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Measurement and Analysis of Sound Insulation Properties in Acoustical Wall Panels Used in Ships

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Summary

Construction of platform supply vessels introduce many complications, among these is the correct installation of walls onboard where the ship must reach a specified level of the sound reduction index in order to attain classification. Therefore this thesis adresses the challenge of predicting sound insulation properties of cabin walls onboard a platform supply vessel. The sound reduction index is predicted using the softwares WinFLAG and Odeon, thus comparing theoretical results to measurements. In addition a method of measuring flanking paths between adjacent rooms is developed and tested.

During the prediction process, sound reduction is calculated in WinFLAG, then used as input data in Odeon to simulate the sound fields and reduction properties. 3D models of seven adjacent cabins on the ship are simulated according to the ISO-10140 standard, providing three results for the reduction index including the measurements. Development of the method to measure flanking paths is based on a sound impact source. This impact source consists of a pendulum with a steel ball being released into the partition wall, causing vibrations in the structure that can be measured in a receiving room.

Towards the end of the thesis work, new information about the partition wall appeared. A more complex wall type had been installed than originally thought. Therefore there was not enough time to repeat the simulations with new features, and the simulations done in Odeon were not applicable to the sound insulation measurements. However, there was enough time to explore new calculations in WinFLAG, and compare these to the measurements instead. The results from these comparisons show that WinFLAG does not cover such complex structures, but both WinFLAG and Odeon are effective programs that can be used to predict sound insulation, if correct information about the partition wall and rooms are provided together with a less complicated wall structure.

Through the final implementation of the impact measurement method, it is discovered that this is a likely way of indicating flanking paths. The impact force is measured on different walls in the source room, and recorded in the receiving room. The results showed a clear difference between the impact force on the partition wall compared to the side and rear wall, displaying little sound traveling through flanking paths. When insulation measurements show poor reduction qualities, this impact method may be an easy way of checking if there are any interfering flanking paths.

This thesis work is conducted in cooperation with DNV GL, represented by Åshild Bergh, and VARD Accomodation.

Sammendrag

Å bygge et skip innebærer flere utfordringer, et av dem er å installere veggpaneler uten å skape noen rigide sammenkoblinger som bidrar til flanketransmisjon. Denne masteroppgaven går ut på å predikere reduksjonstallet for veggpaneler mellom lugarer ombord et supplyskip og utvikle en metode for å kunne måle flanketransmisjon. Reduksjonstallet skal predikeres ved bruk av programmene WinFLAG og Odeon, og dermed sammenlignes med hverandre og fysiske målinger gjort ombord. Metoden for å kunne avdekke flanketransmisjon skal også gjennomføres ved målinger.

Reduksjonstallet som predikeres i WinFLAG, brukes som inndata for skilleveggen i Odeon for å simulere lydfeltet og reduksjonsegenskapene i utvalgte lugarer. ISO-10140 standarden skal følges ved predikering av syv 3D modeller i Odeon, som resulterer i totalt tre ulike reduksjonstall inkludert målinger som kan sammenlignes. Målemetoden for flanketransmisjon er basert på en stålball som slippes i en pendel mot skilleveggen. Denne ballen slår da inntil veggen og forårsaker vibrasjoner i veggkonstruksjonen som kan måles i mottakerrommet.

Mot slutten av masterarbeidet dukket det opp ny informasjon om skilleveggen som var brukt i konstruksjonen ombord. En annen og mer komplisert type vegg hadde blitt installert enn først antatt. Dermed var det ikke nok tid igjen til å rekke en ny runde med simuleringer i Odeon, og målingene gjort ombord kan ikke sammenlignes direkte med Odeon prediksjonen. Derimot ble det prøvd ut nye prediksjoner i WinFLAG som er sammenlignbare med resultatene fra målingene. Konklusjonen fra dette viser at WinFLAG ikke dekker en så kompleks veggtype som var installert, selv om både WinFLAG og Odeon er nyttige programmer å bruke til å predikere lydisolasjon. Dette er forutsatt at man har korrekt informasjon om skilleveggen og en mindre komplisert konstruksjon enn i dette arbeidet.

Flankemetoden gikk ut på at stålballen ble sluppet mot tre ulike vegger; skilleveggen, sideveggen og bakveggen. Målinger fra mottakerrommet viste et klart høyere nivå ved skilleveggen enn de andre, som indikerer lav flanketransmisjon i lugarene. Dersom resultatet av lydisolasjonsmålinger er dårlige, kan denne metoden implementeres for å ha en enkel måte å finne overføringsveier.

Denne masteroppgaven er gjennomført i samarbeid med DNV GL, representert av Åshild Bergh, og VARD Accomodation.

Preface

This master thesis was performed during the autumn of 2015 at the Norwegian University of Science and Technology, at the Institute of Electronics and Telecommunication. The thesis is completed with the cooperation of DNV GL and VARD Accomodation.

I wish to thank Tor Erik Vigran and Peter Svensson for their role as supervisors at the university and for their support and guidance in the field of acoustics. The weekly meetings have been a great help in maintaining my motivation and keeping me on the right track.

A special thanks goes to Åshild Bergh from DNV GL for suggesting this thesis topic, supporting throughout the autumn and assisting with the measurements onboard the ship. An additional thanks to the department of Noise and Vibration at DNV GL for helpful points of view and for covering the travel costs for the thesis work.

Thanks to Lars-Petter Ranheim and Magne Harstad from VARD for arranging the possibility of measuring onboard a platform supply vessel and lending out necessary equipment. In addition thanks for permission to use the General Arrangement in figures 3.4,3.5, 3.7, 3.8, Appendix G and Appendix I. Also, thanks to Magnus Skårbrevik for assisting during the measurements.

Thanks to the mechanical workshop at the faculty of Information Technology, Mathematics and Electrical Engineering for producing the steel ball used in the impact experiments. Last but not the least, a grand thanks to all of my friends, family and classmates for moral support, constructive questions and feedback.

Helene Ellefsen Aasen

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Chapter 1

Introduction

From a manufacturing and classification point of view, the ability of predicting wall insulation before its construction is desireable knowledge. Poorly installed walls onboard ship vessels resulting in low insulation, will lead to difficulties in attaining classification. This is an undesired outcome costing both time and money, and is a problem that can be prevented by more detailed theoretical predictions on beforehand. Today, there is no extensive estimation of the insulation before installation other than looking at the weighted reduction index provided by the wall manufacturer. Sometimes this is adequate and will comply with rules and policies, but when compliance is not the case, some calculations would have prevented simple problems. Occasionally the problem has been flanking paths created by rigid connections during installation, and when measuring the sound insulation there has not been any way of easily checking if there are any significant flanking paths.

This thesis is developed by NTNU and DNV GL in collaboration with VARD Accomodation, where the main goal is to compare theoretical predictions with measurements, and developing a method for measuring flanking paths.

1.1 Problem description

By using the programs WinFLAG and Odeon, a sound reduction index is predicted of the partition wall between cabins onboard a VARD 1 08 platform supply vessel. The reduction index is to be calculated in WinFLAG and simulated in Odeon, then to be compared with on site measurements to see if the softwares are applicable in predicting correctly. In addition a method of measuring potential flanking paths is developed and implemented by measurements onboard the vessel.

1.2 Outline

This master thesis is divided into seven chapters; background material, experiments, results, discussion, further work and conclusion. Chapter two provides the necessary background information concerning sound insulation and flanking paths. Further on the implementation of the experiments with calculations and measurements are described in chapter three, while chapter four presents the results with discussions. Chapter five displays a general discussion and sources of error, along with chapter six about how the thesis work may be continued. Lastly, the conclusion of the work is given in chapter seven.

Chapter 2

Background material

This chapter provides necessary background material for this thesis work. The ISO-10140 standard will be described with associated terms as sound insulation indices. The reverberation time, double wall resonance and insulation is presented with focus on walls, floating floors and flanking paths. In addition a presentation of earlier research considering sound impact systems is presented.

2.1 Reverberation time

With a sound source operating in an enclosure, the absorption in the air and surrounding surfaces prevents the acoustic pressure amplitude from becoming infinitely large [1]. Depending on the distance to surfaces, the sound in a room becomes *diffuse* after a period of time, meaning that the amount of energy density is the same in the entire room. The behaviour of sound signals in a room is dependent on the size of the room as well as the absorption of the surface materials. With these factors, one can calculate the *reverberation* time of a room. The reverberation time T of a room describes the time required for the level of the sound to drop by $60dB$ [1], and is obtained by the *reverberation formula* in Equation 2.1:

$$T = 55.3\frac{V}{Ac} \tag{2.1}$$

T is the reverberation time in seconds, V is the volume of the room in cubic meters, A is the area of the room in metric sabin and $c = 343\frac{m}{s}$ is the speed of sound in air. This equation does not take into account the absorption in the air, but only the absorption of the surfaces in the room.

2.2 Sound insulation

Sound insulation is normally measured by the sound reduction index (**R**) which describes in decibels (dB) how much a wall reduces noise. The sound reduction index

(**R**) is a laboratory-only measurement, and in a field measurement the apparent sound reduction index (**R'**) is normally used, which is usually lower than a laboratory measured result due to flanking. The normalized level difference (D_n) and standardized level difference (D_{nT}) is also presented.

2.2.1 Sound reduction index

The sound reduction index is defined in Equation 2.2:

$$\mathbf{R} = 10lg\frac{W_1}{W_2} \tag{2.2}$$

Where **R** is ten times the common logarithm of the ratio of the sound power, W_1, that is incident on the test element to the sound power, W_2, radiated by the test element to the other side [2]. This is assuming that all transmitted energy is through the test element, and not through flanking. If **R** for a test element is too large, flanking will greatly affect the sound reduction index in practice.

2.2.2 Apparent sound reduction index

The apparent sound reduction index (**R'**) is defined in Equation 2.3:

$$\mathbf{R'} = 10lg\frac{W_1}{W_2 + W_3} \tag{2.3}$$

Where W_3 is the sound power radiated by flanking elements or other significant components [2]. For measurements, both **R** and **R'** are calculated by the Equation 2.4:

$$\mathbf{R} = L_1 - L_2 + 10lg\frac{S}{A} \tag{2.4}$$

Where $L_1 - L_2$ is the difference in average sound pressure level between the source and receiving room, S is the area of the free test opening in which the test element is installed in square meters and A is the equivalent sound absorption area in the receiving room in square meters.

2.2.3 Normalized level difference

The normalized level difference (D_n), measured in decibels, considers the reference absorption area in the receiving room [2], and is presented in Equation 2.5:

$$D_n = D - 10lg\frac{A}{A_0} \tag{2.5}$$

Where D is the level difference, A is the equivalent sound absorption area of the receiving room and A_0 is the reference absorption area, $A_0 = 10m^2$.

2.2.4 Standardized level difference

The standardized level difference (D_{nT}) corrects the measured difference to a standardized reverberation time [3]. Given in Equation 2.6:

$$D_{nT} = D + 10lg\frac{T}{T_0} \tag{2.6}$$

Where D is the level difference, T is the reverberation time in the receiving room and $T_0 = 0.5$s is the reference reverberation time.

2.2.5 Weighted reduction index

The standard ISO 717-1 defines single-number quantities for airborne sound insulation [4]. The single-number quantities are based on the results of measurements using one-third-octave bands and simplifies the formulation of acoustical requirements. After having measured a sound pressure level in third-octave bands a simplification of the result is practical, in other words presenting the sound pressure level with one general value instead of in third-octave band. Reference values presented in Table 2.1[4] given by ISO 717-1, are used when determining a weighted value for the sound pressure level. These reference values are shifted in increments of 1 dB towards the measured curve until the sum of unfavorable deviations is as large as possible but smaller than 32 dB. The value at 500 Hz for the measured curve will then be the weighted value for the entire measurement.

Frequency [Hz]	Reference values [dB]
100	33
125	36
160	39
200	42
250	45
315	48
400	51
500	52
630	53
800	54
1000	55
1250	56
1600	56
2000	56
2500	56
3150	56

Table 2.1: Reference values for airborne sound reduction index calculations.

2.3 ISO-10140 standard

The main task of the International Organization for Standardization (ISO) is preparing International Standards. The standard ISO-10140 describes laboratory measurement of sound insulation of building elements and specifies rules for specific elements and requirements for test conditions. The quantity determined in sound insulation is the sound reduction index, R, as a function of frequency and expressed in decibels (dB). For laboratory measurements using sound pressure level, assuming diffuse sound fields and the only sound radiated into the receiving room is from the test element, R is calculated using Equation (2.4). The general procedure of insulation measurements requires two adjacent rooms, horizontally or vertically, one being the source room and the other the receiving room [5]. In the source room a diffuse field is generated by loudspeakers at two or more positions. Moreover, the average sound pressure levels are measured in both rooms and the reduction index **R** is calculated from the measured sound pressure levels and the reverberation time. The smaller the test element, the more sensitive the results tend to be to edge constraint conditions and to local variations in sound fields.

When measuring impact sound insulation, a standard tapping machine is used to simulate impact sources like human footsteps. The procedure of measuring impact sound insulation requires two vertically adjacent rooms, where the upper one being designated the source room and the lower the receiving room. The airborne sound transmission between the rooms must be at least 10 dB below the level of transmitted impact sound in each frequency band. When testing a floor, the tapping machine shall be placed in at least four different positions with a distance of minimum 0.7 m between the different positions. The distance between the edge of the floor and the tapping machine shall be minimum 0.5 m. However, this will not be considered in this project.

For both airborne and impact sound insulation measurements, the minimum distance between microphones and room boundaries are 0.7 m. The distance between microphones and sound source/test element must be at least 1 m [6]. The average time for each microphone position shall be at least 6 s under 400 Hz, and 4 s for higher frequencies. Background noise levels must also be measured, and should be more than 15 dB below the level of signal and background noise combined at each frequency band. The sound from the source room shall use loudspeakers in at least two positions, either simultaneously or a single loudspeaker moved one time.

For airborne sound insulation measurements the laboratory shall consist of two adjacent rooms with a test opening between them, in which the test element is inserted. The volumes of the test rooms shall be at least $50m^3$, and the two rooms should not have identical volume. The reverberation time should not exceed 2 s or be less than 1 s, if it is the sound reduction index will depend on the reverberation time. Any measured sound being transmitted by an indirect path other than the test element should be negligible. The sound source should be operated as to try and achieve a diffuse sound field, be steady and have a continuous spectrum in the considered frequency range.

2.4 Double wall resonance and coincidence frequency

Before determining which kind of insulation is best, there are two parameters that are crucial to know, the double wall resonance and critical frequency. These concern the energy that passes into the structure of the partition, and how well the insulation provides a barrier to the flow of energy. Sound insulation is described as the capability of the partition to resist taking in airborne acoustic energy and turning it into vibrational energy [7]. The effect of mass is important in sound insulation due to the fact that the higher the mass the greater is the inertia force resisting movement, resulting in a higher sound reduction index. In addition, the insulation depends on the frequency of the applied force, meaning that the higher the frequency the higher the insulation.

A fundamental assumption of the partition is that it has very low stiffness, in other words it is heavy and limp. Unfortunately, stiffness produces resonance. If one strikes a sharp blow on the partition it will oscillate at its own natural frequency for a period of time. If the partition then is forced with sound waves at that particular natural frequency, it will move with a much larger amplitude and have a lower sound reduction index at this frequency. Most partitions have a number of natural frequencies, where the lowest of them is referred to as the *fundamental* frequency.

When dealing with double walls, the coupling between the outer plates will lead to a double wall resonance, with a minimum in the reduction index at the frequency [8] given in Equation 2.7:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{s}{m_1} + \frac{s}{m_2}} \tag{2.7}$$

Where m_1 and m_2 are the masses for the two outer plates and s represents the stiffness of the hollow space between the plates. This equation describes the resonance as a mass spring system, with the outer plates as the masses. Above this resonance frequency, the reduction index will increase by 18 dB/octave. Moreover, a double wall filled with a porous material will have higher reduction than a single wall, as shown in Figure 2.1.

Another unfortunate effect of stiffness is coincidence, which occurs when a bending wave travels in a partition at the same velocity as sound travels in air. The frequency at when this happens is called the *coincidence* frequency and this is not a single frequency phenomenom [7]. Moreover, the effect of stiffness is not desirable. The resonance frequency is generally not a big problem due to the frequency normally being below 100 Hz for most constructions. The coincidence frequency on the other hand causes a problem because it results in a loss of insulation in the mid to high frequency region. Therefore high mass and low stiffness in the partition wall is necessary to achieve high sound reduction index over a wide frequency range. By increasing the damping in the partition one reduces the effects of stiffness, and this is mostly effective in the frequency ranges where resonance and coincidence occurs. In other frequency ranges damping does not have a large impact on the sound reduction index.

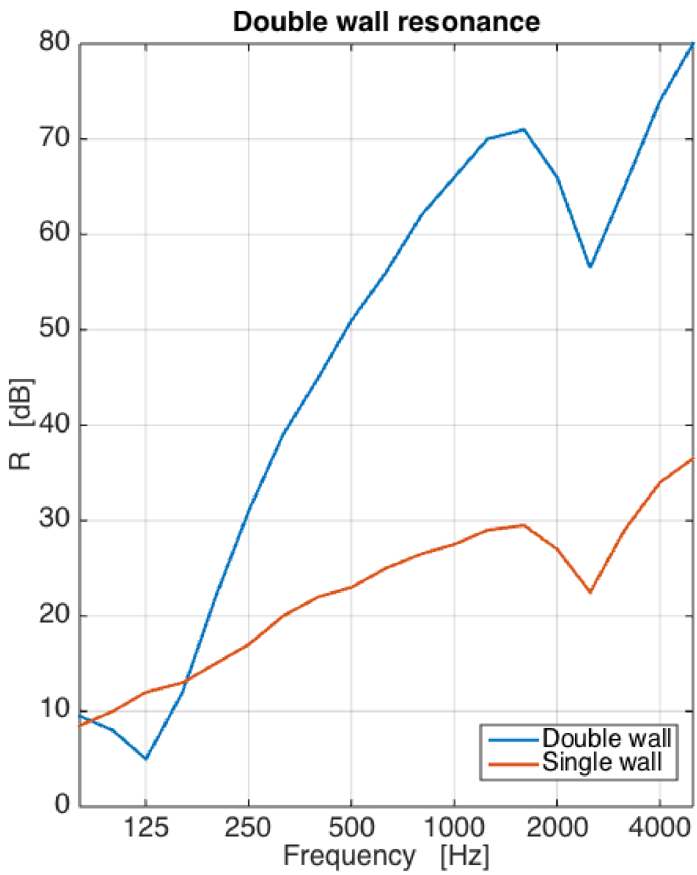

Figure 2.1: Sound reduction index of a double wall with a porous core vs a single wall.

2.5 Wall insulation

Sandwich wall panels are a specific type of wall structure, often used in buildings and other constructions to insulate between rooms [8]. In building acoustics the term sandwich panels is made by three elements, two plates connected together by a light core material. Sandwich insulation walls are often used on offshore supply ships to insulate between cabins on-board. These walls consists of steel plates with a core of mineral wool. An example of a sandwich wall with a core of mineral wool is shown in Figure 2.2.

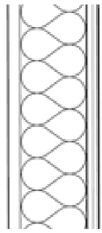

Figure 2.2: Example of a sandwich wall: two steel plates with a core of mineral wool.

High density mineral wool is used between the steel plates due to its characterizations in noise reduction and fire protection. An attribute that comes with sandwich elements is that the dynamic stiffness becomes frequency dependent. In other words, at low frequencies the core material will work as an ideal damping material between the outer plates, and for high frequencies the dynamic stiffness will only consist of the sum of the plates. For the frequencies in between the dynamic stiffness is mainly dependent on the shear stiffness of the core material. Calculating the reduction index for a sandwich wall may be done in the same way as for a homogeneous wall. In addition a calculation for each frequency based on radiation factor must be done, with a boundary frequency given by the dynamic stiffness. The reduction index of a sandwich wall is dependent on the thickness and density of both the steel plates and the mineral wool. These factors determine the critical frequency which is crucial to know in order to avoid a low sound reduction at important frequencies. When the wavelength of the bending waves in the wall matches those of the incident sound [9], the sound energy travels far more efficient through the wall and decreases the sound reduction. Combining several layers of steel with mineral wool will increase the sound insulation above the resonance frequency due to the wall working as a mass-spring-mass system.

An often used supplier of mineral wool in supply ships is Rockwool, which offers two types of wool used for insulation. These types are presented in Table 2.2. Absorption measurements of the same product is shown in Figure A.1, A.2 and A.3 in Appendix A. As one can see in Figure A.3 the absorption greatly improves in low frequencies by doubling the thickness of the mineral wool. The given weighted reduction index variates from 32 dB to above 50 dB for different suppliers and wall types.

Product type	**Nominal density**	**Sound absorption**	**Thickness**
SeaRox SL 320 [10]	$60kg/m^3$	$\alpha_w = 0.85$	50 mm
SeaRox SL 340 [11]	$80kg/m^3$	$\alpha_w = 0.9$ $\alpha_w = 0.95$	50 mm 2x50 mm

Table 2.2: Two types of mineral wool used in marine insulation, made by Rockwool.

2.5.1 Corrugated panel

A corrugated plate is often referred to as orthotropic, meaning the plate is more stiff along one direction than another. Corrugated panels are often preferred over flat isotropic panels due to the orthotropic shape having a higher strength to weigth ratio. It is often easier and cheaper to produce than a flat panel, the downside is that the corrugated panel results in poorer sound transmission loss than for a flat panel of the same thickness [12]. Figure 2.3 displays the shape of a corrugated plate similar to the one used in the sandwich panel onboard the ship, which has the shape of a trapeze. If the bending stiffness is defined around an axis perpendicular to the corrugation, there will be two critical frequencies given by Equation 2.8 [8]:

$$f_1 = \frac{c_0^2}{2\pi}\sqrt{\frac{m}{B_1}} \qquad \textit{and} \qquad f_2 = \frac{c_0^2}{2\pi}\sqrt{\frac{m}{B_2}} \tag{2.8}$$

Where c_0^2 is the speed of sound in air, m is the mass and B_1 and B_2 are the bending stiffnesses on the x and z-axis. Because of the existence of two critical frequencies, theoretical calculations on the sound transmission loss becomes much more complicated than for a flat panel. When adding damping material to the corrugated plate, the high frequency sound transmission loss will be increased. Therefore, corrugated panels together with damping material is an efficient method to attain higher transmission loss performance, just as with flat structures. A construction including corrugated plates with damping material and an intervening air space will increase the sound transmission loss compared to a single-layer structure.

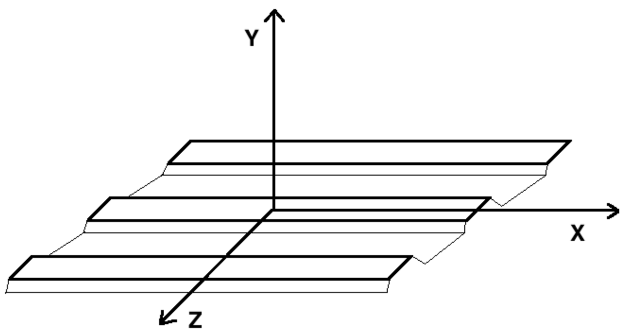

Figure 2.3: A trapezoidally corrugated plate.

However, with the additional damping material and air space, there will exist mass-air-mass resonance and cavity resonance, which makes the theoretical prediction of the transmission loss immensely more complex. In practice however, panels are not infinitely large and measurements do not comply well with the use of theoretical equations for the transmission loss [13]. If comparing transmission losses between a plane and a corrugated panel, experimental results show that below 500 Hz both panels have the same slope but the corrugated plate remains consistently 3 dB below the plane plate. At higher frequencies the difference increases and the corrugated plate is 10 dB below the plane plate at 4 kHz[14].

2.5.2 Perforated panel

A perforated panel is traditionally based on the theory of Helmholtz resonators about air resonance in a cavity [1], where the mass is represented by the air in the holes on the panel and the volume of the air is the spring constant. The typical perforated panel consists of a flat rigid surface with periodically arranged holes. The acoustic performance of a perforated plate depends on their perforation rate, size, thickness and mounting conditions [15]. When the radius of the perforations ranges between 1 mm and 1 cm the term used is *macro-perforated* systems, while with any smaller radius one uses the term *micro-perforated*. If appropriately designed, perforated plates may be used as efficient sound absorbers when combined with air gaps or porous materials. Therefore a resistance must be introduced together with the perforated plate in order for it to attain a practical level of absorption, for example with the use of mineral wool. Another way of obtaining a high enough resistance without the use of porous material, is to use a micro-perforated plate.

The area of the hole is important as it decides the resonance frequency and absorption of the perforated panel. A small diameter of the holes is preferred because of the desired absorption coefficient, the absorption decreases as the open ratio increases. By decreasing the open area ratio or increasing the thickness of the facing, one is able to reduce the resonant frequency of the plate. A perforated plate alone offers most of its absorption in the mid-frequencies, at both high and low frequencies the perforation does not absorb well, therefore the use of mineral wool or open air gaps are introduced to increase the absorption in the high-frequencies. Resonators are practical from a room acoustical point of view due to the reflecting radiation that has a diffusing effect. The natural energy losses in a Helmholtz resonator consists of two components, the viscous losses and the reflected sound energy. Without the viscous losses a perforated plate would not function as an absorbing panel [8]. From a structural point of view, an advantage of using perforated steel is the reduction in weigth of the wall.

2.6 Flanking paths

On the contrary to a laboratory situation, in practice transmission through several paths must also be considered. The sound energy travels along flanking paths in addition to the direct transmission [8]. These flanking paths can be through the wall, ceiling or floor structures, cracks or other possible ways. As shown in Equations 2.5 and 2.6 the index calculated is only the apparent reduction index, which does not take flanking paths into consideration. Therefore, when measuring the sound reduction index of a wall in practice, it may show lower results if the flanking paths have a significant impact on the sound pressure level in the receiving room. Figure 2.4 presents possible flanking paths between two rooms. When designing a room

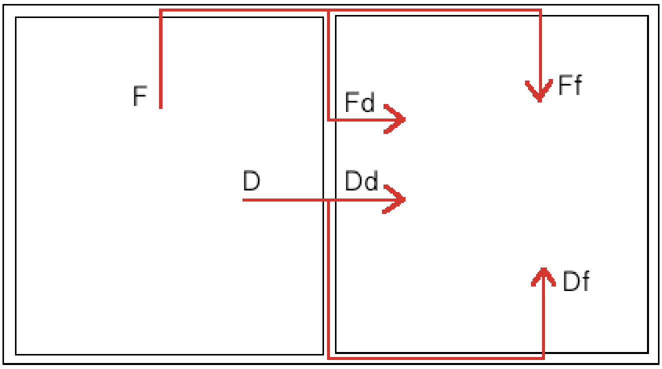

Figure 2.4: 1st order flanking paths between two rooms, F = flanking sound, D = direct sound.

considering insulation, there is no point in having a well insulated wall if the floor or ceiling is not up to the same standards. One should choose all surfaces to complement each other, if not the transmission of sound will choose the easiest way and reduce the sound reduction index. An insulated wall is only as good as the surfaces around it. A mathematical approach of the apparent reduction index [8] is given in Equation 2.9:

$$\mathbf{R'} = 10lg\frac{1}{\tau'} \tag{2.9}$$

where

$$\tau' = \tau_d + \tau_f + \sum \tau_{dt} + \sum \tau_{it} \tag{2.10}$$

Where τ_f and τ_d stands for flanking and direct transmission of the wall, while dt and it is the sum of other indirect or direct transmission in the room. There may be many orders of flanking paths, counting the surfaces and structural joints from the source room to the receiving room. In Figure 2.4 only first order flanking paths are shown, with one surface in the source room, one structural joint and one surface in the receiving room. In practice there are many paths contributing to the overall sound transmission of a wall[16]. The number of paths depends on the size of the building, and when a building becomes larger there is less sound transmitted to the receiving room due to the energy being transmitted to other parts. A rule of thumb is that including the first order flanking paths will halve the difference between the direct path and the overall transmission [16]. Therefore one should include flanking paths when calculating the sound transmission in order to achieve a more correct result. Flanking is greatest when the separating wall is thick and least when it is thin, due to the fact that sound chooses the easiest path, and the greatest transmission occurs when the flanking wall is just over half the thickness of the partition.

Walls radiate more efficiently close to the critical frequency. At the critical frequency of a flanking wall there will be an increase in the vibration which will cause a dip in the noise reduction of the flanking path. When calculating the noise reduction, the critical frequencies of all elementes are assumed to be below the frequency range of interest. Therefore only resonant transmission needs to be considered and non-resonant transmission can be ignored [17]. The area of the flanking walls are not of importance to the noise reduction, but the length of the structural connection between the walls is. In other words, increasing the surface density of the flanking walls will usually reduce the flanking transmission.

If one uses the standard EN 12354-1 for prediction of airborne sound transmission and compares with on site measurements there may be large differences [18]. This is due to the standard being restricted to including only first order flanking paths. As shown by Galbrun [18] the importance of multiple order flanking paths is not included when calculating airborne sound transmission between two adjacent rooms. An error of approximately 5-10 dB must be accounted for when not including multiple flanking paths in the calculation. In other words, measurements will normally show a lower total sound reduction index than calculated reduction of the partition wall. Normally flanking paths includes the transmission of vibrations in the source room to the receiving room, but in this work only the total airborne sound will be investigated.

2.7 WinFLAG software

WinFLAG predicts the sound reduction and absorption coefficient for constructions combined of material layers of different types[19]. The program is used to calculate a theoretical sound reduction index on beforehand in order to use the properties for further simulations in Odeon, and compare it with measurements. The calculations are performed as mean values in one-third-octave bands with a diffuse sound field using the transfer matrix method. Meaning each layer assumed to be of infinite extent is presented by a matrix to be combined with other matrix layers, resulting in physical variables for the whole combination.

WinFLAG uses two types of plates, thickplates and thinplates. With thickplates the wall construction is simulated to have the sandwich elements glued together and is described by a 4x4 matrix. Thinplates simulates free oscillations between the sandwich layers because there is no need to worry about the wave motion inside the plate and has a 2x2 matrix. Porous layers and perforated sheets are presented as 2x2 matrixes as well, meaning that if two layers are glued together, one must describe both of the layers as thickplates. Otherwise it will operate as a thinplate, with a 2x2 matrix instead of 4x4.

2.8 Odeon software

Odeon is a software designed for simulating the interior acoustics of buildings by using the image-source method combined with ray tracing [20]. Early reflections are defined by image sources and ray-radiosity while the late reflections are defined by a ray-tracing method [21]. The room inputs needed to simulate in Odeon are the absorption coefficient in one-octave bands and the sound reduction index. Each surface of the room must have a *material*, described by the absorption coefficient. Additionally the walls can be set to a specific property, for example *Normal* or *Transmission* where the normal setting does not allow sound energy passing through and the transmission type does. For this work only the partition wall will be set to transmission, while the remaining ones are normal.

Odeon offers a variation of source types, where the point source is the one applicable to this experiment by setting the sound power to a specific level at all frequencies. Two simulation experiments is to be used, one with a grid map and the second with a microphone setup coherent with the ISO 10140 standard. The grid map sets a number of grid receivers with many "small" microphones all over a certain height. This simulation presents a colormap of the sound field in the room, while the microphone setup specifies 5 microphone positions in each room, giving a result at that exact spot. In order to simulate with correct room dimensions, 3D-models of each measurement position is created in the program SketchUp.

2.9 Impact noise system

There are not overwhelming amounts of research or standardized method on the subject of measuring impact sound insulation between two adjacent horizontal rooms. A paper has been published by *Huang, Chen and Lai* exploring the possibility of using hard and soft impact sources to measure impact sound through lightweight walls [22]. A hard impactor is considered as for example a steel ball of 50 mm in diameter while a soft impactor could be a silicon ball of 100 mm in diameter [22]. On the other hand, a firm of Australian acoustical consultants has designed and constructed a horizontal tapping machine to be used for measuring impact sound insulation, using springs instead of gravity [23]. However, the first method of implementing a single impact from a ball swinging under gravity will be used in this thesis work because it is simpler and cheaper to apply in the field.

Huang, Chen and Lai implemented a source system of oscillatory impact shown in Figure 2.5, with a pendulum arm of 50 cm and impact angles of 30°, 60° and 90°. The impact sources were divided into hard and soft impactors where different ball types of steel, wood and silicon were used. Measurements were done in a reverberation room and a semi-anechoic room with a background noise of less than 20 dB. The test specimen used between the two rooms included a steel plate and a gypsum partition. The results from this research shows that the heaviest hard impactor, a 50 mm diameter steel ball is the impactor which has the best results in the frequency spectre. The soft impactors and hard wood impactors have a more rapid decay at higher frequencies than the largest steel ball.

Additionally, the steel balls show a greater system stability as the standard deviations are below 1 dB, while the wooden balls have a standard deviation larger than 1 dB. Concerning the impact angles, the variation of impact sound level with changing angles from 30° to 90° is small. Especially the difference between 60° and 90° is negligible. In this case the difference between the angles is smaller for the steel ball than for the silicon ball as well, making the steel ball of 50 mm diameter the preferred impact noise source with an impact angle of 60° or more.

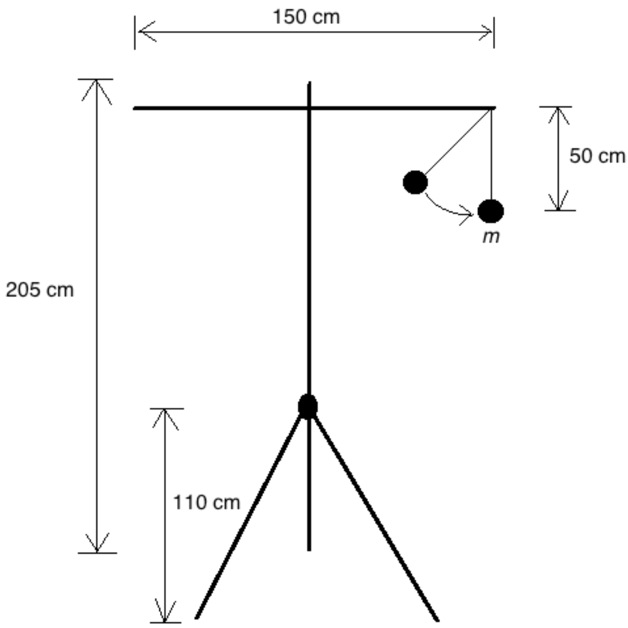

Figure 2.5: Figure of the research impact system.

Chapter 3

Experiments

This chapter presents the measurements and numerical simulations, starting with the equipment list for the measurements. Then a description of the walls onboard is presented, further on the settings used in the program simulations are described. Lastly the implementation of the sound insulation and wall impact measurements are discussed.

