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Acoustical retrofit of an interactive theatre space: A simulation-based potential assessment

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Kurzfassung

Der Fokus dieser Studie bezieht sich auf akustische Schwierigkeiten und Mängel geeigneter Tongestaltung im interaktiven Theater „Narrenschloss“ für Kinder und Jugendliche in Wien, Österreich.

Die Studie kann als eine Neugestaltung des Raumes-beziehungsweise als eine Neugestaltung des akustischen Ambientes eines künstlerischen Raumes beschrieben werden. Das Ziel ist es, Defizite der akustischen Umgebung aufzuzeigen, in der das Publikum Künstler und Schauspieler während der Vorführung richtig hören soll. Das Fallbeispiel zeigt das Endergebnis in Form eines Vorschlages für die Installation geeigneter akustischer Materialien und Elemente, die nötig sind, um eine Gesamtverbesserung der Klangdeformationen in der akustischen Umgebung des Theatersaales zu erreichen.

Die Studie bietet eine Idee für die Raumsanierung und Raumgestaltung, um die Bedürfnisse der Kinder bestmöglich zu befriedigen. Sie basiert sowohl auf einer wissenschaftlichen Betrachtungsweise als auch auf pragmatischen Lösungsansätzen, die vom Theaterdirektor diskutiert und zugelassen wurden. Diese Masterarbeit beschreibt die akustische Nachrüstung des Theatersaales – interaktiven Theater „Narrenschloss“ für Kinder und Jugendliche.

Abstract

The focus of the study is concentrated towards acoustical difficulties and lack of proper sound design in the main hall of the improvisatory children and youngsters´ interactive theatre “Narrenschloss” in Vienna, Austria. The study can be defined as a redesign of space with an agenda to improve sound ambient. The goal is to reveal and improve an acoustical deficit of the improvised theater hall. Young actors and artists though visual acts and performance must be properly heard by an audience as the key factor. This case study concludes with a proposal to improve the sound distorting surrounding by adding adequate acoustical elements and materials within.

This study is offering an idea how to best deal with refurbishing and redesigning of given space to fit the needs of performers. It is based on scientific approach, and also on pragmatic solutions, discussed and approved by the managing director of the theatre. This master thesis describes the acoustical retrofit of the improvised youth theater hall “Narrenschloss”.

Keywords

Acoustic range, acoustical elements, acoustical ambient, acoustics in theatre, acoustical problematic, sound in buildings, sound reverberation, reverberation time, acoustics in buildings;

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This Master thesis is devoted to my family and friends who have inspired me throughout my life, especially my beloved brother Igor Božić.

…in loving memory of MItar Nikolić

“The technology of noise control both inside and outside buildings is well developed today. The problem is that it is too seldom used. Architects continue to “hope” that a row of trees or bushes will solve the problem of noise intrusion from the nearby highway, or perhaps that someone will invent an air curtain that will stop the transmission of sound between two parts of a room! But there are no miracles - there are simply some hard physical facts.”

Robert B. Newman

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Chapter 1 – Introduction

1.1 Introduction of the acoustical retrofit and motivation

Effective communication is based on visual and hearing comprehension. This becomes especially important when we are talking about education, entertainment and cultural events manifested through a theater play. The most important aspect in concert halls and theaters are intelligibility and proper hearing.

All theater plays are expected to occur in environments where the spoken word, music and theatrical effects sound clear. The scope of this thesis is to recognize the acoustical advantages and disadvantages of the given architectural space and discuss possible improvements, which are in the end supposed to improve the ambient experience of the audience. It is easier to perform in acoustically well-adapted theater (Figure 1-1.), than in an improvised theater set.

Figure 1-1. Example of the well-engineered Auditorium in Akzent Theater Vienna

There is a broad field of constructions and special projects to handle in an architect’s career. Architectural acoustics is one of them, integrated in the sound engineering and rooms acoustical improvements makes one of the most interesting themes in architecture.

The theme of this study combines artistic and scientific motives. A personal affection towards theatre and the arts is the motivation for the subject of this thesis. Visits to numerous theaters and the variety of sets gives a spectator a first-hand opportunity to experience well-developed or poor acoustical surroundings. The acquaintanceship with the amateur theater scene in Vienna has raised an opportunity to help Narrenschloss theater with the selection of the study focused on their case.

This research offers an opportunity to gain practical knowledge in solving a real-life acoustical problem of the unique interactive theatre for children and youngsters. With adequate retrofit of the selected theatre hall, the result should be improved artistic space and even more importantly - better ambient space, which would in the end lead to a better cultural experience overall.

1.2 Room acoustic metrics

The room acoustics can be physically measured by defined acoustical parameters. Present study is focused on reverberation time, sound pressure level and sound distribution.

1.2.1 Reverberation time

Reverberation time is the measure used to quantify reverberation and its time required for mean sound pressure level in a room to decay 60 dB, one millionth of their original amplitude. The reverberation time can be calculated, based on the given formula. (Salter, C. M. Inc Associates, 1998).

$T = \frac{KV}{S\overline{\alpha}}$

K $[0{,}16]$= Constant

V $[\mathrm{m3}]$= Room volume

S $[\mathrm{m2}]$= Room surface area

$\overline{\alpha}$ $[\mathrm{x}]$= Average absorption coefficient

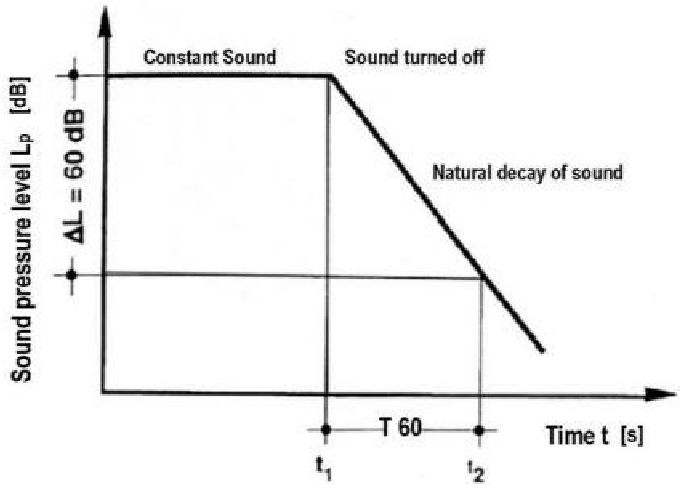

Figure 1-2. Reverberation time defined by sound decay
(Fasold and Veres 1998)

1.2.2 Sound pressure level and sound distribution

"In the frequency range in which our hearing is most sensitive (500–5000 Hz) the intensity of the threshold of sensation and of the threshold of pain in hearing differ by about 13 orders of magnitude. For this reason, it would be impractical to characterise the strength of a sound signal by its sound pressure or its intensity. Instead, a logarithmic quantity, the so-called 'sound pressure level' is generally used for this purpose." (Kuttroff, 2009). It is defined as the ratio of the absolute sound pressure versus sound level in the air. In a cubic room the sound pressure level is decaying is dependent on the equivalent absorption area (Figure 1-3.), as presented in a following equation.

$$Lp\ diff\ = Lw - 10log\frac{A}{4}dB$$

$Lp\ diff$ [dB]= Constant sound pressure level

Lw [dB]= Sound power level

A [m2]= Absorption area

In increasing distances from the sound sources is a constant sound pressure level $Lp\ diff$ (diffuse sound field) created due to sound reflections (Fasold and Veres 2003).

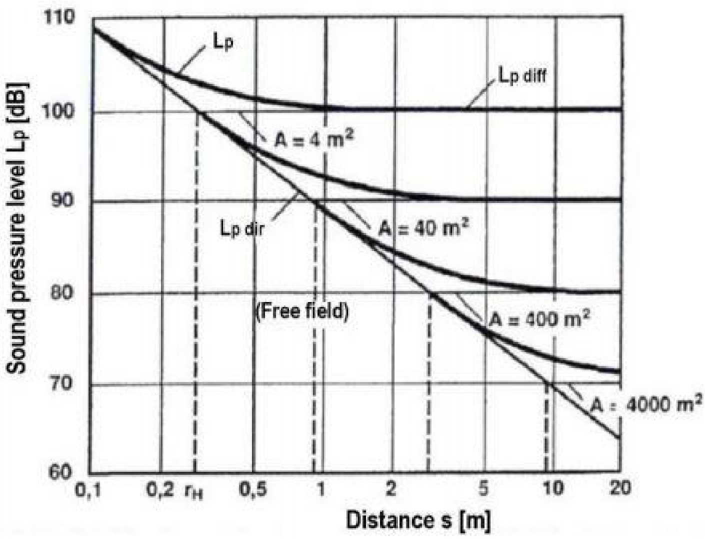

Figure 1-3. Sound pressure level in the diffuse sound field

(Fasold and Veres 1998)

1.2.3 Room acoustic in theaters

Theater acoustics must take into consideration both speech and music. Although if the room design is primarily focused on good speech intelligibility, music, singing and sound effects are secondary, but still represent the major part of the auditory experience. Theater acoustical design is supposed to achieve a consistent and vivid listening ambient.

1.3 Architectural inspiration

Theaters are one of the most important pillars of the cultural heritage. The finest examples of old theaters were erected in the age of ancient Greece and Rome (Tidworth, 1973).

Pythagoras was examining musical tuning and temperament. A single-string instrument called monochord, served him for mathematical calculations of music intervals. Aristotle followed his work and started to talk about production and reception of sound. He was writing about the phenomenon of echoes in the natural environment and how are they caused. All empirical findings and research of Greek and Roman era resulted in acoustically well-developed outdoor theaters.

The shape and architecture of ancient theaters was defined by changes in dramatic techniques (Lawrence 1983). One of the most remarkable ancient architectural constructions of theatre was, and even today still is, the ancient Amphitheatre of Epidaurus (Figure 1-4.).

It was designed in the fourth century B.C. by the Greek sculptor and architect – Polycleitus the Younger. The Amphitheatre is famous for its architectural symmetry and beauty. Greek amphitheaters were constructed in the waythat they had an excellent quality of sound and many are used even today. Greek drama has a special effect when performed in such amphitheaters.

The best features of the Epidaurus Amphitheatre are enclosed in its initial design. Key elements, which emphasized the play, were good line of sight to the stage, use of the reflecting wall and low ambient noise. The ampitheatre was originally built with an auditorium of 34 seat rows. The capacity was designed to host 14.000 spectators at once (Polster, 2003). Afterwards the Romans built an additional 21 rows. The auditorium is divided by plan into 12 tiers in the lower and 22 tiers on the upper floor. The proscenium is constructed in circular shape, with orchestra diameter of 20 meters.

Figure 1-4. Antic Amphitheatre of Epidaurus, Greece (theatre-architecture.eu 2021).

The acoustics of the Amphitheatre are impressive for the age of construction. For modern purposes the theatre is considered too “dry” for non-amplified performances (Angelakis, Rindel, Gade, 2011). It is proof that people were evidently aware of physics and presence of the sound waves. The Amphitheatre was built on a hill, and the constructors were following the natural steepness. It has no natural obstructions and that fact allowed construction of a perfectly symmetrical auditorium. Likewise, they have used mathematical calculations to achieve better sound in the arena. The main construction material of the Amphitheatre is stone. Thick layers of earth ensured its well-preserved state, which was covering the monument for centuries.

Chapter 2 – Background

2.1 Case Study

The case study - analyzed and discussed, is the theatre of the Kindertheater Narrenschloss. Based in the Austrian capital Vienna, the theater has been successfully developing young actors for more than a decade.

Narrenschloss is an interactive theater. It operates as an educational and as well as entertaining institution. It is part of the city's cultural network. The Narrenschloss theater has active members aged from 4 up to 60 years. The focus group are minors (Figure 2-1.). In interactive theatre the audience become part of the play and as such allow plays to evolve and conclude. Visitors become part of the set and the performance includes random members of the audience.

Figure 2-1. Participants of the Narrenschloss Summer camp

Narrenschloss is a non-profit cultural organization with relatively small budget and limited income. That is the reason why the redesign has had a very limited budget and the improvements are done on day-to-day basis, depending on the financial situation and sponsors. The theater was forced to move from Gasometer (Viennese famous artistic venue) to a new undeveloped location. The city of Vienna helped the theatre to gain a new address based in the Stadioncenter shopping center. The location is in the 2^{nd} district of Vienna, just next to the famous Ernst Happel Stadium – the national football stadium of Austria. This new venue had to be completely redesigned. Part of the space redesign process is also the acoustical retrofit of the main theatre hall. The new venue has had to evolve from the classic shopping store to an artistic space for children and youngsters. Narrenschloss includes more than 1.000 m^2 of space. Part of it is for office space, costume rooms, make-up rooms, kitchen and wet rooms. The remaining area is where the various performances are held. Performances are being held in the gallery area, puppet-theater hall, circus theater hall, hidden chambers of Narrenschloss and the main theater hall – which is the main focus of this case study.

The main theatre hall has up to 88 audience seats and is missing most of its compulsory structural components. This retrofit study is going to help with planning the erection of walls (which will compound parts of the stage and backstage areas), auditorium, ceiling and floor elements, as well the acoustical panels like diffusers and absorbers if needed.

2.1.1 Dataset

The main theatre hall is planned to function as a multi-purpose hall, used for various artistic events. The main purpose of the hall is based on theatre plays performed on the main stage. The hall had previously been used as an electronic store warehouse, so as such it was acoustically poorly designed and inadequate for theatre plays. The main hall has integrated main theater stage, improvised curtains which separate the backstage storage area and the auditorium which includes 88 seats (Figure 2-2.). Before the acoustical retrofit takes place, the hall has been used only for rehearsals. The planned retrofit is limited in such a way that all existing technical features in the hall prohibit change: mechanical ventilation, heating/cooling, electric and water supply, fire protective system (sprinklers, hydrant etc.), elevator and evacuation routes (Appendix Figures A-1. and A-2.).

Figure 2-2. Panoramic view of the main hall with stage

2.1.2 Plan of the Narrenschloss main theatre hall

The Narrenschloss main theatre hall plan (Figure 2-3.), reveals the planned arrangement of the hall. The main hall is separated into different areas e,g. a dressing room for the actors and a backstage area with storage space for set props. The auditorium is legally allowed to host overall 90 guests. 88 regular seats and 2 places reserved for the wheelchair users. There are four exits in the hall, of which three are fire escape routes. One exit lead towards the elevator. Measurements on the plan are in centimeters [cm] and square meters [m^2].

MAIN THEATER HALL ROOM ARRAGEMENT:

- Main theater hall gross area: 257,5 m^2
- 1 – Dressing room 12,1 m^2
- 2 – Main stage 67 m^2
- 3 – Backstage area with storage room and back corridor 46 m^2 + 12,3 m^2= 57,3 m^2
- 4 – Auditorium area 100 m^2
- 5 – Main entrance and the corridor area 17,5 m^2

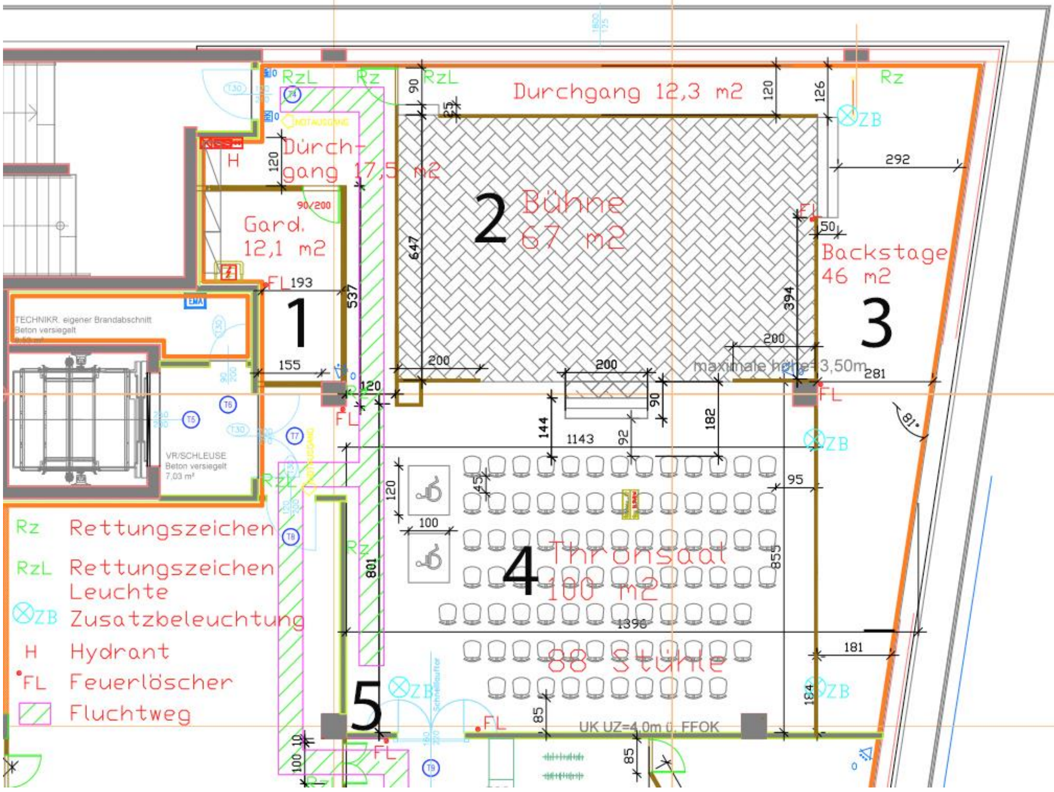

Figure 2-3. Plan of the Narrenschloss main theatre hall

2.1.3 Physical measurements of the hall

Physical quantities of the hall are represented in Figure 2-3. and Table 2-1.

Table 2-1. Main physical measurements/quantities

N (number of seats in the hall) =	88 units
V_1 (gross volume of the hall) =	1 115.78 m^3
V_2 (volume of the hall without stage) =	1 072.23 m^3
S (gross area of the hall) =	237.4 m^2
S_a (area of the auditorium floor space) =	55.68 m^2
S_o (main stage area) =	67 m^2
H (average room height) =	4.35 m
W (average room width) =	16.30 m
L (average room length) =	16.25 m
D (distance from the front of the stage to the most remote listener) =	7.55 m
SD (average stage depth) =	6.47 m
SW (average stage width) =	10.18 m
SH (mean ceiling height above the stage area) =	3.4 m

2.1.4 Materials in the hall

Acoustical ambiance is defined by the room volume, structure of the room and materials used. Structural and surface materials used in the room are wood flooring, double glazed windows, installation ducts made of metal, wooden stage, metal doors, painted concrete walls, painted gypsum walls, painted concrete ceiling, painted concrete beams, theater metal and upholstered chairs and wooden bookshelves. In chapter 5 detailed tables are provided for every case scenario (i.e., Tables 5-1. and 5-2.) with its quantity and absorption coefficient defined. These materials are included as a computer simulated model.

