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MASTERARBEIT

Analysis and design optimization of acoustics in swimming pool halls

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ABSTRACT

Here presented Master thesis comprises an analysis of correlation between acoustic design and sound comfort in the indoor swimming pools, which has manifold effects on athletes, spectators, employees and also architecture.

For athletes, sound comfort means equal sound dispersion during practice, which influences preparation, competition results, and overall performance.

From spectators view is the delivering a lower levels of background noise for a more comfortable environment an important fact and the architectural aspect involves the integration of the absorbent panels with surrounding architecture.

Therefore indoor swimming halls have one of the most difficult of environments to treat acoustically. For a better understanding of the correlation between sound comfort and acoustic concepts, this master thesis explores the technical issues and critical factors that need to be considered in acoustic analysis in swimming halls.

The case study of this research is a swimming hall in Perchtoldsdorf, Austria. This swimming hall is designed for different type of activities, including vide range of visitors, employees, and professional athletes. The presented analysis aims to assess the existing acoustic, and evaluate the adequacies and insufficiencies of the sound comfort in the hall. The results and conclusions presented here are based on modelling the case study in 3D programs, measuring the sound level and reverberation, as well as simulation and analysis of acoustic system in Odeon Software.

The measurements have been taken place in one swimming hall in Perchtoldsdorf.

Based on the outcome of the evaluation, a checklist has been evolved to be considered for possible improvements of the acoustic contribution in a future projects.

KURZFASSUNG

Die vorliegende Diplomarbeit umfasst eine Analyse der Korrelation zwischen akustischem Design und Akustischer Komfort in den Schwimmhallen, die vielfältige Auswirkungen auf Sportler, Zuschauer, Mitarbeiter und auch die Architektur hat.

Für die Athleten bedeutet Akustischer Komfort und letztendlich dessen Einfluss auf das Training, das Wettkampfergebnis und während eines Wettkampfs eine gerechte Schallverteilung.

Während aus der Sicht der Zuschauer die Bereitstellung eines geringeren Hintergrundgeräuschpegels für eine angenehmere Umgebung eine wichtige Tatsache ist, und der architektonische Aspekt beinhaltet die Integration der absorbierenden Materialien in die umgebende Architektur. Daher haben Innenpools eine der schwierigsten akustisch zu behandelnden Umgebungen.

Um ein besseres Verständnis der Wechselbeziehung zwischen Klangkomfort und akustischen Konzepten zu erreichen, wurden die technischen Probleme und auch die kritischen Faktoren untersucht, die berücksichtigt werden müssen.

Die erhaltenen Daten wurden durch Modellierung der Schwimmhalle in 3D-Programmen bearbeitet. Der Schalldruckpegel , Nachhallzeiten und Hintergrundgeräuschpegels wurden bemessen und am Ende Analyse und Simulation des akustischen Systems in Odeon Software durchgefuehrt.

Die Messungen wurden in einer Schwimmhalle im Freizeitzentrum Perchtoldsdorf stattgefunden.

Diese Analyse zielt darauf ab, die bestehende Akustische Lage zu bewerten. Die Angemessenheiten und Unzulänglichkeiten den Akustischen Komfort der Halle zu bewerten und zu untersuchen, die für verschiedene Arten von Aktivitäten, Besucher, Mitarbeiter und auch Profisportler konzipiert wurden. Aufgrund des Ergebnisses wurde eine Checkliste für mögliche Verbesserungen des akustischen Beitrags in zukünftigen Projekten entwickelt.

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SPL (dB)	Sound pressure level	7
PTS	permanent threshold shift	9
F (Hz)	Frequency	14
Rms	Root mean square	18
V (m3)	Volume	18
P (W)	Sound power	20
Phon	Loudness	21
T (s)	Reverberation time (initial value is the time for 60dB decay)	21
LA (dB)	A-weighted sound pressure level	21
LC (dB)	C-weighted sound pressure level	21
STI	Speech transmission index	23
SI (W/m2)	Sound intensity	25
R (dB)	Sound reduction index	26
NRC	Noise reduction index	30
Tmf (s)	Mid-frequency reverberation time	38
Leq (dB)	Equivalent sound pressure level	39
A	Absorption coefficient	53
T20 (s)	Reverberation time for the sound pressure level to decay by 20 dB is measured and multiplied by 3	54
T30 (s)	Reverberation time for the sound pressure level to decay by 30 dB is measured and multiplied by 2	.54
LeqI (dB)	energy-equivalent impulse sound pressure level	55
LN	Statistical noise level/percentile level	55
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1 INTRODUCTION

1.1 Overview

Each sport has different sound comfort system requirements. Modelling a sport hall and designing sound comfort system will avoid unnecessary distraction for athletes and in some cases also having a better condition in terms of safety and sound comfort, for example by installing absorbents or designing a suitable hall shape. These facts can reduce the noise and enhance the acoustical aspects for achieving a better outcome of training and a healthier auditory experience.

Various indoor swimming pools are constructed for specific purposes such as professional training, diving courses, competitive swimming, hobby swimming, kid's area etc. Although nowadays more people can afford a private pool, there are still large numbers of people who prefer to train in the larger pool. Some activities like diving, swim competitions and group courses such as water aerobics, water polo, water volleyball, aqua jogging, school swim courses and etc. are only possible in larger swimming pools. The public swimming pools are mostly eligible for such and are shaped in large volumes with hard surfaced materials, which provides noisy environment for visitors, athletes and also employees.

Since these halls are commonly constructed with hard surfaced materials, the sound waves are being reflected between walls, ceiling, floor and water surface. Generally, the absorbents assembled in the area, would improve the acoustics. However, the potential impact of the absorbent's material on the air conditions makes the choice of possible absorbent difficult. These factors contribute typically a feeble acoustic environment.

Although the acoustic condition is essential for these halls but it is not the priority and will be adapted in later phases. This commonly then becomes more expensive to integrate acoustic solutions into a building during the operation phase instead of the construction phase.

Modelling a swimming pool, designing an acoustic solution, and controlling the sound level will eliminate unnecessary noises and provide acoustic comfort and safer conditions. This results in reducing physical and mental problems and a better outcome from the trainings.

1.2 Motivation

Acoustic nurses many functions in buildings and the primary objective of good sound quality design in any type of building is to provide a well sound concept and safe environment.

One of the difficulties is integrating acoustics in, which may occur in different phases of the building process. Designing an acoustic system reduces the cost in early phases. However, this requires careful study of the sport art and the required demands in order to avoid redesign and future renovations.

The operation of indoor swimming pools is independent of the outdoor weather change and this is the most important advantages of the indoor swimming pools.

In most types of activities in swimming pools, occupants prefer areas to have an acoustic comfort, which means being quieter or to be able to for instance speak normally with less echoes.

Physical activity provides long-term mental and physical health benefits for everyone. Moreover, the acoustic environment influences the health of people, which makes it more important to be observed carefully. Fatigue as well as increased heart rate and hearing damages are caused by noise pollution.

There are some inevitable questions to answer before starting the design of any swimming pools with a desirable acoustic:

- Which activities will take place in the considered area?
- Will other events be held in this hall?
- Where is the area located?
- Are there any background noises in this area?
- What are the surrounded rooms?
- What are the geometry of the hall, and the location of windows?
- Which materials should be applied on the surfaces?
- Which design would provide a good acoustic environment?
- Which absorbents are suitable for the humid conduction?
- Where the absorbents should be installed?

There are different guides for acoustic requirements in indoor swimming pools for each country and this thesis will be a contribution to the subject.

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

1.3 Background

1.3.1 Sound and architecture

Several aspects of the relationship and analogy between sound and architecture have been explored over the years. Sound can be valued in an architectural process when it comes to space, just as architecture is sonic. The Architect deals with sound, creates spaces from different relationships between resonances, echoes and physical proprieties of supposed materials.

The architecture is dealing with two aspects at the same time; one is the exterior-acoustic aspect of the space, two designing sound of the inner space. Sound design can be thought of as an architectural process that operates in the field of acoustics but also expands beyond it to explore perceptual, analytical, narrative, emotional, referential, and aesthetic dimensions.

The aim of investigating the relationship between architecture and sound is to see how physical space influences intangible sound and contrariwise, as well as to present both phenomena as essential factors in promoting transformations.

A room in which we listen usually has a purpose: For example, it is a conference room, a lecture hall, sport facility,an office or a concert hall. The sound perception in a room should be easy and clear.

Each sound source sounds different in a different room. That means: We always hear the room. This is why some rooms sound “dry”, others “reverberant”, “spacious” or “full of pressure”. At the same time, our well-being in the room is related to the acoustic and visual impression. With sound design we can influence this impression and create “illusions”. This means that the room is presented acoustically in a completely different way than it normally is physically due to structural measures. For example bigger, more open or narrower. You can also divide a room into two rooms by different noise atmospheres.The earlier a sound design is included in an architecture project, the more successful it will be in the end. The acoustics can interact with the normal design and complement it, so that a coherent overall concept is created.

1.3.2 Swimming hall acoustics

We strive to find comfort in leisure centers because our everyday lives are so demanding. Swimming pools are common in these facilities because they provide both physical and mental stimulation. Pools, on the other hand, can be very noisy due to a variety of factors such as children playing, shouting, people diving into the pool, lifeguard whistles and etc.

When it comes to designing leisure pools and sports facilities, aesthetics and functionality are often prioritized. The importance of acoustics is often ignored. This means that while the completed building is visually appealing and appears to have served its mission well, the experience is marred by excessive ambient noise and poor speech intelligibility.

Poor acoustical condition in swimming pools can easily ruin the experience for many. Swimming lessons, aqua fitness, sport and health events, infants swimming and other activities are all important to remember when designing an ideal pool environment. These circumstances present a number of difficulties for achieving optimum acoustics in a swimming pool envirnment, where noise can cause discomfort, compromise protection and even increase the risk of permanent hearing loss. The amount of noise in a swimming pool is determined by sound sources, insulation and absorbents. It is important to achieve an optimum combination of these factors

High temperatures, humidity and a lot of chlorine characterize the climate in swimming pools. It is important that building materials and indoor acoustic solutions can withstand high humidity. In addition to building physics issues, the main load on the substructure is the chemical influences from chlorine vapors or salt in brine pools. These have a significantly more corrosive effect than high humidity or water. Absorbents are commonly used to improve acoustical condition, but it is not always easy due to the environmental conditions in the halls. Therefore, it makes a big difference to have products that can withstand high temperatures, are corrosion-resistant, and are anti-bacterial.

In the 1970s, acoustic condition in swimming pool halls were hardly an issue. The challenge was, that many of these halls are domed, which are the most difficult to renovate in terms of acoustic criteria compared to other building forms. Also with today's technology, dome halls are seldom acoustically satisfactory. Improvements in acoustics are easier to achieve for all other designs.Swimming pools offer designers a lot of leeway when it comes to sculpting shape and space. Practical solutions, on the other hand, are frequently needed. For example inclined fronts and roof structures allow better room acoustics. The large room heights can also be used for diving boards or slides.Ceilings are often the only surfaces on which acoustic improvements can be carried out and at the same time, they are also important design elements in a swimming pool halls. Colored ceilings made of wood wool acoustic panels are good examples to set special accents in a spacious swimming pool hall.

The projects listed below are some examples of effective acoustical design for swimming pool halls.

The Emerald Hills Leisure Centre shown in Figure 1 is located in Sherwood park in Canada and was built in 2016. The structure is built as a simple ‘big box' volume. Acoustical problems for this hall could caused by factors such as large space, ceiling height with no height difference, unseparated area and materials used such as glass and tiles. The acoustical solution of the hall is designed with white triangulated standing seam panels, which float above a black pre cast foundation and integrate into four triangulated glazing surfaces. To create a unified and high-quality acoustcal envirnment, the interior acoustic surfaces and ceiling are triangulated above a black hexagonally tiled floor (archdaily 2021).

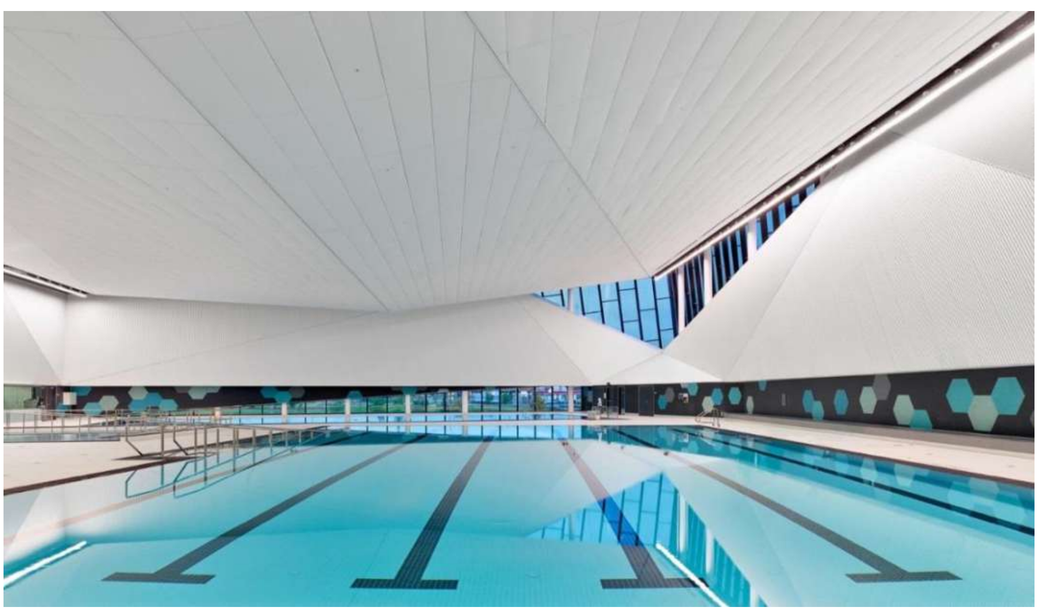


Figure 1 Emerald Hills Leisure Centre (archdaily 2021)

The National Aquatics Center see Figure 2, also known as the 'Water Cube', was constructed for the 2008 Beijing Olympic Games. Five swimming pools are enclosed within the bubble walls, as well as a restaurant, seating and facilities for 17,000 spectators. The form of the hall is inspired by the natural formation of soap bubbles and it was designed with the aim of creating an internal atmosphere where the sounds of enraptured crowds are rich and lively without blocking out commentary and public announcements, which is critical in times of evacuation in relation to that number of people (Arup 2021).

Figure 2 National aquatics center, Beijing (Arup 2021)

The John Jay College swimming Pool is located New York. The facility consists of a 23-meter pool with five lanes. The teak ceiling descends to the pool deck and ends at the privacy viewing window, see Figure 3 (johnjayathletics 2021). Various acoustic effects can be achieved with the wood material, depending on the use of the space for which the ceiling is designed. The used material allows for noise reduction, improves sound absorption, and reduces reverberation.

Figure 3 John Jay College (johnjayathletics 2021)

Ringkøbing swimming pool in Denmark was built in 70's and recently renovated. The existing acoustic panels on the sloping ceilings have been painted white, and panels have been installed on several other ceilings. Inclined roof structure and various room heights allow a better room acoustics, see Figure 4. Le Cap, Sartrouviile, an aquatic center in France is also a good example for the efficient acoustical condition. Triangular-shaped islands are created on the ceiling to reduce reverberation time and improve sound absorption, see Figure 5 (Rockwool 2017)

Figure 4 Ringkøbing swimming pool (Troldtekt 2021)

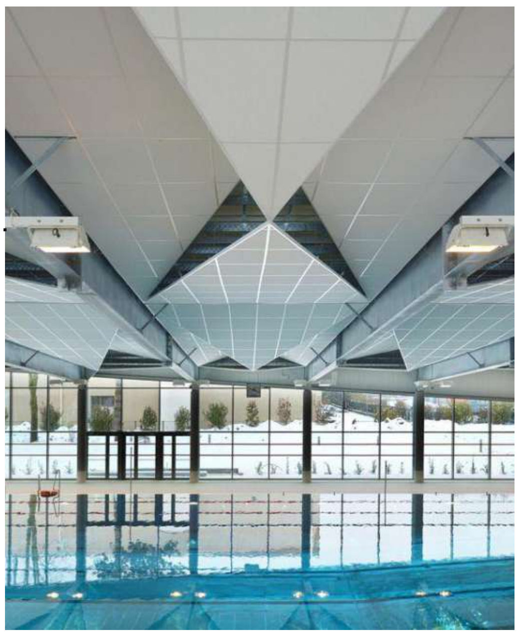


Figure 5 Le Cap, Sartrouviile (Rockwool 2017)

The Bibione Thermae centre is located Venice, Italy. The hall has a very high ceiling and wide windows, which causes long reverberation time, background noise and reflectance of sound. There were three types of acoustic solutions provided: flag, dot, and panels. The panels were installed at various distances from the ceiling, resulting in an eye-catching geometric effect. Sound absorption is improved by combining these elemtns and positioning them vertically and horizontally. These panels were also installed on the walls; see Figure 6 (carusoacoustic 2021).

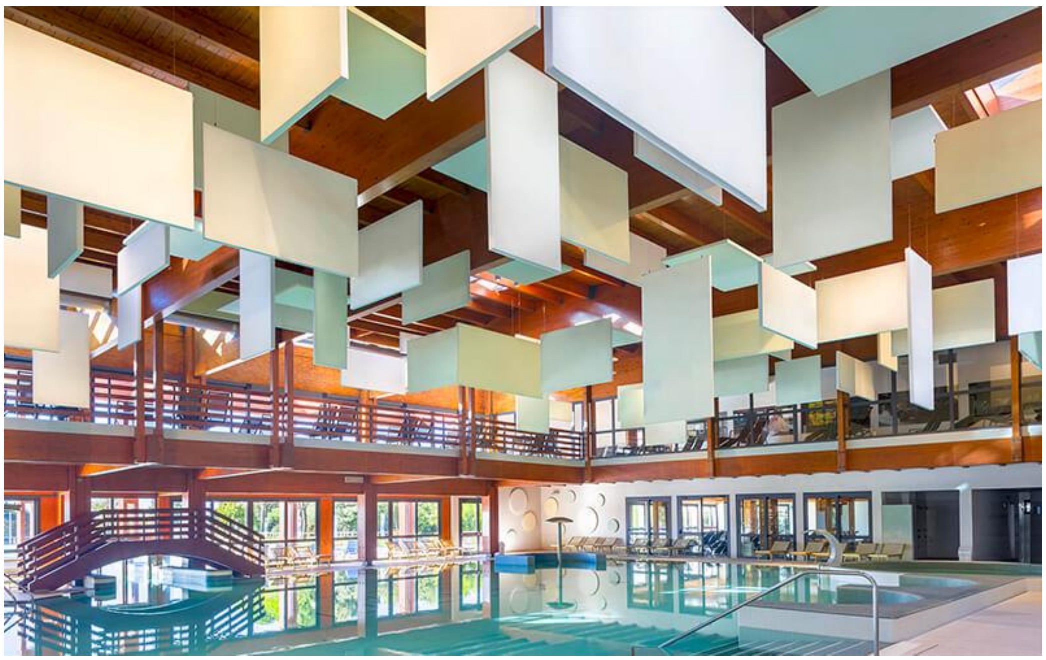


Figure 6 Bibione Thermae centre, Italy (carusoacoustic 2021)

When absorption surfaces are distributed on one side, flutter echoes are a common side effect that is often overlooked. To avoid this, it is critical to always take a holistic approach to room acoustics. This means that, if possible, not only should an absorbent ceiling be installed, but also measures on the walls.

In general, hall conditions such as high ceilings, glass surfaces or facades, tile floors, water surface itself, installation sound, and sound produced by people and activities all have an impact on the acoustical condition in swimming pool halls. Acoustical solutions are most effectively integrated functionally and economically during the design phase. As a result, it is recommended that acoustical solutions be implemented from the start.

1.3.3 Hearing system

In order to have a better understanding of acoustics, the theory of hearing system and the ear have been investigated in this section.

The ear along with the nervous system acts as a frequency analyser. The human ear receives the sound and conveys the information contained in the sound. Therefore, the structure and the physiological elements of the human ear should be discussed briefly.

The ear consists of three parts:

- The visible or external ear
- The middle ear
- The actual hearing organ or inner ear.

The outer ear is formed by the auricle that receives the sound and directs the sound into the auditory canal, see Figure 7.

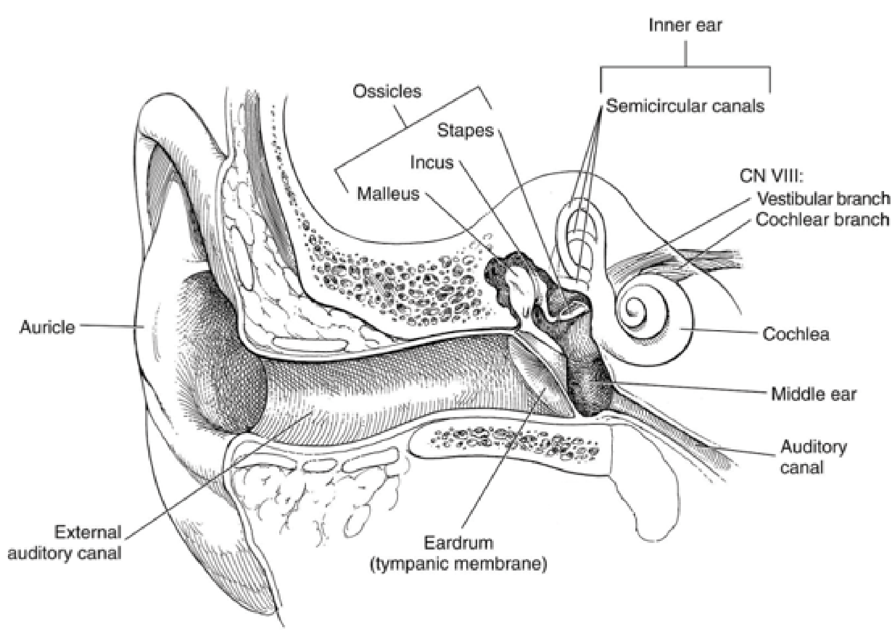


Figure 7 Cross section drawing of outer, middle, and inner ear (nymetrodisability 2008)

Vibrations reach the eardrum via the ear canal, which is stretched over a frame-shaped bone and thus closes the ear canal. The middle ear is an air-filled cavity composed of the tympanic membrane, and the ossicles with the associated muscles, tendons, and ligaments, as well as the Eustachian tube. The vestibular and auditory organs are housed in the inner ear, which is deeply rooted in the temporal bone. The auditory organ is encapsulated by bone and is called the cochlea. The energy of sound is largely lost when sound is transferred from the middle ear (air cavity) to the inner ear (fluid filled cavity). The increasing of air pressure due to the air compression causes an inward bulge of the eardrums, while it bulges outward when the air pressure is decreased. In this way, the air electrical impulses are converted into mechanical vibrations, which are conducted via the ossicles and the auditory nerves to the brain, where the actual sound perception takes place. If you speak louder, the air pressure fluctuations are correspondingly more violent. As a result, the vibrations have stronger pressure changes on the eardrum, so that the sound reported to the brain via the auditory nerves is perceived as louder (Qing 2009).

1.3.4 Sound perception

The notion of frequency is essential in acoustics. 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 (Hansen2001).

Figure 8 shows the hearing threshold as a function of frequency. The sound pressure level is expressed in dB scale and is related to the reference sound pressure where the dashed curve is typical for a young person and the solid curve is a conservative estimate of the hearing threshold for a person with average hearing. The solid upper curve indicates the limit above which a person perceives the sound pressure as painful (pain threshold). This lies in a range between about 120 and 130 dB. The area between the hearing threshold and the feeling threshold covers almost the entire area for which air can be used as the transmission medium for sound: At the lower end, the hearing threshold is 20 to 30 dB above the noise level caused by the thermal noise of the air molecules, and at a sound pressure of 160 dB, non-linear effects occur in the sound propagation in air (Hansen2001).

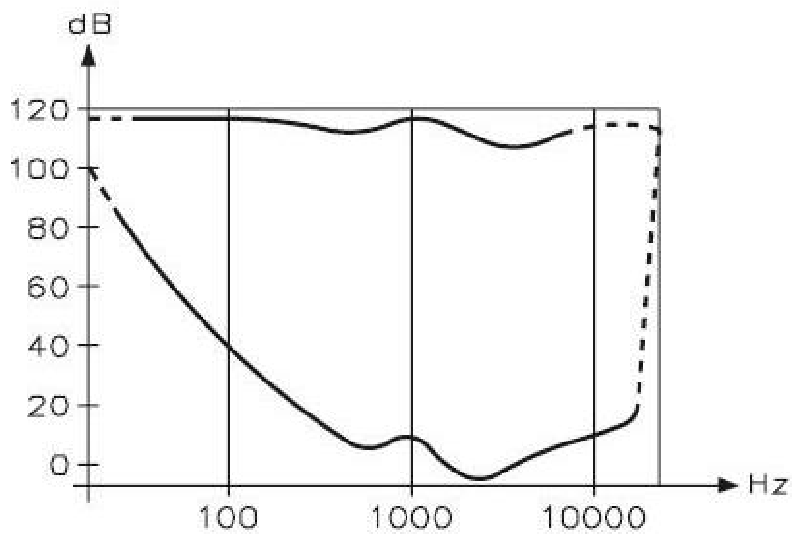


Figure 8 Ear sensitivity (Hansen 2001)

The sound pressure level of a pure tone with a certain frequency is easy to measure, and its value as such hardly gives any idea of the subjectively perceived intensity of two tones with different frequencies or different harmonic structures. This is of great practical importance, as one often compares very different signals with one another, for example speech and music with regard to the (subjectively perceived) volume or the degree of disturbance.

A first step in this direction is the subjective hearing comparison. Test persons are required; the intensity of a pure tone should be adjusted and compared with a second tone so that they hear both tones equally loud. Considerable variation in the results should be observed from trial to trial and it is therefore necessary to average the results over many experiments and many subjects in order to obtain reliable results (Kuttruff 2013).

