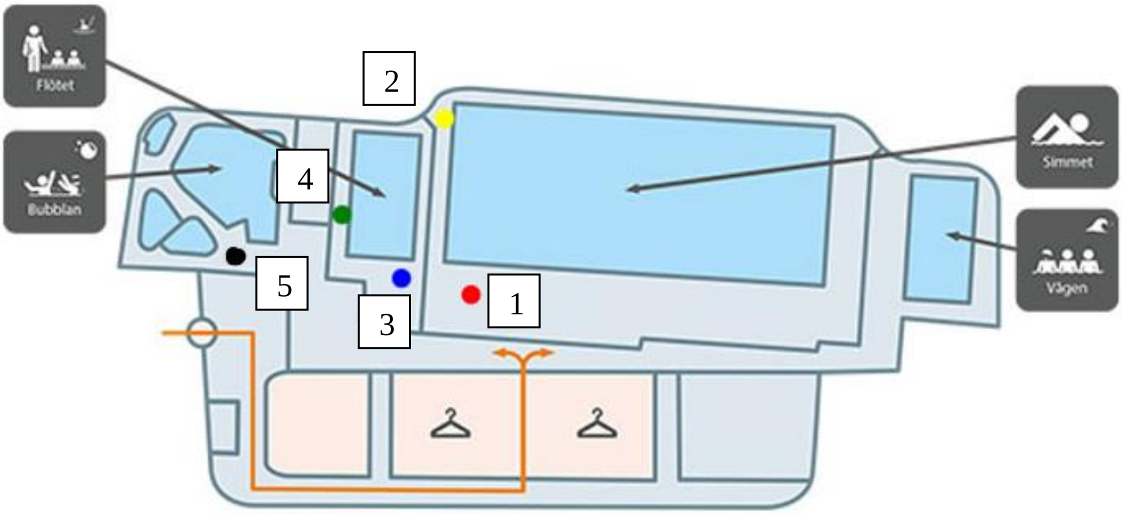


Figure 27: Overview Hylliebadet with marked positions (Hylliebadet, 2016).

Table 8: Measurements

No	Type	Location, position
1	Reverberation time	Large swimming pool, 1
2	Reverberation time	Small swimming pool, 3
3	Background noise	Large swimming pool, 1
4	Background noise	Large swimming pool, 2
5	Background noise	Small swimming pool, 4
6	Activity noise	Large swimming pool, 1
7	Activity noise	Small swimming pool, 3
8	Activity noise	Adventure bath, 5

6.1.4. Reverberation time

Reverberation time was measured in the two rooms between 6 and 7 in the morning, Friday 22nd of April, the measurements are illustrated in figure 28. During the measurements only the measurement operator was present. The major source of sound was the water, mostly due to the drains. Except for this no other sound sources were dominant. The sound pressure level is estimated to be at a high level.

Measurement 1
Location: Large swimming pool, point 1
Positions: 3
Measurements: 6 (2 on each)

Measurement 2
Location: Small swimming pool, point 3
Positions: 2
Measurements: 6 (3 on each)

Figure 28: Measurement 1 and 2

6.1.5. Background noise

Background noise was measured with the Sound Level Meter. The measurements were performed at three positions in two locations. Each measurement was executed for 30 seconds. During the measurements the rooms were completely empty and the music was turned off. Installations were on but the observation is that the main sound source is the water, mainly because of the drain.

Measurement 3
Location: Large swimming pool, point 1
Positions: 1

Measurement 4
Location: Large swimming pool, point 2
Positions: 1

Measurement 5
Location: Small swimming pool, point 4
Positions: 1

6.1.6. Activity noise

During the day measurements of activity noise were measured in three swimming pools. The day and time was chosen to represent a high sound pressure level. According to the employees Sunday afternoons are loudest and the measurements were performed at two different times on Sunday 24th of April. During the measurements a lot of people were in the swimming pools, especially the small pool was crowded. Between the two occasions about the same amount of people were there, approximately a little more at the later occasion. Between the occasions the main differences are music and talking/screaming. The main sources are listed below, separated for the two occasions.

First round of measurements was performed at 13.50 and a second round at 16. 50. For each round, two measurements were performed at each swimming pool and that gives a total of 4 measurements of each location. One measurement is presented in the result in order to show the sound pressure level and the other measurements are used for confirmation. During the same day questionnaires were handed out in order to compare experience with measured values, more about this under 5.2 Questionnaires visitors.

Measurement 6
Location: Large swimming pool, point 1
Measurements: 2
Main sound sources: Music, splashing and some talking / Low music, splashing, talking

Measurement 7
Location: Small swimming pool, point 3
Measurements: 2
Main sound sources: No music, a lot of splashing, talking and screaming / No music, splashing, a lot of screaming and talking

Measurement 8
Location: Adventure bath, point 5
Measurements: 2
Main sound sources: Low music, no splashing, a lot of screaming, sound from water / No music, humming noise from a water installation, some talking and screaming, sound from water

During daytime measurements were performed at two separated occasions. One at 13.50 and another one at 16.50. The measurements are close to each other for the 4 different values. For the 4 measurements at each position the biggest difference is 12 dB and that is in the large swimming pool. In the large pool the second performed measurement at 16.50 is used, in the small one the first one at 16.50 is chosen and in the adventure bath the first one at 13.50 is used. These are the measurements with the highest values and therefore chosen. The latest measurements generally show the highest values except for adventure bath but the difference to the highest value at the later measurement is 1 dB. Since there is a difference in number of persons and music from time to time an average value is not relevant.

6.2. Results

The results from the measurements are presented below.

6.2.1. Reverberation time

The reverberation time is presented in tables 9 and 10 and calculated with a fitted curve, see figure 29 and 30. Complete information is attached in appendix.

Large swimming hall

Table 9: The reverberation time for each frequency from 63 Hz to 8000 Hz.

f (Hz)	63	125	250	500	1000	2000	4000	8000
T20 (s)	1.23	1.08	1.26	1.45	1.45	1.23	0.93	0.45

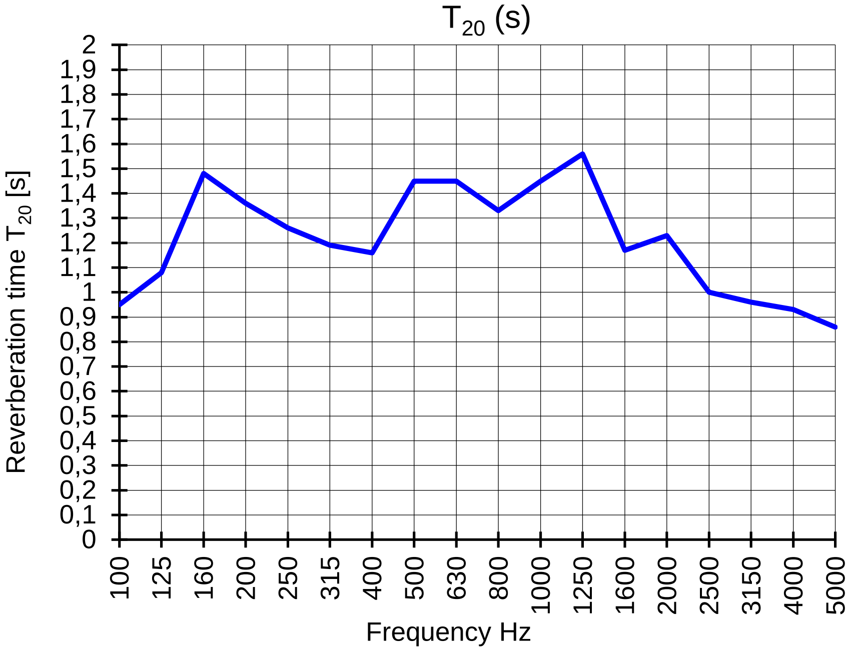


Figure 29: Graphic showing the reverberation time for each frequency for the large swimming hall calculated for frequency 100 to 5000 Hz.

Reverberation time: 1.3 s

Small swimming hall

Table 10: The reverberation time for each frequency from 63 Hz to 8000 Hz.

f (Hz)	63	125	250	500	1000	2000	4000	8000
T20 (s)	1.48	0.75	0.73	0.77	1.19	1.52	1.48	1.28

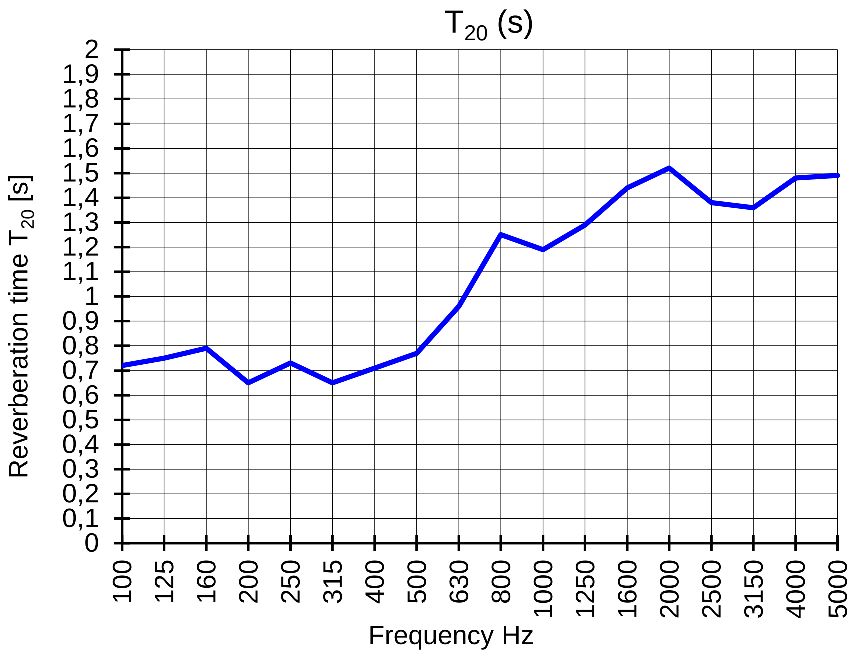


Figure 30: Graphic showing the reverberation time for each frequency for the small swimming hall

Reverberation time: 1.1 s

6.2.2. Sound pressure level

Background noise and activity during daytime is presented in Table 11 below for L_{Zeq} and L_{Aeq} for 30 seconds. L_{Zeq} for the 6 measurements for each third octave band from 125 to 5k Hz is attached in appendix since it may be interesting to analyze the specific third octave band. L_{Zeq} for background noise is also presented for frequencies 31.5 to 200 Hz in order to be comparable to the target values for lower frequencies, see chapter 3. Guidelines.

Table 11: Sound pressure level in dB(A) and dB(Z) for measurement 3-8.

Frequency (Hz)	**L_{Aeq}**	**L_{Zeq}**
Empty		
3, Large	**47.61**	**49.69**
4, Large	**45.10**	**49.05**
5, Small	**57.45**	**56.62**
Activity		
6, Large	**68.20**	**71.65**
7, Small	**72.89**	**72.66**
8, Adventure	**75.05**	**70.98**

Summary

Reverberation time was measured in the large and small swimming pool and the result was 1.3 s respectively 1.1 s, comparable to the guidelines. The sound pressure level was measured before and during activity. The large swimming pool has a background noise level of around 45-47 dB(A) and an activity noise of around 68 dB(A). The small pool values are 57 dB(A) and 73 dB(A). The adventure bath is only measured for activity noise and the level exceeds 75 dB(A).

7. Simulations

7.1. Purpose

Simulations in Odeon Software are conducted in order to value the different parameters effecting the sound environment. Two simulations are made in order to explore the impact of an inclined wall. The results are also compared to performed measurements and used as an empirical basis for analyzes. The simulations are consisting of a model in two versions, both simulated regarding acoustical parameters.

7.2. Model

The model is made in Sketch Up and exported to Odeon software where materials are added to the surfaces. The model is designed with consideration of the swimming hall where measurements were performed. Simplifications are made where places for audiences are excluded for example. The model is representing an idealistic swimming hall and therefore good as reference but may differ from many swimming pools in reality. In order to create a general case dimensions are chosen from Svensk simidrott (2016) for a 50 meter long swimming pool. The length of the model is 60 meters and the width 30 meters. The pool is made to imitate a 50 meters pool but the measurements has a certain deviation. Since the floor and water surface are both hard surfaces this difference is acceptable. All walking edges are 4 meters. The height is 8 meters and the pool is immersed 0.2 meters. The model is divided in surfaces where different materials are attached, see figure 31 and 32. The upper parts of the walls are separated from the lower parts of a height of 3 meters in order to be able to put different type of materials, as in reality.

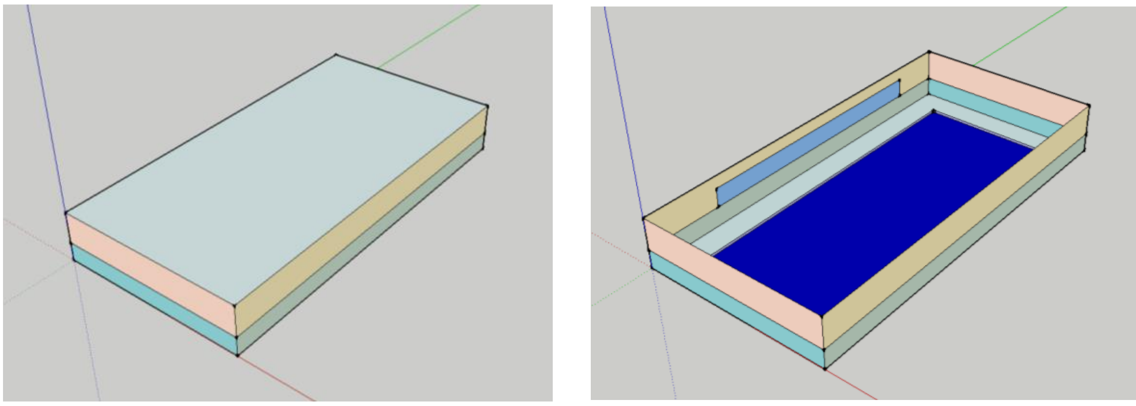


Figure 31: The model with and without the ceiling visible.

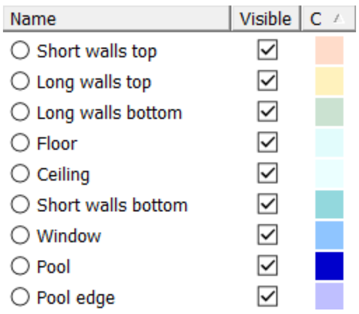


Figure 32: The division of surfaces.

7.3. Execution

Simulations are performed in order to analyze values of reverberation time and STI first and foremost. Other parameters are also received in the calculations, such as EDT. The reverberation time is comparable to executed measurements. The software contains several functions. Global estimate is an estimation of reverberation time depending on room shape, position of absorbing materials and sources (Odeon, 2016). A quick estimate is possible to do initially where diffuse field assumptions are used for quick calculation of the reverberation time with consideration of absorbents. The grid function creates a grid map of room-acoustical parameters and statistics. Ray-tracing is a dynamic display of raytracing from selected source. 3D billiard is an interactive display for visualization of wave fronts to demonstrate scattering, flutter echoes, focusing and coupling effects. All above mentioned functions are used in the simulations.

Materials are addressed to the model in Odeon software. Some material exists in the database and some are added from other sources. The ceiling is covered with absorbents as in reality. The pool area is set as a water surface. The floor and pool edge are set as tile, for specific material chosen see below. The lower parts of both short and long walls are set as tile since this area is vulnerable for contact. The upper parts are set as absorbents. The used absorbent is adapted to be similar to an existing hygiene absorbent and added manually. For the window an option form the database is chosen, see below. For this simulations the glass itself isn’t of interest as much as the impact of the amount of glass. For the simulation the glass is 40 times 3 meters big and is included since swimming halls often has more or less glass surfaces.

Materials
Ceiling: 91 absorbent Hygiene
Floor: 2001 Marble and glazed tile
Pool edge: 2001 Marble and glazed tile
Pool: 9000 Water surface swimming pool
Window: 10005 Glass, large panes of heavy plate glass
Long walls top: 91 absorbent Hygiene
Long walls bottom: 2001 Marble and glazed tile
Short walls top: 91 absorbent Hygiene
Short walls bottom: 2001 Marble and glazed tile

The absorbent in figure 33 below is used and adapted to the material database manually. The absorbent is adapted for hygiene spaces and should be a good choice for the simulation. Simplifications of the absorbent coefficient is made at the lowest and highest frequency, 63 and 8000 Hz, as below, see figure 34. The absorption for tile and water is visible in figure 35 and 33.

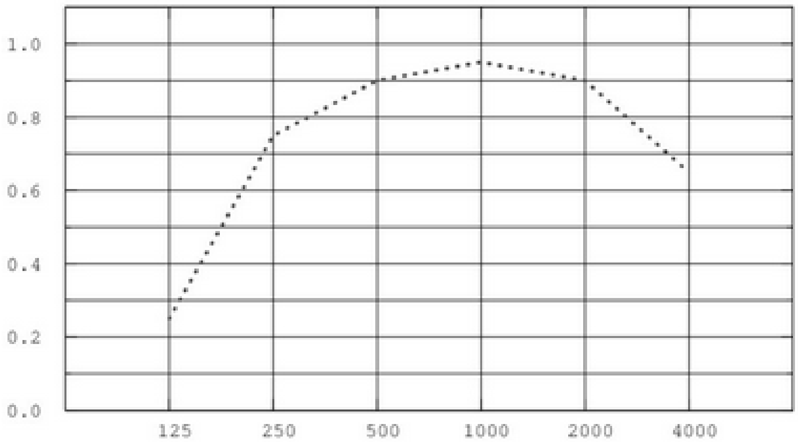


Figure 33: Extract from specifications of a hygiene absorbent (Ecophon Saint-Gobain, 2016). The absorbent coefficient is on the y-axis and the frequency on the x-axis.

Material data

Material number	Material description
91	Absorbent Hygiene

Absorption

Frequency	63	125	250	500	1000	2000	4000	8000	Hz
Abs. Coeff.	0,25000	0,25000	0,75000	0,90000	0,95000	0,90000	0,65000	0,65000	

Figure 34: Absorption coefficient for absorbent.

63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
0,01000	0,01000	0,01000	0,01000	0,01000	0,02000	0,02000	0,02000

Figure 35: Absorption coefficient for tile.

63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
0,01000	0,01000	0,01000	0,01000	0,01000	0,02000	0,02000	0,02000

Figure 36: Absorption coefficient for water surface.

7.3.1. Positions

For the simulation sound source and measurements positions needs to be chosen. The point source is placed close to a corner which is similar to chosen position of conducted measurements. This placement will include more low frequencies, which is desirable. The gain is set to 65 dB. The source is omnidirectional, adapted for room acoustic calculations (Odeon, 2016). Calculations can be done at one or more positions in a room. A single point response gives detailed results of acoustical parameters for a selected receiver. Multi point response gives the results for a specified number of receivers.

Three receivers are placed at different positions in the swimming hall to represent different situations. For example, the STI measurements are largely affected by the distance between source and listener, where shorter distance makes the speech intelligibility higher. Since swimming halls are such a large room people may need to talk to each other over great distance and this is more interesting. At this positions reverberation time T30 and STI are received among several other parameters. The positions are listed in table 12, where the values are the distance in meter from origo, se figure 31, at the form x,y,z.

Table 12: The positions for source and receivers described.

Object	Positions
Point source	2, 2, 1.2
Receiver 1	2, 50, 1.2
Receiver 2	15, 30, 0.5
Receiver 3	20, 2, 1.2

The three positions are visible in figure 37 and the exact positions are described in Table 12. They are placed in order to represent the division in the room and not too close to the source. Receiver 1 and 3 are placed on the edges where people may walk. They are placed 2 meters from the walls in order to avoid reflections, and 1.2 meters above ground to be similar to a person and measurements. Receiver 2 is placed above the water surface since this also is an important place to analyze STI etc. since a lot of visitors spends the most time in the water. The receiver is placed 0.5 meters above ground level to be closer to the surface since people in water are lower, but not too close to catch a lot of reflections.