2.2 Pre-retrofit prediction

Many acoustical problems can be eliminated by implementing the proper redesign of space. A few basic suggestions that could be implemented are avoiding parallel surfaces between the walls, between the floor and ceiling and by avoiding sharp corners. Other considerations during the acoustical retrofit are also possible, for example the implementation of sound diffusers, absorber panels and even base traps. Diffusers disperse audio waves in different directions at different frequencies, while absorber panels prevent waves reflecting off the walls. All these elements will drastically improve overall acoustical performance of the hall. Newly added acoustically effective materials and acoustical elements have to be placed in the correct positions in the room to achieve improvements.

2.2.1 Refurbishment

New elements and new materials will have to be used. Improvements can be made to the walls, floors and ceilings.

Floors. Initially, improvements can be made to the floors. Thicker carpet on the floor can provide a lot of sound absorption. A less reflecting floor will have a great role in an acoustical retrofit. The auditorium can be raised up as in historical theaters (Figure 1-4.). A less effective solution is to have auditorium chairs placed directly on the floor level. Elevation of the spectator stands would also improve the point of view, and a better auditory experience for the audience. Direct sound will have better sound impact on the middle and back part of auditorium. No other improvements to the floors are expected, as the chairs in the auditorium nowadays are adequate, and by prediction they fulfill the acoustical needs. They are made of metal body, wooden plate with upholstery foam, covered with thick fabric.

Walls. According to the main theater hall plan (Figure 2-3.) new separating walls are going to be built to form new areas within. Backstage and wardrobe walls are predicted to be made of acoustically well performing material like insulated gypsum. The existing shape of the hall is considered as an advantage, as the walls are not parallel. Newly built walls can be enriched with acoustical reflectors, sound diffusers and absorbing boards. To achieve better absorbing features it is suggested to add theater curtains on the walls. Concrete surfaces are great reflectors as well as glass surfaces. The main hall has 57 m^2 of fixed windows installed.

Covering them with the curtains at specific points is expected to considerably improve room acoustics.

Ceilings. The main hall has most of the technical installation placed in the concrete ceiling. Suspended heaters, electrical and ventilation ducts, security and fire alarms and fire extinguishers are installed over the whole venue. The situation is photographically documented in Appendix A.2 (Figures A-1. and A-2.). The ventilation ducts are mainly on the left side of the room where the changing room and the corridor are planned. The ventilation ducts are functioning as sound reflectors. It is suggested to add hanging sound absorbers in between which are expected to improve intelligibility and overall sound in the theatre space.

Pre-retrofit ideas that are expected to give better acoustically performing results. Figure 2-4. schematically describes a few of the above-mentioned suggested improvements.

- 1. – Sound absorbing back wall
- 2. – Elevated auditorium
- 3. – Stage
- 4. – Sound source (speaker/actor)
- 5. – Stage curtain
- 6. – Sound reflecting ceiling boards in the stage part
- 7. – Sound reflecting ceiling elements above audience

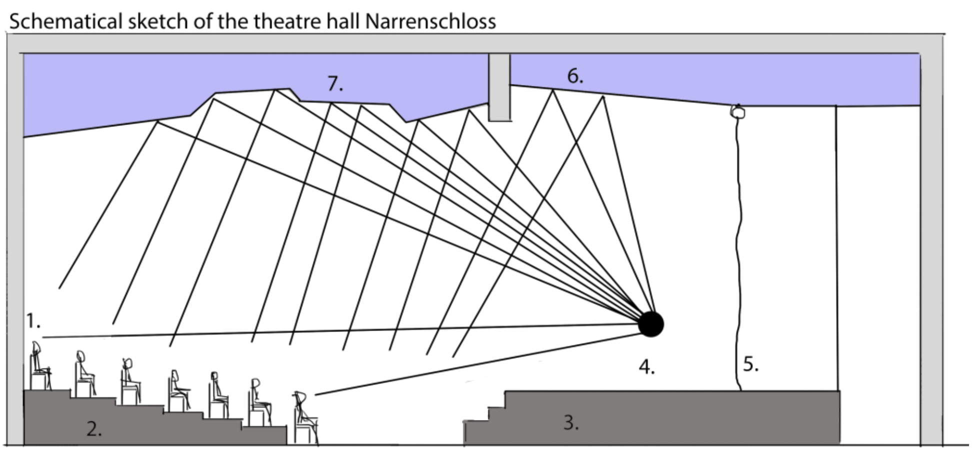

Figure 2-4. Cross section sketch

Chapter 3 – Methodology

Thesis is based on an analytical research methodology. The main Narrenschloss hall has been architecturally and acoustically analysed. Focus is the influence of existing hall elements on overall acoustical performance, therefore which are the acoustical advantages and disadvantages of the given hall design. Within this thesis are integrated the most important rules of acoustical design, historical and traditional practice used in acoustical projects and the definition of acoustically adapted materials. The case study includes measurements of the acoustical performance of the hall and creation of simulation models of the pre-retrofitted and retrofitted theater hall.

Framework:

- What is the acoustical retrofit of theatre?
- What is the historical and traditional practice in acoustics through the years?
- Which are the acoustically adapted materials?
- What is the acoustical performance of the main Narrenschloss theatre hall?
- What could be done to improve acoustical ambient of the space given?

An explanation of the known and newly revealed facts within given topic are supposed to give an answer how to improve room acoustics. The conclusion includes brief comments about the process of work procedures and general overview of the questions raised.

3.1 Research structure

In diagram (Figure 3-1.) the research work structure and the main procedures are represented. The study consists of four cases. Three cases are physically measured with instruments, and all four cases are digitally simulated through a three-dimensional model.

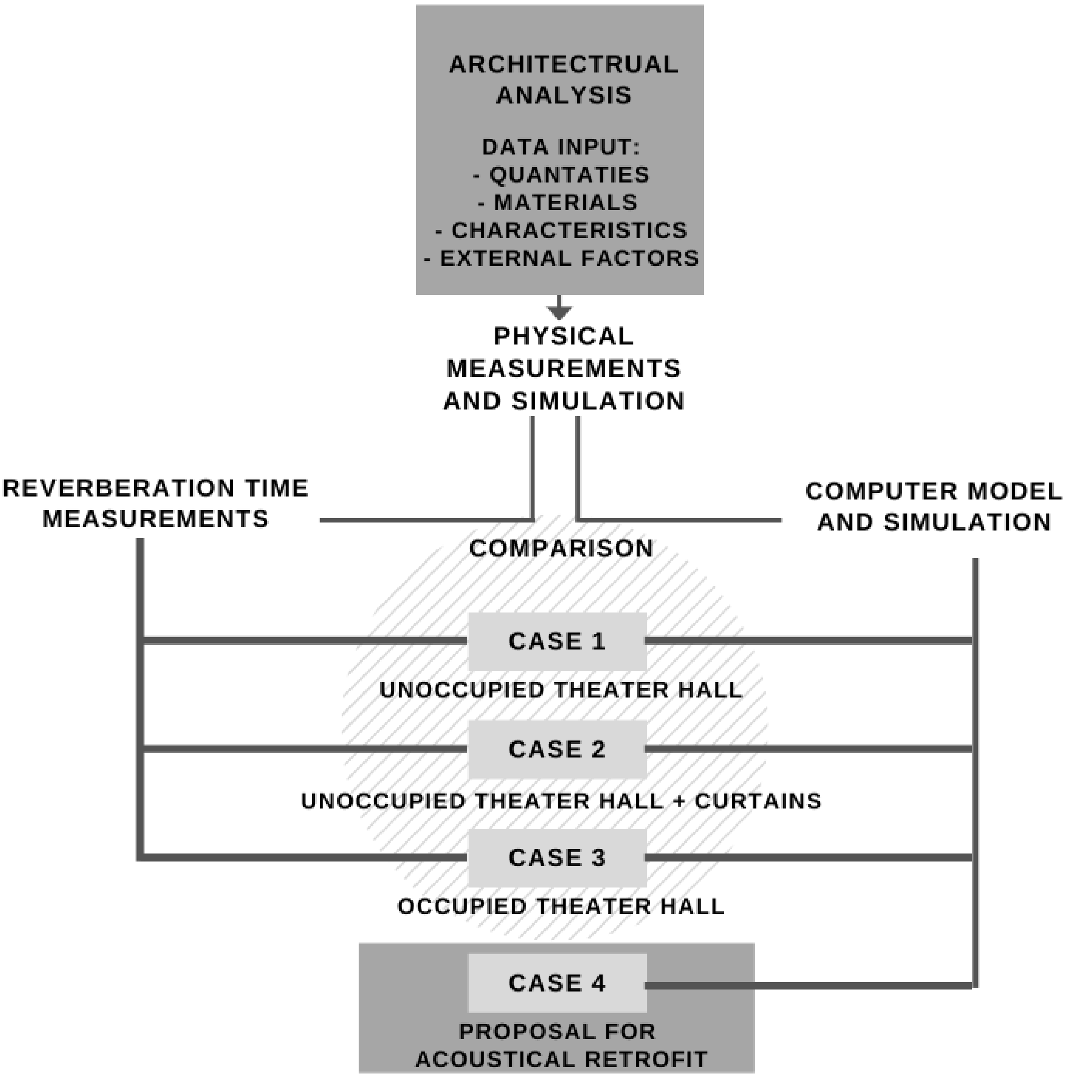

Figure 3-1. Research structure diagram

3.2 Measurements - Equipment and procedures

Acoustical measurements were conducted to define the reverberation time of the Narrenschloss main theater hall. Measurements have had three scenarios – named Case 1, Case 2, and Case 3. Acoustical measurements were conducted in compliance with Austrian technical standards defined by ÖNORM EN ISO 3382-2 (2009).

3.2.1 Measuring equipment

Equipment used for the measuring in the Narrenschloss main hall was Wireless Building Acoustic System including:

- Sound Analyzer (including mic and pre-amp inside the mic): 2 × Norsonic Nor140
- WLAN Router: MOXA AWK-3121-EU
- Building Acoustic Case: 2 × Norsonic Nor515
- Power Amplifier: Norsonic Nor280
- Dodecahedron Loudspeaker: Norsonic Nor270
- Calibrator: Norsonic Nor1251
- Software: Norsonic Control Build

Figure 3-2. Measurement configuration (Lechleitner 2009)

Equipment used to determine the positions of the speakers, microphones and physical distances in general:

- Laser tape measure: Bosch Laser Rangefinder DLE 50 Professional

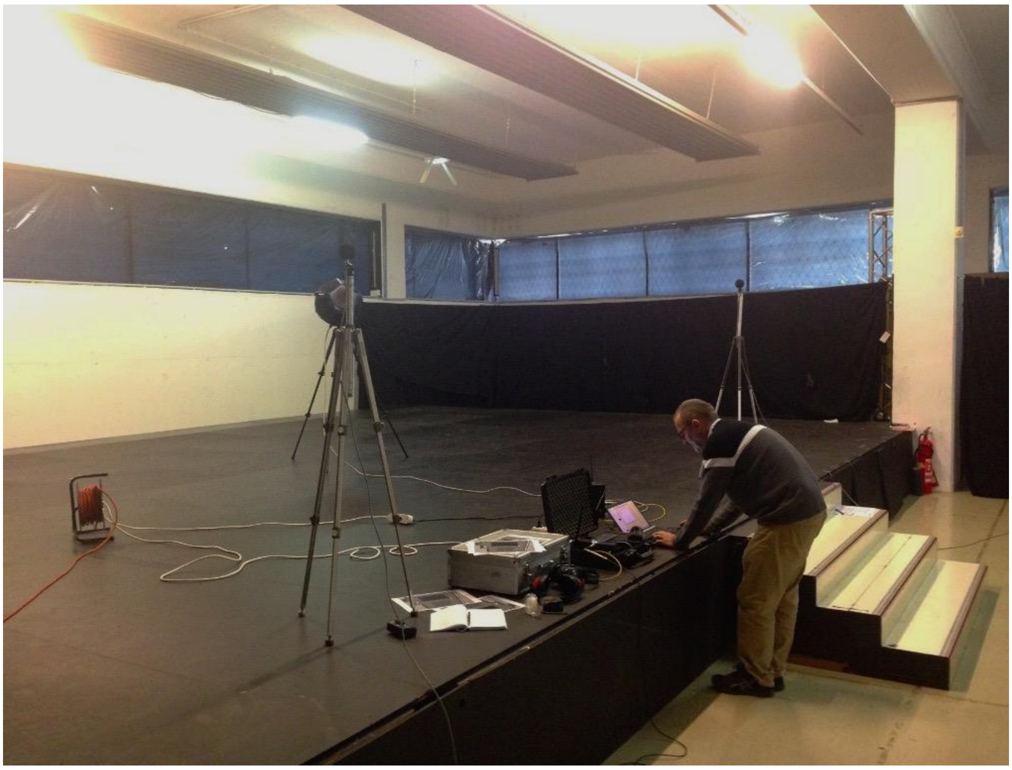

Figure 3-3. Measuring equipment on the main stage

3.2.2 Measuring procedures and data set

The hall was not a perfect case scenario for gathering acoustical data, because it was not completely empty. The day before acoustical measurements were taken, the hall was cleared of equipment and set requisites as much as it was approved by the Theater management. The state of the hall during the measuring process can be seen in Figures 3-5., 3-6. and 3-7.

After equipment installation, the established measurements plan was implemented. The measuring plan (Figure 3-4.) defined 15 points in the room, where we installed speakers and microphones. Every point has its index number and coordinates in meters [m] (Table 3-1.). The 0,0,0 coordinate is in the left bottom corner next to the main entrance.

Temperature of the hall at the time of the measurements was 20º C with 50 % air humidity. The Stadioncenter representatives provided information about the temperature and air humidity as they monitor these parameters on a regular basis. The air conditioning was not operating in the main theatre hall during the acoustical measurements.

Table 3-1. Measurements positions and coordinates

Position/Coordinates:	X (m)	Y (m)	Z (m)
x1	9.55	8.86	2.00
x2	6.55	8.86	2.00
x3	3.55	8.86	2.00
x4	9.55	11.86	2.00
X5 (SPEAKER)	6.55	11.86	2.00
x6	3.55	11.86	2.00
x10	9.55	5.86	1.35
x11	6.55	5.86	1.35
x12	3.55	5.86	1.35
x13	9.55	4.10	1.35
x14	6.55	4.10	1.35
x15	3.55	4.10	1.35
x16	9.55	1.56	1.35
x17	6.55	1.56	1.35
x18	3.55	1.56	1.35

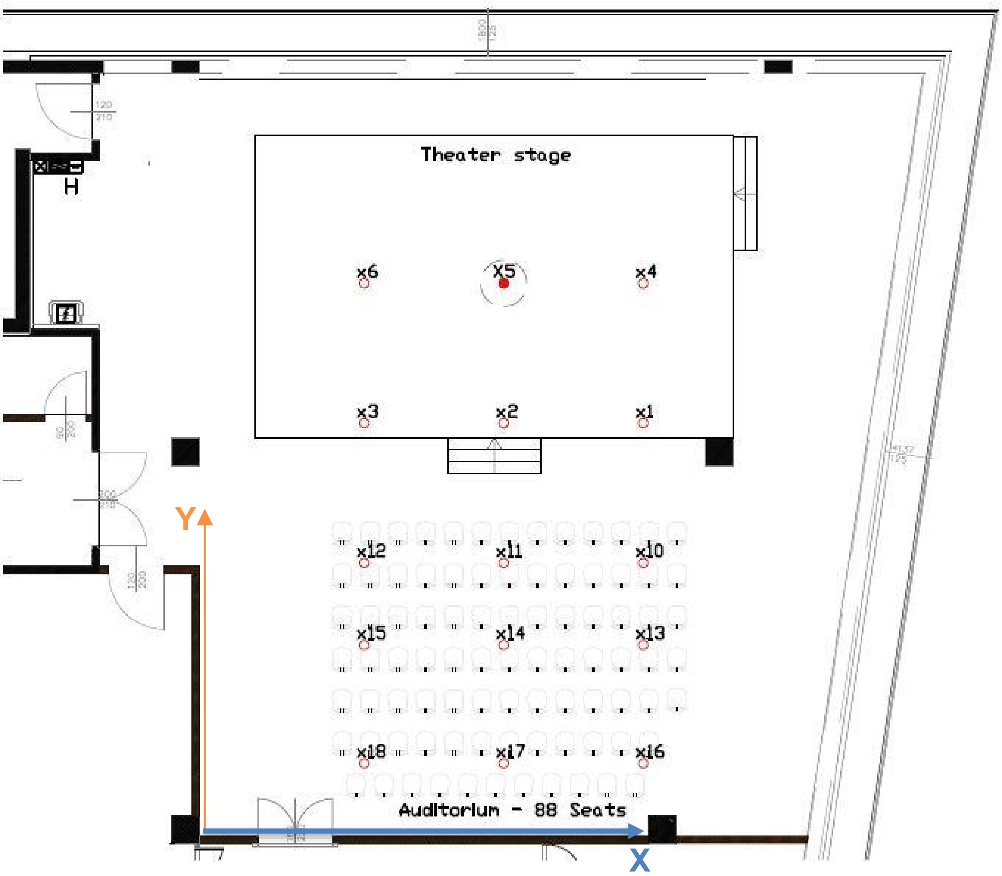

Figure 3-4. Measuring plan points

After the measurement equipment was set and ready for measuring, the positions of microphones and power source (Dodecahedron Loudspeaker Norsonic Nor270) were marked. The sound source was positioned in middle of the stage (point X5).

In all cases the microphone height was set to 135 cm above the floor level (usually it is set to 120 cm). The reason for this setting was the height of the theatre chairs, which was measured to be 105 cm. Microphones were placed on the 9 points positioned in the audience area and 5 points positioned on the stage, closer to the sound source. Positioning of both microphones is important (microphone A and microphone B), as the measuring was conducted with two microphones at the same time. Positions A and B are set, so the measured values at the particular sound recipients are not mixed. While measuring position-B microphone was wireless.

3.3 Measuring scenarios

The measurements were set in three different scenarios. The same number of points were not measured in every case, because of time limitations and coordination with 45 guests, which have contributed to the measuring procedures by their presence (Case 3).

3.3.1 Case 1

In the first case scenario, reverberation time of an unoccupied theatre hall was measured, excluding two adult persons, which were

Figure 3-5. Case 1 stage view of an unoccupied hall

conducting the acoustical measurements. All the audience chairs were set (88 chairs). In case 1 scenario all 14 microphones´ positions were measured. It was important to get the most measurements with the smallest amount of absorbers.

