DIPLOMARBEIT

Acoustic Performance of Repurposed University Learning Environments

unter der Leitung von

Univ.Prof. Dipl.Ing. Dr.techn. Ardeshir Mahdavi

E 259-3 Abteilung für Bauphysik und Bauökologie

Institut für Architekturwissenschaften

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von

Kyle Oldland

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KURZFASSUNG

Es ist unbestritten, dass es derzeit einen Mangel an Lern- / Arbeitsräumen an Universitäten weltweit und insbesondere an der TU Wien gibt. Da die Anzahl dieser Räume konstant bleibt, wurden daher verschiedene Räume an der TU Wien zu multifunktionalen Lern- / Arbeitsräumen umgewidmet, um den räumlichen Bedürfnissen der Studierenden gerecht zu werden, z. B. für Vorlesungen, Besprechungen und/oder Arbeitsräume. Im Fall dieser umfunktionierten multifunktionalen Lernbereiche sind jedoch die Störungen und andere Faktoren, die die Sprachverständlichkeit beeinträchtigen, recht hoch, wodurch sie sich akustisch schlecht als Lernumgebung für Studenten eignen. Darüber hinaus ist erwiesen, dass übermäßige Lärmstörungen und lange Nachhallzeiten die Sprachverständlichkeit verringern, was die Lernfähigkeit und das Wohlbefinden der Studierenden erheblich beeinträchtigen kann. Die Hauptziele dieser Masterarbeit sind daher die Evaluierung von Räumen an der TU Wien, die als multifunktionale Vorlesungs-, Besprechung- und Arbeitsräume adaptiert wurden, indem die vor Ort gemessenen akustischen Leistungsergebnisse mit zwei raumakustischen Simulationstools, Odeon und Pachyderm Acoustical Simulation, verglichen werden. Abschließend werden die Endergebnisse mit den in den Akustiknormen DIN 18041 und ÖNORM B 8115-3 definierten optimalen Nachhallzeiten verglichen, um festzustellen, ob die in der Fallstudie untersuchten Universitätsräume für ihre aktuelle Nutzung geeignet sind. Abschließend werden die verschiedenen Akustiksimulationsprogramme und deren Ergebnisse dargestellt und erläutert.

Keywords

Raumakustik, akustische Performance, multifunktionale Räume, umfunktionierte Lernumgebungen, raumakustische Simulationen, parametrische akustische Simulationen

ABSTRACT

It is indisputable that there is currently a shortage of learning / workspaces at universities worldwide, in particular at the TU Wien. Though the number of these spaces remains constant, various spaces at the TU Wien have been repurposed to function as repurposed multifunctional learning / workspaces to accommodate students' spatial needs such as for lectures, reviews and /or workspaces. However, in the case of these repurposed multifunctional learning areas, disturbances and factors that affect speech intelligibility are quite high; making them acoustically perform poorly as an educational environment for students. Furthermore, it has been proven that excessive noise disturbances and long reverberation times reduce speech clarity, which can significantly affect students' learning ability and wellbeing. Thus, the main objectives of this master thesis are to evaluate spaces at the TU Wien that have been adapted as repurposed multifunctional lecture rooms, review spaces, and workspaces by comparing on-site measured acoustic performance results to two room acoustic performance simulation tools, Odeon and Pachyderm Acoustical Simulation. Conclusively, the final results are compared to optimal reverberation times defined in the acoustics standards DIN 18041 and ÖNORM B 8115-3, which determine whether the university spaces assessed in the case study are suitable for their current use. Finally, the different acoustic simulation programs and their results are outlined and discussed.

Keywords

room acoustics, acoustic performance, multifunctional spaces, repurposed learning environments, room acoustic simulations, parametric acoustic simulations

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CONTENTS

1 INTRODUCTION

1.1 Overview

“Uns reicht’s. Wir fordern den Platz, der uns zusteht! (We've had enough. We demand the space that is rightfully ours!)”, were shouts that could have been heard from more than 100 protesting students in front of the TU Wien in the beginning of December 2019 (Walische, 2019). *“From the very beginning of universities, student protests have been as much part of university life as teaching and research”* (Jarczyk, 2016. p.29). Similarly, to the protest in 2019, but at a much larger scale, *“on October 24, 1987, around 40,000 students took to the streets of Vienna to demonstrate against poor conditions at the universities”* (Jarczyk, 2016. p.33).

Based on existing records found at the Archives of TU Wien, in particular, spatial zoning plans from 1986 indicate that at that time, compared to today, there were hardly any open public academic learning / workspaces for students. Therefore, a shortage of student multifunctional learning / workspaces has been an indisputable issue for several decades. Consequently, at that time, as the former university cafeteria was closed in November 1998, students were outraged, especially, since that was one of the last places where students could publicly work and study (Ebner, 2021). Thus, from the already scarcely existing public student workplaces, students suddenly had no more premises to work in. Nevertheless, shortly after, assorted unused university spaces were repurposed to fulfil students’ spatial demands. However, as exhibited in the previous spatial zoning plans, these rooms were not initially intended for students to work and study in.

In addition, according to Statistik Austria, the number of new students attending public universities has slightly declined in recent years, although, the overall tendency shows that the number of students per semester is still considerably increasing (Statistik Austria, 2020).

To make a comparison the TU Wien has approximately 27,200 students in which 5,592 study architecture (TU Wien, 2020b) and the Technische Universität München has approximately 42,700 students in which 1,465 study architecture (Technische Universität München, 2020). Moreover, Dean of Studies Architecture at the TU Wien, Christian Kühn, explained that roughly 29 architecture students share a single workplace (Walische, 2019). Additionally, Figure 1.1 illustrates that TU München architecture students have nearly 2200% more workspace compared to TU Wien architecture students. Nevertheless, the lack of educational spaces at the TU Wien does not only pertain to student workspaces, but also to lecture rooms, crit / review spaces and other varied student activities.

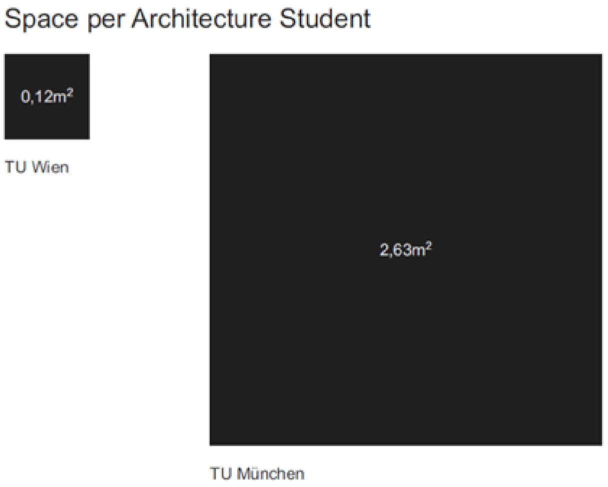


Figure 1.1: Comparison of Space per Architecture Student at TU Wien and TU München adapted from source: (Walische, 2019)

Even though there is a steady increase in the number of students attending universities worldwide, specifically at the TU Wien, the number of educational learning spaces remains constant. Consequently, as a result, various unsuitable spaces at the university have been repurposed to function as repurposed multifunctional learning / workspaces to accommodate students' spatial needs such as for lectures, reviews and / or workspaces.

In addition, disturbances and factors that affect speech intelligibility in learning environments should ideally be identified and targeted in order to control the noise pollution within these educational spaces. Generally, by tactically placing furniture, high sound absorbent materials, and / or acoustic panels, room acoustics can be controlled (Youssef, Rabab S.; Bard, 2014). Though, however, in the case of repurposed multifunctional learning premises, these objects and materials are often scarce or nonexistent. Moreover, performed studies in educational spaces have proven that excessive noise disturbances and late reverberation times reduce speech clarity, which can significantly affect students' performance, learning abilities, and wellbeing (Youssef, Rabab S.; Bard, 2014).

Increasingly, more and more spaces which have not been explicitly designed as multifunctional learning areas are being used as repurposed rooms for assorted functions like temporary lecture rooms, review spaces, and / or student workspaces in which each function has a varying range of number of room occupants and varied acoustic parameters. Accordingly, these unsuitable spaces can negatively impact students' learning abilities, performance, and health. Therefore, in the framework of this research paper, it is desired to assess the current acoustic performance of repurposed learning / workspaces at the TU Wien which are hypothesized to be acoustically inadequate as functional learning spaces for students (Youssef, Rabab S.; Bard, 2014).

The following is a list of rooms at the TU Wien, which have been repurposed, that will be evaluated in this master's thesis in the form of a case study to provide a framework of their current acoustic performance. (TU Wien, 2020a)

- Aufbaulabor, (max. capacity 120 Persons) located in the Campus Karlsplatz building
- Project Room Panigeltrakt EG, (max. capacity 40 persons) located in the Campus Karlsplatz building
- TVFA Halle, (max. capacity 300 persons) located in the institute building at Erzherzog-Johann-Platz

1.2 Motivation

Based on the comparative figure above, it is indisputable that there is currently a shortage of learning spaces at the TU Wien. Likewise, as an architecture student at the university, one can most certainly agree with this statement.

The motivation behind this study is to disclose the acoustic performance of repurposed multifunctional university learning environments by evaluating three assorted spaces at the TU Wien that remain largely understudied, which can most likely be profoundly disrupting how well students perform in these rooms. Moreover, the determined results would indicate whether the assessed spaces are acoustically adequate in their current state to continually be used for such learning purposes or if they shall be retrofitted to continually accommodate students' spatial needs.

Personal experiences of learning and working in these spaces would conjecture that the results will tend to denote that speech intelligibility is rather poor in these spaces. In addition, relevant acoustic performance parameters of the evaluated spaces will be determined and compared. In doing so, the simulation results of two acoustic simulation tools, Odeon and Pachyderm Acoustical Simulation, are compared to on-site acoustic measurements to indicate how consistent the simulated results are. As a result, the reliability of the implemented simulation software can be implied.

Furthermore, an overview of the acoustical performance of these learning / workspaces provide insight and contribute to adding information to an overall building performance evaluation of the TU Wien. More so, resulting benefits to this master's thesis may trigger a drive to improve these and other similar university spaces, making them more suitable for students. Conversely, it is also possible that the findings could reveal unexpected results such as repurposed multifunctional educational spaces which have a suitable acoustic performance regarding the rooms' current use of space.

1.3 Background

1.3.1 Overview

To date, there has been extensive research done in evaluating the acoustic performance of numerous lecture halls at the TU Wien. Moreover, the accuracy of acoustic simulations using leading programs such as Odeon have even been evaluated by comparing the simulated results to on-site acoustic measurements of five TU Wien lecture halls (Lechleitner et al., 2010). Nevertheless, these studies exclusively focus on comparing the evaluation criteria of university spaces that were originally intended and designed to be used for lecture purposes only. Thus, ideally, the outcomes of these research papers indicate that there is conformity to the predicted and concluding results.

Even though the overall tendency shows that there is still a considerably increasing number of new students attending university each semester, there is essentially minimal research performed to evaluate the acoustic performance of repurposed multifunctional learning spaces. Therefore, being that this matter is a current concern for the TU Wien and essentially a concern for other universities around the world which are facing a similar situation like the TU Wien, this thesis is a conclusive work which discloses the acoustic performance of repurposed multifunctional learning spaces and could potentially assist in improving learning environments for students.

Moreover, this thesis proposes to present and summarize other relevant acoustic parameters from other works that may be significant when assessing the multifunctional university premises. Furthermore, these spaces will be evaluated in the form of a case study using two acoustic simulation tools. Therefore, the intent of this paper is not to provide an exhaustive review of all relevant documents, but rather expand on the already established knowledge to develop a framework about acoustical parameters for repurposed multifunctional university spaces.

Since the above-mentioned selected case study spaces were not originally intended to be used for their current purpose, a reputable acoustic simulation tool, Odeon, as well as a lesser-known acoustic simulation plugin, Pachyderm Acoustical Simulation, for, the widely used McNeel Rhinoceros / Grasshopper 3D modelling software will be used to effectively compare on-site measured acoustic results to the results of simulated acoustic models.

Furthermore, since conventional acoustic simulation software is often challenging to use for unacquainted users, it is anticipated that the acoustic simulation plugin, Pachyderm, will deliver comparable results to the room measurements and simulated results from Odeon. Thus, making the intuitive modelling environment of Rhinoceros / Grasshopper an effective straightforward method to performing acoustic simulations.

1.3.2 Multifunctional Student Learning / Workspaces

Being that the university spaces analyzed and evaluated in this work were not intentionally designed or intended to be used for their current purposes and functions, they have been identified as repurposed multifunctional university learning / workspaces for students. Moreover, a multifunctional space can be described as a true integration of different functions in time and space.

Though these spaces are sometimes strictly used for individual events, they are primarily used as learning and workspaces in which numerous student activities such as computer-work, group discussions, model building, and studying take place simultaneously. Thus, the range of assorted functions that take place in each space distinguishes them to be multipurpose rooms. Nevertheless, in accordance with the definition above, since the typical spatial uses regularly occur concurrently, these university spaces will be identified as multifunctional university learning / workspaces.

In addition, these rooms are flexible spaces which can also be used for independent student work. However, more importantly, these spaces encourage students from all fields of study to collaboratively work together as well as exchange ideas and information.

1.3.3 Room Acoustic Measurement Parameters

Room acoustics is the field of acoustics which describes how a diffuse sound field consisting of direct sound and reflective sound propagates in a closed or semi-closed space (Willems et al., 2018). Consequently, room acoustics aims to define the acoustic performance of a given space and indicate an optimized perception of fullness of sound or clarity corresponding to the intended purpose of that space (Willems et al., 2018). Figure 1.2 illustrates these principles which will be outlined in the following section.