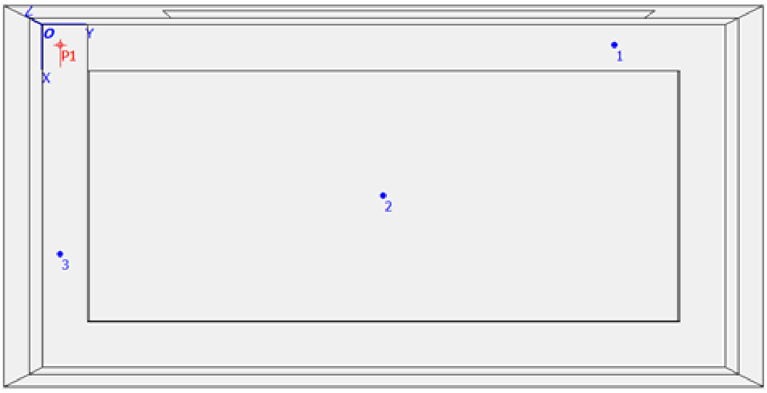


Figure 37: Positions of point source and receivers.

7.3.2. Simulation 1

The first simulation is as the model above without alterations. Different types of calculation functions are used. A simulation with the three receivers and the point source is simulated together and values for the three different positions are received. A global estimate is also performed, which is a simulation ongoing for hours. This gives a value for T30 for the whole room and not related to a position. The functions grid and 3D billiard are used to present the sound distribution in the room. In order to check if the model is sealed 3D rays are used, see figure 38.

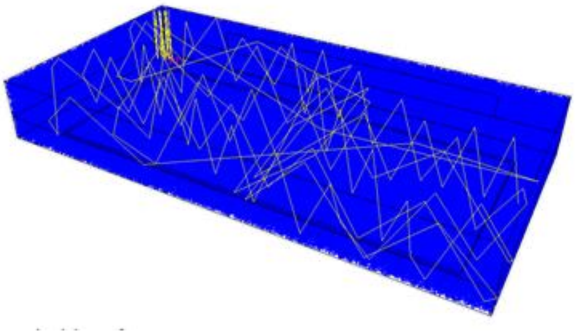


Figure 38: 3D rays illustrated

The figure above shows that the model is sealed and that the simulation is good. In order to visualize the sound distribution 3D Billiard is used. Below the sequence is illustrated.

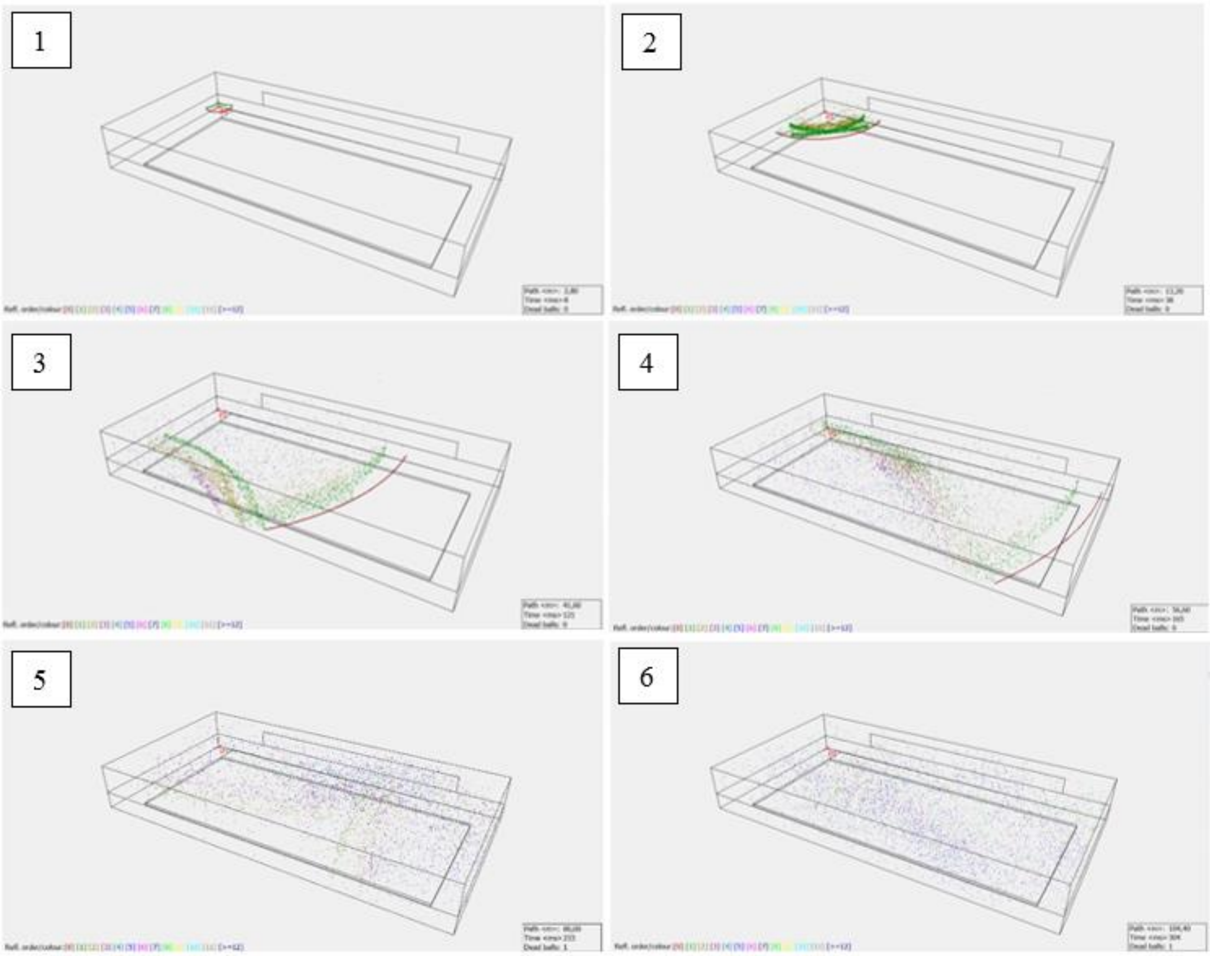


Figure 39: Picture 1-6 showing the development during the 3D billiard simulation.

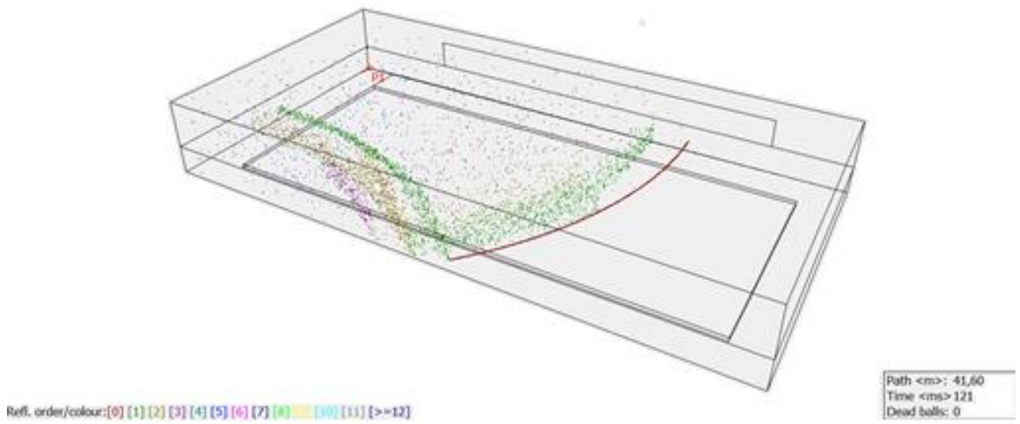


Figure 40: Close up on picture 3. The first reflections have reached the long wall and are directed at the second long wall. The first reflection has still not reached the short wall on the other side from the sound source.

Grid illustrations for T30 and STI for 1000 Hz are shown below in figures 41 and 42. The color gradient is adapted to the scale on the right side in the pictures.

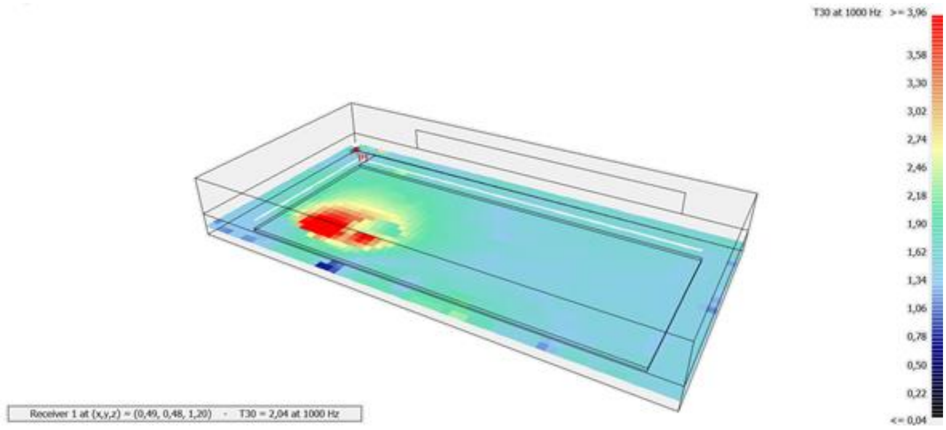


Figure 41: T30 illustrated with grid.

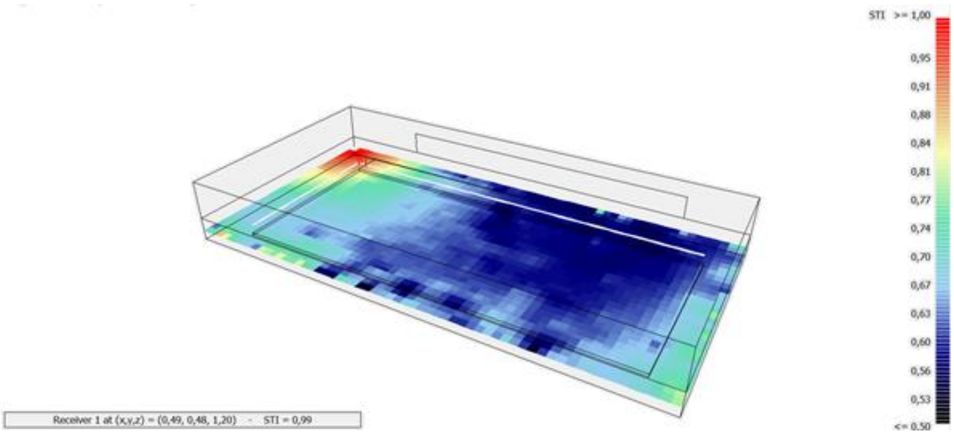


Figure 42: STI illustrated with grid.

The quick simulation returns values immediately, below T30 is visualized for each receiver in figure 43 and the values for each parameter are listed. The complete information is also attached in appendix 4. Global estimate is included in Table 13 and in appendix 4 with more information. The estimated volume is 13890.62 m^3 according to the global estimate.

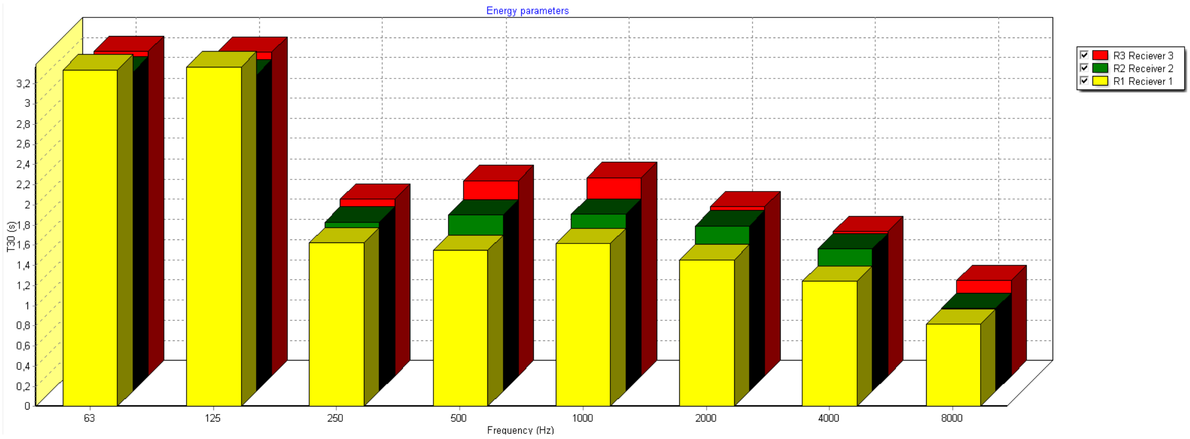


Figure 43: Reverberation time for the calculated frequencies. The scale is to the left and the lower frequencies are at a very high level.

Table 13: Results for reverberation time for the three positions and for the global estimate.

f (Hz)	63	125	250	500	1000	2000	4000	8000
R1	3.34	3.37	1.63	1.55	1.62	1.45	1.24	0.81
R2	3.16	3.13	1.68	1.75	1.75	1.64	1.41	0.82
R3	3.22	3.21	1.75	1.94	1.96	1.67	1.44	0.95
Global	3.32	3.29	1.73	1.57	1.54	1.39	1.28	0.79

Table 14: Results for STI.

Receiver	STI
R1	0.57
R2	0.62
R3	0.70

7.3.3. Simulation 2

In order to examine the impact of an inclined wall the second simulation is similar to the first one in materials etc. but with one tilted wall. The volume increases as well, which adds some more absorbents in total and creates a larger space. The wall is inclined 7 degrees, which is a common angle to use according to interviews. This creates a difference in volume of around 600 m^3 between the simulations.

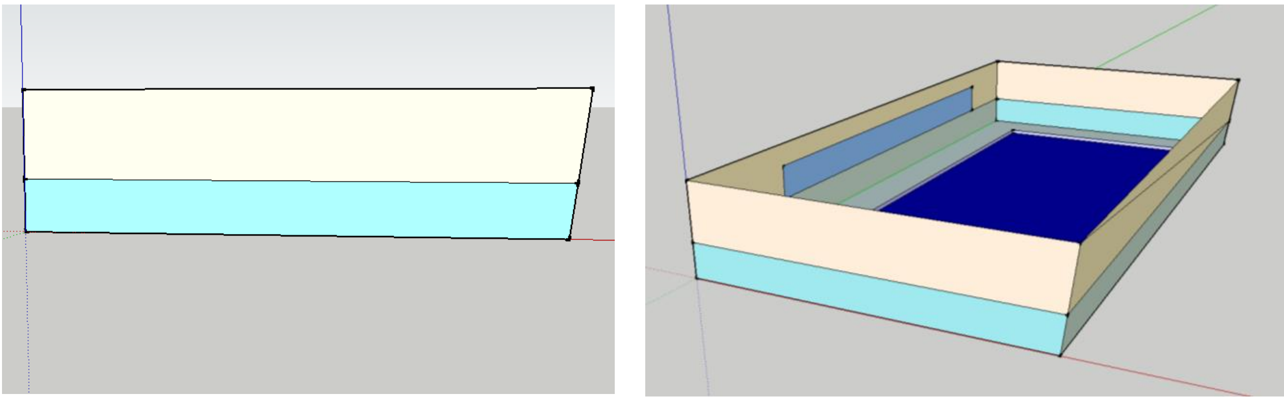


Figure 44: Showing the model after alteration. One long wall is tilted 1 meter at the top edge.

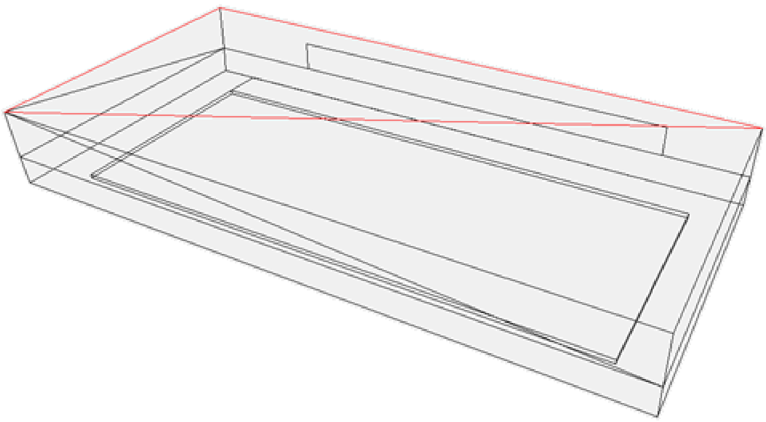


Figure 45: The altered model in Odeon software.

The altered model was exported to Odeon Software and same parameters as for simulation 1 are used. The same positions, see below, and the same materials are applied. The alteration created new surfaces by dividing existing surfaces in two, but this makes no difference since the surfaces are addressed to the same materials as before.

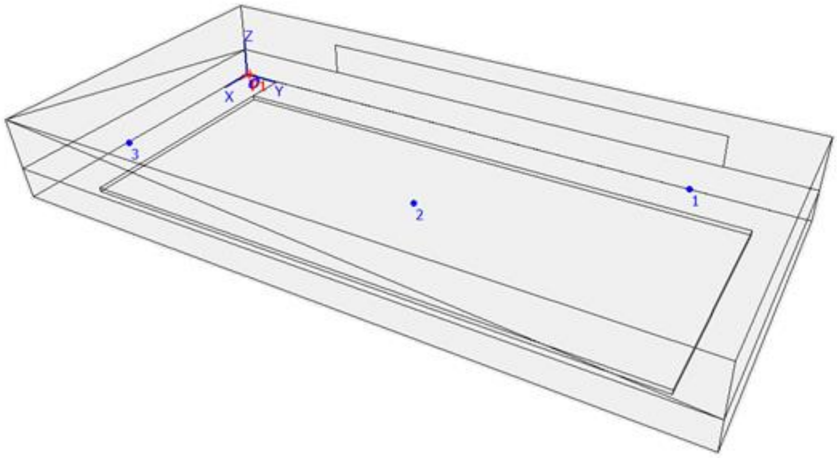


Figure 46: Positions for simulation 2.

Ray tracing shows that this model is sealed, same as for simulation 1. The result for simulation 2 is attached in appendix. The sound waves distribution is illustrated in 3D billiard, where interesting paths appears. The difference made by the inclined wall is visible, see figure 47. The grid calculations show the division for T30 and STI, see figure 48 and 49.

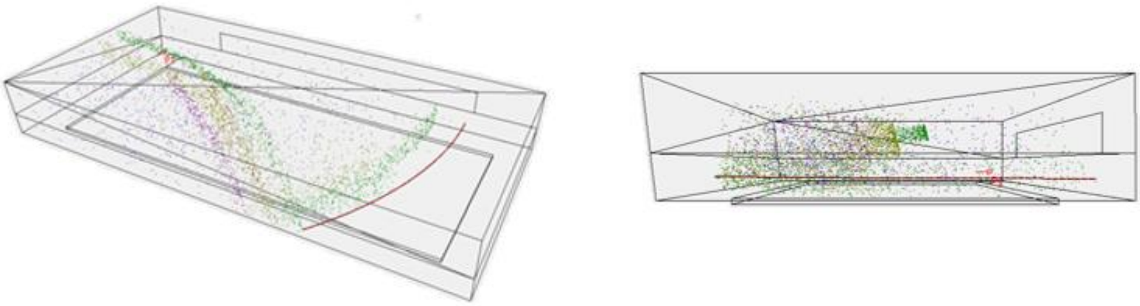


Figure 47: Sound waves distribution after the first reflection at the tilted wall, corresponding to Figure 37. The sound waves distribution is also showed from the side where the altered direction is visible.