3.3.2 Case 2

In the second case scenario (Figure 3-6.), the reverberation time of an unoccupied theatre hall with additional 2.1 m high curtains, was measured. The area of the curtains was 48.51 m^2. Theatre curtains were positioned on metal strings – aligned with two sides of the stage. Curtains are made of 3 mm thick fabric. They were set as a visual barrier - simulating planned gypsum walls (Appendix Figure A-3.). Walls will be constructed with a maximum height of 2.7 m, so the technical installations will not be obstructed. The walls will not

Figure 3-6. Stage view while measuring case 2 scenario

enclose the space completely.

Besides added curtains, no other changes relating to case 1 scenario were made.

In case 2 scenario 10 of total 14 microphone positions were measured. Microphones were measuring positions x4, x6, x10, x11, x12, x14, x15, x16, x17 and x18.

3.3.3 Case 3

In the third case, we have measured same parameters of the theatre hall as in first two scenarios. Case 3 is reconstructed Case 1 scenario but with an audience present (Figure 3-7.).

Figure 3-7. Case 3 - Audience at the acoustical measurements

There was more than 50 % occupancy of the hall capacity achieved. 45 persons were present at the measuring procedures. The audience consisted of adults and minors. Participants were advised to cover their ears, while the acoustical measurements were conducted, due to possible hearing damages of the measuring procedures.

In case 3 scenario, 7 microphone positions were measured. Measured points were x2, x10, x11, x12, x13, x14 and x15. Because of the theatre timetable it was not possible to make more measurements with the audience present.

3.4 Measuring data

Input data has been accumulated in the RT measuring process. In all three scenarios it is possible to observe differences between an unoccupied room, unoccupied with additional curtains and an occupied room. In Figures 3-8., 3-9. and 3-10. show the results of reverberation time measurements and their mean value. In Appendix A.3 the values for all measured points in all three measured scenarios are listed.

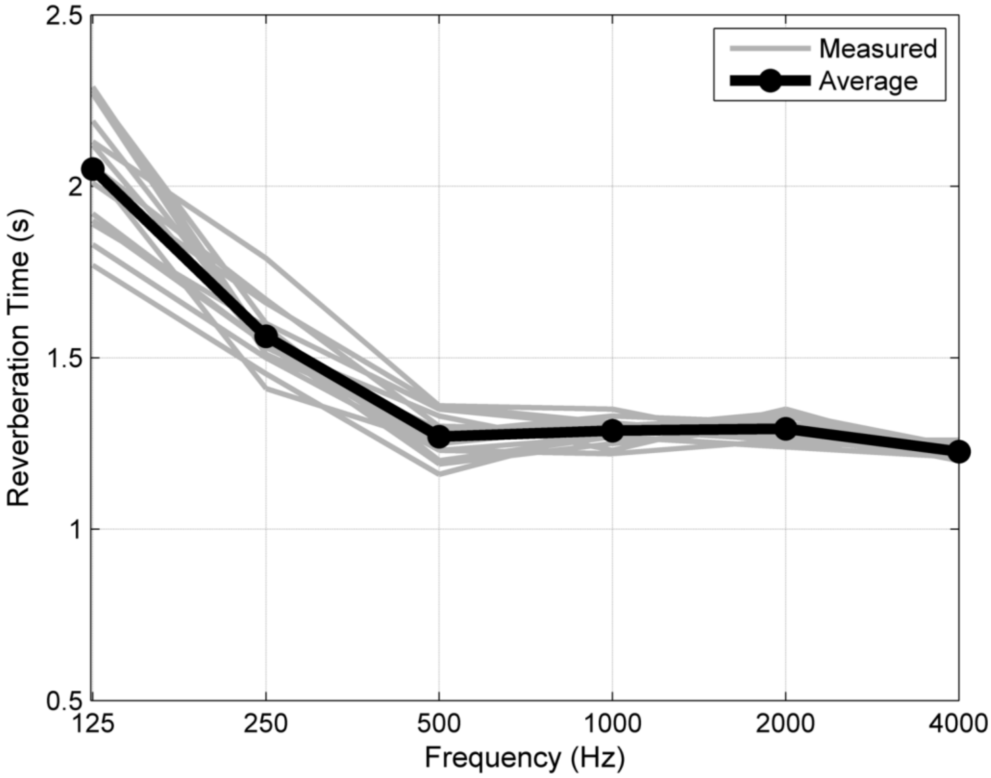

Figure 3-8. Case 1 – Measured RT(30) in unoccupied room

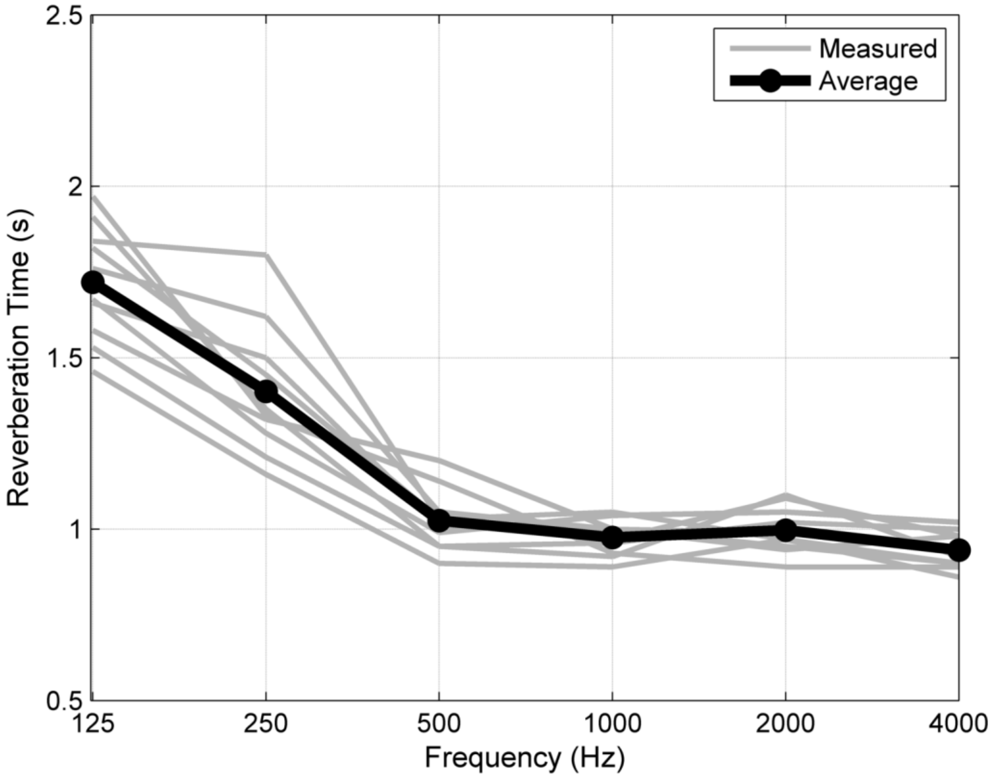

Figure 3-9. Case 2 – Measured RT(30) in unoccupied room with curtains

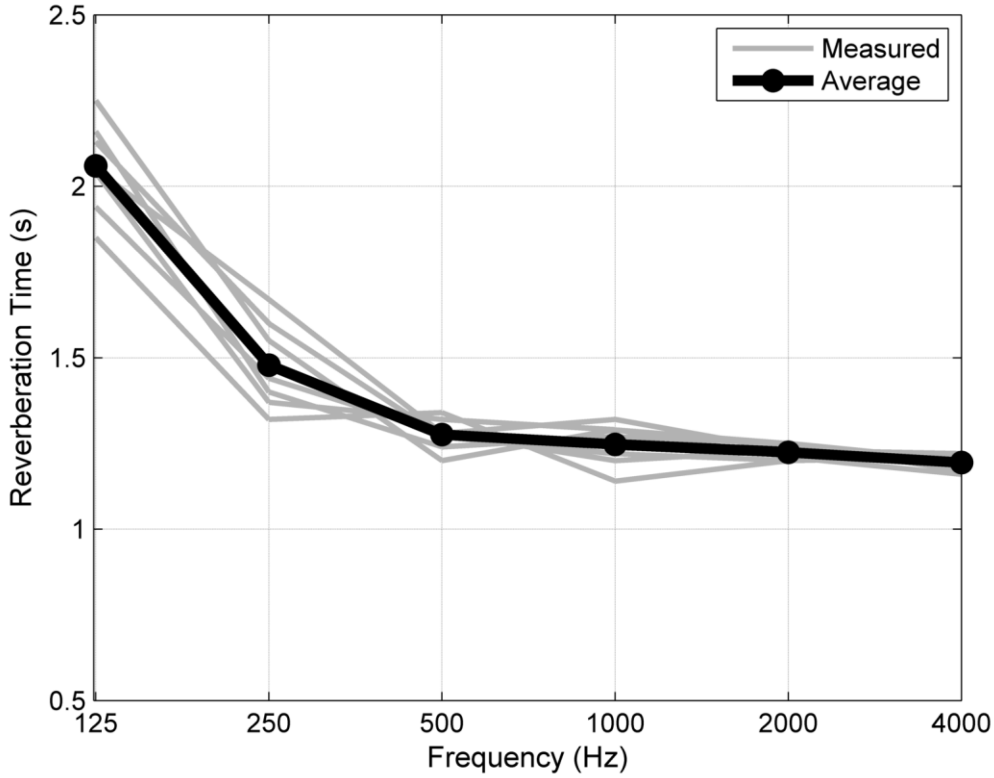

Figure 3-10. Case 3 – Measured RT(30) in occupied room

Chapter 4 – Acoustical simulation model

4.1 Simulation and procedure

The software used for the computer simulation of the acoustical performance of the theatre hall Narrenschloss was ODEON, owned by Danish software developing company ODEON A/S.

4.1.1 Simulation and calibration of room acoustic model

Before the case situation can be simulated in Odeon (11.0), it has to be modelled. Odeon provides a modelling option itself, but for intermediate structures, a 3D model can be built with other software. A 3D model of the main hall had been modelled with the Google product – SketchUp in combination with an Odeon plug-in. The model is simplified according to online guidelines provided by Odeon A/S in a way to minimize the data before exportation (Figure 4-1.). Layers are used due to easier property change in Odeon itself. For each case a scenario model was built.

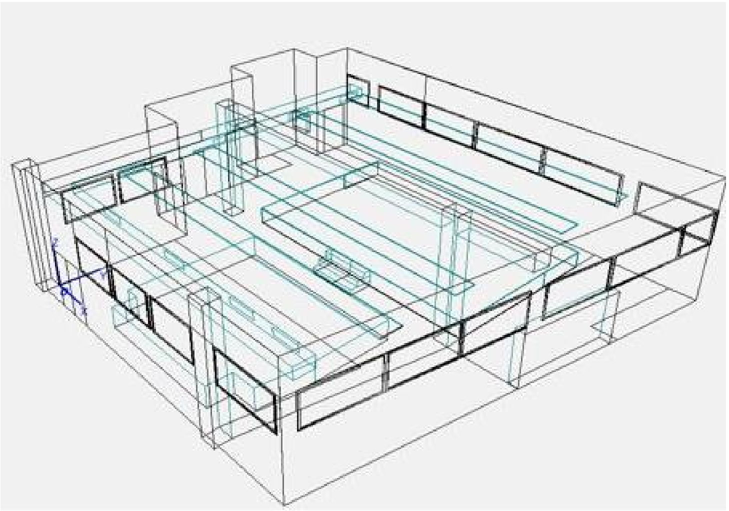

Figure 4-1. Case 1 3D model exported into ODEON

The exported model in Odeon has to have no errors. If there are any, Odeon will report the problems and it can be resolved in SketchUp and exported again. Inspection can be done with a 3D geometry debugger. By using rays in Odeon, the model can be inspected for water tightness. Surfaces have to be set with an adequate absorption coefficient with its frequency ranges. The absorption coefficient defines the material absorption ratio of the sound energy to the impact sound energy. The smaller α coefficient represent greater reflecting material.

4.2 Calibration of room acoustical model

The goal of the created simulations is to achieve the same or at least similar results with the physical measurement scenarios. That is why the data entry for the simulation should be as close to the real situation as possible in order to get realistic results which are comparable in the end. If the results are similar, it will create an opportunity to build a simulated model for the final acoustical design proposal of the Narrenschloss theatre hall. These predictions are key factors for an acoustical retrofit.

Before observation of the simulation cases, it is important to state, that all cases have had the same source and receiver placement. Positions are the same as in the physical measurements' cases (Table 3-1. And 4-1.). The only difference is the starting point of the coordinates. In the Odeon simulation model (Figure 4-2.), the software automatically sets the starting point of the coordinates. The Y coordinate was set 45 cm closer to the source (loudspeaker – position X5/P1). When comparing the physical measurement and simulation model coordinates, it is important to consider these 45 cm.

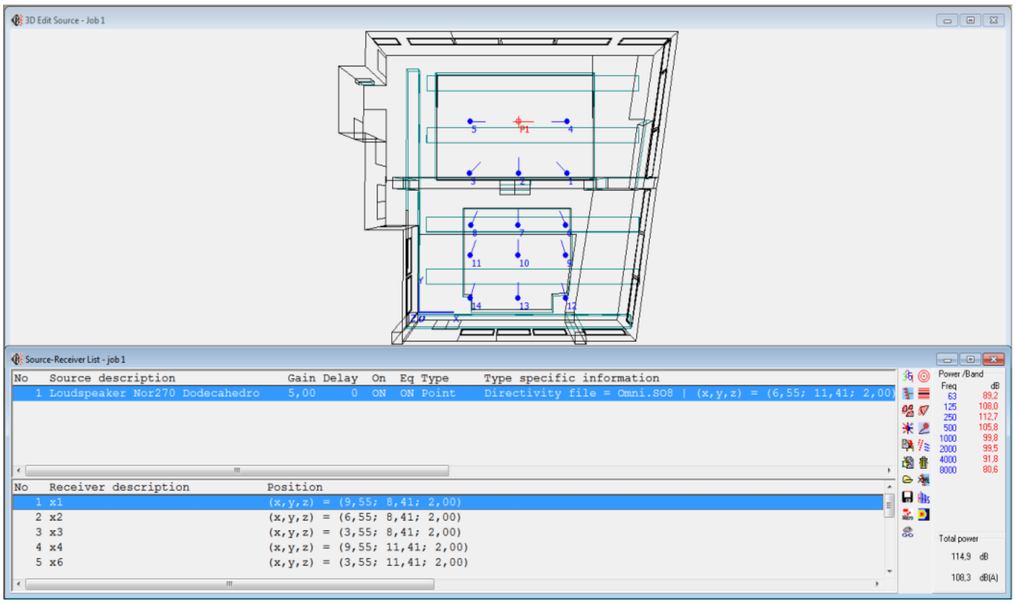

Figure 4-2. Measuring points with coordinates in Odeon

Table 4-1. Positions and coordinates in Odeon

Position:	X (m)	Y (m)	Z (m)
x1 - 1	9.55	8.41	2.00
x2 - 2	6.55	8.41	2.00
x3 - 3	3.55	8.41	2.00
x4 - 4	9.55	11.41	2.00
X5 – P1	6.55	11.41	2.00
x6 - 5	3.55	11.41	2.00
x10 - 6	9.55	5.41	1.35
x11 - 7	6.55	5.41	1.35
x12 - 8	3.55	5.41	1.35
x13 - 9	9.55	3.65	1.35
x14 - 10	6.55	3.65	1.35
x15 - 11	3.55	3.65	1.35
x16 - 12	9.55	1.11	1.35
x17 - 13	6.55	1.11	1.35
x18 - 14	3.55	1.11	1.35

Defining the source prior to simulation demands the source data. In this case, when the source is Dodecahedron Loudspeaker type Norsonic Nor270, values inserted for the simulation can be observed at the Figure 3-1. It is positioned in the center of the stage. The loudspeaker and acoustical equipment values inserted for the simulation were provided by the Building physics and Building ecology departments of the Vienna University of Technology. The equipment was measured in an anechoic chamber in octave bands from 50 Hz to 8000 Hz.

Addition of the levels was done according to the formula (Fasold, W. and Veres, E. 1998. *Schallschutz und Raumakustik in der Praxis: Planungsbeispiele und konstruktive Lösungen. p.21)*:

- $L_{ges} = 10\,log \sum_{j=1}^{n} 10^{\frac{Lj}{10}}\ dB$

All physical acoustical measurement results (chapter 5) are one-third frequency octave band values. Odeon results are already simulated in octave bands. Use of the upper stated formula is essential to compare measured and simulated results, or when inserting Loudspeaker equalization values. It is used physically measured 50 Hz, 63 Hz and 80 Hz octave values and inserted into upper formula to calculate the 63 Hz octave band, which can be inserted into Odeon.

Chapter 5 – Results and discussion

5.1 Comparison measured vs. simulated

The comparison of results between physically measured results and computer-simulated results is based on the acoustical parameter of reverberation time. The recommended reverberation time for the small theatre hall, with an audience up to 100 persons is between 1.0 s to 1.3 s (Figure 5-19.). These are the values, which the retrofit is striving to achieve in the case of the Narrenschloss main theatre hall.

5.1.1 Case 1

The first case scenario simulation model has been built to replicate the real-time situation. The elements in the theatre hall are a little less detailed on behalf of successful importation/simulation in Odeon. 88 chairs are simplified as an audience box. Suspended ceiling heaters and ventilation ducts, beams, columns, windows, stage, doors, floors, walls and ceiling elements are grouped in layers. Every layer has its own material property, and as so determined by its acoustical characteristics. All absorption coefficients (α) in this study are assumption values taken out of ODEON material database (Tables 5-1., 5-2.). These characteristics have to be adjusted for every single element/layer in the material list. In the Odeon 3D model (Figure 5-1). It is possible to compare different materials and their absorbing coefficients (α) by the distinguished (red) dark colour. The charts in Figures 5-2. and 5-3. compare measured and simulated results.