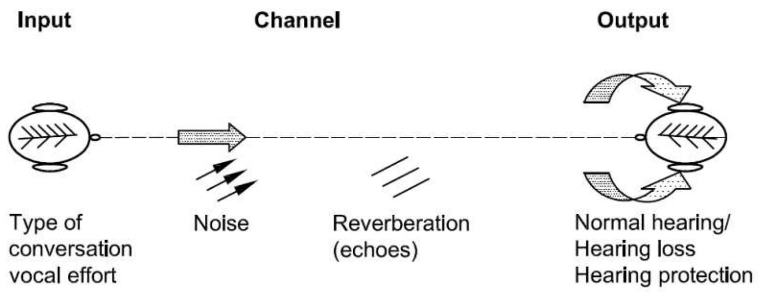


Figure 1.2: Direct communication (person to person) according to ISO 9921:2003

Moreover, the geometry of a space, sound absorption properties and location of surface materials present in a room, along with the positions of sound sources and point receivers are all significant attributes to determine the acoustic condition of a room (Fasold & Veres, 2003). Furthermore, these attributes influence the acoustic quality of a space which describes the suitability of a room for a particular use according to DIN 18041 :2016. A detailed description of distinguished room functions categories, Group A and Group B, can be found in the standard, DIN 18041:2016.

Following, this section elucidates and defines several fundamental room acoustic measurement parameters such as reverberation time (RT), sound pressure level (SPL), sound distribution, and speech intelligibility. which outline the acoustic performance of a space.

Table 1.1 summarizes these room acoustic parameters to offer a better understanding of these fundamental acoustic key performance indicators. In addition, the table also indicates the precision of these room acoustic parameters when comparing on-site measurements and simulated room acoustics results. Therefore, the subjective limen (just noticeable difference, JND) defines an acceptable margin of error per parameter which is relevant when calibrating the acoustic simulation models (Odeon A/S, 2020).

Table 1.1: Room Acoustic Parameters (Odeon A/S, 2020)

Parameter	Definition (ISO 3382-1, 2009 and IEC 60268-16)	Subj. limen
T60 [s]	reverberation time, derived from 0dB to -60dB of the decay curve	5% rel.
T30 [s]	reverberation time, derived from -5dB to -35dB of the decay curve	5% rel.
EDT [s]	early decay time - derived from 0 to -10 dB of the decay curve	5% rel.
D50 [%]	definition, early (0 – 50 ms) to total energy ratio	5% abs.
C80 [dB]	clarity – early (0 – 80 ms) to late (80 ms - ∞) energy ratio	1 dB abs.
TS [ms]	center time, time of first moment of impulse response or gravity time	10 ms abs.
G [dB]	sound level related to omni-directional free field radiation at 10 m distance	1 dB abs.
LF [%]	early lateral (5 – 80 ms) energy ratio, cos2 (lateral angle)	5% abs.
STI (RASTI)	speech transmission index	0,03 abs.

1.3.3.1. Reverberation Time (RT)

Perhaps one of the most significant room acoustic parameters is considered to be reverberation time since it can objectively measure subjective room attributes such as liveness and clarity. It can be further defined as such, *“reverberation time (T_{60}) is defined as the time it takes for a sound to decay by 60 dB after the sound source has been switched off”* (Odeon A/S, 2020). Accordingly, the well-established Sabine equation, Equation (1.1), expresses that the reverberation time is directly proportional to the volume of a room and the equivalent total sound absorption area inside the given space (Fasold & Veres, 2003).

$$T_{60} = 0,16\,\frac{V}{A}\ [s] \tag{1.1}$$

V = room volume [m³]
A = total area of absorption in room [m²]

Thus, the reverberation time can effectively provide insight to critical characteristics of a room. In other words, longer reverberation times can be directly associated to large spaces and / or a large area of reflective surfaces, whereas shorter reverberation times can be directly associated to small spaces and / or a small area of reflective surfaces. Moreover, optimal RT values vary according to particular spatial uses of a space. Figure 1.3, shows the set reverberation time values per room function according to DIN 18041:2016. As seen in Figure 1.3, spaces that are primarily used for speech require a shorter reverberation time compared to rooms used for music which benefit from a longer reverberation time. As a result, respectively, a shorter reverberation time enhances clarity and speech intelligibility, whereas a longer reverberation time promotes fullness of sound and liveness within a space (Fasold & Veres, 2003).

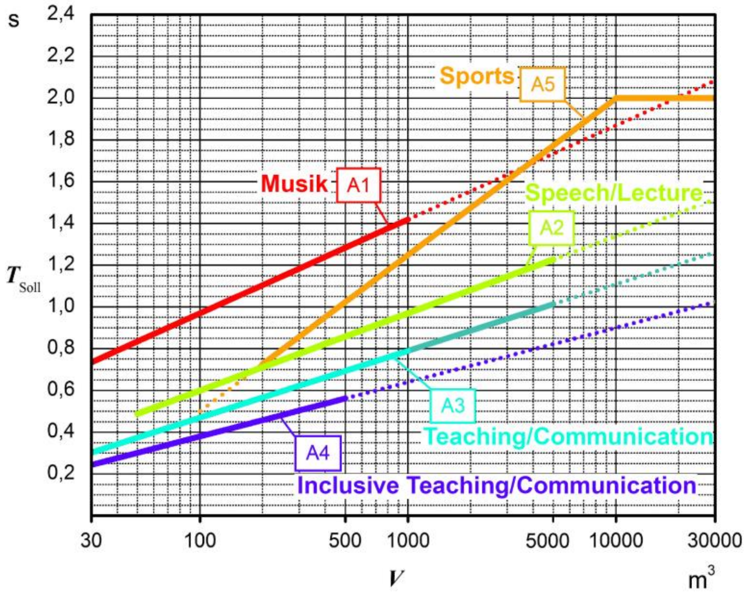


Figure 1.3: Target reverberation time values per spatial use according to and adapted from (DIN 18041:2016-03, 2016)

In practice, however, it is often not possible to effectively measure a sound pressure level decay of 60 dB due to common high levels of background noise present in rooms. Therefore, in this case, smaller decay ranges (10 dB, 15 dB, 20 dB, and 30 dB) can be used to calculate the reverberation time (RT). Thus, T_{30}, depicted in

Figure 1.4, is extrapolated according to T_{60}, whereby it is derived between the decay of -5 dB and -35 dB (Odeon A/S, 2020).

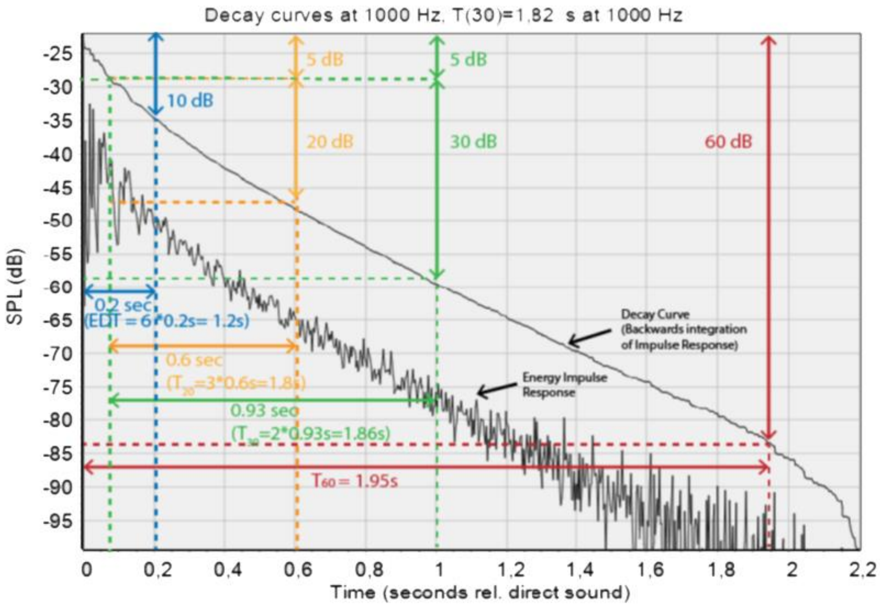


Figure 1.4: Extrapolated decay ranges to calculate RT (Odeon A/S, 2020). *p. 100)*

Furthermore, the acoustic requirements for the reverberation time as defined in DIN 18041 refer to 80% of the normal occupancy and thus, are considered to be conform if the calculated frequency-dependent reverberation times in the frequencies 125 Hz to 4000 Hz lie within the tolerance range (Willems et al., 2018). Figure 1.5 indicates the tolerance range of the reverberation time in relation to the nominal value of the reverberation according to the usage types A1 to A4 specified in DIN 18041.

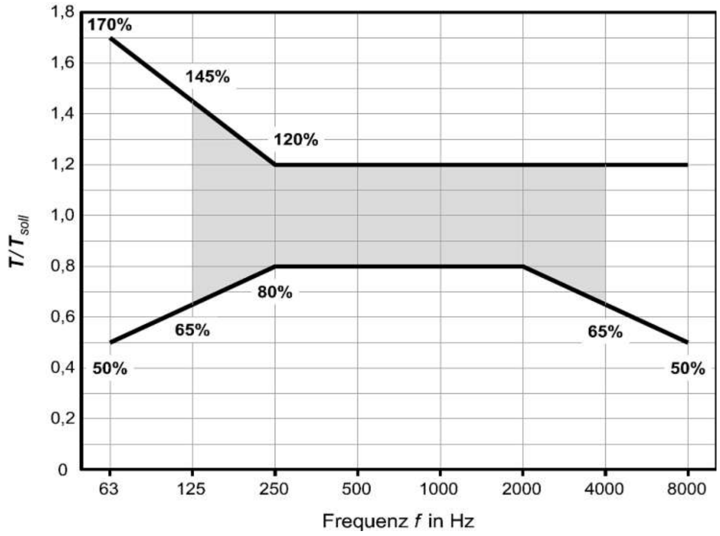


Figure 1.5: Tolerance range of reverberation times as a function of frequency per room use (Willems et al., 2018*. p. 470)*

1.3.3.2. Sound Pressure Level and Sound Distribution

The sound pressure level (SPL) is the resulting pressure variations in the air caused by the sound waves which is measured in decibels (dB) and weighted accordingly to correlate sound level to the hearing and pain thresholds of humans (Fasold & Veres, 2003). Frequency-weightings (A, B, C, D, Z) filter sound level measures to be more comparable to the response of the human ear. The representation of the weighting curves is reciprocal to that of the curves of equal loudness. The most commonly used frequency-weighting is the A filter. The curve of the A filter predicts the sensitivity of human hearing at sensitive lower sound levels (Fasold & Veres, 2003). Equation (1.2) can be used to calculate A-weighted sound pressure levels. Figure 1.6 shows the weighting curves A, B, and C and the respective sound pressure level corrections dependent per frequency.

$$\boldsymbol{L_A\,[dB(A)] = 10\,\lg\left(\sum_{16\,Hz}^{20000\,Hz} 10^{0,1*L_p}\right)} \tag{1.2}$$

L_A = A-weighted sound pressure level [dB(A)]
L_p = sound power level [dB]

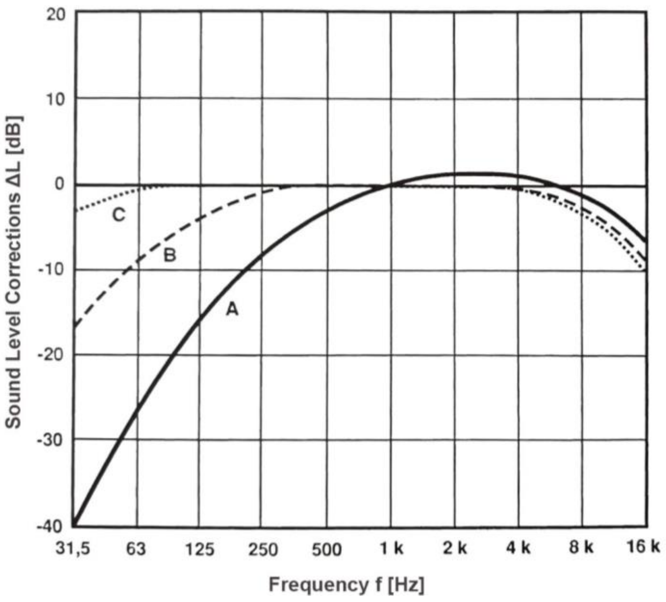


Figure 1.6: Frequency weighting curves A, B, and C (Fasold & Veres, 2003. *p. 50)*

Additionally, relative to the equivalent sound absorption area of a room, especially in nearly cubic spaces, the sound pressure level (SPL) decays as seen in Figure 1.7. That is, the greater the equivalent sound absorption area is in a space, the lower the overall sound pressure level is. However, unlike receivers in a close proximity to a sound source or receivers in outdoor areas, greater distances between a receiver and a source in cubic spaces are irrelevant to the reduction of sound pressure levels. Rather, a constant sound pressure level $L_{p\ diff}$ is obtained (diffuse sound field) which is a result due to the sound reflections. Equation (1.3) expresses how to determine this constant sound pressure level (Fasold & Veres, 2003).