Figure 9 shows curves of equal volume as a function of frequency for different values of the sound pressure level. Each curve shows the course of the SPL of pure tones over the frequency, which is subjectively perceived as being equally loud (Hansen2001).

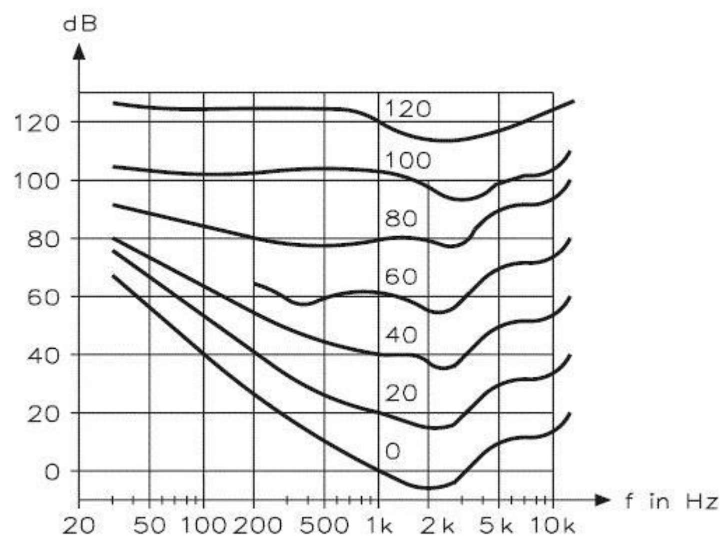


Figure 9 Equal loudness contours (Hansen 2001)

After defining suitable measurement methods for the volume of sound events, it is now also possible to measure the volume of speech under different conditions.

A value of 65 dB (absolute SPL) is typical for the absolute sound pressure at a distance of 1 m for speech. However, this number can vary significantly; it is 40 dB with a low whisper, 70 dB in a noisy office, 80 dB with screaming and about 90 dB with loud shouting. More important for the transmission of speech signals is the dynamics, which means the fluctuation range of the signal and the signal-to-noise ratio, also known as the signal-to-noise ratio, which must be maintained so that the speech remains intelligible. There is a very large variation between the loudest vowel sound and the softest consonant sound, but a dynamic range of 30 dB can be considered sufficient in practice to retain the relevant information (Hansen 2001).

1.3.5 Hearing damage

As can be seen from the above, the hearing is a very sensitive organ which, like all organs of the human body, must be protected from overload and harmful external influences, in order to obtain and ensure its full functionality. Causes such as the effects of aging and disease processes normally change the sensitivity over time and leads to hearing weaknesses or even a complete hearing loss.

The quantitative information on sound perception of the hearing, discussed above always relates to the hearing ability of a healthy “normal hearing person”. In order to avoid acoustic damage, certain limit values with regard to volume, duration and type of impact of sound events must be observed. For this reason, the legislature has set maximum values for permissible noise emissions for various facilities to protect hearing from harmful acoustic environmental influences, which are generally summarized under the term “noise”. There is broad agreement that exceeding certain critical values of sound events leads to permanent damage to hearing. Even a single, short-lasting sound event, which takes less than 1 minute with a very high sound level at the pain threshold of 120dB, for example, an explosion, can cause permanent hearing loss. Once the source of the sound is removed the hearing recovers, known as TTS, temporary threshold shift (Hansen2001).

Likewise, broadband sound events at significantly lower but still high level values from around 85 dB and over can also occur over a period of several hours for example loud machines or loud music also cause irreversible hearing loss, which can cause 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. It has also been shown that the human organism not only has Physiological reactions but also psychological effects. At volume levels between 35 and 65 dB, it responds with psychological effects and at approximately 65 to 90 dB additionally with physiological effects such as circulatory reactions (Ising 2004).

The Figure 10 shows the examples of average sound pressure levels in different activities

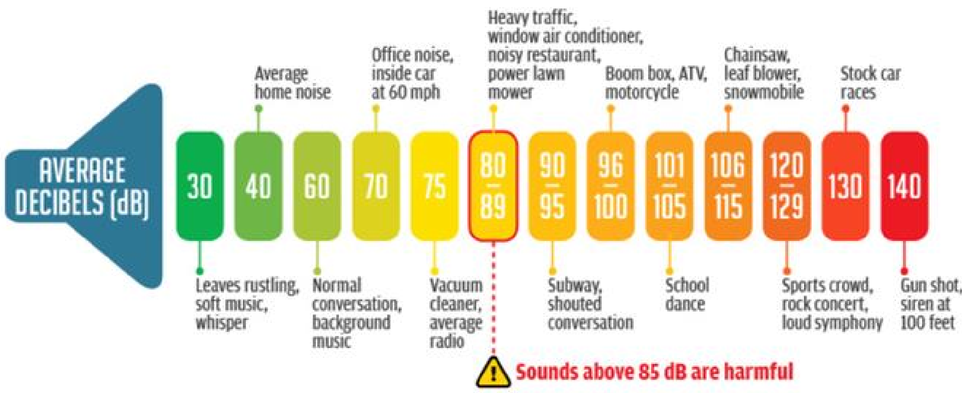


Figure 10 Sound pressure levels (medium 2021)

Excessive noise has been linked to a variety of non-auditory health effects in children, including sleep disruption, annoyance, cardiovascular disease, and decreased cognitive function (ncbi 2021)

Swimming at indoor aquatic facilities is one of the activities, which can have higher sound level and can lead to hearing damages. While indoor water facilities present many advantages, there are several possible sources of excessive noise. Splashing from swimmers and water slides, loud talking and shouting, as well as whistle blowing by the staff are among some of the major contributors to unnecessary noise levels as a visitor, employees to a public swimming pool.

1.4 Fundamental acoustics

1.4.1 Sound

Sound is the term used to describe mechanical vibrations of elastic medium that propagate in gases, liquids or solid bodies as sound waves. Acoustics is the study of sound, of its properties, its origin and expansion, its creation and perception, its measurement and its applications. Sound events are characterized in particular by the frequency of the sound wave (Bruneau 2006).

Table 1 shows the common terms of the sound frequency ranges.

Table 1 **Acoustic spectrum of frequencies (Bruneau 2006)**

Frequency range	description
0 to 20 Hz	infrasound
20 Hz to 20 kHz	audible sound
20 kHz to 1 GHz	ultrasound
1 GHz to 10 THz	hypersound

Due to the different types of sound propagation, a distinction is made between airborne sound and body-borne sound. While airborne sound spreads through the air by way of speech, music or etc., the body-borne sound is released by the stimulation of solid bodies and partially will be emitted again as airborne sound. The sound itself can only be perceived by the human ear as airborne sound. Body-borne sound, on the other hand, is only felt when it has turned into airborne sound. Airborne sound is differentiated in its type of propagation from the place of origin to the human ear in direct sound and reflection sound (Bruneau 2006).

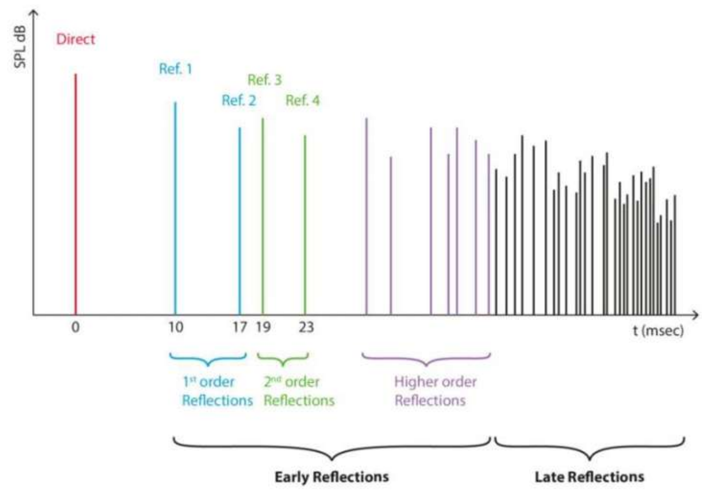


Figure 11 Propagation of sound in room (Odeon 2021)

Direct sound is the type of sound, which travels the shortest way from the sound transmitter to the receiver. This also means that the direct sound has the highest sound level. All further reflections come to the recipient later and have a lower level due to the longer preparation path, see Figure 11.

Reflection sound travels in a given medium; it hits the surface of another medium and bounces back in another direction. The waves are called the incident and reflected sound waves, see Figure 12. Reflection sound is generally differentiated between early and late reflections. However, we cannot determine the late sound reflections in terms of time, since the subjective perception of the listener plays a major role for the type of sound event. In shorter intervals follow the numerous weaker and longer delayed reflections, which define the actual reverberation (Hopkins 2012).

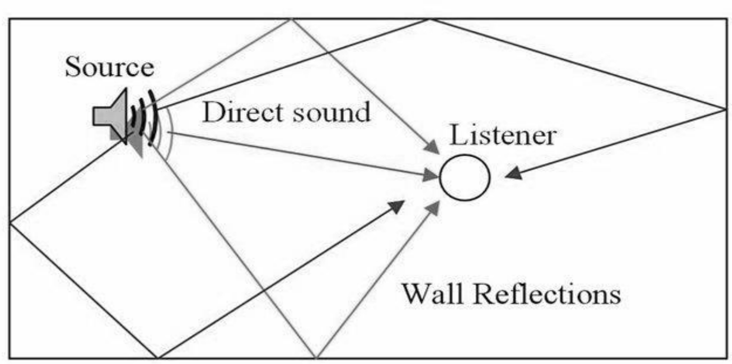


Figure 12 Direct and reflected sound paths in a room (Pop 2005)

The waves can either be longitudinal waves or Transverse waves, see Figure 13. Longitudinal Waves are the ones, in which the particles of the medium vibrate back and forth within the same direction in which the wave is moving. Medium are often solid, liquid or gases. Therefore, sound waves are longitudinal waves. Transverse Wave is a wave in which the particles of the medium vibrate up and down at right angles to the direction in which the wave is moving. These waves are created solely in a very solids and liquids however not in gases (Bruneau 2006).

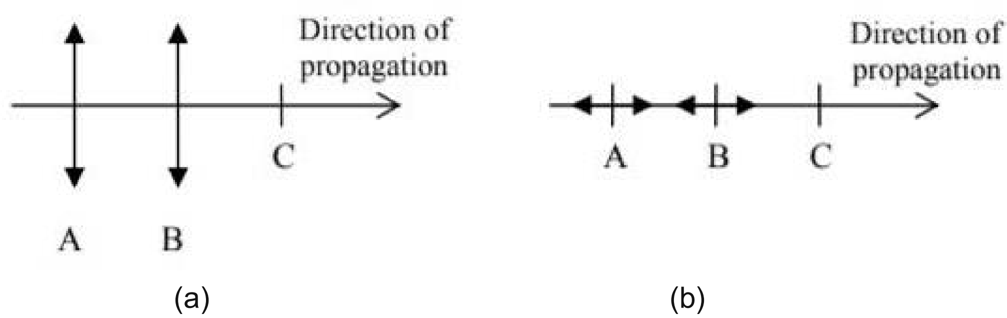


Figure 13 (a) Transverse wave, and (b) longitudinal wave (Bruneau 2006)

In solids, acoustic waves consist of a longitudinal and a transverse component, for any type of stimulation and it depends on the type of bonds existing between the particles. In liquids, the two types of wave always coexist even though the longitudinal vibrations are dominant. Transverse vibrations are basically negligible in gases, although their effects can still be observed when viscosity is taken into account, and particularly near walls that restrict the space considered (Bruneau 2006).

1.4.2 Speed of sound

Speed of sound is the speed at which a sound wave propagates in a medium. The speed at which sound propagates in the air is around 330 m / s. Due to various influencing factors such as temperature, density of the air, wind, etc., it is understandable that this speed is subject to certain fluctuations. The exact speed of sound at 330 m / s and an air pressure of 1 bar = 331.6 m/s. With increasing temperature it increases and is e.g. at 20 ° C = 343.8 m/s. For the sake of simplicity the specified value of 330 m/s has been chosen as a basis. In other media such as solids and liquids, the speed of sound is usually greater. For example it is four times greater in water. The Formula below shows the calculation of the speed of sound (Hansen 2001).

$$c = \sqrt{1{,}4 P0\ \rho} \qquad (1)$$

$P0$=atmospheric pressure
ρ =density of air

1.4.3 Wavelength

Wavelength λ is the distance between two points in the same vibration state, two so called compression points (Figure 14). It is determined by the speed and frequency.
It's a particularly important metric. The wavelength is responsible for the majority of a sound wave's behavior, so it has become the standard by which we determine the physical size of objects. (Hansen 2001).

For example sound will scatter off a flat object that is several wavelengths long in a specular manner. If the object is much smaller than a wavelength, the sound will simply flow around it as it were not there.

The calculation is based on:

$$\lambda = \frac{c}{f} \quad (2)$$

λ = Wavelength (m)
c = speed of propagation (this is 300,000 km / s in air).
f = frequency (Hz)

Depending on the frequency, the sound wave is influenced by objects. High frequencies with smaller wavelengths are reflected on the object and behind the object a sound shadow is formed. With longer wavelengths, sound waves are just slightly interrupted and proceed just as before.

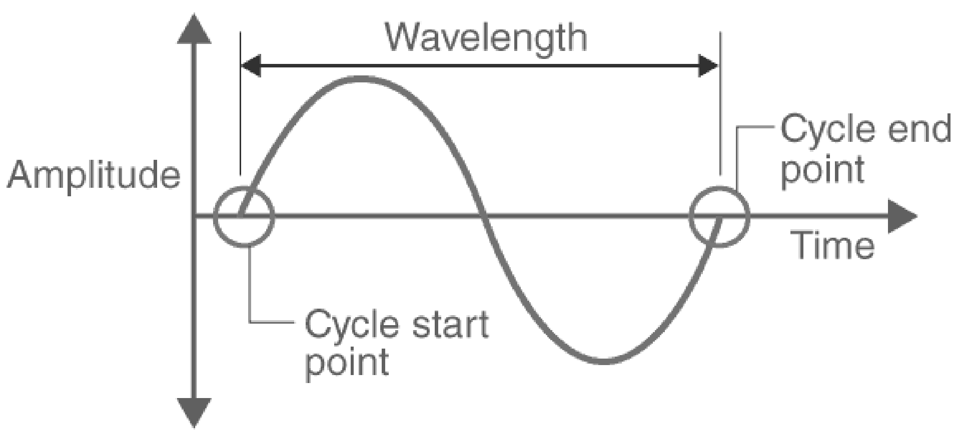


Figure 14 Wavelength (Byjus 2021)

1.4.4 Frequency

The notion of frequency is essential in acoustics. The height of a tone is determined by the F. It depends on the speed with which air compressions and dilutions follow one another. The shorter is the wavelength, the higher the frequency of the sound, which can be observed in Figure 15 (Hansen 2001).

The F is given in the unit Hertz, Hz, and calculated as formula below depending on the period time,

$$f = \frac{1}{T} \tag{3}$$

Sound contains tones with different frequencies. A tone consists only of one fundamental tone with one frequency. Sound, which consists of a large amount of low frequencies, has more impact on individuals. Tiredness, irritation, headache, disturbed sleep and difficulties with concentration are some of the consequences. The audible frequency is from 20 Hz to 20 000 Hz, varying from 17 meters to 17 millimeters in wavelength. Low frequency sound is sound at frequencies from 20 to 200 Hz. The length of the sound waves then ranges between 17 meters and 1.7 meters, making it more difficult to minimize the sound waves due to their long length. Due to this, low frequency sound travels longer and can spread further than higher frequencies across boundaries such as walls. Generally Low frequencies are known to be tiring (Hansen 2001).

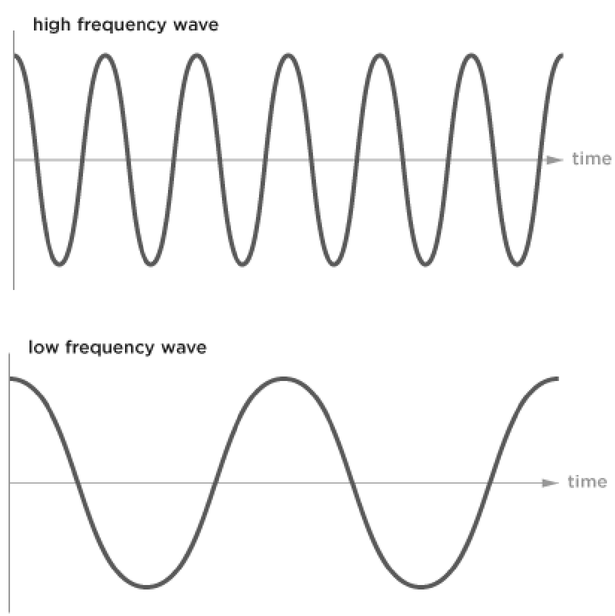
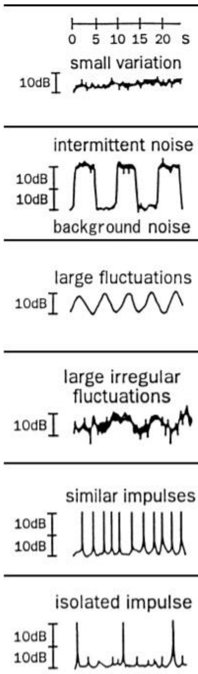


Figure 15 Frequency (Hansen 2001)

1.4.5 Noise

The intensity of noise is different from person to person. Examples are music, Motorbike noise or party noises that are judged differently depending on whether you are the cause or bystanders. Therefore, noise is also a subjective phenomenon. Sound variation often influences the perception of sound. Sound variation is categorized into constant, irregular and impulses over time. The Figure 16 shows the different type of Noises.

For a certain amount of time, sound makes only tiny differences in the sound pressure range. A fan is one example of a constant tone, which is often calculated at the same sound pressure levels. The amount of intermittent sound varies all the time, as an example the engine that starts and stops all the time. Impulses are sounds that are short and unexpected. The aspects are presented by Frequency distribution. Since the perception of sound is subjective, the level of disruption depends on the individual person. Noise covers speech and noisy conditions can obstruct speech and thereby be very distracting. People may increase the volume of speech in a noisy atmosphere and that further increases the current level of sound pressure and is burdensome for the listener (Hansen 2001).



	Characteristics	Type of Source
small variation	Constant continuous sound	Pumps, electric motors, gearboxes, conveyers
intermittent noise / background noise	Constant but intermittent sound	Air compressor, automatic machineryduring a work cycle
large fluctuations	Periodically fluctuating sound	Mass production, surface grinding
large irregular fluctuations	Fluctuating non-periodic sound	Manual work, grinding, welding, component assembly
similar impulses	Repeated impulses	Automatic press, pneumatic drill, riveting
isolated impulse	Single impulse	Hammer blow, material handling, punch press, gunshot, artillery fire

Figure 16 Noise types and their measurement (Hansen 2001)

The presence of constant, active noise sources, such as ventilation and air conditioning systems, increases sound levels in spaces, and this markedly compromises acoustic quality, especially that of swimming hall.

Noise is perceived as unnecessary sound. The disparity is due to the experience of categorizing noise as undesired sound. Having a relation between noise and sound pressure level is normal. Noise is often defined as a high level of sound, but the fact that it is unwanted, regardless of the level, is much more significant.

When a sound interrupts our attention, it is interpreted as distracting, and hence as noise. For the perception of the sound, the acoustic expectation is significant, whether it is desired or not and whether it is anticipated will influence the attitude towards it. In both a psychological and physiological way, noise can be distracting. The noise could be connected as psychological effects to a feeling or an experience, such as tiredness and frustration. Noise is a health concern, according to the World Health Organization (1999), and will possibly continue to be a problem in the next century.

Humans seldom encounter total silence. Purpose-constructed for acoustic studies, spaces such as anechoic chambers are used and can achieve exceptionally low noise levels. Due to the low sound levels, working in such rooms can have a disorientating effect on humans. The movement of blood in vessels near the eardrum can also be audible as a disquieting shushing sound in a very quiet setting.

1.4.6 Measures

It is possible to measure sound in different ways. The most important indicators, such as decibel and sound pressure levels, for the acoustic condition in swimming halls are explained below. The result will be determined by sound pressure level, frequency and durability.

Decibel

Units used for acoustical measurements are mostly sound pressure; sound intensity and sound power P described in Pa, W/m2 and W. Besides this a logarithmic scale is used in order to include the wide range of audible intensities. A ratio of intensities expressed as a logarithmic (base 10) scale is denoted by the decibel (dB). The ratio of two I1/I2 intensities is 10 logs (I1/I2) in the Units with dB. Using an accepted reference intensity of a plane wave having an rms pressure equal to 10-5 dyn cm-2 or equivalently 1 μPa, absolute intensities are expressed. Transmission loss is a decibel measure of relative intensity, the latter being proportional to the square of the acoustic amplitude (Kuttruff 2013).

Sound pressure level

The most widely used measure of acoustic wave intensity is the SPL. It corresponds well with the perception of loudness in humans and is easily measured with relatively cheap instrumentation. The reference around pressure, like that of the intensity, is set to the threshold of human hearing about 1000 Hz for a young person. The resulting amount is 0 dB when the sound pressure is equal to the reference pressure (Kuttruff 2013). The sound pressure level is defined as:

$$SPL = 20Log_{10}\left(\frac{\mathrm{p}_{rms}}{\mathrm{p}_0}\right) \tag{4}$$

p_{rms} is the root mean square pressure

p_0 is the reference sound pressure level of 0.00002 Pa

The sound pressure level and other measurements that vary in time might be measured at the peak, average or rms value. Rms is the mean square of the root; it is related to the content of energy and is widely used (Figure 17). The maximum amplitude is the peak value and the average is the mean value. A common value to be used for measuring sound is sound pressure level, and two main values are used. During a certain amount of time, the equivalent sound pressure level is the mean value. During a certain amount of time, the maximum sound level is defined as the highest temporary sound pressure level (Kuttruff 2013). Figure 18 shows the sound pressure level in different activities.

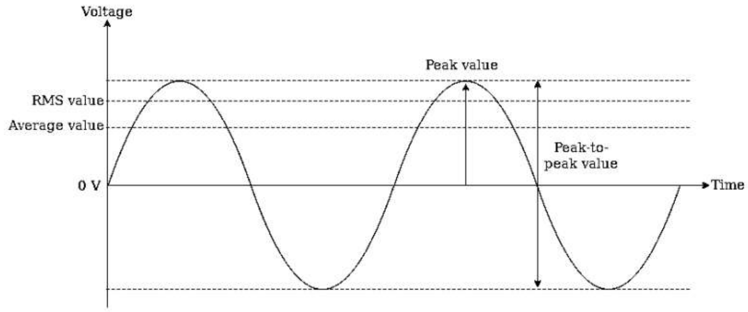


Figure 17 Peak, average and rms (electronics-lab 2021)

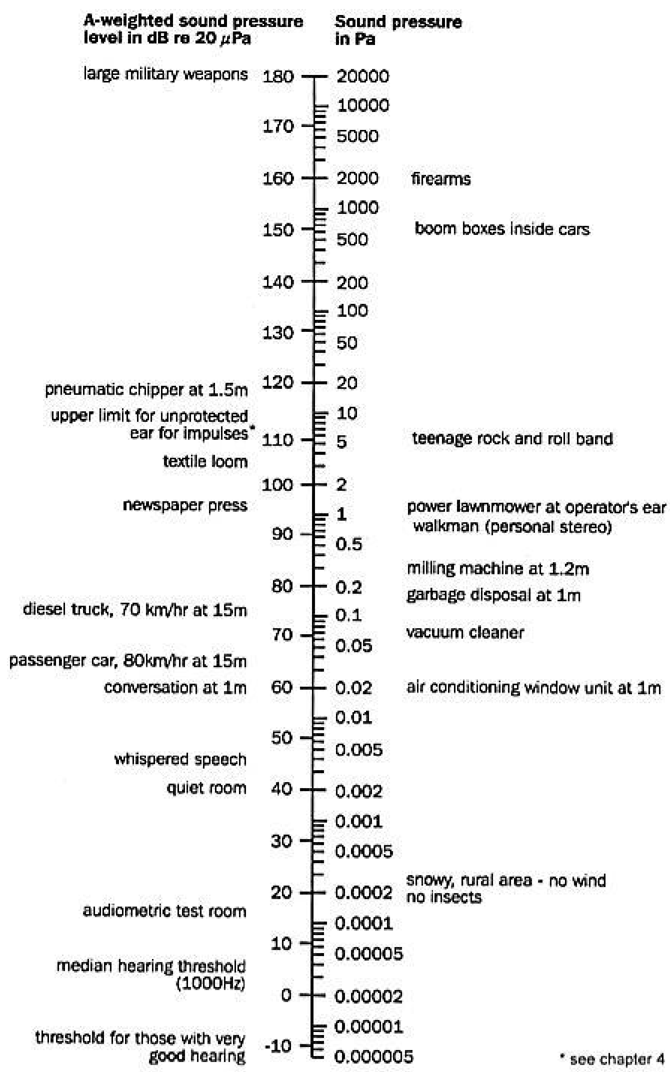


Figure 18 Examples of sound pressure levels (Hansen 2001)

1.4.7 Reverberation time

Whenever sound waves face an obstacle, for instance when a noise source is placed within boundaries, part of the acoustic energy is reflected, a part is absorbed and a part is transmitted. The relative quantities of reflected, absorbed and transmitted acoustic energy are highly dependent on the nature of the obstacle. Different surfaces have different ways of reflecting, absorbing and transmitting an incident sound wave.

A rigid, compact, smooth surface can reflect much more acoustic energy and absorb much less than a porous, soft surface. If the boundary surfaces of a room consist of a material which reflects the incident sound, the sound produced by a source inside the room - the direct sound - rebounds from one boundary to another, giving origin to the reflected sound. The greater the percentage of the incident sound reflected, the greater the contributions of the reflected sound in the closed spaces to the overall sound.