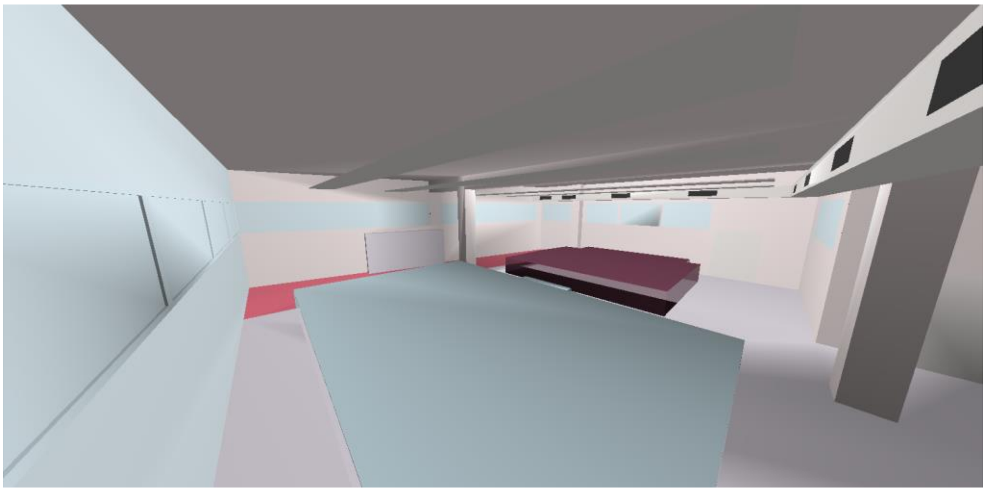

Figure 5-1. Odeon 3D model – Case 1

Table 5-1. Case 1 – Non-calibrated absorption

Absorption Coefficient α								
Non-calibrated								
Layer/Frequency (Hz)	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	***Area (m^2)***
Floor – Wood floor	0.1	0.1	0.07	0.05	0.06	0.06	0.06	***270***
Glass - Windows	0.1	01	007	0.05	0.03	0.02	0.02	***57***
Heaters, Fire hydrant, Vent grill, Ventilation – Metal plate	0.04	0.04	0.04	0.05	0.06	0.06	0.06	***150***
Stage – Wood podium	0.19	0.19	0.14	0.09	0.06	0.06	0.05	***85***
Doors – Metal plate	0.04	0.04	0.04	0.05	0.06	0.06	0.06	***12***
Wall – Concrete	0.02	0.02	0.02	0.03	0.04	0.05	0.05	***150***
Wall – Gypsum	0.08	0.08	0.11	0.05	0.03	0.02	0.03	***80***
Theatre storage/tech	0.01	0.01	0.05	0.99	0.65	0.45	0.4	***50***
Ceiling - Concrete	0.02	0.02	0.02	0.03	0.04	0.05	0.05	***260***
Beam, Columns Concrete	0.02	0.02	0.02	0.03	0.04	0.05	0.05	***70***
Chairs – Empty chairs	0.44	0.44	0.6	0.77	0.89	0.82	0.7	***65***
Bookshelf – Wooden shelf	0.04	0.04	0.04	0.99	0.8	0.35	0.1	***12***

Table 5-2. Case 1 – Calibrated absorption coefficient

Absorption Coefficient α							
Material/Frequency (Hz)	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**
Wood floor	0.05	0.06	0.22	0.22	0.07	0.06	0.06
Concrete	0.01	0.01	0.04	0.05	0.06	0.06	0.06
Theatre storage/tech	0.01	0.01	0.1	0.4	0.5	0.5	0.3

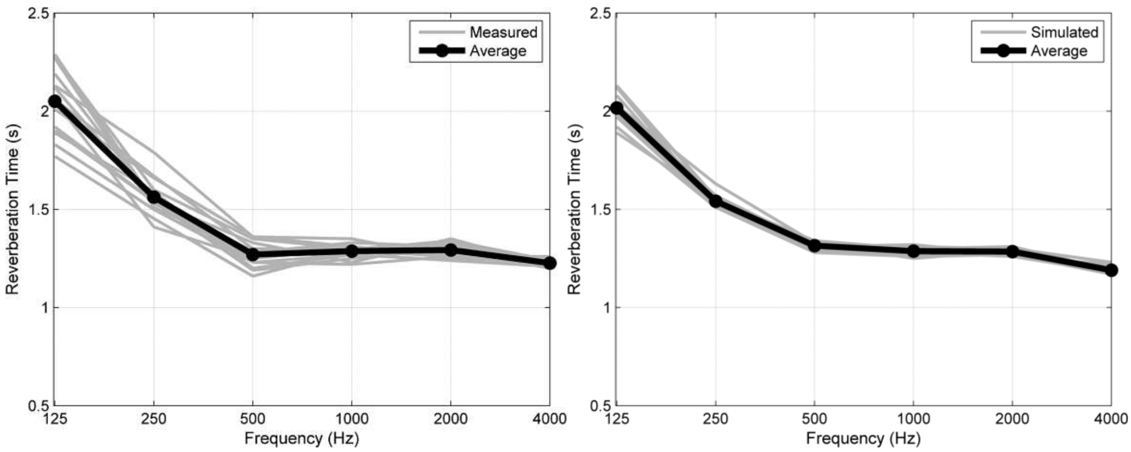

Figure 5-2. Case 1 – Measured and simulated charts

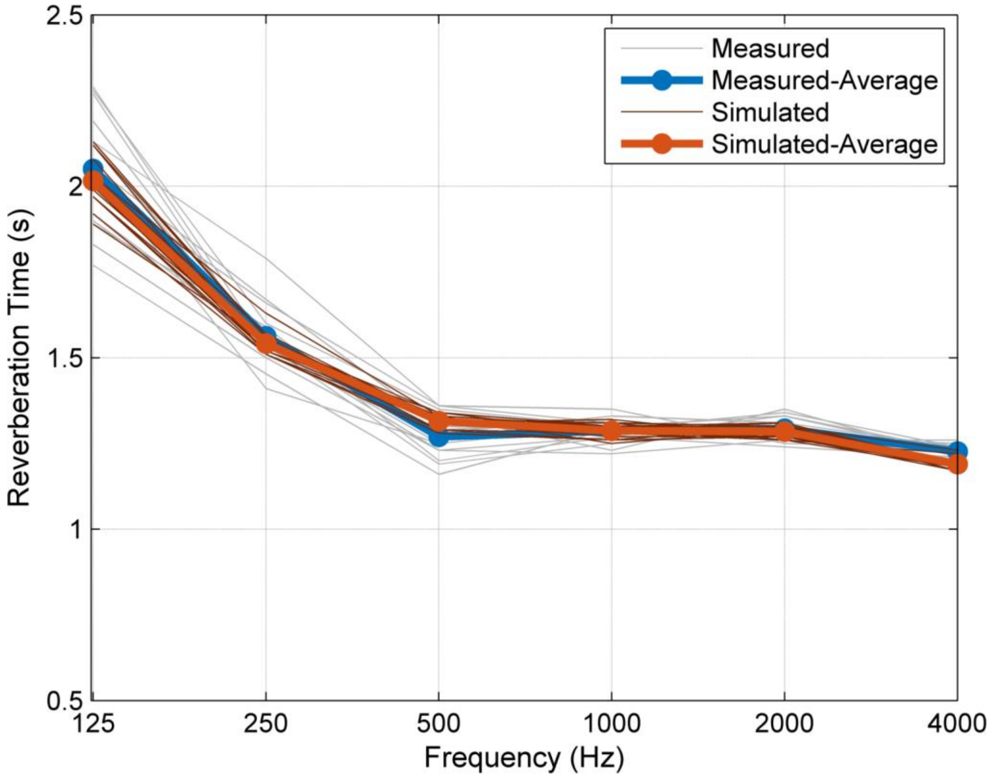

Figure 5-3. Case 1 – Measured/simulated chart combined

Table 5-3. Case 1 – Simulated reverberation time

Point/Frequency (Hz)	125	250	500	1000	2000	4000
Case 1 Point-1	2.19	1.54	1.25	1.3	1.3	1.2
Case 1 Point-2	1.9	1.54	1.23	1.22	1.26	1.22
Case 1 Point-3	2.12	1.53	1.29	1.31	1.27	1.25
Case 1 Point-4	1.92	1.54	1.19	1.25	1.3	1.22
Case 1 Point-6	1.89	1.59	1.2	1.27	1.24	1.21
Case 1 Point-10	1.77	1.453	1.16	1.293	1.34	1.24
Case 1 Point-11	2.05	1.41	1.25	1.3	1.3	1.2
Case 1 Point-12	1.83	1.5	1.23	1.27	1.33	1.23
Case 1 Point-13	2.28	1.6	1.35	1.3	1.33	1.22
Case 1 Point-14	2.01	1.66	1.36	1.35	1.25	1.24
Case 1 Point-15	2.13	1.79	1.36	1.31	1.26	1.26
Case 1 Point-16	2.27	1.51	1.28	1.33	1.31	1.24
Case 1 Point-17	2.06	1.67	1.3	1.29	1.26	1.23
Case 1 Point-18	2.29	1.54	1.33	1.23	1.35	1.21

In Table 5-3. are listed Case 1 scenario simulated values of selected points. Additional charts for every measured/simulated point are in Appendix A.3.

Simulation has provided similar results between the different points, and a correlation between results. The measurements were taking place in the hall, which is positioned next to the overground railways (Viennese Metro Station Stadion). Vibrations and low frequencies by that structure-borne sound can be taken in consideration.

5.1.2 Case 2

The second case simulation model is based on the first case scenario. All materials are the same with their defined absorbing coefficients (Table 5-4.). Calibrated model coefficients are listed in Table 5-5. The new and key feature of this scenario are curtains, aligned by the two sides of the stage and on the right side of the audience area. Curtains are set at the height of 2.1 m. They are set as improvised walls (Figure 5-4.) until the final refurbishment is implemented. As well as being an acoustical improvement for the time being, they are also a visual barrier, dividing the backstage and performance stage areas. The curtain has its thickness, and that is how it is modeled. Curtain areas contribute a large area of absorption. The result is improved reverberation time of the hall (Table 5-6.) in comparison to case 1. In charts represented in Figures 5-5. and 5-6. is possible to compare the results obtained.

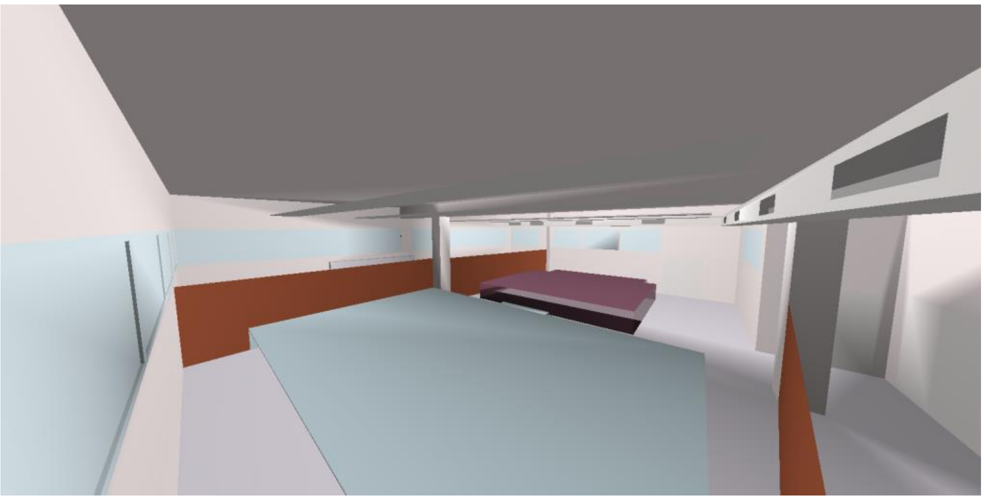

Figure 5-4. Odeon 3D model – Case 2

Table 5-4. Case 2 – Non-calibrated absorption coefficient

Absorption Coefficient α								
Layer/Frequency (Hz)	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	***Area (m^2)***
Case 1 (Table 5-1.)								
+ added Curtains	0.30	0.30	0.45	0.65	0.56	0.59	0.71	**90**

Table 5-5. Case 2 – Calibrated absorption coefficient

Absorption Coefficient α							
Material/Fr. (Hz)	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**
Curtains	0.25	0.25	0.35	0.65	0.56	0.59	0.71

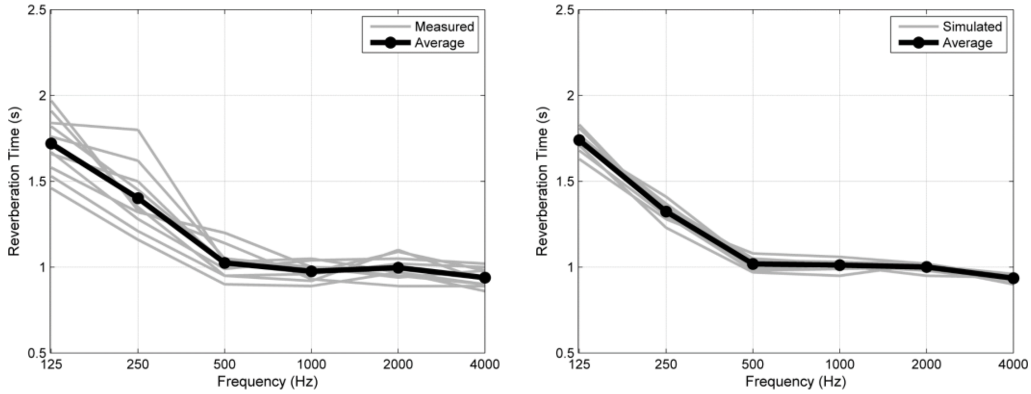

Figure 5-5. Case 2 – Measured and simulated charts

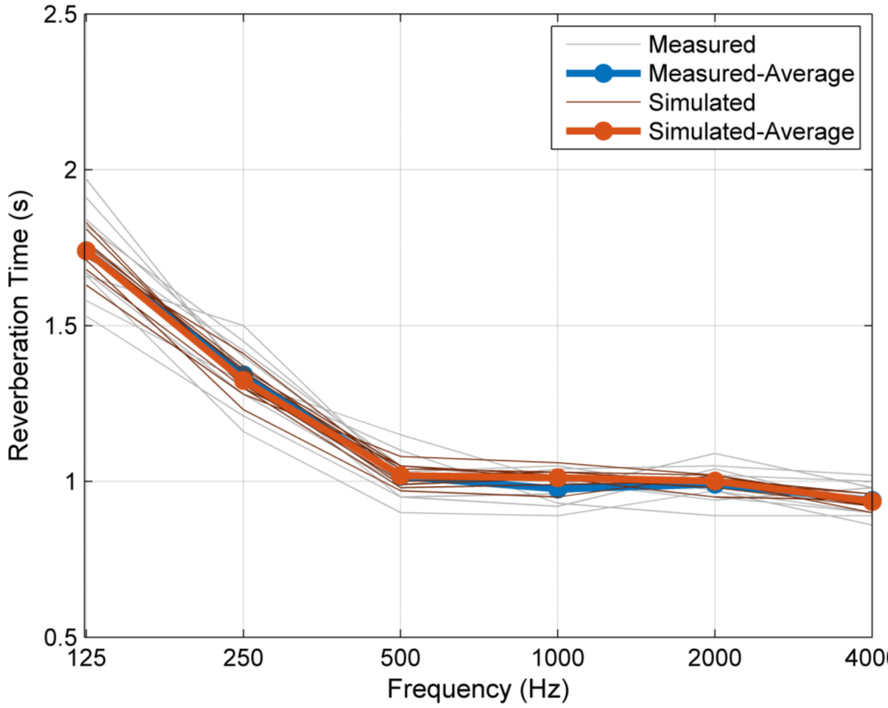

Figure 5-6. Case 2 – Measured/simulated chart combined

Attention has to be drawn to the comparison of the simulation model and the real-time conditions. Errors occur due to a lack of experience and knowledge. Better computer modelling, more experience, improved knowledge, and a more detailed database can provide effective simulation-based assessments.

Table 5-6. Case 2 – Simulated reverberation time

Point/Frequency (Hz)	125	250	500	1000	2000	4000
Case 2 Point-4	1.67	1.28	0.99	1.04	1.05	1.02
Case 2 Point-6	1.66	1.16	0.9	0.89	0.97	0.86
Case 2 Point-10	1.53	1.21	0.95	0.92	1.04	0.92
Case 2 Point-11	1.91	1.35	0.95	0,96	1.02	1
Case 2 Point-12	1.58	1.32	1.15	1	0.99	0.94
Case 2 Point-14	1.66	1.5	1.01	1	0.94	0.98
Case 2 Point-15	1.82	1.45	1.03	0.97	1.09	0.98
Case 2 Point-16	1.84	1.4	1.03	1.05	0.97	0.9
Case 2 Point-17	1.97	1.33	1.1	0.93	0.89	0.89
Case 2 Point-18	1.76	1.42	1.05	1	0.95	0.9

5.1.3 Case 3

The third case scenario simulation model (Figure 5-7.) is the same as the first case scenario. All parameters are the same (Tables 5-7. And 5-8.), with the key difference – occupancy factor. Audience values are added into the simulation. RT results are shown in Table 5-9. There are no visual differences between Case 1 scenario and Case 3 scenario, in Odeon 3D model. Simulation results obtained are comparable in Figures 5-8. and 5-9.