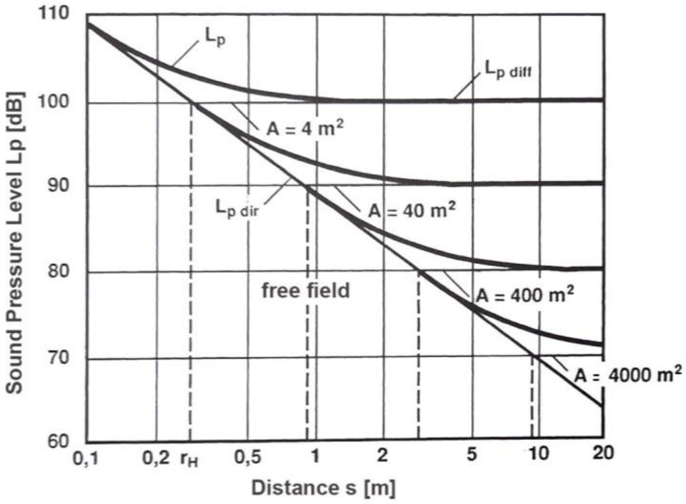


Figure 1.7: Sound pressure level distribution dependent on equivalent absorption areas
(Fasold & Veres, 2003. *p.118)*

$$L_{p\ diff} = L_w - 10\ lg\ \frac{A}{4}\ [dB] \qquad (1.3)$$

$L_{p\ diff}$ = constant sound pressure level [dB]
L_w = sound power level [dB]
A = equivalent absorption area [m²]

Moreover, an exceptional room acoustic performance is obtained when sound is uniformly distributed within a space. Since the SPL is merely a quantity referring to the human perception of sound propagation in a room as sound energy moves from the sound source to a receiver resulting in pressure variations in the air, the loudness and directivity of the source including surface material properties and the geometry of the space are significant. Thus, the propagation of airborne sound, from the point of origin to the human ear, is divided into direct and reflected sound (early reflections and late reflections). Figure 1.8 illustrates the sound propagation of a sound signal in a room. (Willems et al., 2018)

- Reflection delays Δt ≤ 0.05 s correspond to direct sound which overall enhance clarity and intelligibility of the sound.

- Reflection delays 0.05 < Δt ≤ 0.1 s correspond to early reflections which enhance clarity and intelligibility of the sound are desirable for spaces used for speech.
- Reflection delays Δt > 0.1 s correspond to and are considered as part of the diffuse sound field. Diffuse reflections, also known as late reflections, increase the richness of the sound. For spaces that are intended for speech this can create echoes and be undesirable for listeners.

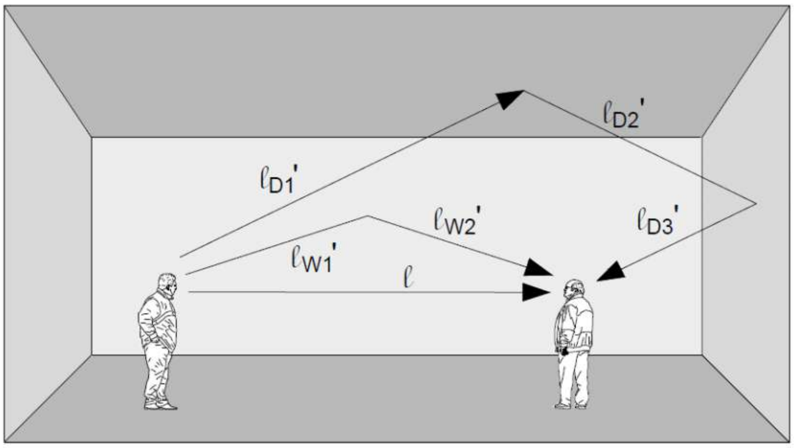


Figure 1.8: Illustration of sound propagation in a closed room (Willems et al., 2018*. p.460)*

1.3.3.3. Assessment of Speech Communication

According to ISO 9921, Ergonomics - Assessment of Speech Communication, which specifies the constraints for the acoustic performance of different types of speech communication, a myriad of dynamic acoustic parameters greatly affect the overall assessment. These factors include but are not limited to according to ISO 9921:2003.

- type of verbal message and application
- sound environment of the room
- speaker-related: vocal effort, gender, non-native speech, distance from receivers (listeners)
- listener-related: directional hearing, distance to sound source, non-native listener

To assess the quality of speech communication, it can be objectively measured in terms of vocal effort and speech intelligibility. Depending on the purpose of the communication, spaces such as lecture rooms, seminar rooms, multifunctional workspaces and / or other assorted room purposes where many people simultaneously talk, the performance of speech communication can be significantly affected, especially if these spaces have few absorbent surfaces.

Consequently, low frequencies often remain unabsorbed which results in a louder background noise level (Willems et al., 2018). To counteract the escalation of noise, speakers are generally provoked to increase their volume of speech in noisy environments so that listeners can continue to understand the speech. Thus, this amplification further worsens the quality of speech communication and the noise level continues to rise (Willems et al., 2018). This effect is most known as the Lombard Effect.

Accordingly, the vocal exertion of the speaker is measured as vocal effort. Vocal effort is outlined in ISO 9921:2003 as "the equivalent continuous A-weighted sound-pressure level of speech measured at a distance of one meter in front a speaker" and corresponds to 6 dB speech level increments shown below in Table 1.2 according to ISO 9921:2003.

Table 1.2: Vocal Effort and related A-weighted speech level according to ISO 9921:2003

Vocal Effort	**Decibels [dB]**
Very Loud	78
Loud	72
Raised	66
Normal	60
Relaxed	54

Moreover, as outlined in ISO 9921:2003, different fields of application require distinct minimal levels of performance of speech communication. For "*person to person communication*" as often the case for workspaces, meetings, lectures, and performances, a normal vocal effort of 60 dB and a good level of intelligibility is recommended according to ISO 9921:2003. Therefore, higher ambient sound pressure levels ($L_{N,\ A}$) in a room cause speakers to increase their vocal effort, presented in Figure 1.9, which for longer durations, like presentations, can be more strenuous for individuals to communicate at higher sound pressure levels compared to lower sound pressure levels. Thus, ambient noise can have a considerable impact on students' performance and learning results as well as the teaching ability of mentors and professors (Willems et al., 2018).

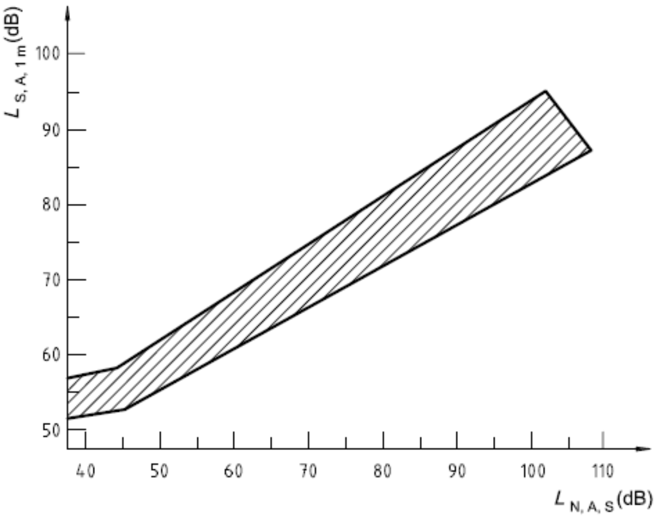


Figure 1.9: Relation between vocal effort and ambient noise according to ISO 9921:2003

In addition, as the vocal effort increases the sound level inevitably intensifies. In particular, when sound level is above $L_{S,\ A,\ 1m}$ = 75 dB, it adversely affects speech quality and is more difficult for listeners to understand.

Additionally, to the above-mentioned parameters, speech quality can also be affected by whether speakers and listeners are natives or non-natives of a particular language. Based on recorded data from 2019, approximately 30% of the students enrolled at the TU Wien are either EU or Non-EU nationals (Technische Universität Wien, 2020b). Namely, in the case of multifunctional university learning areas evaluated in this thesis, it is expected that a considerable number of students using these spaces are non-native speakers and listeners. Therefore, a reduction of speech intelligibility should be avoided. Moreover, an improvement of 4 dB to 5 dB in the signal-to-noise ratio for non-native speakers and / or listeners for them to perceive a similar speech intelligibility as is obtained with native speakers and /or listeners according to ISO 9921:2003. Thus, this slight amplification enhances the speech transmission index (STI) by 0.13 and the SIL by 4 dB. Furthermore, additional research in this subject matter can be found in the works, ‘Predictability and perception for native and non-native listeners’ (Baese-Berk et al., 2018) and ‘Speech intelligibility and listening effort in university classrooms for native and non-native Italian listeners’ (Visentin et al., 2019).

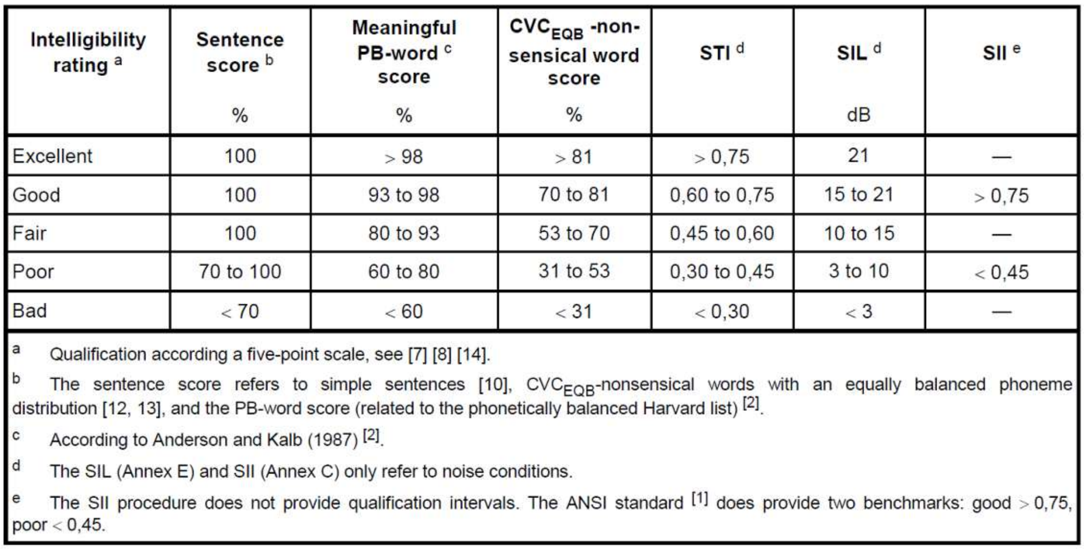
1.3.3.4. Speech Intelligibility

Speech intelligibility, which is directly dependent on background noise level, reverberation time, and geometry of a space, can be outlined as the percentage of a message understood correctly that can objectively be measured or predicted using the Speech Transmission Index (STI), Speech Intelligibility Index (SII), or Speech Interference Level (SIL) according to ISO 9921:2003. Perhaps, the most comprehensive method to evaluate speech intelligibility, is the Speech Transmission Index. In addition, more information to the STI can be found in IEC 60268-16, whereby it is extensively defined.

Overall, the STI value, which is determined by the signal-to-noise ratio in the octave bands, is based on *"the Modulation Transfer Function (MTF) to calculate the changes in the aptitude of the signal envelope over time (the modulation of the signal), between the signal's source and the listener's position"* (Constantinou, 2017).

To achieve good speech intelligibility modulations of the transmitted speech, the signal must be well preserved in the ranging frequency bands. Moreover, the STI indicator is distance dependent and varies per receiver position in relation to the sound source. Table 1.3, which can also be found in ISO 9921:2003, lists the various speech intelligibility assessment methods and the corresponding speech intelligibility ratings dependent on the assessed score per method.

Table 1.3: Intelligibility ratings between intelligibility indices according to ISO 9921:2003



Intelligibility rating [a]	Sentence score [b] %	Meaningful PB-word [c] score %	CVC_{EQB} -non-sensical word score %	STI [d]	SIL [d] dB	SII [e]
Excellent	100	> 98	> 81	> 0,75	21	—
Good	100	93 to 98	70 to 81	0,60 to 0,75	15 to 21	> 0,75
Fair	100	80 to 93	53 to 70	0,45 to 0,60	10 to 15	—
Poor	70 to 100	60 to 80	31 to 53	0,30 to 0,45	3 to 10	< 0,45
Bad	< 70	< 60	< 31	< 0,30	< 3	—

[a] Qualification according a five-point scale, see [7] [8] [14].

[b] The sentence score refers to simple sentences [10], CVC_{EQB}-nonsensical words with an equally balanced phoneme distribution [12, 13], and the PB-word score (related to the phonetically balanced Harvard list) [2].

[c] According to Anderson and Kalb (1987) [2].

[d] The SIL (Annex E) and SII (Annex C) only refer to noise conditions.

[e] The SII procedure does not provide qualification intervals. The ANSI standard [1] does provide two benchmarks: good > 0,75, poor < 0,45.

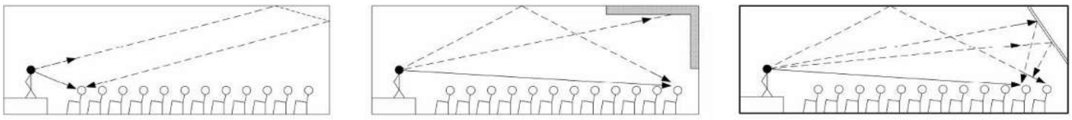
1.3.4 Geometry Based Acoustic Parameters

Not only are room acoustics influenced by the above-mentioned parameters, but the architectural design, referring to the geometry and volume of a defined room as well as the arrangement of the absorbing and reflecting surfaces within a room, can either enhance or hinder the acoustical performance and consequently enrich or disrupt the speech intelligibility. Accordingly, the desired acoustics of a space can in large be achieved by fine-tuning the size and shape of a room as well as the arrangement of stage, podium, and audience areas. In addition, materials with specific sound absorption properties, can be added to reach a desired result and evenly distribute sound energy throughout a room according to DIN 18041:2016.

Ideally rooms used for speech and lectures typically range in volume between 30 m³ and 10,000 m³ according to ÖNORM B 8115-3. Moreover, based on the graph seen in Figure 1.3, or similarly in ÖNORM B 8115-3, the optimal reverberation times corresponding to volume and function of a given occupied space can be approximated according to ÖNORM B 8115-3.

The rooms evaluated in the case study in the following sections, due to their size and volume, can be classified as medium sized rooms and / or small halls. Thus, a room in this classification must, in addition to targeted damping of surfaces through the application of sound-absorbing materials, consider directing sound reflections to improve intelligibility and suppress reflections that would lead to large differences in propagation (Willems et al., 2018).