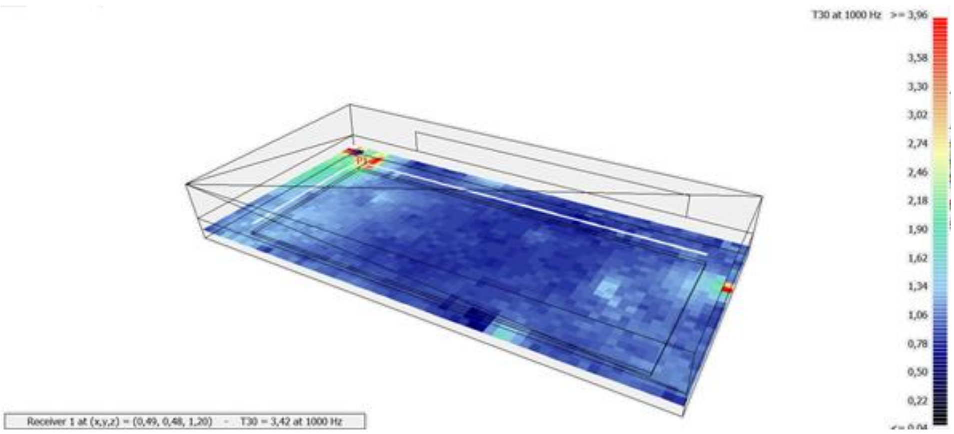


Figure 48: Grid over T30 distribution.

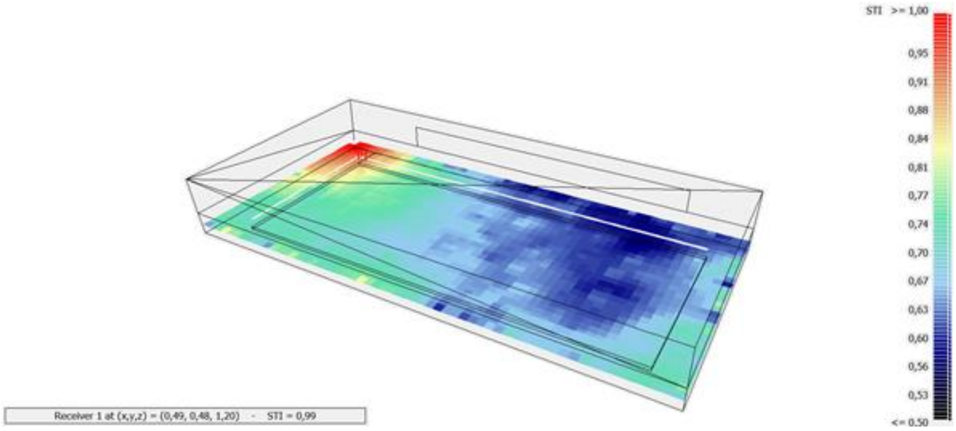


Figure 49: Grid over STI distribution.

Multi point response calculation for the three receiver positions and Global estimate produces results as following. In the global estimate the estimated change of volume is increased from 13890.62 m3 to 14528.46 m3, a difference of about 600 m^3.

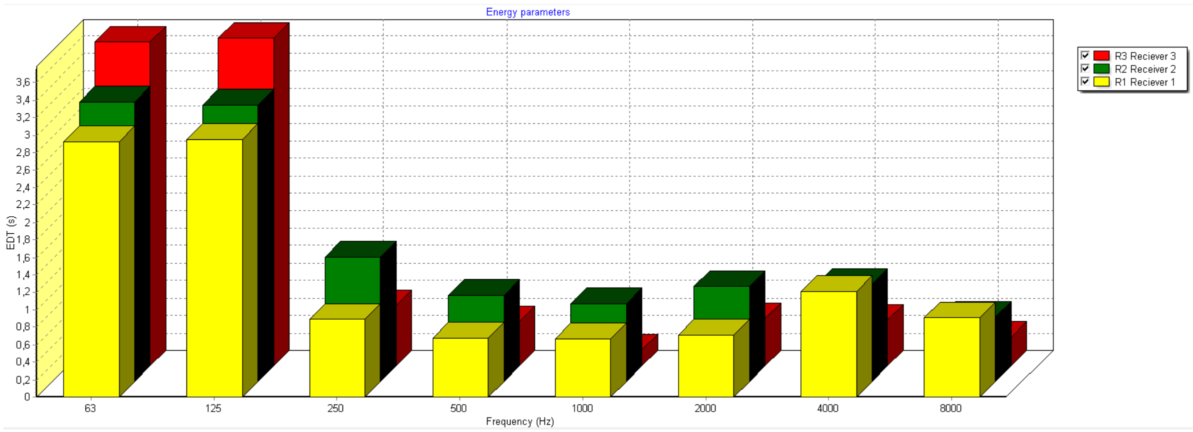


Figure 50: Reverberation time for each calculated frequency. The lower frequencies are at a very high level.

Table 15: Results for reverberation time for the three positions and for the global estimate.

f (Hz)	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
R1	3.18	3.16	1.31	1.02	0.86	0.92	1.06	0.70
R2	3.13	3.07	1.23	0.95	0.94	0.87	1.07	0.76
R3	3.19	3.16	1.35	1.16	1.05	1.08	1.19	0.96
Global	3.22	3.20	1.37	1.05	0.94	0.97	1.17	0.78

Table 16: Results for STI for the three positions.

Receiver	**STI**
R1	0.59
R2	0.66
R3	0.77

7.3.4. Reliability

The simulations produce plausible values and the sound waves distribution etc. are reliable. The model is simplified but in a way that imitates a general case for swimming halls. Places for audience etc. are excluded. The material of the window is chosen from existing data base and another material may be more adapted for swimming halls, but since the window is a small part of the total surfaces it will not make a big impact on the result. The glass is important to represent existing swimming halls according to the state of the art. The simplification of the lowest and highest frequency of absorbent is also a source of error, especially the lowest frequency.

7.4. Sabine's formula

The reverberation time for the model can also be calculated manually with Sabine's formula. The volume and the area of all materials is necessary to know. With the same model as used for simulations the reverberation time is calculated for the model with straight walls. Some simplifications are made, the floor is calculated as one big area with tile instead of divided in pool and floor. The absorbent for each frequency is the same for the two materials tile and water according to Odeon database. The used dimensions, see below, is the same as the model was made after, but the model has some margins that creates a larger volume, the difference is around 510 m^3, an increase of around 4 %. The reverberation time for each frequency from 125 Hz to 4000 Hz is calculated with Sabine's formula and the result is a sum of the contribution from each surface. The result is illustrated in figure 51 and included together with the simulations in Table 17 since it is comparable to simulation 1.

Dimensions

Length: 60 m

Width: 30 m

Height: 8 m

Volume: 14400 m^3

Table 17: Reverberation time

F (Hz)	T (s)
125	4.56
250	1.56
500	1.31
1000	1.24
2000	1.25
4000	1.56

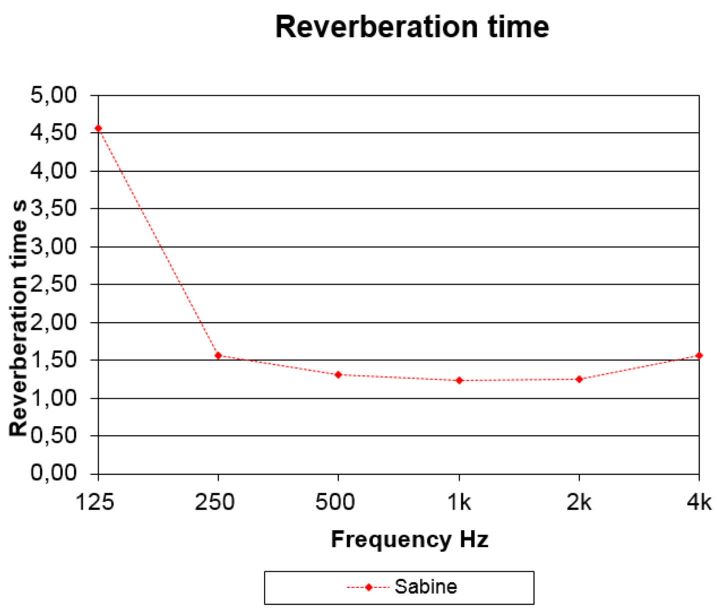


Figure 51: Reverberation time calculated with Sabine's formula.

7.5. Results

The total results from chapter 7 are presented below. Table 18 shows the results for STI from simulations 1 and 2. Results for reverberation time for simulation 1 and 2, both receivers and global estimate from Odeon Software, and reverberation time calculated with Sabine's formula are presented in table 19. In order to compare the results graphics are created, see figure 52-56. The lowest frequency is deviating. A complete set of graphics is also attached in appendix 4.

Table 18: Results for speech intelligibility for the two simulations.

Receiver	**STI Simulation 1**	**STI Simulation 2**
R1	0.57	0.59
R2	0.62	0.66
R3	0.70	0.75

Table 19: Compiled results for reverberation time.

f (Hz)	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Simulation 1								
R1	3.34	3.37	1.63	1.55	1.62	1.45	1.24	0.81
R2	3.16	3.13	1.68	1.75	1.75	1.64	1.41	0.82
R3	3.22	3.21	1.75	1.94	1.96	1.67	1.44	0.95
Global	3.32	3.29	1.73	1.57	1.54	1.39	1.28	0.79
Sabine	-	4.56	1.56	1.31	1.24	1.25	1.56	-
Simulation 2								
R1	3.18	3.16	1.31	1.02	0.86	0.92	1.06	0.70
R2	3.13	3.07	1.23	0.95	0.94	0.87	1.07	0.76
R3	3.19	3.16	1.35	1.16	1.05	1.08	1.19	0.96
Global	3.22	3.20	1.37	1.05	0.94	0.97	1.17	0.78

Graphics:

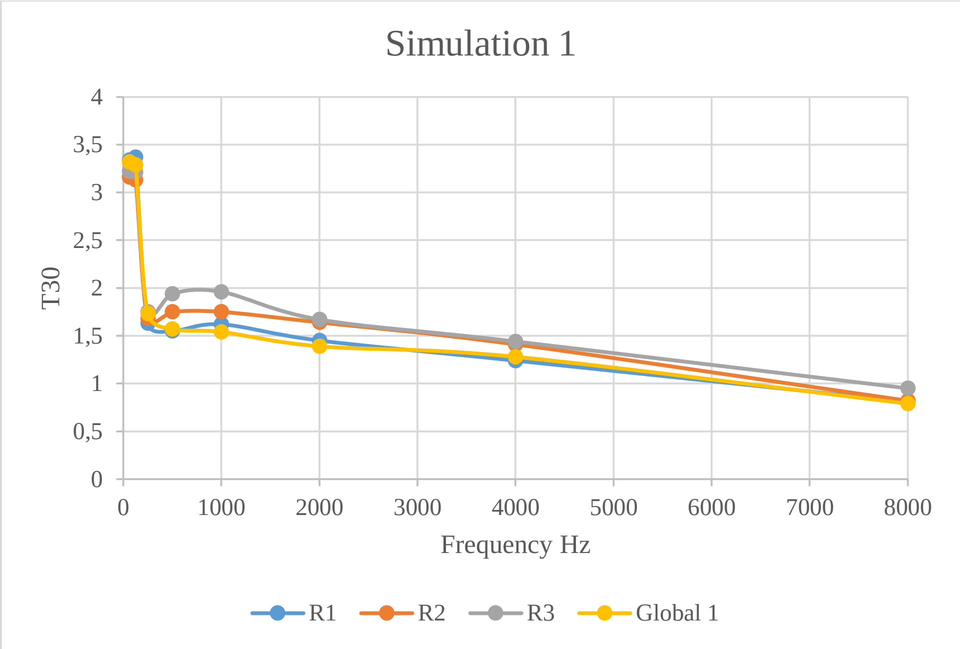


Figure 52: The simulation result for the three receivers and the global estimate.

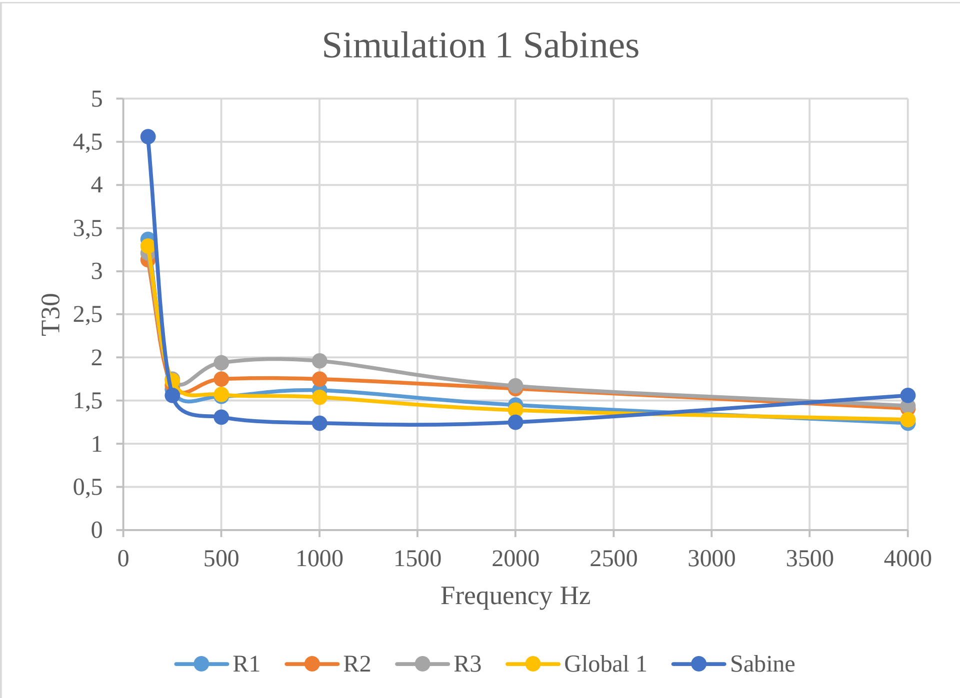


Figure 53: Shows the results for Simulation 1 and related calculations with Sabine's formula. The frequencies is limited do to the calculations with Sabine's, from 125 Hz to 4k Hz is illustrated.

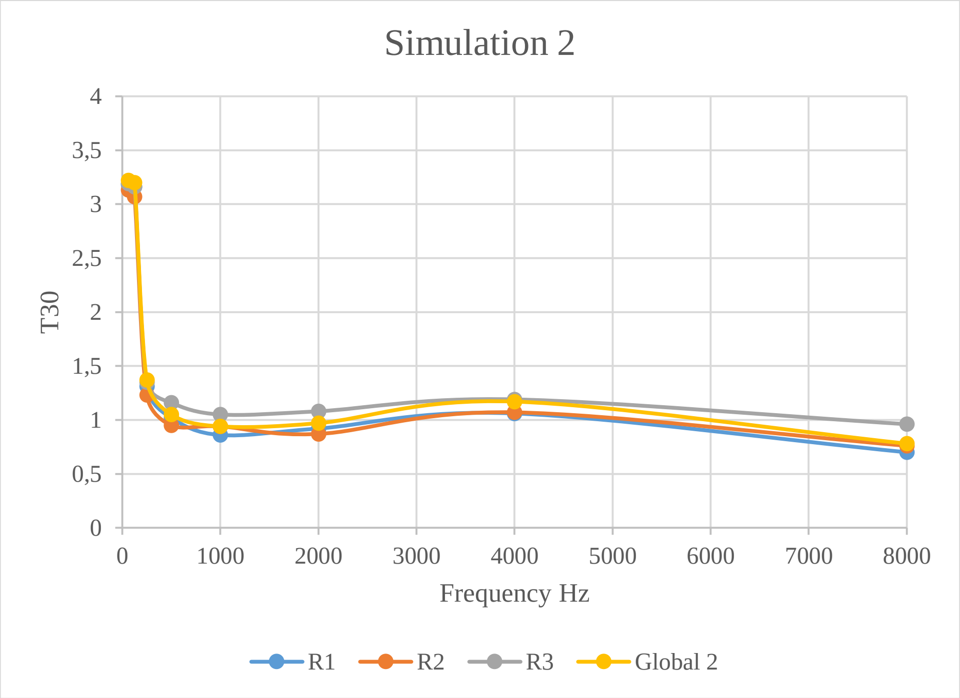


Figure 54: Simulation 2 illustrated .

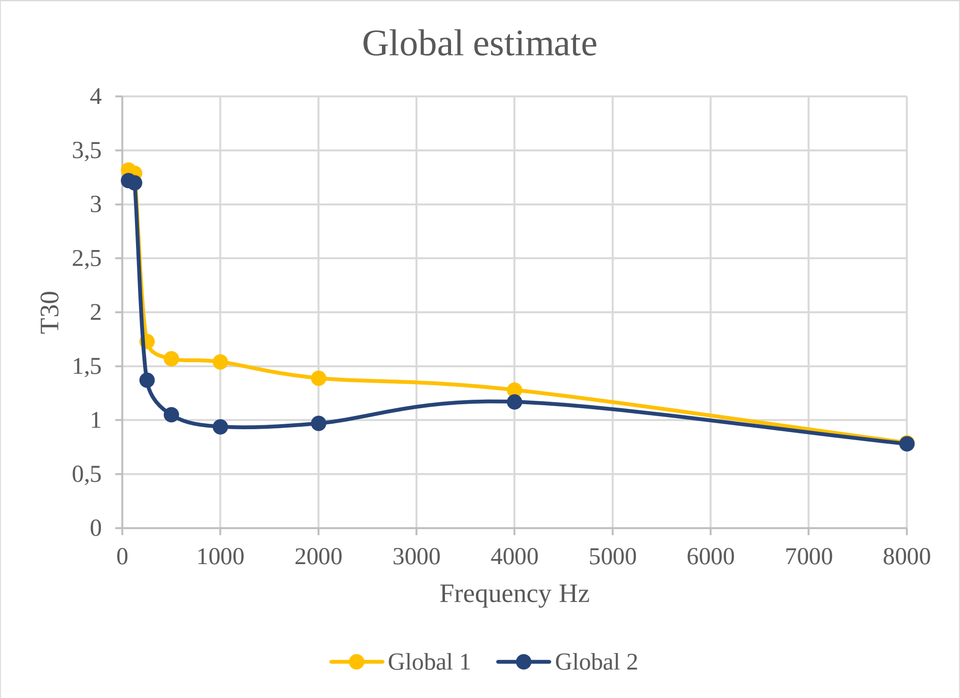


Figure 55: Comparison between global estimate for Simulation 1 and 2.

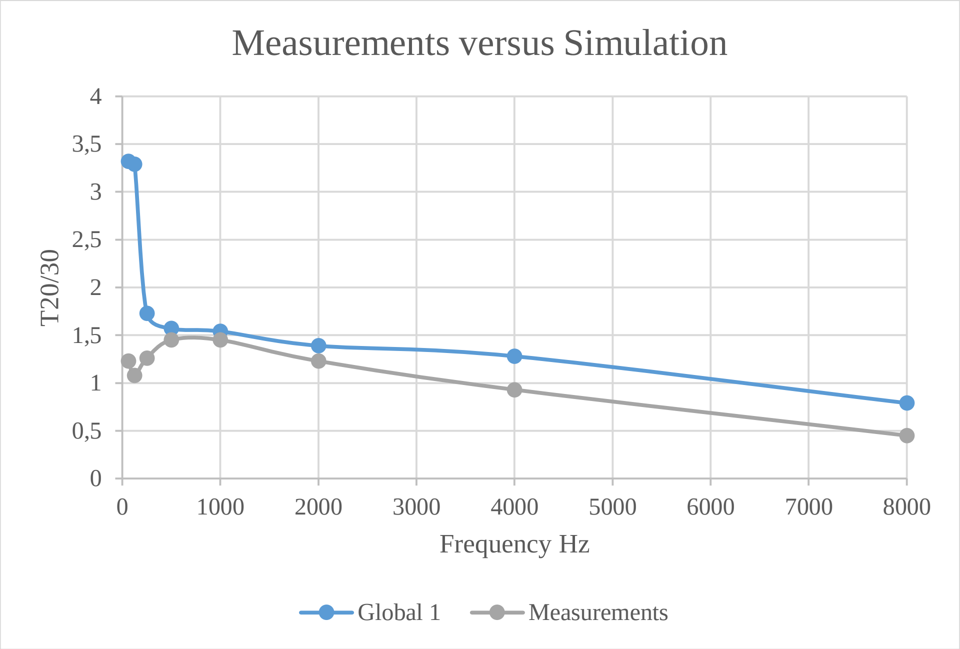


Figure 56: Comparison between the results from global estimate for simulation 1 and the measurements performed in similar swimming hall.