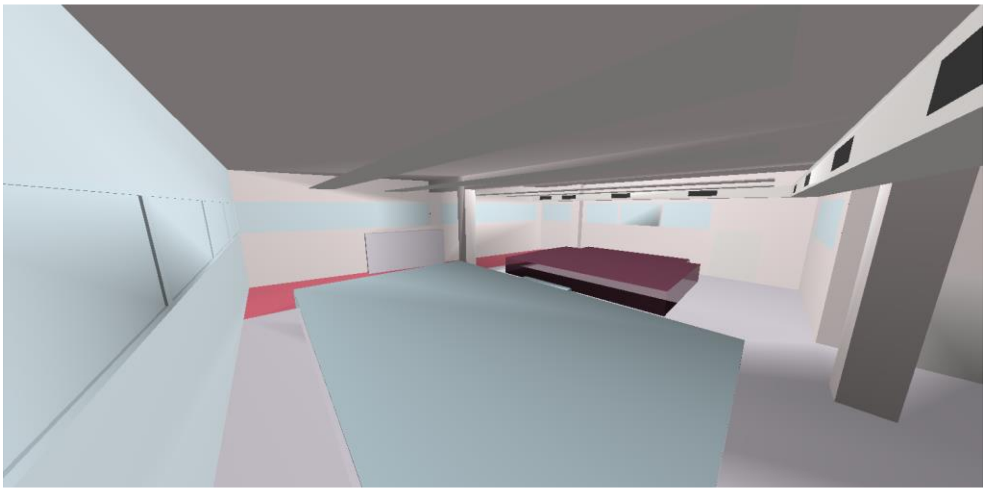

Figure 5-7. Odeon 3D model – Case 3

Table 5-7. Case 3 – Non-calibrated absorption coefficient

Absorption Coefficient α								
Layer/Frequency (Hz)	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	***Area (m^2)***
Case 1 (Table 5-1.)								
Chairs with audience	0.51	0.52	0.64	0.75	0.8	0.83	0.83	**65**

Table 5-8. Case 3 – Calibrated absorption coefficient

Absorption Coefficient α							
Material/Fr. (Hz)	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**
Chairs with audience	0.35	0.40	0.64	0.75	0.8	0.81	0.5

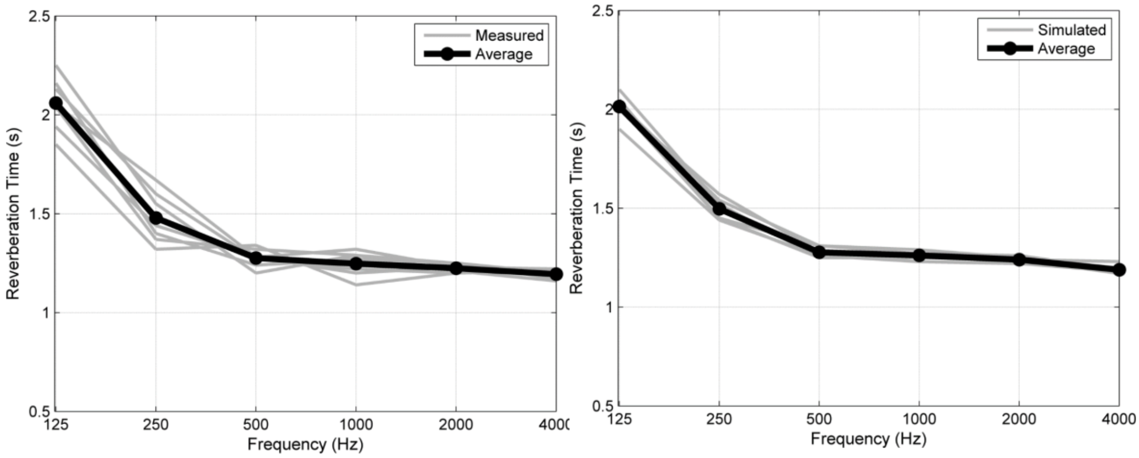

Figure 5-8. Case 3 – Measured and simulated charts

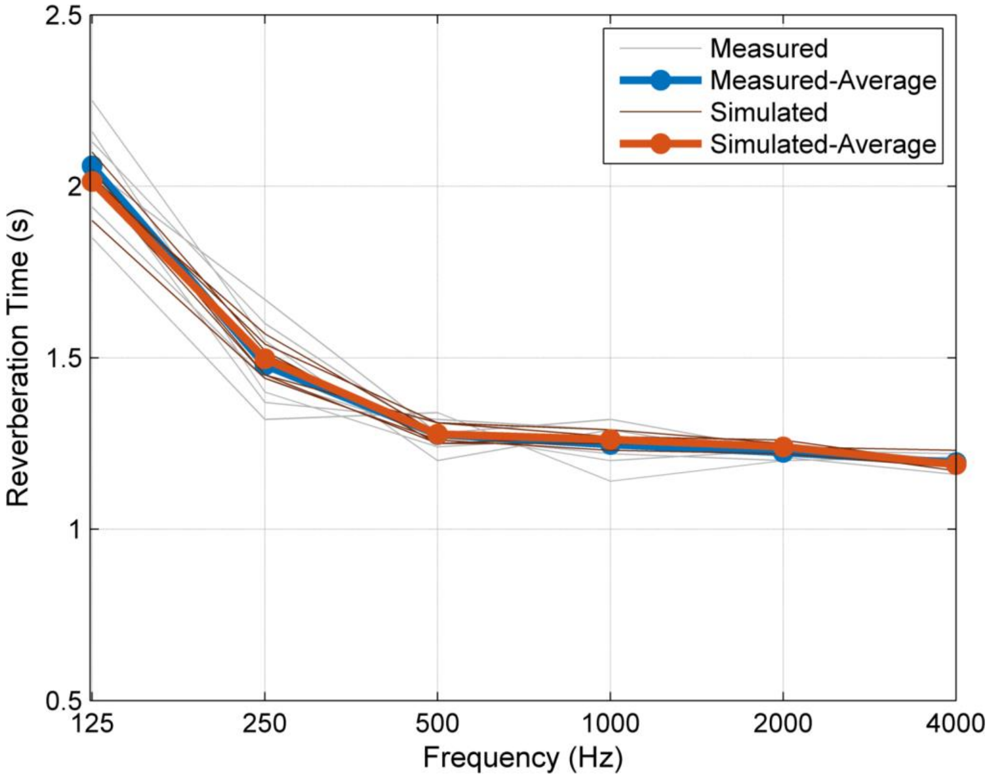

Figure 5-9. Case 3 – Measured/simulated chart combined

With correlating results are first three case scenarios well-structured (calibrated) models for a final assessment. The fourth case scenario was based only on a computer simulation model with focus on details. More detailed procedures can reduce uncertainties and assumptions.

Table 5-9. Case 3 – Simulated reverberation time

Point/Frequency (Hz)	125	250	500	1000	2000	4000
Case 3 Point-2	1.94	1.44	1.28	1.2	1.23	1.22
Case 3 Point-10	1.85	1.32	1.34	1.14	1.2	1.21
Case 3 Point-11	2.04	1.37	1.32	1.29	1.21	1.16
Case 3 Point-12	2.05	1.67	1.28	1.32	1.23	1.19
Case 3 Point-13	2.25	1.55	1.2	1.29	1.25	1.2
Case 3 Point-14	2.13	1.6	1.27	1.22	1.2	1.21
Case 3 Point-15	2.16	1.4	1.24	1.27	1.25	1.17

5.2 Case 4 – Simulated acoustical retrofit

Based on the calibrated results of the three scenarios, Case 4 scenario represent the acoustical retrofit simulation of an improvisatory interactive theatre Narrenschloss. The simulation of the fully refurbished 3D Odeon model (Figures 5.10. to 5.12.) will show results of the future acoustical environment in the theatre hall, based on the observation of the reverberation time.

Reverberation time (RT60) has to be decreased in comparison with Case 1, Case 2 and Case 3 (Figure 5-20.). Optimal reverberation time for defined acoustical space is defined with its purpose and volume. In Figure 5-19. we can determinate optimal reverberation time for our case. Analysed theater hall has a volume of approx. 1100.00 m^3. Optimal RT60 for Narrenschloss main theater hall is 1s.

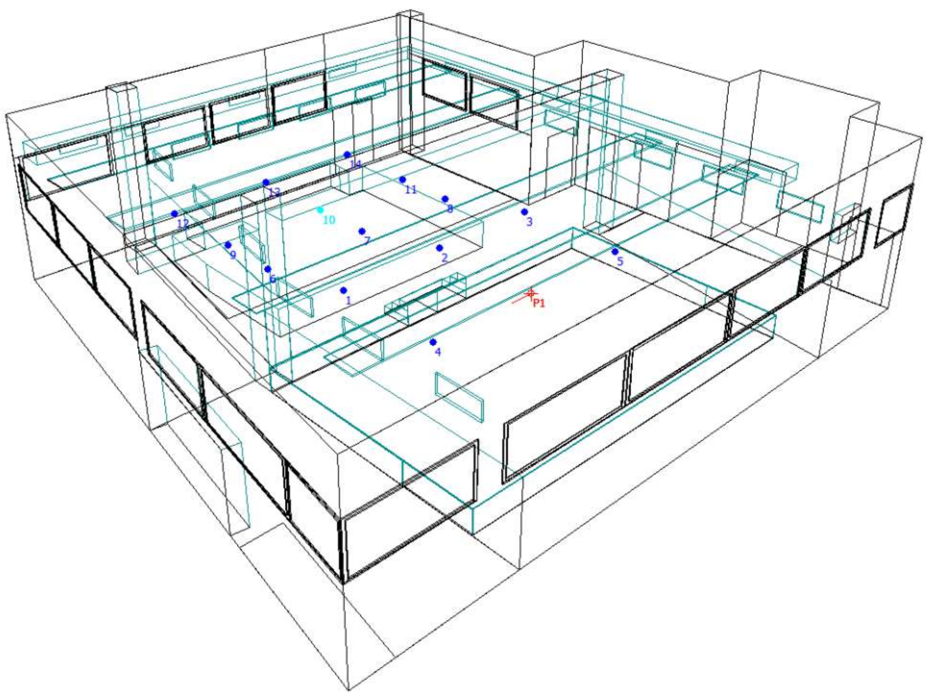

Figure 5-10. Odeon 3D model positioning – Case 4

The analysed room has had a specific limitation in terms of acoustical retrofit. The limitations are set by the owner of the building/shopping center, therefore it is not possible to change any technical instalations. Under technical installations are included electrical systems, fire-protective system/sprinklers, fire alarms, hydrants, water installations in general, ventilation ducts, heaters/coolers or anti-teft alarms. The presented solution is one of the possible acoustical optimizations in terms of acoustical design/retrofit.

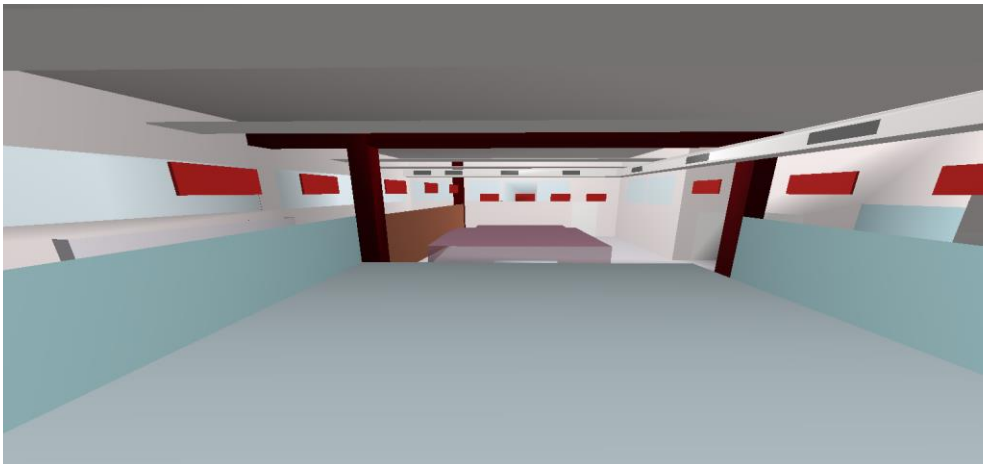

Figure 5-11. Odeon 3D model stage view – Case 4

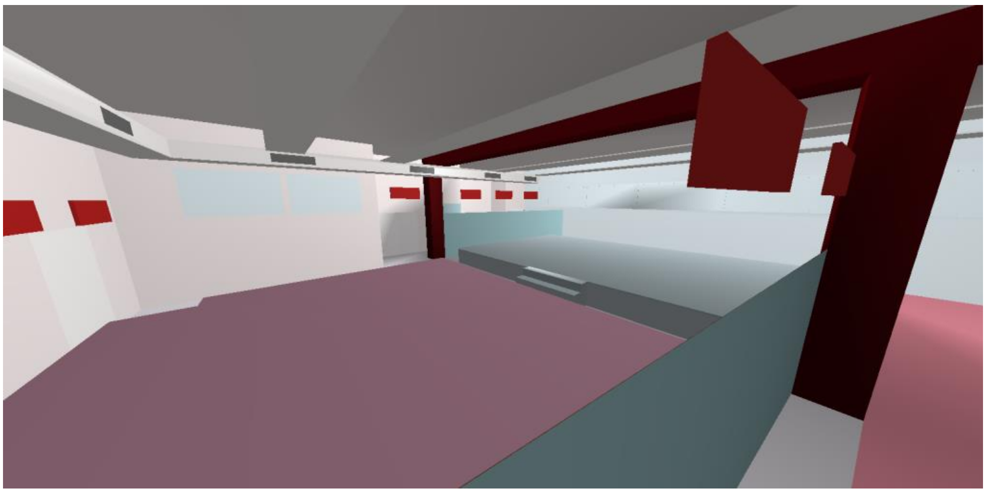

Figure 5-12. Odeon 3D model side view – Case 4

As an acoustical optimization, it is advised to erect gypsum walls insulated with mineral wool. Walls are separating the auditorium and corridor, as well as the main stage and corridor. Walls positions are defined in a Floor Plan (Figure 2-3.). Walls have two functions – architectural to separate two areas, and acoustical to absorbe lower frequencies in the room. Earlier mentioned limitations on the ceilings permit erection of the walls to the maximum height of 270 cm above the floor level.

Acoustical parameters suggest room adaptation with highly absorbing materials. Due to the relatively small room height and a great number of ceiling elements (technical installations) it is not possible to install a highly absorbing suspended ceiling. Although, it is possible to install vertically suspended absorbers with a highly absorbing coefficient

Figure 5-13. Suspended absorbers/Planar element (Knauf Amf 2021).

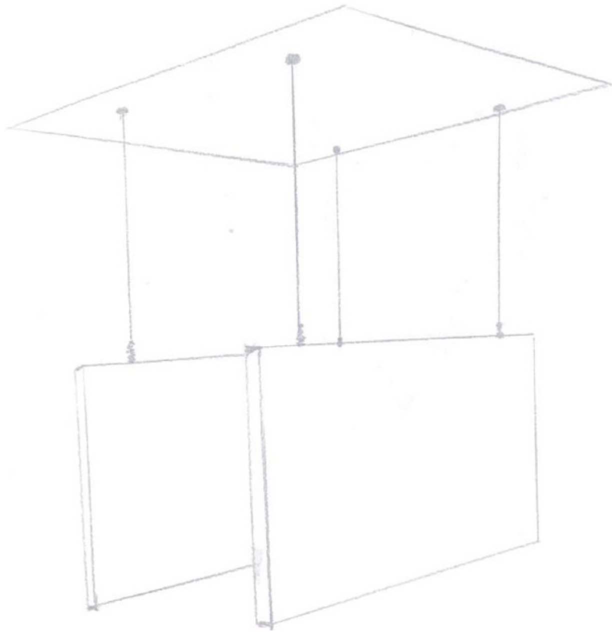

Figure 5-14. Suspended absorbers fixing sketch

(Figures 5-13. and 5-15.). Positioning of the absorbers is set above the newly defined insullated gypsum walls. Absorbers are also added on the wall facing the main stage – behind the auditorium. Total number of the added absorbers is 14. They are mounted directly on the ceiling hanged with bolt fixing and spiral springs (Figure 5-14.)

To improve acoustical absorption in the space given, there are integrated highly absorbing wall absorbers. Selected absorbers have improved low frequency absorbing capacity compared to the suspended absorbers. The position of the wall absorbers is set in a way to fit the architectural function of the room. The selected absorbers are installed on the concrete columns and the beam (Figure 5-15). The installation includes under-construction (Figure 5-16.). Selected materials are robust and can be implemented on the surfaces, which are more likely to damage due to change of theater sets (scenes).

Figure 5-15. Robust absorber – Heradesign Superfine (Knauf Amf 2021).

It is advised to cover the gypsum wall on the inner side, which seperates auditorium and storage area, with an improved acoustic theater curtain. The curtain is going to add absorbing capacity to the room. Materials used in a retrofit are listed in the table below (Table 5-10.) with their absorbing properties. Figures 5-17. and 5-18. represent high absorbing charachteristcs of the selected materials. Acoustical improvements are in the Table 5-10 marked with grey colour and special character *.

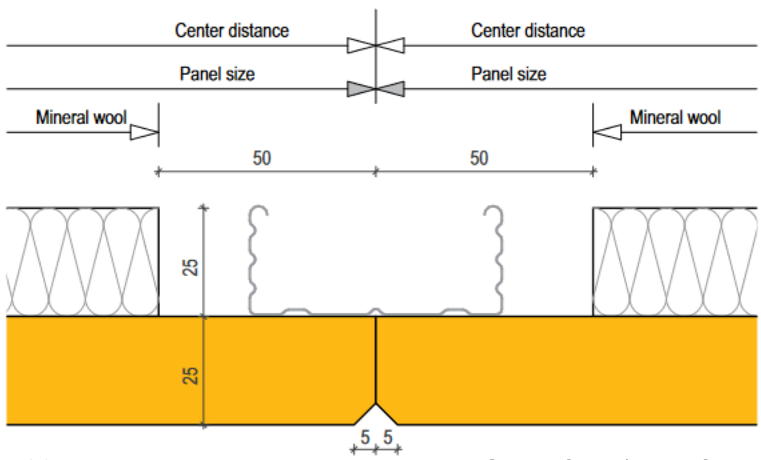

Figure 5-16. Installation detail - Heradesign Superfine (Knauf Amf 2021).