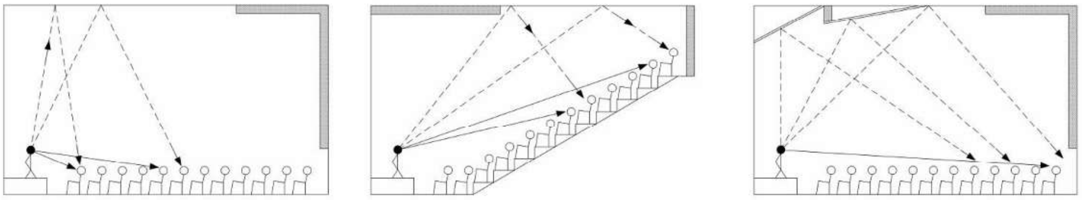
Rooms which are longer than 9 m with directional reflections as in Figure 1.10 *image a* result in reflections with transit time differences of more than 0.05 s, which lead to a deterioration in intelligibility. Therefore, absorption measures according to Figure 1.10 *image b* and *image c* are required for directional reflections. In the latter case, these reflections can possibly be used to increase the sound pressure level in other areas of a room like in Figure 1.10 *images d, e, and f*.



a) unfavorable ceiling reflections

b) favorable ceiling reflections

c) favorable ceiling reflections



d) optimal reflections for back of room

e) optimal reflections for back of room

f) optimal reflections for back of room

Figure 1.10: Display of back wall and ceiling reflections in rooms longer than 9 meters according to ÖNORM B 8115-3, 2005

1.3.5 Acoustics in Repurposed Multifunctional University Spaces

To compensate the ever-growing demand of student learning / workspaces due to the continual increase students attending the TU Wien, unused university spaces, though the number is limited, have been repurposed to fulfil students' spatial demands.

However, many of these rooms were not initially intended for students to work and study in and are often unsuitable in terms of their room acoustic performance and provide little acoustic comfort to the occupants of the spaces. Moreover, performed studies in educational spaces have proven that excessive noise disturbances and long reverberation times reduce speech clarity, which can significantly restrict students' attention level as well as affect students' performance, learning ability, and wellbeing (Youssef, Rabab S.; Bard, 2014).

Whether these repurposed rooms are used for assemblies, learning, studying, working, large-group instructions, holding lectures, hosting varied events, and / or a place to socialize and spend time between university courses, the wide range of activities that take place in such multifunctional university spaces make the room acoustic conditions more complex to control and comply to room acoustic standards.

1.3.6 Noise Disturbance Risk Assesement

Like open plan spaces, multifunctional rooms are meant to be highly flexible for a variety of purposes, yet they are often confronted with disturbing noises which come from activities occurring in adjacent occupied areas of the same room. In addition, circulation areas within large multipurpose rooms greatly influence the background noise level, which negatively distracts room occupants and affects speech intelligibility. Accordingly, the Lombard Effect, as mentioned in section 1.3.3.3 Assessment of Speech Communication, describes that once noise levels exceed 45 dB(A) *"occupants working and talking within the space tend to raise their vocal effort as the background noise level increases, resulting in a spiraling increase in noise levels."* (Canning et al., 2015).

However, to effectively mask noise transmitted from other occupied areas in a room a moderate level of ambient noise, preferably 40 dB(A), helps to mask noise from adjacent spaces without greatly affecting speech intelligibility (Canning et al., 2015). In contrast, speech intelligibility is less critical for individual activities. Nevertheless, noise interference can cause discomfort and a lack of concentration (Canning et al., 2015).

Therefore, it is essential to organize and coordinate activities and events which simultaneously take place in in these multifunctional spaces to effectively control disturbances and intrusive noise levels (Canning et al., 2015). Accordingly, these functions should be evaluated, using a chart similar to Table 1.4, to determine potential noise disturbance risks that may occur when multifunctional rooms are used simultaneously.

Table 1.4: Activity Management Risk Chart adapted from source: (Canning et al., 2015. p.81)

Management Plan	Risk Category		
	High	Moderate	Low
number of groups sharing space	4+ groups	2-3 groups	1 group
point of control	4+ independently operating lecturers/ facilitators	2-3 facilitators with some planning and interaction	1 facilitators
area per student	<3 m²	3-4 m²	>4 m²
time spent in area	usual or permanent place of learning/ working	frequent, but not 100%	occasional/ breakout activities
curriculum groping	different subjects	mixed, but closely linked groups	similar subjects
activity types	frequent critical listening (instruction or discussion in large groups)	critical listening is less frequent, mainly individual/ small group	critical listening occurs as plenary session/ small group work
ograanisation of activities	simultaneous use, independently planned	simultaneous use, but activities planned co-operatively	sequential use
communication distance	>4 m	3-4 m²	<3 m
extraneous circulation	access to other area of the room are required during when occupied	restricted or minimised during function	none
vulnerable listeners	frequent use of multifunctional space	very occasional use	alternative accommodation if necessary

1.3.7 Impact of Noise on Student Performance

It has been reported that acoustical comfort enhances productivity and that increased noise regularly causes aggravation, lack of concentration, as well as it negatively affects a student's cognitive processes and learning abilities (Elmehdi et al., 2019). Not only can high noise levels make it difficult for students to clearly hear the instructor and affect concentration, but some students might consequently, due to the effects of extended acoustic discomfort, be led to "give up" when performing a task or quit completely, which should be a major concern to all universities (Elmehdi et al., 2019).

Furthermore, even if the speech intelligibility of a space is satisfactory, the exertion of both speakers and listeners can vary. An example of this could be that a particular listener must exert him/ herself more to achieve the same performance as other listeners in a room. Thus, if this excessive effort is extended for a long period of time, although the listener might perform well temporarily, the listener will tire more quickly, and the increased cognitive effort cannot be maintained (Profanter, 2015).

Nevertheless, hindrances caused by poor acoustic environmental conditions are sometimes not able to be evaluated merely by the acoustic performance of a space. Accordingly, the subjective perception, psychoacoustics, of sound is an important aspect to room acoustics. *"attempts to qualitatively and quantitatively record and explain the mental sensations triggered by acoustic stimuli"* (Profanter, 2015. p.89). In other words, for example, the sensation "loud" can only be described according to the average hearing threshold of humans although the quantity varies respectively to the subjective perceptions of individuals (Profanter, 2015).

1.3.8 Room Acoustics Simulation Software

The use of room acoustics simulation software has been in practice for several decades and has become integrated in the standard project development processes in the Architecture Engineering and Construction (AEC) industry (Peters, 2015). Although the use of acoustic engineering programs is standard, it is commonly introduced in the final stages of a design rather than in the beginning of the design process (Peters, 2015). More about the implementation of room acoustics simulation tools can be found in section 4.4 Assessment of Acoustic Simulation Software.

Generally, room acoustics simulation software can be categorized into two main approaches, wave-based methods and ray-tracing methods. The ray-tracing approach can be subdivided into geometric methods, image source methods, and hybrid methods (Rindel, 2000).

The methods which are to be outlined below include ray tracing methods (geometric method), image source methods, and hybrid methods, whereby two hybrid method room acoustics simulation tools, Odeon and Pachyderm Acoustical Simulation, are used for the findings of this thesis which is to evaluate the acoustic performance of multifunctional academic spaces at the TU Wien.

Ray-Tracing Method (Geometric Method)

The ray-tracing method of computer acoustic simulations is primary classified as the geometric method. In geometrical acoustics, sound is propagated as rays emitted omnidirectionally from a point source which are then reflected on the surfaces of the geometry. As the particles bounce off a surface or after each reflection, the particles loose energy corresponding to the sound absorption coefficients of that particular surface. The point sound receivers in this type of acoustic simulation collect the data from the particles in a defined volume around the receiver as they are reflected and pass through this volume (Rindel, 2000).

Image Source Method

The image source method *“is based on the principle that a specular (geometrical) reflection can be constructed by mirroring the sound source in the plane of the reflecting surface”* (Rindel, 2000). Moreover, this approach estimates the number of reflections expected to reach a receiver in a given time. Though this method can be useful to quickly generate an accurate acoustic simulation, it ideally works best for rectangular spaces rather than for arbitrary shaped rooms in which image sources exponentially increase according to the reflection order (Peters, 2015)..

Hybrid Method

The majority of the room acoustics simulation tools utilize both ray-tracing and image source methods to reduce the calculation time, yet increase the accuracy of calculations. The combined features of the hybrid approach are depicted in Figure 1.11, which shows the early reflections derived from rays of image sources and the late rays as secondary sources along the exterior surfaces of the room to predict reflection sequences as performed in the room acoustics simulation program Odeon (Rindel, 2000). Moreover, the transition order of early to late reflections in Odeon indicates the reflection order in which early reflections are calculated using the imaged based method and the late reflections are calculated using the ray-tracing method (Odeon A/S, 2020).

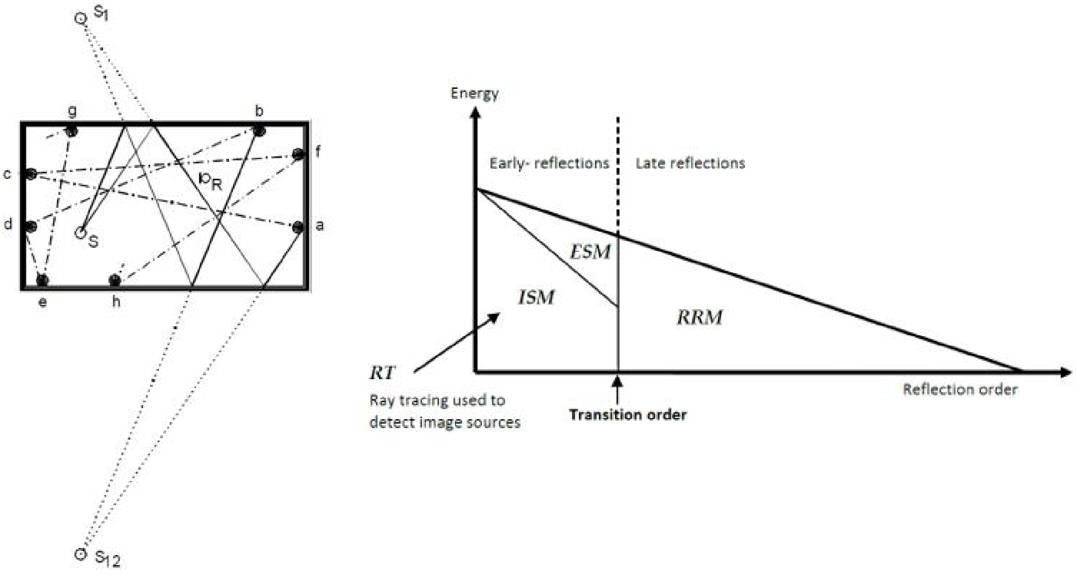


Figure 1.11: Calculation principles of Hybrid Method (Odeon A/S, 2020)*and* (Rindel, 2000)

2 METHOD

2.1 Overview

To address and create an overview of the acoustic performance of the three selected repurposed multifunctional student learning / workspace at the TU Wien, on-site room acoustic measurements were performed to determine existent reverberation times, sound pressure level distribution, background noise levels, and speech intelligibility using equipment provided by the Department of Building Physics and Building Ecology, TU Wien. Thereby, the current acoustical conditions amongst the indicated and evaluated receiver positions of the rooms provide results of a defined control basis for further steps.

In addition, the selected spaces were documented and compared in view of current and past use of space, maximum capacity of occupants, geometry, volume, material properties, as well as individual room characteristics, to reflect the measured and simulated acoustic performance of each space.

Following, the selected multifunctional spaces were modelled in the 3D CAD modeling software McNeel Rhinoceros (Robert McNeel & Associates, 2021) using recorded dimensions taken on-site and plans provided by the TU Wien. The 3D geometry was then imported into the acoustic simulation environment Odeon 11.0 Combined (Odeon A/S, 2021c). Thereafter, materials from the Odeon materials library were applied to the room surfaces to conduct a first acoustic approximation. Other parameters including material scattering coefficients, ambient noise levels and the sound power level were implemented in the simulation environment. The position of the simulated receivers and sound sources correspond to the position of the on-site receivers and sound sources, which were documented during the acoustic measurements, to effectively compare results.

Moreover, the obtained results from each point receiver per simulation iteration, which was also used in the on-site measurements for the reverberation time and SPL decay, were averaged and compared to corresponding on-site receiver measurements to indicate similarities and differences of the values per frequency. Furthermore, the above-mentioned steps were repeated (iterations) until comparable results to the control data were produced.

Once the Odeon model had been calibrated to the on-site measurements, after two iterations, the acoustic simulation environment Pachyderm Acoustical Simulation, which is an acoustic simulation plugin for Rhinoceros / Grasshopper, developed by

Arthur van der Harten, was implemented to conduct further comparisons (food4Rhino, 2021; ORASE, 2021). The same steps performed to calibrate the Odeon simulations were repeated to the Pachyderm interface using the same parameter values so that the two acoustic simulation programs can be compared. Furthermore, this comparison indicates how consistent the acoustic simulation results are in accordance with the on-site measurements. As a result, the reliability of the implemented simulation software can be implied.

Based on the overall findings of both the on-site measurements and simulations, the acoustic performance of the evaluated spaces was defined suitable or inadequate depending on the primary spatial use of the rooms. Therefore, depending to the final results, the repurposed multifunctional learning spaces may need to be retrofitted to provide acoustical comfort for the occupants. In addition, the different simulation environments were evaluated in terms of acoustical parameters used for calculations, usability, as well as the ability to make adaptations to the modelled environments.

Finally, the results were processed and analyzed so that they could be discussed and evaluated. Moreover, the outcome of the results addresses a current issue that the TU Wien is confronted with. Thus, the findings of this master thesis can effectively compare acoustic simulation software and compare result consistency as well as potentially assist in initiating acoustical improvements to student learning spaces.