Even after the noise source has been switched off, this "built-up" noise will continue. This phenomenon is referred to as reverberation and the area where it occurs is referred to as a reverberant sound field, where the amount of noise depends not only on the radiated acoustic power, but also on the size of the room and the acoustic absorption properties of the boundary. Reverberation is defined as the time required for the sound pressure level to decrease 60 dB. Two sound fields are available with a continuous sound source. The direct sound produces the direct sound field, and the reflections create the sound field of the reverberation. It is the correct room acoustic characteristic. The reverberation time can be calculated with Sabine reverberation formula. The formula is derived from empirical studies of the relationship between the volume of a room and the amount of absorptive materials. As below, where T is reverberation time, V is volume, and A is the total area of absorbents, the parameters are related to the reverberation time (Kuttruff 2013).

The formula is optimized for room volumes less than 1000 m3 and Sabine's formula does not measure larger volumes accurately.

(5)

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

T = reverberation time or time required (for sound to decay 60 dB after source has stopped) in seconds.
V = Volume of room in cubic feet.
A = Total square footage of absorption

1.4.8 Weighted system

The human ear is not equally sensitive to sound at different frequencies. The sound measuring device must account for this disparity in sensitivities across the audible spectrum to accurately assess human exposure to noise. For this reason, frequency weighting networks have been developed that are essentially "frequency weighting filters".

The contributions of the various frequencies to the total sound level are "weighted" by these networks, so that sound pressure levels are decreased or increased as a function of frequency before being added together to give an overall level. Thus, whenever the weighting networks are used in a sound measuring system, the various frequencies which constitute the sound contribute differently to the evaluated over-all sound level, in accordance with the given frequency's contribution to the subjective loudness of sound, or noise. "A" and "C" are the two globally standardized weighting networks in common use, which have been designed for various sound levels to conform with the frequency response of the human ear (Figure 19). The "A" network modifies the frequency response to approximately follow the 40 phon equal loudness curve, while the "C" network approximately follows the 100 phon equal loudness curve. In some texts, a "B" network is still listed, but it is no longer used in noise assessments (Hansen 2001).

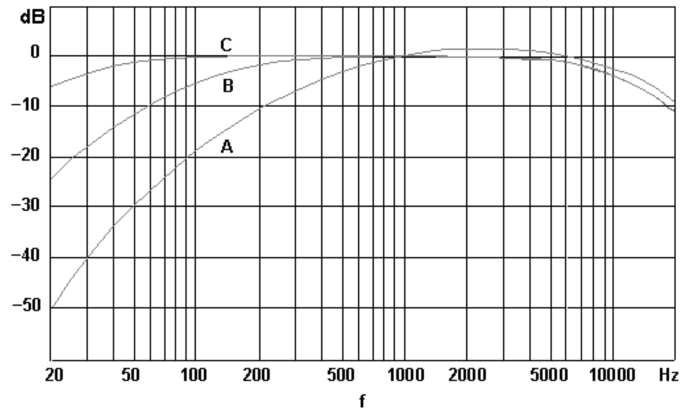


Figure 19 Frequency weighting characteristics for A and C networks (fceia 2021)

In the course of time, the popularity of the A network has increased. From the point of view of habitability, community disruption, and even hearing damage, it is a useful clear means of explaining interior noise conditions, even though the C network better describes the loudness of industrial noise that contributes significantly to hearing damage (Hansen 2001).

1.4.9 Speech intelligibility

The speech intelligibility is one important value for the acoustic condition in swimming halls. Speech intelligibility is the ability to understand speech in a space but it is not the same value at every point in the room. There are many factors, which decrease the quality of the speech intelligibility. Speech intelligibility is always subjective, but there are often ways to calculate it.

Speech is mostly within 100-6000 Hz and has the highest energy content between 300 and 3000 Hz (World Health Organization, 1999). The human speech is mostly between 100 Hz and 8000 Hz, vowels being in the lower frequency range. The speech intelligibility in swimming halls decreases with noise from ventilations, speech, steps, water sound etc. The factors such design of the room, high level or low level of absorption, it may also reduce the speech intelligibility in these halls. Also a high level of background noise can mask speech and late reflections and echoes make it harder.

The percentage heard by the listener will be also affected through the higher level of masking background noise and at higher amount of the high energy frequencies. If there are two or more tones at the same time and their levels are adequately different, it becomes difficult to perceive the tone with lower level. It means that the quieter tone is masked by the louder one. Masking can be described in terms of threshold shift caused by the louder sound due to its overlap within the critical band on the cochlea. Generally tones that are close in frequency mask each other more than those that are widely separated and they mask upward in frequency rather than downward. The louder the masking tone the wider the range of frequencies it can mask (Kuttruff 2013).

For example signals such as fire alarms or whistles can also be masked by background noise. With the intrusion of sound pressure from background noise, people can raise their voices and increase the sound pressure level. In a quiet condition, the sound pressure level at 1 m between the speaker and the listener is around 45-50 dB, but a due to the background noises the outcome of speech will go beyond 30 dB.

The other factors which also influence speech intelligibility are Reverberation, degree of hearing impairment and fluctuations in level time. Reverberation time over 1 s leads to loss in speech discrimination. A long reverberation time provoke decreasing of speech intelligibility, when sound from one word still travels when the next word is heard. The percentage which is understood by listener is the amount of speech intelligibility. The level of understanding is often measured as a percentage of words, phrases or nonsense-syllables. There are also some objective measurements where speech transmission index (STI) is the most common one for areas with excessive echoing or systems that feature complex distortion factors. The index makes the assumption that speech is coded by several speech channels that carry independent information (Kuttruff 2013).

STI is measured over seven octave bands from 125 Hz to 8000 Hz and the result is a weighted value within the limits of 0 and 1 is shown in Table 2.

Table 2 Relation between STI and speech intelligibility (voiceinterconnect 2021)

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

STI with a value of 0.75 of the scale from 0 to 1 is required for a good level of speech intelligibility. For this Value, the reverberation time should be 0.5 seconds or less and with the background noise of less than 30 dB.

The measurement of the Speech Transmission Index is based on the empirical finding that speech intelligibility is mainly determined by the strength of the intensity fluctuations of speech signals. These fluctuations are result of the acoustic separation of sentences, words and phonemes.

The following graphic shows a simplified STI measurement setup. The left one shows the measurement of the microphone signal path and the right one the loudspeaker.

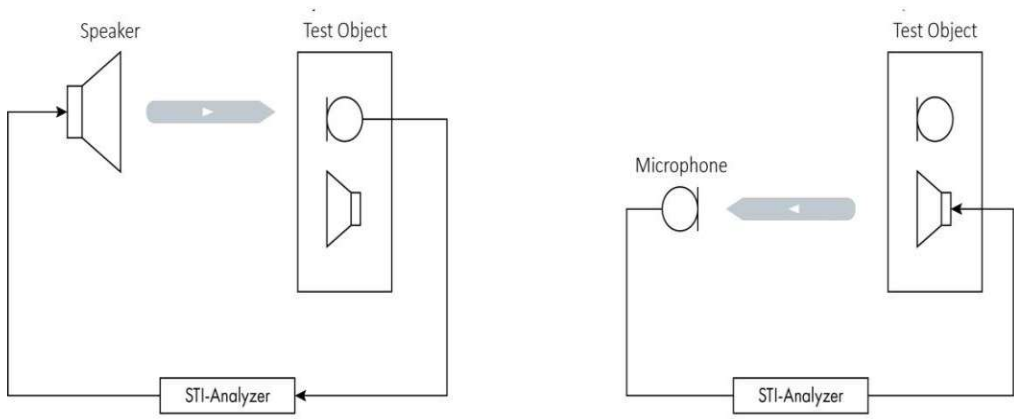
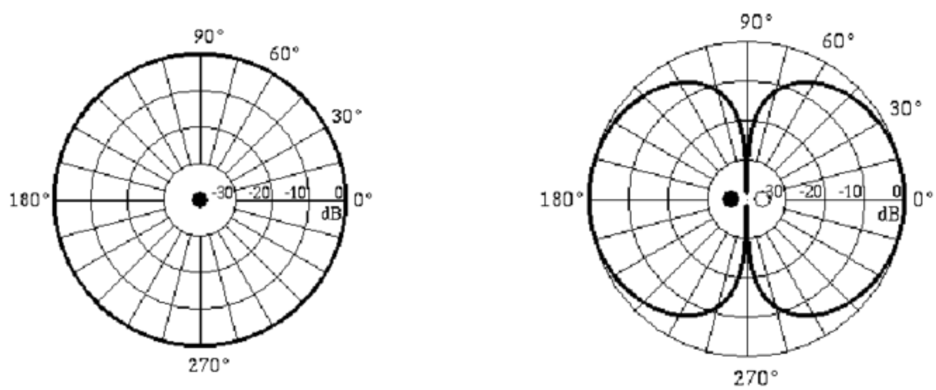


Figure 20 STI measurement setup (voiceinterconnect 2021)

The STI can be measured directly or indirectly, although the methods differ in the type of test signal and their applicability. The direct measurement uses speech-like noise that is modulated in 7 octave frequency bands from 0.125 - 8 kHz with 14 modulation frequencies each in the range 0.63 - 12.5 Hz. This results in 98 measured values from which the STI can be calculated directly. In the indirect method, the impulse response of the transmission system is measured using a suitable test signal and the STI is derived from it using mathematical methods. With both variants, the final value is between 0 and 1, which provides direct information about the quality of speech intelligibility (Kuttruff 2013).

1.5 Architectural acoustics

There is a broad selection of sound sources in architectural acoustics such as Loudspeakers, computers, speech and musical instruments and etc. This is a challenge due to the various attitudes of the sources. There are two different ways to identify the sources, monopole and dipole. Monopole is a sound source that can disperse the sound Spherical from one point and produces harmonic spherical waves if the medium is homogeneous and isotropic, see Figure 21. Sound intensity SI is decreased at a distance from the source as the region of sound energy is greater. The sound pressure level would decrease by 6 dB if the distance doubles. A dipole or an acoustic doublet occurs when a source produces a sound spreading from two directions (Jabbal 2017).



(a) (b)

Figure 21 (a) Monopole source, and (b) and dipole source (Jabbal 2017)

Generally sound is able to spread between the rooms in air or through the building structures. Sources to airborne sounds are such as speech, machines, loudspeakers or sound of water and structure borne noises are created by impact such as footsteps, slamming doors and some installations, which have at the same time an impact on airborne sound. Sound is also transmitted through air ducts, door leaks etc., which can be observed in Figure 22.

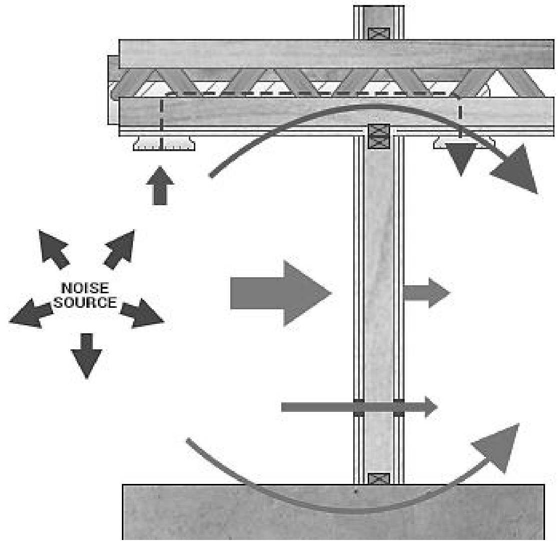


Figure 22 Transmission paths between rooms (everkemproducts 21.03.2021)

Insulations are used to prevent sound transmission. 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 (Hongisto 2000).

$$R = 10log_{10}\left(\frac{W_1}{W_2}\right)\ dB \quad \text{Or} \quad R' = 10log_{10}\left(\frac{W_1}{W_3}\right)\ dB \tag{6}$$

$W1$= sound power incident on the wall
$W2$=sound power transmitted through the wall
$W3$=total sound power transmitted into the receiving room

1.5.1 Diffuse sound field

After the sound waves spread from the source the waves will hit the boundaries in which some waves will be absorbed and the rest will be reflected. The reflections collide with another boundary and the new reflections will be generated. After a period of time this will cause a diffuse sound field where the energy density is constant and the sound pressure is the same everywhere in the room. This is obtained with large rooms with no absorbent materials on walls, ceiling or floor (Kuttruff 2013).

1.5.2 Sound absorbents

Indoor pools are an especially big challenge for soundproofing. Swimming pools are humid areas with high temperatures and chlorine. It is critical that building materials and indoor acoustics can cope with the level of humidity. Absorbents are often used to improve the acoustic condition, but because of the temperature in swimming pools, it is not always simple.

Loud cheers and music, splashing water, these and other noise sources determine the usual background noise in swimming halls and can cause the sound level to increase. The direct sound signal arriving from the sound source to a listener along a straight line is not influenced at all by the walls or the ceiling of a room. Nevertheless, its strength depends on the geometrical data of the hall, namely on the average length of paths which it has to travel, and on the height at which it propagates over the obstacles until it reaches a particular listener.

Hard surfaces of floors, walls and ceilings reflect the sound and ensure that the sound pressure level constantly increases. Additionally, large floor areas, high ceilings and wide rooms worsen the acoustics and promote unpleasant reverberations.

The use of sound absorbers in swimming halls is recommended for various reasons, such as improving the room acoustics and reducing the noise. The presence of sound absorbing objects determines to a large extent the acoustic quality of a swimming hall. Such objects contribute to decreased reverberation time and thus reduce reverberant noise as well as decreased interfering noise levels. The selection of the right sound absorbers should be adjusted to the requirements of the premises (Kuttruff 2013).

The biggest acoustic obstacle for sound insulation in the halls is reverberation and long reverberation times. Sound is mirrored by the hard surfaces of the walls and ceilings and returned to the space, resulting in all the sounds lingering in the room for an unpleasantly long time.

In order to avoid this it is necessary to add sound absorbers on the ceiling and/or walls of the swimming hall. Hanging sound absorbers and acoustic sails are especially effective at eliminating reverberation in swimming pools. They can be easily fitted with suspension or cable systems under the ceiling of the chamber. As a consequence, noise is absorbed and adequate room for silence; relaxation or focus for sport is created.

Generally, all materials can absorb sound energy to a certain degree. However, materials that are explicitly known as sound absorbers can absorb much of the sound energy that collides with them. These advanced materials are generally referred to as "acoustical materials" and are engineered to have high absorption characteristics. There are a variety of sound absorbing materials available. Their ability to absorb sound waves is highly dependent on frequency, composition, thickness, and mounting methods. From a scientific point of view, there are three main types of sound absorbers: porous, panel, and resonance.

Porous Absorbers

Materials with a high coefficient of sound absorption are usually porous. Sound absorbent materials are not dense, they are permeable and the sound waves penetrate the surface of these materials and flow through the fibrous or cellular structure of which they are made up.

Due to the fact, that energy can never be destroyed and it can only be transformed, the porous absorbers transform incident sound energy into heat energy through frictional and viscous resistance. The amount of heat produced by the sound waves is less than 1/1,000,000 watts. By using porous sound absorbers, only a small portion of the sound energy is reflected back into space. These sound absorbers are most efficient for mid-range frequencies or treble tones. They seem to have less effect on lower frequencies. Materials such as mineral wool, carpets, fibreboards, insulation blankets, and certain forms of foam plastic are common for porous sound absorber (Kuttruff 2013).

Panel/ Membrane Absorbers

This absorber is an air impervious, non-rigid, non-porous substance positioned over airspace. As sound energy is applied to the absorber, the oscillating mechanism (the mass of the front panel and the spring created by trapped air) is converted into mechanical energy, see Figure 23.

They are especially effective against low frequencies, such as bass. They also will reflect higher frequency sounds. Common examples are wood or hardboard paneling, suspended plaster ceilings, windows, wood doors, gypsum boards, and wood floors (Kuttruff 2013).

Resonance Absorbers

These types of sound absorbers are only used when you need to monitor sound within a small, but specified frequency range. They're used to concentrate on low-frequency issues.

These types of absorbers operate on the basis of sound pressure. It's basically a mass that vibrates against a spring which is the air inside the resonant absorber, see Figure 24. You may change the resonant frequency by modifying either the mass or the spring stiffness. They function in the same way as a panel absorber. They consist of a mechanical oscillation mechanism with a solid plate and a tight air space. An example would be layers of perforated plasterboard or perforated metal corrugated sheets (Kuttruff 2013).

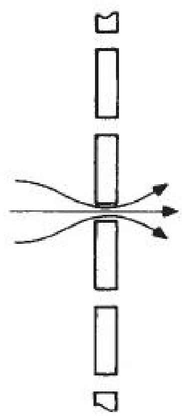


Figure 23 Perforated panel (Kuttruff 2013)

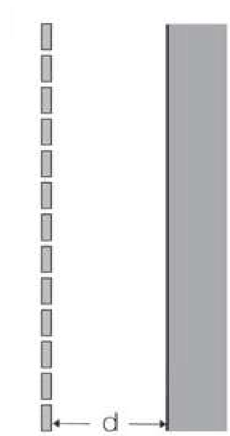


Figure 24 Resonance absorbers: with perforated panel (Kuttruff 2013)

The purpose of most medium to large size swimming halls is to accommodate a large number of spectators and thus enable them to watch events or functions of common interest. The essential acoustic properties are those that are present when the rooms are occupied or at least partially occupied. These properties are primarily defined by the audience itself in particular by the sound absorption affected by people or by their clothes.

The absorption effected by the audience is primarily due to people's clothing and its porosity, too. Since the clothing is not typically very dense, the absorption is substantial only at medium and high frequencies.

Due to the fact that the clothing of the people differs from the person to person, only the average values of the absorption of the audience are available. Generally all the furniture in a room have an influence of the absorption values, but since the seats and all the usual furniture in swimming hall areas are water resistant and not made of fabric, they cause reflections of sound waves instead of absorption.

A Noise Reduction Coefficient is an average rating of how much sound an acoustic product can absorb. The NRC gives scores ranging from 0 to 1. An NRC of 0 indicates that the substance does not absorb any signal. The higher the NRC, the better the product is at absorbing sound. A Noise Reduction Coefficient is calculated by taking into account the thickness and density of a product. An acoustic product with a.95 NRC rating absorbs 95% of sound in the space while reflecting the remaining 5%.(Kuttruff 2013).

1.5.3 Absorption coefficient

Absorption coefficient, α, is a dimensionless measure for a materials capacity to absorb sound waves. The sound absorption coefficient of materials is correlated with frequency, and it varies with different frequencies. The value is decided from standardized measurements of a sample of the material in a reverberation chamber (Farina 1997).

Table 3 shows absorption coefficient of some hard surfaces.

To enable simple comparison between products acoustic materials are classed on a scale from A to E, with A-rated products having the highest rated sound absorption performance.

This is measured by the international standard EN ISO 354 and classified by the international standard EN ISO 11654 (acousticcomfort 2021). The Figure 25 shows the absorbent classes.

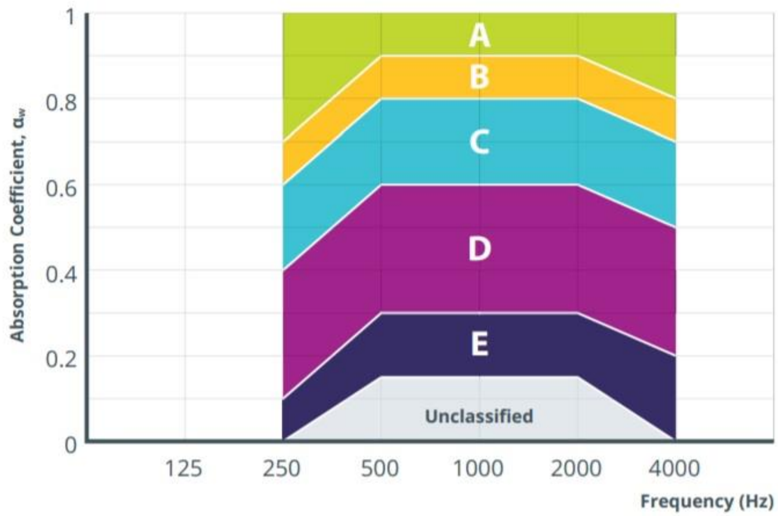


Figure 25 Absorbent classes (acousticcomfort 2021)

Table 3 Absorption coefficients of wall materials (Kuttruff 2013)

Material	*Centre frequency of octave band (Hz)*					
	125	*250*	*500*	*1000*	*2000*	*4000*
Hard surfaces (brick walls, plaster, hard floors, etc.)	0.02	0.02	0.03	0.03	0.04	0.05

1.6 Room acoustics

Acoustics has an impact on the experience in a room and can be used to create the desired situations. This chapter deals with the use of acoustics in buildings and also introduced in areas such as swimming halls.

Acoustic designs in rooms have a variety of purposes and the shape of the room has an effect on the acoustic environment. Examples of this are the size, shape, surfaces, size and location of the absorbents

A complete or partial reflection of the sound normally causes a change in propagation direction. This can have an effect on the entire frequency spectrum or only a small portion of it. In addition to shifting direction, the sound's energy is drained. Figure 26 depicts two different forms of reflections, one on a flat surface and the other on a corner. The angle of incidence equals the angle of reflection, whereby it must be conditional that the surface on which the sound is reflected has a certain size relative to the wavelength, according to the reflection rules. As a sound wave is mirrored back from a corner, it is reflected twice, resulting in a beam that is parallel to the incident (Kuttruff 2013).

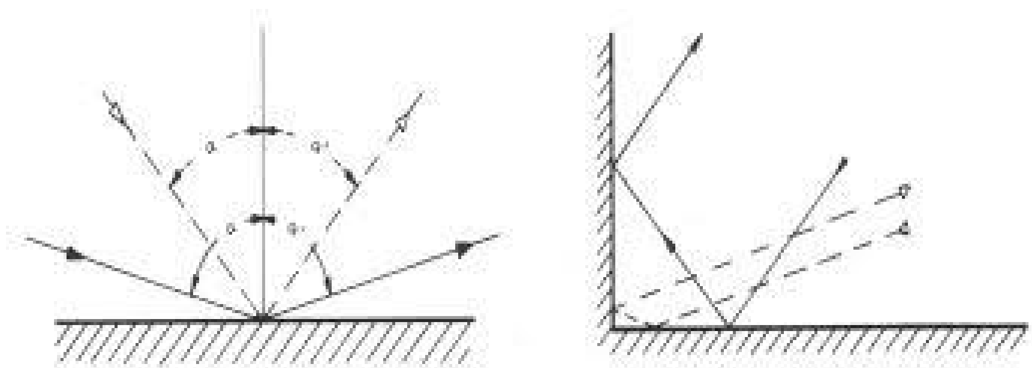


Figure 26 Sound reflection : flat surface and corner (Kuttruff 2013)

Curved wall surfaces are often used in acoustics to eliminate distracting reflections while still distributing sound equally across the room. In so-called whispering galleries, you can see this phenomenon up close and personal. Even if the speaker's voice cannot be understood over the direct line, the dome shape in its focal point causes the sound to be concentrated, allowing the listener to understand even whispered speech. The Figure 27 shows the possible reflections that occur when hitting a concave surface. The distance between the sound source and the reflective surface is greater than half the radius of curvature r / 2, but smaller than r.

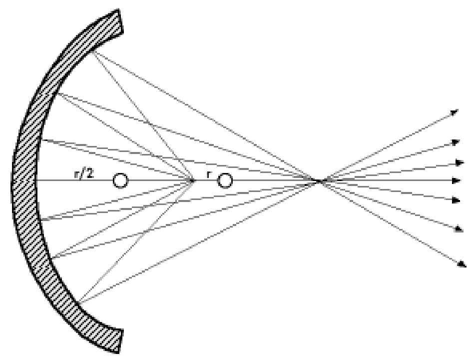


Figure 27 Reflection; sound source within half the radius of curvature (Kuttruff 2013)

When the sound source is half the radius of curvature, the reflected rays leave the mirror parallel to each other. The easiest way to take advantage of this effect is to use a parabolic mirror. That is, the distance between the sound source and the reflecting surface is half the radius of curvature of the surface (r / 2), as shown in Figure 28.

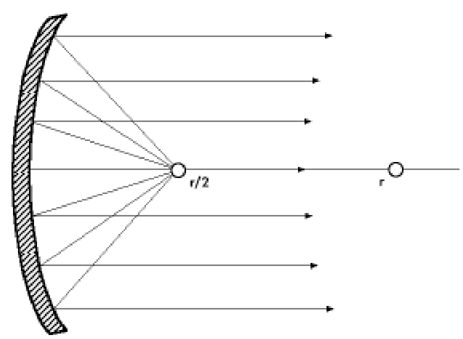


Figure 28 Reflection; sound source within half the radius of curvature (Kuttruff 2013)

For better comparability, the following figure shows the reflection effect of a convex surface.

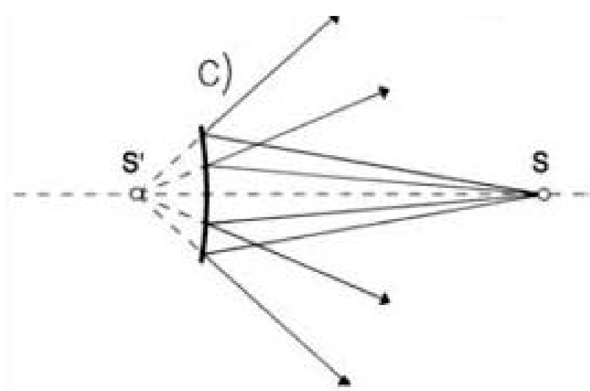


Figure 29 Reflection on a concave surface (Kuttruff 2013)

Before the equilibrium is achieved, the SI at the point will rise due to reflections, indicating that the energy absorbed by the room is equal to the energy radiated by the sound source. When the sound source has passed, the sound gradually fades, and the decay is determined by the amount of absorbents in the room, which we discussed in previous chapters as the reverberation period (Kuttruff 2013).