Table 5-10. Case 4 – Calibrated absorption coefficient

Absorption Coefficient α								
Layer/Frequency (Hz)	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	***Area (m^2)***
Floor – Wood floor	0.05	0.06	0.22	0.22	0.07	0.06	0.06	**270**
Glass - Windows	0.1	01	007	0.05	0.03	0.02	0.02	
Heaters, Fire hydrant, Vent grill, Ventilation – Metal plate	0.04	0.04	0.04	0.05	0.06	0.06	0.06	**150**
Stage – Wood podium	0.19	0.19	0.14	0.09	0.06	0.06	0.05	**85**
Doors – Metal plate	0.04	0.04	0.04	0.05	0.06	0.06	0.06	**12**
Wall – Concrete	0.01	0.01	0.04	0.05	0.06	0.06	0.06	**150**
Wall – Gypsum	0.08	0.08	0.11	0.05	0.03	0.02	0.03	**80**
Theatre stuff	0.01	0.01	0.1	0.4	0.5	0.5	0.3	**50**
Ceiling - Concrete	0.01	0.01	0.04	0.05	0.06	0.06	0.06	**260**
Beam, Columns Concrete	0.01	0.01	0.04	0.05	0.06	0.06	0.06	**70**
Chairs with audience	0.51	0.52	0.64	0.75	0.8	0.83	0.83	**65**
Bookshelf – Wooden shelf	0.04	0.04	0.04	0.99	0.8	0.35	0.1	**12**
Curtains*	**0.25**	**0.25**	**0.35**	**0.65**	**0.56**	**0.59**	**0.71**	**16**
New Walls – Gypsum*	**0.3**	**0.3**	**0.12**	**0.08**	**0.06**	**0.06**	**0.05**	**74**
Heradesign Superfine*	**0.6**	**0.7**	**0.95**	**1**	**1**	**1**	**0.95**	**70**
Suspended absorbers/PI.E.*	**0.2**	**0.29**	**0.48**	**0.97**	**0.92**	**0.86**	**0.89**	**20**

***Acoustical design elements implementation**

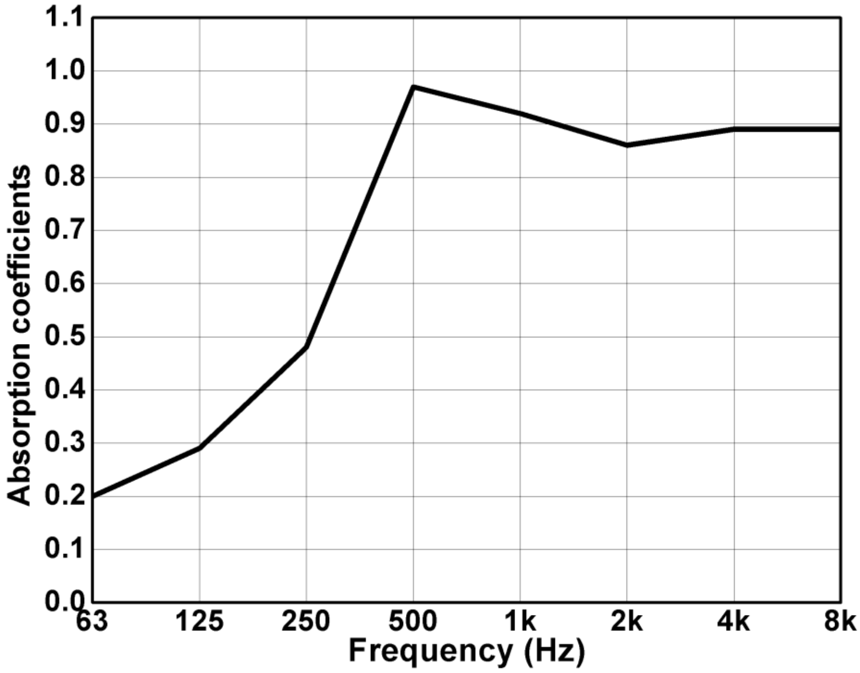

Figure 5-17. Absorption coefficients (α) of one planar element (Pernikl 2012)

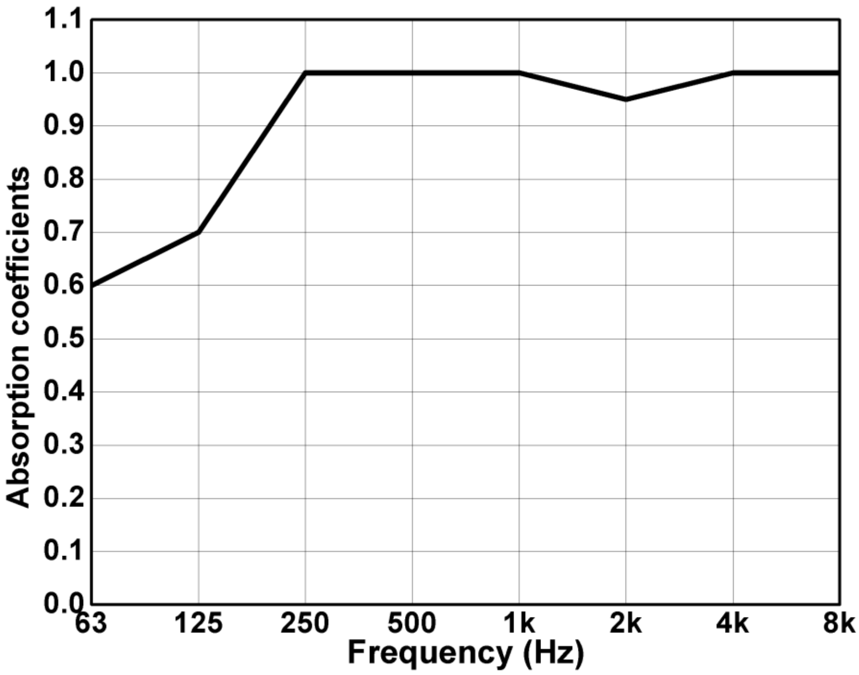

Figure 5-18. Absorption coefficients (α) of Heradesign Superfine (Knauf Amf 2021).

Case 4 is a prediction of the reverberation time in the new hall refurbishment. There is no physically measured data for this case. Acoustical retrofit is having a positive effect, correlating to the performed simulation scenario. In Table 5-11. We can observe the positive outcome of the planned acoustical retrofit. Simulated reverberation time for the Case 4 scenario is as desired approximately 1 s. (Figure 5-19.) Table 5-12. describes´ simulated Sound pressure level values in planned retrofit.

Table 5-11. Case 4 – Simulated reverberation time

Point/Frequency (Hz)	125	250	500	1000	2000	4000
Case 4 Point-1	1.16	0.98	0.87	0.89	0.9	0.89
Case 4 Point-2	1.14	1.01	0.88	0.91	0.92	0.87
Case 4 Point-3	1.12	0.99	0.93	0.88	0.9	0.88
Case 4 Point-4	1.14	0.98	0.89	0.89	0.94	0.91
Case 4 Point-6	1.16	0.97	0.93	0.88	0.93	0.88
Case 4 Point-10	1.14	0.95	0.87	0.92	0.91	0.89
Case 4 Point-11	1.13	0.95	0.9	0.93	0.9	0.87
Case 4 Point-12	1.13	1.01	0.91	0.89	0.93	0.89
Case 4 Point-13	1.15	0.95	0.86	0.89	0.92	0.84
Case 4 Point-14	1.15	1	0.91	0.9	0.93	0.85
Case 4 Point-15	1.15	0.97	0.88	0.91	0.89	0.87
Case 4 Point-16	1.16	1.03	0.85	0.88	0.93	0.86
Case 4 Point-17	1.09	0.98	0.87	0.9	0.94	0.88
Case 4 Point-18	1.09	0.98	0.87	0.9	0.94	0.88

Table 5-12. Case 4 – Sound Pressure Level [dB]

Points	SPL(A) [dB]
Case 4 Point-18	89.3
Case 4 Point-17	88.8
Case 4 Point-16	88.1
Case 4 Point-15	89.5
Case 4 Point-14	89.6
Case 4 Point-13	88.8
Case 4 Point-12	90.4
Case 4 Point-11	90.3
Case 4 Point-10	89.7
Case 4 Point-6	94
Case 4 Point-4	93.9
Case 4 Point-3	92.5
Case 4 Point-2	93.5
Case 4 Point-1	92.7

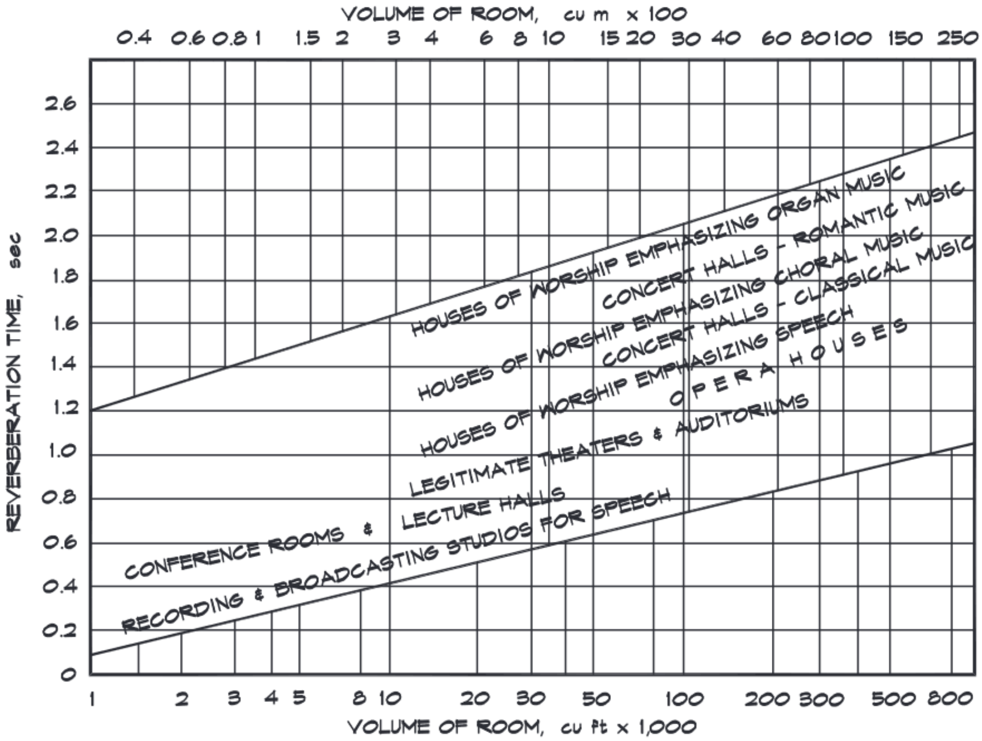

Figure 5-19. Suggested RT based on Volume for various room designs (Marshall 2014)

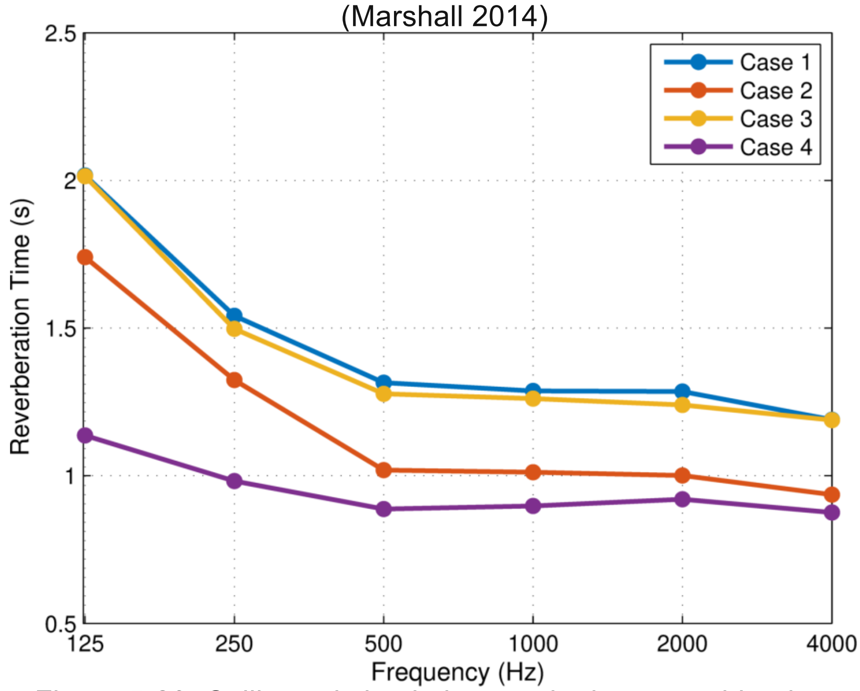

Figure 5-20. Calibrated simulation result-charts combined

Greater differences of results are, as expected, in the non-calibrated model. The calibrated computer model simulation provided closer results to the measurements. With new high-absorbing materials, the simulation had given results (Table 5-11.) which confirmed pre-measuring predictions, even though all predicted adaptations were not included. Possible measurements after refurbishment would provide better data and reveal possible acoustical disadvantages. The retrofit was not implemented by the plan described, due to the theatres' lack of funding.

Chapter 6 – Conclusion

The calibration of acoustical simulation models, backed with detailed and precise measuring procedures can provide efficient simulated-based acoustical predictions.

Observing different computational design evaluation concepts reveals the common practice of simplification of models in the beginning and detailed simulation in later stages of design phases. That fact can also be seen as a potential ground for errors and cause of differences between non-calibrated and measured results.

Early design schemes of relevant physical phenomena involved in building performance are not implying lesser levels of complexity in comparison to the more detailed ones. The main difference for the simulation process lies in the resolution of the specifications of constitutive building components both in terms of geometric and "behavioral" properties. Realistic prediction of the sound field involves a non-uniform reverberant field, non-specular reflection, non-isotropic source emission, and diffraction phenomena. It is suggested, even in the first phases of the design process of a building model, to rely on evaluations based on simulation methods, which are depending on "first-principles-based" modeling of the fundamental physical processes involved (Mahdavi, Liu, Ilal, 1997).

Living in a technological era with constant improvements of computer software and measuring instruments it is possible to make more and more detailed analyses of building environment and architectural design. Better tools are a base for better computer model designs, which will provide greater accuracy and in the longer term an economical benefit due to improved architectural acoustics design. Architectural professionals can improve this type of research and simulation procedures. (Sieben and Kinzey, 2010).

Research, measuring, simulations, and all activities connected to the matter provide more data, but also reveal errors and raise new questions. The key factor is as already mentioned – exercise, a gain of new knowledge, and researching. This study was focused on measuring reverberation time. Non-calibrated model results were inaccurate and imprecise compared to the calibrated simulation model, which has presented comparable results with acoustical measurements.

The thesis has introduced Case 1, 2 and 3 as a simulation model of an improvisatory theater hall, that can be representative for various scenarios of the same acoustical room. Case 4 simulation model presented one of the possible acoustical retrofits. Simulated results presented improvement of reverberation time in the room and can be used for its intended purpose. Although it is suggested to do the measurements after the retrofit has taken place. Additional measurements provide an opportunity to compare simulated/predicted results with a real-life situation and reveal achieved results or eventual unexpected deviations.

Chapter 7 – References

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Appendix

A.1 Address of the Narrenschloss and contact of the Narrenschloss representatives

Address:

Kindertheater Narrenschloss

1. OG Stadioncenter

Olympiaplatz 2, 1020 Wien

Austria, EU

Web-address:

http://www.narrenschloss.org/

Email address:

postkutsche@narrenschloss.org

Contact person:

Managing director

Violeta Radić

+43 660 6338750

A. 2 Additional photographs

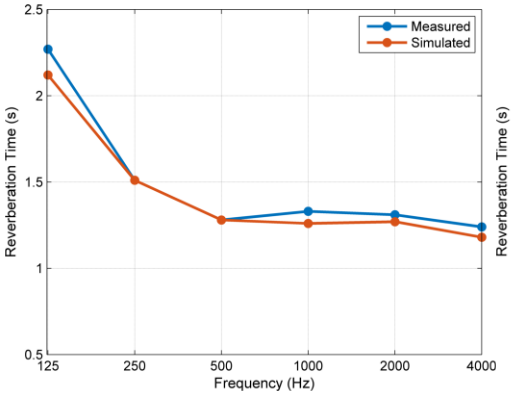
Figure A-1. Ventilation ducts and heaters

Figure A-2. Stage view of the ceiling

Figure A-3. Case 2 scenario auditorium

A.3 Additional charts

Case 1:



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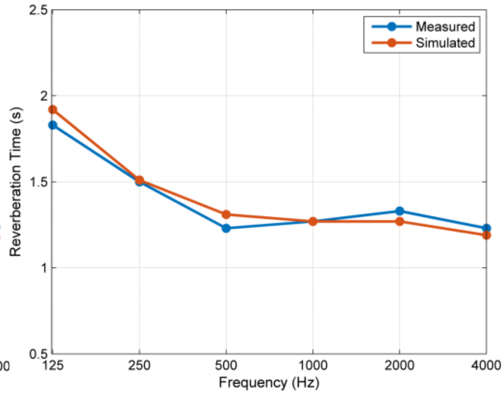

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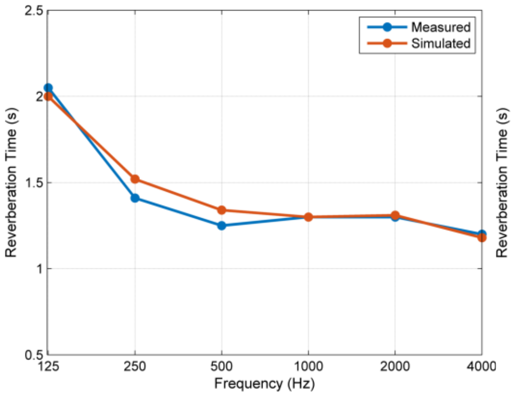

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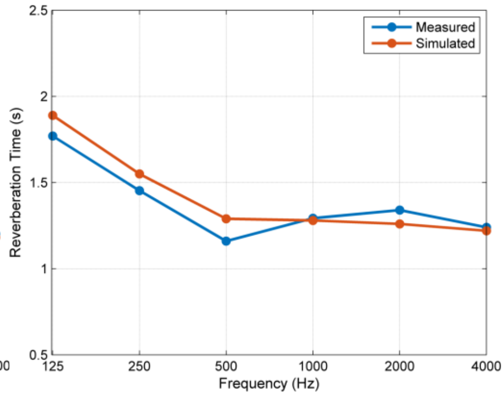

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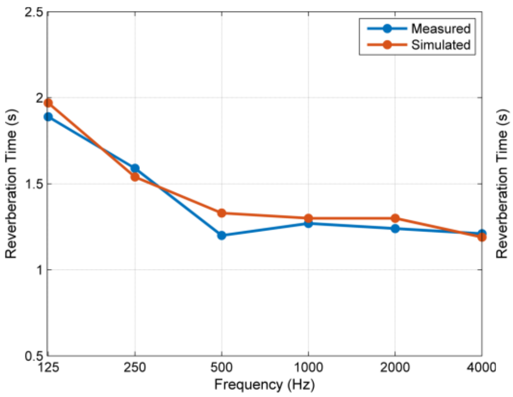

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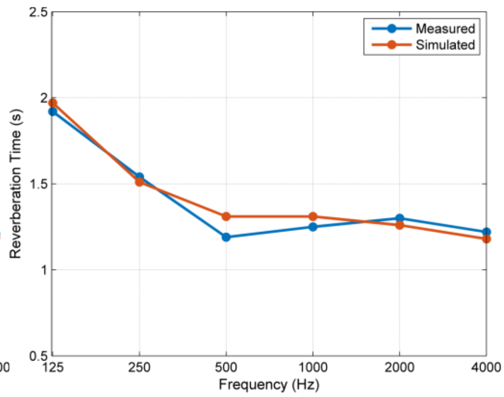

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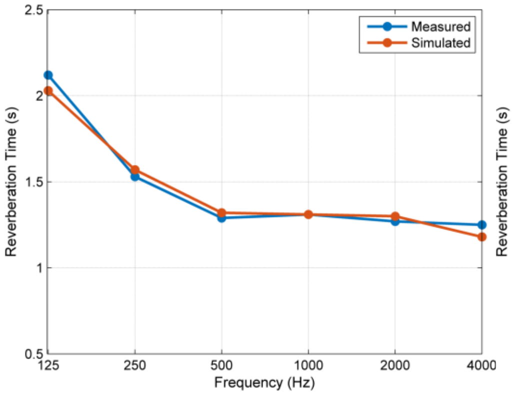
Figure A-4. Charts Case 1 – Measurement points x1-x10