2.2 Hypothesis

It is hypothesized that the repurposed multifunctional university learning spaces at the TU Wien, based on the evaluation of a sample of selected rooms, are to be acoustically inadequate as functional learning spaces for students.

2.3 Case Study

To narrow the selection of spaces to be evaluated in this master thesis, a criteria list was established to determine which university rooms to consider for evaluation based on the following:

- use of space
- maximum room occupancy
- geometry of learning space
- volume of space
- room characteristics which could influence the acoustic performance

Moreover, to vary the range of university learning environments, the reduced selection of rooms was compared to each other based on these individual parameters. The spaces that were the most different to each other were used in this case study for this thesis. This case study examines the acoustic performance of three selected repurposed learning environments, Aufbaulabor, Project Room Panigeltrakt EG, and TVFA Halle (institute building, Erzherzog-Johann-Platz) at the TU Wien.

Two of the selected rooms, Aufbaulabor and Project Room Panigeltrakt EG, are located in the main university building, Campus Karlsplatz. The third evaluated space is the TVFA Halle (Technische Versuchs- und Forschungsanstalt Halle - Technical Testing and Research Institute Hall) located in the institute building next to Erzherzog-Johann-Platz.

For an overview of the spaces in relation to their surroundings, please refer to A. Site Plans.

The room selection is introduced below in Figure 2.1.

Figure 2.1: Case study room selection (TU Wien Fakultät für Architektur und Raumplanung, 2021)

2.3.1 Aufbaulabor

The Aufbaulabor is located on the first floor in the main university building, Campus Karlzplatz. It was originally constructed for practical laboratory courses for the Technical Physics field of studies in 1918 (Sequenz, 1965). Since then, the space has been adapted into a multifunctional learning area/ workspace for students of all fields of study, however, the room is primarily used by architecture students.

Figure 2.2: Images of the Aufbaulabor, TU Wien (TU Wien, 2020a)

With a total volume of 1,318 m^3 and a usable floor area of about 266 m^2, the Aufbaulabor has a maximum capacity of 120 seats. The tables and chairs can be moved accordingly depending on the individual event and /or use of the space. For the most part, the room furniture is usually arranged so that the tables and chairs are positioned parallel along the walls of the room as seen in Figure 2.2.

At the time the acoustic measurements were performed, several tables were placed in the middle zone of the room to account for furniture arrangements of the wide-ranging activities that take place in the Aufbaulabor. Figure 2.3 documents the condition of the room during the acoustic measurements and Figure 2.4 illustrates the floor plan and section used to construct the 3D geometry for the acoustic simulations.

Figure 2.3: State of Aufbaulabor during on-site measurements (images taken by author)

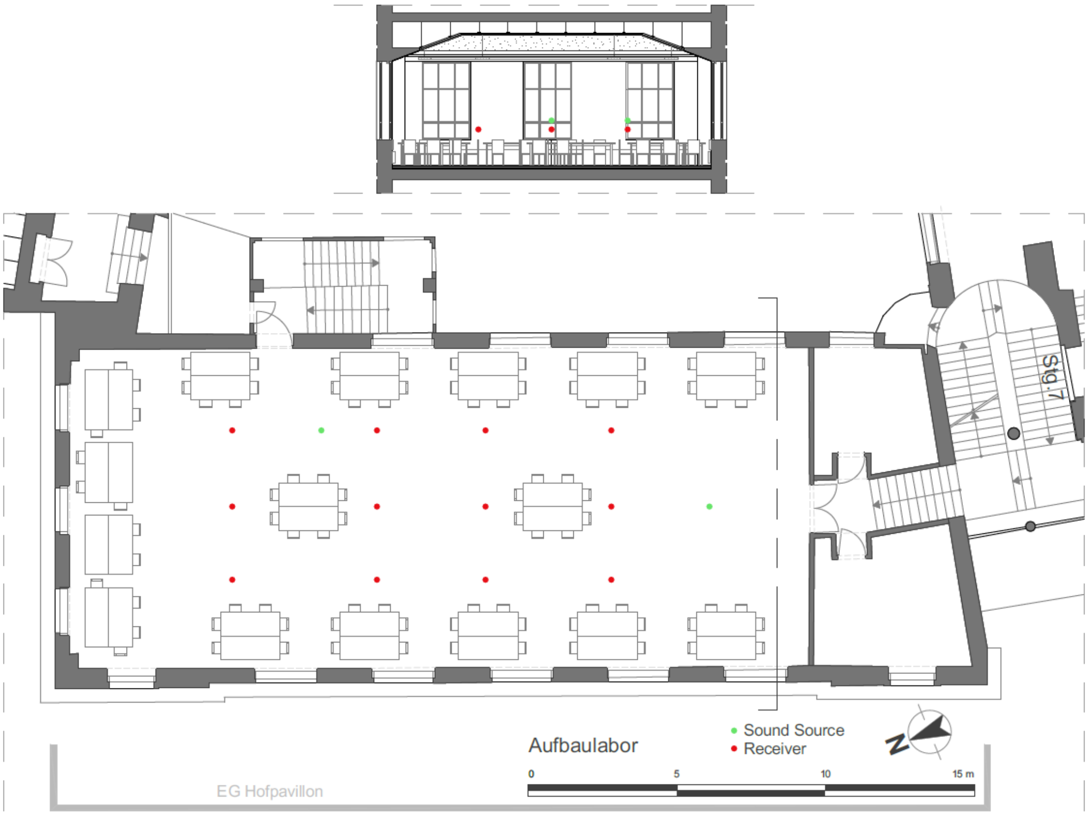


Figure 2.4: Section and plan of Aufbaulabor. (●) Receiver positions during on-site measurements (●) Speaker positions during on-site measurements

Moreover, the use of this space is widely varied. Even though it is primarily used for numerous weekly architecture project reviews, students from all fields of study usually concurrently occupy all available tables throughout the day. The range of activities which the students perform, to name a few, include computer-work, eating, listening to music, model building including the use of power tools, presenting projects, project discussions, reading, and studying.

Nevertheless, the Aufbaulabor is not only used for typical university functions. In the past this space has been regularly used for architecture exhibitions, IT competitions such as the ‘TU Wien Capture the Flag Competition’, summer camp courses like the ‘techNIKE’ which was an event for TU Wien employees’ daughters that were interested in technical sciences. In addition, the Aufbaulabor has also been used for numerous external university events such as for the Buskers Festival at Karlsplatz and many assorted presentations. Maybe even most interestingly, it was regularly used for Argentine tango dance lessons (TU Wien, 2020a). The images below in Figure 2.5 illustrate some of the many uses of the Aufbaulabor.

Figure 2.5: Varied uses of the Aufbaulabor (TU Wien Fakultät für Architektur und Raumplanung, 2021), (Tango Argentino @ TU Wien, 2017)

2.3.2 Project Room Panigltrakt EG

The Project Room Panigltrakt EG (often shortend to Panigltrakt) is located on the ground floor in the main university building, Campus Karlzplatz. Like the Aufbaulabor, this space was not originally intended as a multifunctional learning area/ workspace for university students. Although there is little historical information on this space, it is known that the Project Room Panigltrakt has been a seminar room for over 30 years (TU Wien, 2020a).

Figure 2.6: Image of the Project Room Panigltrakt EG, TU Wien
(TU Wien, 2020a)

With a total volume of 490 m^3 and a floor area of 80 m^2, the Project Room Panigltrakt EG has a maximum capacity of 40 seats. The tables and chairs can be moved accordingly depending on the individual event and /or use of the space. For the most part, in the past, the room furniture was usually arranged in one large table block so that the tables were pushed together in the center of the room and chairs were positioned around the outer edges of the tables which was well suitable for group discussions. However, at the time the acoustic measurements were performed, the tables were separated to create equal individual table groups arranged evenly throughout the room with center aisles between them as seen in Figure 2.6. This arrangement was chosen to reflect the current main use of the room as individual project workspaces for students. Figure 2.7 documents the condition of the room during the acoustic measurements and Figure 2.8 illustrates the floor plan and section used to construct the 3D geometry for the acoustic simulations.

Figure 2.7: State of Project Room Panigltrakt during on-site measurements (images taken by author)

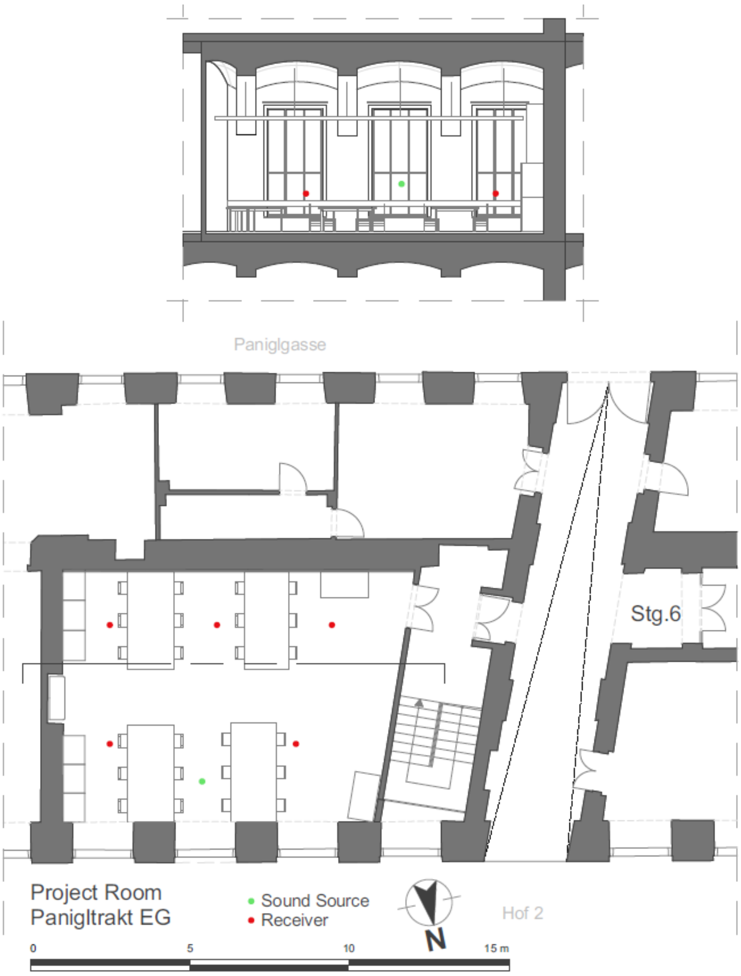


Figure 2.8: Section and plan of Panigltrakt. (●) Receiver positions during on-site measurements (●) Speaker position during on-site measurements

Though the space has been officially defined as a seminar room, based on the information provided on the TU Wien university website, it is possible to view past room reservations to the year 2014. After extensively, reviewing the records, several room reservations particularly stood out.

In addition to primarily being used as a conference room for weekly project reviews, lectures, mentoring lessons and presentations, the Project Room Panigltrakt EG has also been used for exams including board exams. Furthermore, the 2017 Buskers Festival and the Popfest Karlsplatz 2015 and 2019 have used the space as a backstage room. It has also been used to host several external organizations' conferences as well as the 'Summer Camp Musical & English' for children. To broaden the space usage even more, the Project Room Panigltrakt EG has been used as a rehearsal space for the TU Wien Orchestra (TU Wien, 2020a).

The range of activities which have taken place in the university room justifies that it is a multifunctional learning area/ workspace for students. The images below in Figure 2.9 illustrate some of the many uses of the Project Room Panigltrakt EG.

Figure 2.9: Varied uses of the Project Room Panigltrakt EG (TU Wien Department for Raumgestaltung und Entwerfen, 2021)

2.3.3 TVFA Halle

The TVFA Halle is located on the ground floor in the institute building at Erzherzog-Johann-Platz which is opposite the TU Wien EI building in the Gußhausstraße. The hall was originally constructed as a garage and was specifically adapted for testing by the Technical Testing and Research Institute (TVFA - Technische Versuchs- und Forschungsanstalt) in 1970s into a testing hall (TU Wien, 2020a). Since 2017 TU Wien has acquired the hall and has been using it mainly for exhibitions as well as student workspaces for large design workshops.

Compared to the previous two repurposed student learning areas/ workspaces, this room is significantly larger in size. With a total volume of approximately 5,910 m^3 and a floor area of roughly 500 m^2, the TVFA Halle has a maximum capacity of 300 seats. The tables and chairs can be moved accordingly depending on the individual event and /or use of the space. For the most part, the room furniture is usually arranged along the perimeter of the room leaving the center area largely open for displays which can be seen below in Figure 2.10 (TU Wien Fakultät für Architektur und Raumplanung, 2021).

Figure 2.10: Images of the TVFA Halle, TU Wien (TU Wien Department for Raumgestaltung und Entwerfen, 2021)

At the time the acoustic measurements were performed, several tables were placed in the middle zone of the room to account for furniture arrangements of the wide-ranging events that take place in the TVFA Halle. Figure 2.11 documents the condition of the room during the acoustic measurements and Figure 2.12 illustrates the floor plan and section used to construct the 3D geometry for the acoustic simulations.