1.6.1 Room design

The aim of acoustic design is to achieve a pleasant acoustic environment adapted to the usage of the room. In rooms with several usages are difficult to achieve a perfect solution. In order to accomplish the sound requirements, the function of the room should be studied carefully. Numerous factors should be considered for the inhomogeneous spatial distribution of reverberant energy. At each reflection of the sound wave, there are various acoustic properties of materials, such as absorption and scattering, it influences the sound field to varying degrees. Room forms, which can be categorized by the three-dimensional ratio, such as flat space, long space, often have a major effect on the sound. Other factors, which also need to be considered, include air absorption and specular early reflections. One of the facts is the number of people who will use the room at maximum capacity and another fact is to know if the room has a non-communicative or communicative function. For the non-communicative rooms are the criteria simple to achieve the goal but for the communicative room a short reverberation time, early reflections are desired. Early reflections reach the ear of the listener within 50 milliseconds and they prevent the echoes. More and stronger early reflections create a clearer speech. The shape of the room has an important role on the acoustics.

The dimensions, Volume, shape of the ceiling, materials, opening and boundaries have an impact on the outcome. Sound may be a way of distinguishing a space with a residual sound that produces a particular acoustic atmosphere for a room. In other words, we can distinguish the space from the way it sounds.

1.6.2 Swimming halls

Swimming and generally water activities produce a high degree of sound pressure level in which understanding the instructions and being able to communicate is very important.

Due to the swimming hall requirements and the climate, the materials which are used, are usually hard surfaces and they increase sound pressure level and sound distribution, which is disturbing. In swimming halls, sound is allowed to travel far and one sound source can disturb many people.

The background noises of the technical devices such as water pumps, ventilations and air conditions have a great impact on sound quality.

In order to be able to achieving the safety measures and give instructions, good speech intelligibility at short distance is necessary as well as the background noise needs to be reduced.

The 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.

Usually these types of absorbents are improving the sound comfort: a wall-to-wall sound-absorbing ceiling, wall absorbers wherever possible, free-hanging units where a wall-to-wall ceiling is not applicable, which should be water-resistant, chloride-resistant, and corrosion resistant and can withstand high humidity and high temperatures.

1.7 Guidelines

Planning an Acoustic environment requires guidance in order to achieve a sufficient level. Relevant items from the Austrian Standard for acoustics in swimming halls are presented below. Values for reverberation time and sound pressure level are obtained.

Due to the Austrian standard, ÖNORM B 2608: 2014 04 15: Sports halls - guidelines for planning and execution the requirement of the ÖNorm B8115 -3 are applicable.

1. ÖNorm EN 15288-1 (Swimming pools for public use - Part 1: Safety requirements for design):

   Table 4 shows permitted values according to ÖNorm EN 15288-1.

   Table 4 ÖNorm EN 15288-1, acoustic regulations

Reverberation time	Sound pressure level
> 2.0 s	>85 dB

   According to Austrian regulations, the optimum amount to avoid hearing loss is 85 dB, but more sensitive people are at risk already at 75 dB(A). Taking into account the room volume a reverberation time down to 0.7 s is achievable. It is recommended to measure the reverberation time according to EN ISO 3382-2.

   According to the ÖNorm EN 15288-1, the target values for avoiding inconvenience are LAeq 30 dB.

2. ÖNorm B8115-3 (Sound insulation and room acoustics in building construction - Part 3: Room acoustics).

Tables 5 and 6 shows permitted values according to ÖNorm B8115-3.

Table 5 ÖNorm B8115-3, reverberation time regulations

Reverberation time	
Communication (30 - 1000 m3), e.g. classrooms	T = 0.32
Language (30 - 10000 m3). e.g. lecture hall	T = 0.37
Music performances (30 - 10000 m3), e.g. rooms in music school	T = 0.45
Music rehearsal rooms (30 - 1000 m3), e.g. rehearsal rooms for orchestras	T = 0.47

:

Table 6 Minimum values for average sound absorption level (ÖNorm B8115-3)

Oktavband-Mittenfrequenz	Hz	250	500	1000	2000	4000
α_m	–	0,20	0,25	0,25	0,25	0,20

3. The German Standards, DIN EN 15 288.

Table 7 shows permitted values according to DIN EN 15 288.

Table 7 DIN EN 15 288, acoustic regulations

Reverberation time	Sound pressure level
> 2.0 s	>85 dB

Taking the room volume into account, a reverberation time of 0.7 s can be achieved.

4. There is also a guideline for pool construction as German Society for Bathing (Bäder, K. 2013).

Tables 8 and 9 shows permitted values according to German society for bathing.

Table 8 German acoustic guidelines

reverberation time	Speech Transmission Index	Sound pressure level
T = 1.7 - 2.0 s	0.5 STI	Leq ≥ 80 dB (A)

Table 9 Noise emission guidelines

Noise emissions in outdoor pools LwAeq / person [dB]				
Toddler pool	fun pool	jumping pool	swimming pool	sunbathing area
85	85	85	75	70

5. According to German swimming association E.V. (Construction and equipment requirements for competitive swimming pools):

Table 10 shows permitted values according to German swimming association E.V.

Table 10 German swimming association guidelines

Reverberation time f> 500 Hz	Sound pressure level
> 1.7 s	>85 dB

6. According to UK Department for Education. Building bulletin 93, Acoustic design of schools: Performance standards.

Tables 11, 12 and 13 shows permitted values according to UK Building bulletin 93.

Table 11 UK department of education, acoustic regulations

noise level LAeq , 30mins	sound pressure level L'nT,w dB
55dB	65 dB

Tmf seconds: ≤ (1.5 - 2.0) dependant on size of space.

Table 12 Performance standards for sports halls Tmf as a function of floor area (Department for Education 2015)

Floor area	Maximum Tmf seconds
<280 m2	1.5
280-530 m2	2.0 ((530-floor area)/500)
>530 m2	2.0

Table 13 Background noise level

Type of room	Upper limit for the indoor ambient noise level LAeq,30mins dB	
	New build	Refurbishment
Swimming pool	50	55

2 METHODOLOGY

This thesis provides a method to determine the acoustical properties and criteria as relevant to swimming halls. Although this procedure is intended for use in existing halls, certain metrics can be applied to approximate the performance of proposed sound comfort designs.

This research builds up on existing published materials, codes and regulations. The literature review presented in the previous section helps to summarize the available information about the subject and the current common practice. It helps a better understanding of the basis of the sound and leads to the methodology development.

The methodology includes: defining the research questions (see 1.2 Motivation), selecting a case study, examining the particular problem, analysing the data and studying the relationship between the cause and effect. In this regards, the steps below are considered in this study:

- Measuring the sound pressure level of the selected case study, during the empty situation.
- Simulating the current situation with Odeon simulation software.
- Simulating a sound scene for the same area regarding to the national and international standards with Odeon.
- Searching for more efficient sound absorbent for the required area.
- Evaluating and comparing the achieved results with standards to define the deficiencies.
- Repeating two previous steps till reaching the desire result.

Figure 30 shows the workflow of this thesis.

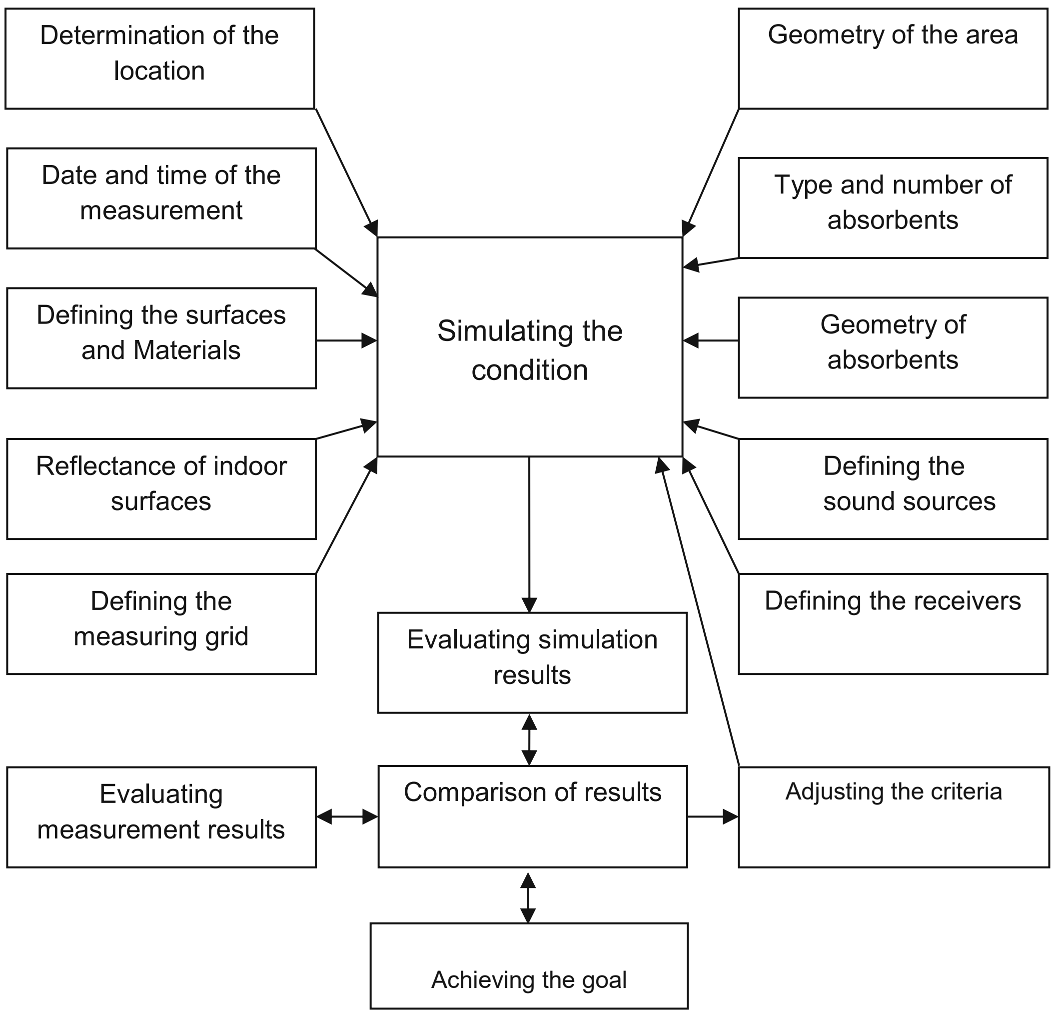


Figure 30 Illustration of measuring and simulating process

2.1 Case study

The case study of this thesis is a Swimming hall in Perchtoldsdorf, Austria (see figure 31). This swimming hall was opened in 1978 and renovated once since then. The renovation only affected the outside of the pool area and not the surfaces inside. It consists of a large swimming pool (25 meters long) for exercise and practice, a narrow platform for sitting on one side and lounge chairs along the other sides see figure 33 and 34. There is also a smaller pool that has a very low depth for small children with a small pool slide and lounge chairs around see figure 35. At the end of the hall there is also a whirlpool which is separated through glass walls see figure 36.

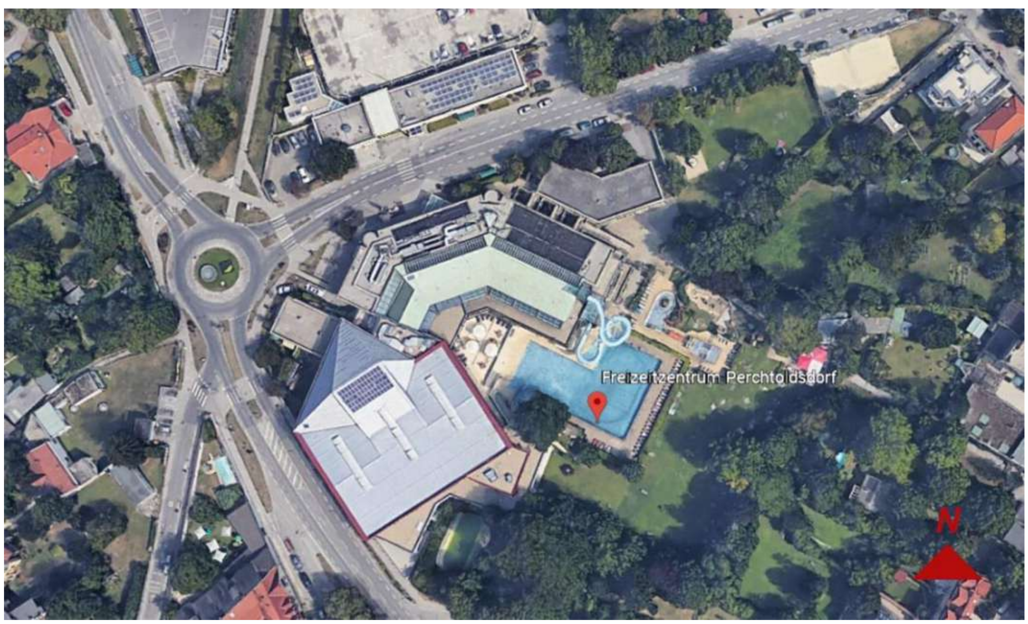


Figure 31 Perchtoldsdorf Swimming Hall, location (Google Earth 2021)

2.2 Measurements

Measurements were performed on 23.03.2021 between 9 to 11:15 a.m. Since the study focused on the larger rooms in the swimming halls the measurements were performed in the space with 25 meter long pool, and a smaller pool for kids in the same hall, see figure 32 and 35.

The followings were documented prior to the measurement;

- Geometry of the halls;
- Type and number of absorbents as well as detailed information on the geometry of the absorbent arrangement;
- Surfaces, materials and the properties of the materials (e.g., reflectance) of the elements in the Hall;
- Type of measurement equipment, manufacturer, serial number, class, calibration;
- Measuring grid and / or position of the measurement points;

The measurement was carried out during the Covid-19 period and the pandemic had a significant effect on public buildings among them public swimming pools. Due to the Covid-19 regulations in Austria the sport facilities were closed in particular the indoor sport facilities. Therefore measurement during the activities was not possible. The water from all indoor pools was drained as a result of these regulations. This had an impact on the evaluation of the current situation. The measurements were performed with empty swimming basins. The important fact is the lack of water reflections. Therefore the unpredictability, which was caused by the water surface reflections, was lost. Measurements of reverberation time, background noise and sound pressure level were performed during the above explained condition.

The measurements were mainly performed in one big hall, (see figure 32). The floor plan and photos presented below show the locations and conditions of the measurements. The hall was empty and quiet, except from the heater noise. The outdoor wall has big openings. There are also skylights on both sides, as shown on figures 37 and 38.on one wall along the pool an acoustic solution is used. This wall, consist of a layer of brick plus insulation (see figure 40 and 41). Other walls surrounding the hall are mostly glass. All walls are vertically straight, with horizontal irregularities. The ceiling above is flat and not covered by absorbents. The changing rooms are along the pool on a balcony (see figure 33). Around the pool hall are different spaces which are separated with glass walls such as a coffee shop, sauna area and a barbershop. The outside pool is close to this hall but approximately 2 meters below the hall level see figures 41 and 42. The building next to the indoor pool is a climbing hall.

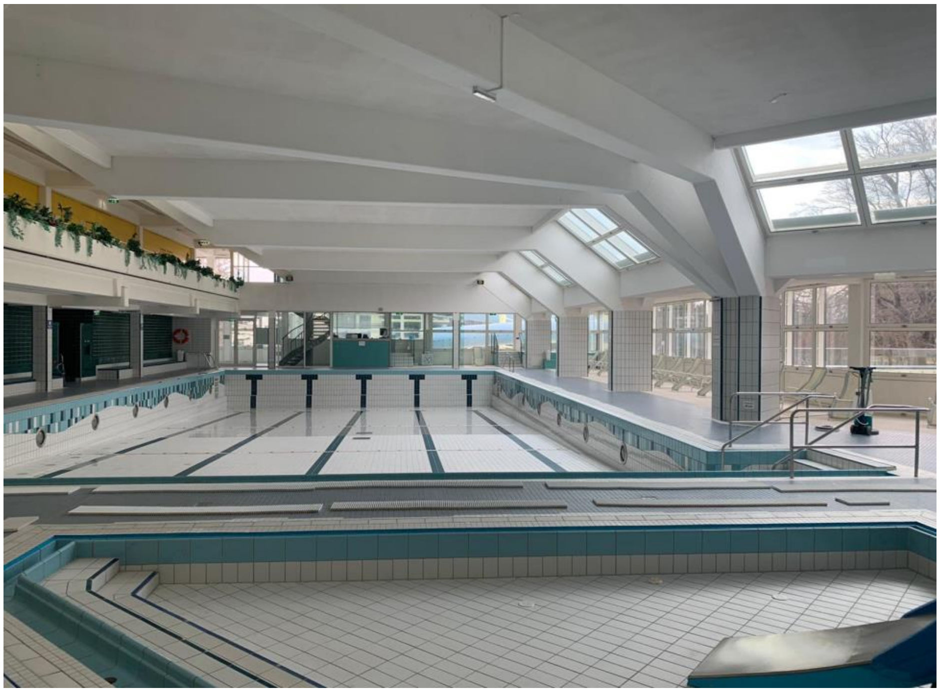


Figure 32 Swimming hall Perchtoldorf

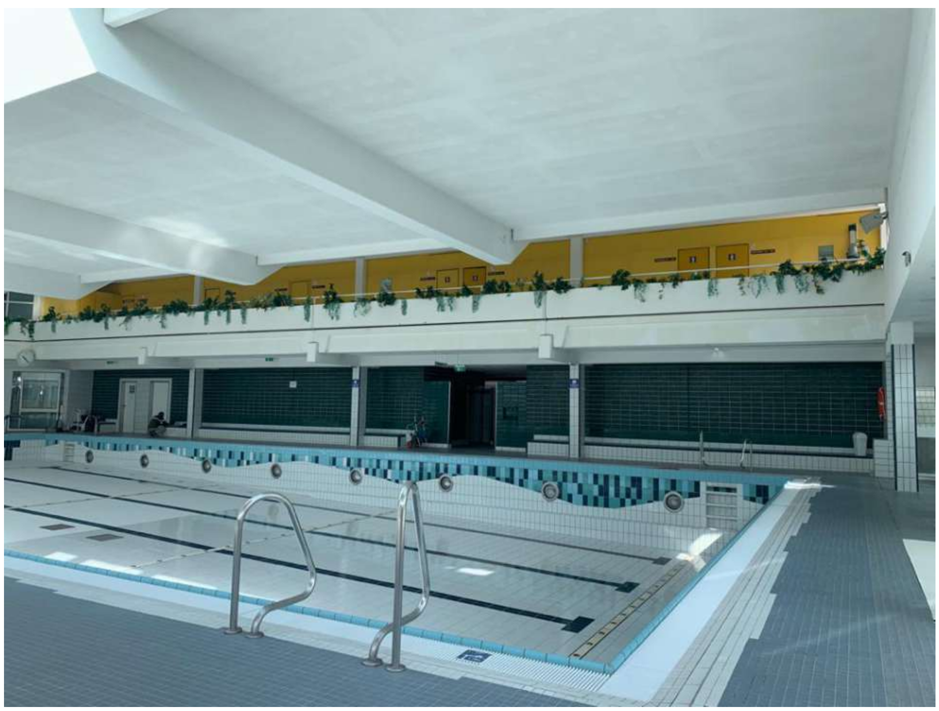


Figure 33 Lounge chairs along south side

Figure 34 Sitting platform on north side and the upper level with changing rooms

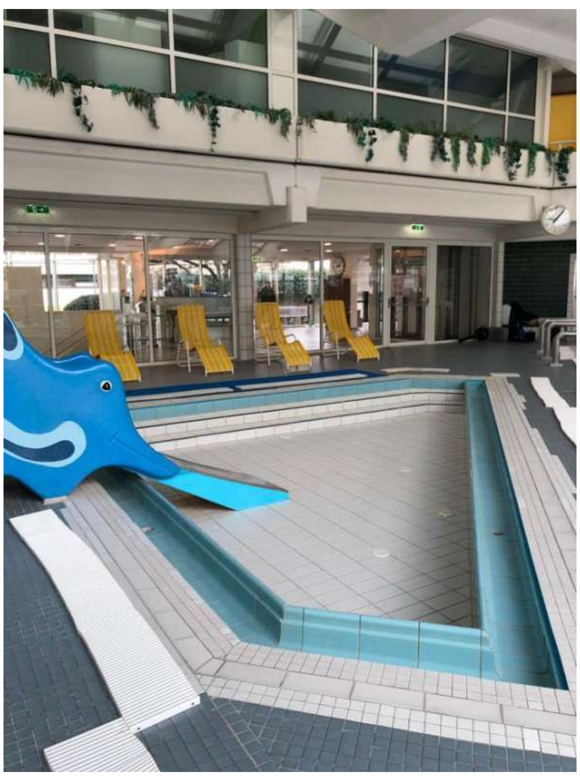


Figure 35 Kid's pool area

Figure 36 Whirlpool area

Figure 37 Windows and skylights on the south side

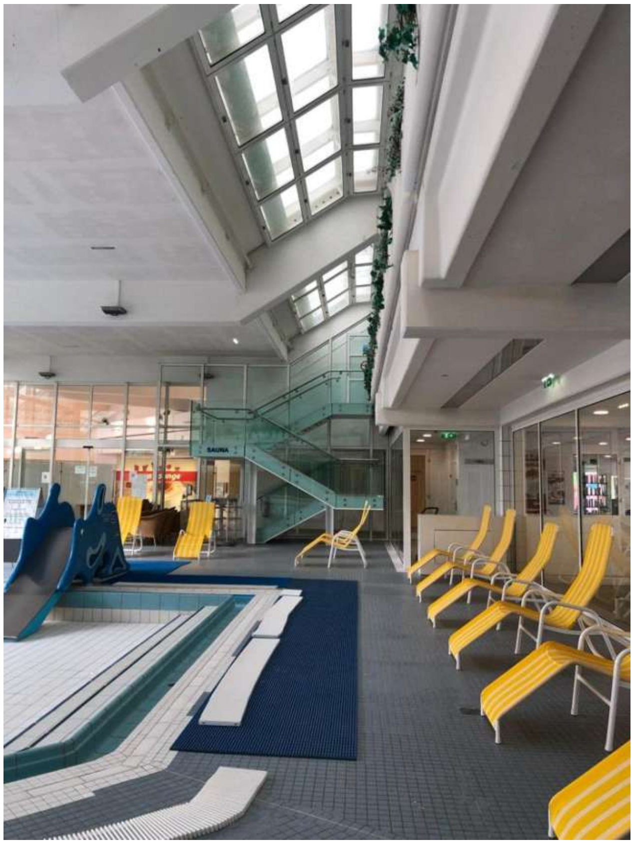


Figure 38 Skylights at north side

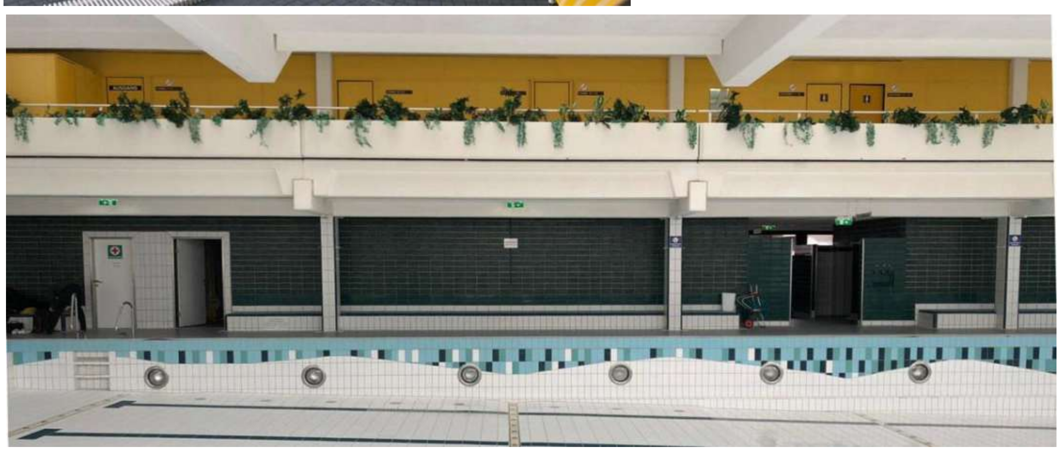


Figure 39 North wall with insulation solution

Figure 40 Insulation Material

Figure 41 Outdoor Swimming pool, level difference

Figure 42 Outdoor Swimming pool, level difference

2.2.1 Swimming hall plans

Figures below show the Plans of the Hall. The measurements were carried out by a laser measuring device. The swimming pool hall is west-east oriented. It can be entered from two sides, either from the foyer area or from the changing rooms and from the indoor pool there is an entrance to the outdoor pool. The outside area of the hall was not available for the measurement and is roughly estimated. Figure 36 shows the surrounding area of the Pool hall. The figures 44-48 are showing the floor plan, inside view and sections of the hall. The main pool features a dimension of 25.00m x 12.50m. The height of ceiling above the pool is 5.0m, the sitting platform ceiling is 2.70m and the ceiling height of the other sections is 6.50m.