Summary

The simulations provide results for reverberation time and STI. The reverberation time is also calculated with Sabine's formula and measured in Chapter 6. The STI value varies from 0.57 to 0.75. The reverberation time is illustrated in graphics where all the calculated frequencies are visible. The graphics shows the results for the simulations compared to each other, to Sabine's formula and to measurements.

8. Discussion

8.1. Parameters

In order to reach a conclusion and answer the problem formulation the different parts of the thesis need to be compared and the results discussed. The theory is a basis for the evaluation of the executed parts; interviews, measurements and simulations. The theoretical parameters are discussed first, followed by the more practical parts.

8.1.1. How to create a successful swimming hall

According to theory it is important to include acousticians in the early design phase in order to create a cost effective project with a satisfying acoustic environment. The interviews support the theory. The respondents emphasize the importance of including acoustic questions in the initial phase of a project in order to be successful. According to the interviews experience is important in order to be successful with a swimming hall. Another way to improve the result is to have architects and acousticians collaborate and make solutions together. It is important that the acoustic environment is sufficient as well as it shouldn't affect the design in a negative way. Design is one of the biggest compromises that occurs in swimming halls where collaboration is a solution. Cost is not a big issue and with acoustics included early in the design phase this problem would be even more reduced. Moisture is a factor to consider but not necessarily a problem regarding acoustic solutions. Acoustics is more and more prioritized in the design of swimming halls and is getting included earlier in the project. This is a good trend that should keep increasing, which it seems to be by the higher importance of work environment and the increased knowledge about the sounds impact on our health. As all other projects one main goal is to be cost efficient and at the same time create an appreciated building. For swimming halls the acoustic environment has been more included in this the past years. Factors of success is that the swimming halls should be adapted for everyone, fulfill the need of the municipality, be attractive and also have a good acoustic environment. To prevent health consequences, it is important to have strategic actions planned and to have control over the noise level.

8.1.2. Demands

The demands existing for swimming halls are found in the Swedish Standard and gives some guidance for reverberation time and sound from installations. According to the interviews the demands are not sufficient for swimming halls but experience and already known solutions are more important. According to reference projects the demands applies for new constructions and are used more as an aim than a demand for renovations, and also for new buildings but are of a greater importance then. The reverberation time should be 1.2 s or 1.5 s at the highest according to the standard and most respondents seems to aim for 1.5 s in large rooms and 1.2 s in smaller rooms. It seems to be a guideline and the results aren't always verified. The values for reverberation time are assumed to be sufficient for swimming halls. The measurements show that the demands are possible to achieve.

8.1.3. Work environment

The work environment is important for the performance. The acoustic environment is a part of that where tiredness, decreased performance and consequences such as higher level of stress hormones occurs according to the theory chapter. This is best discussed with the opinions of the employees at the swimming hall but the consulted visitors and professionals also contributes to the topic. The general opinion of the interviewed persons is that it is an exhausting work environment and that it is of increasing importance during the design of swimming halls. The visitors seldom experience tiredness and that is connected with the time spent in the swimming hall, since the employees who spends longer time in the swimming halls suffers from tiredness and headaches. The consulted employees agree on that the sound pressure level is high and that it is having a negative impact on their work, especially communication and safety. This shows that the work environment is important to consider in the design of swimming halls in order to achieve sufficient circumstances for the employees and to avoid the possible consequences. At a worksite noise from the occupancy is less disturbing than extraneous noise and the sound pressure level needs to be controlled. Temperature may cause a decreased quality might be compensated by raised vocal level which creates even higher sound pressure levels. Sound, climate, air quality, ergonomic, light and lightning are examples of factors contributing to the indoor environment and should all be considered in the design phase.

8.1.4. Swimming halls

In order to achieve a good acoustic environment in swimming halls they should be designed with short reverberation time, increased speech intelligibility, low sound pressure level and have no reflections or echoes. The sound pressure level should also decline with increasing distance. Ideal design to achieve this is a small volume, low ceiling height, low background noise level, absorbents on ceiling and walls, no hard surfaces and inclined walls. This is difficult to achieve in a swimming hall. The purpose of a swimming hall needs larger volumes to fit the pool and hard surfaces are necessary due to the climate and functions. The ceiling height is adjustable and this may be a factor to work with. The water creates a high level of background noise, which is also measured in the thesis and the background level is already at the level for inconvenience. Absorbents in the ceiling is already implemented according to state of the art. The measurements provides results for two rooms where the result differs. The smaller room has a lower reverberation time and this shows that the volume is important.

8.1.5. Speech intelligibility

Speech intelligibility in a swimming hall may be hard to achieve. According to the interviews speech intelligibility is an important factor in swimming halls, and it will affect the educational situation. The desired speech intelligibility is at a high level where conversations and screams should be easily heard. The most important parameters are the background noise and the acoustic characteristics of the room. The background noise is high in swimming halls and the sound pressure level reaches even higher levels with full activity. The background noise masks speech and alarm signals and makes it harder to understand conversations and hear warnings. Echoes and late reflections are also masking speech and reverberation times over 1 second will lead to impaired speech intelligibility. Swimming halls often has a reverberation time above 1 s and the speech intelligibility is harmed, see STI related to simulations. Since a value of STI seldom is reached over 0.8, the SNR value above 15 dB(A) is a useful demand to achieve, further more about this under 8.2.2. Sound pressure level.

The human speech is mostly between 100 Hz and 8000 Hz, vowels being in the lower frequency range and consonants in the higher. The simulations calculate values for these frequencies and the reverberation time is generally decreasing with the frequency, which strengthens the vowels and reduces the consonants. This is the case for simulation 1. For simulation 2 the lower range of frequencies is more reduced by the inclined wall and the speech intelligibility is improved since consonants are more important for the ability to understand speech. More about the STI values for the simulations are discussed further down.

One problem is that people tend to raise the voice level when talking in large spaces such as swimming halls and in order to be heard over the high background level that occurs in swimming halls according to theory parts and interviews. The hard surfaces create more echoes and allows the sound to travel a long distance and disturb a lot of people, and these are examples of when sound creates more sound. Solutions for this are primarily shorter reverberation time and lowered background noise.

8.1.6. Solutions

The design of swimming halls is complex due to the climate and function demands. According to the interviews the most common solutions to reach a desired acoustic environment are absorbents and to tilt a wall. The measurements are used to evaluate some solutions and inclined walls are tested in the simulations.

In order to achieve a good acoustic environment in a large space such as swimming halls absorbents needs to be applied to ceiling and walls to avoid hard parallel surfaces. In swimming halls, the amount of absorbents should be maximized on the available surfaces. Absorbents should be placed at the height of the ear, which makes panel absorbents important in swimming halls since absorbents at this height needs to be resistant. Soft absorbents are placed higher on the wall, from 3 meters and up. Ceiling absorbents covering as much as possible of the area are always used in swimming halls according to interviews. As mentioned in chapter 2.1.3 absorbents are divided in classes. According to the reference projects the highest class is chosen for alternations of ceiling absorbents in existing swimming halls. Since the swimming hall never can be too acoustic altered according to interviews this class is assumed to be preferable for all cases. Porous absorbents seem to be preferable, at least at the ceiling. In order to reduce more frequencies different types of absorbents should be used in swimming halls. Porous absorbents for higher frequencies and panel absorbents for lower. Perforations are also effective but might lead to a less convenient sound. In order to create a comfortable sound diffusing solutions are also important.

Inclined walls are a suggested solution since it is diffusing and solves problems with for example walls of glass, where absorbents aren’t a possibility. According to the interviews inclined walls are a good and used solution. Inclined walls are improving the acoustic environment according to the simulations. The inclination may differ and a higher angle is more effective. The simulations use 7 degrees and the difference is noticeable. The acoustic environment is affected by noise from the outside but this doesn’t seem to be a current problem with swimming halls. Air conditioner etc. needs to be chosen with consideration of the acoustic aspect but since the water is producing a high sound pressure level this isn’t a problem for now. Colours and visual expression should be considered while choosing the acoustic solutions.

The use of glass creates troubles and less amount of windows would improve the acoustic environment in swimming halls. The use of glass is common and traditional and has good qualities, such as a better view out or between rooms. When constructing a new swimming hall, the amount of glass should be discussed where positive and negative aspects should be weighted against each other. If a larger amount of glass is to be used compromises are likely to be necessary. The swimming hall where measurements were performed has some of the discussed features. The ceiling is completely covered with absorbents and the ceiling height is relatively low. The walls have perforated sheets and absorbents. The façade has some glass, and is straight. The good parts are the different kinds of absorbents, the ceiling height and the low amount of glass. Improvements would be to tilt a wall and to exchange some or the glass wall between the rooms in favour of absorbents.

8.1.7. Subjectivity

The questionnaires address the subjective opinion about the acoustic environment. The contribution to the thesis is an argument for that visitors in the swimming hall are lightly affected by high sound pressure levels, as for the case at Hylliebadet. Measurements show high sound pressure levels, on the limit for risk of hearing damage, but the questionnaires show that people still are satisfied with the acoustic environment. This may depend on the expectations, as described in the theory chapter: the sources we like are less disturbing than sources we can't control by our self. High sound pressure level at a club is not experienced as disturbing by most of the visitors and the same applies for swimming hall according to the questionnaire response. Swimming halls are known to be loud and the sound is connected to happiness and is therefore experienced as desired. The time of exposure is relevant as well, the visitors are in the pool area for a shorter amount of time. The reverberation time is according to reference projects the most common value to use and easiest to experience. The reverberation time seems to have the biggest impact on the subjectively experience and in this case it may be an explanation for the appreciated environment, since the reverberation time is assumed to be sufficient. One interesting aspect deriving from the questionnaires is that the impact of acoustic environment is scattered. Some thinks that it affects the experience and the choice of swimming hall and some thinks that it doesn't affect. This is important since the acoustic environment is hard to judge only by measurement values, the subjective experience is important as well. The sound pressure level should never exceed the limit for danger for health and safety reasons but apparently a high level isn't discouraging.

8.2. Measurements

The measurements primarily resulted in values for reverberation time and sound pressure level. The reverberation time is only measured once in each room but the measurement was performed according to standard and without any disturbing factors, and should be reliable. The reverberation time is similar to other swimming halls according to state of the art and close to the expectations which also strengthens the measurements. The sound pressure level was measured before and during activity for two respectively three locations. The values are at an even level and without deviations for the several measurements which points to reliable measurements. The consistency shows that the values are commonly achieved for the current activity, and an occasional maximum value is not received. The achieved values represent the worst occasion. The model is idealized but this should create a worst case scenario, since people, furniture etc. exist in real swimming hall as well as the design may differ from case to case.

8.2.1. Reverberation time

The Swedish standard recommends a value for reverberation time of 1.5 s respectively 1.2 s. The results were 1.3 for the large swimming pool and 1.1 for the small one. This is assumed to be satisfying according to the recommendations. The reason for the sufficient values seems to be great consideration with acoustics where a lot of absorbents are used and the amount of glass is restricted.

8.2.2. Sound pressure level

The background noise sound pressure level was 47.6 and 57.5 dB(A) at the highest for the large receptively small swimming hall. The sound pressure level was around 68-75 dB(A) during activity for the three measured rooms. According to Arbetsmiljöverket the maximum level before risk for hearing damage is 85 dB(A) during a longer period of time, but from 75 dB(A) there is a risk for more sensitive people. Target values in order to avoid inconvenience according to Folkhälsomyndigheten is L_{Aeq} 30 dB(A) which is exceeded already by the background sound pressure level. The highest measured level is 75 dB(A) and this is on the limit for damage.

The low frequencies are compared to target values according to Folkhälsomyndigheten and the sound pressure level exceeds the target values for the small swimming pool for frequencies 50-200 Hz. Sound consisting of a large amount of low frequencies are known to affect people more. The large swimming pool is under the target values for the background noise. This means that the background level for the small swimming hall may be experienced as uncomfortable already when it is empty and this should be considered in the design of swimming halls in order to achieve a good acoustic environment.

In order to achieve a good level of speech intelligibility the Signal to Noise rate should exceed 15 dB(A). This is the difference between for example speech and the noise level from people's activities. During activity the measured sound pressure exceeds 68 dB(A) and a normal voice level in public is at 52 dB(A) and maximum shouting at 77 dB(A). This is not a sufficient Signal to Noise level for speech and conversations are therefore hard to practice. Alarm signals etc. may exceed the necessary of 15 dB(A). This is crucial for safety reasons, but the signal need to be at a very high level, about 90 dB(A), which also is a danger. This would be improved with a lower sound pressure level.

According to the questionnaires the visitors during the time for the measurements of sound pressure level were still satisfied with the acoustic environment. This shows the importance of the subjectively of the subject. People visiting a swimming hall are expecting higher sound pressure levels and the duration is short. Employees in the swimming hall are exposed to the sound pressure level for longer time and the work environment needs to be considered.

8.3. Simulations

The simulations provide values for STI and reverberation time. These are discussed separated and the reverberation time is connected to the measurement and calculations with Sabine's formula. STI is also discussed more qualitative above.

8.3.1. STI

The speech intelligibility is investigated in simulations where three different positions are calculated for two scenarios, straight and inclined wall. The results are included below, same as table 18.

Receiver	STI Simulation 1	STI Simulation 2
R1	0.57	0.59
R2	0.62	0.66
R3	0.70	0.75

The results vary from 0.57 to 0.75, increasing for Simulation 2 for each receiver. This shows that the speech intelligibility increases with the impact of tilting a wall. The difference increases with the distance from the sound source on the receivers. This is also visible in figure 39. The position furthest away, receiver 1, has the lowest STI and is evaluated as fair according to Brüel & Kjaer (2013), see 2.4 Speech intelligibility. Most results are evaluated as good and with the difficulty of swimming halls in mind this seems sufficient, although the limit for satisfying speech intelligibility in a classroom is above 0.75 and this is only reached for position 3 for the simulation with an inclined wall. This shows that only some parts of the swimming hall have excellent speech intelligibility and education in swimming halls may be difficult in general. Communication is rated as good in the questionnaires but this is referred to a short distance. The insufficient levels of speech intelligibility show that speech intelligibility is hard to achieve in swimming halls which above all may affect the safety aspect and acoustic solutions must therefore be prioritized.

Only the absorbents, as in simulation 1, create an acoustic environment that is below desired but with increased amount of absorbent the STI should probably reach desired levels. In the simulations absorbents on the upper parts of the walls are used and with panel absorbents on the lower part this should improve a lot. Panel absorbents are good for lower frequencies and will contribute to the acoustic environment in more than one way. Tilting a wall seems to be an efficient solution, since the sound waves are diffused and directed to the ceiling where absorbents can reduce the reflections quicker according to the interviews.

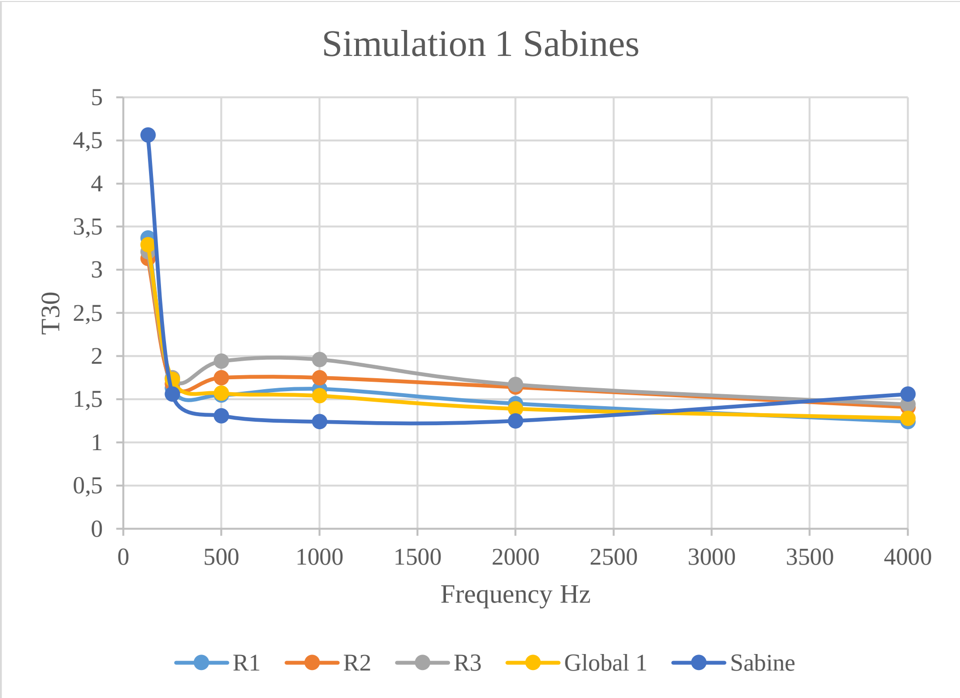
8.3.2. Reverberation time

The simulations are compared one by one. The reverberation time is calculated for frequencies 63 to 8000 Hz. Common for the simulation results is a very high reverberation time for the lowest frequency. This is an error that occurs in the simulations, this is discussed further down.

Simulation 1

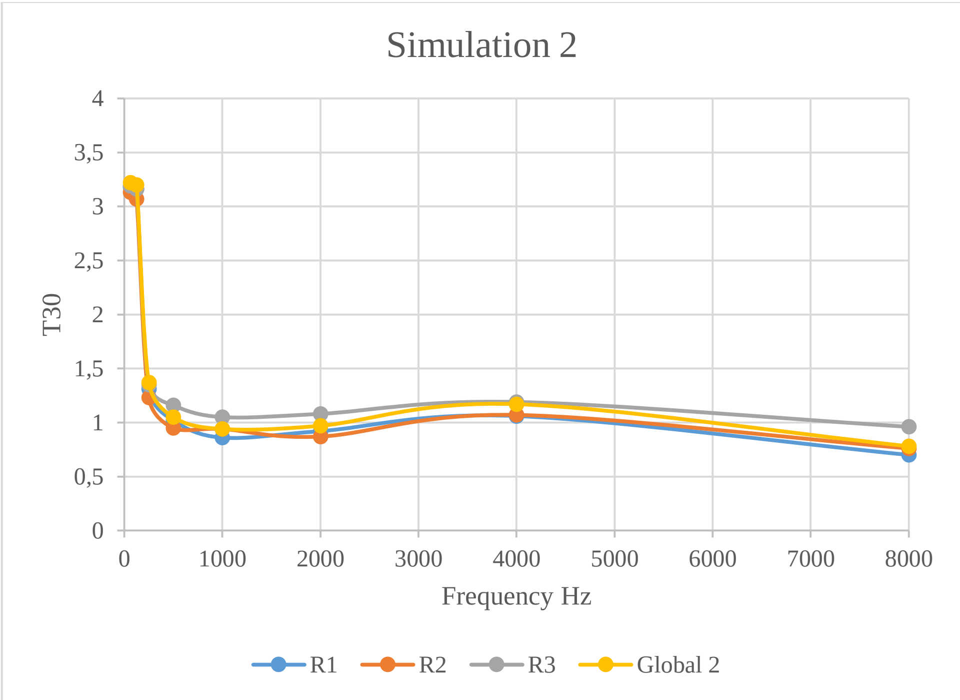
Simulation 1 is compared regarding the global estimate, different positions and Sabine's formula, and further down the measurements as well. Figure 53, included below, shows the differences between the positions, global estimate and Sabine's formula. The reverberation times calculated in the simulation are similar to each other but deviating from Sabine's formula. Sabine's formula is not adapted for this volumes which may be an error. The three positions and global estimate follows mostly the same pattern but on different levels. Receiver 3, closest to the sound source, has the highest reverberation time and the receivers are in order after distance, with receiver 1 with the lowest reverberation time. The positions are in order from highest to lowest reverberation time with increasing distance. The global estimate is below the receivers. This is understandable, looking at grid, figure 41, where positions 2 and 3 are exposed to higher reverberation time than most other parts of the swimming hall. Global estimate and receiver 1 are very similar, which seems correct since the reverberation time is quite even in the hall except for one spot and the overall value should be close to the most common value.