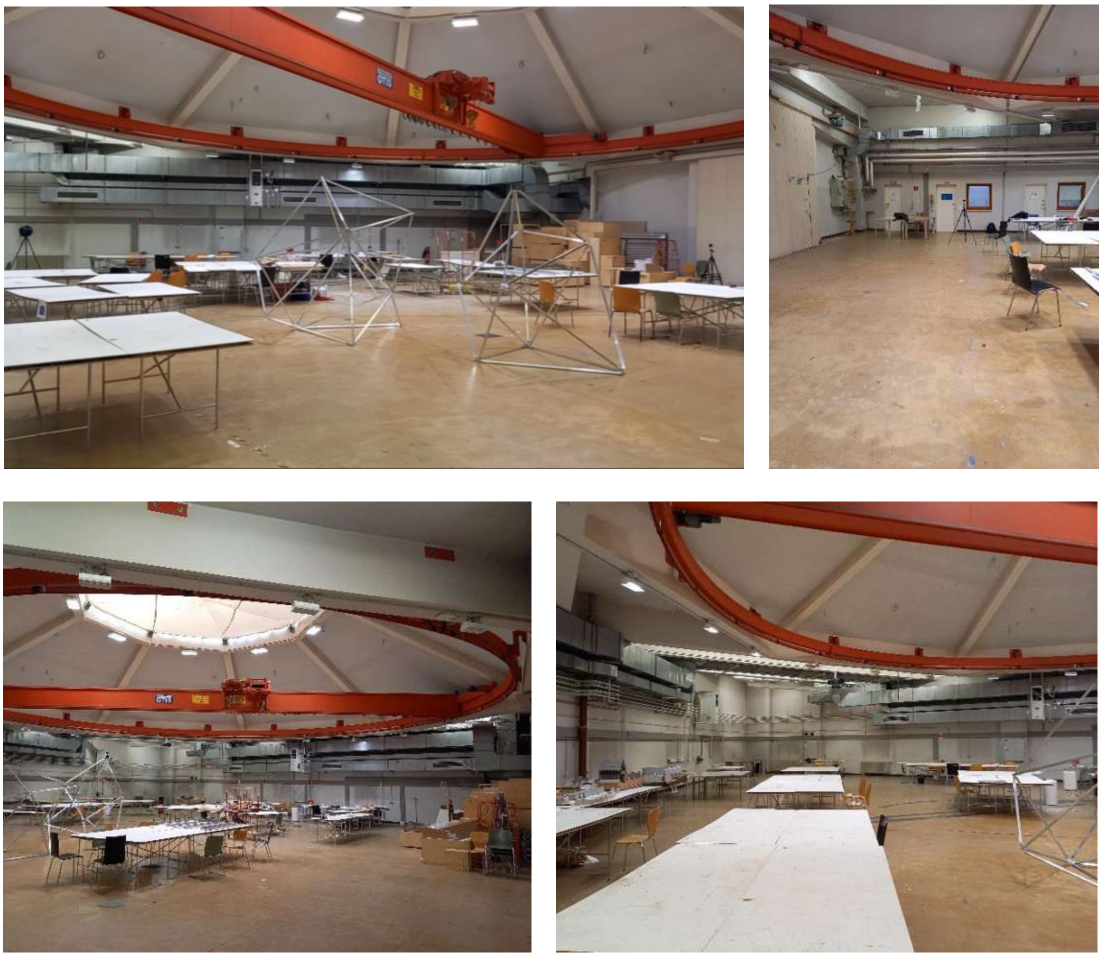


Figure 2.11: State of the TVFA Halle during on-site measurements (images taken by author)

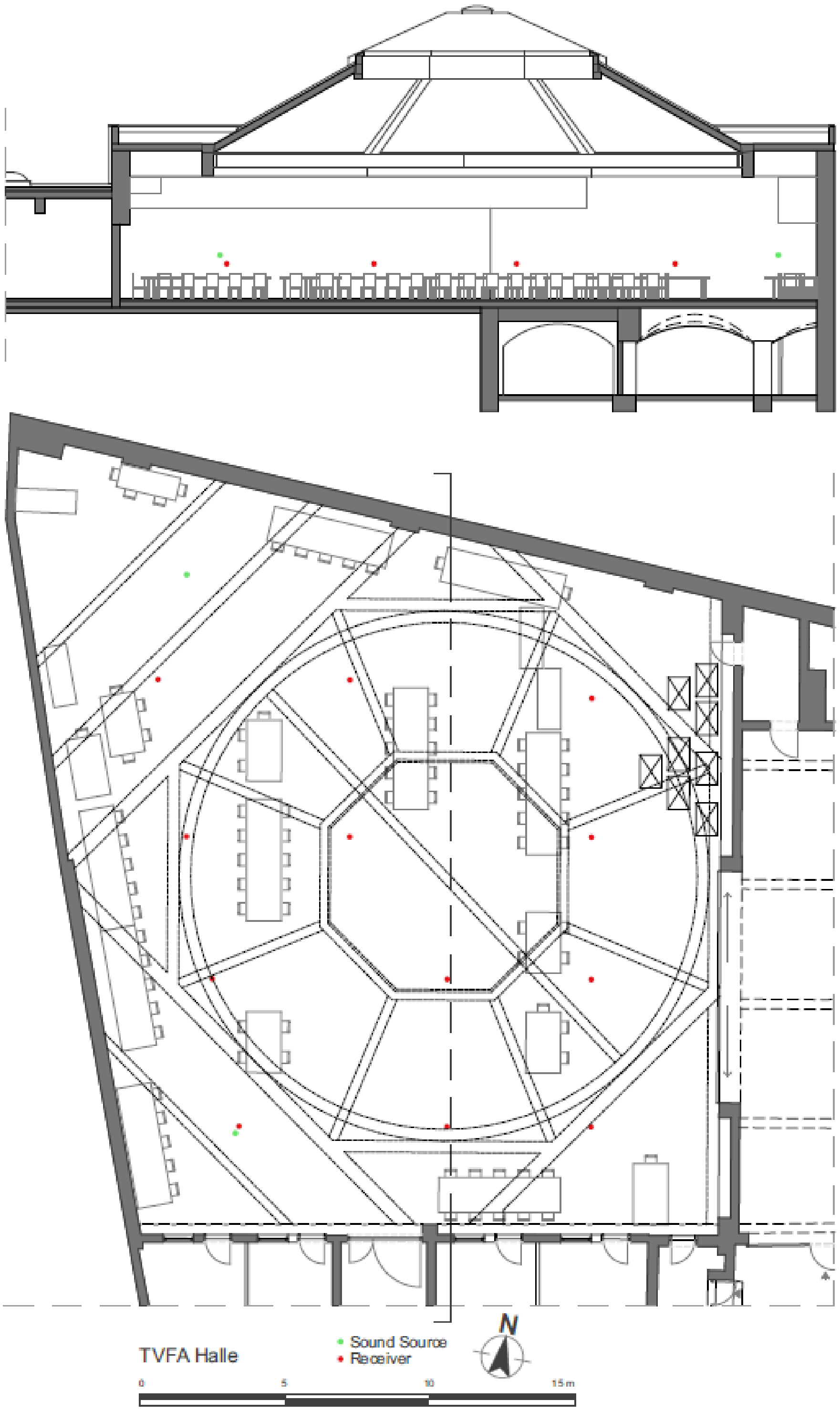


Figure 2.12: Section and plan of Panigltrakt. (●) Receiver positions during on-site measurements (●) Speaker positions during on-site measurements

Though the hall can be used by students of all fields of study, it is predominantly occupied by architecture students. As like the previous two spaces this multifunctional hall provides students with space for discussions, general computer-work, and presentations as well as a place to study and build models. Moreover, large design projects can be constructed and assembled here, seen in Figure 2.11 and

Figure 2.14, which may require the use of power tools and the aid of lifting equipment like an overhead crane or forklift. Though the range of activities in this space is limitless, a few events that took place in the TVFA Halle are listed in the following.

According to the TU Wien university website, this space has been regularly used for weekly reviews for design studios, workshops and presentations by the Institute of Architecture and Design, Institute of Urban Design and Landscape Architecture, and Institute of Spatial Planning, Figure 2.13 (TU Wien Fakultät für Architektur und Raumplanung, 2021).

Figure 2.13: Use of the TVFA Halle for design studios and workshops (TU Wien Department for Hochbau und Entwerfen, 2021)

In addition, full scale mock-up projects, which demand plenty of space and high ceilings, projects like the VIVI House which is shown in Figure 2.14 have been constructed here in the past.

Figure 2.14: Construction of VIVI House in the TVFA Halle (Kichler, 2018)

Furthermore, varied events, such as conferences, ‘Sommerschule Green Building Solutions’, 2017 and 2019 Archdiplom Exhibition, along with numerous semester project course exhibitions have been hosted in the TVFA Halle. The images below in Figure 2.15, Figure 2.16,and Figure 2.17 illustrate some of the many uses of this space.

Figure 2.15: Use of the TVFA Halle for presentations and conferences
(TU Wien Department for Gebäudelehre und Entwerfen, 2021)

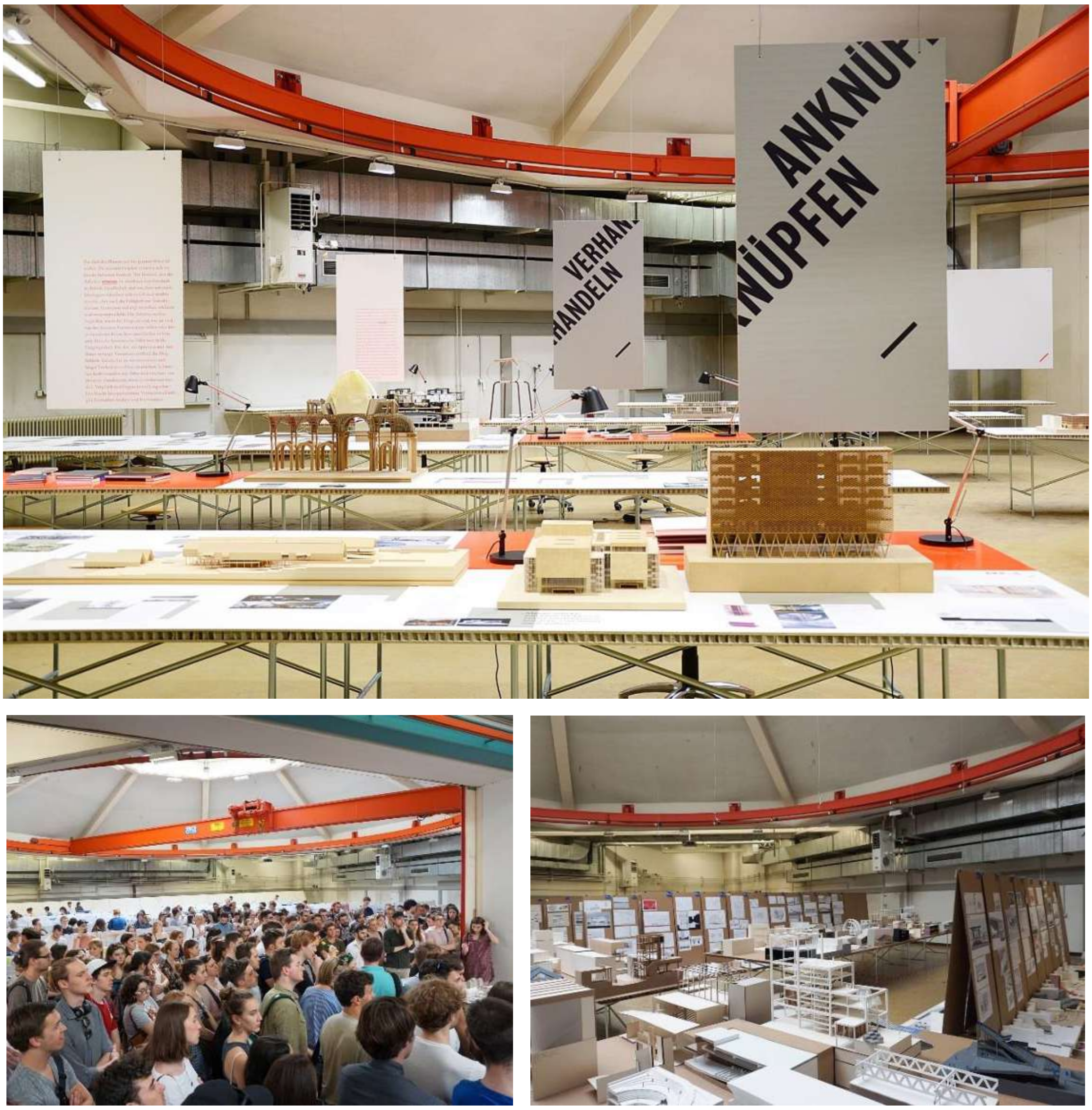


Figure 2.16: Use of the TVFA Halle for exhibitions (Extraplan, 2021; TU Wien Department for Hochbau und Entwerfen, 2021)

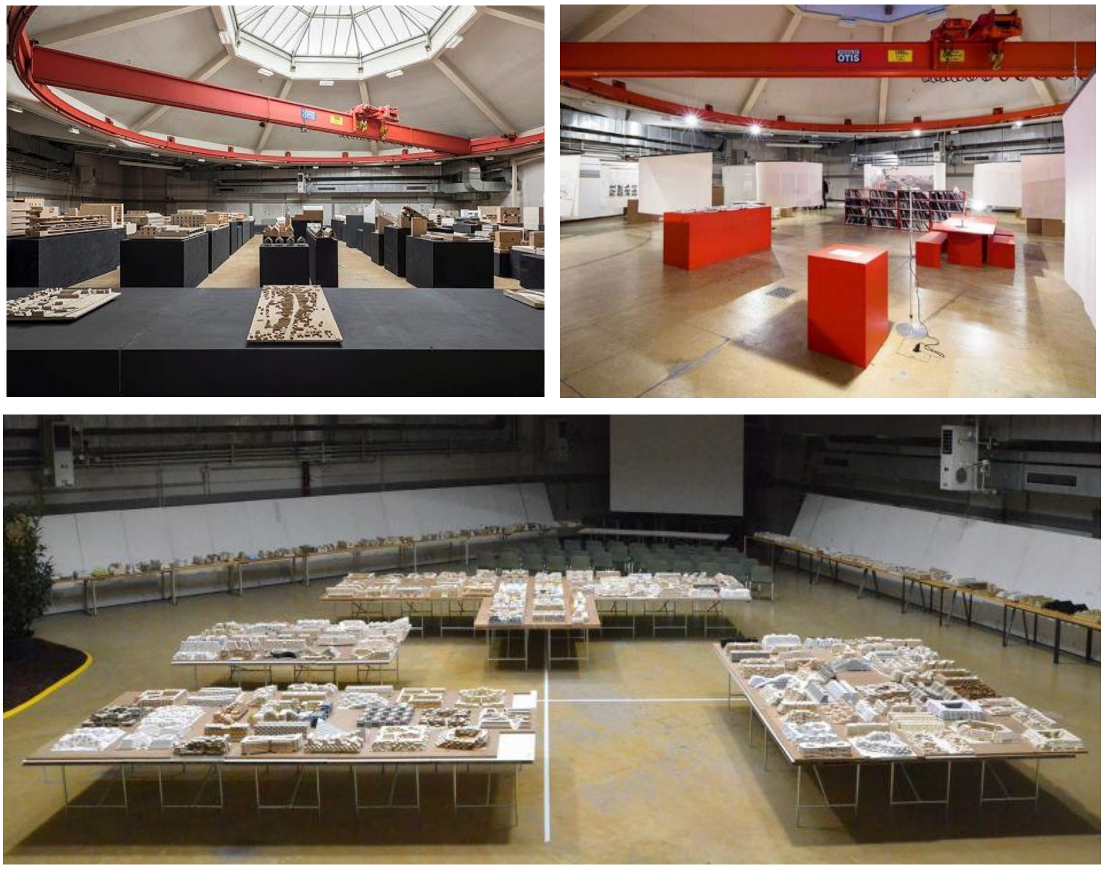


Figure 2.17: Use of the TVFA Halle for exhibitions
(TU Wien Fakultät für Architektur und Raumplanung, 2021)

In addition to the above-mentioned activities and events, the TVFA Halle has been used as a rehearsal space, Figure 2.18, for the TU Wien Orchestra (TU Wien, 2020a). Accordingly, the broad usage of the hall defines this space as a multifunctional learning area/ workspace for students.