3.1 Equipment used for the measurements

- Norsonic Precision Sound Analyser, nor 140 serial no. 1405825
- Norsonic Precision Sound Analyser, nor 140 serial no. 1405264
- Norsonic Power Amplifier, nor280 serial no. 28004159
- Norsonic Hemi-dodecahedron loudspeaker, nor275 serial no.2755196
- Norsonic Calibrator 1251 serial no. 34071
- Norsonic Wireless remote control 280
- Steel ball, 50mm diameter, 515gr, 50cm pendulum
- Power supply cable
- Norsonic 4513 cable
- Norsonic 1494/5 cable
- Measuring tape

3.2 Room details

A wall panel called W-B50 produced by Staco [24] was first considered when predicting in WinFLAG and Odeon. This wall is shown in Figure 3.1 and consists of a surface material of 0.6 mm thick galvanized steel plate with a 150μm thick PVC film and a core of mineral wool with density $140kg/m^3$. This wall is $50mm \pm 0.5mm$ thick and has a sound reduction index of $R_w = 32dB$. However, the wall which was actually used onboard and measured, was the W-B50D type shown in Figure 3.2. This wall has a very different interior consisting of an air gap with a corrugated and perforated steel sheet of 0.4 mm thickness, and a mineral wool density of $200kg/m^3$, giving a new sound reduction index of $R_w = 41dB$. The perforated holes had a diameter of 3 mm, with a distance of 6 mm between the center of each holes, resulting in an open area of 23%. The W-B50D panels are 550 mm wide with thickness of 50 mm and installed as shown in Figure 3.3 with a **U** shaped clip locking the panels together. In addition to this, the cabins with walls against the ship side uses another type of wall, which is the same construction as the W-B50 only 25 mm thinner.

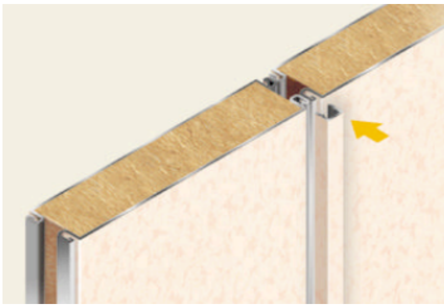

Figure 3.1: Staco W-B50 wall panel.

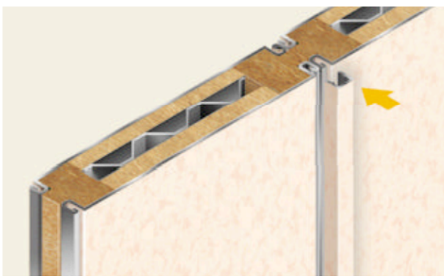

Figure 3.2: Staco W-B50D wall panel.

The ceiling panels in the cabins are 25 mm thick, 275 mm wide and made of galvanized steel. The floating floor constructions are displayed in Figure 3.4 and 3.5, and they vary between the two considered decks. On B-Deck there are two different floating floors due to some cabins being more exposed to structure-borne noise placed directly over the machine room several decks below. The same principle applies to C-Deck

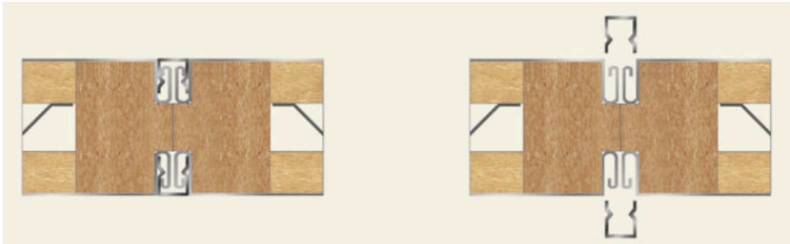

Figure 3.3: Clip joint W-B50D.

with two different floors, but overall these floors are thinner because the distance to the machine room is increased.

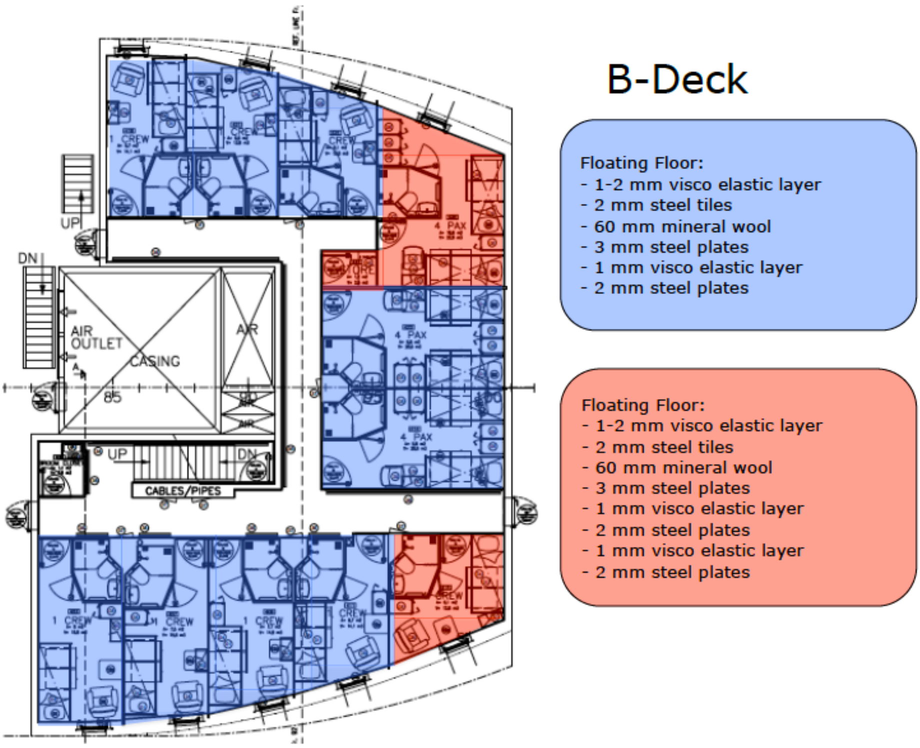

Figure 3.4: Floating floor construction for B-Deck.

3.3 WinFLAG

Calculations were made in one-third-octave bands with a diffuse field for wall panel W-B50, se Figure 3.1 with the parameter values given in Table B.1 in Appendix B.

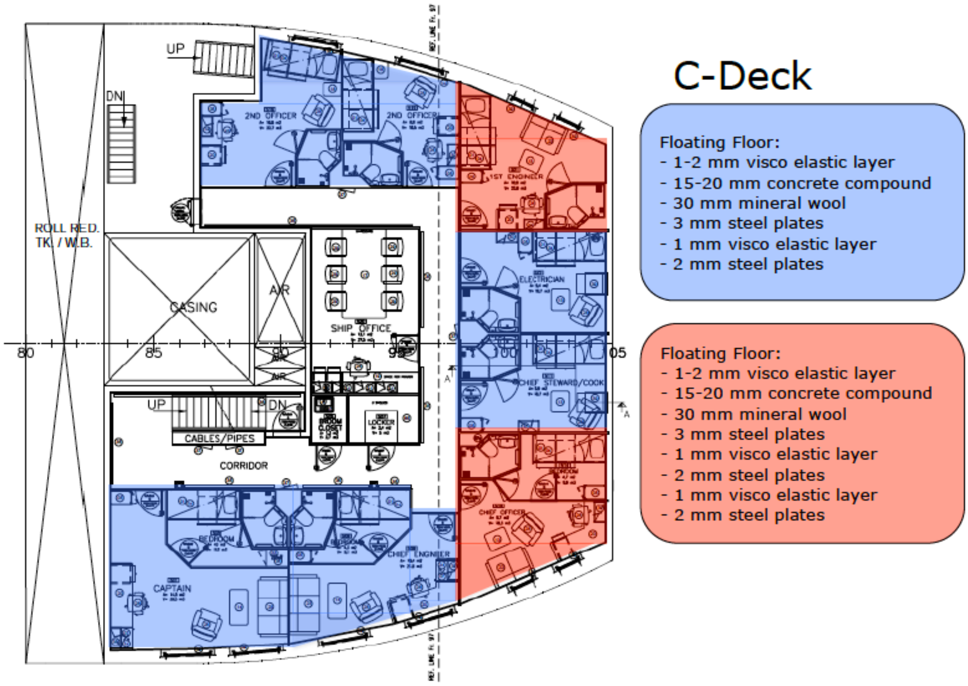

Figure 3.5: Floating floor construction for C-Deck.

Trying to calculate a sound reduction index for the wall panel W-B50D is more complicated, due to the steel sheet inside the wall being both corrugated and perforated (see Figure 3.2). WinFLAG does not offer a way of calculating a combined structure which is both corrugated and perforated. It has one model for corrugated plates and another for perforated plates. Therefore, to be able to try and predict a likely reduction index of the partition wall, the main focus is towards the perforation of the plate as the perforation would have a larger impact on the sound properties than the corrugation. In this case, the manufacturer stated that the mineral wool and outer steel plates were glued together, while the corrugated and perforated sheet was hot pressed to the mineral wool. This gives a variety of different possibilities of simulating the partition wall using WinFLAG, and four different models were tested.

The main idea behind the simulation was to focus on the perforation instead of the corrugation. Moreover, thinplate models could well operate with a perforated plate layer, while thickplates only operates with other thickplates in order to simulate the glue in-between. Therefore two models of the perforated plate were used, one as a perforated plate and an equivalent thickplate model made to possess the same properties as the perforated plate. Figure 3.6 shows the two models and their corresponding sound reduction indices. The four different models consist of variations with thick-

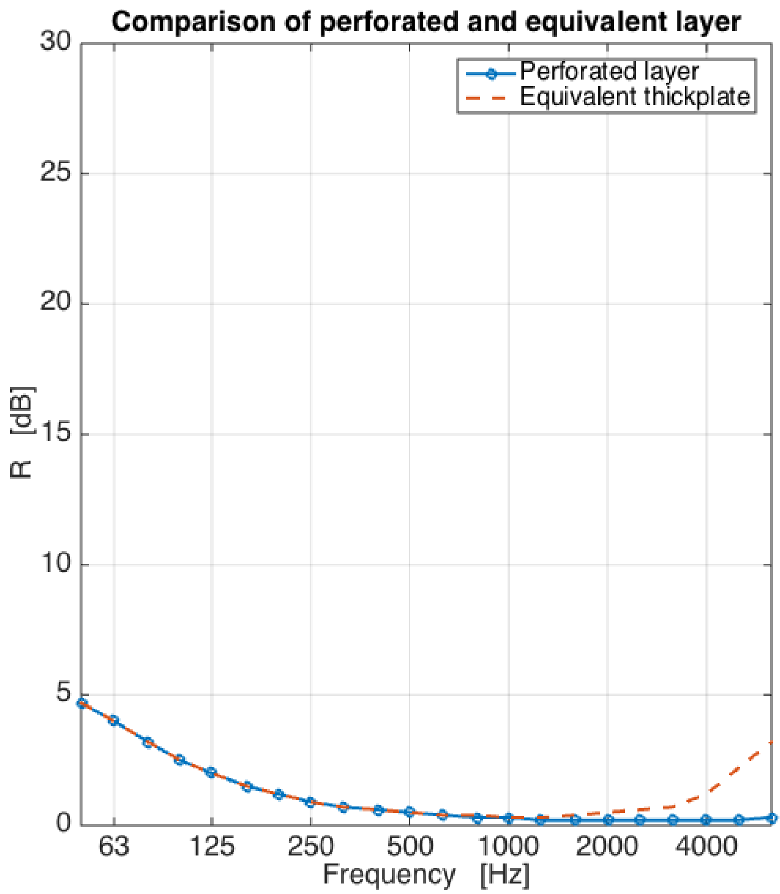

Figure 3.6: Perforated layer and equivalent thickplate reduction index.

plates, perforated plate, equivalent plate and air. A more detailed overview of each model is given in Table 3.1, and the propeties of layers are also shown in Appendix B. The results are presented in Section 4.1.

3.4 Odeon

Odeon simulations require sound reduction indices and absorption coefficients as input data for the wall constructions. The sound reduction indices and absorption coefficients for the wall panels were computed with WinFLAG, and other surface absorption coefficients are presented in Appendix C.

Test 1	Test 2
Steel thickplate 0.6 mm Mineral wool thickplate 48.5 mm Steel thickplate 0.6 mm	Steel thickplate 0.6 mm Mineral wool thickplate 15 mm Equivalent perforated thickplate Mineral wool thickplate 15 mm Steel thickplate 0.6 mm
Test 3	**Test 4**
Steel thickplate 0.6 mm Mineral wool thickplate 15 mm Perforated plate 0.4 mm Mineral wool thickplate 15 mm Steel thickplate 0.6 mm	Steel thickplate 0.6 mm Mineral wool thickplate 15 mm Air 8 mm Perforated plate 0.4 mm Air 8 mm Mineral wool thickplate 15 mm Steel thickplate 0.6 mm

Table 3.1: Models for wall panel W-B50D prediction in WinFLAG.

3.4.1 Simulated cases

The simulation cases were chosen in order to give a representative overview of the ship, and a total of seven cases were chosen, shown in Figure 3.7 and 3.8. 3D-models were made in SketchUP [25] for each case as two adjacent rooms. These models are presented in Figures D.1-D.7 in Appendix D. The seven simulated cases consists of five adjacent rooms which have a wall on the ship side, while the two remaining cases are in the middle of the ship. None of the adjacent rooms are identical.

3.4.2 Surface settings

When uploading a 3D-model in Odeon, each surface needs to be assigned an absorption coefficient. Assigning a coefficient is done by either using one of the predefined surfaces in Odeon, or by creating a personal one. Due to the properties of the wall panels being calculated in WinFLAG, personal surfaces were created for the W-B50 wall with the absorption coefficient and sound reduction index shown in Table 3.2. In the simulations only the separating wall between the cabins was set to *transmission* type, while the remaining surfaces were set to *normal* type. By setting a wall to transmission type additional information about the sound reduction is needed, otherwise only the absorption coefficient is needed. The absorption coefficients for the remaining surfaces are presented in Table C.1 in Appendix C. In addition to the separating wall there were a number of different surfaces as the ceiling, floor, bed, chair and plywood panels. The upfacing surface of the bed was set to have an absorption coefficient as a mattress, while the supporting frame had a plywood paneling absorption. This is due to the beds onboard usually being supported by a wooden frame, and the predefined plywood paneling coefficients in Odeon had reasonable values. This situation was applied to the upholstered chairs as well. Lastly, the absorption for both the floor and ceiling

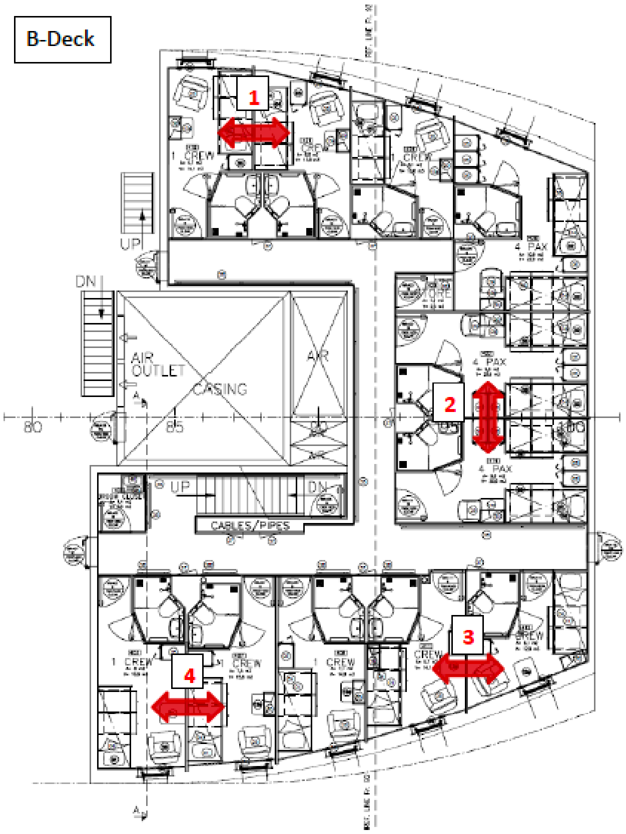

Figure 3.7: Measurement positions for B-Deck.

was set to the same.

3.4.3 General settings

All beds have a height of 0.4 m while chairs have a sitting height of 0.5 m with a backrest of 1 m. For all cases there were two sound source positions, positioned as described in the ISO-10140 standard with a minimum of 0.7 m distance from boundaries. The sound source simulated pink noise, with a level of 94 dB in each frequency band. The simulations in Odeon are done in two ways with the first presented by a grid calculation. A grid calculation consists of defining a height of 1.2 m in both source room and receiver room, where microphones are placed with a distance of 0.05 m from each other at this height. An indication of how the sound field behaves in a room is given by this simulation. The grid simulations were done in all source and receiver rooms and to check if the sound field was consistent at different heights, two extra positions were chosen to perform an additional grid simulation at heights 0.55

Figure 3.8: Measurement positions for C-Deck.

m and 1.9 m. Positions 3 and 6 (see Figure 3.7 and 3.8) were chosen for in order to have one position in the middle of the ship and one with a wall on the ship side. Additionally the rooms in position 6 had almost identical furnishings and area while position 3 did not.

The second simulation done in Odeon was in accordance with ISO-10140, with five microphone positions in both source room and receiver room. Classic calculations were carried out as with measurements to check if this method was coherent with the input reduction data of the transmission wall. The simulations were done with two source positions, followed by calculations in order to get a theoretical reduction index. The placement of both source and microphones are presented in Appendix E with corresponding coordinates for the positions in Appendix F, origo is shown on each figure. Results are presented in Section 4.2.

Frequency [Hz]	**Abs. coeff.** [α]	**SRI** [dB]
50	0,23	21
63	0,24	19,7
80	0,25	17,9
100	0,26	15,8
125	0,3	13,1
160	0,66	8,4
200	0,34	14
250	0,13	23,8
315	0,07	31,5
400	0,04	38,4
500	0,02	45,1
630	0,01	51,8
800	0,01	58,5
1000	0	65,3
1250	0	72,3
1600	0	79,7
2000	0	86,9
2500	0	94,5
3150	0	102,4
4000	0	110,6
5000	0	119,1
6300	0	124,4

Table 3.2: Surface material properties used in Odeon for W-B50.

3.5 Sound insulation measurements

The sound insulation measurements followed the ISO-10140 standard using a moving microphone, meaning one measurement over a period of minimum 30 seconds was made instead of five different microphone positions as done in the simulation. Two repetitions were made resulting in four results of the sound reduction index for each case. The source positions used during the measurements are shown in Figures G.1-G.14 in Appendix G. Due to space limitations in the smallest cabins, the source positions do not differ a lot between the first and second round of measurements. Detailed results for each measurement position is presented in Appendix H and the overall results are presented in Section 4.3.

3.6 Impact wall insulation

In addition to regular sound insulation measurements, a method for wall impact sound has been developed. The method used was adopted from the research results by *Huan, Chen and Lai*[22] in order to identify flanking paths onboard. The general idea was to see if this method could give an overview of the influence of the flanking paths on a structure like this ship. A steel ball with a diameter of 50 mm, weight 515 g and a pendulum arm length of 50 cm was made as shown in Figures 3.9 and 3.10. The procedure consisted of holding the pendulum against the wall, lifting the steel ball $L_2 = 25cm$ and then releasing it. The distance 25 cm was chosen in order to obtain an angle of 60°. The corresponding sound pressure level was measured in the receiving room when the steel ball hit the wall. The real time analyser was preset to measure over a period of eight seconds in order to have an identical period during all measurements.

Positions of the impact sources are shown in Appendix I, using the same rooms as for the insulation measurements. Six positions where chosen in each source room, except for cases 5 and 7 which had seven and eight positions due to different layout of the rooms. The sources were spread in two positions per wall, two on the partition wall, two on the side wall and two on the rear wall. The fourth wall in the rooms usually consisted of the bathroom and door, therefore the impact method was not implemented here. The impact positions were placed in the middle of a wall panel (each panel was 55 mm wide) at a height of 1.15 m, with the exception of position 7 where the height had to be altered to 1.33 m due to a firmly mounted sofa. This was the height of the steel ball impact, not the top of the pendulum. The impact force was repeated three times in each source position, giving at least six impact forces on each wall. Results are presented in Section 4.4.

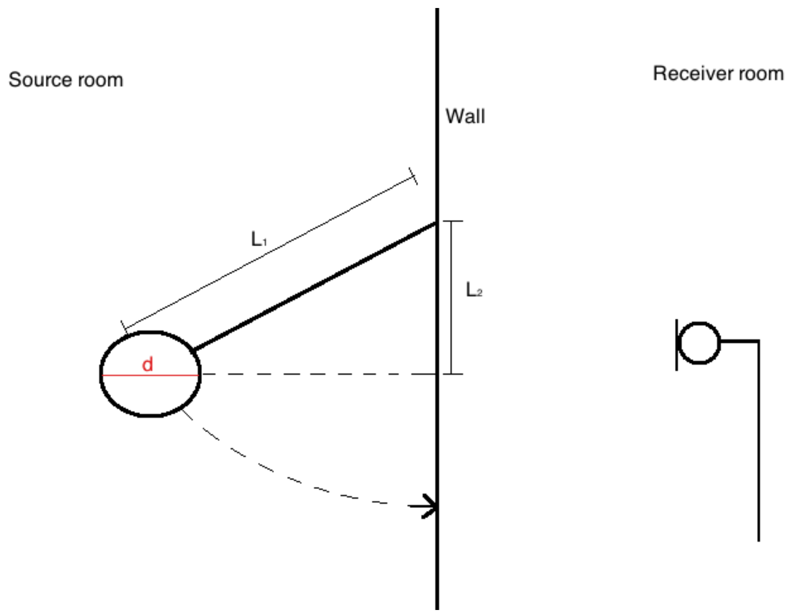

Figure 3.9: Measurement setting for impact wall insulation, $d = 50mm$, $L_1 = 50cm$ and $L_2 = 25cm$.

Figure 3.10: Picture of the produced steel ball.

Chapter 4

Results and discussion

This chapter presents the main results from the predictions and measurements. Focus will be on the averaged results in order to maintain a general view, with comments on results that differ from the average. Please note different scales between the predicted figures and the measured figures.

4.1 WinFLAG prediction

Figure 4.1 displays the WinFLAG predicted sound reduction index for the first type of wall, W-B50(Figure 3.1). The model was predicted with thinplates because it was unclear whether the sandwich elements were glued together or not. Moreover, the result from this calculation showed a weighted sound reduction index of $R_w = 34dB$ while the manufacturer stated a value of $R_w = 32dB$. The real wall was glued and the calculation was not, causing a higher level of predicted sound reduction because the wall is able to oscillate freely. Later the same model was tested with thickplates to see the changes between a sandwich wall which is glued together and one which is not. This result is displayed in Figure 4.1 as the green graph. In hindsight, the value used for the loss factor of the galvanized steel plate is not of a reasonable level. The level used must be for a freely suspended plate, and the prediction should have used a higher level than 0.002. Fortunately, a better loss factor of 0.05 was used for the W-B50D prediction.

The more interesting results however, are the ones were WinFLAG predicted a sandwich wall with the perforated plate. Four different models were tested in order to check the influences of different settings, presented in Section 3.3. Test 1 was based on the idea of keeping it simple, trying to construct a model that resembles the measured characteristics without the perforated sheet. Therefore the first model consists only of two steel plates and one layer of thickplate mineral wool with the thickness of the entire wall. The wool thickplate had the original wool density properties, while the remaining plates were tweaked in order to accentuate the behaviour of the measured

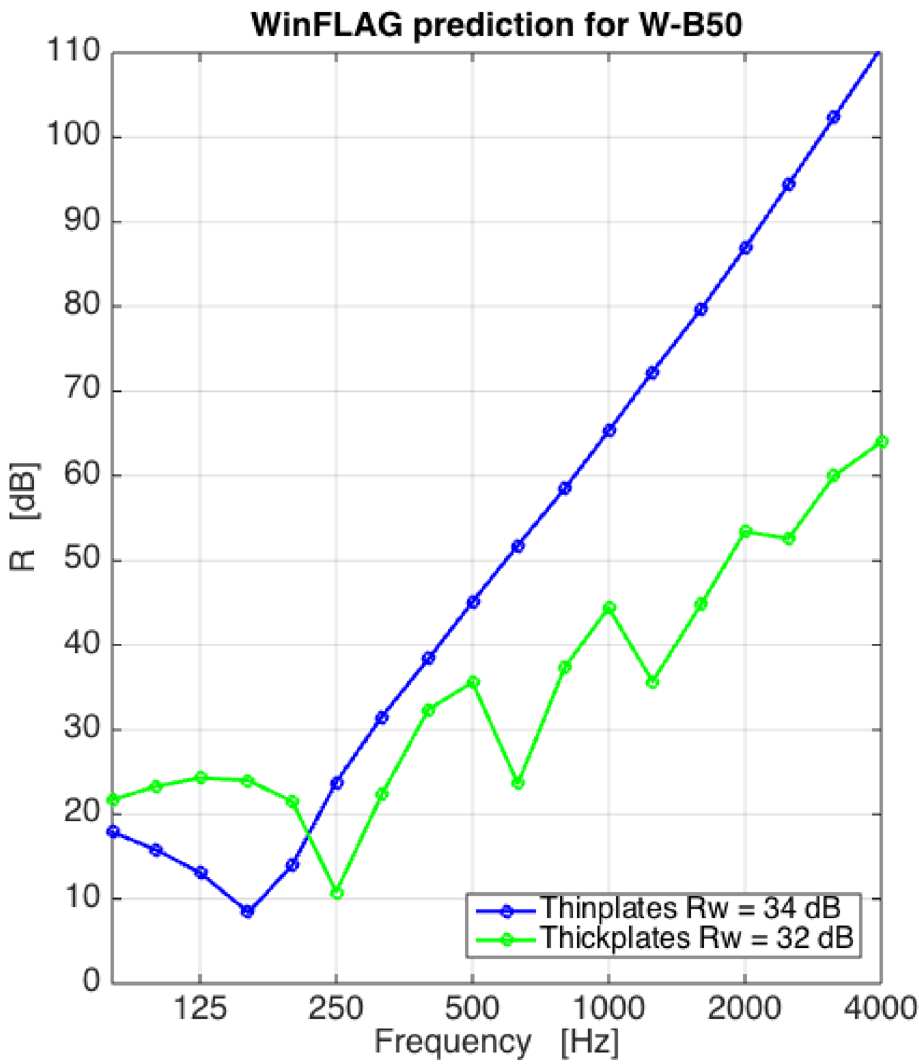

Figure 4.1: Thinplates compared to thickplates for wall type W-B50 in WinFLAG.

results. Test 2 consisted of a more detailed construction, where the equivalent thickplate model of the perforated sheet was introduced and the wool layer was reduced to the corresponding thickness as in the installed wall. Test 3 had the same construction as test 2, only with the perforated sheet layer instead of the equivalent thickplate. Test 4 included two air spaces on each side of the perforated sheet because the real contruction is corrugated with air gaps in between.

Figure 4.2 displays the four models that represents wall panel W-B50D(Figure 3.2) along with the averaged measured result. As one can see, the introduction of air gaps in test 4 displays few similarities with the measured wall, even though the weighted sound reduction index is at 40 dB. Clearly, using air gaps in model 4 does not give any reasonable results, as it absorbes to much at high frequencies. Test 2 and 3 both resulted in a weighted sound reduction index of 40 dB as well, and these two models were very similar. The differences between these two models is that test 2 simulates the entire wall as glued together, while test 3 uses a perforated sheet instead of an equivalent thickplate. Making the two outer layers in test 3 glued, while the perforated core is not. This is shown in the higher frequencies, were test 3 has a steady increased reduction while test 2 has a dip in the curve around 2kHz.

Moreover, the simplest model, test 1, displays the best results compared to the measurements. Test 1 resembles the measured values with a similar curve up to about 1.6 kHz and a weighted sound reduction index of 42 dB. Above 1.6 kHz the measured reduction evens out while test 1 increases. When comparing the four theoretical WinFLAG results to the measured results, there is no special model that exclusively resembles the measurements of the wall. However, test 1 is able to show a good approximation up to 1.6 kHz, giving some valuable information about how an equivalent theoretical model can be used. In this case, where the perforation rate is as high as 23%, the perforation itself will not influce the absorption much. Therefore instead of using a perforated sheet in the sandwich construction, a layer of mineral wool as the entire core resembles reality much more, and is a better approximation than introducing more layers as air or a perforated sheet.

Combining a theory for a steel sheet which is both corrugated and perforated is very challenging. In WinFLAG, which does not support such complex walls, there are some limitations to the results one can achieve. The perforation became the main focus of the wall due to this having a larger impact than the corrugation. By trying different models consisting of thickplates, perforated sheet and air, the results are not quite similar to the measured results. There are many variables that influence the calculation of this wall. In real life the steel sheet is corrugated, therefore it does not have any glued connection to the mineral wool along the entire sheet side but only a little part of it. In WinFLAG the steel sheet is simulated to be flat and perforated, therefore when using the perforated thickplate equivalent it simulates the entire area as glued together with the mineral wool. This leads to all the layers in the wall being unable to oscillate, making it more stiff and reducing the reduction significantly.

Moreover, when using a thickplate layer equivalent for the mineral wool, the software finds difficulty in simulating the high absorption, but this is the only way of simulating the mineral wool as glued to the outer steel plate. The air gaps were introduced in order to try and simulate the small air gaps which exists in the structure due to the corrugated nature, but this idea did not lead to any valuable results. However, the thickplate equivalent of the perforated sheet worked very well. When comparing

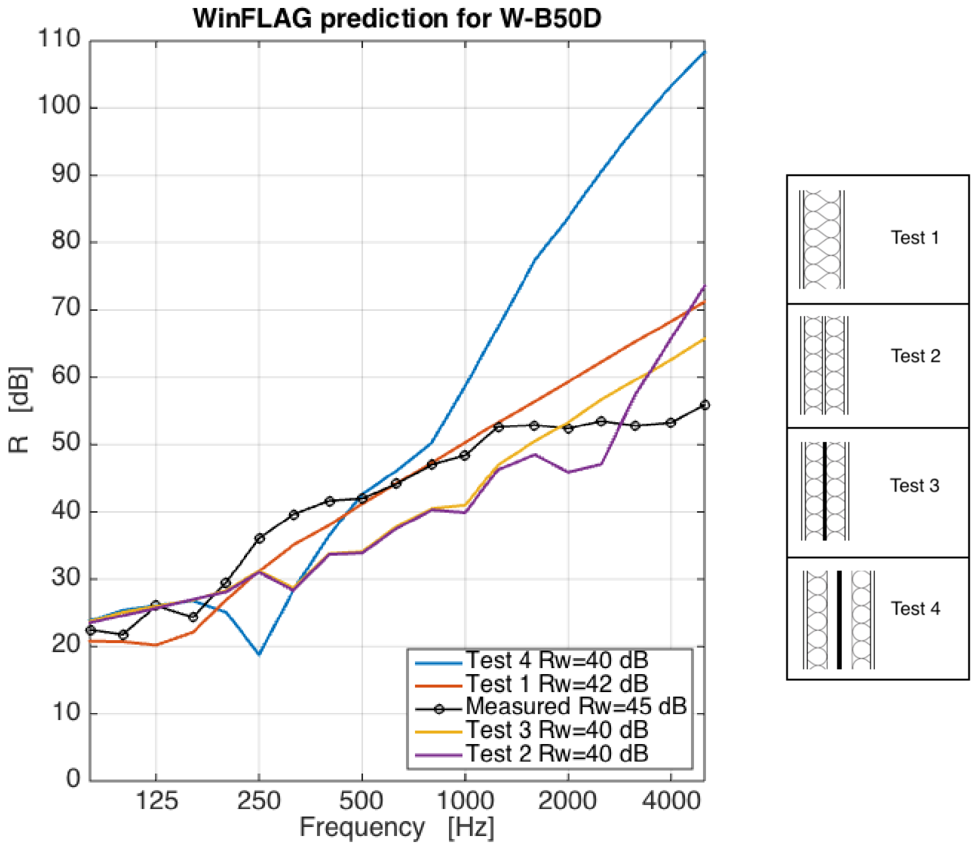

Figure 4.2: Prediction of four models for wall panel W-B50D in WinFLAG.

test 2 and 3, the differences were small. The theoretical models for this wall does come up short when there is no way of introducing the corrugation of the steel sheet. In other words one does not know how much this influences the sound properties of the wall. Comparing the measurements with the predicted models is difficult when the software can not introduce all the layers as they actually are.

4.2 Odeon prediction

The first simulation in Odeon is shown by an extract of the grid prediction results presented as 3D models in Appendix J with two figures of case 3 and 4. When looking at the simulated sound fields in the source rooms in Figures J.1 and J.3, the sound level variation in the entire room is about 2 dB. The same trend appeares in the source rooms with all cases, where the sound field was more or less constant no matter the geometry, area or placement of the sound source. Therefore, the variation in the sound field does not have a large impact on the incident wall. Odeon is a functional tool to find out how the sound source will behave in a space, in this way one is able to determine where to place the source in order to achieve the best sound field. The sound fields in the receiver rooms are shown in Figures J.2 and J.4. It is clearly loudest close to the partition wall in the receiver rooms and reducing further from it, especially in the small entrance area where the sound pressure level often reaches its lowest level. In the receiver rooms however, the sound level variation differs more than in the source room, usually between 5-8 dB in the entire room.

Individual results show that room cases 2 and 4 have the lowest reduction, where the adjacent rooms are almost identical, while room cases 5 and 7 are large rooms with the highest reduction. Large rooms reduce more, and case 7 has an additional separate sleeping quarter that result in a higher sound reduction. With an extra room there is more absorbtion than in the smaller rooms, therefore the smaller rooms do not achieve a sound reduction as good as the large rooms. This is a parallel that can be drawn to the measurements as well.

In addition predictions at three different heights were made in cases 3 and 6. Both cases displayed the same results, therefore only results from case 6 is presented in Appendix K. This height prediction showed that the difference in the sound fields is small between the three heights. At 0.55 m height the sound level is at its highest and with the largest range, but the sound field evens out when increasing the height. This is mirrored in the receving room, with a higher level close to the ground than the ceiling. Otherwise this prediction confirms the diffuse field theory that a sound field is constant everywhere with the addition of direct sound. At 0.55 m height the variance of the sound field is maximum 3 dB, it is 2 dB at 1.20 m and only 1 dB at 1.9 m height. The receiving room has a larger variance but displays the same behaviour, with the variance decreasing with increasing height.

Results from the five microphone method predictions are shown in Figure 4.3 by sound reduction indices for all cases, and numerical values are presented in Table L.1 in Appendix L. Figure 4.3 reveals that the reduction characteristics are similar for all cases. There are some minor variations in the level which are due to different areas and number of absorbing elements. Using the classical calculation method, the predictions with five microphone positions result in a more exact sound reduction index calculation than only looking at the grid simulations. The sound reduction indices were calculated in octave bands as displayed in Table L.1. Cases 2 and 4 are the ones with lowest reduction, while the larger rooms have better reduction. Larger rooms tend to have better sound reduction because the sound field reaches a more stable state in the room as discovered in the grid simulations. In a smaller cabin there are shorter distances to the border conditions, resulting in a less diffuse sound field. Overall the predicted weighted reduction indices range from 33 dB to 39 dB.