The reverberation time would be improved if the spot is reduced and if the curves is lowered at the mid frequencies. This would probably be improved with an addition of panel absorbents as well as a larger amount of absorbents in general. In order to reduce the spot, the first reflections needs to be reduced, this would be achieved with absorbents all over the wall since the source and receivers are below current absorbents and a lot of sound is bounced back immediately. This is also possible to achieve with a diffuse field such as an inclined wall.



Simulation 2

Simulation 2 is compared with the three positions and global estimate in figure 54 included below. The curves are similar to each other, as for simulation 1. This strengthens the simulation. Position 3 has the highest reverberation time, same as for simulation 1. Position 1 and 2 is close to each other, varied for each frequency. This points to that the inclined wall is diffusing the sound and the reflections are reduced earlier. This makes the diffuse sound field bigger and the difference between positions in the swimming hall less, see figure 57 further down where the grids for reverberation time are compared.



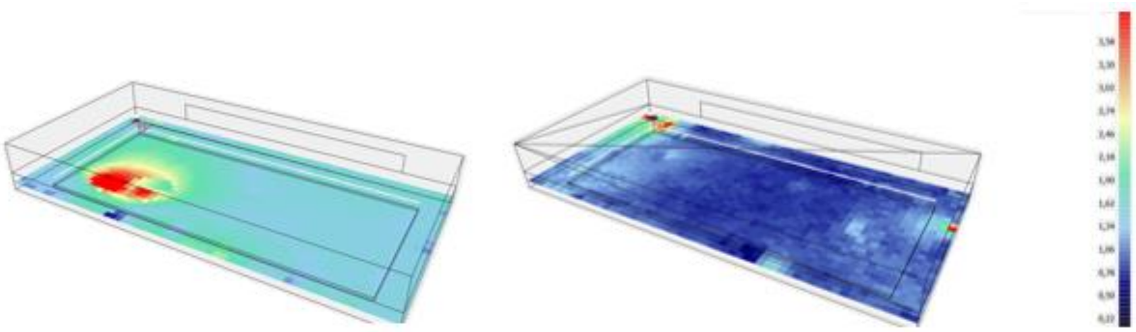
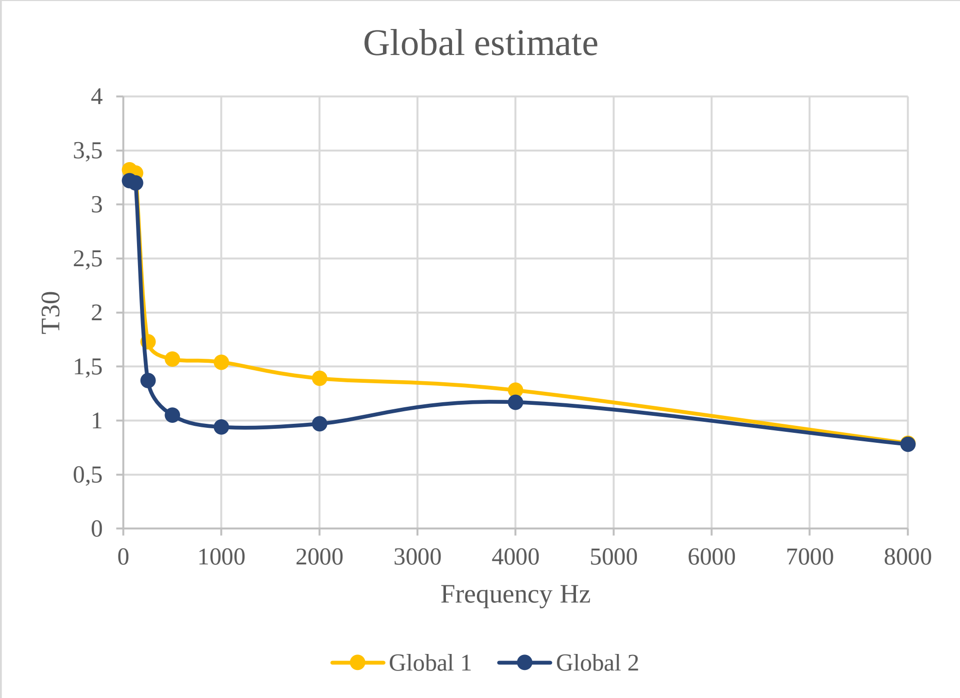


Figure 57: Comparison between reverberation time for simulation 1 and simulation 2.

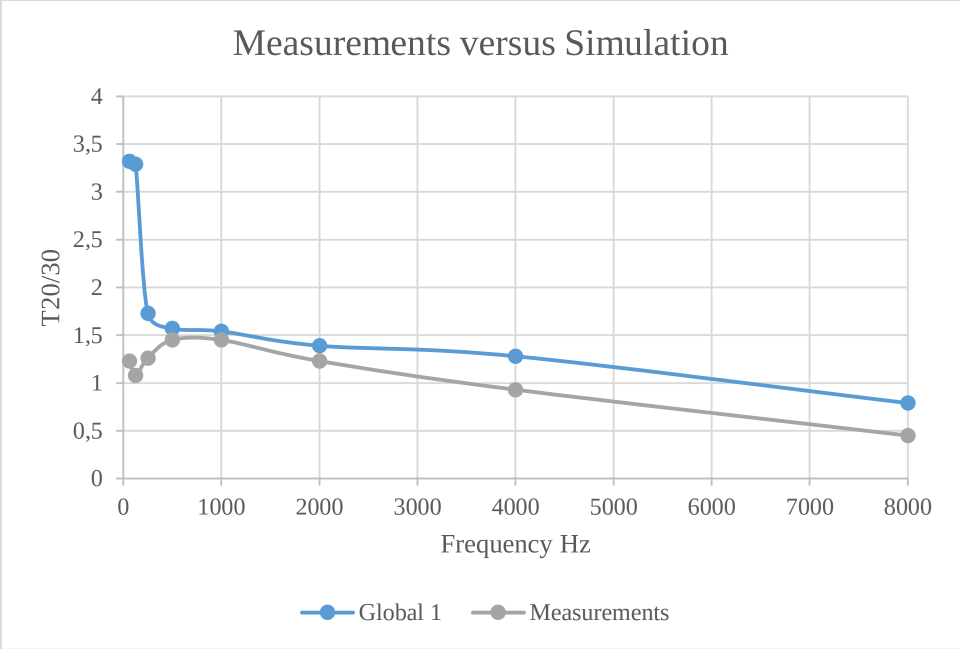
Global estimate

The simulations are compared to each other regarding global estimate. The curves are similar at the beginning and at the end but a deviation occurs quite early. The difference is largest at 1000 Hz where simulation 1 is at approximately 1.5 and simulation 2 at 0.9 s. This depends on the impact of the inclined wall since that is the difference between the simulations. The curves are not shaped similar, simulation 1 is straighter and simulation 2 has a dip at the mid frequencies. Lower frequencies are harder to reduce and the longer wavelengths are less effected by the inclined wall. Simulation 2 is better since it has a more preferable movement pattern and reaches better levels of reverberation time, which shows that tilting a wall is a good alteration.



Simulation versus measurements

The simulations are made to be similar to the measurements. Simulation 1 with the straight wall is compared to performed measurements. Expect for the lowest frequency the curves are similar and the simulation seems to be accurate, see figure 56 included below. The simulation has a higher reverberation time. The difference between measurements and simulations is that the simulation is simplified, the platform for audiences is excluded and the only absorbents are soft ones on the upper part of the walls. The measurements were performed at a swimming hall with great consideration of the acoustic environment and absorbents covered large parts of the wall in probably an effective way. The real case is better than the simulated swimming hall, probably due to better absorbents and different types. One improvement of the real case would have been to tilt a wall but the measurement values shows a relatively good reverberation time The comparison is between T20 and T30, which is different ways to calculate reverberation time. T20 is comparable to the Swedish standard.



Lowest frequency

The comparison is made for frequencies 63 to 8000 Hz. Common for all simulations are the peak at 63 Hz. The absorption coefficient is assumed at that frequency and that is an error. But the very high value implies that something else is wrong as well. The low frequencies are generally harder to measure and calculate as well as to reduce in reality. Most likely the simulation builds on theory where the lower frequencies are not calculated in a sufficient way and deviates from the way the lower frequency waves behave in the current room. Lower frequencies are usually higher in a room but this seems excessive.

9. Conclusion

Swimming halls are complex buildings and it is a challenges to achieve a desired acoustic environment. In order to create a swimming hall with proper acoustic environment important parameters are reverberation time, background noise and speech intelligibility. The conclusion is also presented in terms of guidelines below.

The aim is to shorten the reverberation time closer to 1 s and to lower the background noise in order to avoid inconvenience and to increase the speech intelligibility. A reverberation time around 1.3 s for a large space and 1.1 s for a small space is still experienced as good acoustic environment for visitors. The subjective factor is important to consider. The swimming hall should be designed for sound pressure levels below the recommended limit but the visitors are not highly affected. The employees are exposed for an exhausting work environment and this is an incitement to work for a lower sound pressure level. Speech intelligibility is important for safety mainly. Conversations at small distances are still easy but communication between the employees are disturbed.

There are several solutions existing to achieve a desired acoustic environment. The ceiling height should be considered and lowered when possible in order to receive a shorter reverberation time. Absorbents should be used for the whole ceiling and on large parts of the wall, no parallel hard surfaces can exist. Different types of absorbents are necessary to create a better acoustic environment and to protect the absorbent from damage from people and climate. One wall should be inclined if possible in order to achieve a better situation with lower reverberation time and increased speech intelligibility. The disadvantages with tilting a wall, such as construction complexity and visual confusion, are small in comparison with the acoustic improvement. Education is simplified with the above mentioned solutions but screens are also useful. At last the drain and water solutions should be studied in order to find more quiet solutions. If the background level can be lowered, it would improve the acoustic environment a lot and increase the speech intelligibility. This is also achieved by less hard surfaces and shorter reverberation time but the sound source is important to adjust.

In order to achieve a good acoustic environment, the way of work needs to be considered. The design phase is crucial for the result and hence an acoustician should be included as early as possible in the project, before the design is determined. A lot of acoustic solutions are depending on the shape of the room and a lot of improvements can be done during the design phase. Experience is important in order to know useful solutions since guidelines are insufficient and also in order to handle the complexity of swimming halls. Collaboration between acousticians and architects would be a factor of success with sufficient acoustic solutions as well as an appreciated visual expression.

Guidelines

Goals:

- Reverberation time closer to 1 s.
- Lower background level.
- Excellent speech intelligibility.

Suggested solutions:

- Low ceiling height.
- Inclined wall.
- Absorbents, maximized amount and different types.
- Water as sound source, find more quiet solutions.
- Screens, for educational purposes.

How to succeed:

- Design phase, consider acoustics.
- Utilize experience.
- Collaboration between architects and acousticians.

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Appendix 1: SS 25268:2007 and Certification (Swedish)

Tabell 11 – Längsta efterklangstid i rum, T_{20}, för undervisningslokaler: gymnasial och högre utbildning

	T_{20} s			
	Ljudklass			
Typ av utrymme	A	B	C	D
11a Utrymmen för gemensam undervisning *exempelvis klassrum, lärosalar, lektionssalar*	0,6	0,6	0,6	0,8
11b Utrymmen för undervisning eller samtal i mindre grupper *exempelvis grupprum, konferensrum*	0,5	0,6	0,6	0,8
11c Utrymmen för undervisning i små grupper i öppna utrymmen *exempelvis utbildningslandskap*	0,4	0,4	0,4	0,6
11d Utrymmen för undervisning i musik *exempelvis musiksal, dramarum, musikövningsrum*	0,8	0,8	0,8	–
11e Stora utrymmen för idrott *exempelvis gymnastiksal, idrottshall, simhall*	1,2	1,5	1,5	2,0
11f Utrymmen för verksamhet med kraftig ljudalstring *exempelvis slöjdsal trä och metall, teknikrum, storköksutrymme, diskrum*	0,4	0,5	0,5	0,6
11g Utrymme för samvaro eller matservering större än 100 m^2 *exempelvis uppehållsrum, matsal, restaurang, cafeteria*	0,5	0,6	0,6	0,8
11h Övriga utrymmen där människor vistas mer än tillfälligt *exempelvis vilrum, lärarrum, personalrum, kontor, expedition, studierum, bibliotek, mediatek*	0,5	0,6	0,6	–
11i Utrymmen där människor vistas tillfälligt *exempelvis korridorer, entréer, kopieringsutrymmen, omklädningsrum*	0,6	0,8	0,8	–
11j – dock i trapphus	1,0	1,2	1,5	–

Tabell 17 – Längsta efterklangstid i rum, T_{20}, för undervisningslokaler: skolor, förskolor och fritidshem

	T_{20} s			
	Ljudklass			
Typ av utrymme	A	B	C	D
17a Utrymmen för gemensam undervisning *exempelvis klassrum, lektionssalar*	0,5	0,5	0,5	0,8
17b Utrymmen för undervisning eller elevarbete i mindre grupper *exempelvis grupprum, hemvist, konferensrum, lekrum*	0,4	0,5	0,5	0,6
17c Utrymmen för undervisning i musik *exempelvis musiksal, musikövningsrum*	0,6	0,6	0,6	0,8
17d Stora utrymmen för idrott *exempelvis gymnastiksal, idrottshall, simhall*	1,0	1,2	1,2	2,0
17e Utrymme för samvaro eller matservering större än 100 m^2 samt utrymme för matlagning *exempelvis uppehållsrum, matsal, cafeteria, storköksutrymme*	0,4	0,5	0,5	0,6
17f Övriga utrymmen där människor vistas mer än tillfälligt *exempelvis rum för vila, lärare, personal, kontor, expedition, studierum, bibliotek, mediatek*	0,5	0,6	0,6	–
17g Utrymmen där människor vistas tillfälligt *exempelvis korridorer, entréer, kopieringsutrymmen, omklädningsrum*	0,5	0,5	0,5	0,8
17h – dock i trapphus	0,8	0,8	0,8	1,0

Tabell 12 – Högsta A- och C-vägd ljudnivå från installationer, för undervisningslokaler: gymnasial och högre utbildning

	L_{pA} dB				L_{pC} dB			
	Ljudklass				Ljudklass			
Typ av utrymme	A	B	C	D	A	B	C	D
12a Utrymmen för föreläsningar, mer än 50 personer *exempelvis aula, hörsal, föreläsningssal*	26	26	30	30	45	45	50	50
12b Utrymmen för undervisning, upp till 50 personer *exempelvis klassrum, lärosal, lektionssal, musiksal, dramarum, utbildningslandskap, grupprum*	26	30	30	30[a]	45	50	50	50
12c Utrymmen för skolhälsovård, enskilt arbete, enskild undervisning, samtal, vila *exempelvis talklinik, kurator, psykolog, skolhälsovård, lärare, personal, kontor, expedition, konferens, studierum, bibliotek, mediatek, musikövning*	30	35	35	40	50	55	55	55
12d Utrymme för beredning av mat *exempelvis storkök*	50	50	55	–	65	–	–	–
12e Övriga utrymmen där människor vistas mer än tillfälligt *exempelvis uppehållsrum, matsal, cafeteria, storkök, gymnastiksal*	35	35	40	40	55	55	–	–
12f Utrymmen där människor vistas tillfälligt *exempelvis korridor, entréhall, trapphus, kopiering, kapprum, WC, omklädningsrum*	40	40	45	–	60	–	–	–

[a] I utrymme för gruppvis undervisning i utrymmen med många installationer, exempelvis slöjdsal trä/metall, teknikundervisning, undervisningskök, kan i undantagsfall 5 dB högre värden godtas

Miljöbyggnad version 2.2, 141001, vers 141104
Sammanfattning av betygskriterier för nyproducerade byggnader

Om det skulle finnas skillnader mellan olika dokument så är det kriterierna i manualen och svar från tekniska rådet som gäller.

Indikator		BRONS			SILVER			GULD			Kommentarer och tips
1 Energianvändning	Alla byggnader	≤ BBR			≤ 75 % av BBR			≤ 65 % av BBR			Ingen skillnad mellan elvärmda och icke-elvärmda byggnader.
	Handels- och lokalbyggnader med hall där mycket spillenergi genereras	Energianvändning vid referensdrift ≤ BBR			Energianvändning ≤ 75% av BBR Energitekniska egenskaper hos byggnad med installationer är ej sämre BRONS Energirutiner ska finnas.			Energianvändning ≤ 50% av BBR Energitekniska egenskaper hos byggnad med installationer är ej sämre BRONS Energirutiner ska finnas.			
2 Värmeeffektbehov	W/m²A_{temp}	I	II	III	I	II	III	I	II	III	Nytt för 2.2 är att betygskriterierna har justerats efter var i landet som byggnaden ligger.
	Ej elvärmda	≤ 84	≤ 72	≤ 60	≤ 56	≤ 48	≤ 40	≤ 34	≤ 29	≤ 25	
	Elvärmda	≤ 56	≤ 48	≤ 40	≤ 42	≤ 36	≤ 30	≤ 28	≤ 24	≤ 20	
3 Solvärmelast	Lokaler	SVL < 48 W/m²golv			SVL < 43 W/m²golv			SVL < 32 W/m²golv			
	Bostäder	SVL < 38 W/m²golv			SVL < 29 W/m²golv			SVL < 18 W/m²golv			
4 Energislag	Bostäder Lokaler	> 50 % av byggnadens energibehov hör till Miljökategorierna 1, 2 och 3.			> 10 % av byggnadens energibehov hör till Miljökategori 1 *och* < 25 % Miljökategori 4 Alternativt: > 50 % hör till Miljökategori 2 *och* < 25 % Miljökategori 4.			> 20 % av byggnadens energibehov hör till Miljökategori 1 *och* < 20 % vardera Miljökategori 3 och 4 Alternativt > 50 % hör till Miljökategori 2 och < 20 % till Miljökategori 3 och 4.			Gör fjärrvärmeleverantörer uppmärksamma på att uppgifterna om bränsleslag i betygsverktyget kan uppdateras.
5 Ljudmiljö	Bostäder Lokaler	Ljudklass C på de fyra bedömda ljudparametrarna enligt SS 25267 eller SS 25268.			Minst två av de fyra bedömda ljudparametrarna i SS 25267 eller SS 25268 ska uppfylla ljudklass B eller högre. Övriga bedömda till minst ljudklass C.			Minst ljudklass B på alla de bedömda ljudparametrarna enligt SS 25267 eller SS 25268. Godkänt enkätresultat			Ingen ändring: Bedömningen i MB omfattar stegljud, luftljud, ljud utifrån och från installationer, inte efterklangstid.
6 Radon	Bostäder Lokaler	≤ 200 Bq/m³			≤ 100 Bq/m³			≤ 50 Bq/m³			Om konstruktionen utformas ”radonsäker” är det inte nödvändigt att mäta radonhalten i marken.
7 Ventilationsstandard	Lokaler	Uteluftsflöde ≥ 7 l/s,person + 0,35 l/s,m²golv eller enligt råd i AFS 2009:2			BRONS + Möjlighet till forcering av ventilationsflöde i mötesrum, konferensrum, samlingssalar eller motsvarande med varierande belastning. Ofta benämnt ”CAV-system med möjlighet till forcering i enstaka vistelserum”. Manuell styrning accepteras.			BRONS + Automatiskt behovsstyrt av ventilationsflöde i vistelserum med varierande belastning. Ofta benämnt ”VAV-system”. Godkänt enkätresultat eller egendeklaration.			Betygskriterierna är inte ändrade men är tydligare förklarade.
	Bostäder	Uteluftsflöde ≥ 0,35 l/s,m² golv			BRONS + Möjlighet till forcering av frånluftsflöde i kök enligt BFS 1998:38. Kolfilterfläkt är inte accepterat som alternativ.			SILVER + Frånluftsflöde i bad-, dusch- eller tvättrum enligt BFS 1998:38. Godkänt enkätresultat			
8 Kvävedioxid	Bostäder Lokaler	> 40 µg/m³			≤ 40 µg/m³			≤ 20 µg/m³ Alternativt: Byggnad utanför tätort om avståndet till kraftigt trafikerade vägar (fler än 10 000 fordon/dygn) är större än 250 m.			Förtydligat att det inte är nödvändigt att mäta kvävedioxidhalten vid verifiering om BRONS söks.