Figure 2.18: Use of the TVFA Halle for rehearsals for the TU Wien Orchestra
(TU Wien Department for Raumgestaltung und Entwerfen, 2021)

2.4 Acoustical Measurements

Sound analysis equipment was used to measure reverberation time, sound level distribution, and background noise levels. These on-site measurements were conducted in the rooms in an unoccupied state and conform to DIN EN ISO 3382-1 and DIN EN ISO 3382-2. Table 2.1 and Figure 2.19 list the components and configuration of the acoustic measuring equipment provided by the Department of Building Physics and Building Ecology, TU Wien which were used to perform the acoustic measurements.

Table 2.1: NORSONIC Measurement Equipment used for on-site measurements (Norsonic, 2012)

Dodecahedron Omni Loudspeaker	**Nor276**
Power Amplifier	Nor280
Building Acoustic Case	Nor515
Wireless Building Acoustic System	Nor1516B
Sound Analyzer (handheld device + microphone and stand)	Nor140
Sound Analyzer (handheld device + microphone and stand)	Nor140
Notebook + WLAN	
Software	CtrlBuild and NorBuild

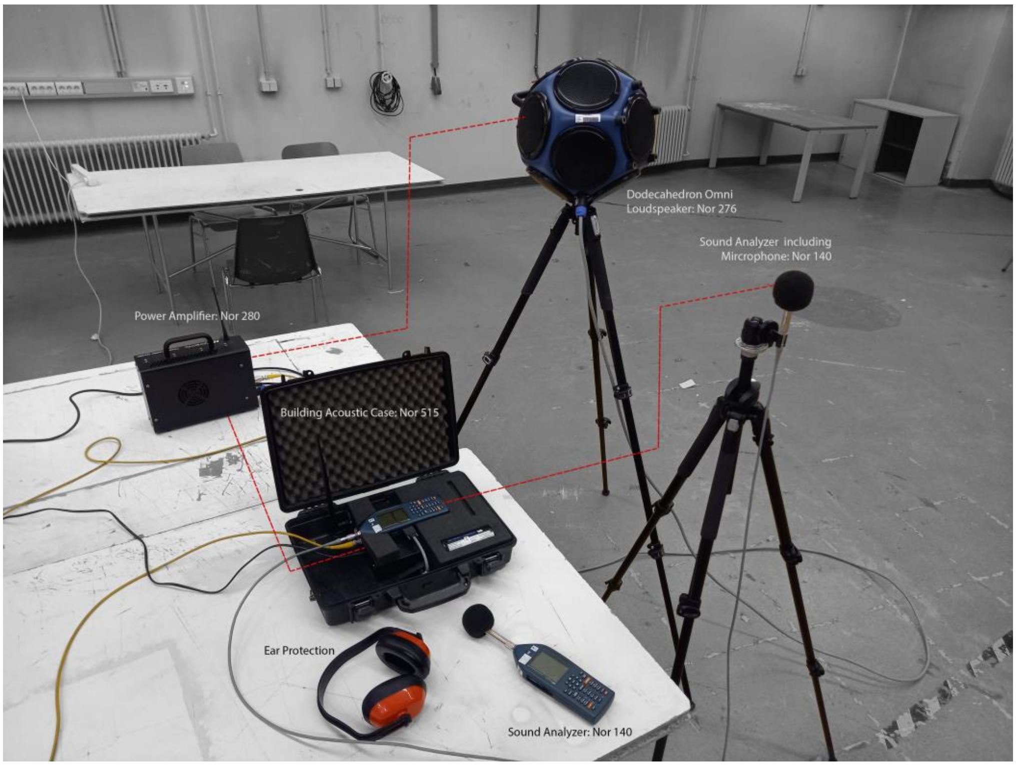


Figure 2.19: Equipment used for on-site measurements

The following lists general information about the acoustic measurements performed on-site.

- The frequency range of each measurement was between 125 Hz – 4000 Hz.
- The sound source was positioned 1.50 m from the ground.
- Two microphones were used at defined positions to obtain results. The microphones were positioned at least 1.00 m from the surrounding surfaces and at a height of the was 1.20 m above the ground.
- To measure the sound level distribution a pink noise with constant volume was used during all single point receiver measurements per sound source position. The measured time at each position was 20 s.
- The reverberation times were measured similarly. Though, after 10 s, the sound radiation was interrupted and the decay data was recorded.

For an understanding of the exact arrangement of sound source and receiver positions per room, please refer to the individual floor plans and sections in section 2.3 Case Study and / or section 2.5 Acoustic Simulations.

2.5 Acoustic Simulations

The acoustic performance of the three selected repurposed learning environments, Aufbaulabor, Project Room Panigeltrakt EG, and TVFA Halle at the TU Wien were further evaluated using two room acoustics simulation programs, Odeon 11.00 Combined and a plugin for the 3D CAD modeling program Rhinoceros (Rhino) called Pachyderm Acoustical Simulation. Moreover, the 3D room geometries were constructed in Rhino and exported in DXF format to be used in Odeon. Moreover, the geometries of the three rooms were marginally simplified to prominent features within the spaces. In addition, room furniture such as tables, chairs, shelves, etc. were reduced and defined as areas on adjacent floors and walls and scatter coefficients were increased on surface areas that were cluttered and / or uneven.

To calibrate the simulation models, two iterations were performed in which room acoustic parameters such as the measured ambient noise levels, surface materials and their sound absorption coefficients were applied and / or adjusted until the simulated results approximated the on-site measurement results. Iteration I can be described as a rough first approximation of the acoustic parameters, whereas Iteration II fine-tunes the models and is considered to be calibrated near the actual measured room acoustics results. These mentioned simulation adjustments are further outlined in the following subsections. Additionally, corresponding simulated results can be found in 3.3 Simulation Results of Calibrated Models and Appendix B.

Once the acoustic simulation models generated comparable results like the on-site measurements, a final simulation (Iteration III simulated audience), whereby the results are presented in section 3.4 Simulation Results of Audience Models, was conducted to include a simulated audience in each of the spaces.

2.5.1 Aufbaulabor

Represented below, Table 2.2 outlines the corresponding distances between the sound sources and receivers and Figure 2.20 illustrates the individual sound sources and receiver positions used for both on-site measurements and acoustic simulations in the Aufbaulabor.

Table 2.2: Distance per receiver position to corresponding sound source

Aufbaulabor

Receiver	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3	4.1	4.2	4.3
Distance to S1	4.2m	3.3m	4.2m	8.0m	7.6m	8.0m	11.5m	11.2m	11.5m	16.3m	16.1m	16.3m
Distance to S2	11.0m	10.1m	9.8m	7.5m	6.1m	5.5m	3.4m	3.2m	1.9m	5.9m	4.0m	3.0m

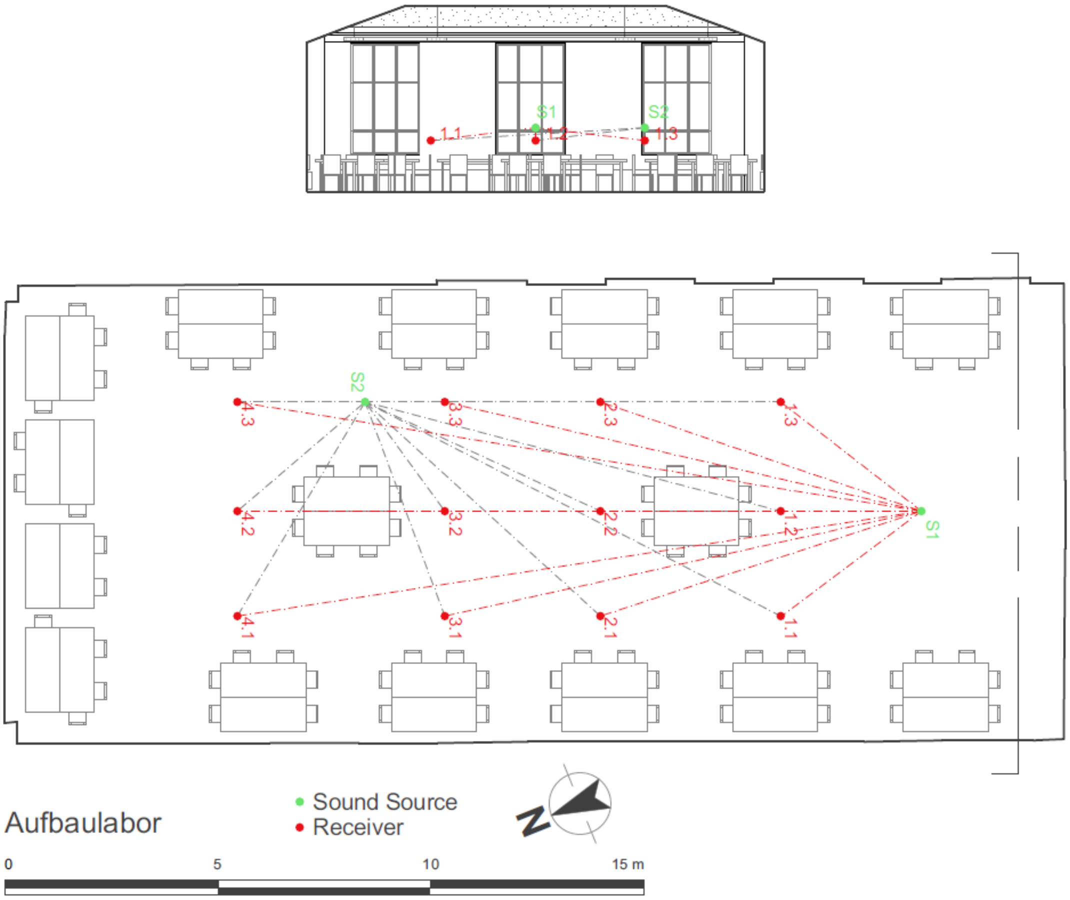


Figure 2.20: Aufbaulabor: (●) Receiver positions during on-site measurements (●) Speaker positions during on-site measurements

Aufbaulabor Simulation Iteration I and Iteration II

Calibrating the Aufbaulabor acoustic simulation models to the on-site measurements required surface materials and their properties to be defined and adjusted. The majority of the surface materials used in the Odeon simulation models were taken from the standard Odeon materials library. Since the exact definition of the actual surface materials including their sound absorption coefficients are unknown, assumptions were made to approximate the existing materials and their corresponding sound absorption coefficients. In addition, metallic-like and highly reflective surfaces, for example the entrance door and the projection screens, were simplified and assigned the properties of a highly reflective painted plaster material from the Odeon materials library.

Surface materials that could not be approximated using the standard Odeon library materials, such as those used for unoccupied wooden audience seating areas and mineral fiber panels on the walls, were added to the existing materials library using comparable materials and their sound absorption coefficients found in (Fasold & Veres, 2003)

Subsequently, the specified surface materials used in each simulated Aufbaulabor Odeon iteration were created and defined in the Pachyderm simulation iterations to match scatter and sound absorption coefficients of the implemented materials in the Odeon simulations.

Table 2.3 lists the surface materials and their corresponding sound absorption coefficients in octave-band frequencies used for each surface in the Aufbaulabor per simulated model iteration. Moreover, the surface areas of the individual building components and the adjustments per calibrating iteration, Iteration I, Iteration II, as well as the final calibrated model, Iteration III with a simulated audience, are also presented in the table.