4.2.1 Predicted Odeon results and input data

The sound reduction indices input data in Odeon were taken directly from the predictions in WinFLAG. Therefore, the calculations of the sound reduction index result in Odeon should be similar to the input values of the partition wall. The prediction of the sound reduction index was done according to ISO-10140-2 with the five microphone method. Displayed in Figure 4.3 are the input values of the sound reduction indices given by WinFLAG in a dashed black line, while the remaining lines are the calculated sound reduction indices predicted by Odeon for each case. At first glance the curves are alike in the frequency range 200 Hz - 2 kHz, and differ in the lowest and highest frequencies.

However, the WinFLAG results are given in one-third-octave bands, while Odeon operates with one-octave bands. Therefore the figure does not display the information at the critical frequency for the predictions. In theory, these graphs show a correct consistency between the input data and Odeon results, which is how it should be. Moreover the black dashed line increases above 2 kHz while Odeon's results stagnates. This is due to the predictions in Odeon not giving any numerical results above 2 kHz in the receiving room through the partition wall, therefore the result from 2 kHz is copied to 4 kHz. With these two considerations, the results in Odeon are coherent with the input data and shows that Odeon can be used to do insulation predictions if the input data is correct. Predicting in Odeon shows an influence on the results, meaning that the program takes into consideration the geometry of the room, furniture and other factors.

The disparities between the cases are small and must be the result of difference in volume and furnishing, since all the surfaces have the same absorption and an identical partition wall. Therefore, if WinFLAG is precise in its prediction and there are no major flanking paths, Odeon will be able to predict reasonable sound reduction indices. By using Odeon and correctly made 3D models, one will be able to have a

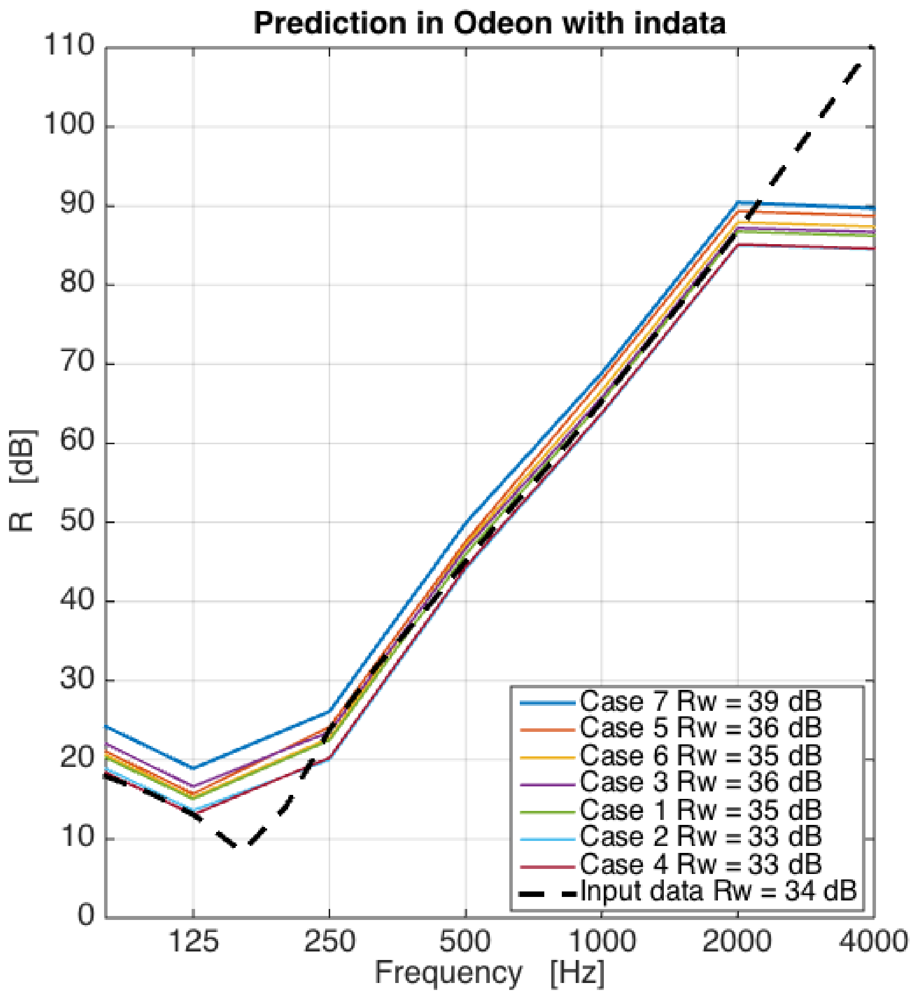

Figure 4.3: Sound reduction indices of case predictions in Odeon and input data.

more precise prediction of how the sound properties will behave in one particular room while WinFLAG only considers the specified wall. Therefore if there are any doubts of how good a partition wall is, Odeon can be used to introduce variations as for example furniture and surface absorptions to check the level of influence of other factors on the transmission loss.

A downside of predicting in Odeon, is that the results are displayed in octave bands, which could lead to some gaps in the information about critical frequencies of the partition wall, whereas WinFLAG operates in one-third-octave bands. On the other hand

Odeon shows an advantage when dealing with non rectangular rooms. Even though the wall predicted in Odeon was not identical to the measured one, the predictions showed interesting results in case 5 because the source room had a special geometry(see Figure D.5), and showed that the position of the sound sources influences the sound reduction index shown in Appendix M. In other words, before embarking with measurements, one could use Odeon to check where one should place the sound source in order to attain the best possible diffuse field. Additionally the reverberation time is predicted in Odeon as well, giving another significant variable that can be compared to measurements.

4.3 Sound insulation measurements

Results from the measurements are shown in Figure 4.4 and 4.5 with all the seven cases in the first graph, and the average with the standard error in the second. The individual case results are presented in tables in Appendix N. In Figure 4.4 case 2 and 7 stand out with the best sound reduction index results, which corresponds with their large volumes. The furnishings of all rooms mostly contained one bed and one upholstered chair, with the exception of case 7 which included a sofa. In addition case 7 had a separate room for the bedroom, but the measurements were made from the lounge due to this zone having the largest partition wall area. A large area consisting of a sleeping quarter and a sofa in case 7 will influence the sound insulation between the rooms. The results display the highest sound reduction indices in case 2 and 7, which have a weighted reduction of 46 dB and 47 dB.

The lowest sound reduction index is in case 4 with a weighted reduction of 41 dB. Case 4 was actually not the smallest room in area, there were two smaller rooms that displayed better sound reduction indices. When looking at the averaged graph there are two frequencies which can be suspected to be close to the resonance frequencies of the partition wall, 100 Hz and 160 Hz showed by a dip in the curve. In the smaller rooms there were some difficulties positioning the sound sources without touching the boundaries. A small room area might contribute to better sound reduction because the sound source is close to reflecting surfaces, which will enhance the sound pressure level. Individual weighted sound reduction indices vary from 41 dB to 47 dB, and may be studied in Appendix H for each case. The placement of the sound sources are presented in Appendix G. The reverberation times of the receiver rooms were all measured one time, with one microphone position. These results are presented in tables in Appendix O along with the volumes of the receiver rooms as well.

4.3.1 Influence of source positions

In one particular room, case 5, there was a significant difference in the sound reduction index result based on the placement of the sources. In Figure H.5a the difference between the two sound source positions for the first measurement round was as large as 3 dB, while for the second round of measurements the difference between source positions were 4 dB. The source positions are displayed in Figures G.9 and G.10 where

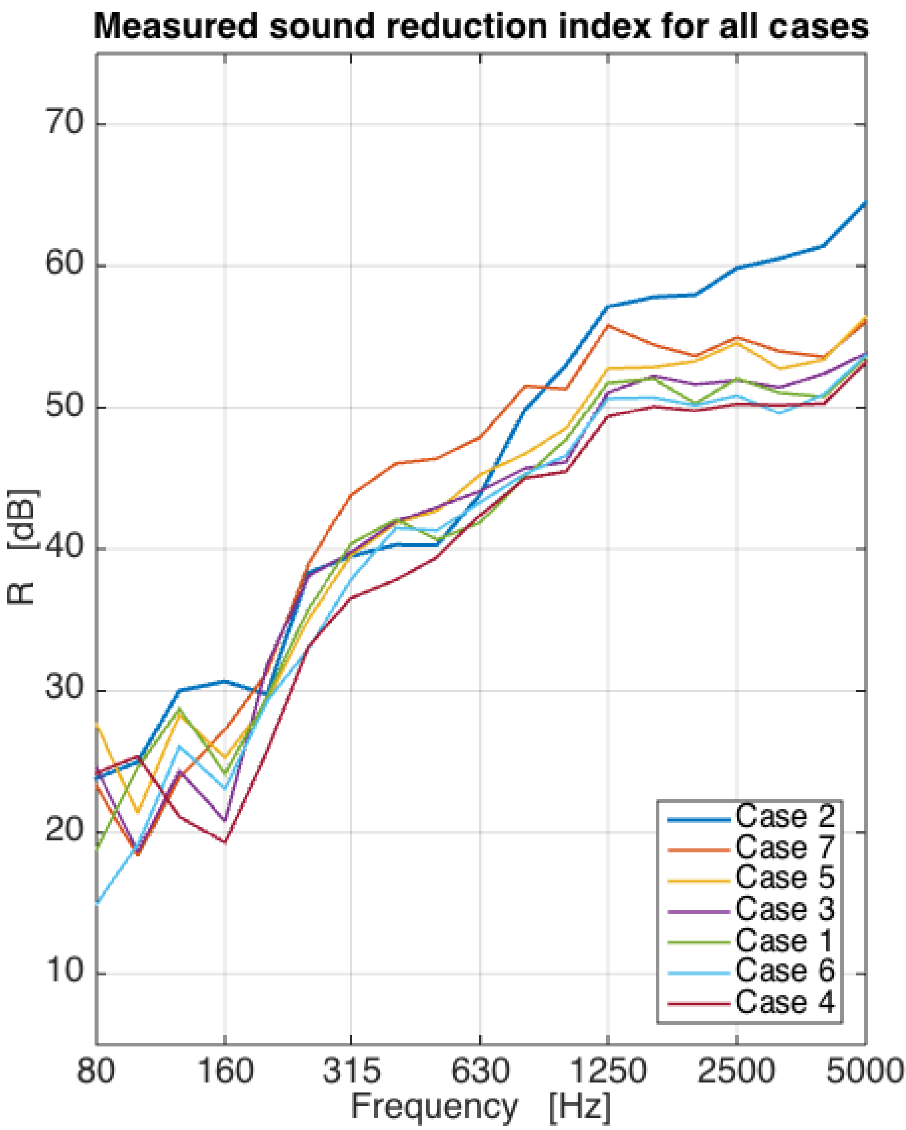

Figure 4.4: Sound reduction indices for all measured cases.

source 1 is in the back of the room while source 2 is closer to the partition wall. The shape of this room has a large impact on the measurements. The moving microphone measurement was done in the middle of the source room, between the two square shapes. With the microphone in the middle of the room, the sound pressure level in

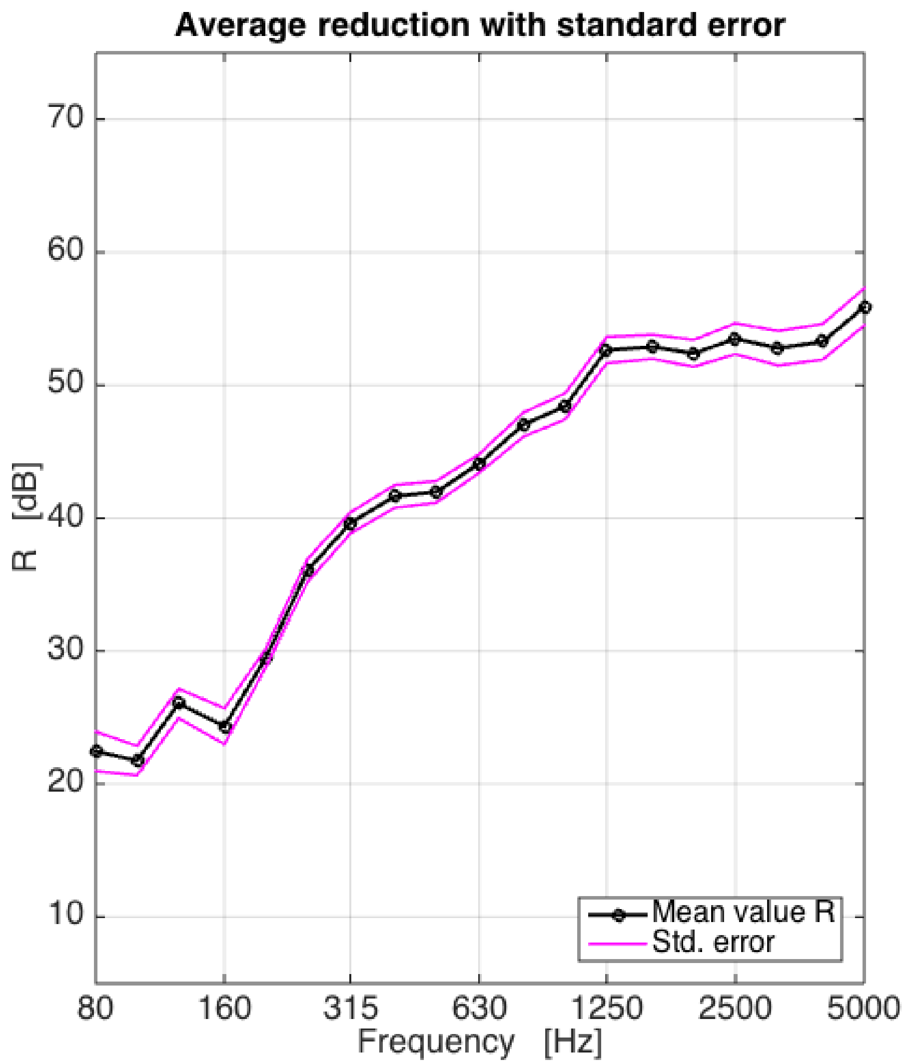

Figure 4.5: Averaged sound reduction index with standard error.

the source room was similar at both source positions. While the receiving room showed a lower sound pressure level at source position 1 than source position 2, resulting in a higher sound reduction index when the source was positioned far from the partition wall. In other words, this room has a larger amount of uncertainty due to the large difference between the source positions. Source position 2 will contribute to a higher sound pressure level close to the partition wall and will not obtain the same reduction level as source 1.

Even if the sound reduction index is different for the Odeon predictions compared to measurements on account of being two entirely different walls, a comparison of difference in source positions gives some interesting results. These source positions were also simulated in Odeon, and as shown in Figure 4.6 there is a similar difference in the source positions between Odeon and the measurements. Both measured and predicted results indicate different sound reduction indices for the two source positions. In the predictions source 1 has a better sound reduction level than source two, just as with the measured case 5. Therefore one could have predicted the difference in reduction by looking at the source positions in the simulations. Using Odeon to predict how the sound will behave in a room can lead to a better knowledge of where to place sound sources when measuring, and predict certain behaviours concerning shape of the room, furniture or other important factors.

4.3.2 Small vs large rooms

Firstly, the volume of the rooms vary from $12.8m^3$ to $20.8m^3$. In this comparison the small rooms will consist of the volumes up to $17m^3$, and the large rooms are the ones above $17m^3$. Room cases 1,3 and 4 are therefore in the category of small rooms while cases 2,5,6 and 7 are large rooms. The result is presented by averaging the sound reduction index of the two groups with corresponding standard error in Figure 4.7. The small rooms are in this circumstance too small to avoid the challenge of close boundaries, causing a less diffuse sound field close to the partition wall. Figure 4.7 displays that above 630 Hz the standard error of the small and large rooms do not overlap, while in the lower frequency range the standard errors overlap meaning the largest difference are at higher frequencies. The small rooms show a more distinct dip in the curve at the critical frequency 160 Hz than the large rooms, but otherwise the response is similar. Another reason for an improved insulation in the large rooms may be the additional furniture causing a larger amount of absorption than the small rooms.

The results from the insulation measurements shows that the partition wall is either up to the standards given by the manufacturer or better. The weighted sound reduction indices vary from $41dB$ to $47dB$, given a sound reduction index of $41dB$ by the manufacturer. The reasons for better measured results can be a number of things. Firstly, the rooms where the measurements took place were far too small compared to desired volumes by the ISO-10140 standard, therefore the sound field in each room do not have the space to reach a true diffuse state. Secondly the partition wall was smaller than $10m^2$ in all room cases. The standard notes that when the partition wall is smaller than $10m^2$, the area used in the calculations of the sound reduction index must not be be set to anything less than $10m^2$.

Comparing theory with reality becomes difficult in this situation because of the late arrival of correct information. It is disappointing to not be able to properly compare Odeon and WinFLAG with the insulation measurements. This would have been inter-

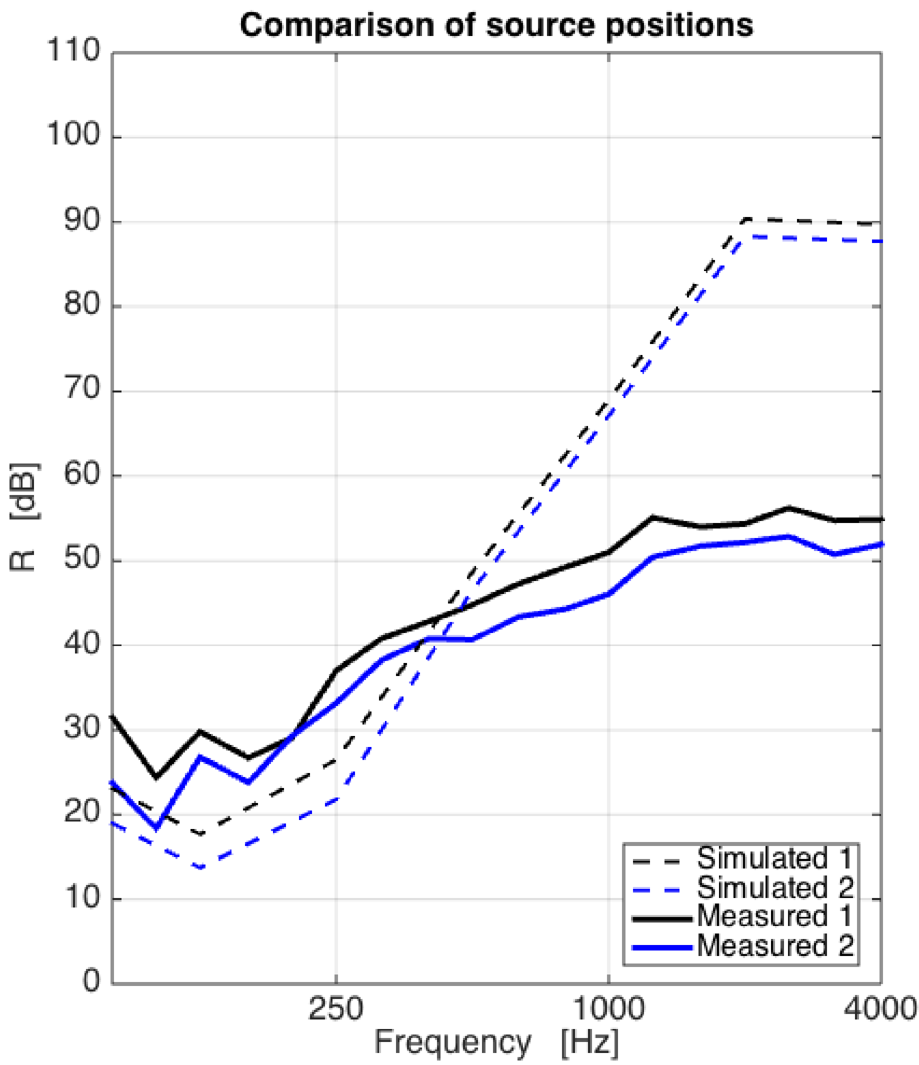

Figure 4.6: Sound reduction indices for two different source positions in case 5. The simulations were done for wall type W-B50, while the measured wall is of type W-B50D.

esting information to actually see how close the predicted levels could have been and get a more exact idea if Odeon is suitable for transmission loss calculations. Theoretical calculations with both corrugated and perforated plates combined is not included in the software WinFLAG, making it challenging to predict the transmission loss for the W-B50D sandwich wall.

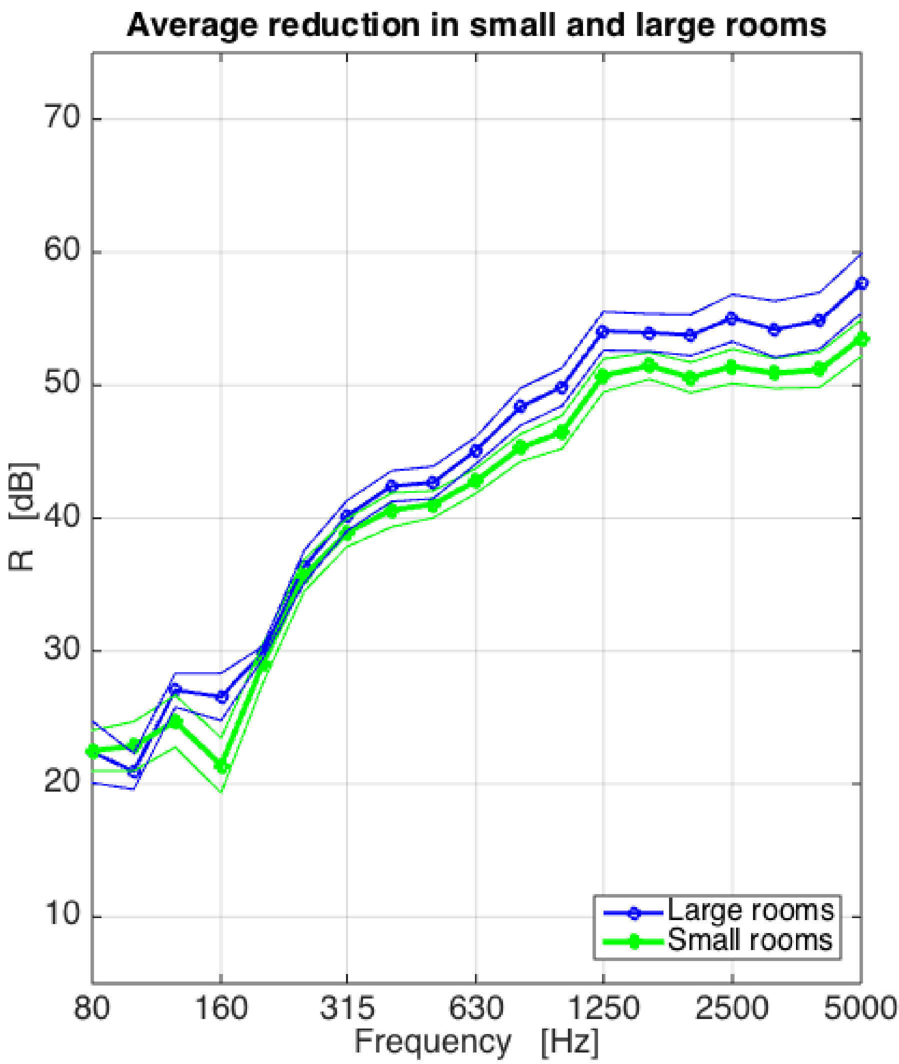

Figure 4.7: Measured sound reduction indices for the large cases (2,5,6,7) vs the small cases (1,3,4).

4.4 Impact measurements

The wall impact measurement results are shown in Figure 4.8 by a mean of the three walls in all cases. As shown in the figure the impact force on the partition wall is higher than the other walls, indicating that there is not a lot of sound traveling through flanked paths. When looking at the frequency spectre the reaction is similar with all the walls, where sound in the lower frequencies dominates. Above 1 kHz the side and rear wall leans toward the background noise, while the partition wall keeps a higher level even through the higher frequencies. An interesting aspect is the impact from the side and rear wall, and that these two are quite similar. A surprising detail is the rather good signal-to-noise ratio between the background noise and measured impact level. If the graph of the side and rear wall tended towards the partition wall, this would indicate the presence of flanking paths. Overall this does not occur in Figure 4.8 because it is averaged, but when looking at each case in more detail there are some noticeable results.

There is a trend occurring in the shipside cases where the side wall levels are closer to the partition wall at low frequencies. This concerns cases 1,3,4,5 and 7 and these detailed graphs are presented in Appendix P. As mentioned in Section 3.2, the wall against the ship side is thinner than the partition wall and attached to the steel of the ship side with a window. Combining these factors results in a larger amount of sound traveling in this wall compared to the midship cases. The wall is attached to a steel construction which includes the window through the ship side, making it a path for traveling sound. The window construction creates a more rigid connection where low frequency sound travels better than a wall without a window. Looking at case 2 and 6 the impact on the side walls do not overlap with the partition wall at all. The difference between these two groups of rooms is only the connection to the ship side with a window. The two rooms positioned in the middle of the ship, with no connection to the outer ship side or other important steel constructions, show a large gap between the partition wall and the side wall impact. Thus confirming the theory of low frequency sound traveling through the window.

However, another question arises due to the method of these wall impact measurements, because the impact sound is made in the source room, how much of the sound can one believe is delivered to the receiving room through flanking paths? The impact of the steel ball in the source room will generate a sound level as well, making it a source of airborne sound transmission. How much of the result is contributed by airborne sound transmission? At least one can assume that the impact sound force is identical each time, thus creating the same sound level in the room for all cases. In this way the measurements will give the same transmitted airborne sound, and can therefore be neglected when looking at the results. Moreover, in the future a more correct way of using this method would be to implement the impact force on the outside walls. In this manner one would erase the contributing levels from airborne sound transmission from the source room, and only focus on the impact force from the outside walls. In this particular experiment it would have been difficult to have the impact source from outside on the ship side, but in other environments it could be easily implemented.

The impact measurements performed in this thesis is only in an experimental phase, and has many factors to be considered before it can be used in a professional manner.

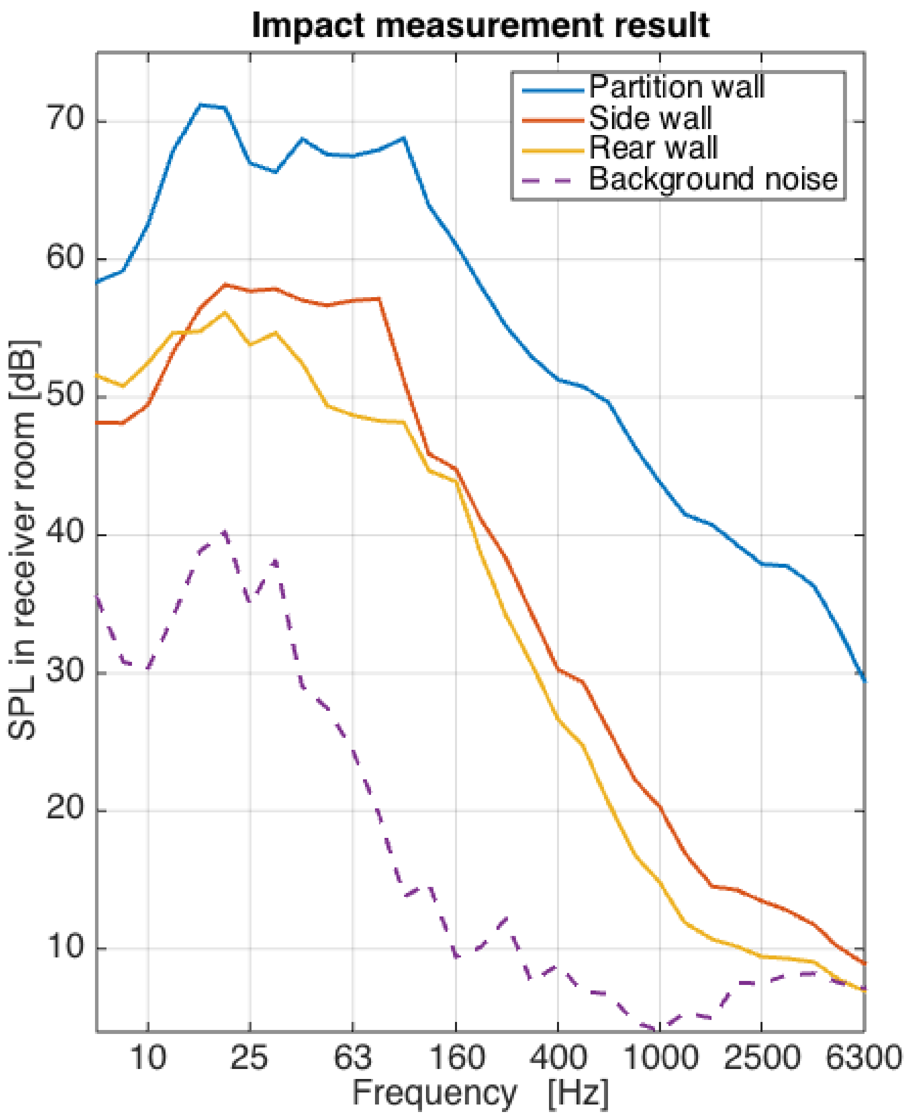

Figure 4.8: Mean value of wall impact measurements across cases.

The method of using a steel ball to simulate an impact sound source on a wall is not standardized, making it difficult to predict the faults of the method before measurements have been performed. The results show a clear difference in sound transmission between the partition wall and the side and rear wall. Since the level at the partition wall is much higher than the side and rear wall, the results indicates that there are no significant flanking paths in the structure. If there were any flanking paths the graphs would be more overlapping. These measurements display a well built structure with few rigid connections that transfer sound energy.

Because the ship side cabins have a side wall construction which is narrower with a window, the results show a larger sound energy transfer at the side wall in the ship side cabins than the mid ship cabins. By these means, the experiment shows an opportunity of detecting flanking paths with an easy measurement method. In other words an impact sound source could help locate flanking paths if there are any doubts that the construction is not adequate.

The process further for this method is to determine details around how the measurements should be performed. During the measurements some solutions were not up to the best standard as is could be. The sound analyzer was preset to measure a period of eight seconds, but the start of the impact sound was not defined. Therefore the start time of the impact sound could be anywhere in the first five seconds of the measurement period, giving each measurement a different period for the decay of the impact. The impact sound only lasts a fraction of a second, and the sound pressure level is stabilized after maximum a second, so the measurement should include the important decay. But in order to have entirely identical measurements each time, there should be another way of implementing this. For example one could adjust the sound analyzer to begin a measurement with a trigger, setting a limit level so that the analyzer would immediately start a measurement when the sound reached a specific level. In this way each measurement would begin with the exact same impact and with the same period. This application was unfortunately not available with the provided equipment during this work. Since there are no other standardized way of measuring these paths today, this method might be useful if it is further developed.

Chapter 5

General discussion and sources of error

This chapter includes a general discussion together with possible sources of error for the experiments.

5.1 General discussion

Predicting wall panel W-B50D in WinFLAG with a corrugated and perforated panel is difficult, especially when trying to include the special properties of corrugation and perforation together. The results from four different models displayed that the simplest model, test 1 with only two outer steel plates and a thickplate core, resembled the measurements the most (see Figure 4.2). Apparently, a perforated sheet with a perforation rate of 23% does not have a large impact in the absorption of the wall because the holes are too large. In addition, no model included any corrugation in the simulation due to limited time, thus the focus was mainly with the perforation. Therefore one does not know how much the corrugation influences the acoustic properties of the wall, but it might introduce two critical frequencies. The measurements showed two apparent dips in the reduction curve at 100 Hz and 160 Hz, this fact is more clear when looking at the individual sound reduction indices for the room cases, see Appendix H.

Simulations for wall panel W-B50 demonstrated that Odeon gives output which correspond to the input data. This displays that Odeon is fitted for calculating the sound reduction of a wall when simulating with the five microphone method, even though Odeon falls short at high frequencies. Otherwise, Odeon is an efficient tool to use when wanting to introduce variations that contribute to the sound field which WinFLAG is not able to do. A disadvantage with Odeon is that it is not able to include flanking paths, making it unfit for simulation if there are large contributions by flanking.

The insulation measurements were done according to standard, and the averaged result proved to have a sound reduction index of $R_w = 45dB$ which is higher than the value given by the manufacturer, $R_w = 41dB$. However, these room cases were smaller than the advised room volume given in the ISO-10140 standard, which could affect the measured result in a positive direction. The comparison of source positions between measured and Odeon results showed a significant similarity, where room case 5 displayed that source position 1, close to the partition wall, resulted in a lower reduction index than source position 2. This implies an importance of where one should place the sound source, and Odeon can help simulate it beforehand in order to predict the most representative result. In case 5, perhaps one should have had a larger set of repetitions to even out the differences, and have a broader placement of the sources in the entire room.

The impact results displayed that little sound was transmitted through flanking paths, with a larger amount of low frequency sound transmitted at ship side walls. Influence of airborne sound transmission is unknown in this instance, therefore one does not know how reliable these results are with the presence of many uncertainties. The results so far does display better transmission through the partition wall, therefore indicating that there are few flanking paths in the structure of the adjacent rooms.

5.2 Sources of error

To use WinFLAG properly, one must know the exact structure of the wall. How many layers are there, are the layers glued, thickness, density, E-modulus and so on. These values are not always known, and some were unknown in this thesis work as well. Some values were given by the manufacturer, but some were found in published articles and the like, making it unsure if this particular wall actually consisted of the precise values used. Specifically, the loss factor used for the W-B50 wall was to low, which could contribute to an unreasonable result of the sound reduction index. Moreover one needs to specify the area of the transmitting wall, which is this case was set to $5m^2$ as it was closest to most of the walls in real life. WinFLAG does not calculate with any specific boundary conditions either, making it imprecise in the results.

Before being able to simulate acoustics, Odeon is in need of input values as absorption coefficients and sound reduction indices. Variables as materials of the surfaces and absorption coefficients were used without having exact information. The absorption of furnishings were unknown, so an approximation was used by finding such information elsewhere. The same was done with the absorption of the ceiling and floor surfaces, using an estimation of probable values. Still when comparing Odeon results to its input data, there are small variations. Therefore these uncertainties does not have an immensely large impact on the simulations. But these are considerations that often are unknown before on site measurements, and therefore must be thoroughly explored before usage in order to minimize sources of error. Additionally, Odeon does not take flanking paths into account. So when flanking paths are a big contribution to the sound transmisison, Odeon will not be able to calculate correctly.