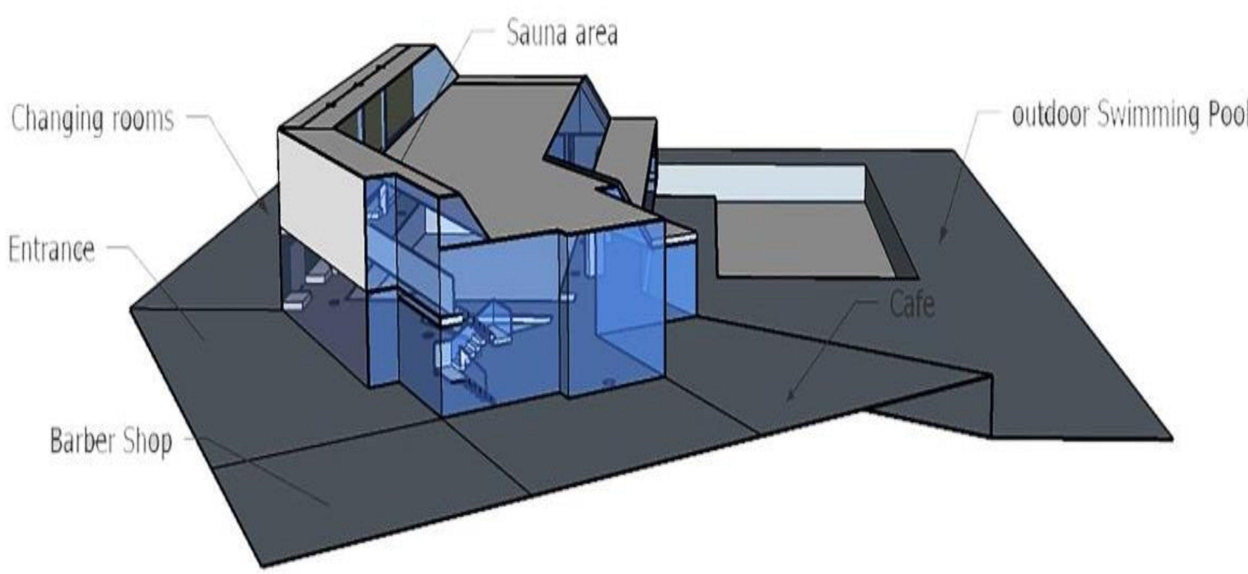


Figure 43 3D View of the Area

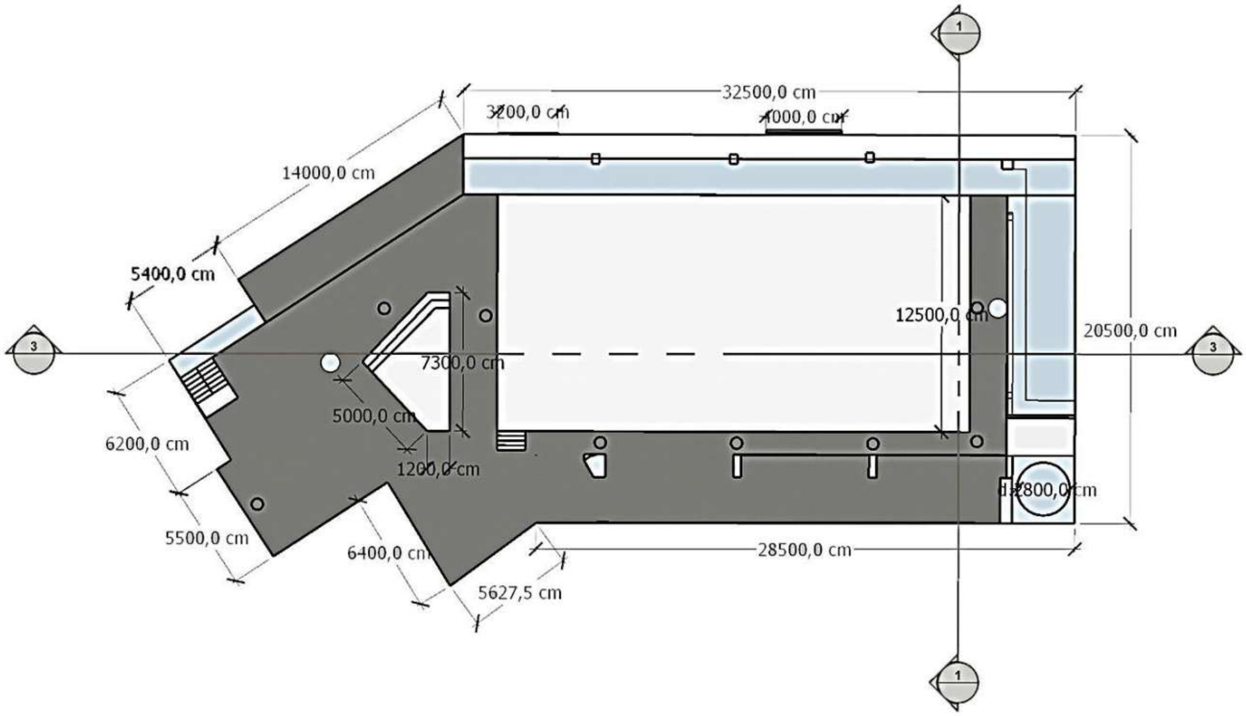


Figure 44 Floor plan

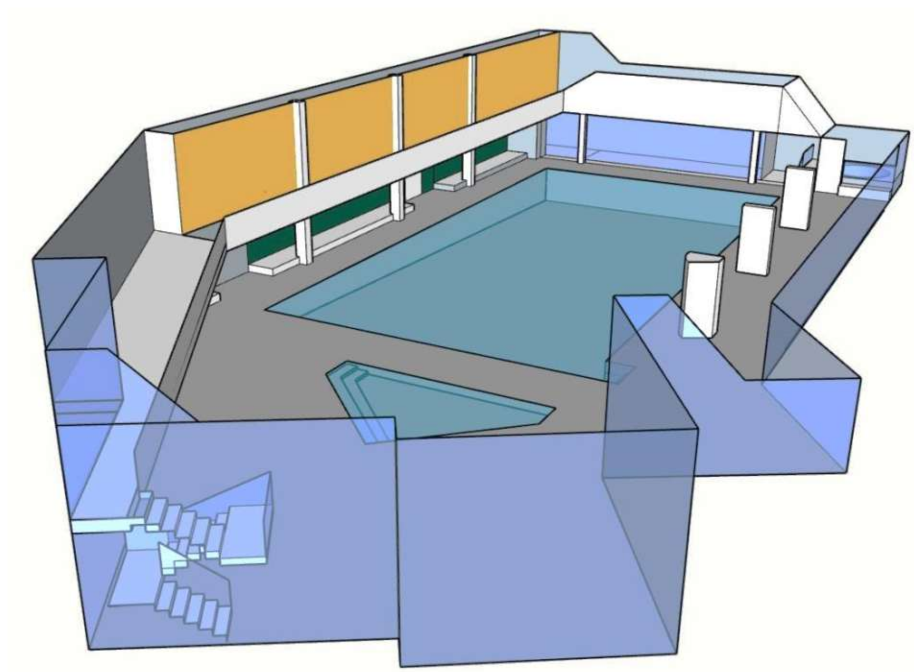


Figure 45 3D inside view

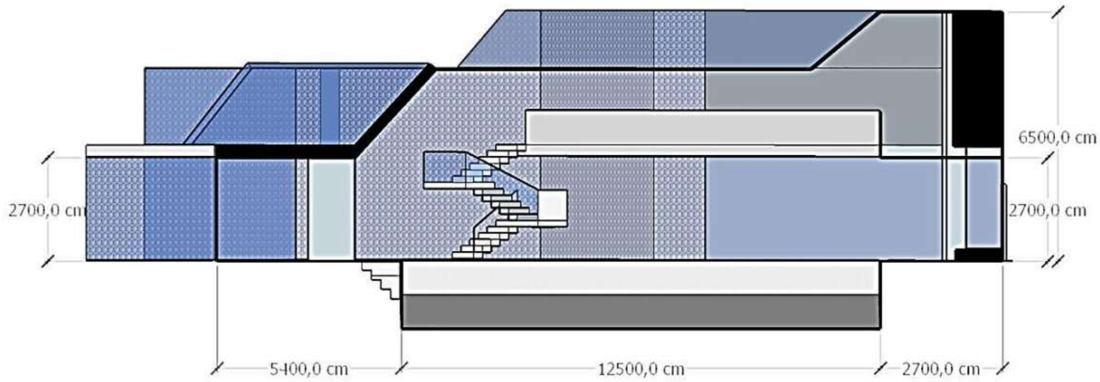


Figure 46 Section 1 (Section marked in Figure 38)

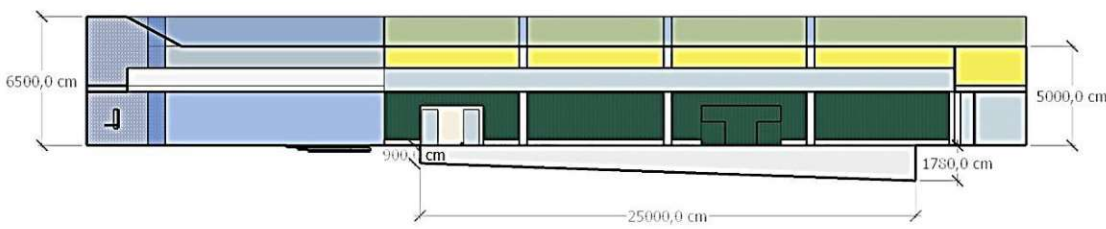


Figure 47 Section 3 (Section marked in Figure 38)

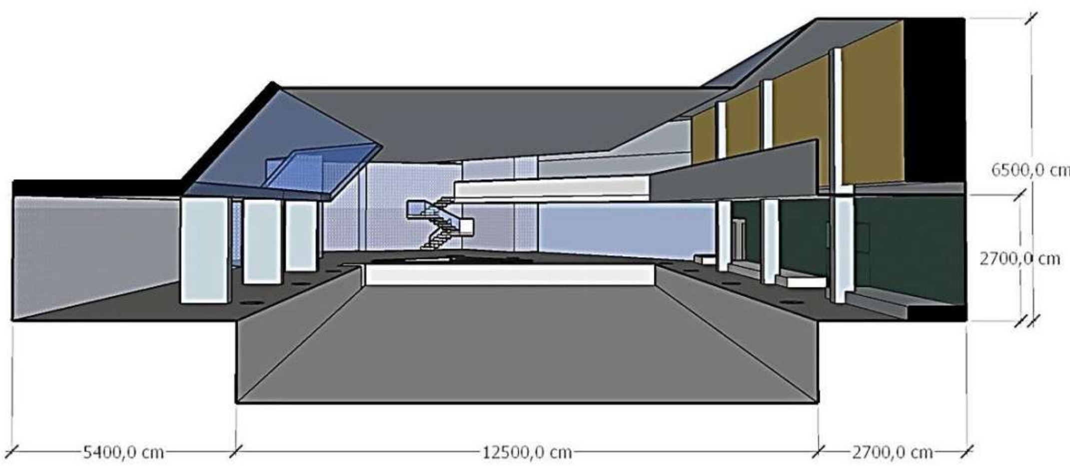


Figure 48 Inside View, east side

2.2.2 Measurement positions

A proper measurement grid must be established before field measurements can be carried out. The number of analysis points and their distance have been carefully calculated. The grid is usually defined by the dimensions of the pool basin, hence it was considered in this calculation. The deck area, the access areas and the area close to small pool were also considered in this grid.

The Loudspeaker was positioned differently for measuring the reverberation time, which is shown as L1 and L2 in Figure 48.

Point 1.0 is close to the kid's pool.

Around the Main pool where measured on these point:

1.1 / 1.2 / 1.3 / 1.4 / 1.5 / 2.0 / 2.1 / 2.2 / 2.3 / 2.4 / 2.5 / 3.0

The point 4.0 is in front of the café entrance.

All mentioned points above are shown in Figure 49.

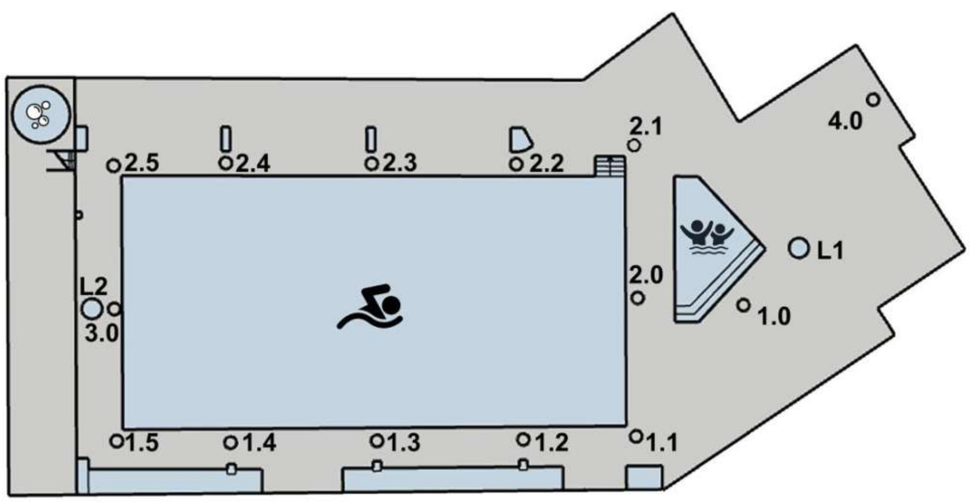


Figure 49 Floor plan with measuring points

The tables below explain the measurements applied to the different points. The height of the loudspeaker Norsonic Nor276 was adjusted to 1.70 meter and the Receiver was adjusted to 1.20 meter above the ground level.

Reverberation times and back ground noise were measured at points presented in Table 14, and 15, accordingly. Moreover sound pressure levels were measured at all points with loudspeaker position L1 (see Table 16).

Table 14 Reverberation Time measured points

Loudspeaker L1	2.0	1.3	2.2	
Loudspeaker L2	1.3	1.4	2.	2.4

Table 15 Background noise measured points

1.3	2.0	2.3	3.0	4.0

Table 16 Sound pressure level measured points

1.0	1.1	1.2	1.3	1.4
1.5	2.0	2.1	2.2	2.3
2.4	2.5	3.0	4.0	

2.3 Equipment

The measurements are performed with a Sound Level Meter Type Nor140 from Norsonic Company, Figure 50. For the sound pressure level and reverberation time measurements an omnidirectional loudspeaker Norsonic Nor276 and a power amplifier Norsonic Nor280 were used additionally (see figures 51 and 53).

Reverberation time was measured in two times with two different position of loudspeaker. In this case, the sound level Meter was connected via router to the laptop, Figure 51.

2.3.1 Sound level meter

The Nor140 is a real-time sound analyzer with sound recording (see Figure 50). The measuring device covers a wide range of application areas. With a modular device platform, which includes all applications. Individual measurement functions may be used based on current specifications and can be retrofitted as choices. The dynamics of the device include more than 120dB in a single measurement range.

The handheld device will calculate reverberation time and STI. The broadband impulse response can be measured and all room acoustic parameters can be calculated with the aid of laptop and room acoustics software. For impulse and noise excitation, the Nor140 tests the decay curve. In real time, all frequency bands are calculated in octave or third octave. The two reverberation times T30 and T20 are determined for each frequency band and each decay curve. All values are automatically normalized to the required decay time for 60 dB. The device is also supplied with the NorXfer software for transferring the measurement data to the PC. This program is used to transfer the measurement results from the internal memory or from the SD card to the PC. The measurement data can also be converted into an Excel or text format (Norsonic 2021).

The Nor140 determines various parameters; the parameters below were measured by this device in this Thesis:

- SPL Instantaneous sound pressure level
- Leq Energy-equivalent sound pressure level
- LeqI energy-equivalent impulse sound pressure level
- LN percentile level / level statistics (e.g. L95%)

Due to the large distance in the hall it was necessary to use Wireless measuring system without microphone cable

In this case the Nor140 was controlled from the laptop, the USB connection between the measuring device and the laptop was replaced by a wireless connection. After each measurement, the results were transmitted from the Nor140 to the control center by radio, which is shown in Figure 51.

Figure 50 Sound level Meter

Figure 51 SLM connected to a router

2.3.2 Loudspeaker Nor276 / amplifier Nor280

The loudspeaker's output power level is up to 120 decibels of noise signal. The speaker is mounted on a tripod to ensure proper positioning and minimize unnecessary reflections and structural transmissions (Norsonic 2021).

The Nor280 Power Amplifier has equalization circuitry that is calibrated to the loudspeaker and is built to enhance high and low frequencies in order to increase device output during measurements. In the frequency range of 50-5000 Hz, the amplifier produces 120 dB of sound power (Norsonic 2021).

Figure 52 Loudspeaker

Figure 53 Amplifier

2.4 Simulation software

The software used for this thesis was ODEON 11 combined. This software is professional and commercial simulation software. This modeling software is easy to use for simulating acoustics of closed rooms, open spaces, buildings and outdoor areas. It implements predicting the acoustics of new buildings and also for evaluating and recommending improvements in existing ones.

In Odeon project, you can import CAD files such as dwg and.dxf. The CAD layers remain intact, allowing for a fast and simple model derivation. For the selection of Materials, the database offers a selection from various predefined elements, which have different absorption coefficients, or it is also possible to set the values manually. Visualizations of acoustics are also possible through different options such as ray tracing, color map and billiard ball.

2.5 Simulation setup and workflow

The geometry of the buildings was modelled in the 3D software SketchUp and exported to Odeon as dxf- File. Next step was to defining the type and the position of Sound sources L1 and L2 and the position of receivers in the hall. Due to the lack of Information such as existing structure, exact Materials of the surfaces and type of Windows, Materials of the integrated Odeon model were chosen to approximate the measured sound condition. The main Materials, which were chosen for this Model are described in Table 17 (Odeon database);

Table 17 Chosen Material in Odeon

North wall pool level	55 mm perforated bricks on edge
Upper north wall	16 mm wood on 40 mm studs
Windows	Double glazing, 2-3 mm glass, 10 mm gap
South wall	Single pane of glass, 3 mm
Columns, stairs	Concrete or terrazzo
Ceiling	gypsum board, 2 layers total 32 mm

It is also important to defining the accuracy, the Impulse response length, and the number of late rays to achieve a precise result. After running the simulation, the results were investigated through numbers, graphs and soundmaps. To attain more accurate results the materials were adjusted many times.

3 RESULTS & DISCUSSION

The measurement and simulation results of the case study object are listed in the following section. Following that, the results of the sound pressure level measurement, reverberation time, and background noise are shown, accompanied by an analysis and comparison to the standards. The sound performance status is defined by the measurement review.

The results of the simulation efforts are summarized in the following subchapter. First, the initial model was generated independently of any measurement results, which is based on plan material and the software's default absorption coefficients values. Following that, a few calibration runs of the model involved the use of measurement-derived data. Since the exact used material and insulation is uncertain, the absorption coefficients were altered to improve the simulation model's correspondence to the measurements.

An indicator for evaluating approximation to the existing condition was established to make simulation runs comparable. The indicator demonstrates the extent to which the simulation effects differ from the measurements.

Proposals for enhancing the sound condition's output will be discussed at the end of the results and discussion section.

3.1 Measurement

3.1.1 Reverberation time

Table 18, Figures 54 and 55 show the measured reverberation time results with speaker position L1.

Table 18 Reverberation time measurement Results, Speaker L1

		Frq [Hz]	*63*	*125*	*250*	*500*	*1000*	*2000*	*4000*
Speaker L1	**P 2.0**	*T20*	-	2.63	2.45	2.62	2.40	1.99	1.27
		T30	-	2.04	2.55	2.48	2.43	1.95	1.23
	P 1.3	*T20*	-	1.71	2.09	3.07	2.40	1.94	1.30
		T30	-	2.08	2.23	2.55	2.60	2.01	1.29
	P 2.2	*T20*	-	2.33	2.55	3.02	2.53	1.92	1.31
		T30	-	2.02	2.45	2.76	2.53	1.96	1.35

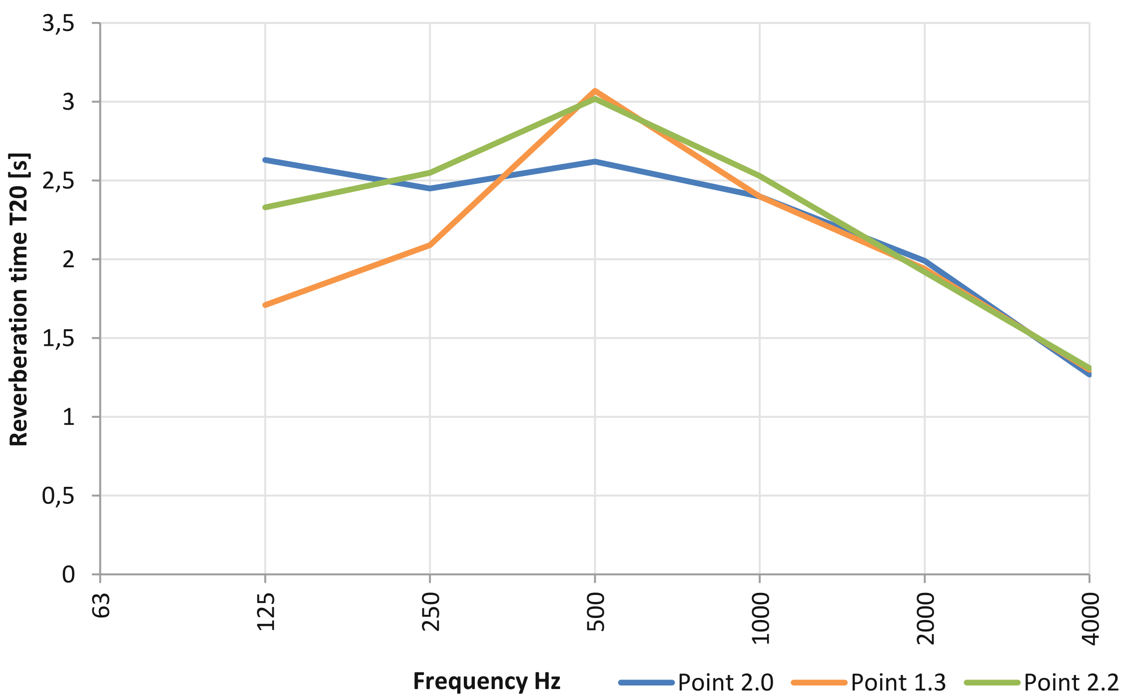


Figure 54 Reverberation for frequency 100 to 5000 Hz (T20), L1

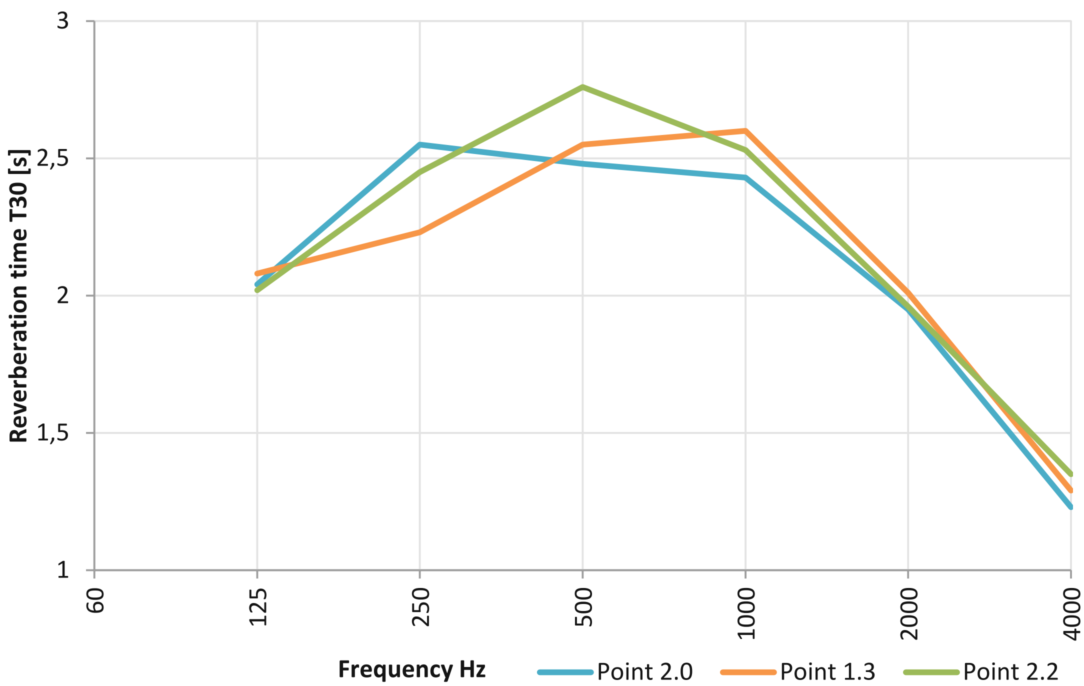


Figure 55 Reverberation for frequency 100 to 5000 Hz (T30), L1

Measured reverberation time results with speaker position L2 are shown in Table 19, Figure 56 and 57.