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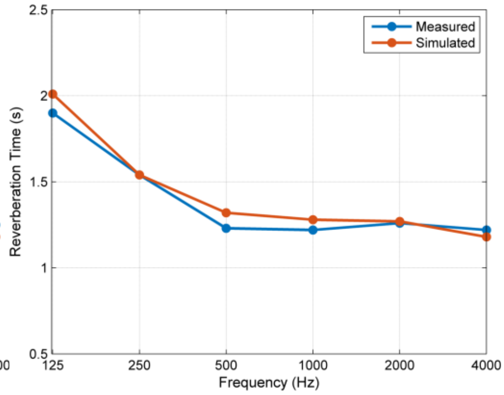

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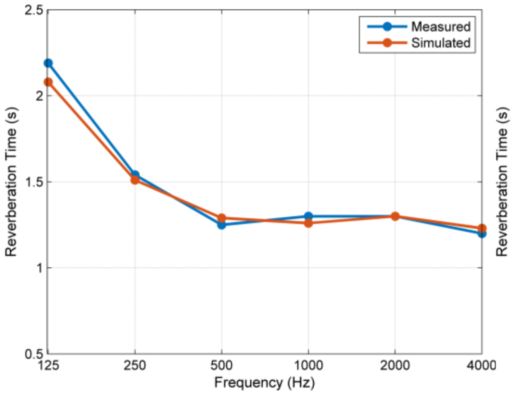

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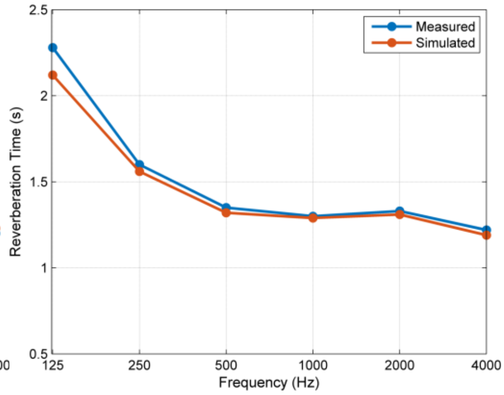

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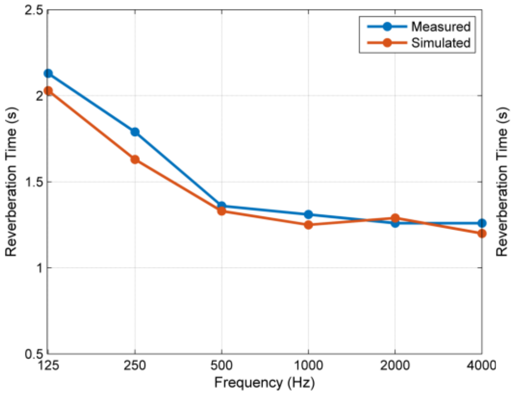

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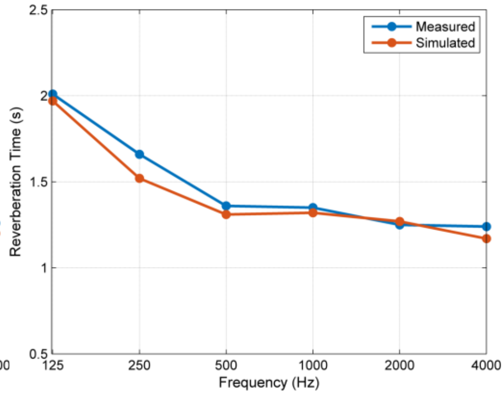

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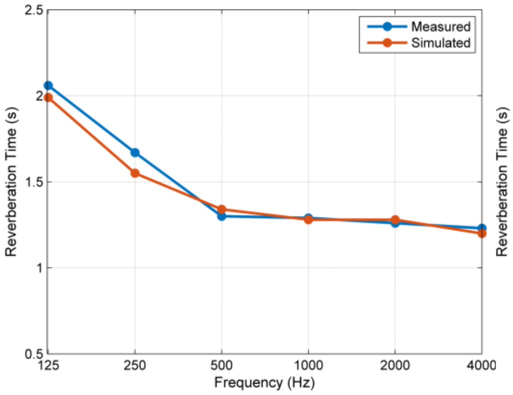

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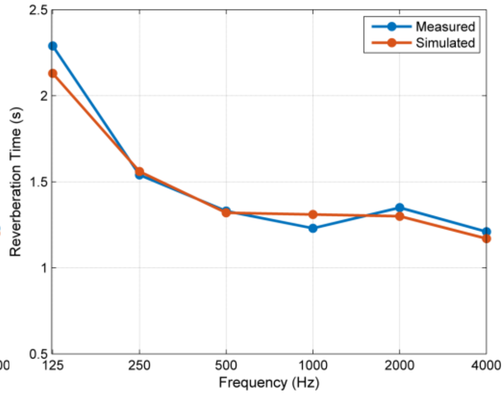
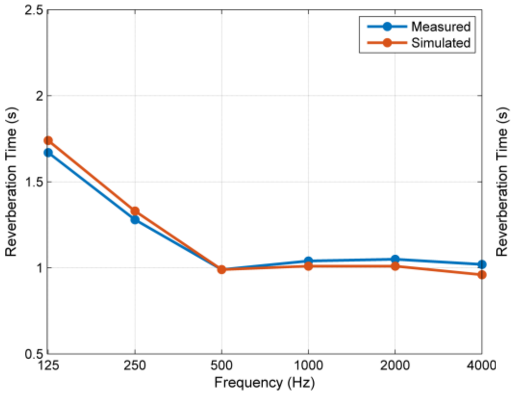


Point-x18

Figure A-5. Charts Case 1 – Measurement points x11-x18

Case 2:



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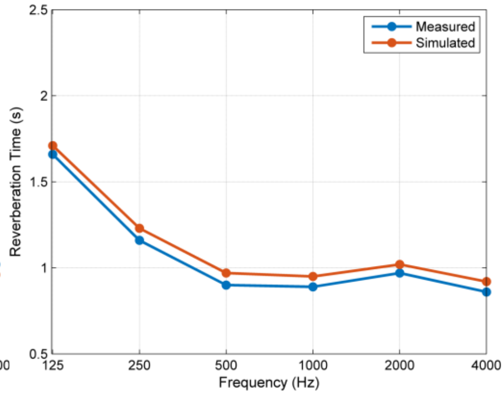

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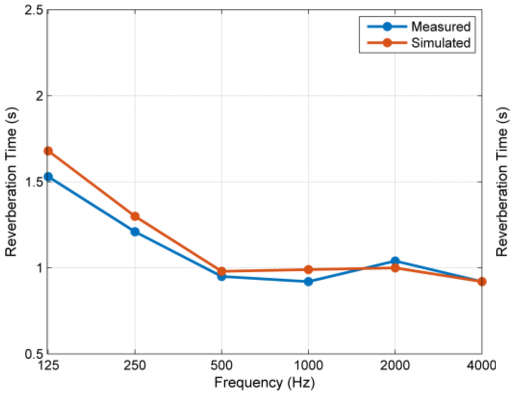

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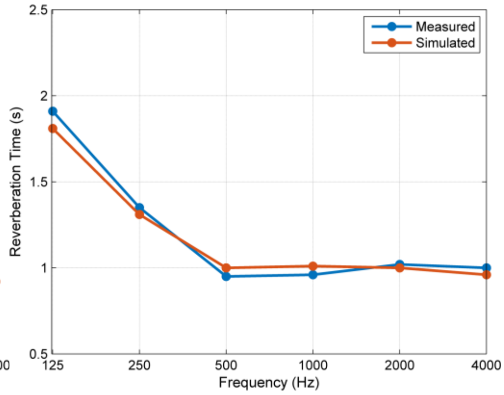

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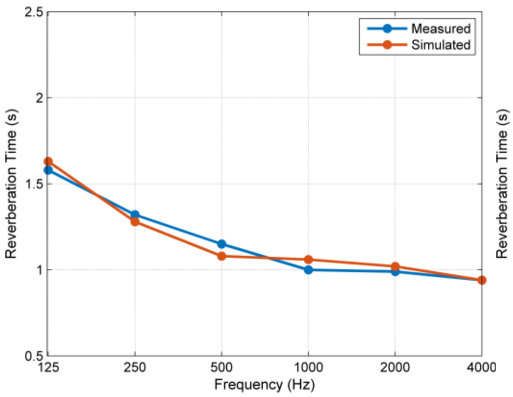

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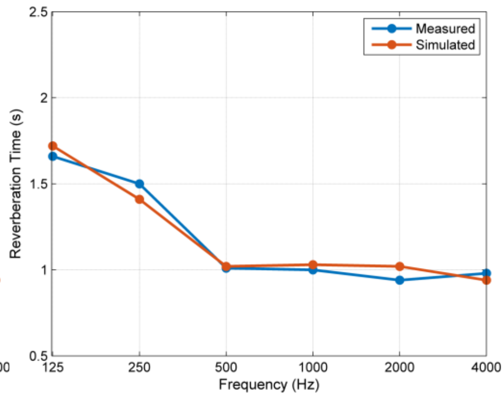

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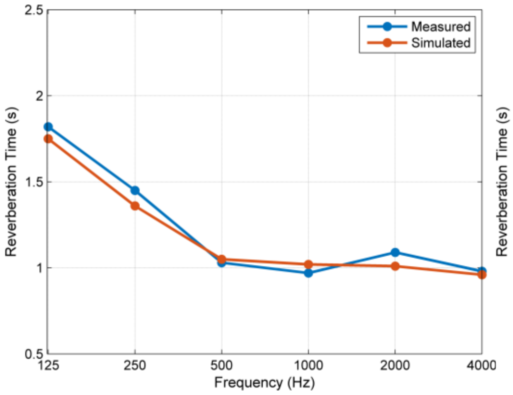
Figure A-6. Charts Case 2 – Measurement points x4-x14



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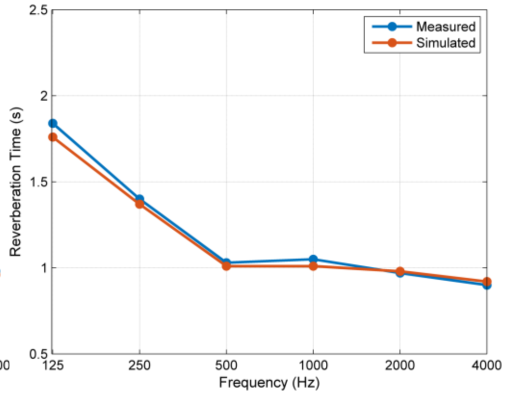

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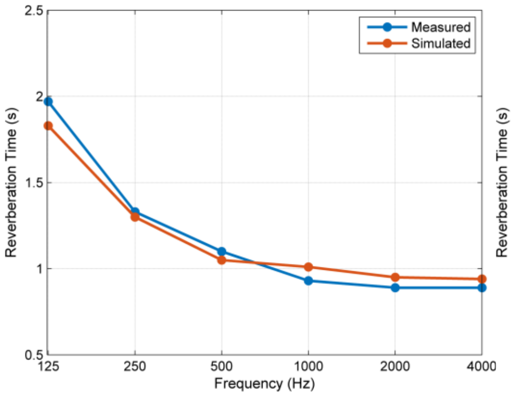

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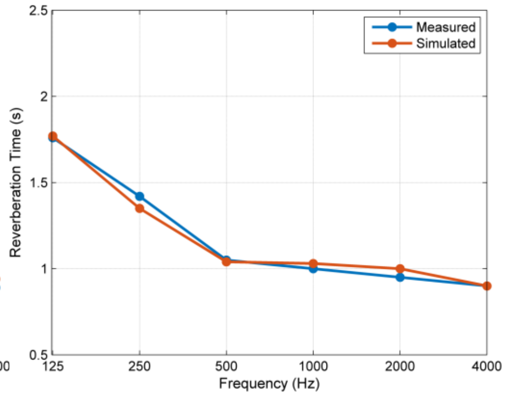

Point-x18

Figure A-7. Charts Case 2 – Measurement points x15-x18

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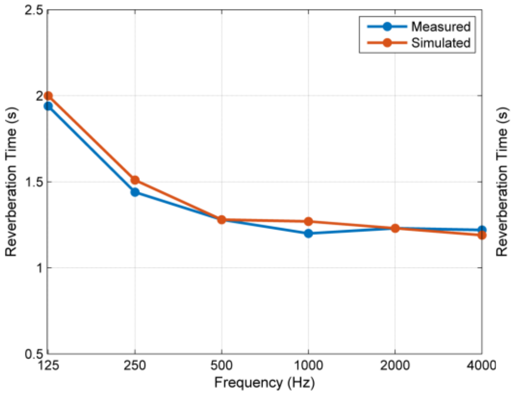

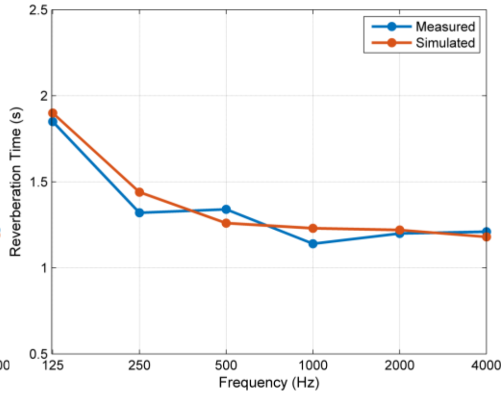

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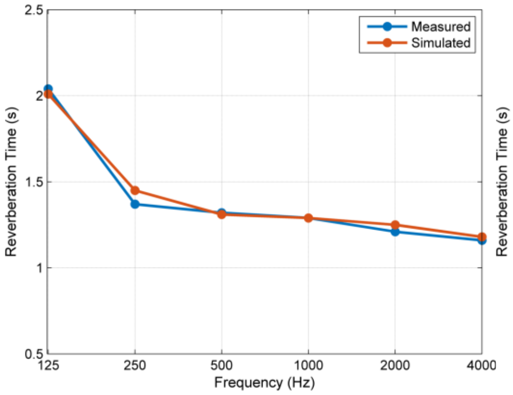
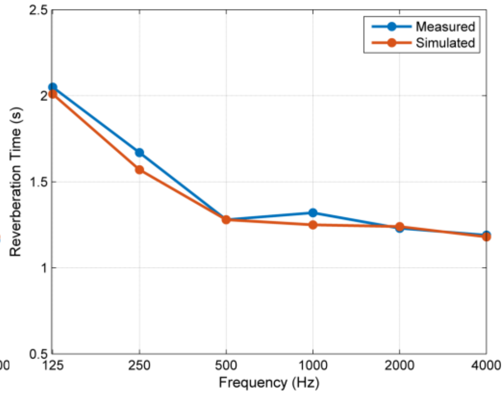
Point-x10





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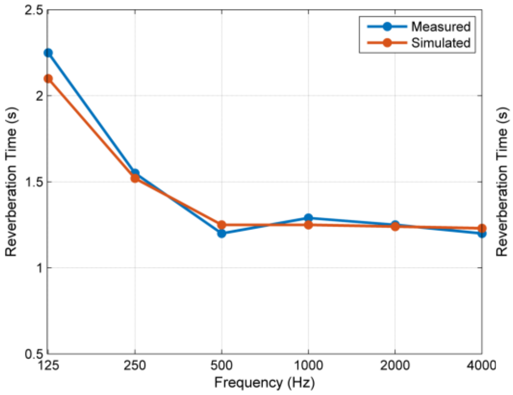

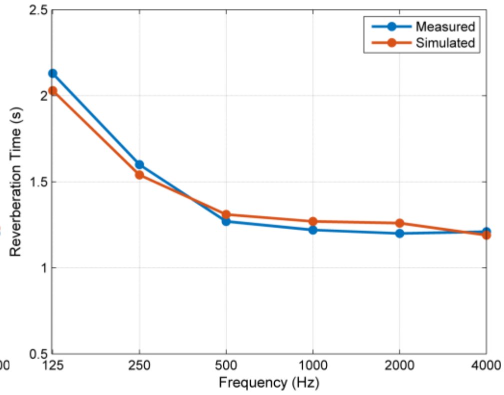

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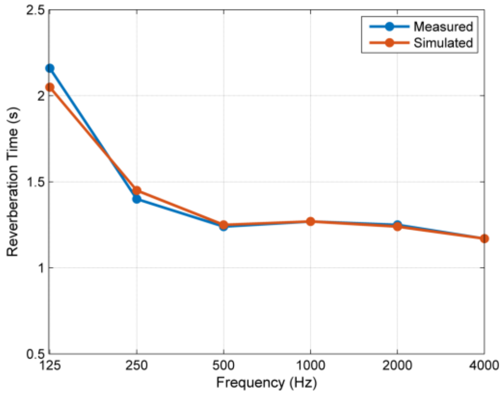

Figure A-8. Charts Case 3 – Measurement points x2-x15

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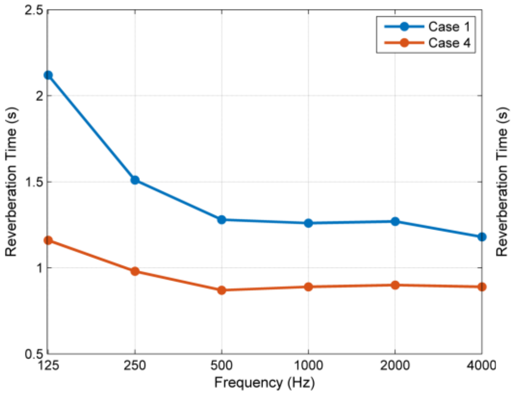

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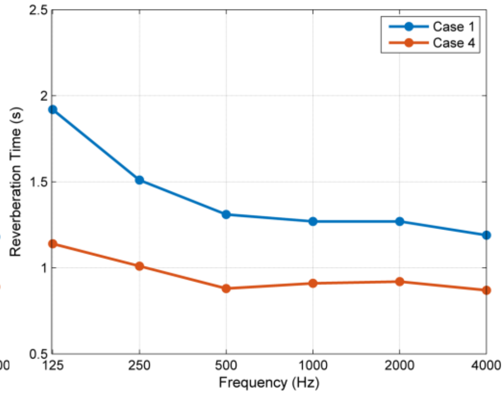

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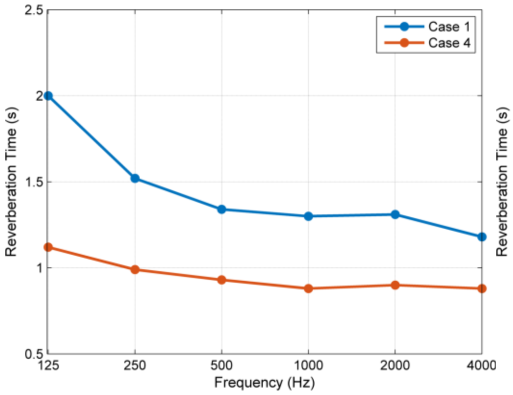