Concerning the classical insulation measurements, there are some factors that contribute to uncertainty. Described in the ISO 10140 standard such measurements should be taken in appropriately large rooms that should have a minimum volume of $50m^3$. This was not the case for these measurements, where the largest room barely was above $20m^3$. Therefore a measurement taken close to the sound source in a small room could lead to a better perception of the partition wall insulation than it actually is. Another factor is that the partition wall is smaller than $10m^2$. As mentioned in the standard, when the partition is smaller than $10m^2$ one should use $10m^2$ as the area in the calculations for the measured reduction index. This will also lead to a better reduction of the wall than it actually possesses. Additionally, the reverberation measurements were only performed one time in one microphone position, which will lead to a significant level of uncertainty when the reverberation measurement has not been repeated a certain number of times to reduce the standard error.

Concerning the wall impact measurements there are many sources of error because it is not a standardized method. For example it was difficult to make sure the same height was implemented at each impact. Therefore one is not sure if the same amount of impact force was identical for each repetition, which leads to variations in the obtained results. The preset measuring time on the sound level analyzer was only eight seconds, so the impact was most likely recorded somewhere during the first five seconds. This was not consistent, therefore the measured decay was of different length for all impacts. In addition the source impact was conducted inside the source room, this will contribute to an airborne noise source as well. This airborne noise will then contribute to the measurement results with airborne sound transmission through the partition wall. However, the amount of this contribution is unknown.

Chapter 6

Further Work

This chapter provides some recommendations for what the continued work should be focused on.

The insulation results in this work are based on a standardized measurement technique. But this thesis was based upon seven cases measured twice, which is not a large test scale. Therefore, to describe the partition wall more accurately a larger number of measurements should be done to reduce the standard error. Additionally only one reverberation measurement was done in each receiver room, causing a rather high uncertainty. The reverberation measurement should have been repeated several times at different microphone positions. A comparison between measured reverberation times and predicted reverberation in Odeon has not been done, this can be further explored. Another way of focusing more on the performance of the wall panel alone, is to perform the insulation measurements in a reverberation room that is large enough according to standards. Furthermore, the results show a difference in reduction with the source positions in case 5. One can investigate the influence of source positions when measuring the insulation of a wall.

Moreover, the challenge of theoretically calculating the transmission of a perforated and corrugated wall is a source of new research. Today there are no simple ways of calculating a perforated and corrugated plate. Perforated and corrugated steel plates are widely used in the industry today, mostly to enhance other properties like weight and stiffness. These plates introduce another type of acoustic behaviour that has not been explored enough so far. The use of an equivalent thickplate for the perforated plate showed to have almost identical properties. In other words, exploring the use of equivalent layers in WinFLAG to perform calculations for a perforated or corrugated sheet could be of use. The use of WinFLAG for more complex wall types as the W-B50D could be further investigated together with proper measurements of such a wall in a reverberation room.

The software Odeon has previously not been used much for insulation problems because it is developed to predict the sound properties inside a single room. In this thesis work Odeon has been compared to the input data which was calculated with WinFLAG, but the original idea of checking if Odeon could be used to predict the transmission loss of two adjacent rooms has not been properly performed. Therefore an evaluation of Odeon simulations compared to both WinFLAG output and measurements should be done, in order to compare the results of the same wall type. Due to misinformation the hypothesis of using Odeon to predict transmission loss has not been carefully evaluated as previously wanted. In addition, the uncertainty of the prediction in Odeon has not been calculated. This value should be calculated and compared to the ISO standard to check if this type of prediction is within the uncertainty boundaries set for measurements.

Furthermore, WinFLAG is an efficient tool when needing input properties of the partition wall to simulate in Odeon. Comparisons between Odeon results and the input data were quite similar. However, one is not certain what caused the small differences between the rooms. A study of what influences the reduction index in Odeon compared to WinFLAG could be of interest. The factors as absorption coefficients of surfaces, geometry of the room or number of furniture could be taken into consideration.

The impact measurement method should be continued by developing a method for measuring flanking paths easily. The measurements done in this thesis work are not standardized and difficult to quality check because of few measurement positions. Therefore impact measurements should be done in a larger test scale to reduce the standard error and get more reliable results. Deciding the number of repetitions per position should be explored further, if three is enough or one should increase this number to reduce the standard error. In addition the number of positions per wall and placement of these should be standardized. More extensive measurements should be conducted exploring this method to confirm if it has any value of displaying the scope of flanking paths. The measurements were done in relatively small compartments, with the impact source on the inside of the source room. A new experiment should test if an impact source on the outside of the source room will show similar results as with the impact source within.

The work should be continued with testing in larger adjacent rooms as well, to see if the distance of the traveling path has an impact on the measurements. Moreover the theory behind a measurement like this has not been calculated. What does the vibrations in the wall caused by a steel ball look like? How do they travel along their path to the receiver room? This thesis performed the experiment onboard a ship, where there are numerous steel constructions that can be flanking paths. Therefore to establish the pure connection between two adjacent rooms a similar method should be used in a construction consisting of only two rooms. In this way there would be no extensive construction contributing to the results.

Chapter 7

Conclusion

In this thesis work various techniques have been explored to theoretically predict the sound reduction index of a sandwich wall, together with sound insulation measurements and development of an impact source system. Here are the conclusions of the conducted thesis:

- The software WinFLAG is easy to use and understand, but introduces challenges when dealing with a complicated structured wall. The simplest way of predicting the sound reduction index of a corrugated and perforated sandwich wall is to find an equivalent layer for the entire core instead of introducing different layers. The models studied in this thesis vary with thickplates, perforated plate and air. The introduction of air to simulate the air gaps in the corrugated steel sheet does not result in reasonable reduction levels because it leads to too much absorption at high frequencies. The equivalent single layer core displayed a sound reduction index of $R_w = 42$dB, while the averaged sound reduction index of the measurements was $R_w = 45$dB. Using the equivalent core was the simplest way of predicting the sound reduction of the wall, and this model matched best with the measurements up to 1.6 GHz.

- Odeon was used to simulate the sound fields in the rooms, along with a classical calculation of the reduction index of the first type of wall, W-B50. The simulations showed that the sound sources kept a constant field within the rooms, usually with a maximum variation of about 2 dB. Room case 5 showed a large difference in the reduction rate between the two source positions. When the source was close to the partition wall the sound reduction index was at its lowest level, while far from the wall the reduction increased. The calculation of the sound reduction indices in Odeon showed compliance with the used input data with little variability, showing that Odeon will behave similarly to the output from WinFLAG even though variabilities as area and absorption are included.

- Even though a comparison between Odeon and the measurements was not possible due to the walls being two different constructions, Odeon can be used as a means to predict the sound reduction of a wall assuming the input data is accurate and there are no major flanking paths. If the prediction can not be done correctly in WinFLAG there is no point of using it as input data in Odeon. To conclude, a wall of simple construction can be easily predicted with the means of WinFLAG and Odeon, but it fails to produce exact values when a wall is as complicated as the W-B50D. The advantage of using Odeon in addition to WinFLAG is that one can introduce different variables to check the influence of for example furniture or source positions.

- The insulation measurements showed either a compliance or performed better than the manufacturer's given weighted sound reduction index $R_w = 41dB$. The measured weighted sound reduction indices in the seven room cases ranged from $41dB - 47dB$, most of them being above the manufacturer's value. The larger rooms displayed a higher reduction than the small ones, and room case 5 showed a difference of $3 - 4dB$ between the two source positions. Case 5 was not of a rectangular shape as the other rooms, and this characteristic behaviour corresponds to the Odeon simulations.

- The tested impact method proved to show some flanking paths. Overall the average results displayed that the impact on the partition wall was higher than the side and rear wall, showing little noise traveling through flanking paths. This indicates few rigid connections and a well built structure. When looking at the results individually however, the room cases at the ship side proved to have worse insulation on the side wall. At low frequencies the transmitted sound from the impact source at the side wall reached the same level as the partition wall, which displays sound traveling through flanking paths through the side wall. The connection between these ship side cabins is that all had a window constructed together with the outer hull. To conclude, the impact method displays some flanking, and can be a valuable attribute if the method is further developed.

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[35] Steel poisson(visited on 04.09.2015). https://www.engineersedge.com/materials/poissons_ratio_metals_materials_chart_13160.htm, .

[36] Pvc loss factor(visited on 03.09.2015). https://books.google.no/books?id=jDeRCSqtev4C&pg=PA410&lpg=PA410&dq=loss+factor+pvc+acoustics&source=bl&ots=dGg6xt-b_4&sig=owRbkDvD65ql0OrV3mGNcWRpq4w&hl=no&sa=X&ved=0CB0Q6AEwAGoVChMI4r_r1OXaxwIVR4osCh1AIAo3#v=onepage&q=loss%20factor%20pvc%20acoustics&f=false, .

[37] S. S. Jung, Y. T. Kim, Y. B. Lee, S. H. Shin, D. Kim, and H. C. Kim. Measurement of the resonance frequency, the loss factor, and the dynamic young's modulus in structural steel and polycarbonate by using an acoustic velocity sensor. *Journal of the Korean Physical Society*, 49(5):1961–1966, November 2006.

[38] Absorption of common household materials(visited on 09.09.2015). http://www.audiorecording.me/absorption-coefficient-of-common-household-materials-diy-treatment.html/2.

Appendix A

Appendix

Absorption measurements for SeaRox products. Figure A.1 [26] displays 50 mm SeaRox 320, figure A.2 [27] displays 50 mm SeaRox 340 and A.3 [28] displays 2x50 mm SeaRox 340.

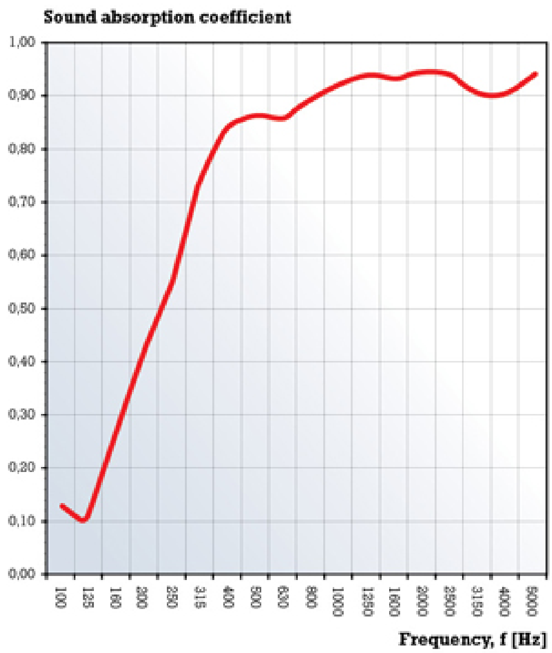


Figure A.1: SeaRox 320 absorption measurement, 50 mm.

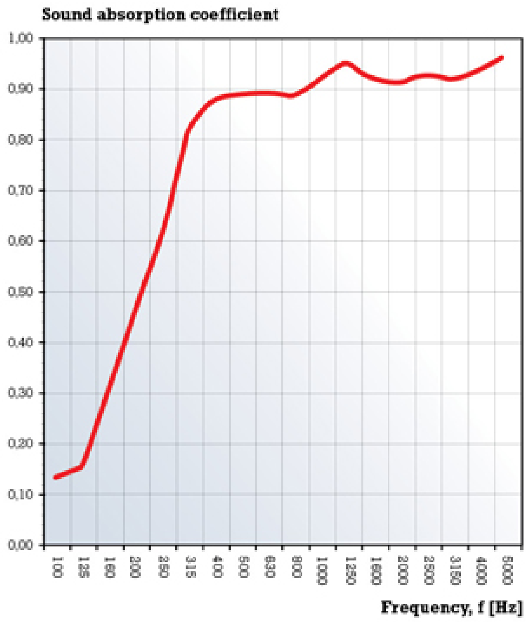


Figure A.2: SeaRox 340 absorption measurement, 50 mm.

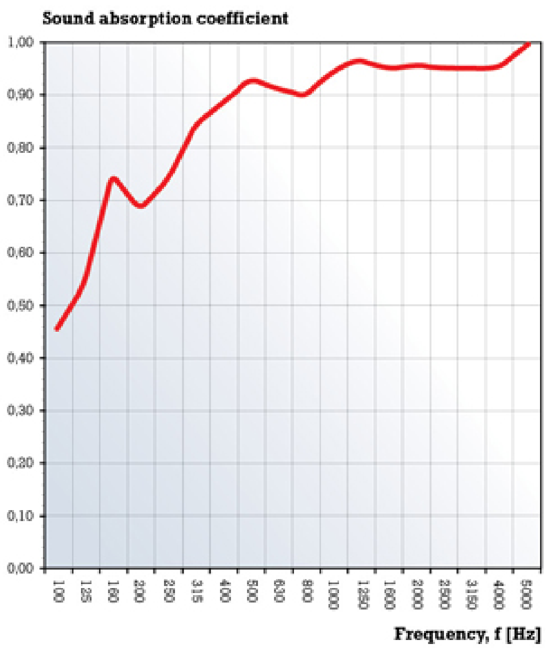


Figure A.3: SeaRox 340 absorption measurement, 2x50 mm.

Appendix **B**

Appendix

Detailed descriptions of the parameter values used in WinFLAG for wall panels W-B50 and W-B50D.

	PVC film	**Galvanized steel**	**Mineral wool**
Thickness [mm]	0.15 mm	0.6 mm	48.5/23.5 mm
Density [kg/m^3]	1380 kg/m^3 [29]	7850 kg/m^3 [30]	140 kg/m^3 [31]
E-modulus	3.25 [32]	200 [33]	-
Poissons number	0.3858 [34]	0.285 [35]	-
Loss factor	0.3 [36]	0.002 [37]	-
Resistivity [$kPas/m^2$]	-	-	90 $kPas/m^2$ [8]

Table B.1: Parameters used for wall panel W-B50.

TEST 1	**Steel plate**	**Wool thickplate**
Thickness	0,6 mm	48.5 mm
Density	7800 kg/m^3	200 kg/m^3
E-modulus	200 GPa	200 GPa
Poissons number	0,3	0,2
Loss factor	0,05	0,5

Table B.2: Parameters for test 1, wall panel W-B50D.

TEST 2	**Steel plate**	**Wool thickplate**	**Equivalent perf. thickplate**
Thickness	0.6 mm	15 mm	15 mm
Density	7800 kg/m^3	200 kg/m^3	2 kg/m^3
E-modulus	200 GPa	500 GPa	0.01 GPa
Poissons number	0,3	0,2	0.2
Loss factor	0,05	0,5	0.05

Table B.3: Parameters for test 2, wall panel W-B50D.

TEST 3	**Steel plate**	**Wool thickplate**	**Perforated plate**
Thickness	0.6 mm	15 mm	0.4 mm
Density	7800 kg/m^3	200 kg/m^3	7800 kg/m^3
E-modulus	200 GPa	500 GPa	-
Poissons number	0,3	0,2	-
Loss factor	0,05	0,5	-
Diameter holes	-	-	3 mm
Area/hole	-	-	30 mm^2
Resistance	-	-	0 Pa$\frac{s}{m}$

Table B.4: Parameters for test 3, wall panel W-B50D.

TEST 4	**Steel plate**	**Wool thickplate**	**Air**	**Perforated plate**
Thickness	0.6 mm	15 mm	8 mm	0.4 mm
Density	7800 kg/m^3	200 kg/m^3	-	7800 kg/m^3
E-modulus	200 GPa	600 GPa	-	-
Poissons number	0,3	0,2	-	-
Loss factor	0,05	0,5	-	-
Diameter holes	-	-	-	3 mm
Area/hole	-	-	-	30 mm^2
Resistance	-	-	-	0 Pa$\frac{s}{m}$

Table B.5: Parameters for test 4, wall panel W-B50D.

Appendix **C**

Appendix

Table of absorption coefficients for surfaces used in Odeon prediction.

Frequency [Hz]	**Floor+ceiling**	**Mattress** [38]	**Chair** [38]	**Plywood**
63	0,2	0,04	0,49	0,28
125	0,2	0,33	0,66	0,28
250	0,15	0,86	0,8	0,22
500	0,15	1,0	0,88	0,17
1000	0,1	1,0	0,82	0,09
2000	0,1	1,0	0,7	0,1
4000	0,1	1,0	0,7	0,11
8000	0,05	1,0	0,7	0,11

Table C.1: Absorption coefficient α used in Odeon predictions for all surfaces.

Appendix D

Appendix

Figures of the 3D-models made in SketchUP.

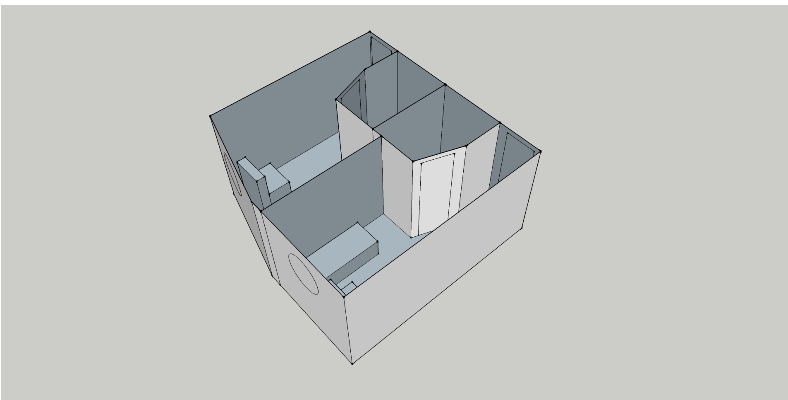


Figure D.1: 3D-model of case 1, B-Deck port side.

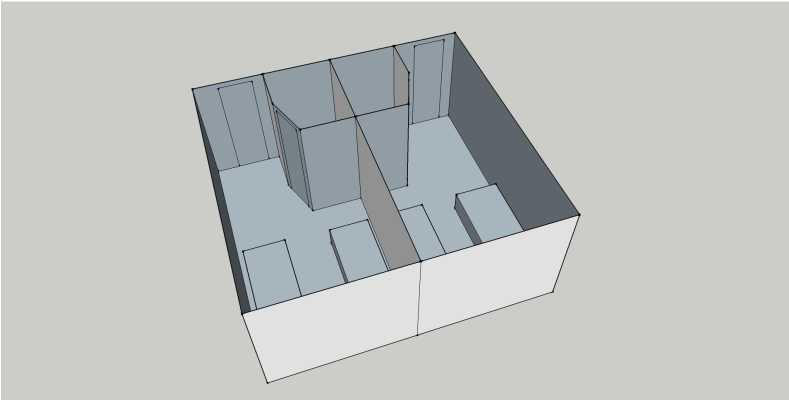


Figure D.2: 3D-model of case 2, B-Deck mid ship.

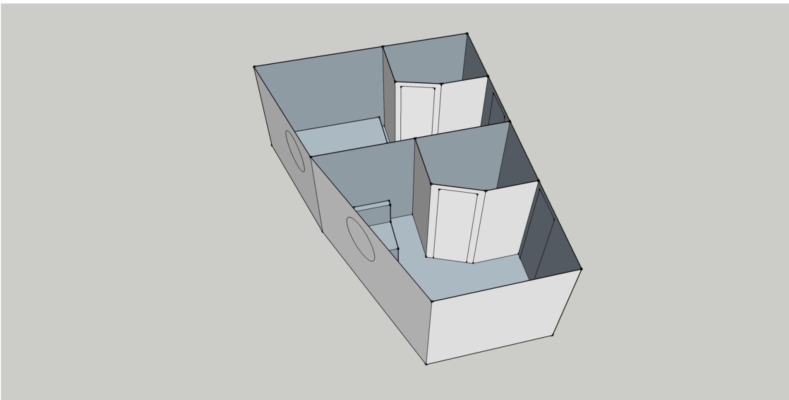


Figure D.3: 3D-model of case 3, B-Deck bow starboard side.

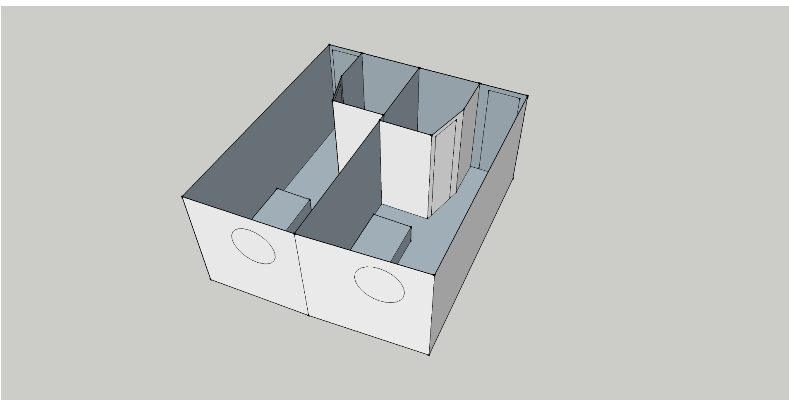


Figure D.4: 3D-model of case 4, B-Deck aft starboard side.

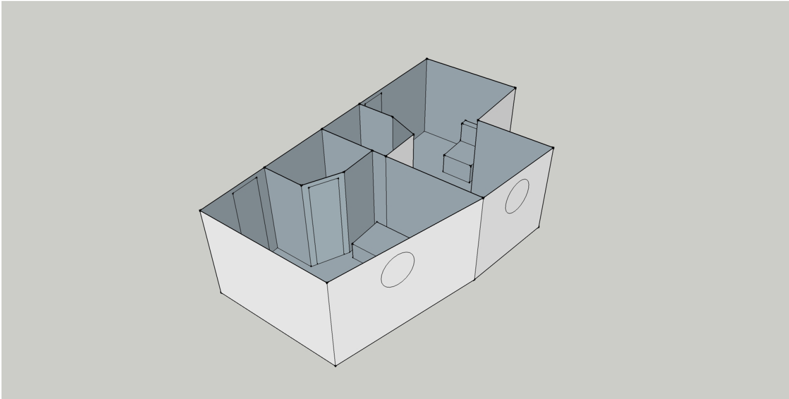


Figure D.5: 3D-model of case 5, C-Deck port side.

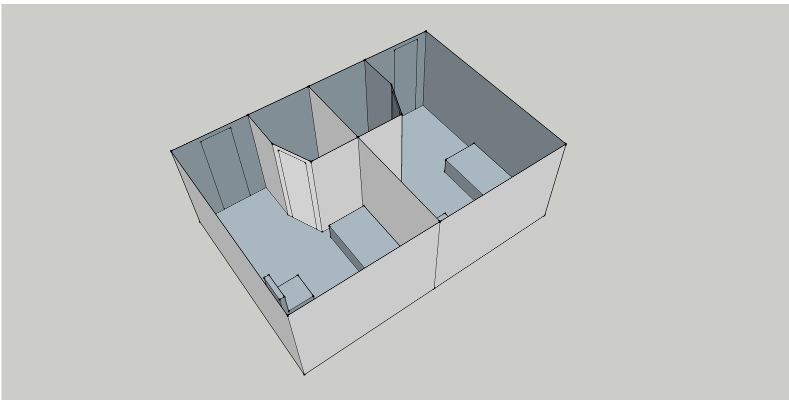


Figure D.6: 3D-model of case 6, C-Deck mid ship.

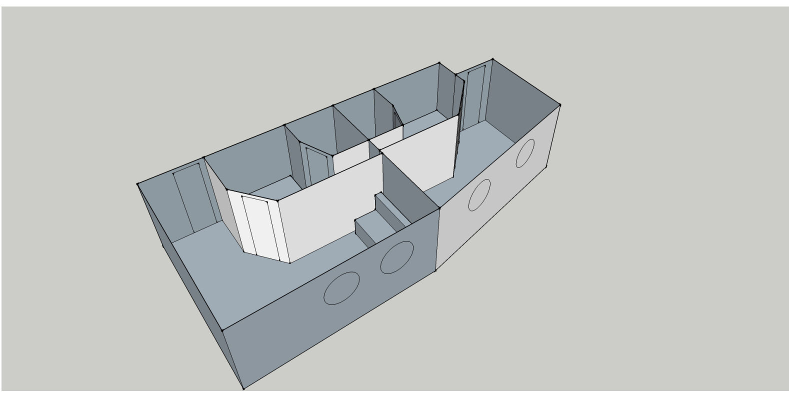


Figure D.7: 3D-model of case 7, C-Deck starboard side.

Appendix E

Appendix

Figures of microphone positions for predicted sound reduction indices in Odeon. Marked as the sound source in the figures is P1 while the numbers are the microphone positions.

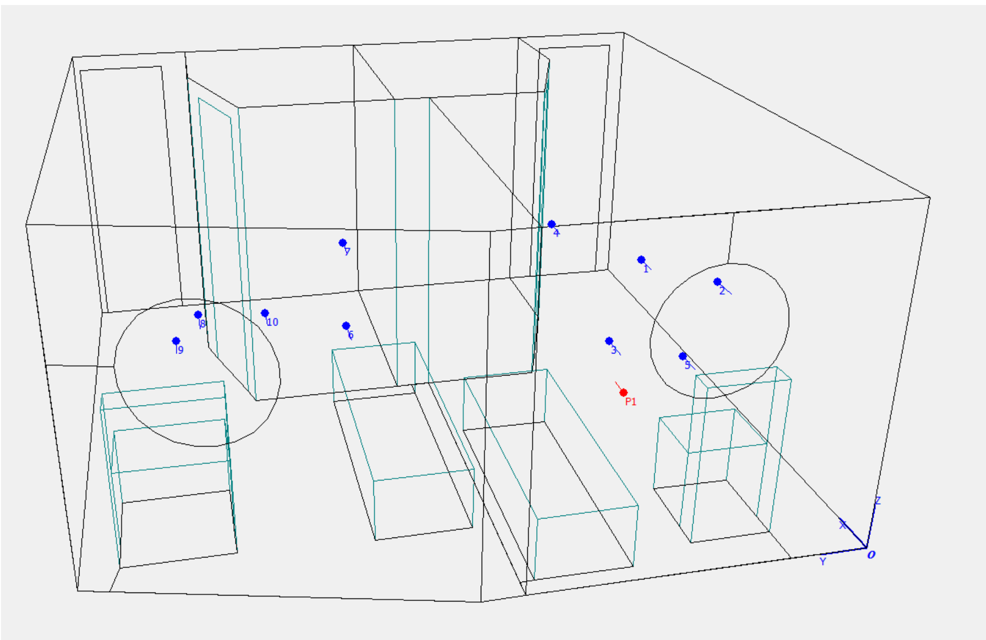


Figure E.1: Case 1, microphone positions for source position 1.

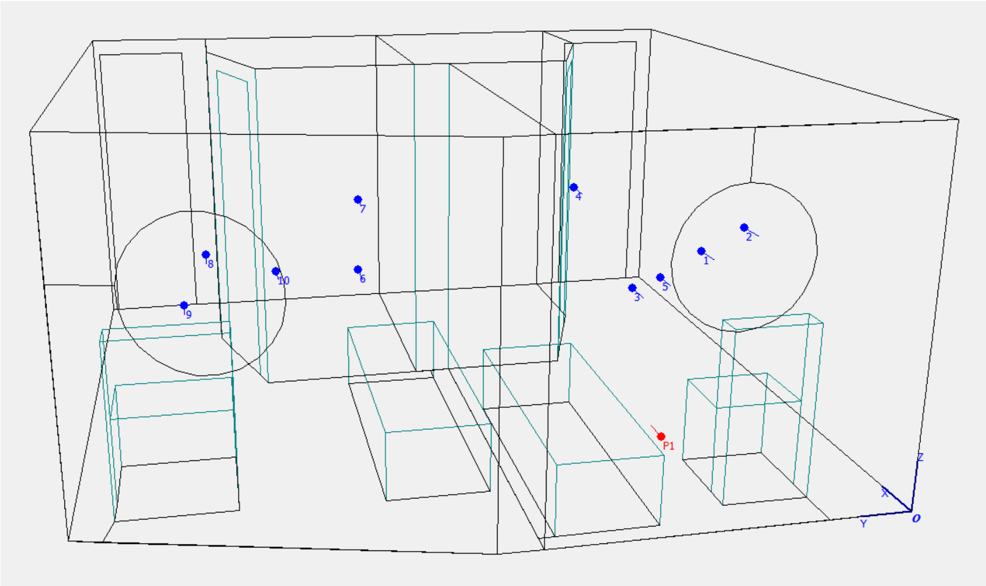


Figure E.2: Case 1, microphone positions for source position 2.

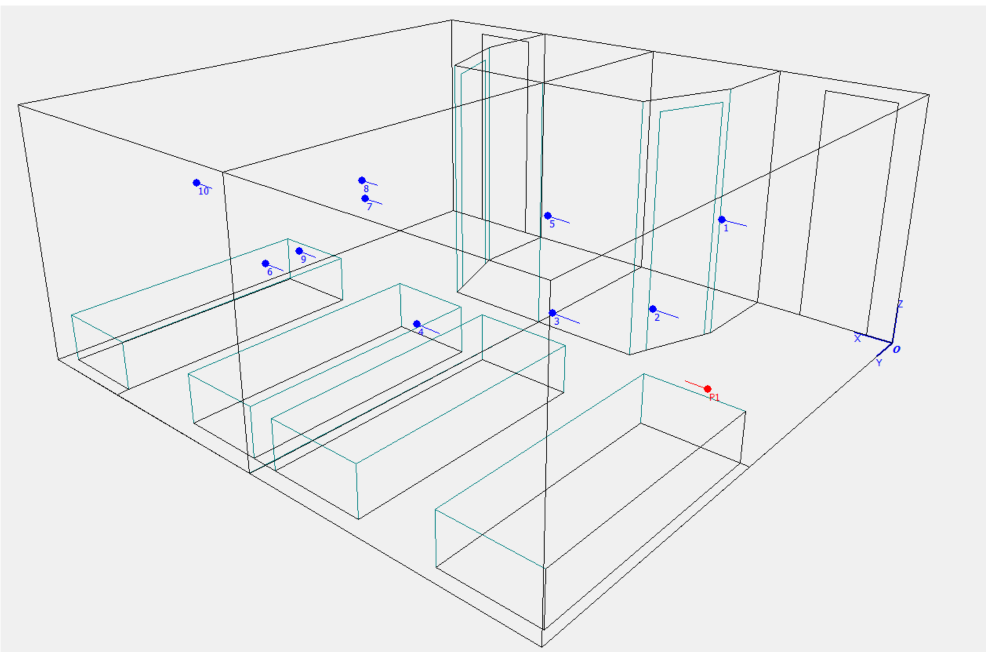


Figure E.3: Case 2, microphone positions for source position 1.

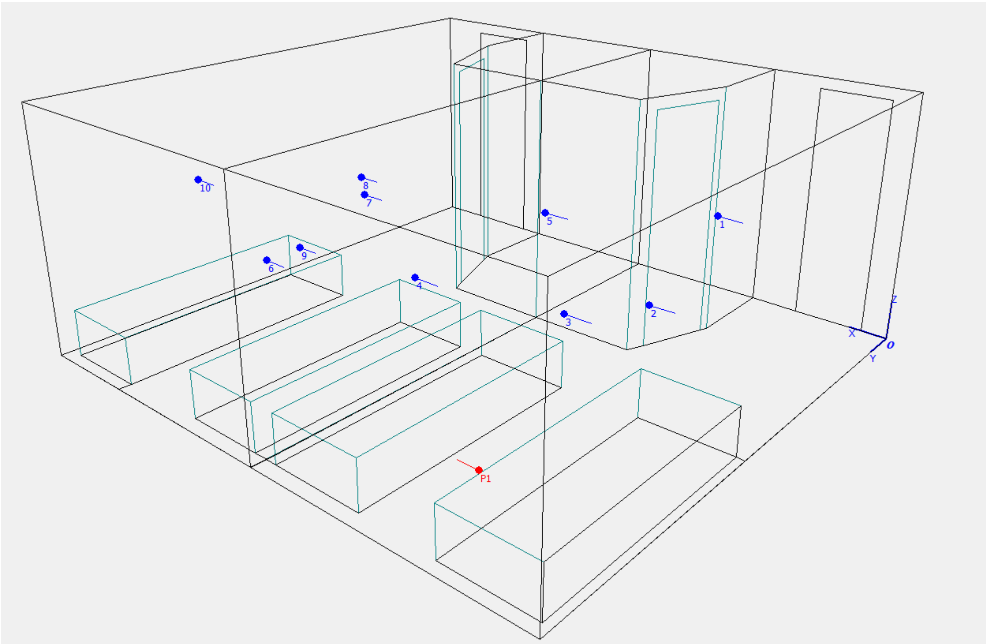


Figure E.4: Case 2, microphone positions for source position 2.

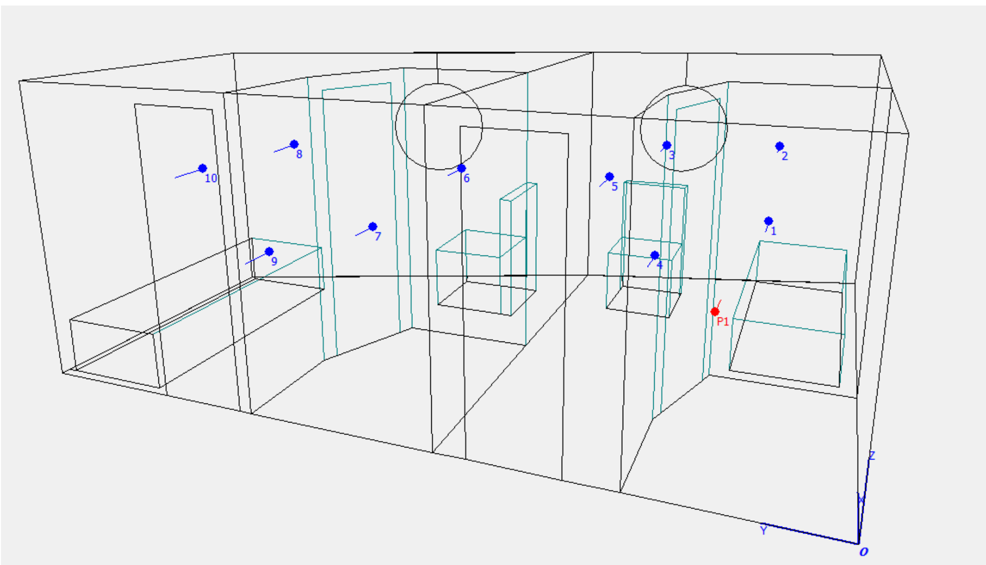


Figure E.5: Case 3, microphone positions for source position 1.