Table 19 Reverberation time measurement Results, Speaker L2

		Frq [Hz]	*63*	*125*	*250*	*500*	*1000*	*2000*	*4000*
Speaker L2	**P 1.3**	*T20*	-	2.58	2.83	3.24	2.37	2.04	1.18
		T30	-	2.40	2.77	2.73	2.56	2.10	1.19
	P 1.4	*T20*	-	1.99	2.59	2.92	2.53	2.01	1.33
		T30	-	2.33	2.49	2.72	2.43	2.05	1.30
	P 2.3	*T20*	-	2.06	2.81	2.68	2.55	1.95	1.27
		T30	-	2.14	2.52	2.73	2.47	2.02	1.26
	P 2.4	*T20*	-	2.60	3.73	2.93	2.30	1.84	1.24
		T30	-	1.97	2.75	2.74	2.55	1.86	1.22

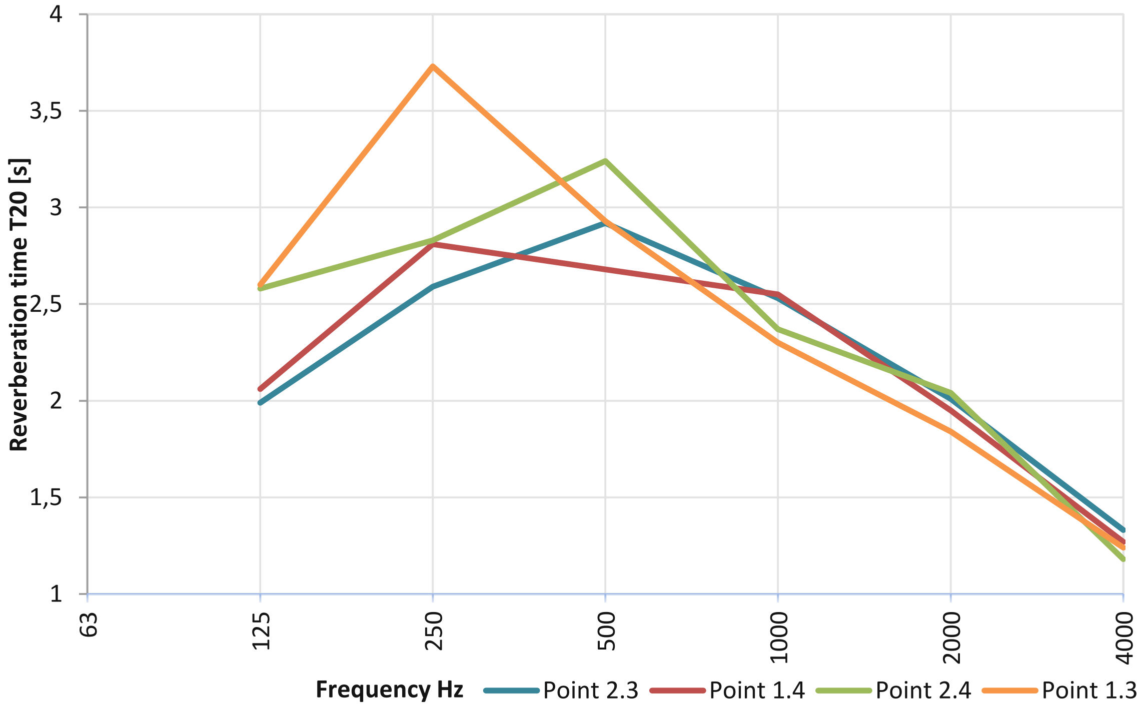


Figure 56 Reverberation for frequency 100 to 5000 Hz (T20), L2

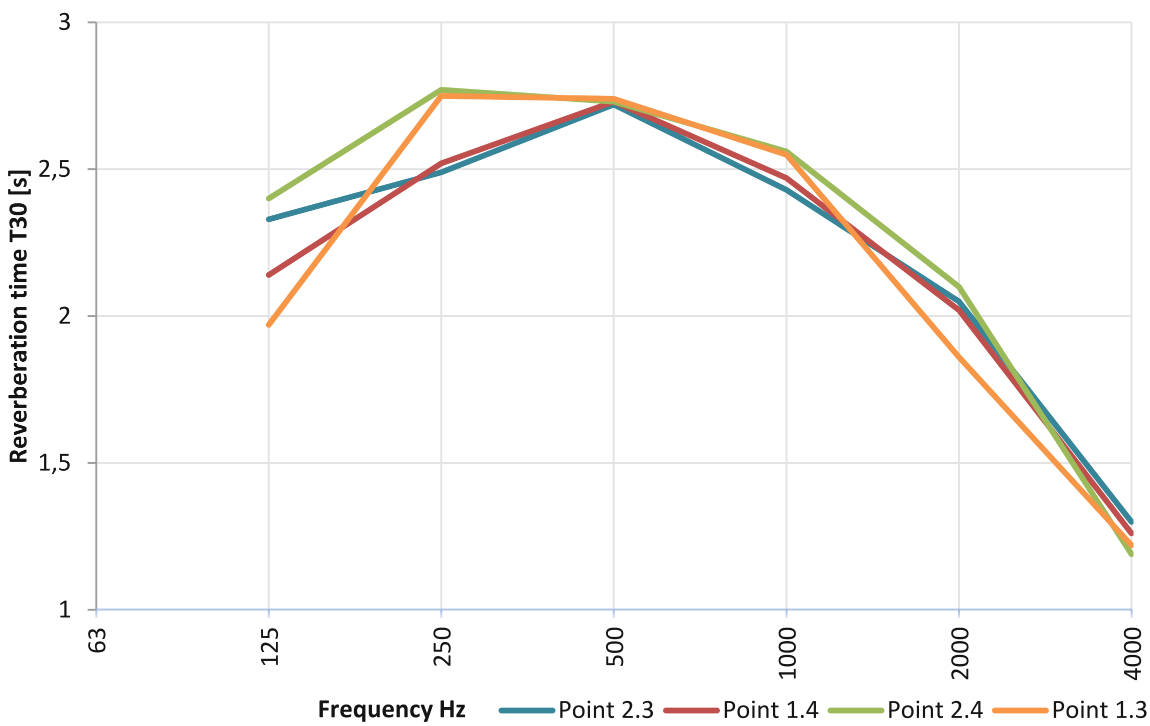


Figure 57 Reverberation for frequency 100 to 5000 Hz (T20), L2

3.1.2 Sound pressure levels

Measured sound pressure level results with speaker position L1 are shown in Table 20 and 21.

Table 20 Sound pressure level measurement Results

Points	LAeq (Hz)	LZeq (Hz)
1.0	100.6	105.3
1.1	95.3	100.1
1.2	92.6	97.5
1.3	91.5	96.7
1.4	90.5	95.5
1.5	90.4	95.5
2.0	96.4	101.4
2.1	96.2	101.2
2.2	94.4	99.3
2.3	91.2	96.3
2.4	90.6	95.7
2.5	90.1	95.5
3.0	90.9	96.6
4.0	96.1	100.6

Table 21 Sound Pressure level Results (Hz)

	Frequenzspektrum LIN																				
	50	63	80	100	125	160	200	250	315	400	500	630	800	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0
P 1.0	63,3	76,9	81,3	85,7	90,3	92	95,9	99,8	97,8	94,6	93,5	91	90,2	89	87,5	86,7	86,3	83	82,4	86,7	90,4
P 1.1	60,5	72,8	81,1	85,4	83,8	89,5	91,7	92,9	91,6	90,4	88	86,2	85	83,6	81	82,2	80,2	76,1	76,9	81,3	85,9
P 1.2	62,7	70	72,9	73,9	80,6	86,7	87,9	91,6	89,9	88,2	84,3	82,9	82	81,2	79,3	80,5	77,9	74,6	74,2	78,6	80,4
P 1.3	59,5	65,5	72,8	77,6	82,8	85	90	89,4	88,8	86,6	82,4	82,4	82,4	80,4	78,7	78,8	76,5	72,5	72,5	76,7	79
P 1.4	58,3	66	70,3	76,6	82,1	82,4	86	89,7	88,1	84,9	82,4	81,7	81,9	80,1	77,2	77,3	74,8	71,4	70,8	74,6	77,1
P 1.5	50,6	65,8	72,3	74,6	78,5	84,2	85,5	90,8	87,1	84,5	83,8	81,8	81	78,8	77	77,3	74,5	71	70,6	74,6	76,3
P 2.0	61,4	76,4	81,1	82,9	88,1	88,3	92,6	96,1	91,9	91,7	87,9	85,5	85,3	85,1	82,2	84,2	82,1	78,2	78,1	83,6	86,2
P 2.1	63,8	76	80,5	81,5	85,6	88,1	91,4	96,8	91,9	90,6	87,7	86,7	85,3	84,4	82,9	83,6	81,6	78,2	78,4	83,1	85
P 2.2	63,6	71,7	78,3	79,1	82,3	87,8	91	93,2	91,5	88,3	87,2	85,8	85	82,7	80,6	81,4	78,6	76,7	76,5	80,7	82,2
P 2.3	61,7	67	76,9	73,3	79,7	84,4	89,1	90	87,2	86,5	83,8	81,8	81,7	80,6	77,8	78,2	75,8	72,4	72,2	76,3	78
P 2.4	55,7	68	70,3	76,6	81,5	83,1	87,7	90	87,5	84,7	83,4	81,2	81,2	80,2	77,8	77,6	74,8	72	71,5	75,1	77,5
P 2.5	53,5	64,6	68,5	76,3	78,6	83,1	88,8	89,2	87,4	85,2	83,1	80,3	79,9	79,1	77,2	77	74,7	71,2	70,8	74,6	75,6
P 3.0	57,8	63	68,9	72,5	84,8	84,9	88	88,6	87,4	86,5	83,6	82,4	81,5	80,5	78,1	78,2	76,1	72,2	71,3	75,5	76,9
P 4.0	66,6	79	82,7	83	85,9	90,1	91,6	93,3	91,4	90,9	88,4	87	86,5	86,4	81,9	83,1	81,6	79	77,1	82,8	84,9

Figure 58 and 59 show the LAeq and LZeq in each point.

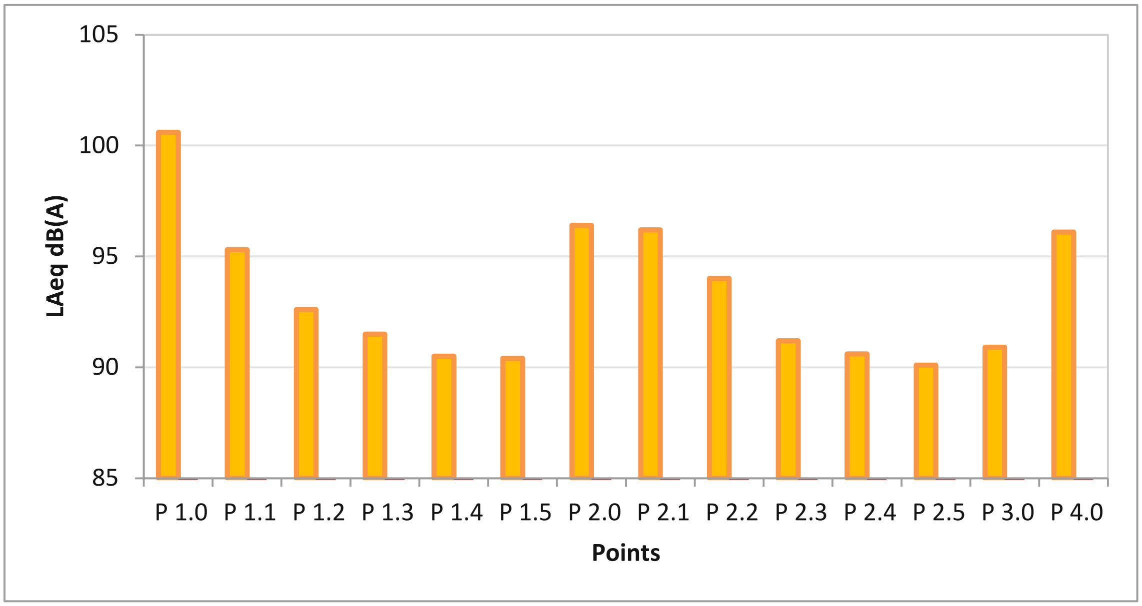


Figure 58 LAeq (dB(A))

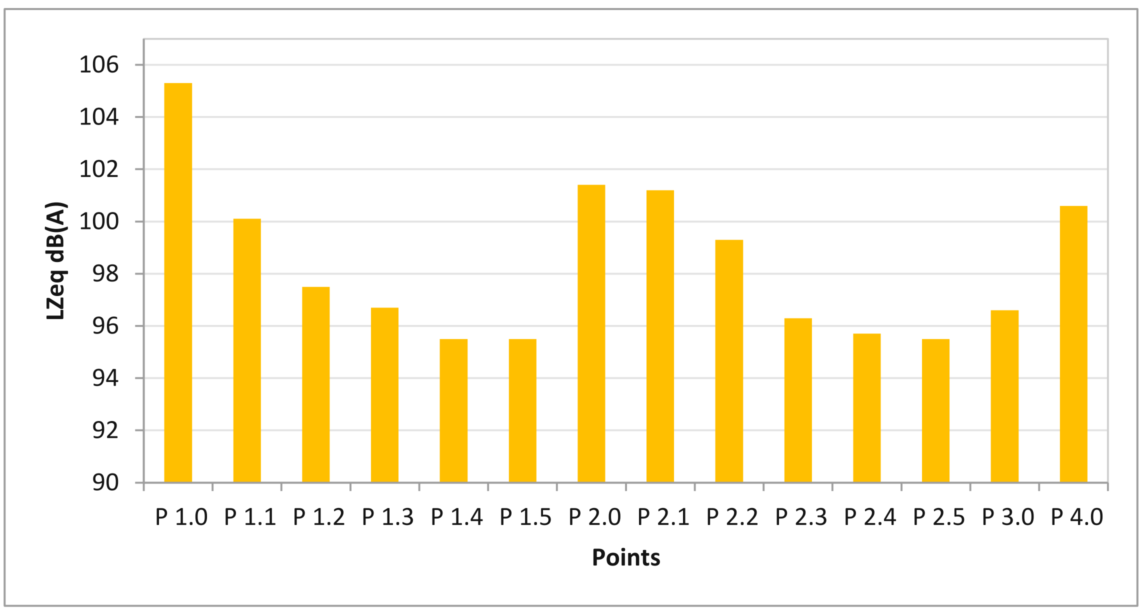


Figure 59 LZeq (dB(A))

3.1.3 Background noise

The results of background noise from measurement are shown in Table 22. The LAeq and LAzq differences in 5 points are shown in Figure 60.

Table 22 Background noise measurement Results

Points	LAeq (dB(A))	LZeq (dB(A))
2.0	36.9	69.0
2.3	36.2	70.0
3.0	39.0	72.9
1.3	38.4	71.0
4.0	39.0	73.3

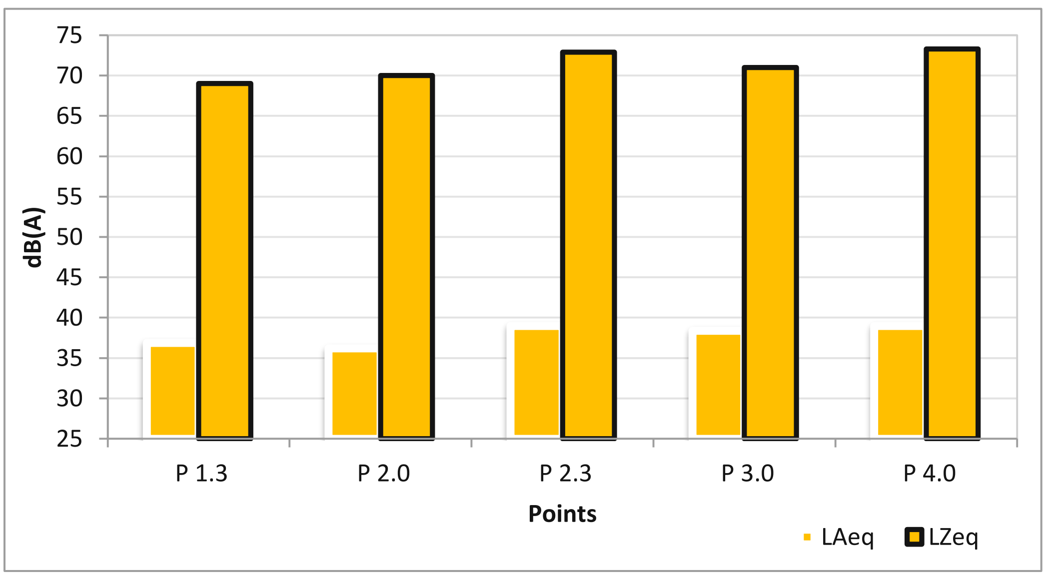


Figure 60 LAeq vs LZeq

3.1.4 Measurement analysis

The Austrian standard recommends a value for reverberation time of less than 2s. The results were 2.2s for the swimming pool. According to the guidelines, this is considered to be unsatisfactory.

Tables 20 and 21 illustrate the measured sound pressure level values at the pool area. The grid points closest to the source, as predicted, have the highest SPL values. At point 1.0, the maximum sound pressure level was measured at 102.89 dB. The sound level is proportional to the distance between the sound source and the location of measurement. As we can see from the results, the SPL values drop in receivers that are further away from the sound source.

As shown in the table 21, the background noise level range was 36.2-39.0 dB (A), with an average of 37.6 dB (A) and at point 4.0, the background noise LAeq was measured at 39.0 Hz.

The SPL values could not be measured and compared to the standard regulations because the measurement during visiting hours of the swimming pool was not permitted under Covid-19 regulations. There is a possibility that the SPL values in the hall during operation hours are higher than permitted values. In this case the standards would recommend supplementary sound absorbents to achieve satisfactory sound levels. For reducing the reverberation time in case of high reverberation time values it is recommended to replace the materials with elements, which have higher absorption coefficients values.

3.3 Simulation results

Software simulations are used to value the various parameters that influence the sound environment. Three simulations are run to investigate the effect of the Materials' absorption coefficient. The results are compared to actual measurements and used as a foundation for further analysis. The simulations where implemented in three different versions, each of which is simulated in terms of acoustic parameters. The importance of the absorption coefficients values of the materials is shown by the effects of these various simulations.

The model was created in Sketch Up and then exported to Odeon software, where materials were applied to the surfaces and receiver and sound source positions were assigned to the hall. The model is based on the proportions of the swimming hall, where the measurements were taken. Main structure is established; however specifics such as small openings were left out for simplicity's sake.

The original simulation is a model that hasn't been modified. A variety of calculation functions are employed. The values for the various positions are received after a simulation with 14 receivers and two sound sources is run. In addition, a global estimate is made. A 3D billiard is used to reflect sound propagation in the room. 3D rays were also implemented to verify that the model was sealed.

The second simulation was modified so that the result of reverberation time is similar to the measurement result. The material for the ceiling was chosen based on the calculation of absorption coefficients values.

The third simulation is built on the calibrated simulation with the addition of a water surface.

3.3.1 Materials

The model is divided into surfaces such that various materials can be attached to different surfaces. For the initial simulation model the materials were chosen from the Odeon database, whereas for the calibration another material was chosen for the ceiling to improve the RT condition of the hall.

Due to the fact that the ceiling is coated with unknown absorbents, the model was given a material with a similar absorption coefficient based on the results of the measurements.

The floor and columns on the ground floor, as well as the swimming pool, are all tiled. The first-floor columns, ceiling racks and staircase are all made of concrete. In calibrated simulation, the properties of the material used for the ceiling were calculated, which we will discuss in the related chapter.

The Material information that was allocated to the surfaces in the calibrated simulation is shown in the table 23.

Table 23 Material overview

Material overview, absorption area in m² (63-8000 Hz)	**Surface area m²**
55 mm perforated bricks on edge, 33 holes per brick, 23% perforation, over 70 mm	88.6
16 mm wood on 40 mm studs (Ref. Dalenbäck, CATT)	113.6
Double glazing, 2-3 mm glass, 10 mm gap (Kristensen, 1984)	271.8
Single pane of glass, 3 mm (Fasold & Winkler, 1976)	340.2
Concrete or terrazzo Ref. (Harris, 1991)	475.9
gypsum board with calculated absorption coefficient values	763.6
Marble or glazed tile (Harris, 1991)	1099.1
Total absorption area	**3152.9**

3.3.2 Receivers and sound sources

For the simulation the position of the sound source and measurements need to be chosen. The sound sources shown in graph 61 as P1 and P2 are omnidirectional and located along the length of the pool, which is similar to the positions of conducted measurements. The sound power for each frequency was assigned to the speakers manually, as shown in table 24.

Since swimming pools are large spaces where people may communicate over long distances, the receivers were positioned in various locations in the pool to illustrate various scenarios. The distance between the source and the listener, for example, has a significant impact on STI measurements, with a shorter distance resulting in increased speech intelligibility. Calculations were implemented at 14 different sound receivers which are located similarly to the measurement condition and shown on Figure 61. To stop reflections, the receivers were moved further away from the walls. To be comparable to a human and measures, 1.5 meters above the ground.

Table 24 Assigned sound power

frequency (Hz)	63	125	250	500	1000	2000	4000	8000
sound power (dB)	96	108	116	112	107	105	108	107

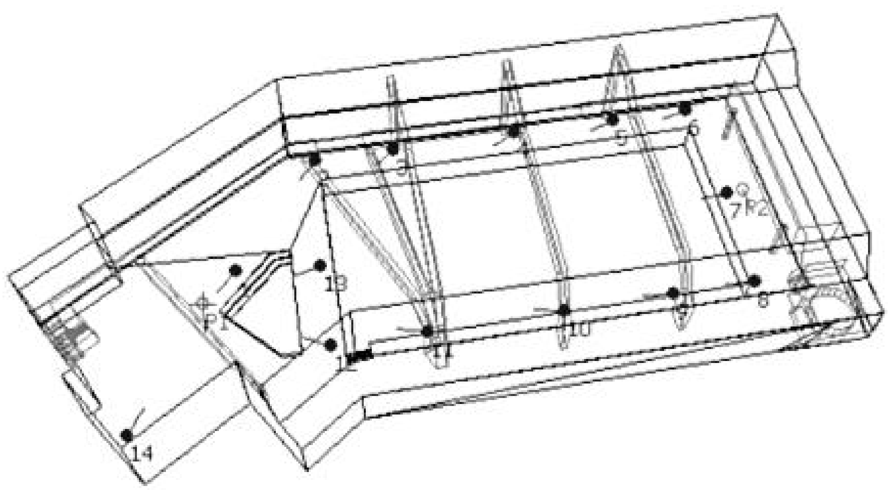


Figure 61 Position of sound sources and receivers

The order of the positions is explained in the table below.

Table 25 Point's order

Symbols in simulation	1	2	3	4	5	6	7	8	9	10	11	12	13	14
actual points	1.0	1.1	1.2	1.3	1.4	1.5	3.0	2.5	2.4	2.3	2.2	2.1	2.0	4.0

3.3.3 Initial simulation results

In this chapter the results of the initial simulation are shown. Table 26 contains the SPL results of the initial simulation. SPL changes can be observed in Figure 62.

Table 26 SPL initial model SPL results

SPL simulation results, Speaker L1							
	63 Hz	125 Hz	250 Hz	500 Hz	1.0 kHz	2.0 kHz	4.0 kHz
P 1.0	82.1	94.1	102.4	98.4	93.2	90.7	92.7
P 1.1	79.4	91.5	99.9	95.9	90.5	87.8	89.3
P 1.2	78.5	90.7	99	94.9	89.5	86.7	88
P 1.3	76.9	89.2	97.4	93.3	87.9	85	86.1
P 1.4	76.3	88.5	96.8	92.6	87.1	84.2	85
P 1.5	75.4	87.7	96	91.8	86.3	83.4	84.1
P 2.0	80.4	92.5	100.8	96.8	91.5	89	90.7
P 2.1	80.2	92.2	100.6	96.6	91.3	88.7	90.4
P 2.2	79.4	91.5	99.8	95.8	90.7	88	89.5
P 2.3	77.3	89.4	97.7	93.7	88.3	85.5	86.7
P 2.4	76.2	88.5	93.8	92.7	87.2	84.3	85.3
P 2.5	75.2	87.4	95.7	91.5	86.1	83.2	83.9
P 3.0	75.2	84.5	95.9	91.7	86.3	83.4	77.3
P 4.0	81	93	101.4	97.4	92.1	89.7	91.6

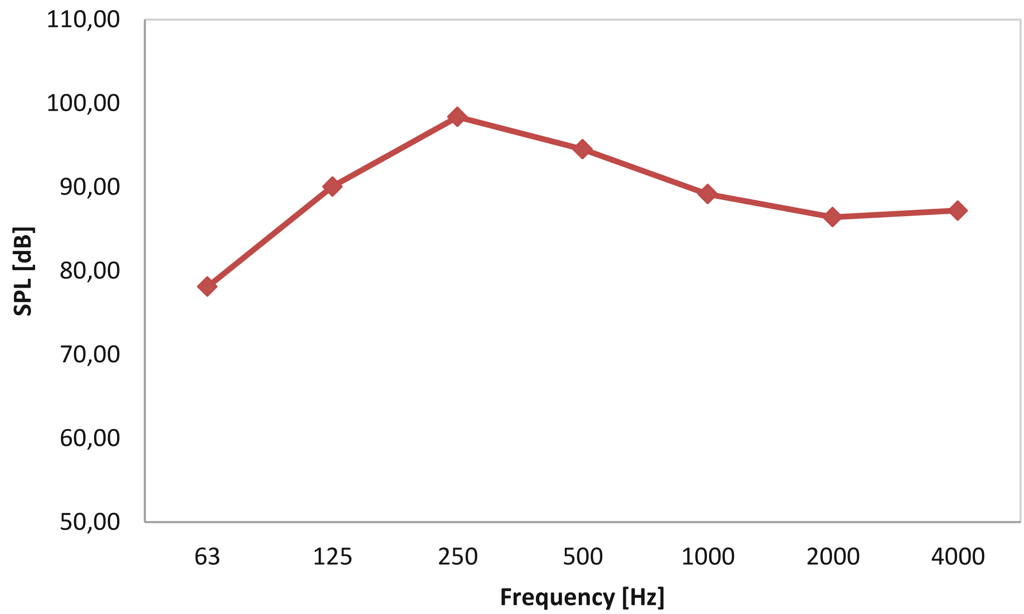


Figure 62 Initial model, SPL average

The reverberation time were simulated 2 times. Results are shown in table 27. RT changes are shown in Figure 63. An interactive view of wave fronts is shown in 3D billiard to illustrate scattering, flutter echoes, focusing, and coupling effects, see Figure 64.