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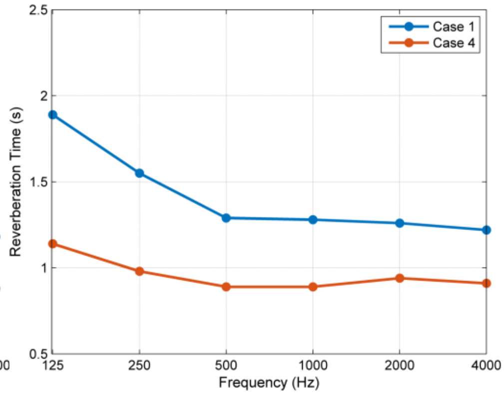

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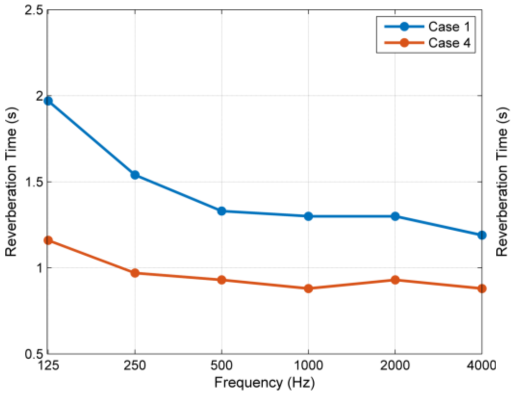

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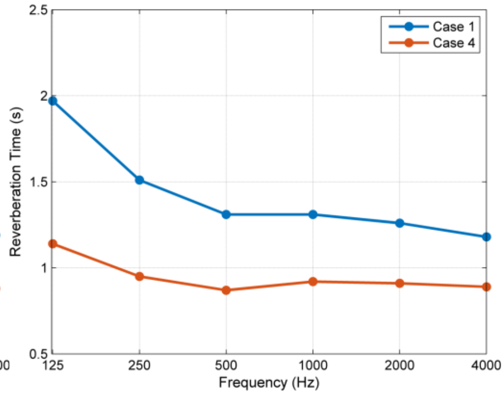
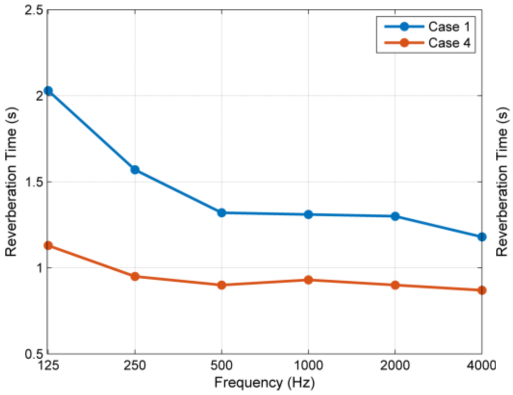


Point-x10

Figure A-9. Charts Case 4 – Measurement points x1-x10



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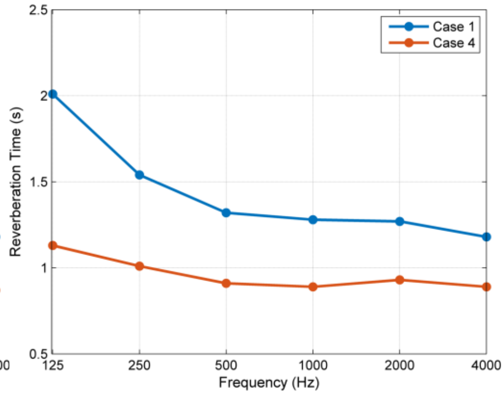

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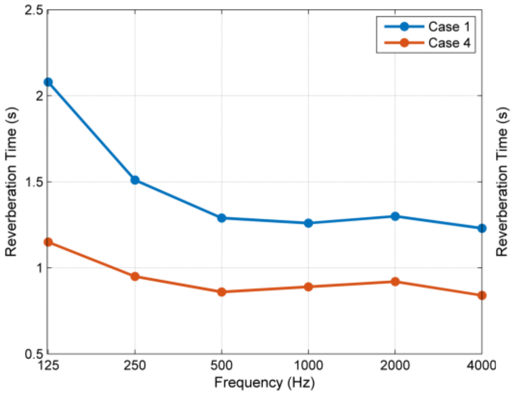

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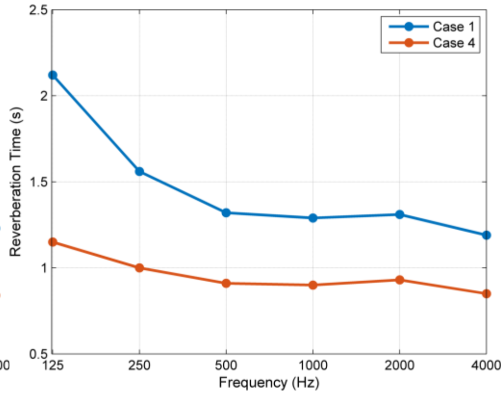
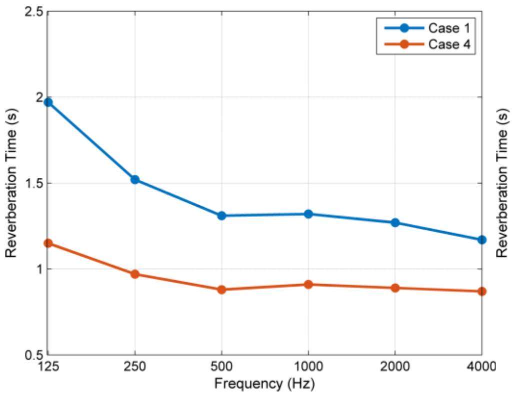
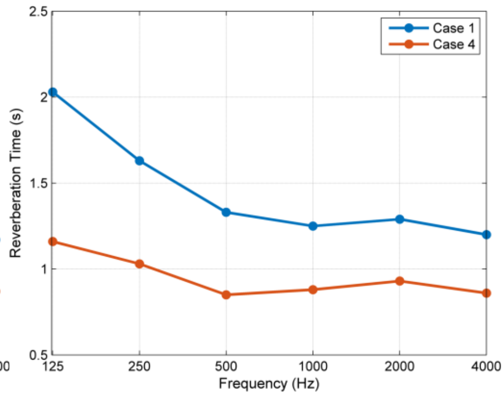


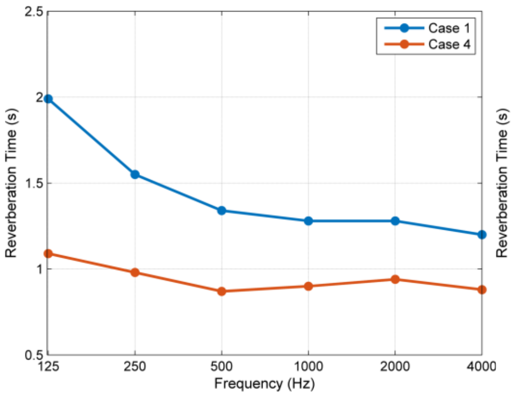
Point-x14



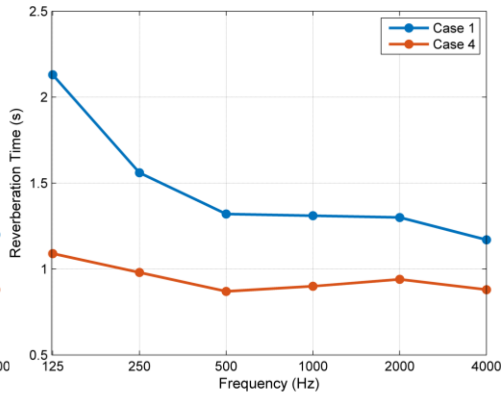
Point-x15



Point-x16



Point-x17



Point-x18

Figure A-10. Charts Case 4 – Measurement points x11-x18

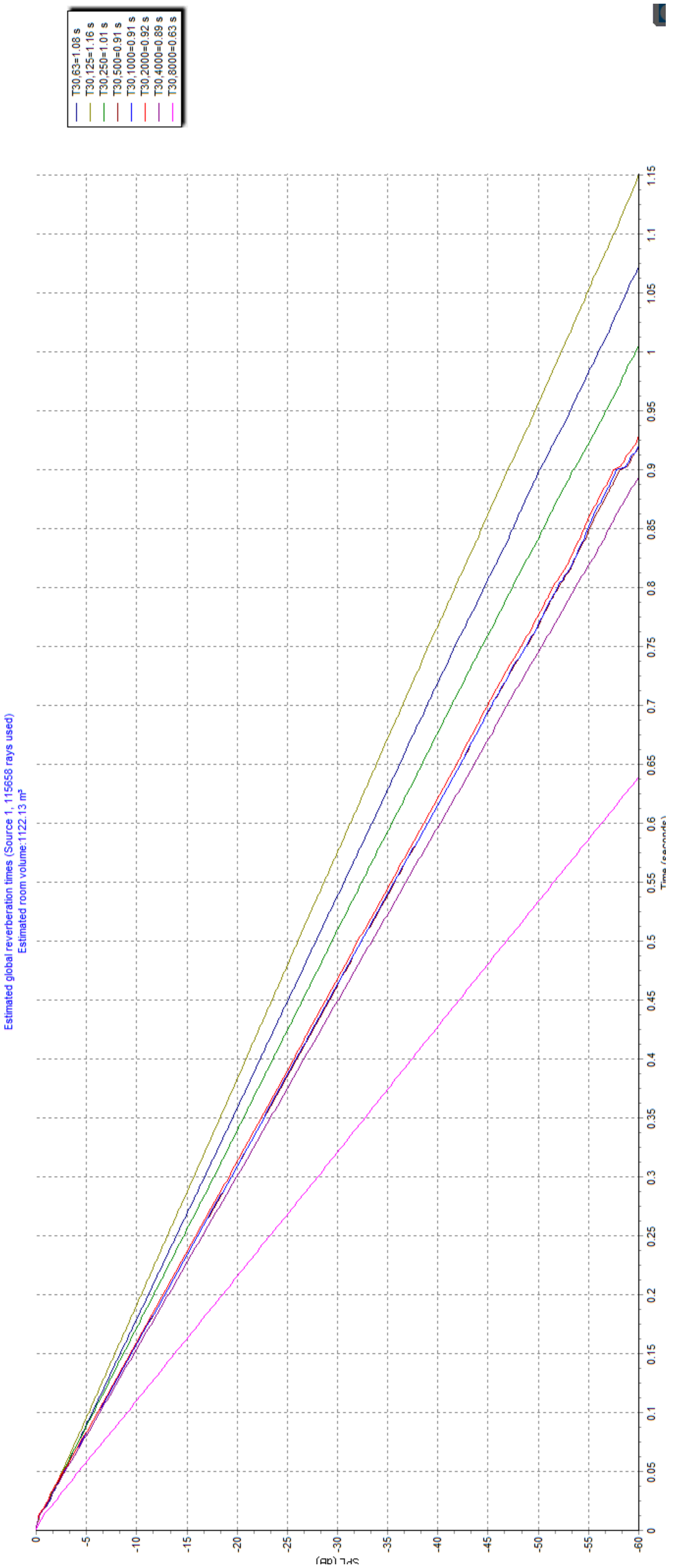


Figure A-11. Case 4 – Global estimate

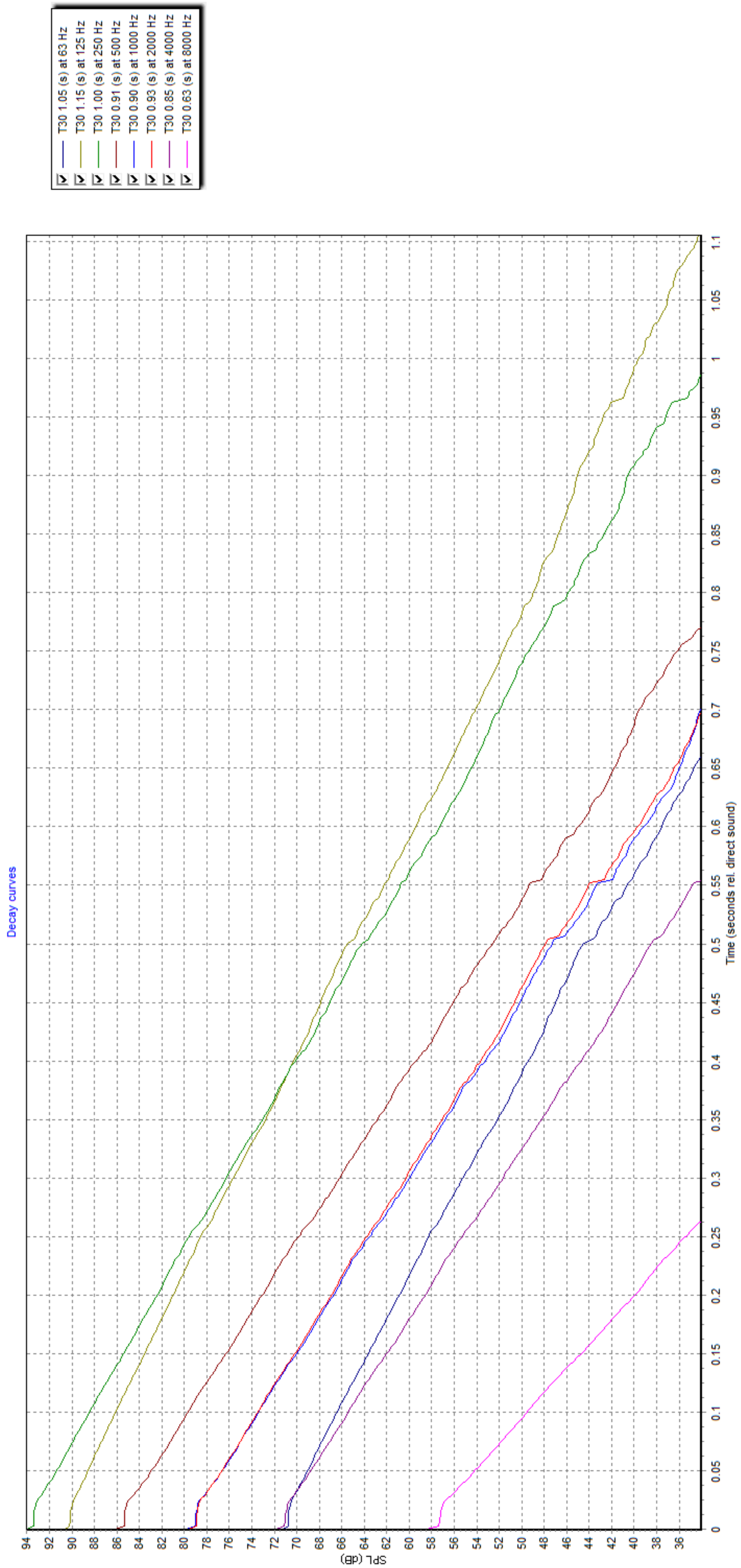


Figure A-12. Case 4 – Decay curve of point 14

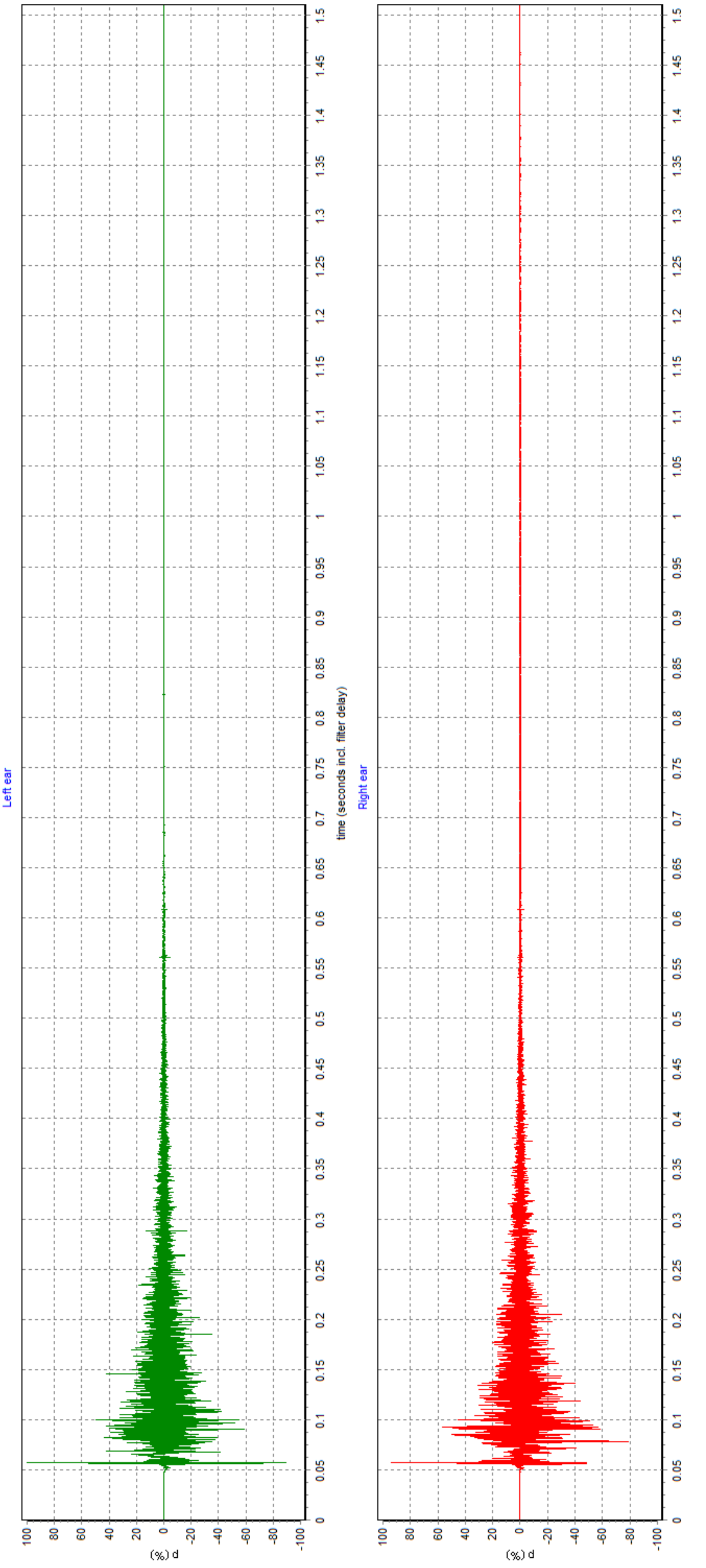


Figure A-13. Case 4 – BinauRal Impulse Response of point 14