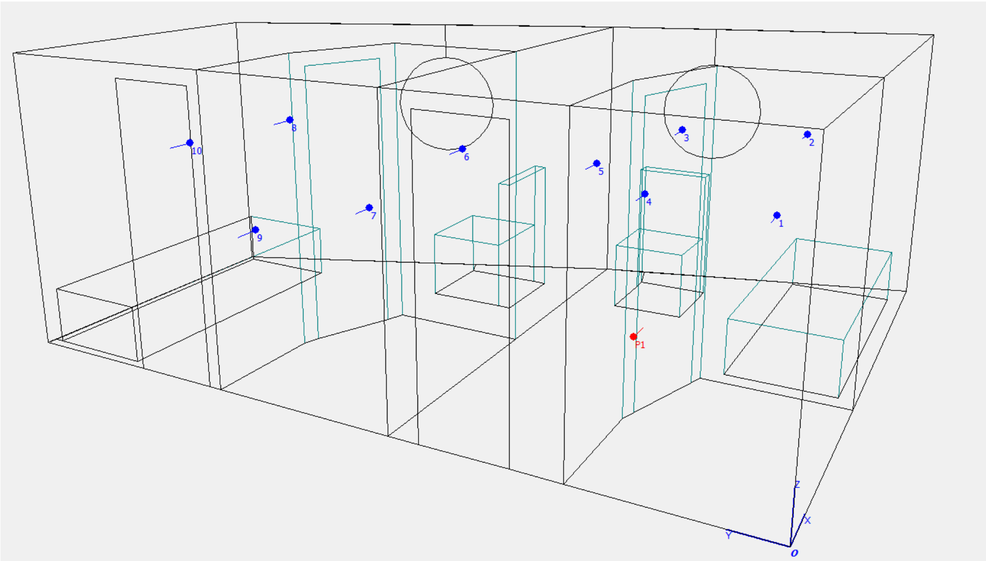


Figure E.6: Case 3, microphone positions for source position 2.

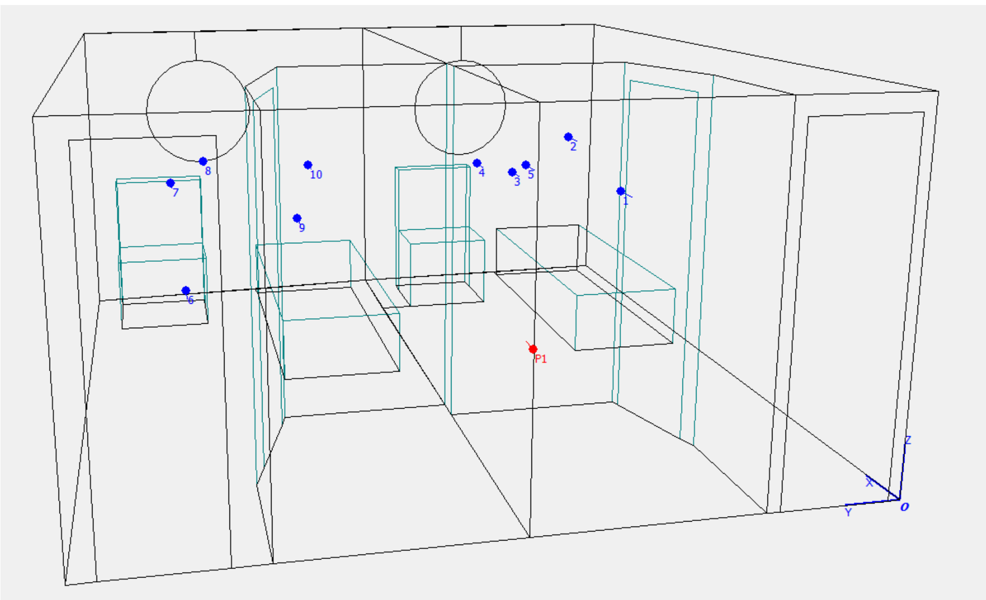


Figure E.7: Case 4, microphone positions for source position 1.

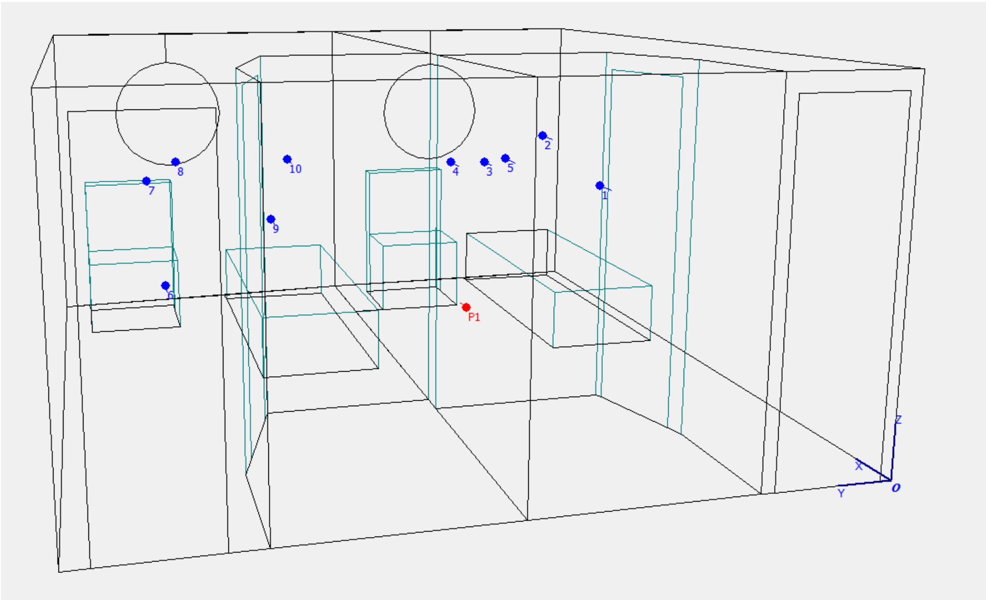


Figure E.8: Case 4, microphone positions for source position 2.

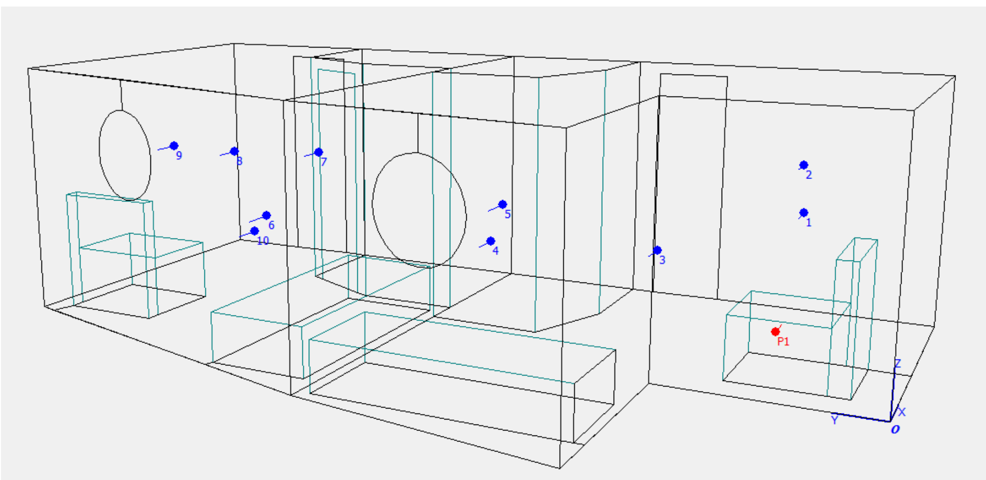


Figure E.9: Case 5, microphone positions for source position 1.

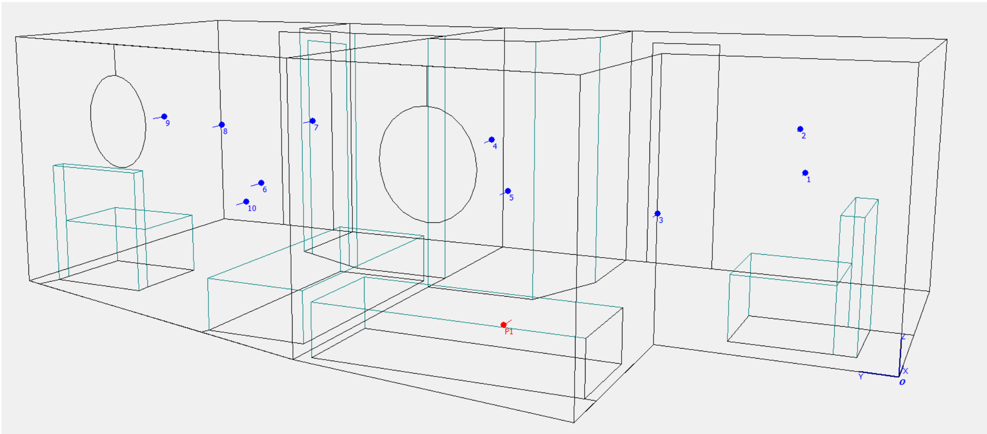


Figure E.10: Case 5, microphone positions for source position 2.

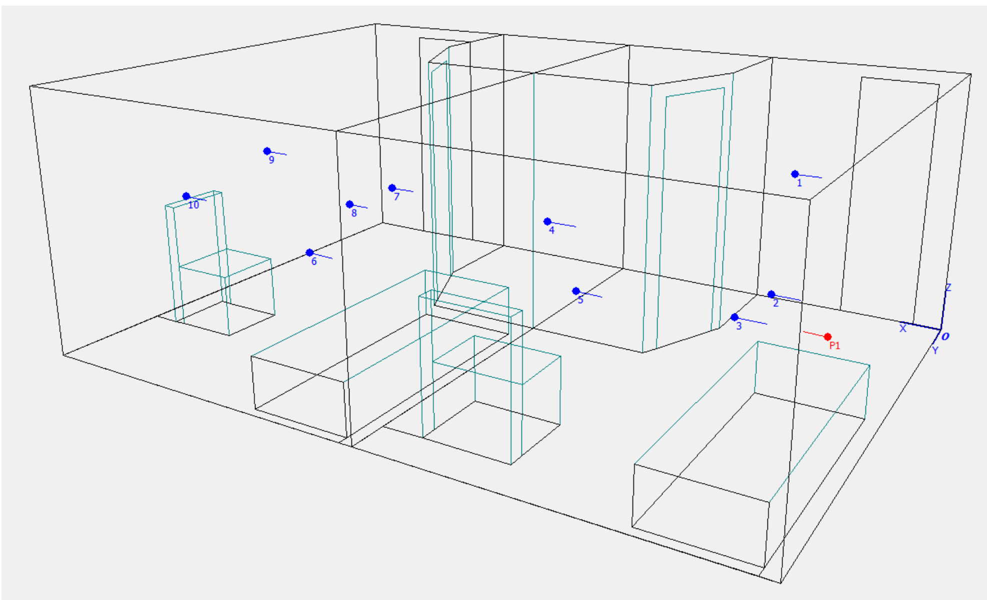


Figure E.11: Case 6, microphone positions for source position 1.

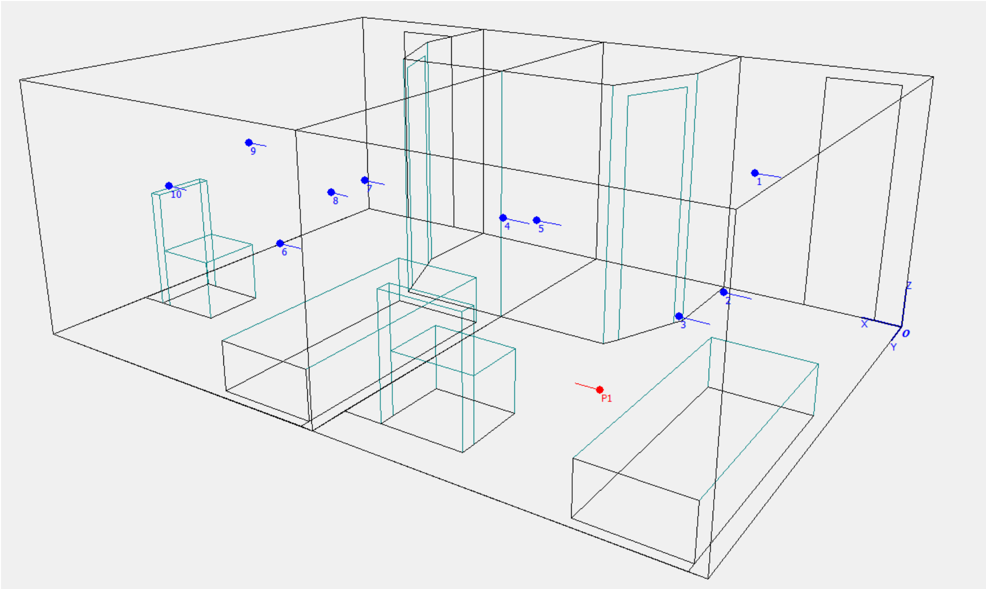


Figure E.12: Case 6, microphone positions for source position 2.

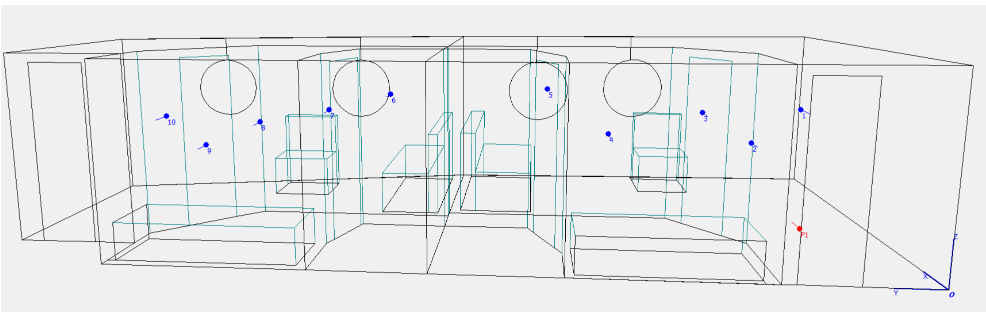


Figure E.13: Case 7, microphone positions for source position 1.

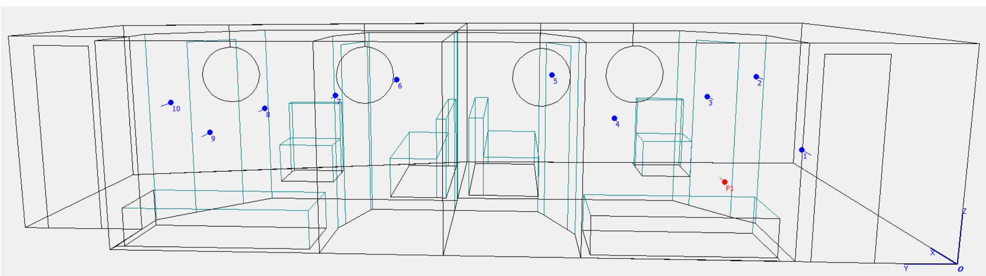


Figure E.14: Case 7, microphone positions for source position 2.

Appendix F

Appendix

Tables of the microphone positions showed in Appendix E.

Mic no.	Coordinates source 1	Coordinates source 2
1	(1.80, 0.72, 1.10)	(1.30, 0.70, 1.10)
2	(0.72, 0.72, 1.40)	(0.72, 0.72, 1.40)
3	(0.71, 1.35, 1.10)	(0.71, 1.35, 1.10)
4	(1.80, 1.35, 1.40)	(1.80, 1.35, 1.40)
5	(1.10, 0.70, 0.74)	(1.92, 0.70, 0.74)
6	(1.00, 2.80, 1.20)	(1.00, 2.80, 1.20)
7	(1.75, 2.70, 1.40)	(1.75, 2.70, 1.40)
8	(1.10, 3.60, 1.30)	(1.10, 3.60, 1.30)
9	(2.00, 3.75, 0.72)	(2.00, 3.75, 0.72)
10	(1.70, 3.20, 1.00)	(1.70, 3.20, 1.00)

Table F.1: Coordinates [x,y,z] of microphones for case 1.

Mic no.	Coordinates source 1	Coordinates source 2
1	(0.72, 1.75, 1.40)	(0.72, 1.75, 1.40)
2	(0.72, 2.60, 1.00)	(0.72, 2.60, 1.00)
3	(0.80, 3.60, 1.30)	(0.70, 3.60, 1.30)
4	(1.75, 3.80, 1.00)	(1.75, 3.80, 1.30)
5	(1.70, 2.50, 1.40)	(1.92, 0.70, 0.74)
6	(3.30, 3.80, 1.00)	(3.30, 3.80, 1.00)
7	(3.40, 2.70, 1.20)	(3.40, 2.70, 1.20)
8	(4.20, 2.00, 1.00)	(4.20, 2.00, 1.00)
9	(3.90, 3.00, 0.70)	(3.90, 3.00, 0.70)
10	(4.23, 3.70, 1.40)	(4.23, 3.70, 1.40)

Table F.2: Coordinates [x,y,z] of microphones for case 2.

Mic no.	Coordinates source 1	Coordinates source 2
1	(2.30, 0.70, 1.00)	(2.30, 0.70, 1.00)
2	(3.20, 0.72, 1.40)	(3.20, 0.72, 1.40)
3	(2.90, 1.60, 1.40)	(2.90, 1.60, 1.40)
4	(2.10, 1.50, 0.70)	(2.40, 1.70, 1.00)
5	(1.60, 1.75, 1.40)	(1.60, 1.75, 1.40)
6	(2.30, 3.20, 1.20)	(2.30, 3.20, 1.20)
7	(2.00, 3.90, 0.70)	(2.00, 3.90, 0.70)
8	(1.80, 4.50, 1.40)	(1.80, 4.50, 1.40)
9	(1.10, 4.30, 0.70)	(1.10, 4.30, 0.70)
10	(0.80, 4.60, 1.40)	(0.80, 4.60, 1.40)

Table F.3: Coordinates [x,y,z] of microphones for case 3.

Mic no.	Coordinates source 1	Coordinates source 2
1	(2.20, 0.70, 1.20)	(2.20, 0.70, 1.20)
2	(3.20, 0.72, 1.40)	(3.20, 0.72, 1.40)
3	(4.00, 0.90, 1.00)	(4.00, 0.90, 1.10)
4	(3.40, 1.35, 1.20)	(3.40, 1.35, 1.20)
5	(2.20, 1.35, 1.40)	(2.20, 1.35, 1.40)
6	(2.20, 3.50, 0.70)	(2.20, 3.50, 0.70)
7	(3.10, 3.55, 1.20)	(3.10, 3.55, 1.20)
8	(3.90, 3.30, 1.20)	(3.90, 3.30, 1.20)
9	(3.60, 2.65, 0.80)	(3.60, 2.65, 0.80)
10	(2.50, 2.70, 1.40)	(2.50, 2.70, 1.40)

Table F.4: Coordinates [x,y,z] of microphones for case 4.

Mic no.	Coordinates source 1	Coordinates source 2
1	(0.80, 0.80, 1.20)	(0.80, 0.80, 1.20)
2	(1.70, 1.00, 1.40)	(1.70, 1.00, 1.40)
3	(0.80, 1.90, 0.80)	(0.80, 1.90, 0.80)
4	(0.10, 3.00, 0.90)	(0.10, 3.00, 1.40)
5	(-0.80, 2.50, 1.40)	(-0.80, 2.50, 1.20)
6	(-0.30, 4.80, 1.00)	(-0.30, 4.80, 1.00)
7	(0.50, 4.80, 1.40)	(0.50, 4.80, 1.40)
8	(1.20, 6.20, 1.20)	(1.20, 6.20, 1.20)
9	(0.20, 6.10, 1.40)	(0.20, 6.10, 1.40)
10	(0.30, 5.35, 0.70)	(0.30, 5.35, 0.70)

Table F.5: Coordinates [x,y,z] of microphones for case 5.

Mic no.	Coordinates source 1	Coordinates source 2
1	(1.00, 1.00, 1.40)	(1.00, 1.00, 1.40)
2	(0.80, 2.00, 0.80)	(0.80, 2.00, 0.80)
3	(0.70, 3.00, 1.00)	(0.70, 3.00, 1.00)
4	(2.00, 3.00, 1.40)	(2.00, 3.00, 1.40)
5	(2.10, 2.40, 0.70)	(2.10, 2.40, 1.20)
6	(3.70, 3.40, 1.00)	(3.70, 3.40, 1.00)
7	(3.80, 2.30, 1.20)	(3.80, 2.30, 1.20)
8	(4.90, 1.50, 0.70)	(4.90, 1.50, 0.70)
9	(4.90, 2.50, 1.40)	(4.90, 2.50, 1.40)
10	(5.00, 3.30, 1.20)	(5.00, 3.30, 1.20)

Table F.6: Coordinates [x,y,z] of microphones for case 6.

Mic no.	Coordinates source 1	Coordinates source 2
1	(2.00, 0.80, 1.40)	(2.00, 0.80, 0.70)
2	(3.60, 0.90, 0.70)	(3.60, 0.90, 1.40)
3	(3.00, 1.70, 1.20)	(3.00, 1.70, 1.20)
4	(3.00, 2.90, 0.90)	(3.00, 2.90, 0.90)
5	(3.70, 3.70, 1.40)	(3.70, 3.70, 1.40)
6	(3.00, 5.80, 1.40)	(3.00, 5.80, 1.40)
7	(2.86, 6.60, 1.20)	(2.86, 6.60, 1.20)
8	(3.00, 7.60, 1.00)	(3.00, 7.60, 1.00)
9	(2.80, 8.30, 0.70)	(2.80, 8.30, 0.70)
10	(2.10, 8.50, 1.20)	(2.10, 8.50, 1.20)

Table F.7: Coordinates [x,y,z] of microphones for case 7.

Appendix G

Appendix

Sound source positions for the sound insulation measurements.

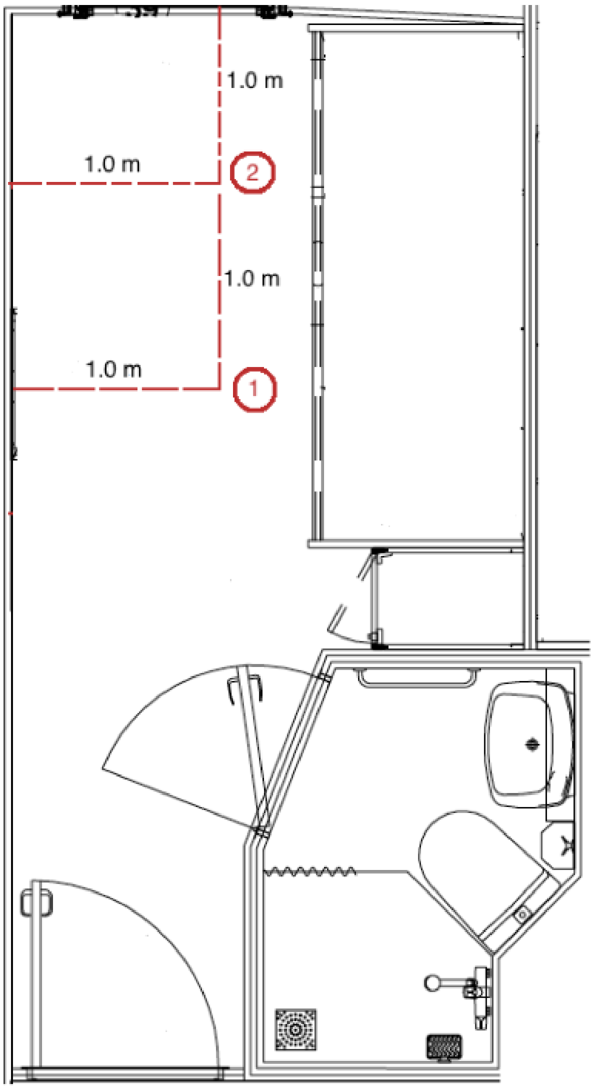


Figure G.1: Case 1, source positions for first round.

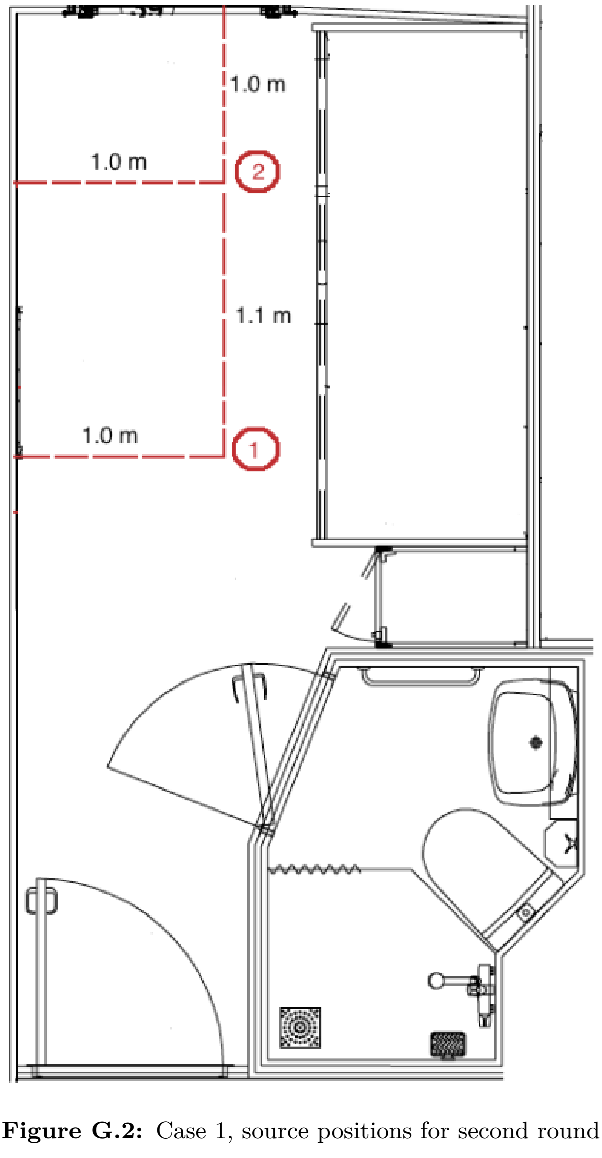


Figure G.2: Case 1, source positions for second round.

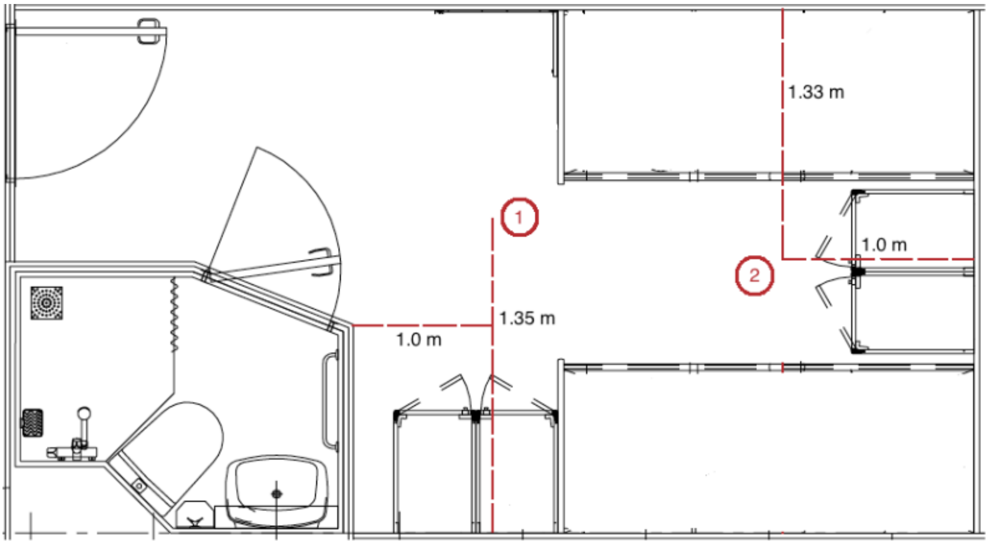


Figure G.3: Case 2, source positions for first round.

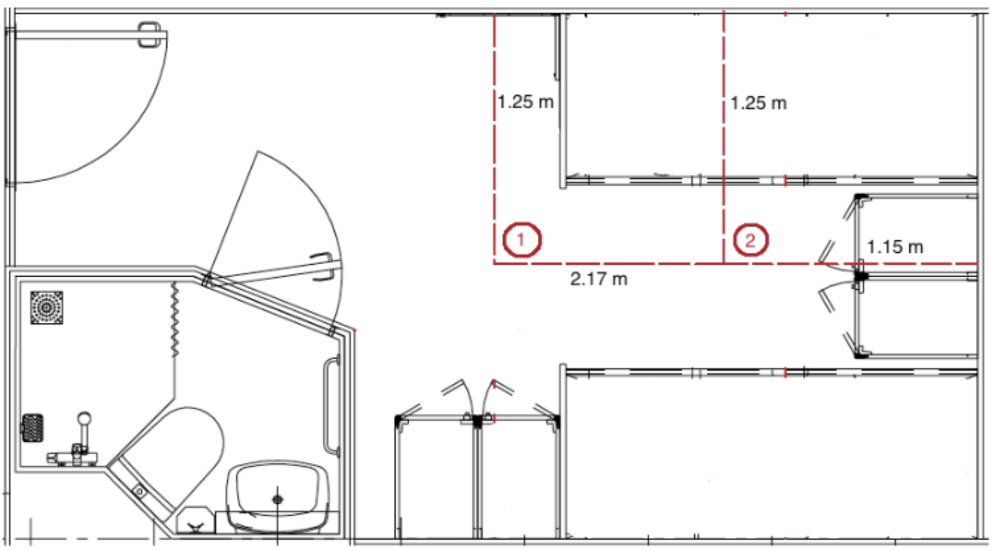


Figure G.4: Case 2, source positions for second round.

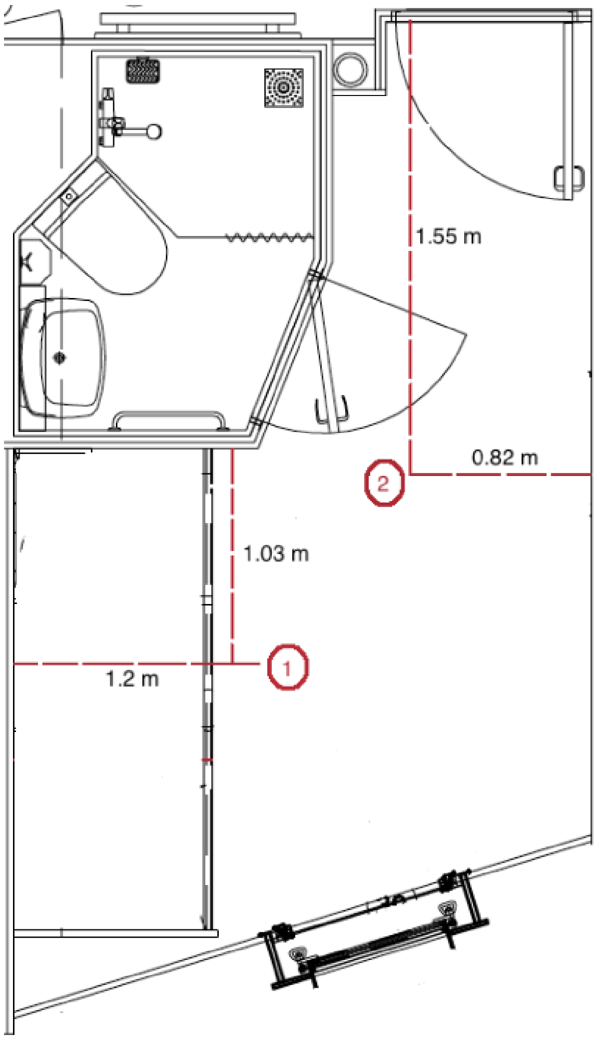


Figure G.5: Case 3, source positions for first round.

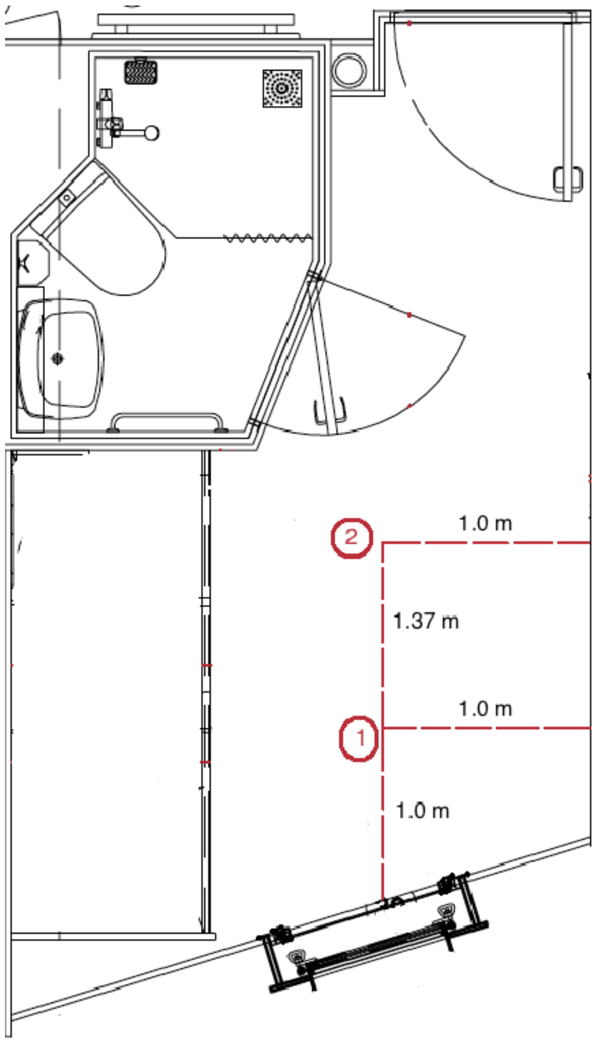


Figure G.6: Case 3, source positions for second round.

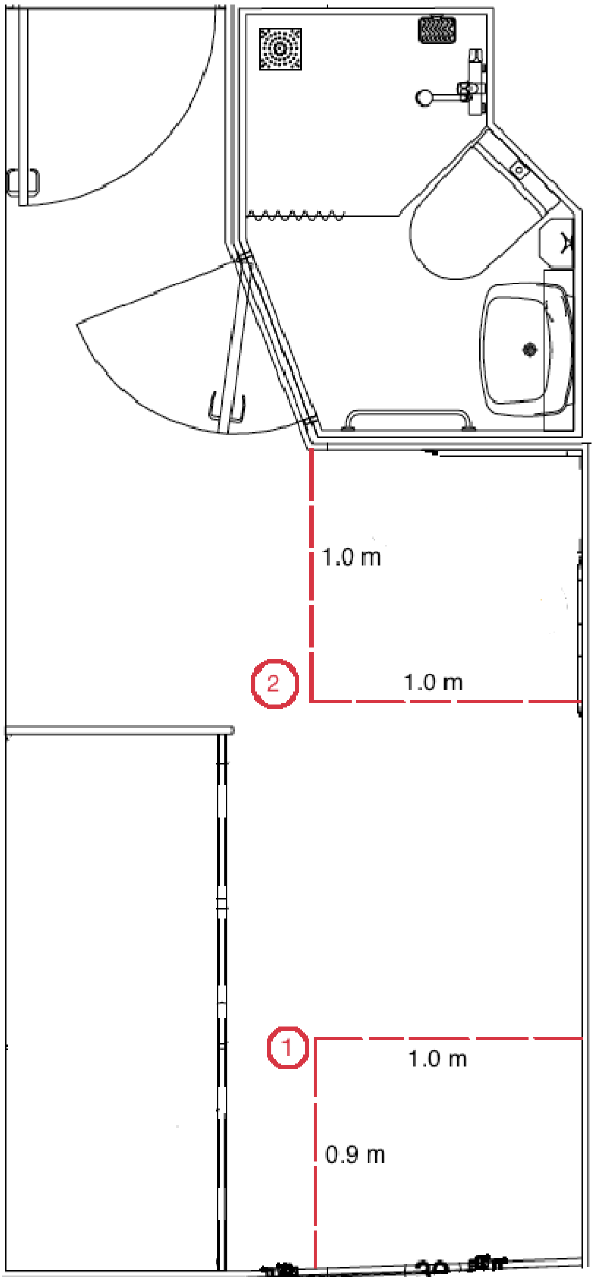


Figure G.7: Case 4, source positions for first round.