Speaker L1, Points 1.3, 2.0, 2.2
Speaker L2, Points 1.3, 1.4, 2.0, 2.2

Table 27 Initial model, T30 [s]

T30 [s]								
	L1			L2				mean Value
Frequency [Hz]	P 1.3	P 2.2	P 2.0	P 2.4	P 2.3	P 1.4	P 1.3	
63	2.57	2.55	2.57	2.57	2.6	2.64	2.57	**2.58**
125	2.64	2.61	2.63	2.63	2.66	2.69	2.64	**2.64**
250	2.8	2.81	2.79	2.81	2.81	2.86	2.8	**2.81**
500	2.76	2.75	2.74	2.76	2.75	2.82	2.76	**2.76**
1000	2.66	2.62	2.64	2.66	2.64	2.71	2.66	**2.66**
2000	2.43	2.39	2.41	2.43	2.45	2.48	2.43	**2.43**
4000	1.88	1.85	1.88	1.86	1.92	1.87	1.88	**1.88**
8000	1.02	1	1	1.02	1.01	1.01	1.02	**1.01**

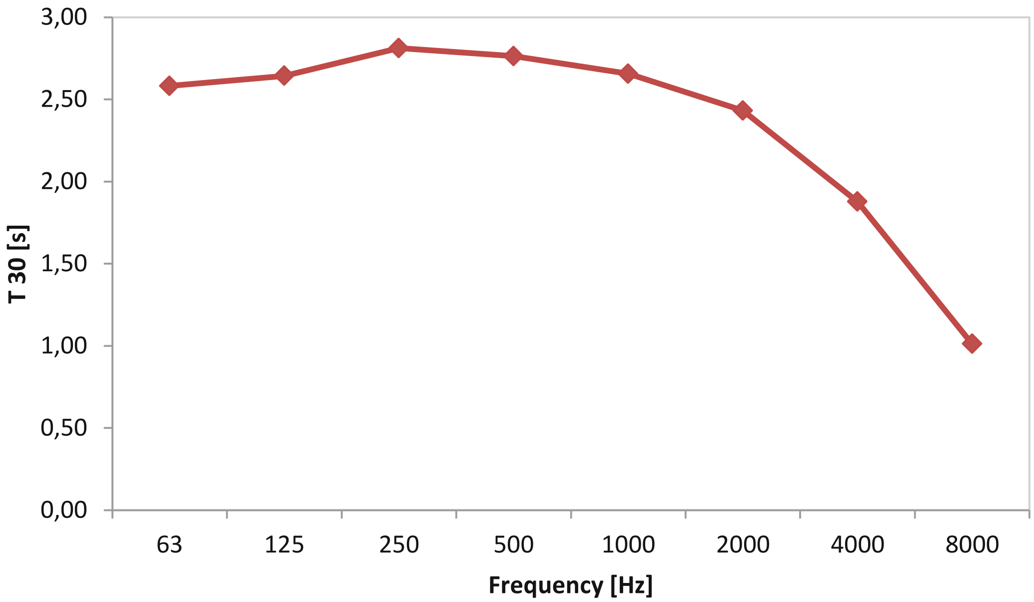


Figure 63 Initial model, T30 mean values

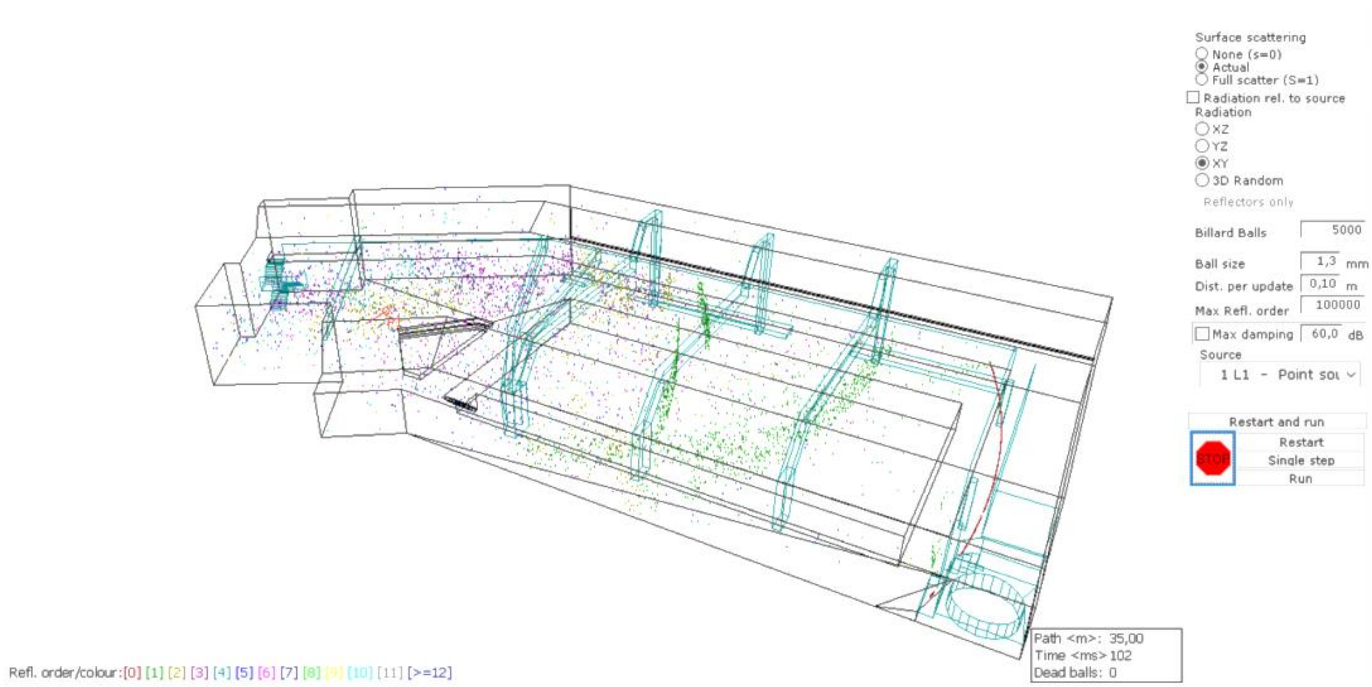


Figure 64 3D billiard

3.3.4 Calibrated simulation results

In this chapter the results of the calibrated simulation are shown. Assigned materials are shown in table 23. Table 28 and Figure 65 show calibrated model SPL values.

Table 28 Calibrated model, SPL results

SPL calibrated results, Speaker L1							
	63 Hz	125 Hz	250 Hz	500 Hz	1.0 kHz	2.0 kHz	4.0 kHz
P 1.0	81.5	93.5	103	99.3	93.4	91.3	93.8
P 1.1	77	89.1	99.1	95.5	89.7	87.4	89.6
P 1.2	75.6	87.8	97.7	96.6	88.5	86.1	88.2
P 1.3	73.6	85.9	96.1	93.2	87	84.5	86.4
P 1.4	72.7	84.9	95.3	92.4	86.2	83.6	85.5
P 1.5	72	84.3	94.6	91.9	85.6	83	84.8
P 2.0	78.5	90.5	100.7	97.2	91	88.9	91.1
P 2.1	78.6	90.7	100.8	97.3	91.1	89	91.2
P 2.2	77	89.1	99.3	95.8	89.7	87.5	89.6
P 2.3	74.6	86.7	97.1	93.9	87.6	85.2	87
P 2.4	73.2	85.2	95.8	92.8	86.4	84	85.6
P 2.5	72.3	84.5	95.2	92.2	85.8	83.3	84.9
P 3.0	73	85.2	96	92.9	86.4	84	85.6
P 4.0	79.7	91.7	101.6	98	91.9	89.9	92.1

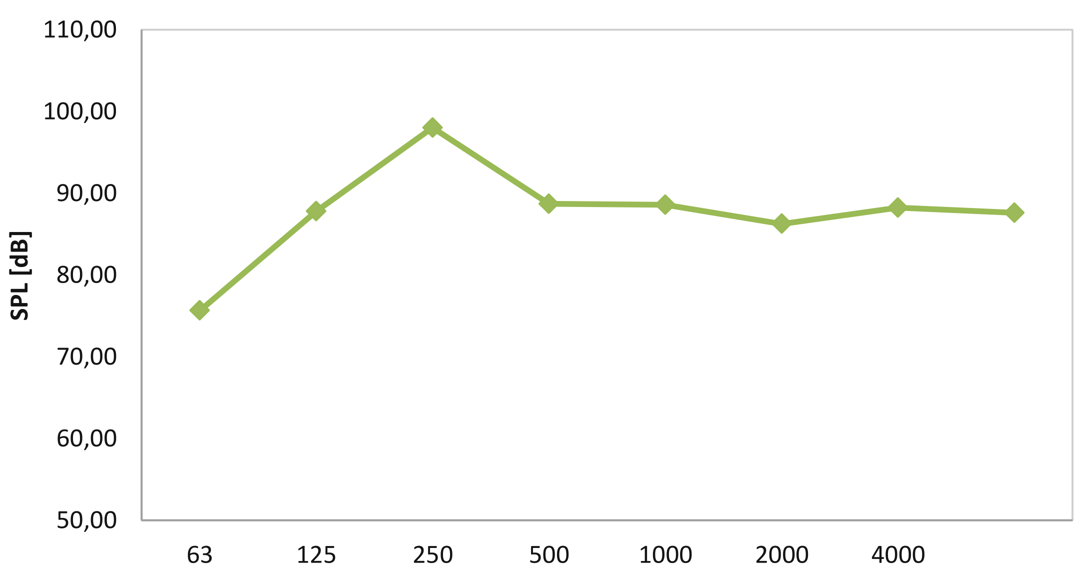


Figure 65 Calibrated model, SPL average

Since the exploration of alternative material selection options did not sufficiently reduce the gap between the measured reverberation times and the initial simulations, it was decided to make use of a virtual absorption element realised in terms of the ceiling surface. Thereby, the absorption coefficients of these virtual element were selected in a way that the resulting calculated reverberation times (based on the Sabine formula) would match the measured reverberation time. The resulting absorption coefficient are shown in the table below.

Table 29 Calibrated absorption coefficients of the ceiling material

63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
0.32	0.32	0.123	0.17	0.2	0.26	0.49	0.49

The table below shows the RT values.

Table 30 Calibrated model, T30

	T30 [s]							
	L1			L2				mean Value
Frequency [Hz]	P 1.3	P 2.2	P 2.0	P 2.4	P 2.3	P 1.4	P 1.3	
63	2.07	2.06	2.57	2.03	2.04	2.03	2.02	**2.12**
125	2.28	2.29	2.63	2.27	2.27	2.23	2.22	**2.31**
250	2.93	2.68	2.79	2.67	2.64	2.63	2.66	**2.71**
500	2.69	2.7	2.74	2.67	2.67	2.64	2.66	**2.68**
1000	2.61	2.61	2.64	2.6	2.59	2.56	2.57	**2.60**
2000	1.98	1.99	2.41	1.93	1.95	1.98	1.96	**2.03**
4000	1.28	1.3	1.88	1.25	1.24	1.27	1.32	**1.36**
8000	0.83	0.8	1	0.82	0.82	0.82	0.83	**0.85**

RT changes are shown in Figure 66. An interactive view of STI values is shown in Figure 67.

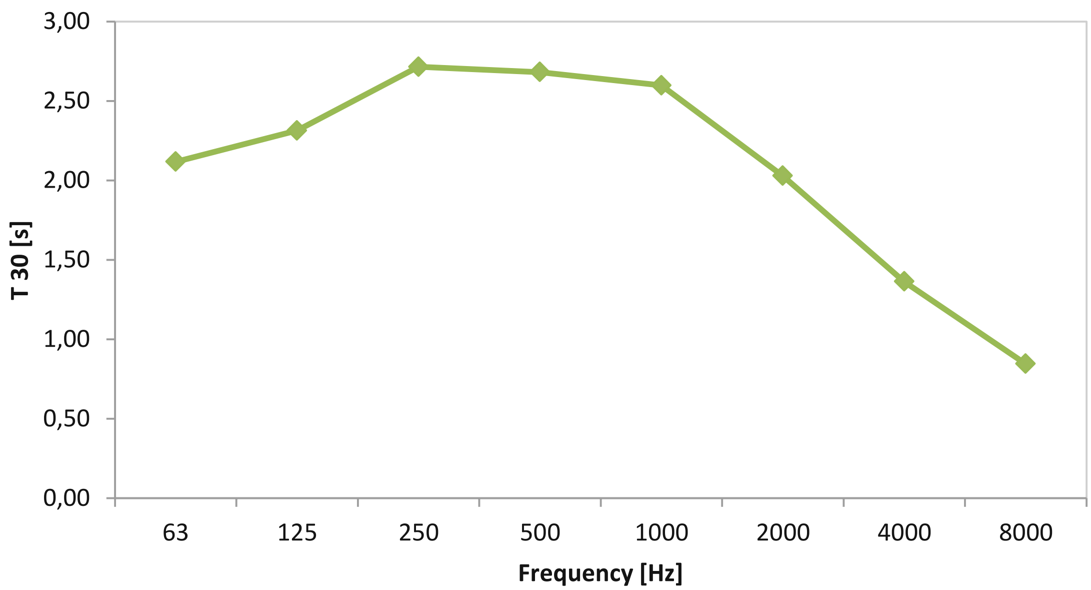


Figure 66 Calibrated model, T30 mean values

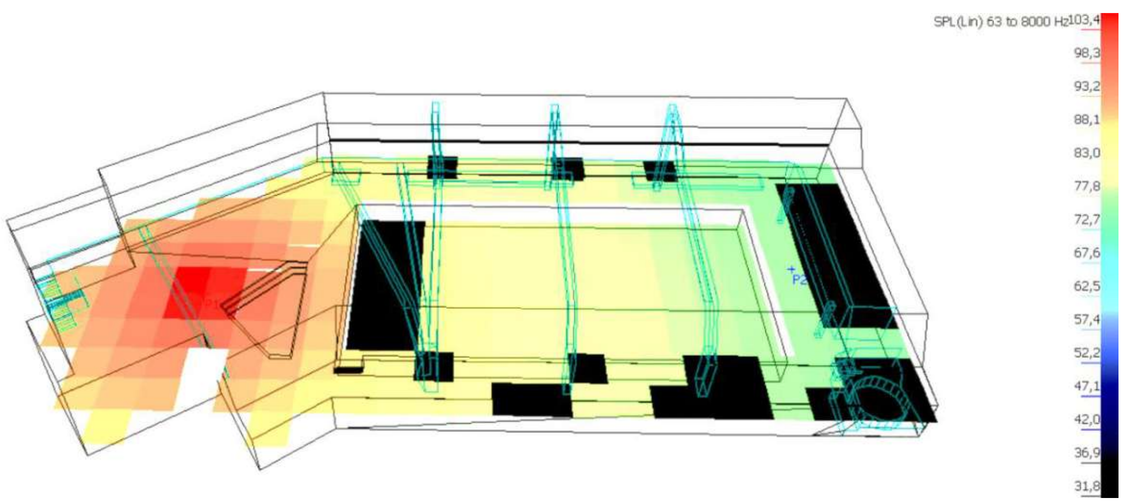


Figure 67 Calibrated model, 3D direct sound, A-weighted

Table below shows the STI values of the calibrated model. STI Values for each point are shown in graph 68.

Table 31 Calibrated model, STI values

P 1.0	P 1.1	P 1.2	P 1.3	P 1.4	P 1.5	P 2.0	P 2.1	P 2.2	P 2.3	P 2.4	P 2.5	P 3.0	P 4.0
0.6	0.49	0.45	0.4	0.39	0.4	0.49	0.5	0.47	0.4	0.37	0.38	0.41	0.59

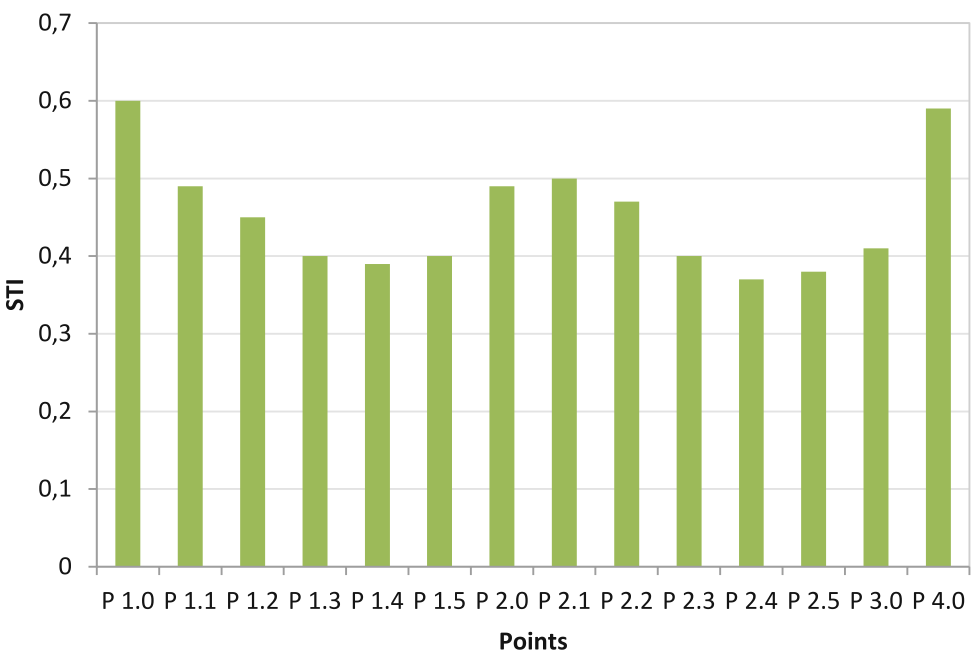


Figure 68 Calibrated model, STI

3.3.5 Simulation with water results

In this simulation water surface for both pools were assigned to the model. The values were taken from the database in Odeon, as shown in Table 32.

Table 32 Water surface absorption coefficient values

	63 Hz	125 Hz	250 Hz	500 Hz	1.0 kHz	2.0 kHz	4.0 kHz	8.0 kHz	surface area m²
Water surface in swimming pool (Knudsen & Harris, 1950, 1978)	3.2	3.2	3.2	3.2	3.2	6.4	6.4	6.4	322

The SPL results for the hall with water surface are shown in the table below.

Table 33 Simulation with water, SPL results

SPL results with water, Speaker L1							
	63 Hz	125 Hz	250 Hz	500 Hz	1.0 kHz	2.0 kHz	4.0 kHz
P 1.0	73.6	86.2	96.8	91.5	86.1	81.9	81.3
P 1.1	73.7	86.6	95.7	91.4	86.3	82	81.5
P 1.2	74.5	87.4	96.3	92	87	82.8	82.3
P 1.3	76.3	89	97.7	93.6	88.6	84.7	84.7
P 1.4	77.7	90.3	98.8	94.7	89.7	86.1	86.5
P 1.5	79.1	91.6	99.8	95.7	90.8	87.4	88.4
P 2.0	74.1	86.8	96.4	91.9	86.5	82.4	82
P 2.1	73.6	86.4	95.9	91.3	86	81.8	81.3
P 2.2	74.9	87.6	96.9	92.4	87.2	83.4	83.3
P 2.3	77.3	89.8	98.6	94.3	89.1	85.5	85.8
P 2.4	78.4	90.8	99.7	95.4	90.2	86.9	87.4
P 2.5	80.1	92.4	101.3	97	91.7	88.6	89.6
P 3.0	86.9	99	107.3	103.2	98.1	95.8	98.3
P 4.0	72.4	85.2	95.1	90.4	85	80.8	80

RT changes are shown in Figure 69. An interactive view of STI values is shown in Figure 70.

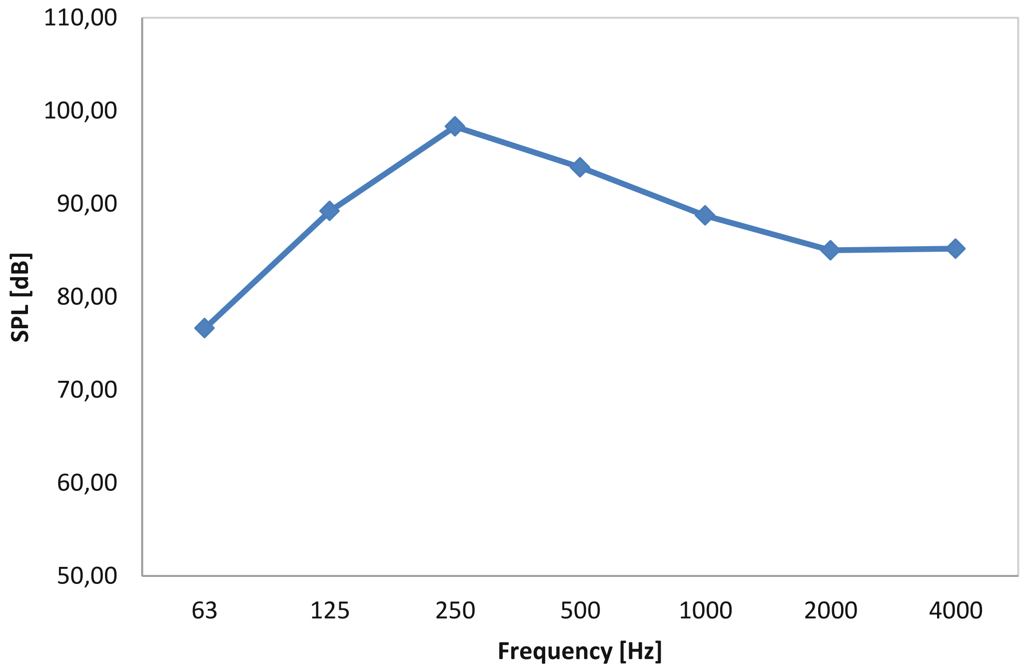


Figure 69 Simulation with water, SPL average

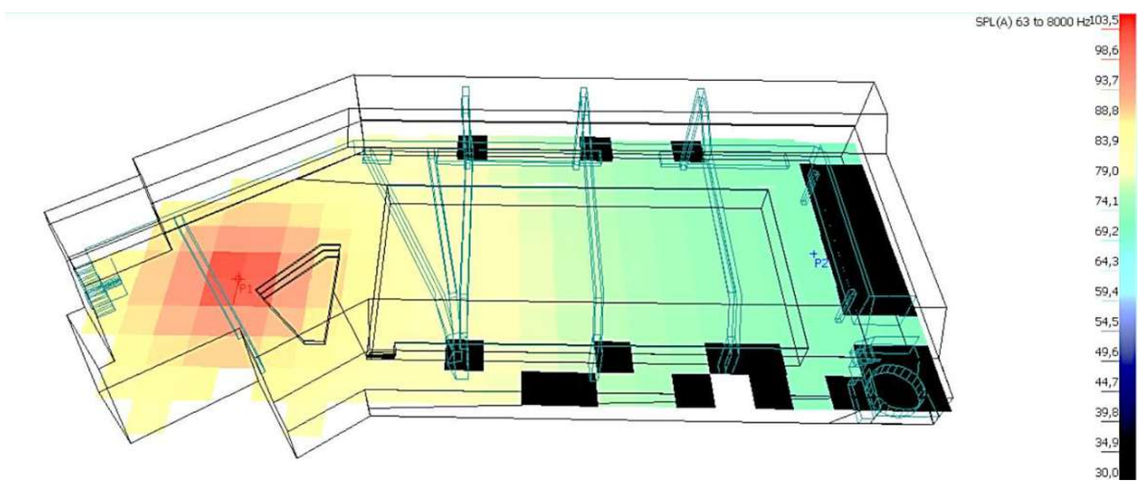


Figure 70 Simulation with water, 3D direct sound, A-weighted

The Table 34 shows the RT mean values of the hall. Figure 71 shows the RT mean values.

Table 34 Simulation with water, RT mean values

T30 [s]								
	L1			L2				mean Value
Frequency [Hz]	P 1.3	P 2.2	P 2.0	P 2.4	P 2.3	P 1.4	P 1.3	
63	1.83	1.81	1.78	1.76	1.83	1.76	1.79	**1.79**
125	2.01	2.01	1.98	1.95	2.01	1.98	2.01	**1.99**
250	2.68	2.74	2.69	2.64	2.65	2.63	2.65	**2.67**
500	2.39	2.46	2.39	2.35	2.36	2.36	2.38	**2.38**
1000	2.27	2.31	2.27	2.24	2.26	2.27	2.3	**2.27**
2000	1.76	1.79	1.76	1.72	1.78	1.71	1.73	**1.75**
4000	1.2	1.19	1.19	1.15	1.16	1.1	1.17	**1.17**
8000	0.78	0.78	0.77	0.75	0.76	0.75	0.74	**0.76**

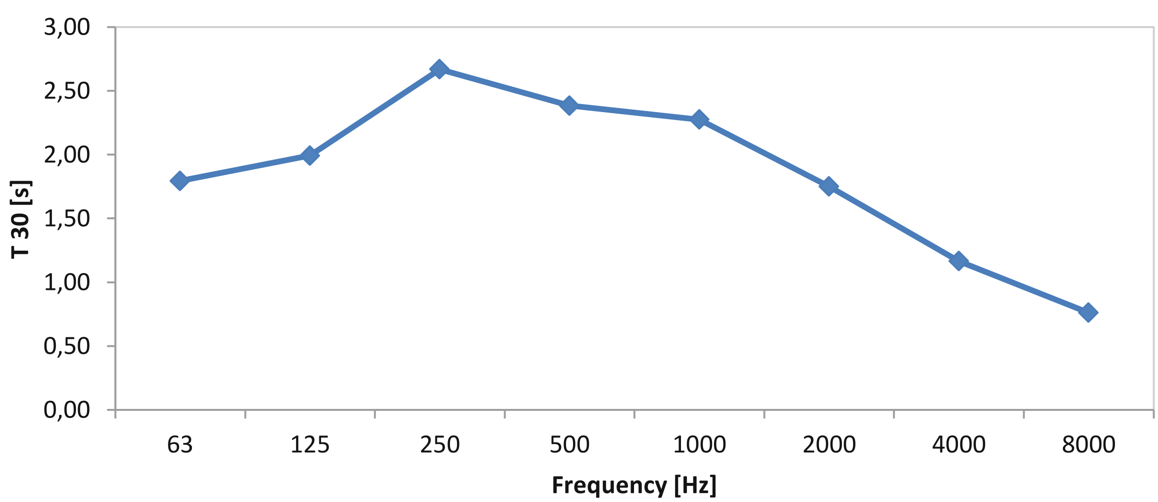


Figure 71 Simulation with water, RT mean values

The Table 35 shows STI values of the hall and Figure 72 shows the STI values for each point.