Indikator		BRONS	SILVER	GULD	Kommentarer och tips
9 **Fuktsäkerhet**	Bostäder Lokaler	Byggnaden är fuktsäkerhetsprojekterad och utförd enligt BBR avsnitt 6:5, dvs fuktkritiska konstruktioner är identifierade och dokumenterade, kontrollplaner finns och utförandet dokumenteras.	BRONS + Aktuella branschregler följs för utförande av våtrum. Fuktsäkerhetsprojektering enligt ByggaF eller motsvarande. Fuktmätningar i betong utförs enligt RBK (Rådet för Bygg-Kompetens)	SILVER + Krav på diplomerad fuktsakkunnig (beställarens expert) och en fuktsäkerhetsansvarig (entreprenörens expert). I småhus krävs en fuktsäkerhetsansvarig (entreprenörens expert) Godkänt enkätresultat	
10 **Termiskt klimat vinter**	Alla byggnader	PPD ≤ 20 %.	PPD ≤ 15 %	PPD ≤ 10 % Godkänt enkätresultat.	
	Småhus	TF < 0,4 Värmekälla under fönster eller skydd mot kallras, dvs lufthastigheten < 0,15 m/s	TF < 0,3 Värmekälla under fönster eller skydd mot kallras, dvs lufthastigheten < 0,15 m/s	PPD ≤ 10 % visad med datorsimulering Godkänt enkätresultat.	
11 **Termiskt klimat sommar**	Alla bostäder Lokaler	PPD ≤ 20 % Öppningsbara fönster i bostäder och skolor.	PPD ≤ 15 % Öppningsbara fönster i bostäder och skolor.	PPD ≤ 10 % Öppningsbara fönster i bostäder och skolor. Godkänt enkätresultat.	
	Småhus Flerbostadshus	SVF < 0,048 Öppningsbara fönster	SVF < 0,036 Öppningsbara fönster	SVF < 0,025 Öppningsbara fönster Godkänt enkätresultat.	Nytt för 2.2 är att den förenklade metoden kan användas i skolor.
	Skolor	SVF < 0,06 Öppningsbara fönster	SVF < 0,054 Öppningsbara fönster	PPD ≤ 10 % Öppningsbara fönster i bostäder och skolor. Godkänt enkätresultat.	
12 **Dagsljus**	Bostäder Lokaler	Dagsljusfaktor > 1,0 %	Dagsljusfaktor ≥ 1,2 %	Dagsljusfaktor ≥ 1,2 % visad med datorsimulering. Godkänt enkätresultat.	
	Bostäder	AF ≥ 10 %	AF ≥ 15 %	Dagsljusfaktor ≥ 1,2 % visad med datorsimulering. Godkänt enkätresultat.	Accepterat att använda AF-metoden i fler fall än tidigare, se manualen.
	Handelsbyggnader Lokalbyggnader och arbetsplatser i hall	I försäljningsutrymme eller hall med arbetsplatser är • DF ≥ 1,0 % eller utblicksarean ≥ 40 % *eller* • så är DF ≥ 1,0 % i tillhörande pausrum Resten av byggnaden bedöms enligt kriterier för "Lokalbyggnad".	I försäljningsutrymme eller hall med arbetsplatser är • DF ≥ 1,2% eller utblicksarean ≥ 50 % *eller* • så är DF ≥ 1,2 % i tillhörande pausrum och det ligger i nära anslutning till försäljningsutrymmet eller hall Resten av byggnaden bedöms som "Lokalbyggnad".	I försäljningsutrymme eller hall med arbetsplatser är • DF ≥ 1,2 % eller utblicksarean ≥ 50 % *och* • DF ≥ 1,2 % i tillhörande pausrum Resten av byggnaden bedöms som "Lokalbyggnad" Godkänt resultat från enkät eller egendeklaration.	
13 **Legionella**	Flerbostadshus Lokaler	Temperatur på stillastående tappvarmvatten i t ex beredare och ackumulatortankar ≥ 60˚C. Gemensam rörledning till flera duschplatser där temperaturen är högst 38°C ska inte vara längre än 5 meter. Handdukstorkar och andra värmare är inte kopplade på vvc-ledningen. Proppade ledningar ska vara så korta att temperaturen på stillastående vatten ≥ 50°C.	BRONS + Riskvärdering genomförs med avseende på tillväxt och spridning av legionella i äldre- och gruppboende, hotell, sporthallar, simhallar, sjukhus. Erforderliga åtgärder genomförs som minskar legionellarisken. Legionellaskydd enligt "Branschregler Säker Vatteninstallation".	SILVER + Termometrar monteras på utgående varmvatten och på returen i varje vvc-krets. Instruktioner ska finnas för regelbundna kontroller av vv- och vvc-temperatur i äldre- och gruppboende, hotell, sporthallar, simhallar, sjukhus och flerbostadshus.	För SILVER är det enligt 2.2 inte nödvändigt att genomföra en riskvärdering i flerbostadshus.
	Småhus	-	Temperaturen på stillastående tappvarmvatten i t ex beredare och ackumulatortankar ≥ 60˚C.	SILVER+ Legionellaskydd enligt "Säker Vatten".	
14 **Dokumentation av byggvaror**	Bostäder Lokaler	En byggnadsrelaterad loggbok upprättas med information om byggvaror i produktkategorier E, F, G, H, I, J, K, L, M, N och Z enligt BSAB 96. Loggboken ska minst innehålla uppgifter om typ av byggvara, varunamn, tillverkare, innehållsdeklaration och årtal för dess upprättande.	BRONS+ Loggboken är digital och administreras på företagsnivå hos fastighetsägaren.	SILVER+ Loggboken innehåller information om byggvarornas placering och ungefärliga mängd i byggnaden.	Observera att inga VVS- eller elbyggvaror ingår i bedömningen.
15 **Utfasning av farliga ämnen**	Bostäder Lokaler	Dokumentation saknas.	Utfasningsämnen enligt KEMI:s kriterier förekommer endast i mindre omfattning i loggbokens byggvaror, dessa är dokumenterade i en avvikelselista.	Utfasningsämnen enligt KEMI:s kriterier förekommer inte i de dokumenterade byggvarorna i loggboken.	Observera att inga VVS- eller elbyggvaror ingår i bedömningen.

Appendix 2: Questionnaire

Questionnaire response. Number is sometimes representing values, see questionnaire. Thick numbers is a sum. The response rate is illustrated further down and followed by the questionnaires in English and Swedish.

Age

	Below 18	*18-25*	*26-40*	*41-65*	*Above 65*	
Occasion 1	3	1	14	22	3	**43**
Occasion 2	3	5	6	11	18	**43**
Occasion 3	4	4	25	14	0	**47**
Total	**10**	**10**	**45**	**47**	**21**	**133**

How often do you visit swimming halls?

	1	*2*	*3*	*4*	*5*	
Occasion 1	0	4	1	24	14	**43**
Occasion 2	1	6	11	12	12	**42**
Occasion 3	8	17	13	4	5	**47**
Total	**1**	**10**	**12**	**36**	**26**	**132**

In what purpose do you visit the swimming hall today?

	1	*2*	*3*	*4*	*5*	
Occasion 1	30	3	0	0	4	**37**
Occasion 2	28	7	0	0	2	**37**
Occasion 3	5	9	2	21	2	**39**
Total	**63**	**19**	**2**	**21**	**8**	**113**

How satisfied are you with your experience in the swimming hall today?

Not pleased at all	*1*	*2*	*3*	*4*	*5*	*Very pleased*
Occasion 1	0	0	2	17	24	**43**
Occasion 2	0	0	3	16	24	**43**
Occasion 3	0	1	11	22	13	**47**
Total	**0**	**1**	**16**	**55**	**61**	**133**

How do you experience the acoustic environment?

Noisy	*1*	*2*	*3*	*4*	*5*	*Comfortable*
Occasion 1	1	1	1	13	23	**39**
Occasion 2	0	2	4	15	22	**43**
Occasion 3	1	3	20	8	15	**47**
Total	**2**	**6**	**25**	**36**	**60**	**129**

How does the sound environment affect your experience?

Not at all	*1*	*2*	*3*	*4*	*5*	*A lot*
Occasion 1	7	5	10	14	7	**43**
Occasion 2	3	5	6	11	18	**43**
Occasion 3	7	7	13	7	13	**47**
Total	**17**	**17**	**29**	**32**	**38**	**133**

How do you experience the acoustic environment?

Hard	*1*	*2*	*3*	*4*	*5*	*Easy*
Occasion 1	0	2	10	13	16	**41**
Occasion 2	0	2	8	22	11	**43**
Occasion 3	0	4	11	15	17	**47**
Total	**0**	**8**	**29**	**50**	**44**	**131**

How do you experience the look of the swimming hall on the inside?

Bad	*1*	*2*	*3*	*4*	*5*	*Good*
Occasion 1	1	5	14	16	7	**43**
Occasion 2	0	3	16	18	5	**42**
Occasion 3	1	2	15	19	8	**45**
Total	**2**	**10**	**45**	**53**	**20**	**130**

How do you experience the sound level in this swimming hall compared to other swimming halls?

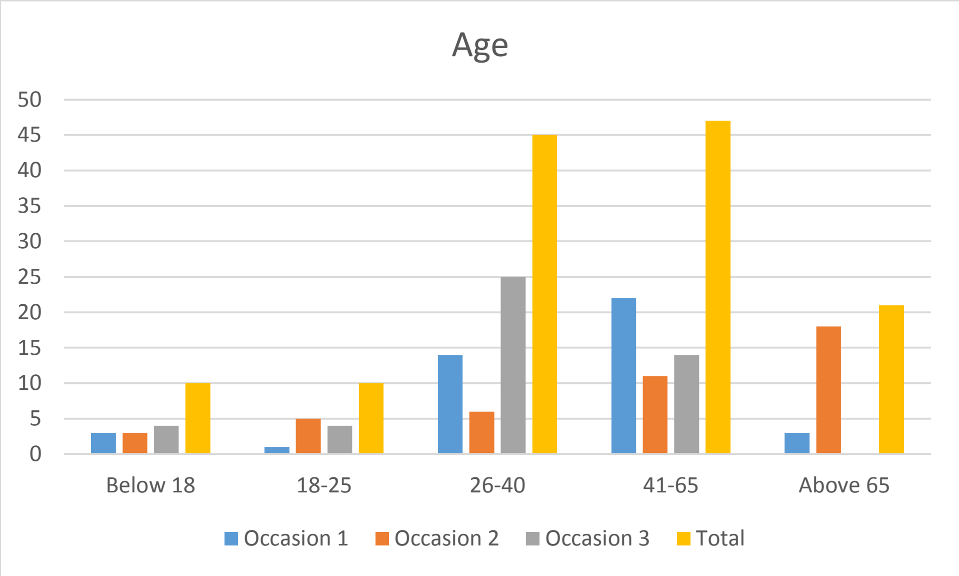
A lot worse	*1*	*2*	*3*	*4*	*5 A lot better*	*6 Don't know*
Occasion 1	0	3	4	10	12	13
Occasion 2	0	0	2	19	7	13
Occasion 3	2	3	11	11	9	9
Total	**2**	**6**	**17**	**40**	**28**	**35**
						126

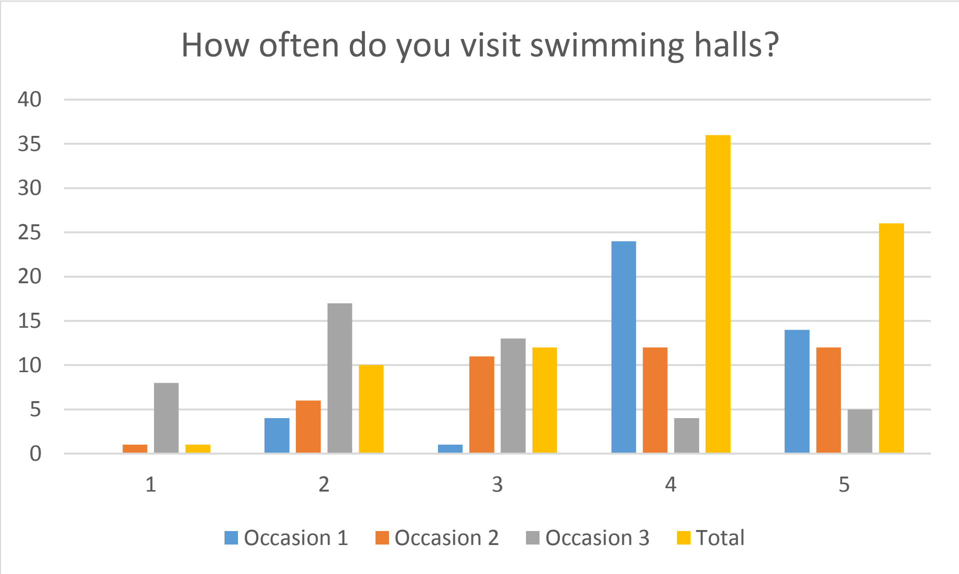
How does the acoustic environment effect your choice of swimming hall?

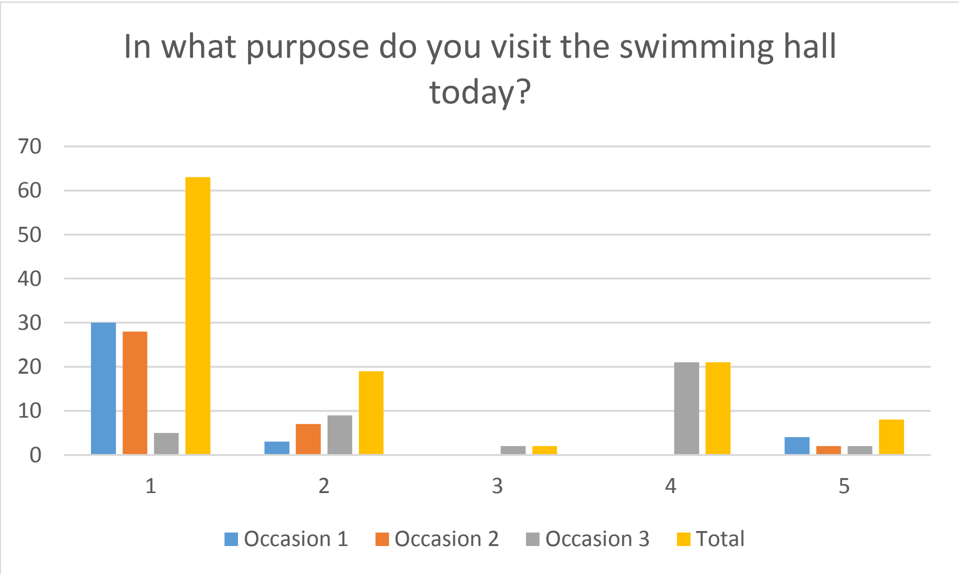
Not at all	*1*	*2*	*3*	*4*	*5*	*A lot*
Occasion 1	8	7	8	13	7	**43**
Occasion 2	9	7	7	9	9	**41**
Occasion 3	8	13	10	9	5	**45**
Total	**25**	**27**	**25**	**31**	**21**	**129**

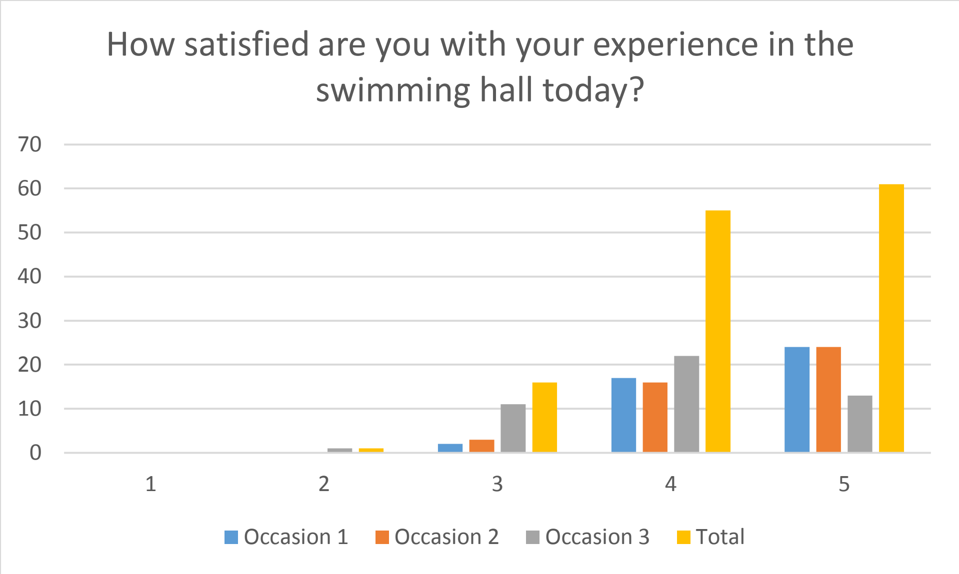
How often do you experience mental tiredness, headache etc. after a visit in a swimming hall?