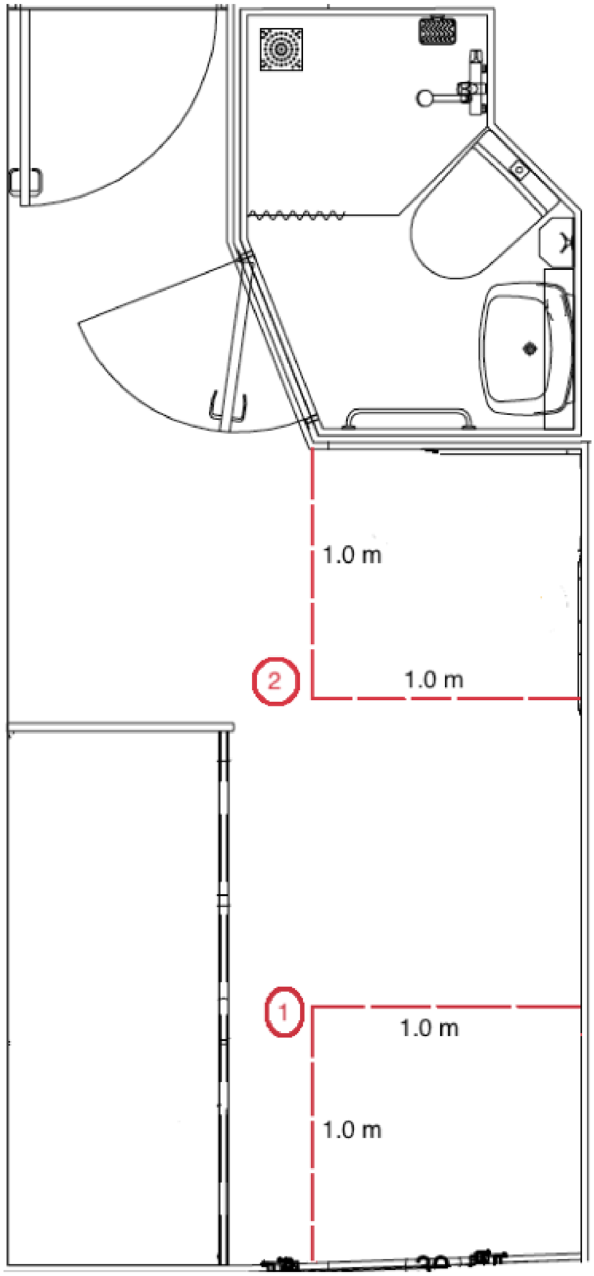


Figure G.8: Case 4, source positions for second round.

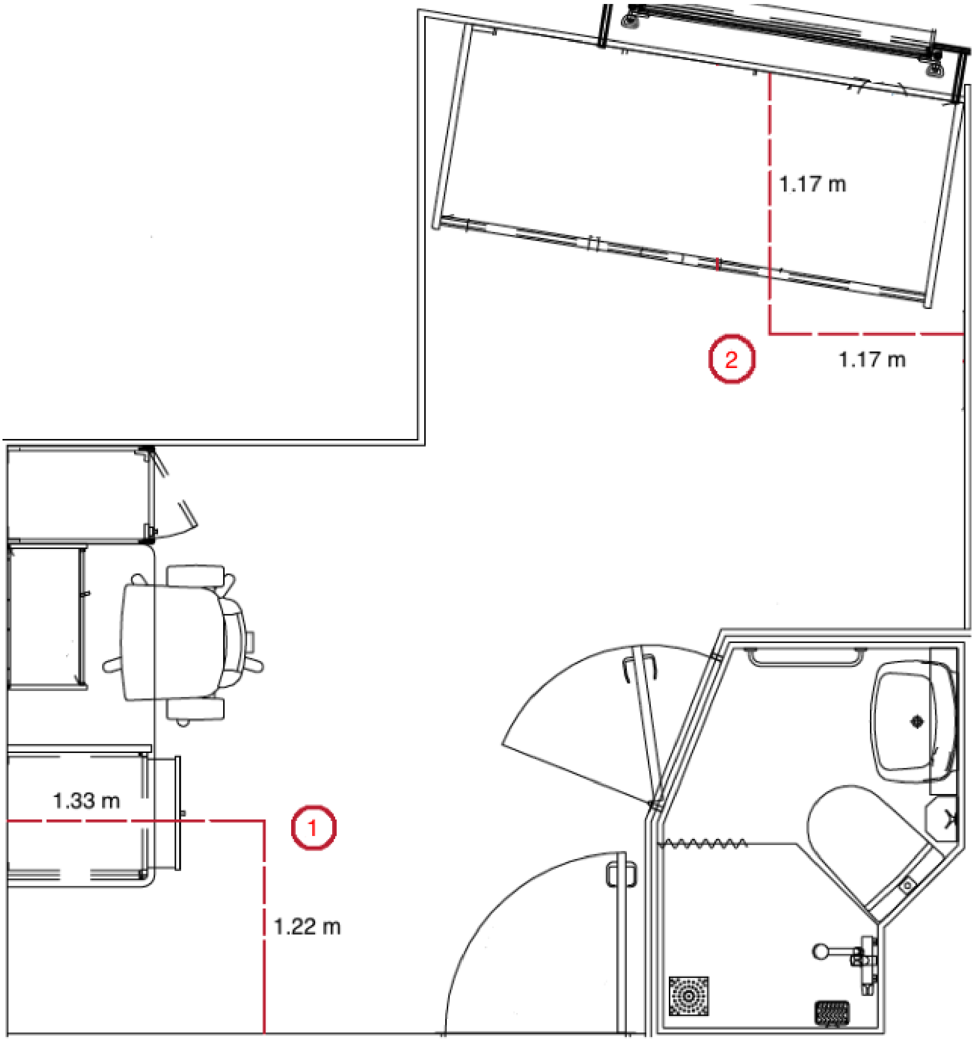


Figure G.9: Case 5, source positions for first round.

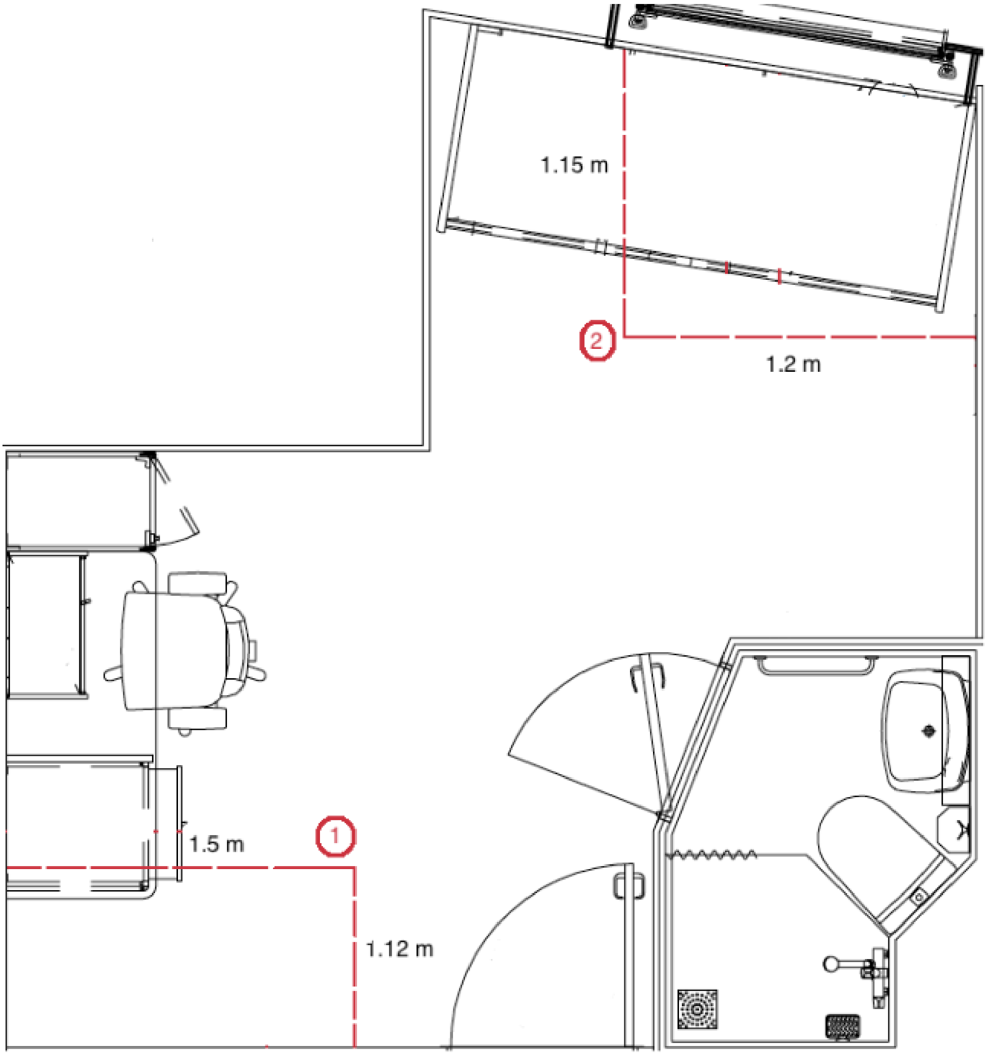


Figure G.10: Case 5, source positions for second round.

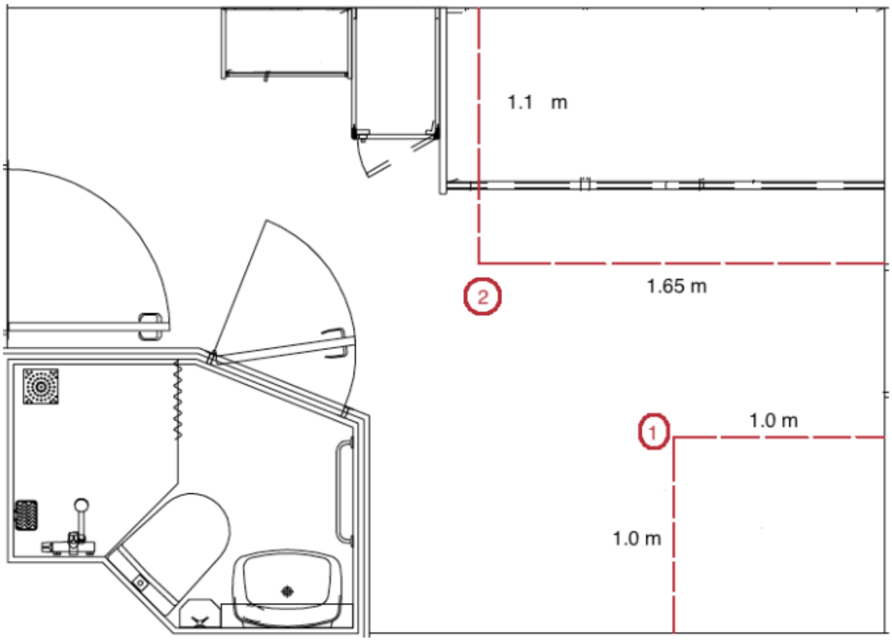


Figure G.11: Case 6, source positions for first round.

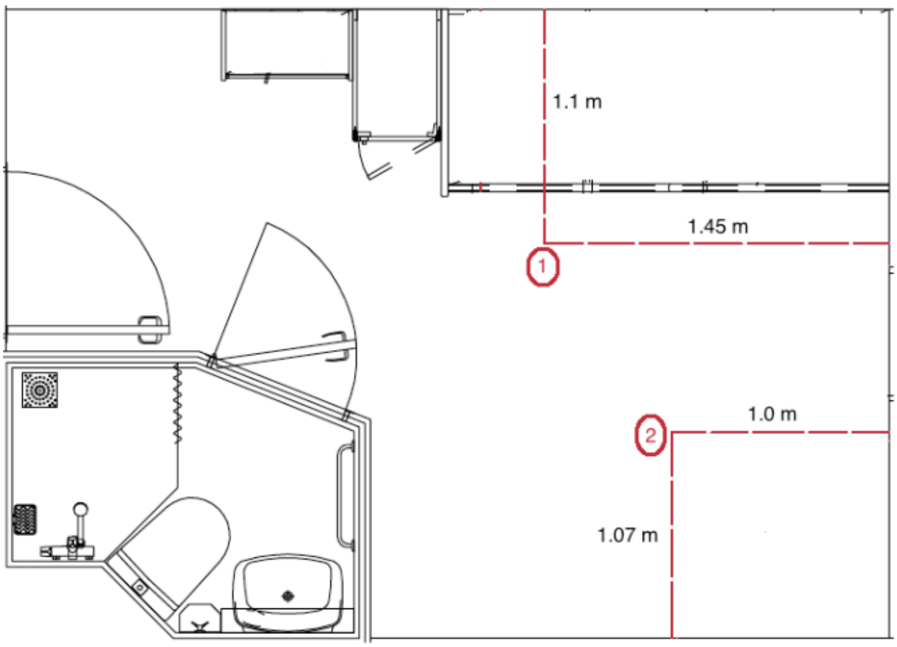


Figure G.12: Case 6, source positions for second round.

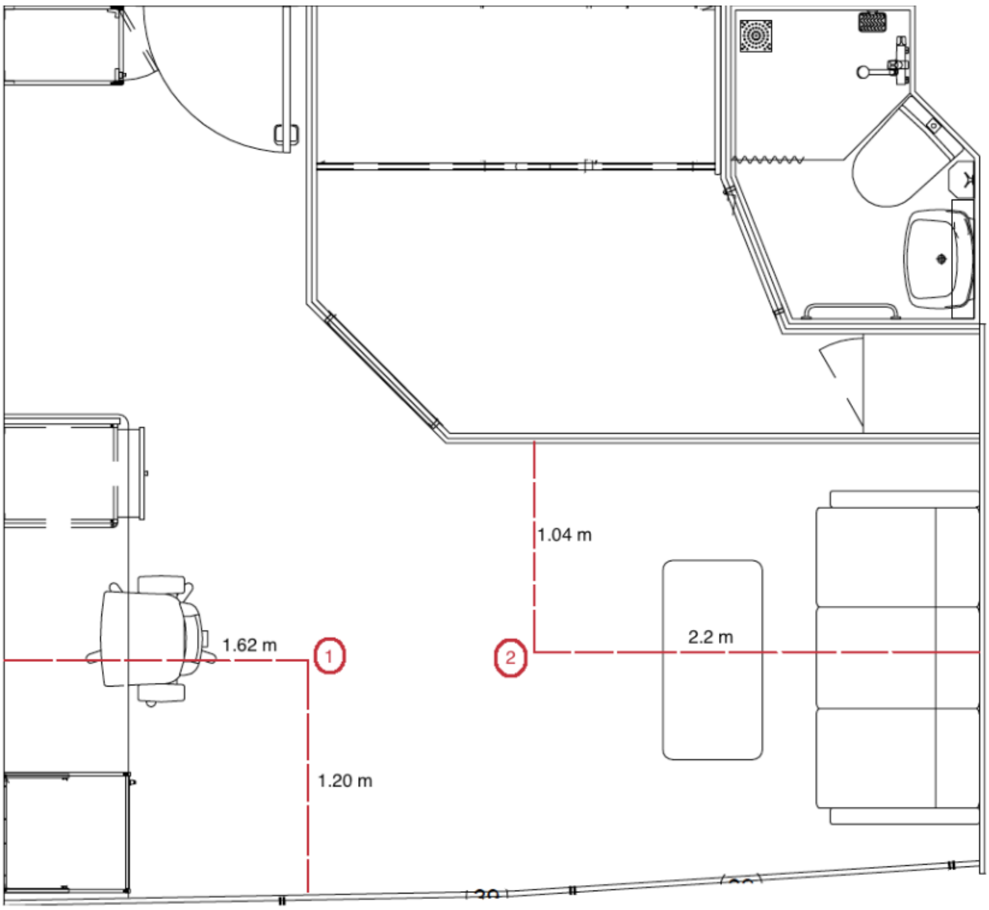


Figure G.13: Case 7, source positions for first round.

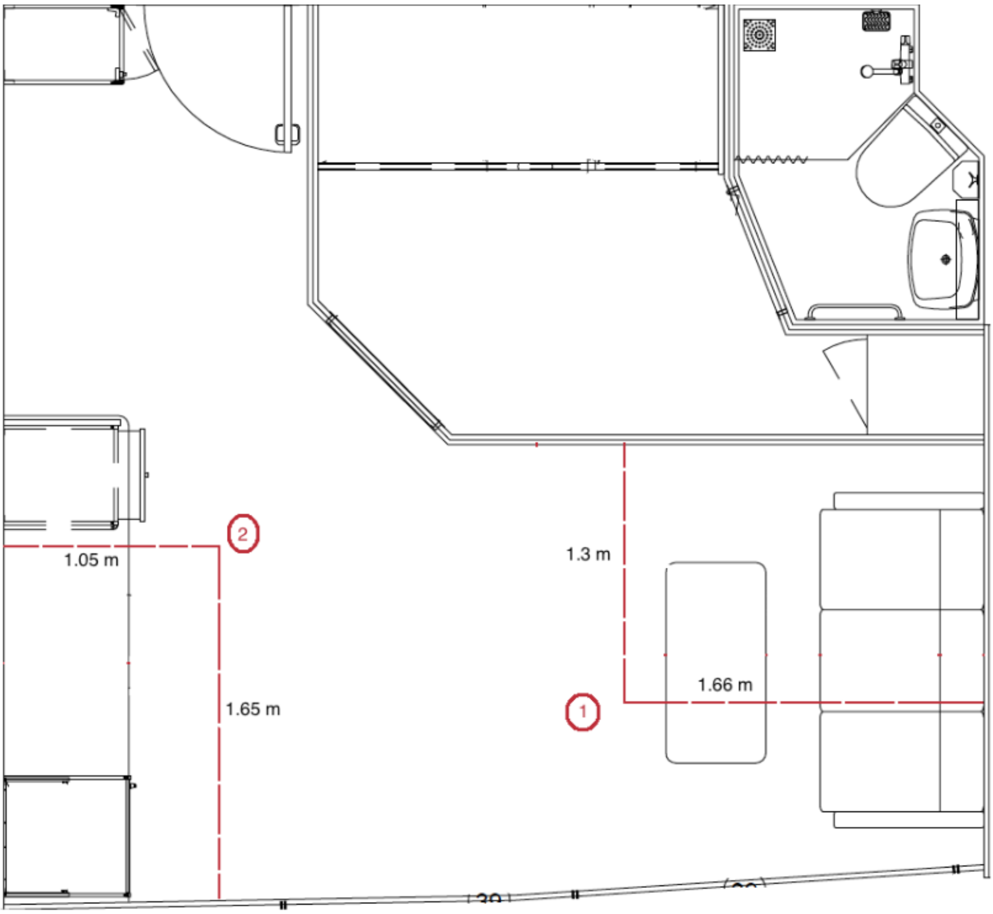
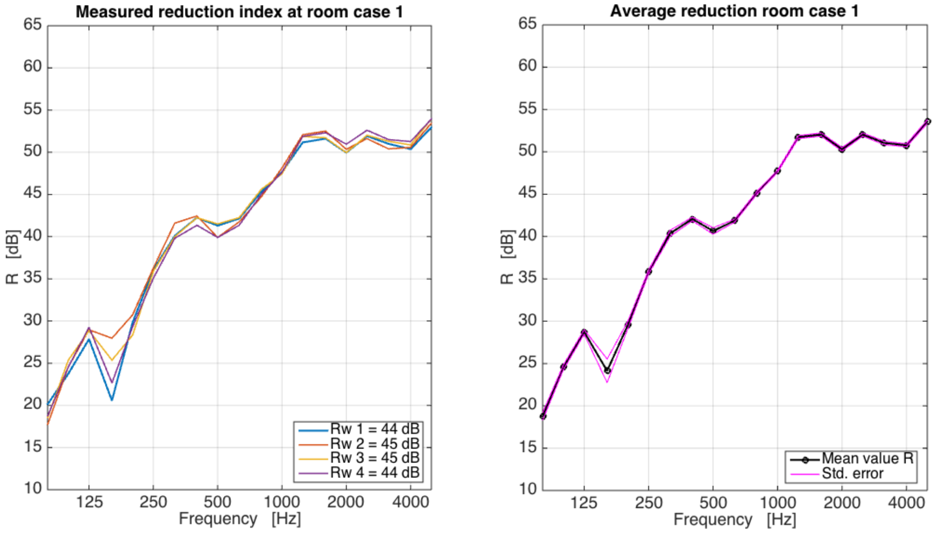


Figure G.14: Case 7, source positions for second round.

Appendix H

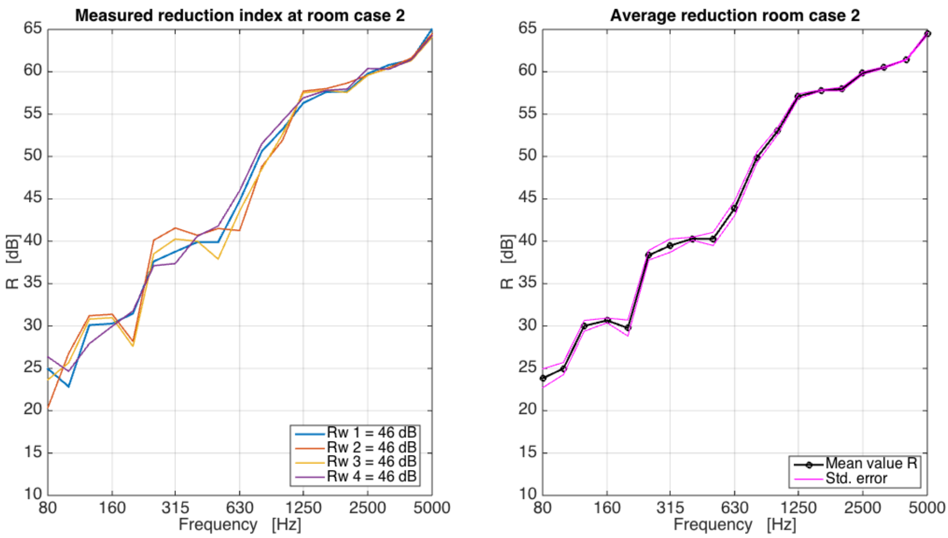
Appendix

Detailed figures of measured sound reduction indices for each case.
R_w1 and R_w2 displays the reduction indices for source position 1 and 2 for the first round of measurements, and R_w3 and R_w4 displays the reduction indices for source position 1 and 2 for the second round of measurements.



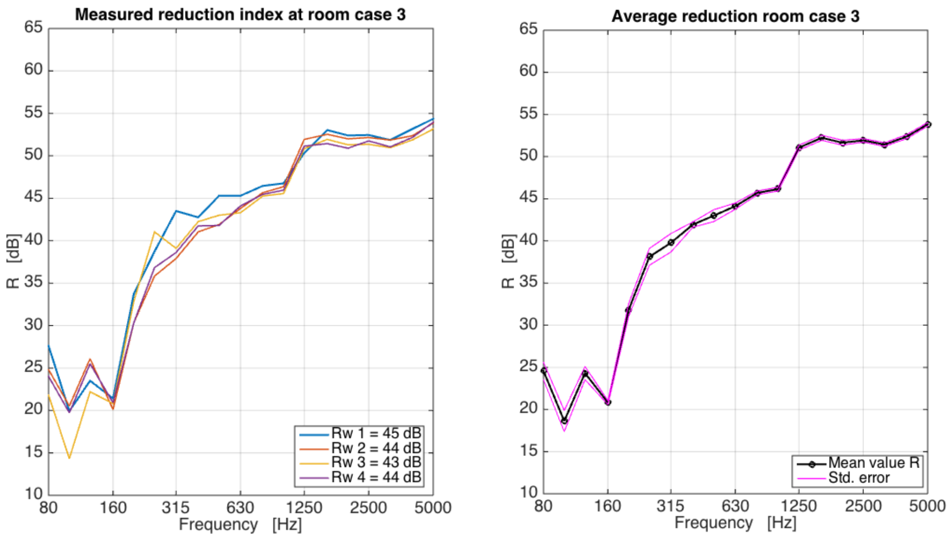
(a) Sound reduction indices. **(b)** Average reduction index.

Figure H.1: Sound reduction index for room case 1.



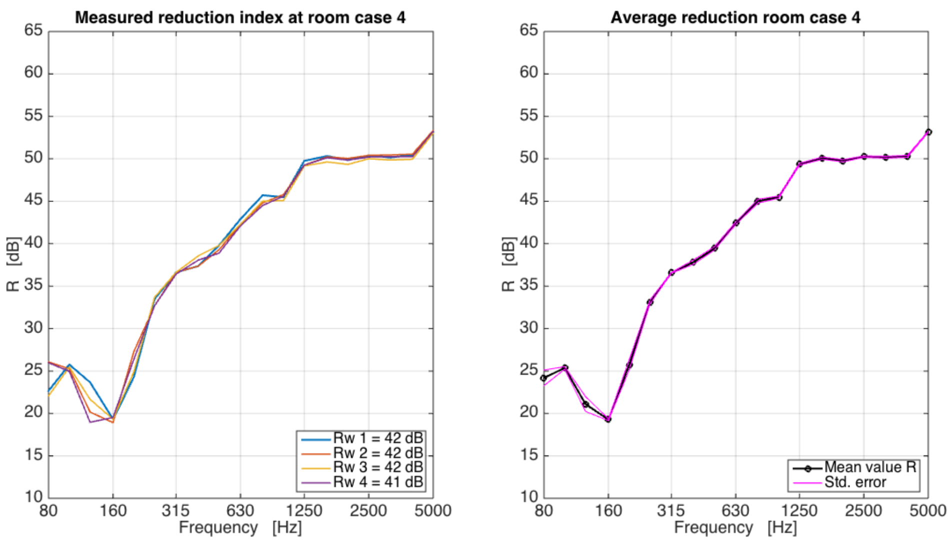
(a) Sound reduction indices. **(b)** Average reduction index.

Figure H.2: Sound reduction index for room case 2.



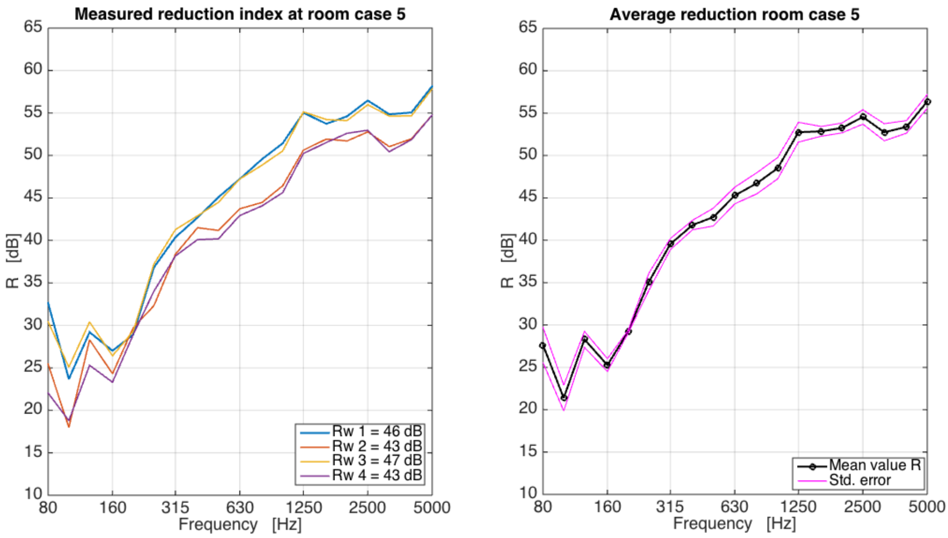
(a) Sound reduction indices. **(b)** Average reduction index.

Figure H.3: Sound reduction index for room case 3.



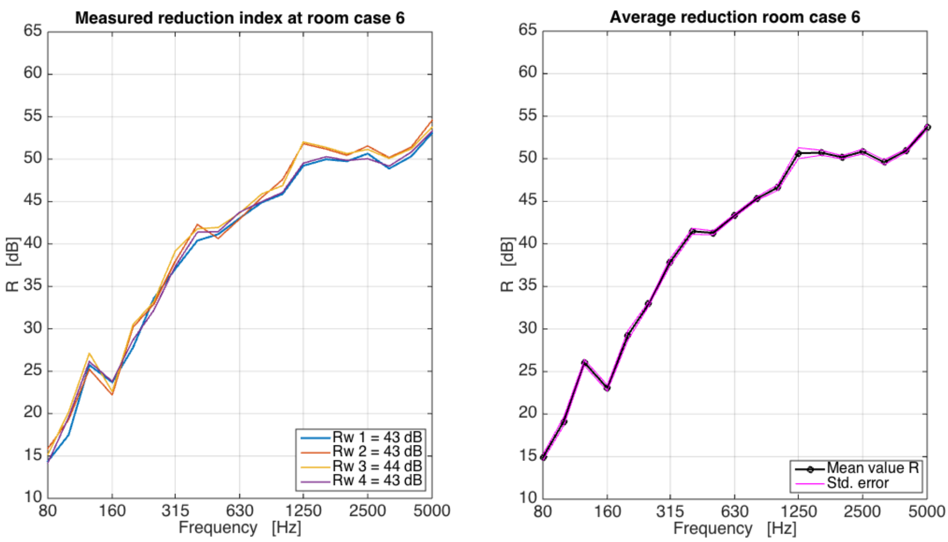
(a) Sound reduction indices. **(b)** Average reduction index.

Figure H.4: Sound reduction index for room case 4.



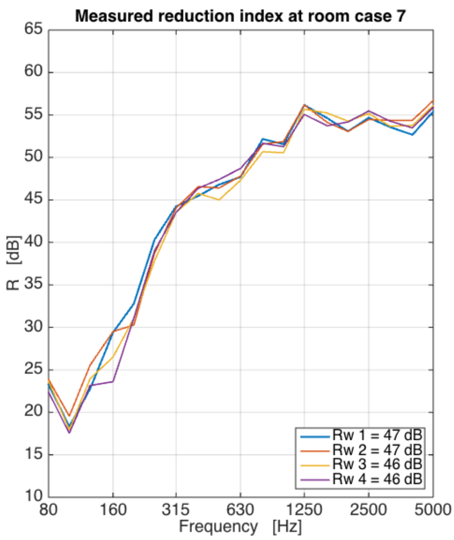
(a) Sound reduction indices. **(b)** Average reduction index.

Figure H.5: Sound reduction index for room case 5.

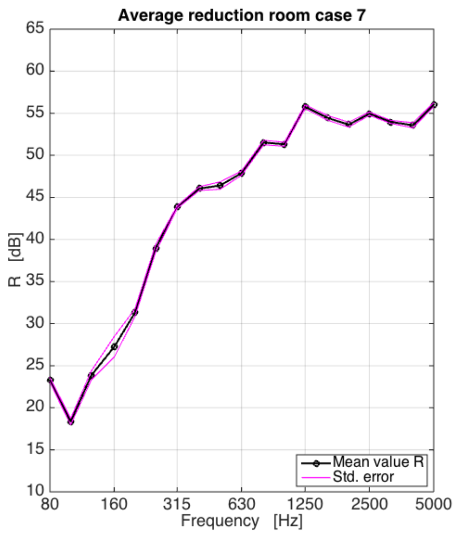


(a) Sound reduction indices. **(b)** Average reduction index.

Figure H.6: Sound reduction index for room case 6.



(a) Sound reduction indices.



(b) Average reduction index.

Figure H.7: Sound reduction index for room case 7.

Appendix I

Appendix

Figures of noise source positions for the wall impact noise method.

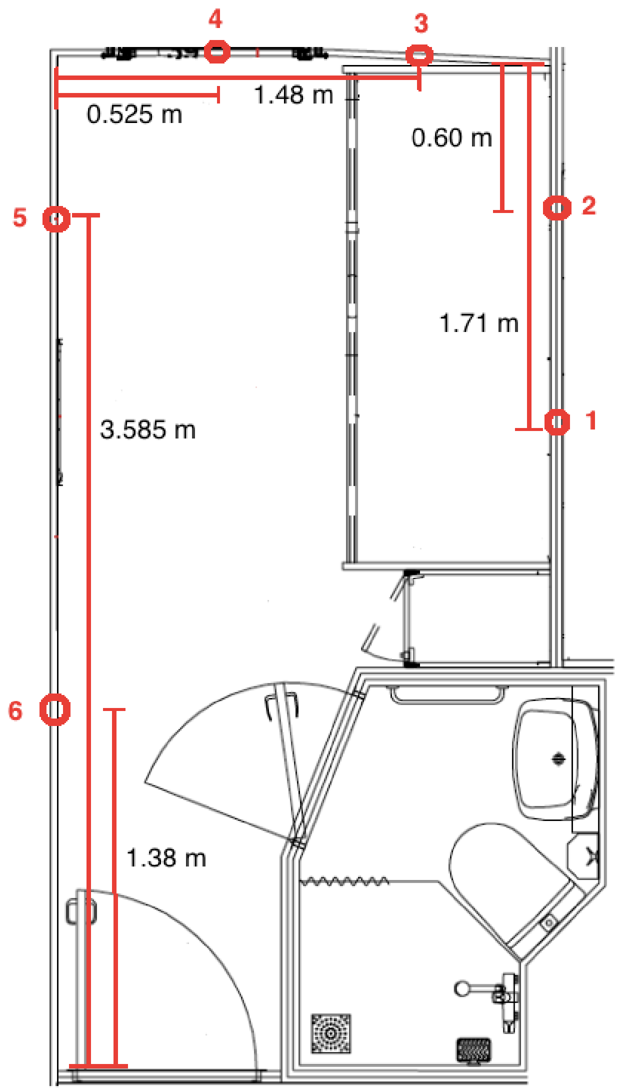


Figure I.1: Case 1, wall impact noise source positions.