Table 35 Simulation with water, STI values

P1.0	P 1.1	P 1.2	P 1.3	P 1.4	P 1.5	P 2.0	P2.1	P 2.2	P 2.3	P 2.4	P 2.5	P 3.0	P 4.0
0.6	0.49	0.46	0.42	0.41	0.43	0.49	0.5	0.48	0.42	0.39	0.41	0.43	0.59

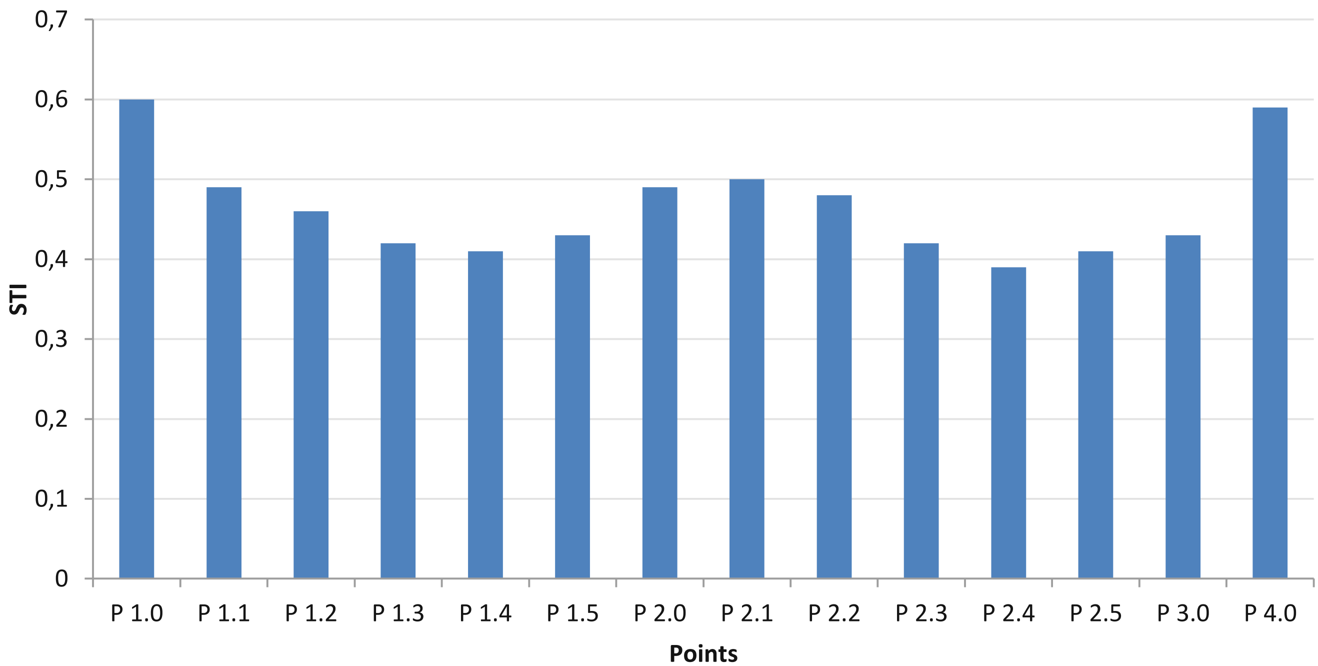


Figure 72Simulation with water, STI

3.4 Comparison of measurements and simulation results

Table 36 shows the difference of average SPL in 4 cases in each frequency, which is also shown in Figure 73 with related colors to each case.

Table 36 SPL average comparison

Average SPL [dB]							
Band (Hz)	63	125	250	500	1000	2000	4000
measured	76.80	88.70	95.66	91.00	86.93	83.20	83.72
initial model	78.11	90.05	98.37	94.51	89.14	86.40	87.19
calibrated	75.7	88.3	98	93.4	88.1	84.3	84.1
with water	76	88.6	98.2	93.6	88.2	84.5	84.3

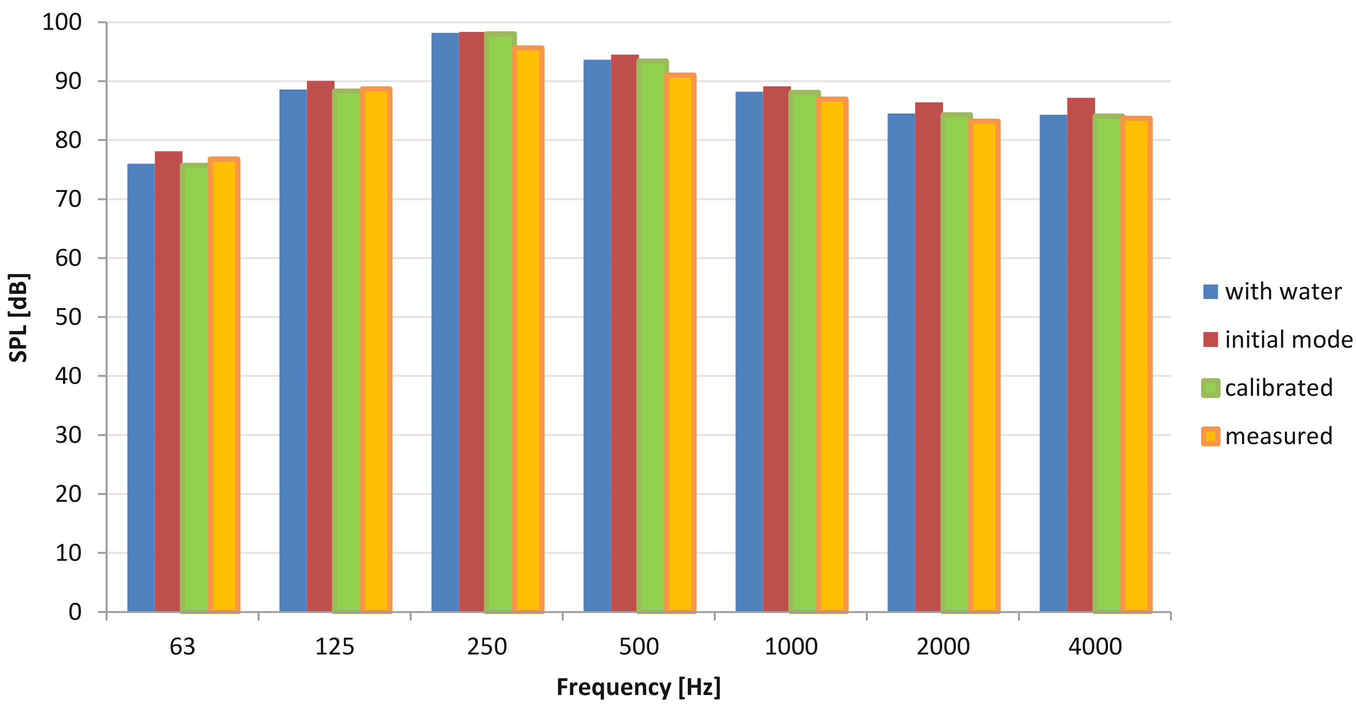


Figure 73 SPL average comparison, Speaker L1

The SPL graph examines the many frequencies and shows the loudness of each frequency. As a result, in the measurement and calibrated model, SPL values are very similar. The factors that influence loudness as a psychological correlate of physical strength include frequency, bandwidth, spectral composition, time structure and the duration of sound signal exposure. Individuals can perceive loudness differently when exposed to the same sound. Since sound pressure as a sound field quantity moves the eardrums, our hearing is a sound pressure receptor.

As we discussed earlier being exposed to SPL over 85 for duration of 40 hours a week can lead to hearing damage. A person can endure SPL of 85 dB for about 8 hours before hearing impairment occurs and an hour with the SPL of 94 dB.

For a sound source with spherical radiation in the free field, the following theoretical rule applies:

Doubling the distance between the sound source and the measuring point reduces the sound level in the free field by 6 dB. Halving the distance leads to one of 6 dB. The Figure below explains the above theory (Schwerdtfeger,S 2021).

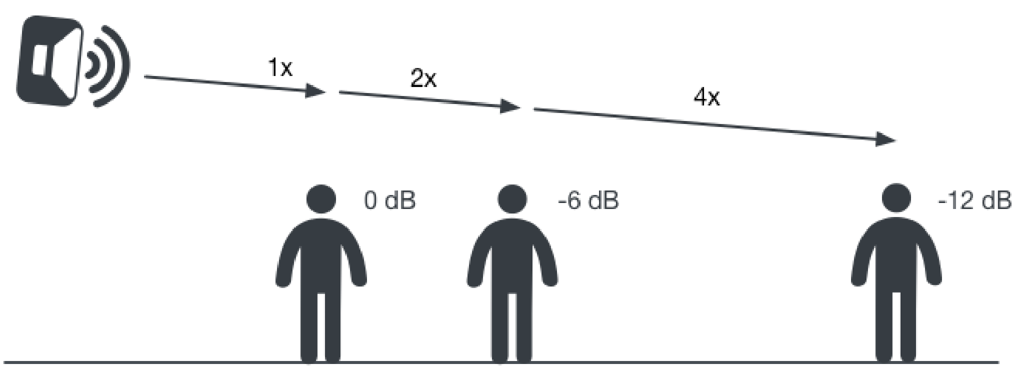


Figure 74 SPL and distance (Schwerdtfeger,S. 2021)

SPL(A) and relative sound pressure level drop are depicted in tables 37 and 38. The sound level is proportional to the distance between the sound source and the measurement location. As shown in figures 75 and 76, the lower the SPL(A) values, the greater the distance to receiver position (RP). The RP is the nearest receiver to the sound source L1. For example as shown in the measurement results the SPL value at receiver point 1.1 is 95.3 dB at distance -5.3 m to RP and at distance -10.5 m to RP, the SPL value is decreased to 90.4 dB.

Table 37 SPL(A) comparison

	SPL(A) dB			
	measurement	initial model	calibrated	with water
P 1.0	100.6	101.7	100.9	100.9
P 2.0	96.4	99.2	98	98.4
P 1.1	95.3	97.8	96.4	96.5
P 2.1	96.2	99.4	98.2	98.4
P 4.0	96.1	100.2	99.2	99.1
P 1.2	92.7	96.4	94.9	95.5
P 2.2	94.4	97.8	96.6	96.9
P 1.3	91.5	94.8	93.2	93.6
P 2.3	91.2	95.5	94.1	94.3
P 1.4	90.5	94	92.3	92.6
P 2.4	90.6	94.3	92.7	92.9
P 3.0	90.9	94.3	92.8	92.7
P 1.5	90.4	93.4	91.6	91.8
P 2.5	90.1	93.7	92.1	92

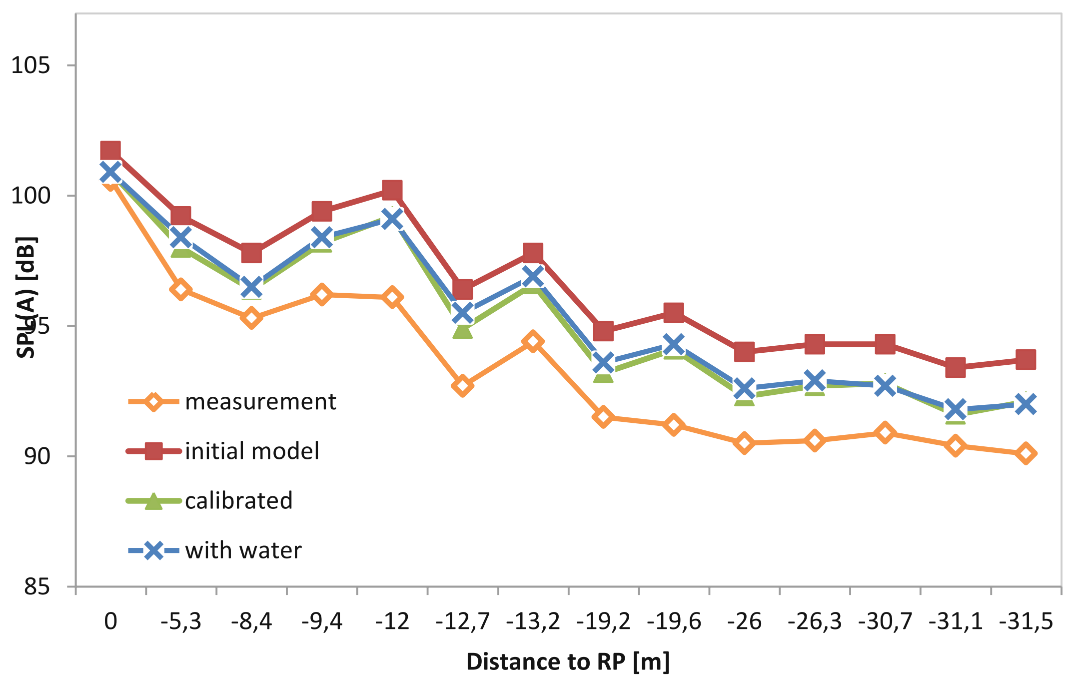


Figure 75 SPL(A) drop comparison

Table 38 Relative sound pressure level comparison

		L_{rel}			
Points	Distance (m) to RP	measurement	initial model	calibrated	with water
P 1.0 (RP)	0	0	0	0	0
P 2.0	-5.3	-4.2	-2.5	-2.9	-2.5
P 1.1	-8.4	-5.3	-3.9	-4.5	-4.4
P 2.1	-9.4	-4.4	-2.3	-2.7	-2.5
P 4.0	-12	-4.5	-1.5	-1.7	-1.8
P 1.2	-12.7	-7.9	-5.3	-6	-5.4
P 2.2	-13.2	-6.2	-3.9	-4.3	-4
P 1.3	-19.2	-9.1	-6.9	-7.7	-7.3
P 2.3	-19.6	-9.4	-6.2	-6.8	-6.6
P 1.4	-26	-10.1	-7.7	-8.6	-8.3
P 2.4	-26.3	-10	-7.4	-8.2	-8
P 3.0	-30.7	-9.7	-7.4	-8.1	-8.2
P 1.5	-31.1	-10.2	-8.3	-9.3	-9.1
P 2.5	-31.5	-10.5	-8	-8.8	-8.9

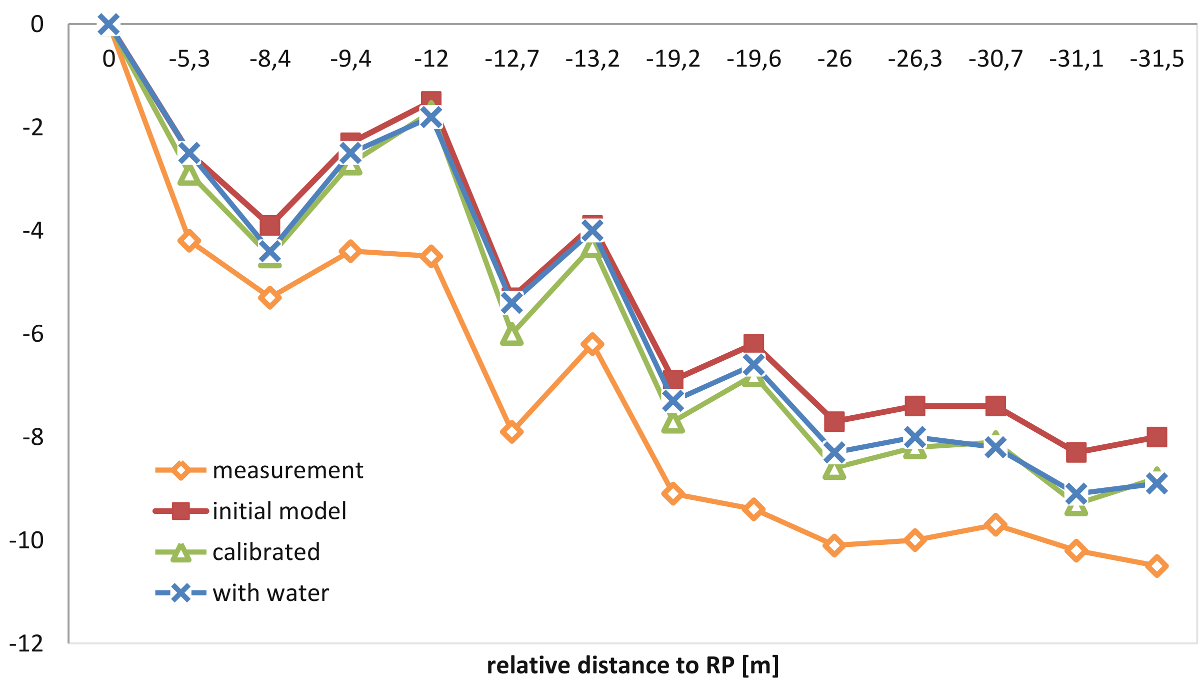


Figure 76 Relative sound pressure level drop comparison

Sound may be reflected, absorbed, or both depending on the material. Every material has an absorption coefficient value in each frequency, for example when sound strikes a concrete wall, the wall will reflect the majority of the sound wave, leaving only a small amount to be absorbed, which means the absorption coefficient of concrete is low.

The measured reverberation times for the swimming hall vary considerably, with a difference of 0.9 seconds between the limits. Austrian regulation requires a lower reverberation time and thus a higher sound absorption area to floor surface ratio in this case study.

Table 39 and Figure 77 provide a comparison of RT mean values.

Table 39 RT mean values

	RT mean Values			
frequency [Hz]	measured	simulated	calibrated	with water
125	2.16	2.65	2.31	1.99
250	2.54	2.82	2.68	2.67
500	2.71	2.77	2.68	2.38
1000	2.52	2.66	2.6	2.27
2000	2	2.44	2.03	1.75
4000	1.27	1.88	1.36	1.17

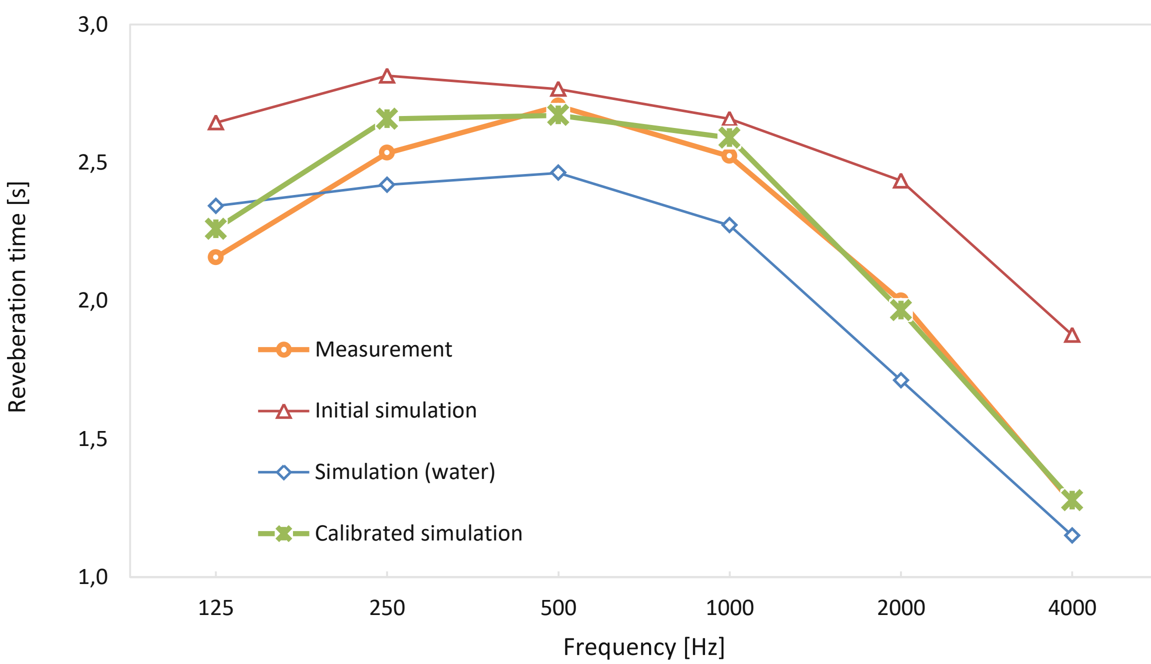


Figure 77 RT mean value, comparison

According to Table 2 in chapter 1.4.9; a value of STI = 1 stands for perfect intelligibility, while STI = 0 means that the information content has been completely lost. As we can see in Table 31, the STI values of the calibrated simulation are between 0.37- 0.6. These findings indicate that the STI is of low quality in some areas and moderate quality in others, which is not a satisfactory condition. Background noise and the room's acoustic characteristics are the most significant parameters. In swimming pools, background noise is high, and the sound pressure level rises much higher when the pool is full.

Background noise obstructs speech, making it difficult to understand a conversation. In swimming halls the reverberation time is always over 1s, which leads to impaired speech intelligibility.

Vowels are in the lower frequency range and consonants are in the higher frequency range in human speech, which is mostly between 100 Hz and 8000 Hz. The simulations measure values for these frequencies, and the reverberation time decreases with frequency, strengthening vowels while weakening consonants.

4 CONCLUSION

The objective of this master thesis is analysis and optimization of sound comfort in a case study the swimming hall in Perchtoldsdorf, Austria. The emphasis is on how the 43-year-old swimming hall's sound output compares to the current sound standards. The findings and flaws discovered are likely to be broadly and specifically relevant to all Vienna's swimming halls.

Based on the experience of locating acoustic limit values in different countries, it should be emphasized that the entire system of building codes and related documents is critical in practice for obtaining complete knowledge and access to the applicable acoustic. Due to a complex variety of documents issued by institutes, committees, standardization organizations and numerous other authorities in many countries, getting a full overview of acoustic guidelines and recommendations is difficult and there is often no joint document linking those documents together. This case study was conducted in Austria and included a guide to the Austrian acoustic regulations for swimming halls.

The data derived from measurements shows the deficiency of the current sound condition of the hall and the data obtained from simulations also proves that the actual sound comfort design has some problems despite of the insulated wall and ceiling in the swimming hall.

Reverberation time, background noise, and speech intelligibility are all essential parameters to consider when designing an acoustic environment for a swimming hall. The aim is to reduce the reverberation time to less than 1 s and reduce background noise to reduce inconvenience and boost speech intelligibility.

Even though the software is capable of importing several types of data from other CAD programs, the simulation with sound simulation program has its own limitations and inaccuracies. Since Odeon material database is limited, it's helpful to know the exact materials that were used or to use Sabine's Formula to calculate the absorption coefficient value of the material on hand.

Harmonization of descriptors, like other acoustic environments, can assist in the discussion and optimization of acoustic parameters and facilitate the exchange of construction solutions. The following conclusions were drawn after reviewing this case study in order to allow for requirement comparisons:

Based on the fact that the visitors are only in the pool area for a short time, the duration of exposure is also important. According to other studies, reverberation time is the most commonly used and easiest to experience. Therefore it is essential to apply the reverberation time measurement precisely. While reverberation time can be measured on site and allows on site verification of requirements, it is easier to apply sound absorption during the design stage of a swimming hall.

The values obtained reflect the worst case scenario. Because the absorption coefficient values of people's clothing, furniture, and other items that occur in real swimming pool were not included in the simulation, despite the fact that the model was calibrated. The simulation model was a simplified version of real scenario. During the modeling process, the surface information from the pool halls was reduced and averaged.

Using panel absorbents, as well as a greater amount of absorbents content in general, can reduce reverberation time. Since the source and receivers are below the current absorbents in the ceiling and only one wall in the hall is covered by absorbent material, a significant amount of sound is immediately reflected back. A diffuse field, such as an inclined wall, can also be used to improve this condition. To ameliorate the acoustic condition in general and protect the absorbent from potential damage caused by people or humidity, different types of absorbents are needed. Using less hard surfaces also supports the reduction of sound reflectance.

Panel absorbents are effective at lower frequencies and will improve the acoustic environment in many ways. Tilting the walls can also be an effective solution since sound waves are diffused and guided to the ceiling, where absorbents can eliminate reflections more quickly. This can reduce reverberation time and improved speech intelligibility.

Many acoustic solutions are dependent on the shape of the hall and many changes can be made during the design stage. Experience is essential to find proper solutions in the case of a complex swimming pool, since the instructions are inadequate. Collaboration between acousticians and architects will be a key factor in ensuring that adequate acoustic solutions are implemented.

The checklist presented below includes the items to be considered in order to keep track of the recommended measures for improving an existing sound condition.

	Checklist
1	Determine the location
2	Ascertain Geometry of the halls
3	Ascertain amount, size and place of windows and skylights
4	Determine the existing fixed objects in the room
5	Identify material of objects, walls, floor and ceiling
6	Determine the absorbents in the hall
7	Determine the type and size of absorbents
8	Reflectance of the room surfaces
9	Verify background noises
10	Identify type of installation
11	Determine date and time of measurement
12	Defining the measuring grid
13	Defining the position of the sound sources and measurement points
14	Determine the measurement equipment, manufacturer, serial number, class, calibration
15	Measuring background noise
16	Measuring reverberation time
17	Measuring sound pressure level
18	Verify speech intelligibility
19	Simulating the current situation with Odeon
20	Application of known calculation methods
21	Simulating a sound scene for the same area with regards to the national and international standards with Odeon.
22	Evaluating and comparing the achieved results to define the deficiencies.
23	Repeating the two previous steps till reaching the desired result.

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