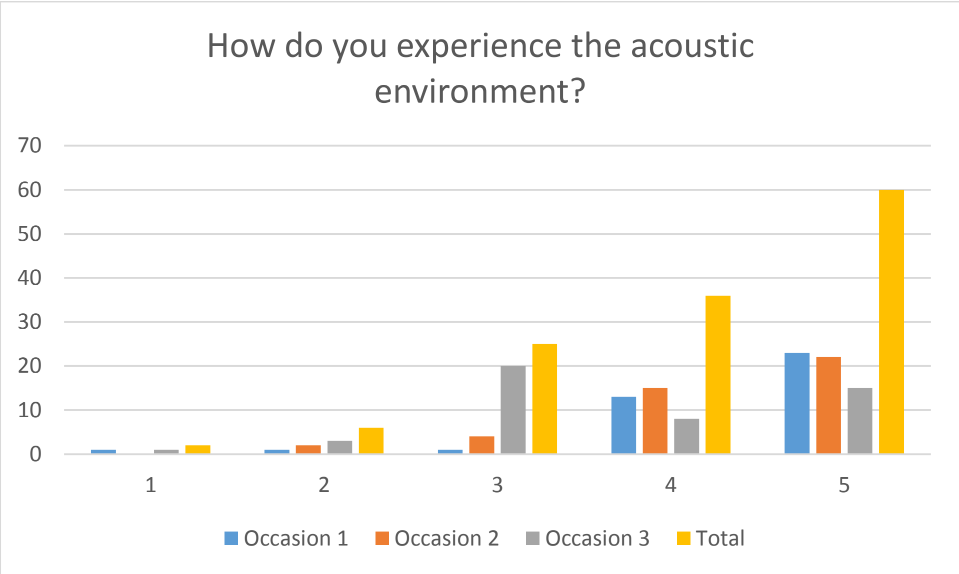
Never	*1*	*2*	*3*	*4*	*5*	*Always*
Occasion 1	23	17	3	0	0	**43**
Occasion 2	14	15	8	4	0	**41**
Occasion 3	14	9	12	8	2	**45**
Total	**51**	**41**	**23**	**12**	**2**	**129**

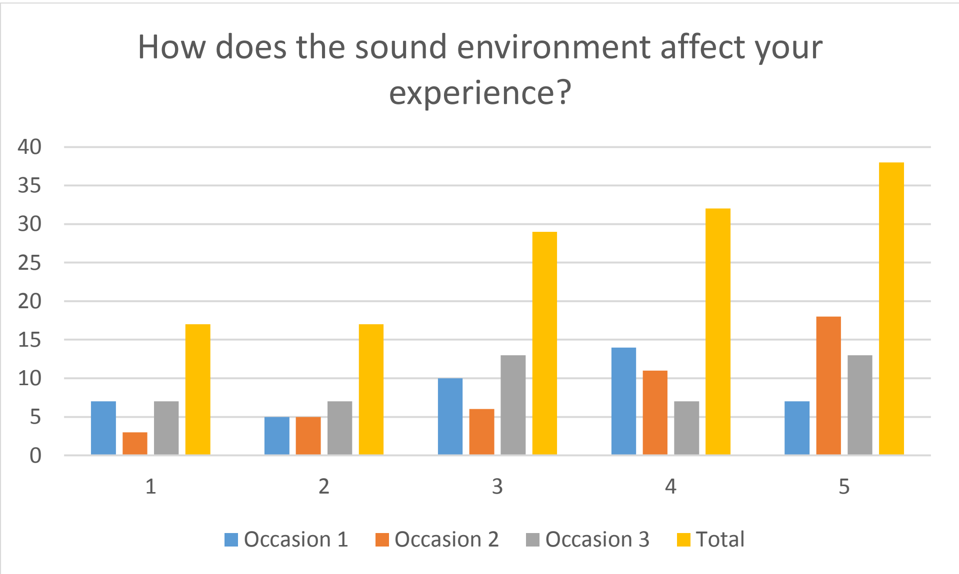

Age
50
45
40
35
30
25
20
15
10
5
0
Below 18
18-25
26-40
41-65
Above 65
Occasion 1
Occasion 2
Occasion 3
Total

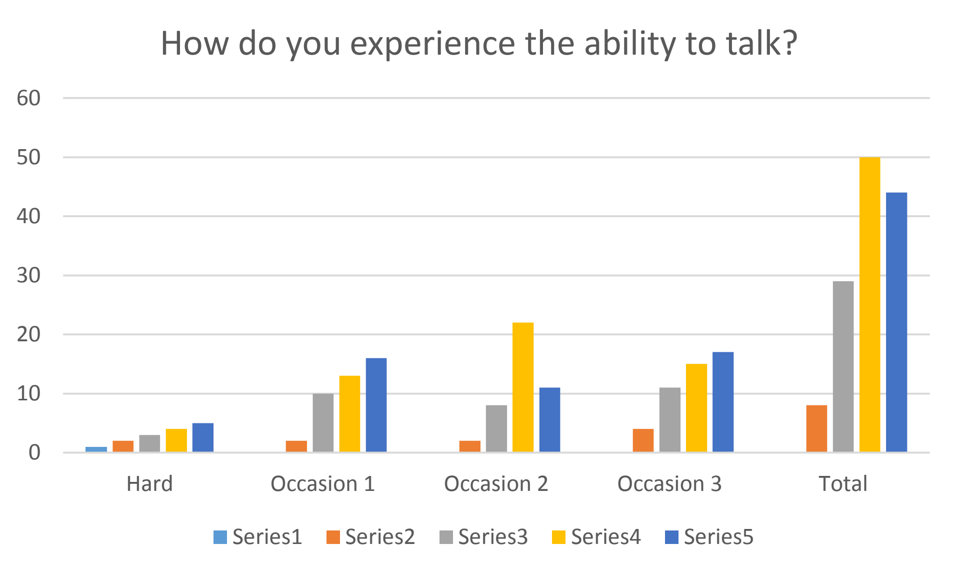

How often do you visit swimming halls?
40
35
30
25
20
15
10
5
0
1
2
3
4
5
Occasion 1
Occasion 2
Occasion 3
Total

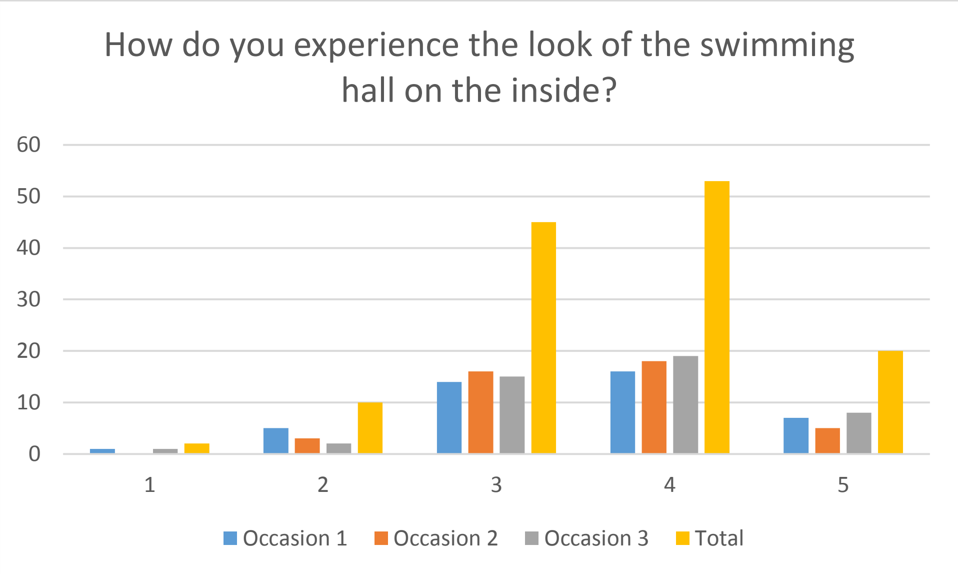

In what purpose do you visit the swimming hall today?
70
60
50
40
30
20
10
0
1
2
3
4
5
Occasion 1
Occasion 2
Occasion 3
Total

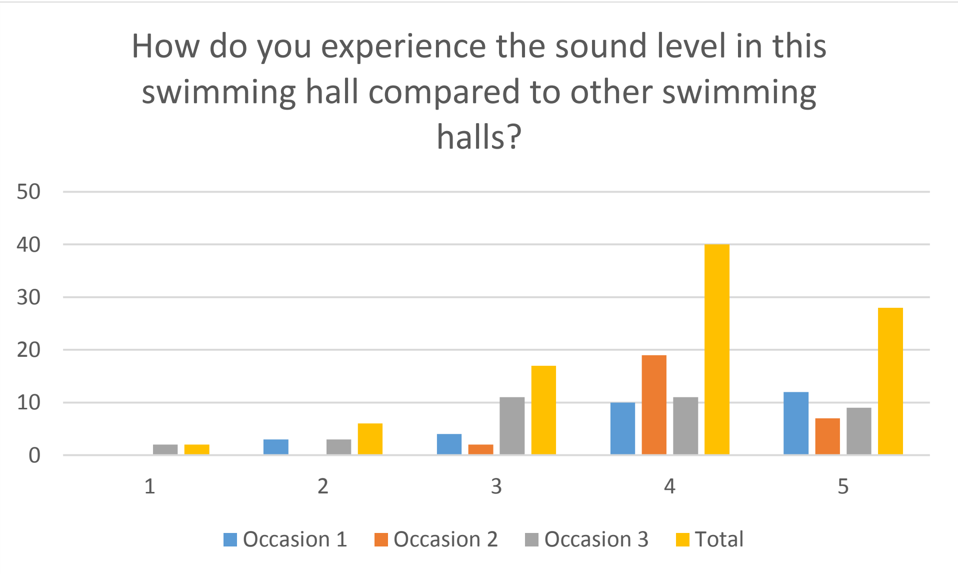

How satisfied are you with your experience in the swimming hall today?
70
60
50
40
30
20
10
0
1
2
3
4
5
Occasion 1
Occasion 2
Occasion 3
Total

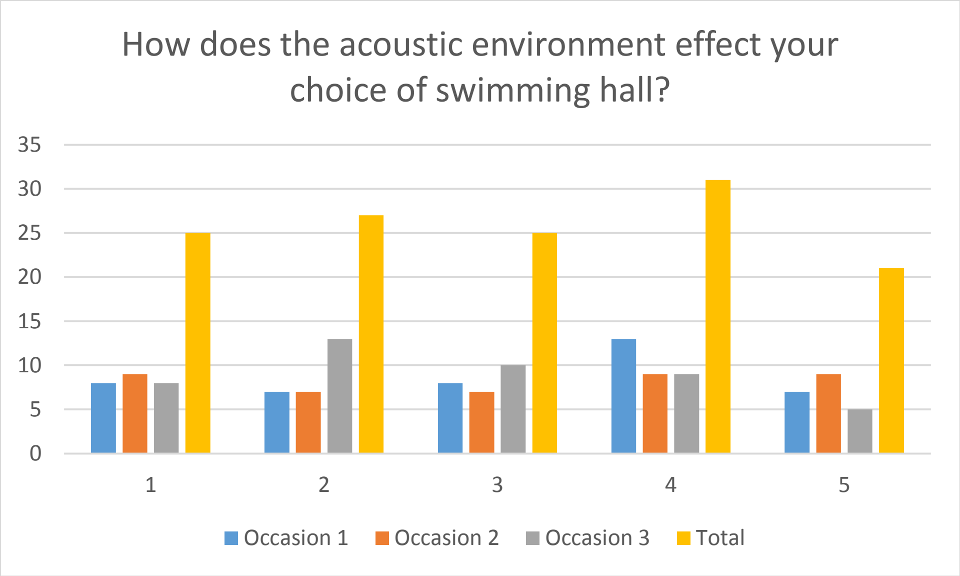

How do you experience the acoustic environment?
70
60
50
40
30
20
10
0
1
2
3
4
5
Occasion 1
Occasion 2
Occasion 3
Total

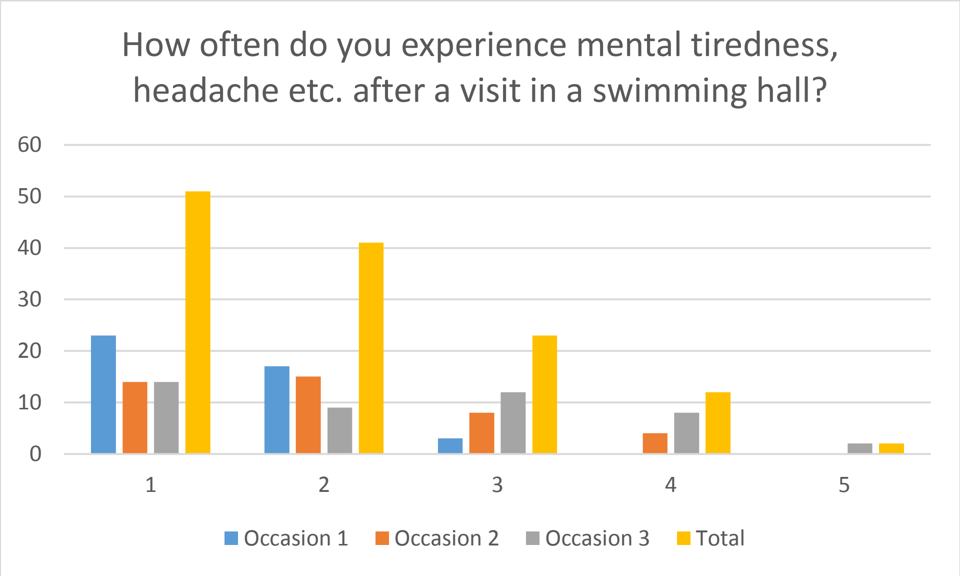

How does the sound environment affect your experience?
40
35
30
25
20
15
10
5
0
1
2
3
4
5
Occasion 1
Occasion 2
Occasion 3
Total


How do you experience the ability to talk?
60
50
40
30
20
10
0
Hard
Occasion 1
Occasion 2
Occasion 3
Total
Series1
Series2
Series3
Series4
Series5


How do you experience the look of the swimming hall on the inside?
60
50
40
30
20
10
0
1
2
3
4
5
Occasion 1
Occasion 2
Occasion 3
Total


How do you experience the sound level in this swimming hall compared to other swimming halls?
50
40
30
20
10
0
1
2
3
4
5
Occasion 1
Occasion 2
Occasion 3
Total


How does the acoustic environment effect your choice of swimming hall?
35
30
25
20
15
10
5
0
1
2
3
4
5
Occasion 1
Occasion 2
Occasion 3
Total


How often do you experience mental tiredness, headache etc. after a visit in a swimming hall?
60
50
40
30
20
10
0
1
2
3
4
5
Occasion 1
Occasion 2
Occasion 3
Total

Acoustic design in swimming halls

This questionnaire is a part of a Master Thesis at LTH in collaboration with ÅF Sound and Vibrations in order to find possible improvements for the acoustic environment in swimming halls. The questions is answered in a scale from 1 to 5, answer by put one cross *X* in the box that suits your opinion the most.

Date, time and place:

Information

Age?

☐ Below 18 ☐ 18-25 ☐ 26-40 ☐ 41-65 ☐ Above 65

How often do you visit swimming halls?

☐ Max 1 time per year ☐ A few times per yearr ☐ 1 time per month ☐ 1 time per week ☐ Several times a wee

In what purpose do you visit the swimming hall today?

☐ Exercise ☐ Relaxation ☐ Adventure bath ☐ With kids ☐ Other

This swimming hall

How satisfied are you with your experience in the swimming hall today?

Not pleased at all 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Very pleased

How do you experience the acoustic environment?

Noisy 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Comfortable

How does the sound environment affects your experience?

Not at all 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ A lot

How do you experience the ability to talk is?

Hard 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Easy

How do you experience the ability to have oversight over for example kids?

Hard 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Easy

How do you experience the look of the swimming hall on the inside?

Bad 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Good

How do you experience the sound level in this swimming hall compared to other swimming halls?

A lot worse 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ A lot better ☐ Don't know

All swimming halls

How does the acoustic environment effect your choice of swimming hall?

Not at all 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ A lot

How often do you experience mental tiredness, headache etc. after a visit in a swimming hall?

Never 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Always

Other comments:

____

____

____

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Thanks for your coorperation!

Best regards Malin Hall

Akustisk utformning av simhallar

Denna enkät utförs som en del i ett examensarbete på LTH i samarbete med ÅF Ljud och Vibrationer för att hitta förbättringar av ljudmiljön i simhallar. Svarsalternativen anges i skala 1-5, svara genom att kryssa i den ruta som överensstämmer bäst med din åsikt.

Datum, tid och plats:

Personuppgifter

Ålder?

☐ Under 18 ☐ 18-25 ☐ 26-40 ☐ 41-65 ☐ Över 65

Hur ofta besöker du simhallar?

☐ Max 1 gång per år ☐ Några gånger per år ☐ 1 gång i månaden ☐ 1 gång i veckan ☐ Flera gånger i veckan

I vilket syfte besöker du simhallen idag?

☐ Motion ☐ Relax ☐ Äventyrsbad ☐ Här med barn ☐ Annat

Specifikt för simhallen

Hur nöjd är du med din upplevelse i simhallen idag?

Inte nöjd alls 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Jättenöjd

Hur upplever du ljudmiljön?

Bullrig 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Behaglig

Hur påverkar ljudmiljön din upplevelse av besöket?

Inte alls 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Väldigt mycket

Hur upplever du att det är att kommunicera?

Svårt 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Lätt

Hur upplever du att det är att ha översikt över t.ex. barn?

Svårt 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Lätt

Hur estetiskt tilltalande är simhallen invändigt?

Inte alls 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Väldigt

Hur är ljudmiljön i denna simhall jämfört med andra simhallar generellt?

Mycket sämre 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Mycket bättre ☐ Vet ej

Generellt i simhallar

Hur påverkar ljudmiljön ditt val av simhall?

Inte alls 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Jättemycket

Hur ofta upplever du mental trötthet, huvudvärk m.m efter besök i simhallar?

Aldrig 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Alltid

Övriga kommentarer:

Tack för din medverkan!

Med vänlig hälsning Malin Hall

Appendix 3: Measurements

Fitted curves and tables of measurement results are attached below.

Field measurements of reverberation time - ISO 3382-2:2008

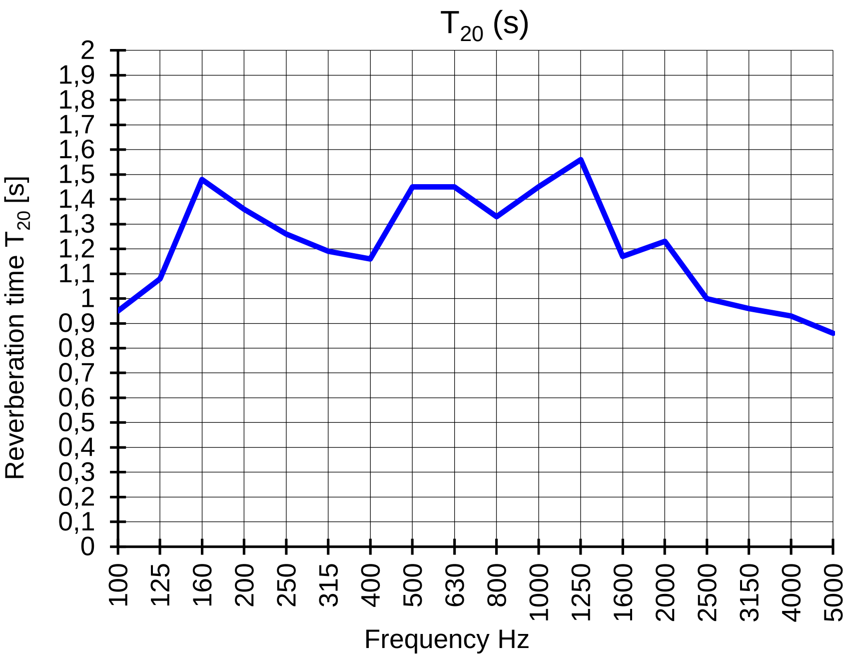
Sheet: **1**

Operator: Malin Hall
Object: Hylliebadet
Room: Large swimming pool

Date: 2016-04-22

Demand: T20 ≤ 1,5

f (Hz)	T_{20} (s)
100	1,0
125	1,08
160	1,48
200	1,36
250	1,26
315	1,19
400	1,16
500	1,45
630	1,45
800	1,33
1000	1,45
1250	1,56
1600	1,17
2000	1,23
2500	1
3150	0,96
4000	0,93
5000	0,86



Evaluation according to 3382-2:2008

T_{20} = 1.3 s

Date: 2016-05-30

Sign.: MH

Field measurement of reverberation time - ISO 3382-2:2008

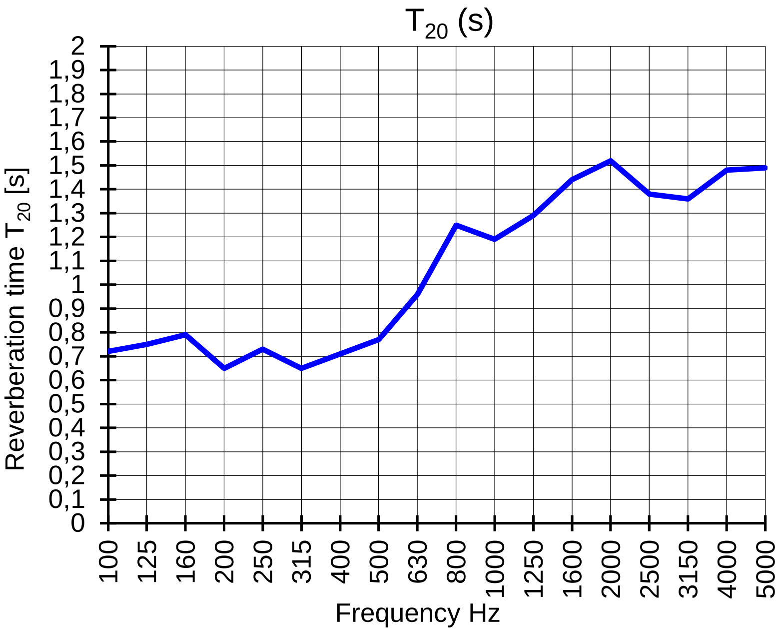
Sheet: **2**

Operator: Malin Hall
Object: Hylliebadet
Room: Small swimming pool

Date: 2016-04-22

Demand: T20 ≤ 1,2

f (Hz)	T_{20} (s)
100	0,7
125	0,75
160	0,79
200	0,65
250	0,73
315	0,65
400	0,71
500	0,77
630	0,96
800	1,25
1000	1,19
1250	1,29
1600	1,44
2000	1,52
2500	1,38
3150	1,36
4000	1,48
5000	1,49