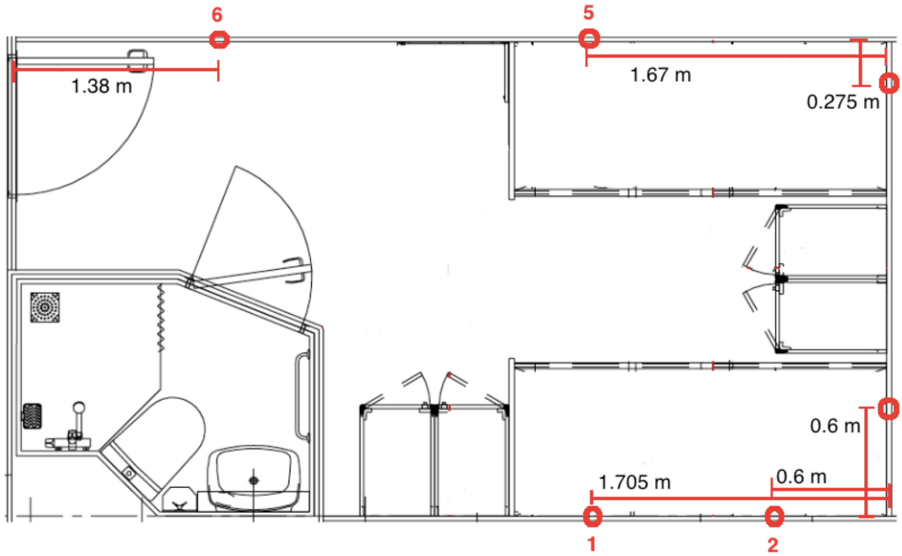


Figure I.2: Case 2, wall impact noise source positions.

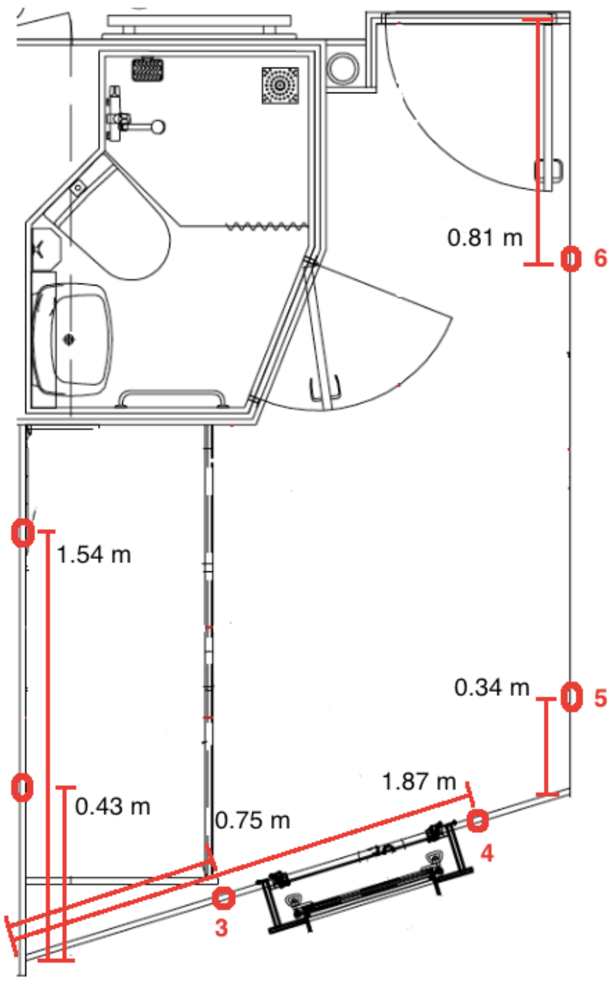


Figure I.3: Case 3, wall impact noise source positions.

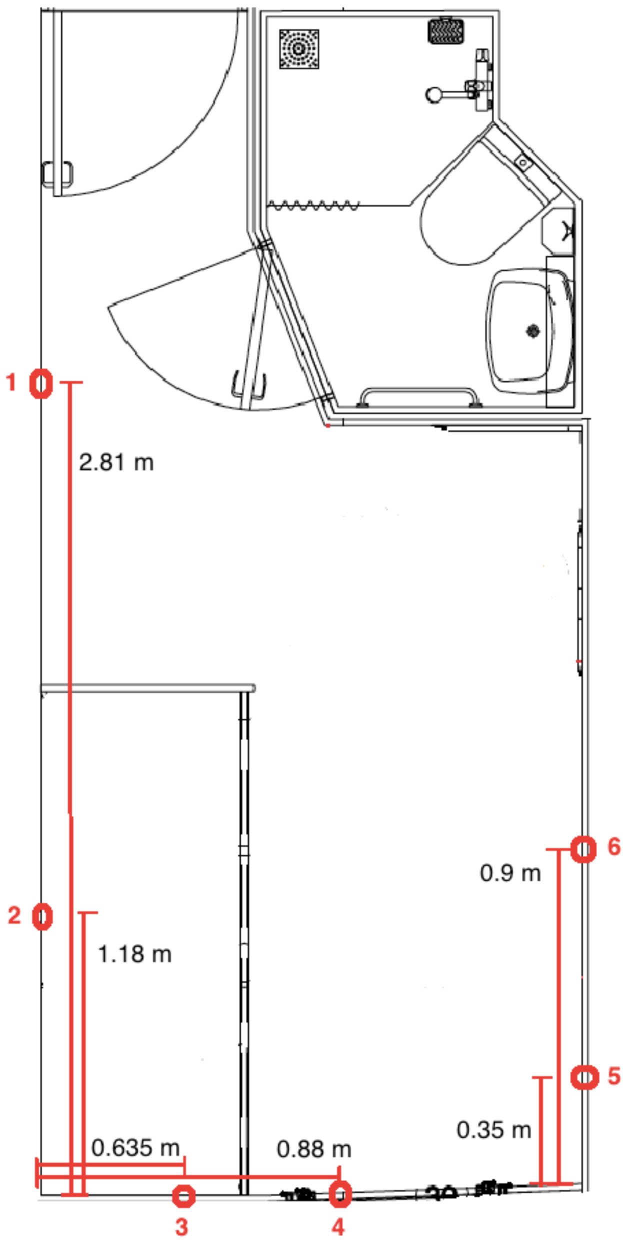


Figure I.4: Case 4, wall impact noise source positions.

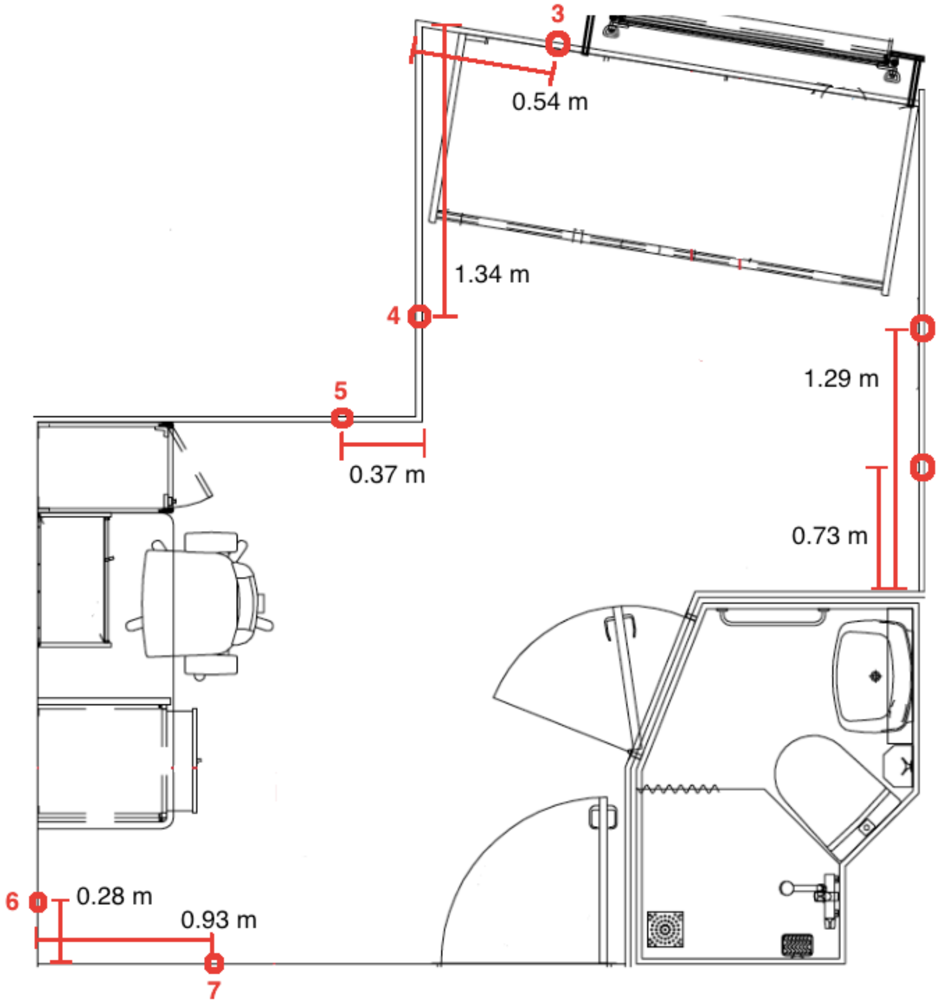


Figure I.5: Case 5, wall impact noise source positions.

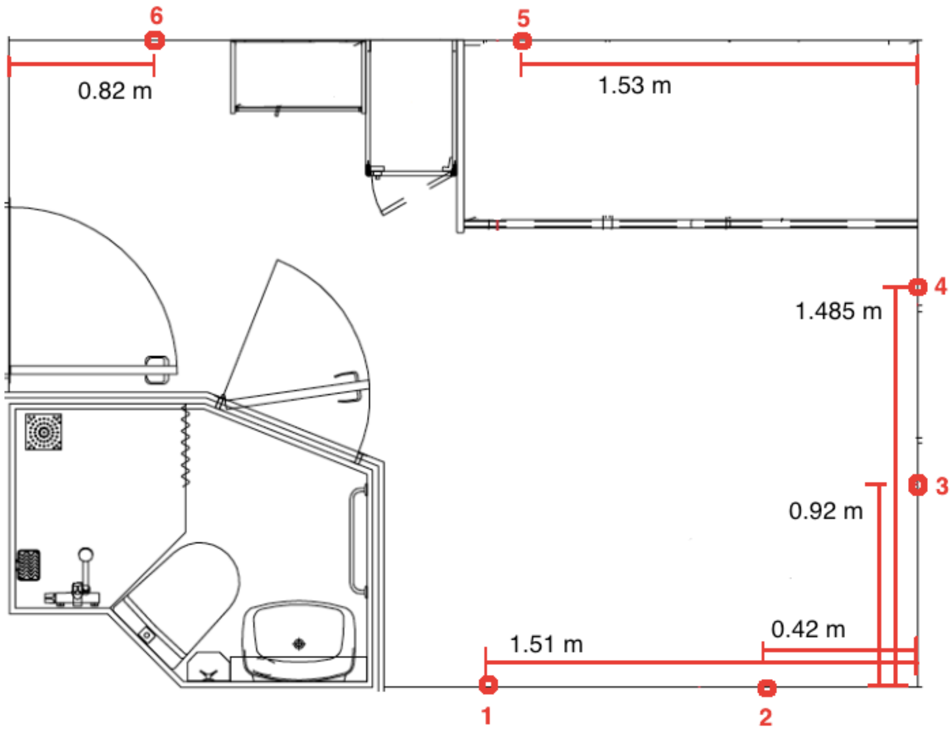


Figure I.6: Case 6, wall impact noise source positions.

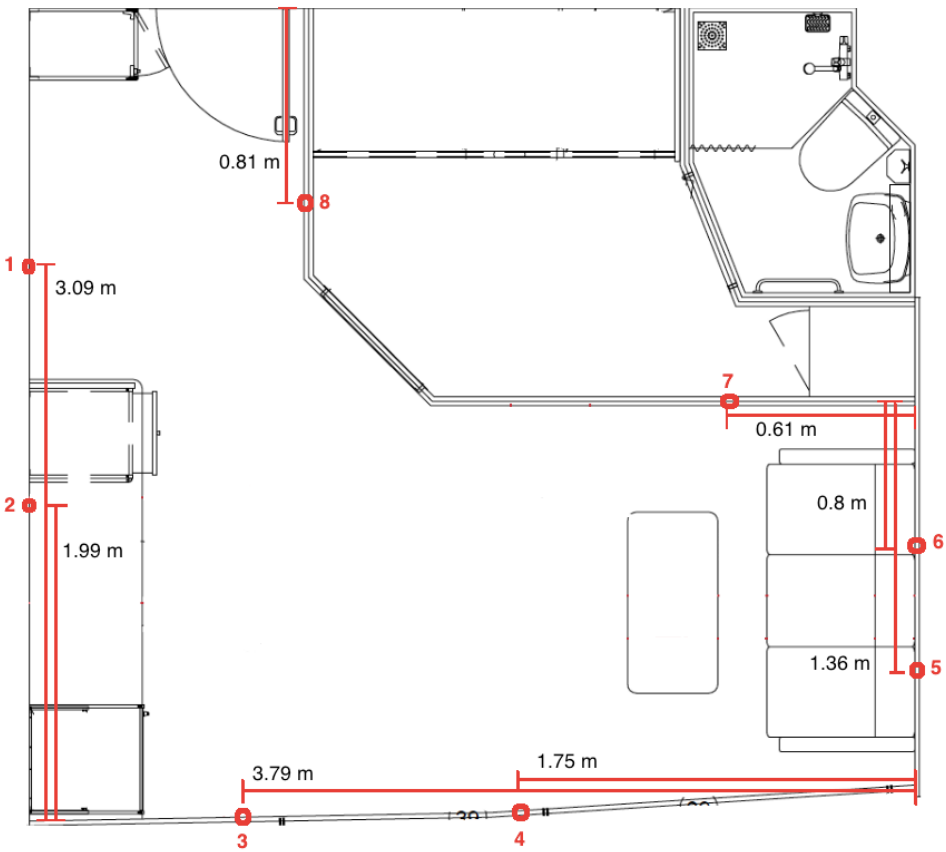


Figure I.7: Case 7, wall impact noise source positions.

Appendix J

Appendix

Simulated 3D results in Odeon for case 3 and case 4.

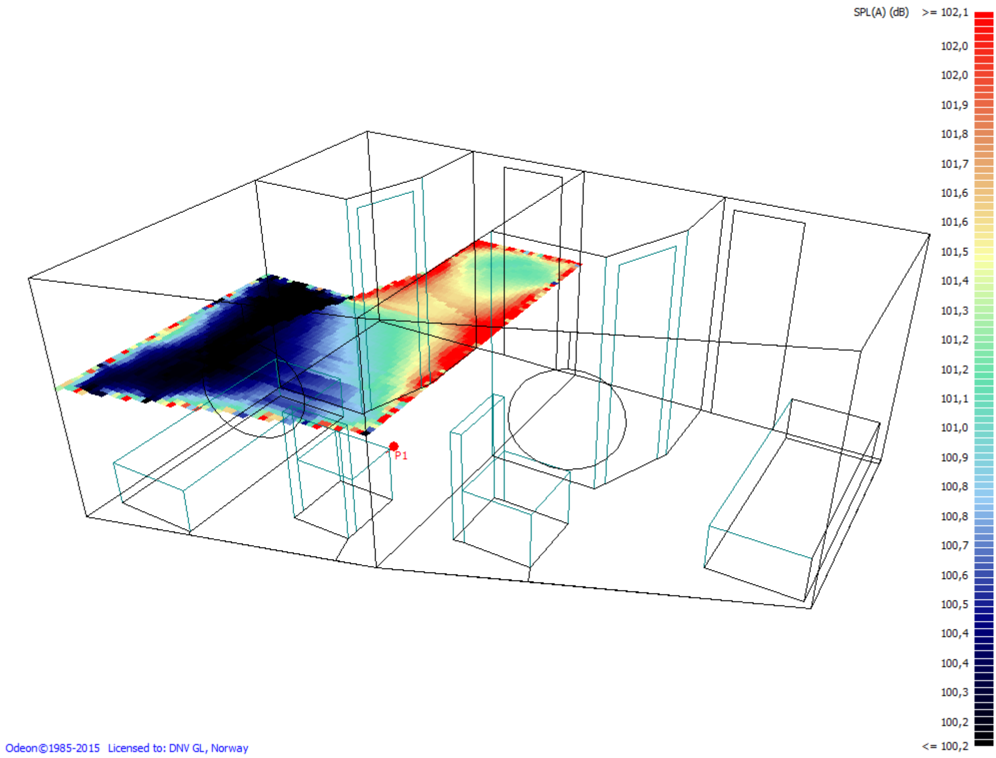


Figure J.1: 3D prediction result in source room, source position 2, case 3.

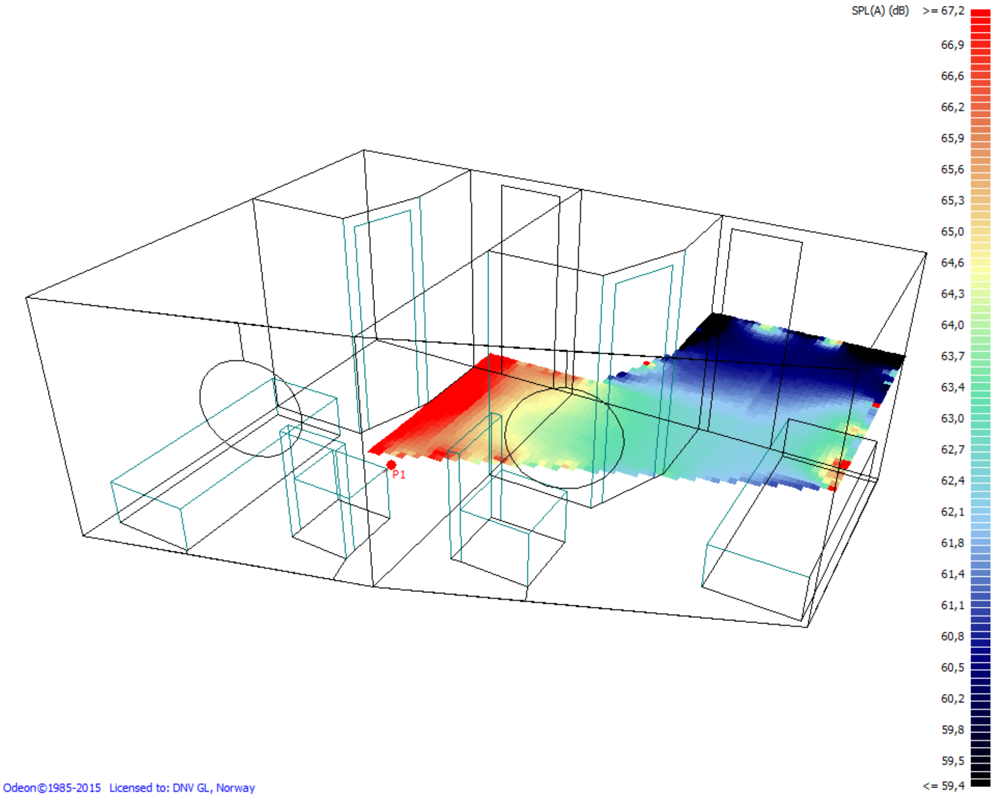


Figure J.2: 3D prediction result in receiver room, source position 2, case 3.

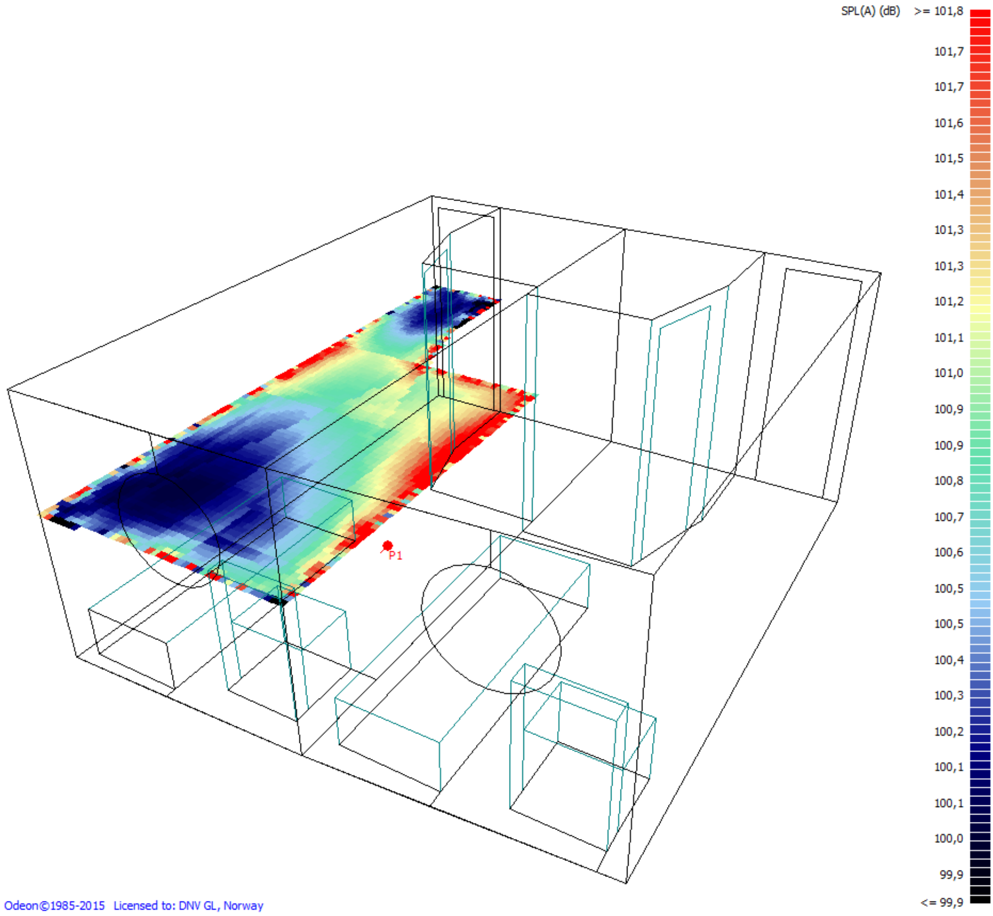


Figure J.3: 3D prediction result in source room, source position 1, case 4.

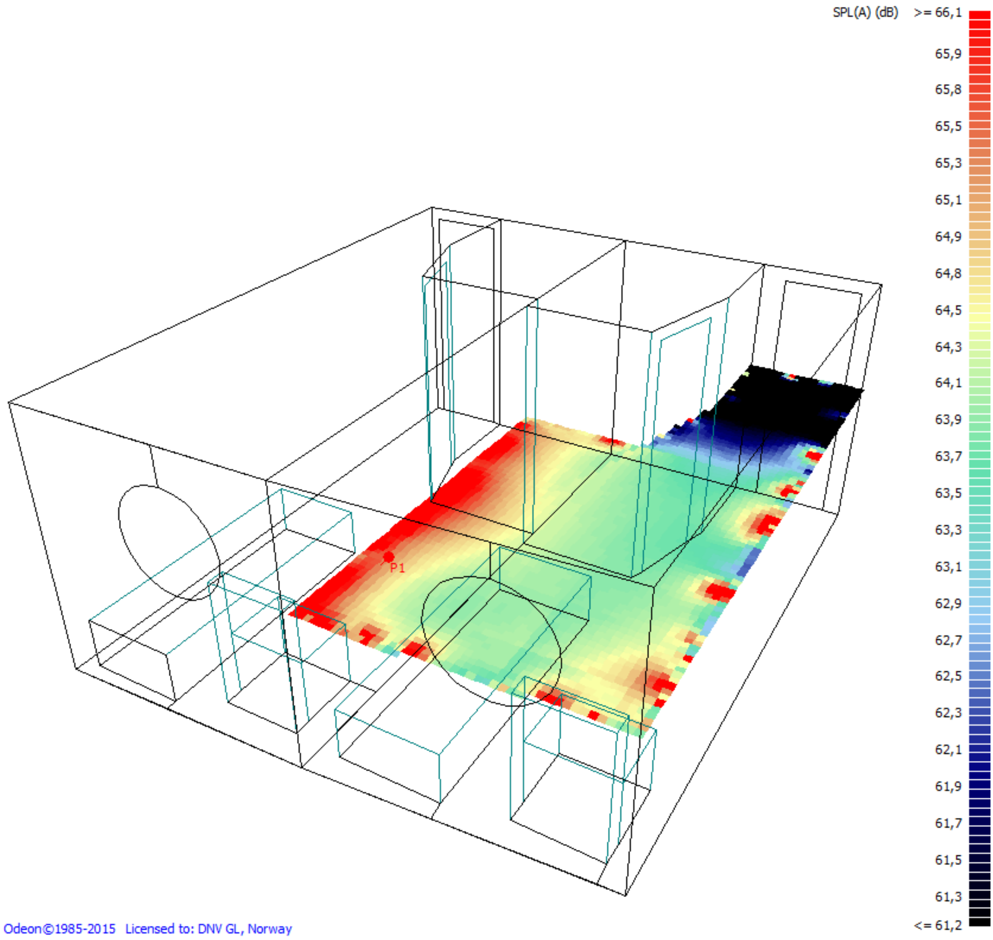


Figure J.4: 3D prediction result in receiver room, source position 1, case 4.

Appendix K

Appendix

Simulated 3D results in Odeon for three heights at case 6.

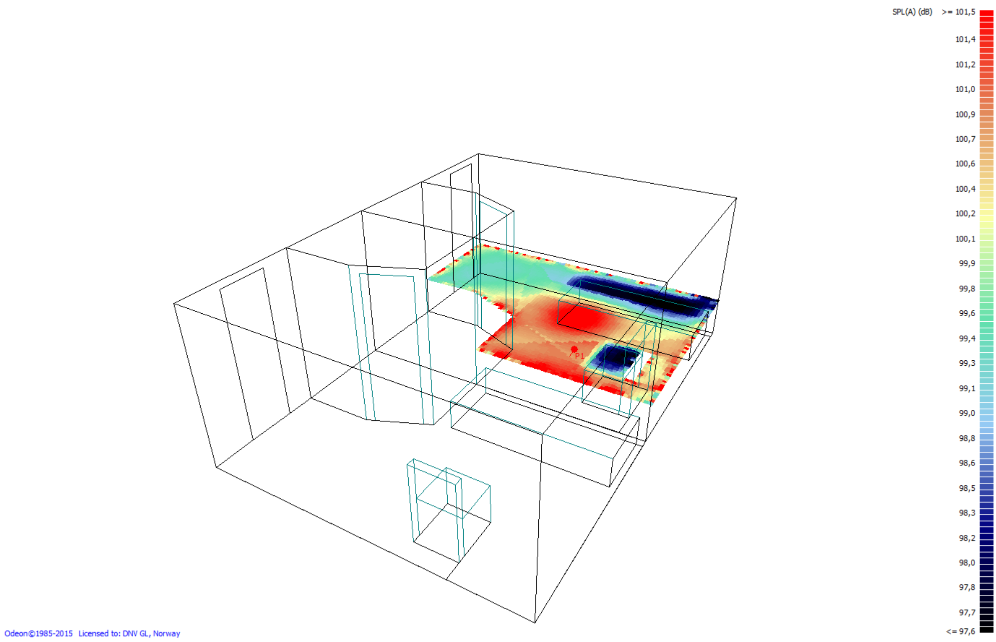


Figure K.1: Case 6, source position 2, 0.55 meter height.

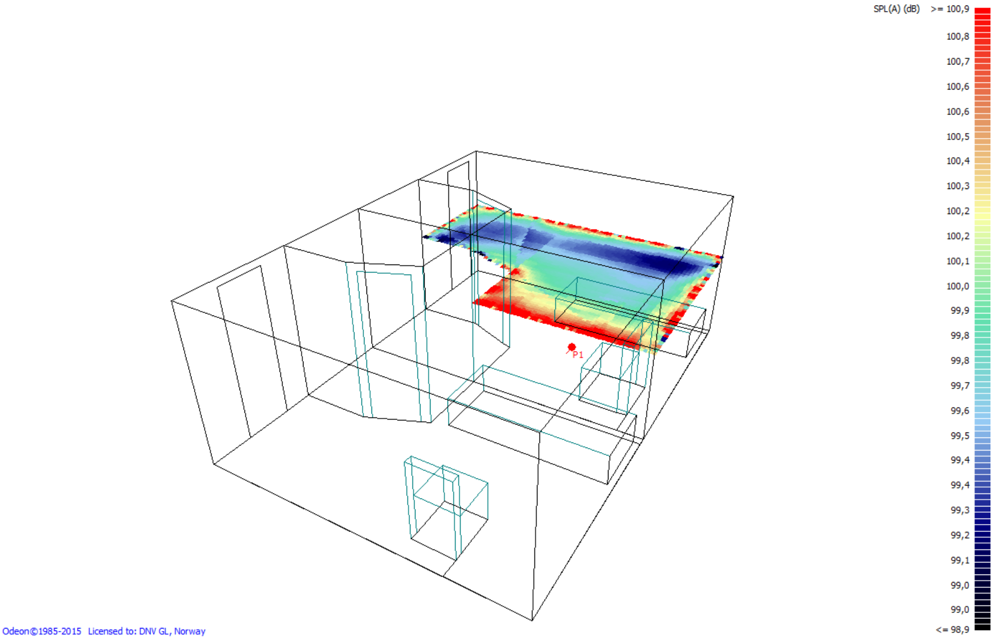


Figure K.2: Case 6, source position 2, 1.2 meter height.

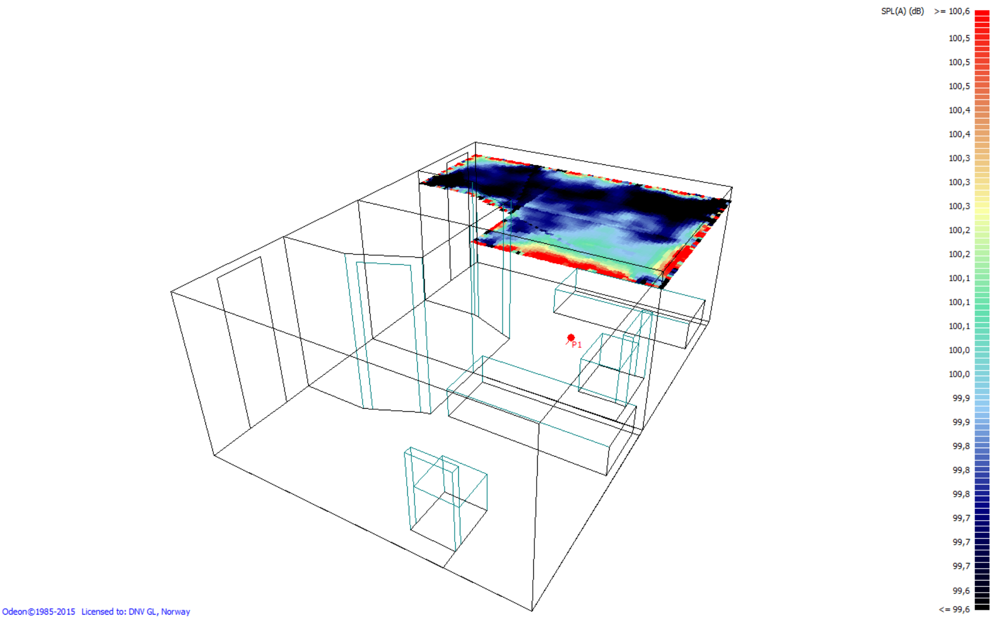


Figure K.3: Case 6, source position 2, 1.9 meter height.

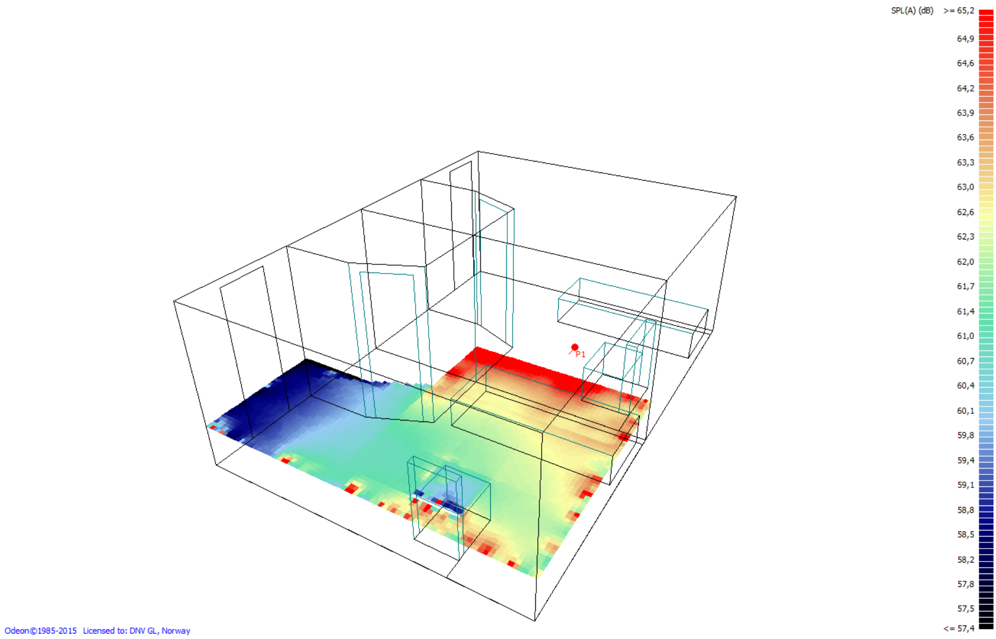


Figure K.4: Case 6, source position 2, 0.55 meter height, receiver room.

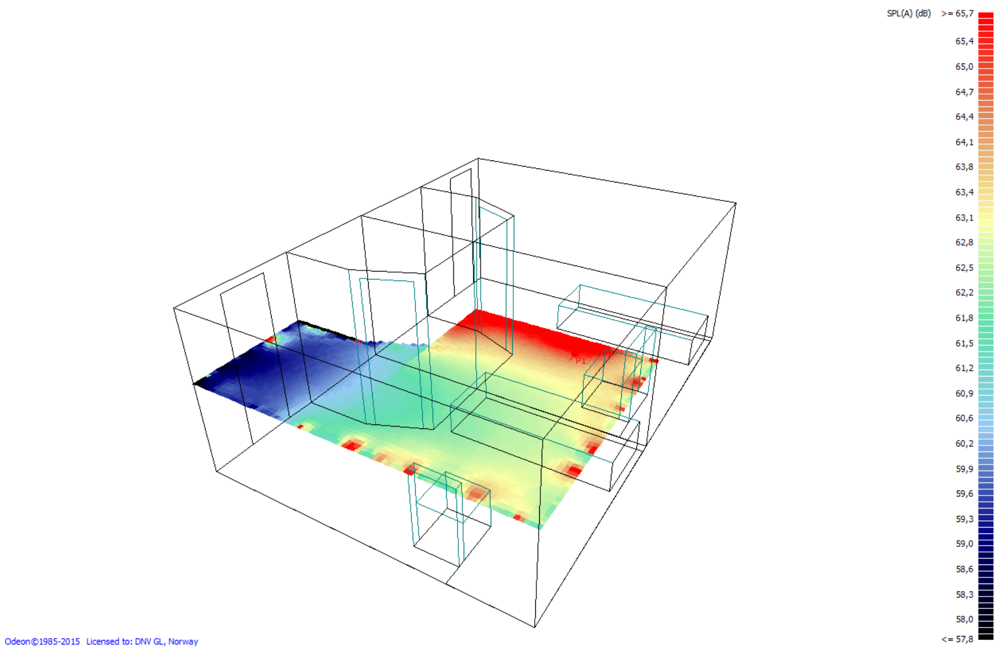


Figure K.5: Case 6, source position 2, 1.2 meter height, receiver room.

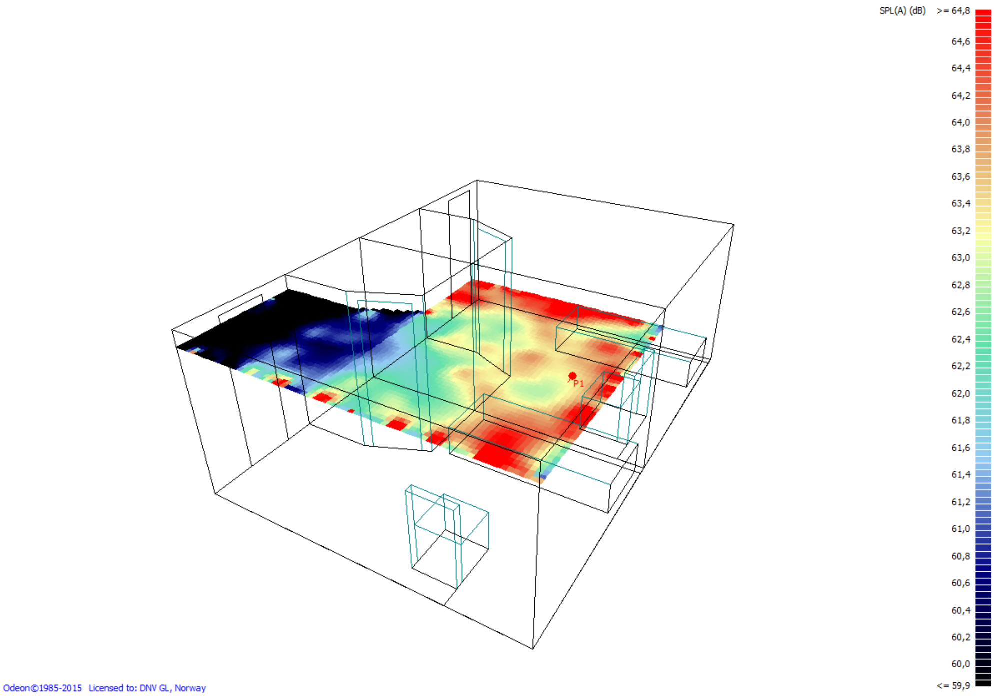


Figure K.6: Case 6, source position 2, 1.9 meter height, receiver room.

Appendix L

Appendix

Table of calculated sound reduction indices in Odeon.

Freq. [Hz]	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
63	23.0 dB	21.7 dB	24.9 dB	21.2 dB	23.9 dB	23.5 dB	27.1 dB
125	15.0 dB	13.6 dB	16.6 dB	13.1 dB	15.7 dB	15.2 dB	18.9 dB
250	22.5 dB	20.0 dB	23.5 dB	20.2 dB	24.1 dB	22.7 dB	26.1 dB
500	46.0 dB	44.1 dB	46.7 dB	44.4 dB	47.6 dB	47.2 dB	49.9 dB
1000	65.3 dB	63.6 dB	65.8 dB	63.8 dB	68.0 dB	66.7 dB	68.9 dB
2000	86.8 dB	85.0 dB	87.2 dB	85.1 dB	89.3 dB	88.0 dB	90.4 dB
4000	86.2 dB	84.6 dB	86.7 dB	84.6 dB	88.7 dB	87.4 dB	89.7 dB
A-weighted	35.0 dB	33.0 dB	36.0 dB	33.0 dB	36.0 dB	35.0 dB	39.0 dB

Table L.1: Sound reduction indices for case predictions in Odeon.

Appendix M

Appendix

Simulated 3D results in Odeon for case 5.

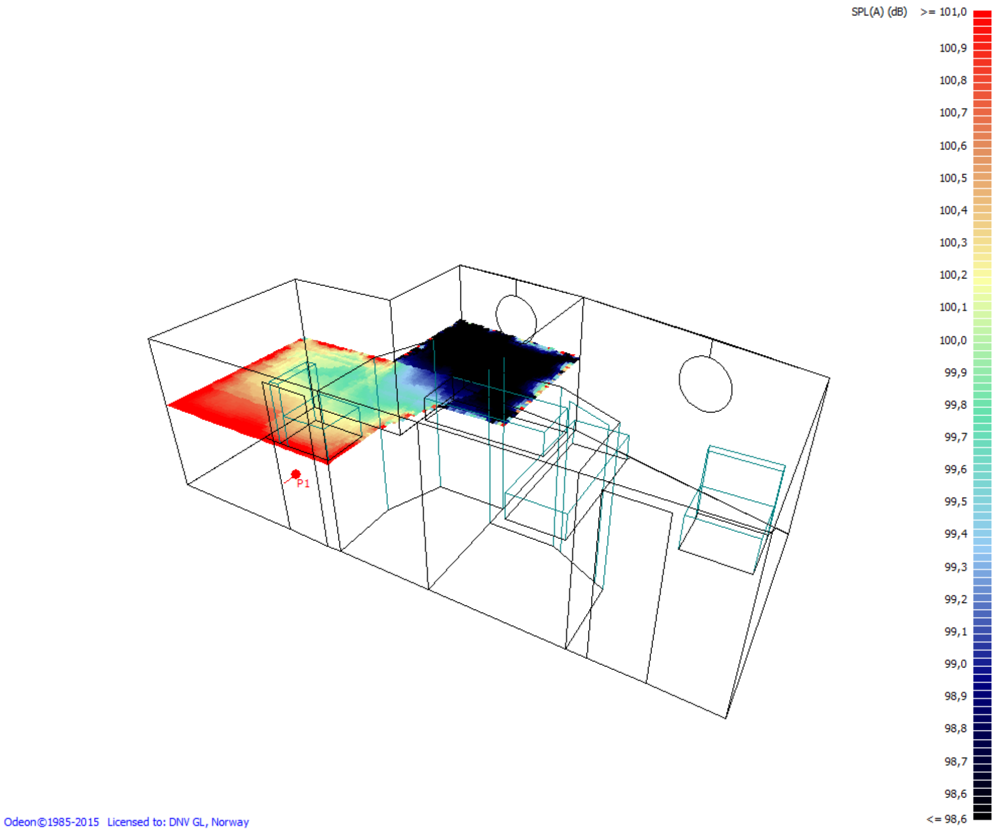


Figure M.1: 3D prediction result in source room, source position 1, case 5.

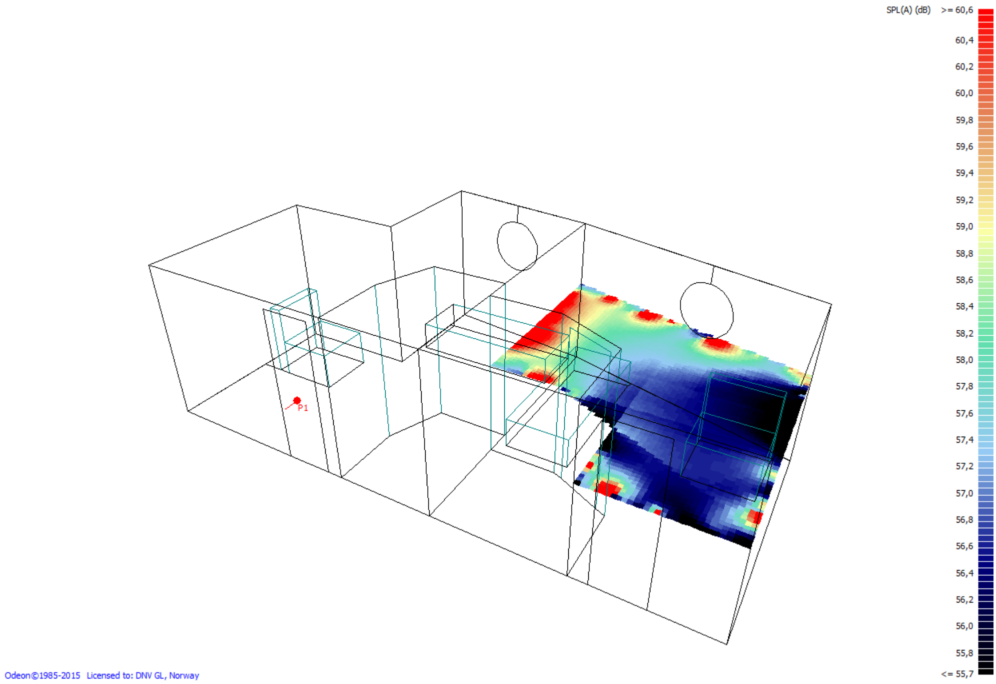


Figure M.2: 3D prediction result in receiver room, source position 1, case 5.

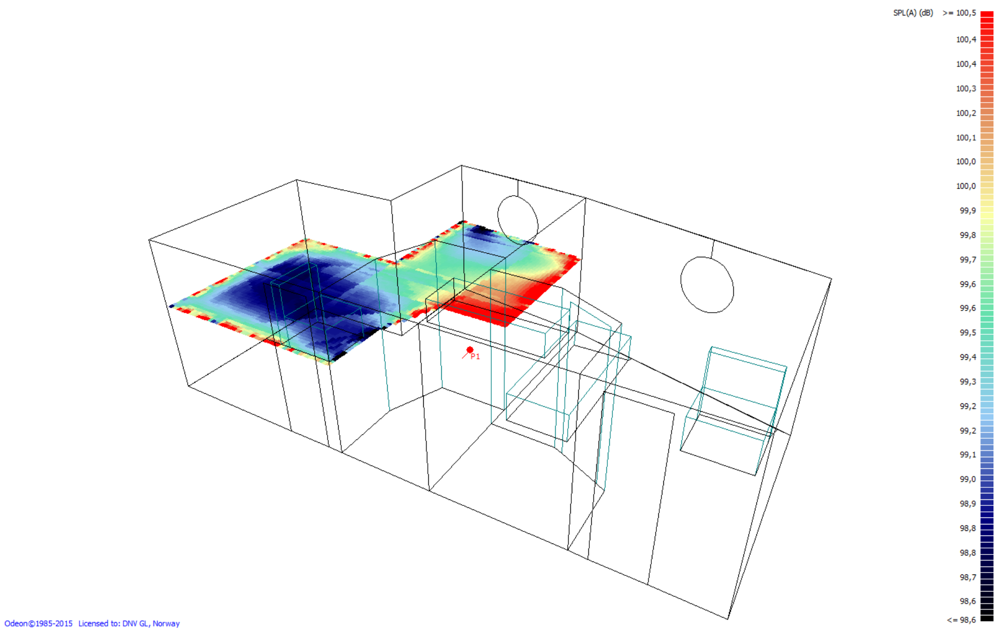


Figure M.3: 3D prediction result in source room, source position 2, case 5.

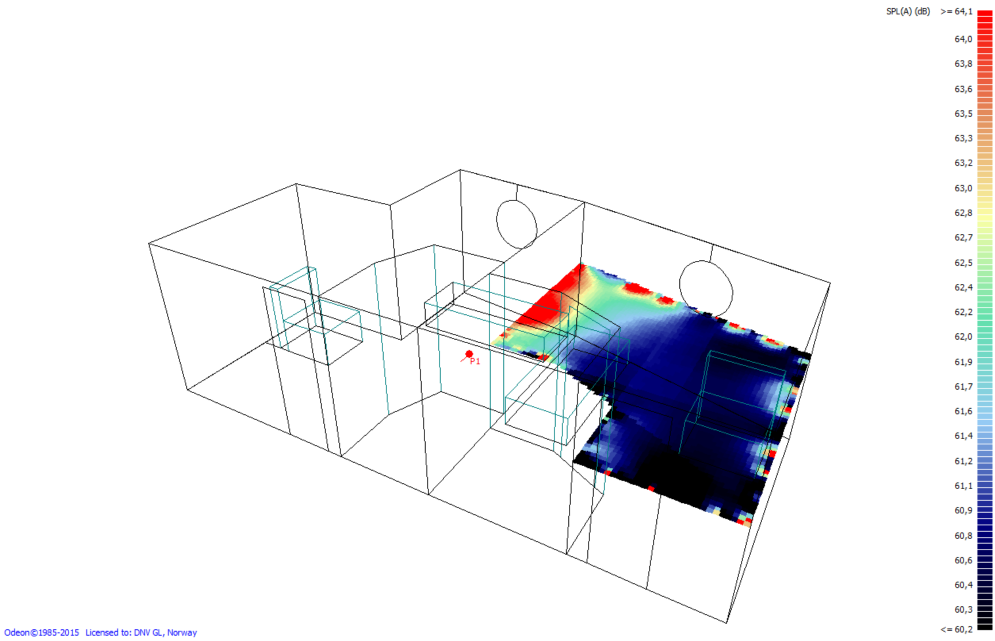


Figure M.4: 3D prediction result in receiver room, source position 2, case 5.

Appendix N

Appendix

Table results of the measured sound reduction indices for all frequencies and cases.

Freq. [Hz]	R_1	R_2	R_3	R_4
63	24.2 dB	24.1 dB	25.1 dB	23.6 dB
80	20.1 dB	17.7 dB	18.5 dB	18.7 dB
100	23.8 dB	24.6 dB	25.4 dB	24.6 dB
125	27.9 dB	29.0 dB	28.9 dB	29.3 dB
160	20.6 dB	28.0 dB	25.6 dB	22.7 dB
200	29.8 dB	30.7 dB	28.3 dB	29.3 dB
250	36.1 dB	36.3 dB	35.9 dB	35.1 dB
315	40.1 dB	41.6 dB	40.0 dB	39.8 dB
400	42.2 dB	42.4 dB	42.2 dB	41.3 dB
500	41.3 dB	39.9 dB	41.5 dB	39.9 dB
630	42.1 dB	41.7 dB	42.2 dB	41.3 dB
800	45.3 dB	44.7 dB	45.6 dB	45.0 dB
1000	47.6 dB	48.1 dB	47.4 dB	47.6 dB
1250	51.2 dB	52.1 dB	51.9 dB	51.9 dB
1600	51.6 dB	52.5 dB	51.7 dB	52.3 dB
2000	50.0 dB	50.4 dB	50.0 dB	51.0 dB
2500	51.9 dB	51.6 dB	52.0 dB	52.6 dB
3150	51.0 dB	50.4 dB	51.3 dB	51.5 dB
4000	50.4 dB	50.6 dB	50.9 dB	51.3 dB
5000	52.9 dB	53.4 dB	53.9 dB	53.9 dB
A-weighted	44.0 dB	45.0 dB	45.0 dB	44.0 dB

Table N.1: Sound reduction indices for case 1.

Freq. [Hz]	R_1	R_2	R_3	R_4
80	24.9 dB	20.3 dB	23.6 dB	26.3 dB
100	22.8 dB	26.7 dB	25.6 dB	24.6 dB
125	30.1 dB	31.2 dB	30.8 dB	27.9 dB
160	30.3 dB	31.4 dB	31.0 dB	30.0 dB
200	31.5 dB	28.2 dB	27.6 dB	31.8 dB
250	37.6 dB	40.1 dB	38.5 dB	37.1 dB
315	38.8 dB	41.6 dB	40.3 dB	37.4 dB
400	39.9 dB	40.7 dB	40.0 dB	40.6 dB
500	39.9 dB	41.5 dB	37.9 dB	41.8 dB
630	44.8 dB	41.3 dB	43.6 dB	46.0 dB
800	50.6 dB	48.8 dB	48.5 dB	51.5 dB
1000	53.2 dB	51.9 dB	52.6 dB	54.2 dB
1250	56.3 dB	57.7 dB	57.5 dB	56.9 dB
1600	57.6 dB	58.0 dB	57.8 dB	57.8 dB
2000	57.7 dB	58.7 dB	57.6 dB	58.0 dB
2500	59.8 dB	59.6 dB	59.6 dB	60.4 dB
3150	60.8 dB	60.5 dB	60.4 dB	60.3 dB
4000	61.4 dB	61.6 dB	61.3 dB	61.4 dB
8000	65.1 dB	64.5 dB	64.1 dB	64.3 dB
A-weighted	46.0 dB	46.0 dB	46.0 dB	46.0 dB

Table N.2: Sound reduction indices for case 2.

Freq. [Hz]	R_1	R_2	R_3	R_4
80	27.6 dB	24.8 dB	21.8 dB	24.0 dB
100	19.9 dB	20.5 dB	14.3 dB	19.7 dB
125	23.5 dB	26.1 dB	22.2 dB	25.5 dB
160	21.4 dB	20.1 dB	20.8 dB	20.9 dB
200	33.7 dB	30.3 dB	32.8 dB	30.3 dB
250	38.7 dB	35.8 dB	41.0 dB	36.8 dB
315	43.5 dB	37.9 dB	39.1 dB	38.6 dB
400	42.7 dB	41.0 dB	42.2 dB	41.7 dB
500	45.3 dB	41.9 dB	43.0 dB	41.8 dB
630	45.3 dB	43.8 dB	43.3 dB	44.1 dB
800	46.5 dB	45.7 dB	45.3 dB	45.5 dB
1000	46.8 dB	46.4 dB	45.6 dB	46.0 dB
1250	50.3 dB	51.9 dB	50.8 dB	51.1 dB
1600	53.0 dB	52.5 dB	51.9 dB	51.4 dB
2000	52.4 dB	52.0 dB	51.3 dB	50.9 dB
2500	52.5 dB	52.2 dB	51.4 dB	51.8 dB
3150	51.9 dB	51.9 dB	51.0 dB	51.1 dB
4000	53.2 dB	52.4 dB	51.9 dB	52.2 dB
8000	54.4 dB	53.9 dB	53.2 dB	54.0 dB
A-weighted	45.0 dB	44.0 dB	43.0 dB	44.0 dB

Table N.3: Sound reduction indices for case 3.

Freq. [Hz]	R_1	R_2	R_3	R_4
80	22.7 dB	26.1 dB	22.1 dB	26.0 dB
100	25.8 dB	25.3 dB	25.5 dB	25.0 dB
125	23.7 dB	20.2 dB	21.7 dB	19.0 dB
160	19.3 dB	18.9 dB	19.3 dB	19.5 dB
200	24.3 dB	27.3 dB	24.9 dB	26.4 dB
250	33.5 dB	32.7 dB	33.7 dB	32.7 dB
315	36.6 dB	36.6 dB	36.6 dB	36.4 dB
400	37.4 dB	37.4 dB	38.6 dB	38.1 dB
500	39.8 dB	39.3 dB	39.8 dB	38.9 dB
630	42.9 dB	42.3 dB	42.3 dB	42.1 dB
800	45.7 dB	44.8 dB	45.0 dB	44.5 dB
1000	45.5 dB	45.8 dB	45.1 dB	45.6 dB
1250	49.8 dB	49.3 dB	49.2 dB	49.3 dB
1600	50.3 dB	50.2 dB	49.6 dB	50.1 dB
2000	49.8 dB	50.0 dB	49.3 dB	49.8 dB
2500	50.4 dB	50.4 dB	50.0 dB	50.2 dB
3150	50.2 dB	50.5 dB	49.9 dB	50.3 dB
4000	50.4 dB	50.5 dB	49.9 dB	50.2 dB
8000	53.1 dB	53.3 dB	53.0 dB	53.2 dB
A-weighted	42.0 dB	42.0 dB	42.0 dB	41.0 dB

Table N.4: Sound reduction indices for case 4.

Freq. [Hz]	R_1	R_2	R_3	R_4
80	32.6 dB	25.4 dB	30.4 dB	22.0 dB
100	23.7 dB	18.0 dB	25.1 dB	18.8 dB
125	29.2 dB	28.3 dB	30.4 dB	25.3 dB
160	27.0 dB	24.3 dB	26.4 dB	23.3 dB
200	28.9 dB	29.7 dB	29.3 dB	28.9 dB
250	36.8 dB	32.3 dB	37.2 dB	34.0 dB
315	40.4 dB	38.4 dB	41.3 dB	38.2 dB
400	42.7 dB	41.5 dB	42.9 dB	40.1 dB
500	45.1 dB	41.2 dB	44.5 dB	40.2 dB
630	47.2 dB	43.7 dB	47.2 dB	42.9 dB
800	49.6 dB	44.5 dB	48.9 dB	44.1 dB
1000	51.4 dB	46.4 dB	50.5 dB	45.6 dB
1250	55.0 dB	50.6 dB	55.1 dB	50.2 dB
1600	53.7 dB	51.9 dB	54.2 dB	51.5 dB
2000	54.6 dB	51.7 dB	54.1 dB	52.6 dB
2500	56.5 dB	52.8 dB	56.0 dB	53.0 dB
3150	54.8 dB	51.0 dB	54.6 dB	50.4 dB
4000	55.1 dB	52.0 dB	54.7 dB	51.9 dB
8000	58.2 dB	54.8 dB	57.9 dB	54.8 dB
A-weighted	46.0 dB	43.0 dB	47.0 dB	43.0 dB

Table N.5: Sound reduction indices for case 5.

Freq. [Hz]	R_1	R_2	R_3	R_4
80	14.4 dB	15.9 dB	15.2 dB	14.2 dB
100	17.5 dB	19.3 dB	20.2 dB	19.6 dB
125	25.7 dB	25.2 dB	27.1 dB	26.1 dB
160	23.7 dB	22.2 dB	22.6 dB	23.8 dB
200	27.8 dB	30.2 dB	30.5 dB	28.7 dB
250	33.6 dB	32.9 dB	33.2 dB	32.2 dB
315	37.1 dB	38.0 dB	39.2 dB	37.4 dB
400	40.4 dB	42.3 dB	41.8 dB	41.4 dB
500	41.1 dB	40.6 dB	41.9 dB	41.4 dB
630	43.0 dB	42.9 dB	43.6 dB	43.7 dB
800	44.9 dB	45.5 dB	45.9 dB	45.0 dB
1000	45.9 dB	47.6 dB	46.9 dB	46.1 dB
1250	49.2 dB	51.8 dB	52.0 dB	49.5 dB
1600	50.0 dB	51.2 dB	51.4 dB	50.3 dB
2000	49.8 dB	50.5 dB	50.7 dB	49.9 dB
2500	50.7 dB	51.6 dB	51.2 dB	50.1 dB
3150	48.9 dB	50.2 dB	50.1 dB	49.2 dB
4000	50.3 dB	51.4 dB	51.2 dB	50.8 dB
8000	53.1 dB	54.6 dB	53.8 dB	53.3 dB
A-weighted	43.0 dB	43.0 dB	44.0 dB	43.0 dB

Table N.6: Sound reduction indices for case 6.

Freq. [Hz]	R_1	R_2	R_3	R_4
80	23.3 dB	23.9 dB	23.7 dB	22.4 dB
100	18.3 dB	19.5 dB	17.9 dB	17.5 dB
125	22.8 dB	25.6 dB	24.0 dB	23.2 dB
160	29.4 dB	29.5 dB	26.5 dB	23.6 dB
200	32.8 dB	30.3 dB	31.1 dB	31.1 dB
250	40.3 dB	38.7 dB	37.8 dB	39.0 dB
315	44.2 dB	44.0 dB	43.5 dB	43.5 dB
400	45.5 dB	46.6 dB	45.8 dB	46.4 dB
500	46.8 dB	46.4 dB	45.0 dB	47.4 dB
630	47.7 dB	47.8 dB	47.3 dB	48.7 dB
800	52.2 dB	51.6 dB	50.7 dB	51.7 dB
1000	51.6 dB	51.9 dB	50.6 dB	51.3 dB
1250	56.2 dB	56.2 dB	55.7 dB	55.1 dB
1600	54.6 dB	54.1 dB	55.2 dB	53.7 dB
2000	53.1 dB	53.1 dB	54.3 dB	54.2 dB
2500	54.7 dB	54.5 dB	55.2 dB	55.5 dB
3150	53.6 dB	54.4 dB	53.7 dB	54.3 dB
4000	52.7 dB	54.4 dB	53.8 dB	53.5 dB
8000	55.4 dB	56.7 dB	56.1 dB	55.9 dB
A-weighted	47.0 dB	47.0 dB	46.0 dB	46.0 dB

Table N.7: Sound reduction indices for case 7.

Appendix **O**

Appendix

Table of volumes and measured reverberation time for each case.

Case	**Volume**
Case 1	14.54 m^3
Case 2	20.80 m^3
Case 3	12.80 m^3
Case 4	15.17 m^3
Case 5	18.67 m^3
Case 6	18.17 m^3
Case 7	17.65 m^3

Table O.1: Room volumes for all cases.

Freq. [Hz]	**Case 1**	**Case 2**	**Case 3**	**Case 4**
80	0.25 s	0.3 s	0.65 s	0.47 s
100	0.22 s	0.28 s	0.35 s	0.48 s
125	0.29 s	0.42 s	0.31 s	0.27 s
160	0.29 s	0.24 s	0.22 s	0.3 s
200	0.24 s	0.24 s	0.32 s	0.46 s
250	0.35 s	0.35 s	0.26 s	0.29 s
315	0.3 s	0.33 s	0.31 s	0.3 s
400	0.31 s	0.29 s	0.36 s	0.31 s
500	0.3 s	0.29 s	0.39 s	0.35 s
630	0.31 s	0.33 s	0.27 s	0.36 s
800	0.28 s	0.35 s	0.3 s	0.36 s
1000	0.31 s	0.32 s	0.3 s	0.35 s
1250	0.35 s	0.35 s	0.32 s	0.39 s
1600	0.33 s	0.35 s	0.32 s	0.37 s
2000	0.29 s	0.33 s	0.31 s	0.38 s
2500	0.33 s	0.34 s	0.3 s	0.36 s
3150	0.3 s	0.35 s	0.28 s	0.39 s
4000	0.35 s	0.35 s	0.33 s	0.38 s
5000	0.34 s	0.34 s	0.3 s	0.38 s
T_{30}	0.32 s	0.34 s	0.3 s	0.36 s

Table O.2: Reverberation times for cases 1,2,3 and 4.

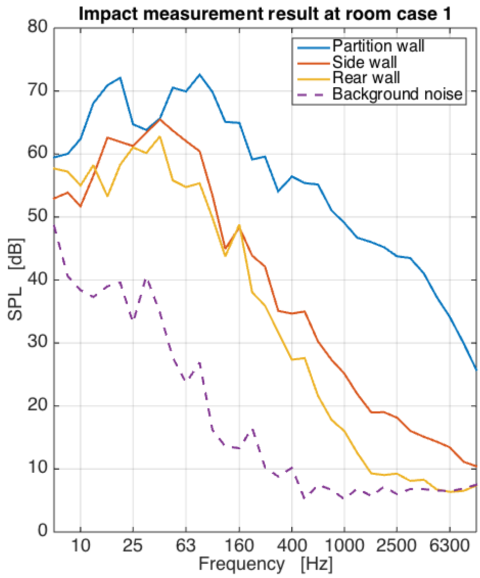
Freq. [Hz]	**Case 5**	**Case 6**	**Case 7**
80	0.6 s	0.23 s	0.28 s
100	0.45 s	0.55 s	0.18 s
125	0.26 s	0.57 s	0.15 s
160	0.36 s	0.22 s	0.39 s
200	0.3 s	0.34 s	0.33 s
250	0.25 s	0.31 s	0.41 s
315	0.29 s	0.33 s	0.32 s
400	0.32 s	0.42 s	0.37 s
500	0.42 s	0.37 s	0.34 s
630	0.37 s	0.51 s	0.34 s
800	0.31 s	0.45 s	0.37 s
1000	0.33 s	0.47 s	0.3 s
1250	0.37 s	0.52 s	0.37 s
1600	0.37 s	0.54 s	0.35 s
2000	0.36 s	0.5 s	0.37 s
2500	0.41 s	0.5 s	0.37 s
3150	0.38 s	0.47 s	0.37 s
4000	0.39 s	0.51 s	0.37 s
5000	0.39 s	0.47 s	0.39 s
T_{30}	0.35 s	0.48 s	0.37 s

Table O.3: Reverberation times for cases 5,6 and 7.

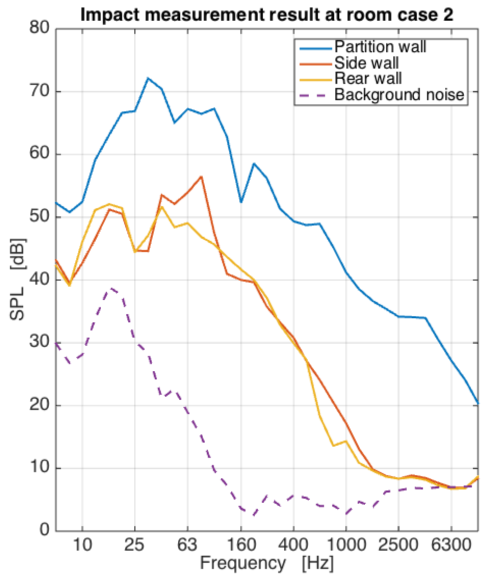
Appendix P

Appendix

Detailed figures of the wall impact results for each case.

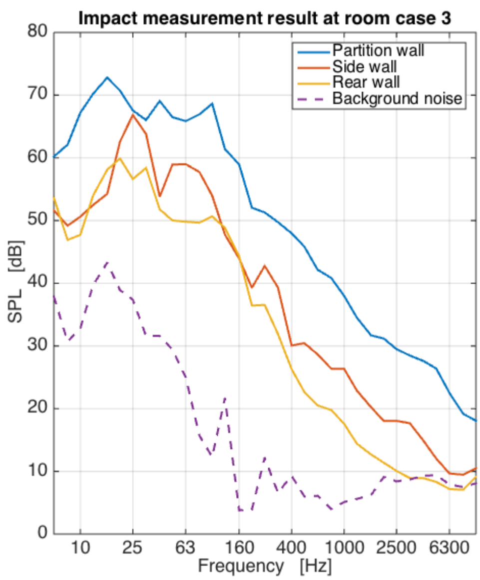


(a) Case 1.

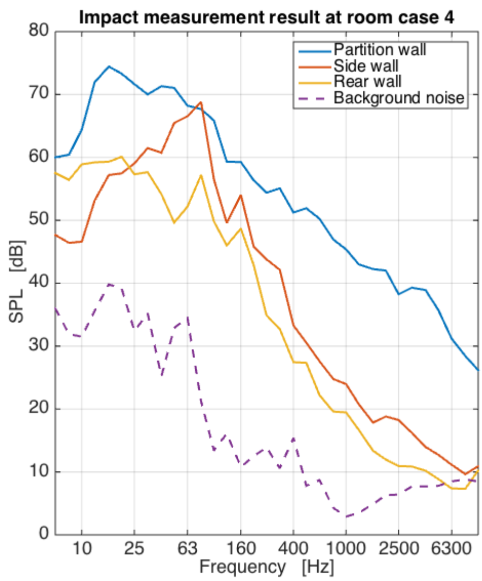


(b) Case 2.

Figure P.1: Impact results for cases 1 and 2.

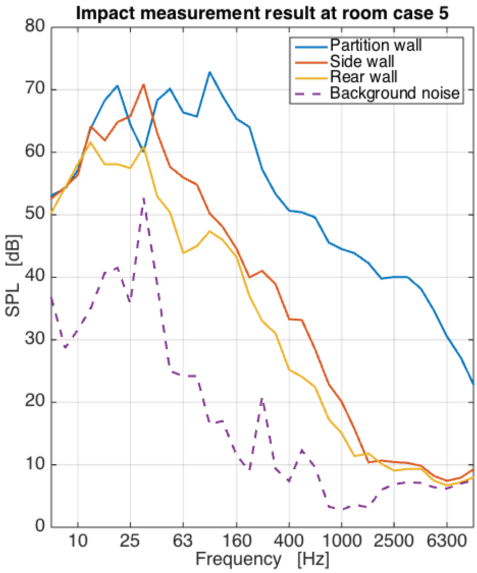


(a) Case 3.

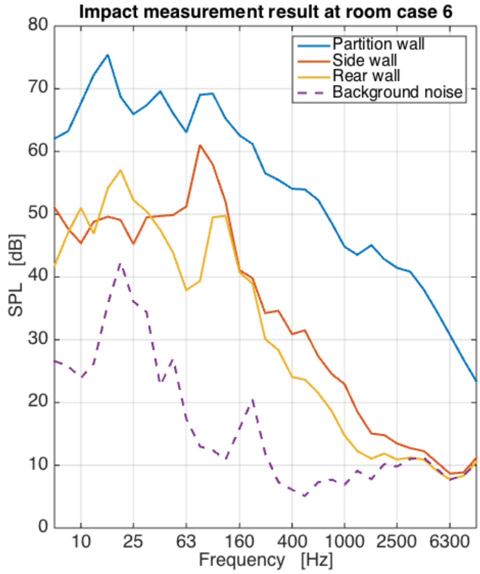


(b) Case 4.

Figure P.2: Impact results for cases 3 and 4.



(a) Case 5.



(b) Case 6.

Figure P.3: Impact results for cases 5 and 6.

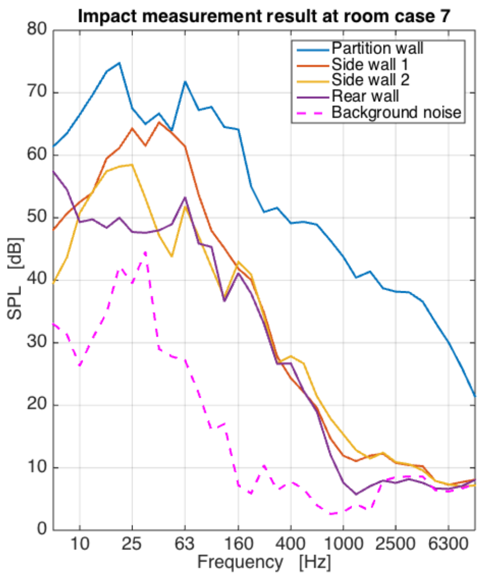


Figure P.4: Impact results for case 7.