Evaluation according to 3382-2:2008

T_{20} = 1.1 s

Date: 2016-05-30

Sign.: MH

Table 1: Sound pressure level for each frequency

f (Hz)	**125**	**160**	**200**	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**	**L_{Zeq}**	**L_{Aeq}**
Empty																			
3. Large	33.18	31.61	21.81	30.04	31.32	32.53	32.16	34.05	37.56	39.67	40.52	38.64	36.64	34.77	33.90	31.37	29.00	**49.69**	**47.61**
4. Large	32.66	31.29	31.51	31.50	33.72	35.29	34.58	35.36	37.33	37.72	36.92	34.32	32.73	31.14	29.39	26.96	24.22	**49.05**	**45.10**
5. Small	48.69	44.21	42.86	43.20	42.19	43.80	46.54	48.71	47.69	47.38	48.40	47.98	46.42	45.82	44.73	43.26	41.70	**56.62**	**57.45**
Activity																			
6. Large	55.48	53.97	53.15	53.82	55.76	58.45	61.45	61.07	58.77	59.37	59.18	57.90	56.60	53.80	53.23	50.97	49.06	**71.65**	**68.20**
7. Small	48.97	54.52	53.93	54.63	56.85	61.11	63.17	65.20	62.96	64.96	65.67	62.60	62.06	58.71	56.25	55.59	52.05	**72.66**	**72.89**
8. Adv.	60.55	61.84	61.48	61.96	61.03	62.88	66.49	66.61	66.24	67.63	65.91	65.30	64.02	61.14	59.48	57.14	53.86	**70.98**	**75.05**

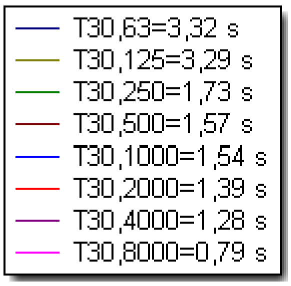
Table 2: Target values

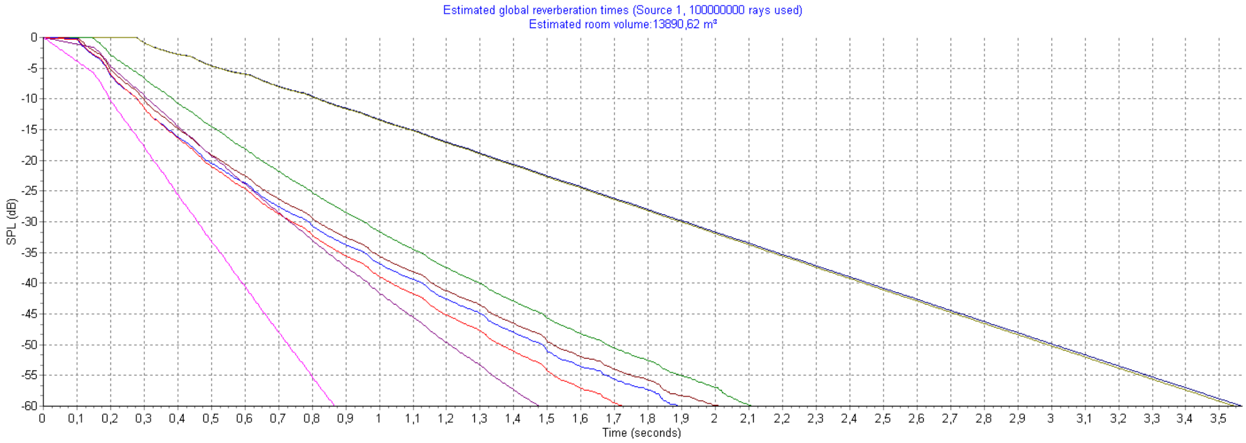
f (Hz)	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
Empty, L_{Zeq}									
3. Large	42.06	38.31	39.33	38.21	34.25	37.31	33.18	31.61	31.81
4. Large	41.34	38.04	37.24	38.74	35.30	33.08	32.66	31.29	31.51
5. Small	49.95	41.49	**47.07**	**43.16**	**41.62**	**46.48**	**48.69**	**44.21**	**42.86**
Target values	56	49	43	42	40	38	36	34	32

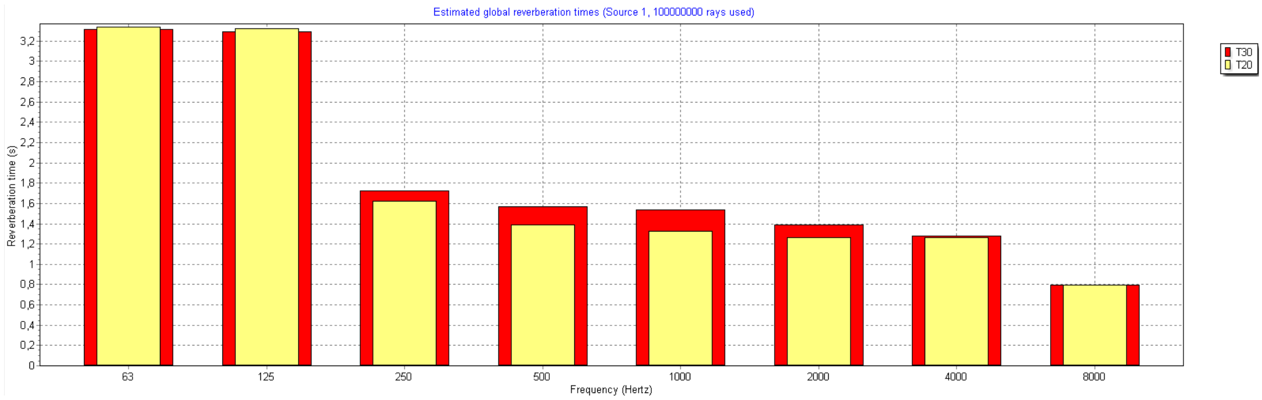
Appendix 4: Simulations

Results from Global estimate, where 100000000 rays are used, followed by textfiles for simulation 1 and 2 including complete results for the three receivers.

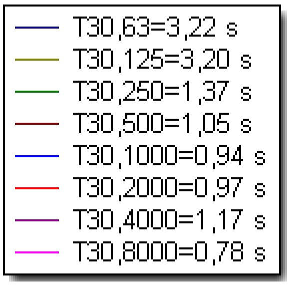
Global estimate for Simulation 1:

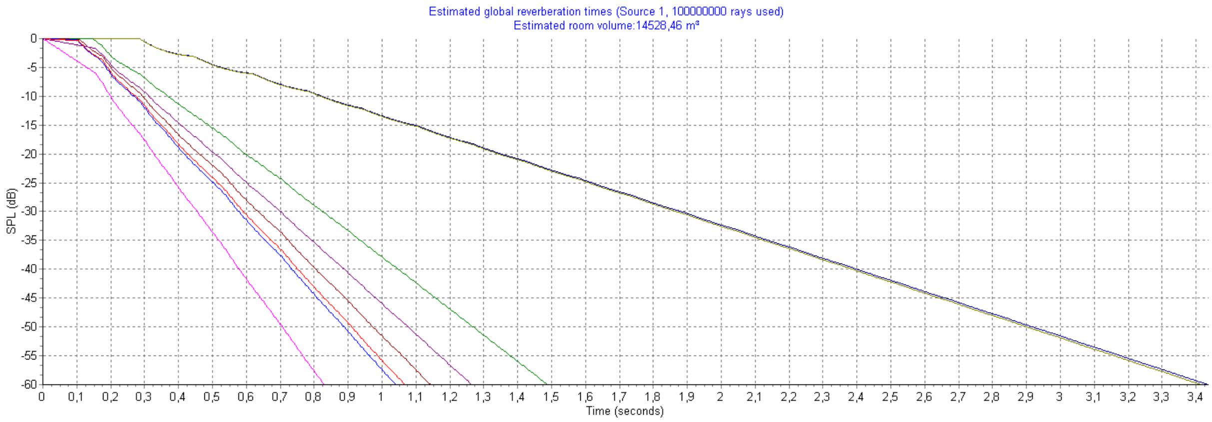


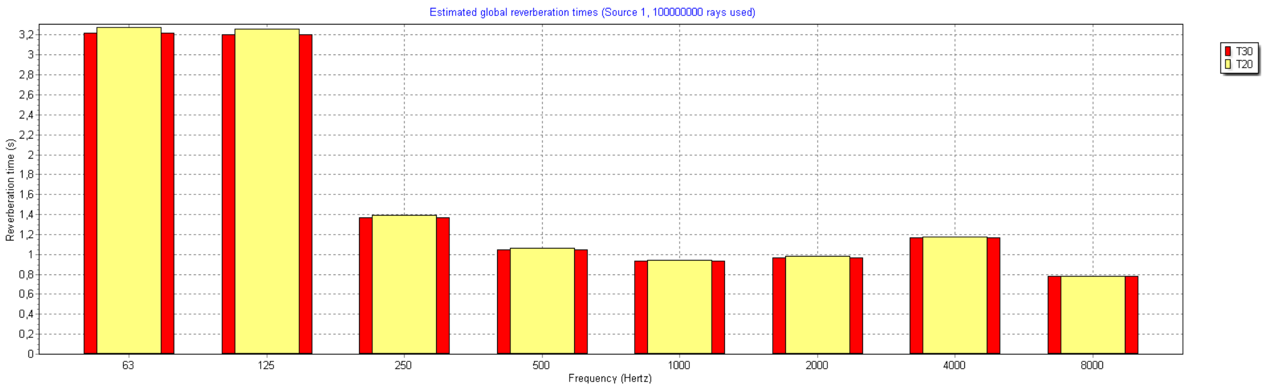




Global estimate for Simulation 2:







Simulation 1:

Active sources

Source number 1
Source type Point
Description Point Source 1
Position (x,y,z) = (2,000, 2,000, 1,200)
Orientation Azimuth = 0,00 Elevation = 0,00 Rotation = 0,00
Directivity file Omni.SO8
Delay 0
Gain 65,00
Equalisation (63 Hz - 8000 Hz) 0,0 / 0,0 / 0,0 / 0,0 / 0,0 / 0,0 / 0,0 / 0,0 /

Parameters ordered by position

Point response energy parameters for job 1
Receiver Number: 1 Reciever 1 (x,y,z) = (2,00, 50,00, 1,20)

Param,	simulated		63	125	250	500	1000	2000	4000	8000
EDT	3,27	3,24	1,21	0,88	1,15	0,61	1,21	0,59		
T30	3,34	3,37	1,63	1,55	1,62	1,45	1,24	0,81		
SPL	40,5	40,4	34,7	32,7	31,9	31,6	32,1	26,5		
C80	-5,5	-5,4	-0,5	0,8	1,1	1,1	0,5	3,1		
D50	0,13	0,14	0,33	0,38	0,38	0,38	0,38	0,53		
Ts	235	233	88	70	68	69	77	54		
LF80	0,183	0,179	0,157	0,141	0,140	0,148	0,153	0,130		
SPL(A)	38,7									
LG80*	30,4									
STI	0,57									

Point response energy parameters for job 1
Receiver Number: 2 Receiver 2 (x,y,z) = (15,00, 30,00, 0,50)

Param,	simulated		63	125	250	500	1000	2000	4000	8000
EDT	3,53	3,53	1,64	1,45	1,30	1,11	1,07	0,61		
T30	3,16	3,13	1,68	1,75	1,75	1,64	1,41	0,82		
SPL	42,1	42,1	36,6	35,0	34,3	34,1	34,7	31,0		
C80	-2,3	-2,1	4,2	6,0	6,6	6,7	6,1	9,9		
D50	0,26	0,26	0,59	0,67	0,68	0,69	0,66	0,78		
Ts	224	222	81	62	53	51	56	33		
LF80	0,218	0,216	0,210	0,188	0,189	0,189	0,197	0,171		
SPL(A)	41,3									
LG80*	31,1									
STI	0,62									

Point response energy parameters for job 1
Receiver Number: 3 Reciever 3 (x,y,z) = (20,00, 2,00, 1,20)

Param,	simulated		63	125	250	500	1000	2000	4000	8000
EDT	3,95	3,87	1,28	0,67	0,49	0,69	0,66	0,36		
T30	3,22	3,21	1,75	1,94	1,96	1,67	1,44	0,95		
SPL	42,3	42,3	38,3	37,2	36,7	36,4	36,9	34,6		
C80	0,8	1,0	8,0	10,1	10,5	10,0	9,4	13,9		
D50	0,43	0,44	0,75	0,80	0,80	0,80	0,79	0,87		
Ts	184	179	52	36	33	33	37	20		
LF80	0,088	0,079	0,053	0,037	0,032	0,050	0,052	0,046		
SPL(A)	43,6									
LG80*	29,8									
STI	0,70									

Statistics: Minimum, Average and Maximum for job: 1

EDT(s)

Frequency		63	125	250	500	1000	2000	4000	8000
Mimimum	3,27	3,24	1,21	0,67	0,49	0,61	0,66	0,36	
Average	3,58	3,54	1,38	1,00	0,98	0,80	0,98	0,52	
Maximum	3,95	3,87	1,64	1,45	1,30	1,11	1,21	0,61	

T30(s)

Frequency		63	125	250	500	1000	2000	4000	8000
Mimimum	3,16	3,13	1,63	1,55	1,62	1,45	1,24	0,81	
Average	3,24	3,24	1,68	1,75	1,78	1,59	1,36	0,86	
Maximum	3,34	3,37	1,75	1,94	1,96	1,67	1,44	0,95	

SPL(dB)

Frequency		63	125	250	500	1000	2000	4000	8000
Mimimum	40,5	40,4	34,7	32,7	31,9	31,6	32,1	26,5	
Average	41,6	41,6	36,5	35,0	34,3	34,0	34,6	30,7	
Maximum	42,3	42,3	38,3	37,2	36,7	36,4	36,9	34,6	

C80(dB)

Frequency		63	125	250	500	1000	2000	4000	8000
Mimimum	-5,5	-5,4	-0,5	0,8	1,1	1,1	0,5	3,1	
Average	-2,3	-2,2	3,9	5,6	6,1	5,9	5,3	9,0	
Maximum	0,8	1,0	8,0	10,1	10,5	10,0	9,4	13,9	

D50

Frequency		63	125	250	500	1000	2000	4000	8000
Mimimum	0,13	0,14	0,33	0,38	0,38	0,38	0,38	0,53	
Average	0,27	0,28	0,56	0,61	0,62	0,62	0,61	0,73	
Maximum	0,43	0,44	0,75	0,80	0,80	0,80	0,79	0,87	

Ts(ms)

Frequency		63	125	250	500	1000	2000	4000	8000
Mimimum	184	179	52	36	33	33	37	20	
Average	214	211	74	56	51	51	57	36	
Maximum	235	233	88	70	68	69	77	54	

SPL(A),min	38,7
SPL(A),avr	41,2
SPL(A),max	43,6

LG80*,min	29,8
LG80*,arv	30,5
LG80*,max	31,1

STI,min 0,57
STI,avr 0,63
STI,max 0,70

Simulation 2:

Active sources

Source number 1
Source type Point
Description Point Source 1
Position (x,y,z) = (2,000, 2,000, 1,200)
Orientation Azimuth = 0,00 Elevation = 0,00 Rotation = 0,00
Directivity file Omni.SO8
Delay 0
Gain 65,00
Equalisation (63 Hz - 8000 Hz) 0,0 / 0,0 / 0,0 / 0,0 / 0,0 / 0,0 / 0,0 / 0,0 /

Parameters ordered by position

Point response energy parameters for job 1
Receiver Number: 1 Reciever 1 (x,y,z) = (2,00, 50,00, 1,20)

Param,	simulated		63	125	250	500	1000	2000	4000	8000
EDT	2,93	2,95	0,89	0,68	0,67	0,71	1,21	0,91		
T30	3,18	3,16	1,31	1,02	0,86	0,92	1,06	0,70		
SPL	40,5	40,5	33,7	31,4	30,4	30,2	31,2	25,7		
C80	-6,4	-6,4	0,6	3,8	5,0	4,2	1,6	4,6		
D50	0,11	0,12	0,40	0,53	0,55	0,53	0,45	0,61		
Ts	234	232	82	54	48	53	72	48		
LF80	0,149	0,144	0,131	0,120	0,117	0,127	0,131	0,116		
SPL(A)	37,6									
LG80*	29,7									
STI	0,59									

Point response energy parameters for job 1
Receiver Number: 2 Receiver 2 (x,y,z) = (15,00, 30,00, 0,50)

Param,	simulated		63	125	250	500	1000	2000	4000	8000
EDT	3,20	3,16	1,42	0,99	0,89	1,08	1,11	0,74		
T30	3,13	3,07	1,23	0,95	0,94	0,87	1,07	0,76		
SPL	42,0	42,0	36,0	34,3	33,6	33,5	34,4	30,7		
C80	-2,9	-2,8	4,8	7,5	8,2	7,8	6,0	9,7		
D50	0,25	0,26	0,66	0,79	0,81	0,80	0,71	0,83		
Ts	220	218	61	38	34	37	51	30		
LF80	0,185	0,183	0,132	0,090	0,084	0,098	0,132	0,116		
SPL(A)	40,8									
LG80*	30,6									
STI	0,66									

Point response energy parameters for job 1
Receiver Number: 3 Reciever 3 (x,y,z) = (20,00, 2,00, 1,20)

Param,	simulated		63	125	250	500	1000	2000	4000	8000
EDT	3,71	3,76	0,69	0,51	0,19	0,54	0,52	0,33		
T30	3,19	3,16	1,35	1,16	1,05	1,08	1,19	0,96		
SPL	42,2	42,2	38,0	36,7	36,1	36,0	36,7	34,5		
C80	1,1	1,2	9,4	12,2	13,0	11,9	10,0	13,5		
D50	0,46	0,47	0,82	0,89	0,91	0,88	0,83	0,90		
Ts	171	167	38	23	19	22	31	18		
LF80	0,096	0,088	0,059	0,041	0,034	0,054	0,059	0,051		
SPL(A)	43,2									
LG80*	28,5									
STI	0,75									

Statistics: Minimum, Average and Maximum for job: 1

EDT(s)

Frequency		63	125	250	500	1000	2000	4000	8000
Mimimum	2,93	2,95	0,69	0,51	0,19	0,54	0,52	0,33	
Average	3,28	3,29	1,00	0,72	0,58	0,78	0,95	0,66	
Maximum	3,71	3,76	1,42	0,99	0,89	1,08	1,21	0,91	

T30(s)

Frequency		63	125	250	500	1000	2000	4000	8000
Mimimum	3,13	3,07	1,23	0,95	0,86	0,87	1,06	0,70	
Average	3,17	3,13	1,30	1,04	0,95	0,96	1,11	0,81	
Maximum	3,19	3,16	1,35	1,16	1,05	1,08	1,19	0,96	

SPL(dB)

Frequency		63	125	250	500	1000	2000	4000	8000
Mimimum	40,5	40,5	33,7	31,4	30,4	30,2	31,2	25,7	
Average	41,6	41,5	35,9	34,1	33,4	33,2	34,1	30,3	
Maximum	42,2	42,2	38,0	36,7	36,1	36,0	36,7	34,5	

C80(dB)

Frequency		63	125	250	500	1000	2000	4000	8000
Mimimum	-6,4	-6,4	0,6	3,8	5,0	4,2	1,6	4,6	
Average	-2,8	-2,6	4,9	7,8	8,7	8,0	5,9	9,3	
Maximum	1,1	1,2	9,4	12,2	13,0	11,9	10,0	13,5	

D50

Frequency		63	125	250	500	1000	2000	4000	8000
Mimimum	0,11	0,12	0,40	0,53	0,55	0,53	0,45	0,61	
Average	0,27	0,28	0,63	0,74	0,76	0,74	0,66	0,78	
Maximum	0,46	0,47	0,82	0,89	0,91	0,88	0,83	0,90	

Ts(ms)

Frequency		63	125	250	500	1000	2000	4000	8000
Mimimum	171	167	38	23	19	22	31	18	
Average	208	206	60	38	34	37	51	32	
Maximum	234	232	82	54	48	53	72	48	

SPL(A),min 37,6
SPL(A),avr 40,5
SPL(A),max 43,2

LG80*,min 28,5
LG80*,arv 29,6
LG80*,max 30,6

STI,min 0,59
STI,avr 0,67
STI,max 0,75