Table 2.3 Surface materials and absorption coefficients by frequency used to calibrate the simulated Aufbaulabor model in Iteration I and Iteration II and the final calibrated model with an audience in Iteration III, adapted from source:(Odeon A/S, 2021a)

Aufbaulabor

Surface		Area [m^2]	Iteration	Material Description	Scatter	sound absorption coefficients by frequency [α]							
						63 [HZ]	125 [HZ]	250 [HZ]	500 [HZ]	1000 [HZ]	2000 [Hz]	4000 [Hz]	8000 [Hz]
Floor		266.0	I, II, III	parquet on counterfloor	0.05	0.20	0.20	0.15	0.10	0.10	0.05	0.10	0.10
Audience Zone	unoccupied	54.4	I, II	wooden chairs, unoccupied	0.30	0.05	0.05	0.05	0.05	0.10	0.10	0.15	0.15
	occupied		III	audience on wooden chairs, 1 per sq.m		0.16	0.16	0.24	0.56	0.69	0.81	0.78	0.78
Walls		157.0	I	painted plaster surface	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
			II, III	plaster, gypsum or smooth finish on lath		0.14	0.14	0.10	0.06	0.04	0.04	0.03	0.03
Walls (with furniture infront)		26.9	I	painted plaster surface	0.30	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
			II, III	plaster, gypsum or smooth finish on lath		0.14	0.14	0.10	0.06	0.04	0.04	0.03	0.03
Ceiling (plastered)		57.2	I, II, III	painted plaster surface	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Suspended Ceiling		217.6	I, II, III	mineral fiber ceiling tiles	0.05	0.34	0.34	0.43	0.54	0.67	0.65	0.64	0.64
			II, III	(middle section) hardly pressed mineral fiber ceiling tiles		0.45	0.45	0.60	0.60	0.80	0.80	0.65	0.65
Sound Insulation Panels		44.3	I	plaster, gypsum or rough finish on lath	0.05	0.14	0.14	0.10	0.06	0.05	0.04	0.03	0.03
			II, III	mineral fiber board without cover flush to wall		0.15	0.15	0.30	0.65	0.85	1.00	1.00	0.80
Projection Screens		7.9	I, II, III	painted plaster surface	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Entrance Door		3.2	I, II, III	painted plaster surface	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Side Door		2.5	I, II, III	double glazing, 2-3mm glass, 10mm gap	0.05	0.10	0.10	0.07	0.05	0.03	0.02	0.02	0.02
Windows		66.8	I, II, III	double glazing, 2-3mm glass, >30mm gap	0.05	0.15	0.15	0.05	0.03	0.03	0.02	0.02	0.02

2.5.2 Project Room Panigltrakt EG

Represented below, Table 2.4 outlines the individual sound sources and receiver positions in the Project Room Panigltrakt EG. Moreover, Figure 2.21 illustrates the corresponding distances between the sound sources and receiver positions used for both on-site measurements and acoustic simulations in the Project Room Panigltrakt EG.

Table 2.4: Distance per receiver position to corresponding sound source

Project Room Panigltrakt EG

Receiver	1.1	1.2	1.3	2.1	2.3
Distance to S1	6.5m	5.0m	5.8m	3.2m	3.2m

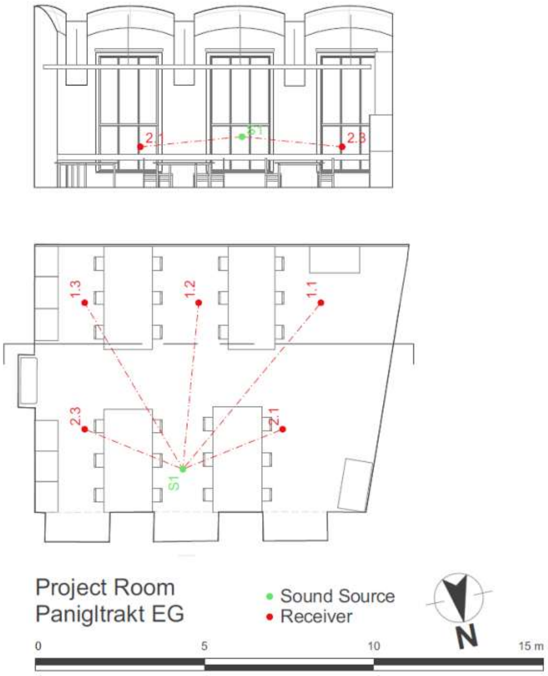


Figure 2.21: Panigltrakt: (●) Receiver positions during on-site measurements (●) Speaker positions during on-site measurements

Panigltrakt Simulation Iteration I and Iteration II

Like the Aufbaulabor, the exact definition of the actual Panigltrakt room surface materials including their sound absorption coefficients are unknown. Therefore, assumptions were made to approximate these materials and their corresponding sound absorption coefficients based on materials in the existing Odeon materials library. Additionally, the large metal surfaces of the ventilation unit were assigned a highly reflective painted plaster material from the Odeon materials library with similar acoustic properties. Surface materials used for unoccupied wooden audience seating areas and mineral fiber panels on the walls, were added to the existing Odeon materials library as described above. These specified surface materials used in each simulated Panigltrakt Odeon iteration were then created and defined in the Pachyderm simulation iterations so that the simulation results of both programs could be consistently compared.

Table 2.5 lists the surface materials and their corresponding sound absorption coefficients in octave-band frequencies used for each surface in the Project Room

Panigltrakt EG per simulated model iteration. Moreover, the surface areas of the individual building components and the adjustments per calibrating iteration, Iteration I, Iteration II, as well as the final calibrated model, Iteration III with a simulated audience, are also presented in the table.

Table 2.5 Surface materials and absorption coefficients by frequency used to calibrate the simulated Panigltrakt model in Iteration I and Iteration II and the final calibrated model with an audience in Iteration III, adapted from source: (Odeon A/S, 2021a)

Panigltrakt

Surface		Area [m²]	Iteration	Material Description	Scatter	sound absorption coefficients by frequency [α]							
						63 [HZ]	125 [HZ]	250 [HZ]	500 [HZ]	1000 [HZ]	2000 [Hz]	4000 [Hz]	8000 [Hz]
Floor		79.8	I	linoleum or vinyl stuck to concrete	0.05	0.02	0.02	0.02	0.03	0.04	0.04	0.05	0.05
			II, III	linoleum or vinyl + underlayer stuck to concrete		0.02	0.02	0.02	0.04	0.05	0.05	0.10	0.10
Audience Zone	unoccupied	20.2	I, II	wooden chairs, unoccupied	0.30	0.05	0.05	0.05	0.05	0.10	0.10	0.15	0.15
	occupied		III	audience on wooden chairs, 1 per sq.m		0.16	0.16	0.24	0.56	0.69	0.81	0.78	0.78
Walls		194.8	I	painted plaster surface	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
		128.0	II, III	plaster, gypsum or smooth finish on lath		0.14	0.14	0.10	0.06	0.04	0.04	0.03	0.03
Beams		41.6	I	painted plaster surface	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
			II, III	plaster, gypsum or smooth finish on lath		0.14	0.14	0.10	0.06	0.04	0.04	0.03	0.03
Vaulted Ceiling		73.5	I	painted plaster surface	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
			II, III	plaster, gypsum or smooth finish on lath		0.14	0.14	0.10	0.06	0.04	0.04	0.03	0.03
Pin Board		12.4	I	plaster, gypsum or rough finish on lath	0.05	0.14	0.14	0.10	0.06	0.05	0.04	0.03	0.03
			II, III	mineral fiber board without cover flush to wall		0.15	0.15	0.30	0.65	0.85	1.00	1.00	0.80
Locker Zone		3.9	I	solid wooden door	0.05	0.14	0.14	0.10	0.06	0.08	0.10	0.10	0.10
		12.0	II, III										
Ventilation Zone		1.3	I	painted plaster surface	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
		9.6	II, III										
Entrance Door		3	I, II, III	solid wooden door	0.05	0.14	0.14	0.1	0.06	0.08	0.1	0.1	0.1
Windows		17.9	I, II, III	double glazing, 2-3mm glass, 10mm gap	0.05	0.1	0.1	0.07	0.05	0.03	0.02	0.02	0.02

2.5.3 TVFA Halle

Represented below, Table 2.6 outlines the corresponding distances between the sound sources and receivers and Figure 2.22 illustrates the individual sound sources and receiver positions used for both on-site measurements and acoustic simulations in the TVFA Halle.

Table 2.6: Distance per receiver position to corresponding sound source

TVFA Halle

Receiver	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3	4.1	4.2	4.3
Distance to S1	12.3m	7.3m	0.4m	13.4m	9.0m	5.4m	16.0m	11.0m	10.4m	19.4m	16.2m	15.9m
Distance to S2	23.6m	21.1m	19.1m	19.7m	16.6m	14.0m	16.6m	10.7m	9.0m	14.6m	6.7m	3.7m

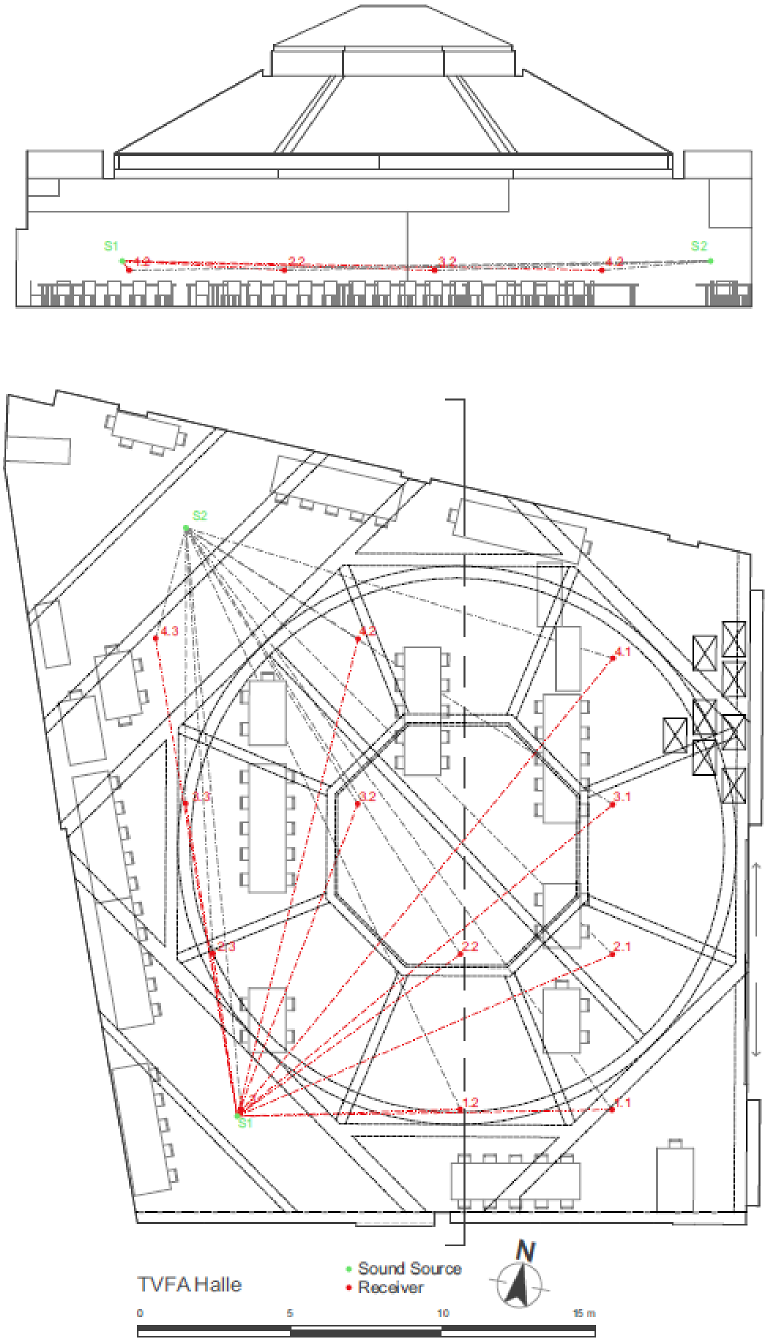


Figure 2.22: TVFA Halle: (●) Receiver positions during on-site measurements (●) Speaker positions during on-site measurements

TVFA Halle Simulation Iteration I and Iteration II

As with the other spaces, the exact definition of the room surface materials in the TVFA Halle including their sound absorption coefficients are unknown. Therefore, assumptions were made to approximate the actual materials and their corresponding sound absorption coefficients based on materials in the existing Odeon materials library. Metallic-like and highly reflective surfaces such as the ventilation ducts, overhead crane and sliding garage door were assigned the properties of a highly reflective painted plaster material from the Odeon materials library. The surface material used for unoccupied wooden audience seating areas was added to the existing Odeon materials library as described above. The specified surface materials used in each simulated TVFA Halle Odeon iteration were then created and defined in the Pachyderm simulation iterations so that the simulation results of both programs could be compared.

Table 2.7 lists the surface materials and their corresponding sound absorption coefficients in octave-band frequencies used for each surface in the TVFA Halle per simulated model iteration. Moreover, the surface areas of the individual building components and the adjustments per calibrating iteration, Iteration I, Iteration II, as well as the final calibrated model, Iteration III with a simulated audience, are also presented in the table.

Table 2.7: Surface materials and absorption coefficients by frequency used to calibrate the simulated TVFA Halle model in Iteration I and Iteration II and the final calibrated model with an audience in Iteration III, adapted from source: (Odeon A/S, 2021a)

TVFA Halle

Surface		Area [m²]	Iteration	Material Description	Scatter	sound absorption coefficients by frequency [α]							
						63 [HZ]	125 [HZ]	250 [HZ]	500 [HZ]	1000 [HZ]	2000 [Hz]	4000 [Hz]	8000 [Hz]
Floor		484.2	I	smooth concrete, painted or glazed	0.05	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
			II, III	rough concrete		0.02	0.02	0.03	0.03	0.03	0.04	0.07	0.07
Audience Zone	unoccupied	66.8	I, II	wooden chairs, unoccupied	0.30	0.05	0.05	0.05	0.05	0.10	0.10	0.15	0.15
	occupied		III	audience on wooden chairs, 1 per sq.m		0.16	0.16	0.24	0.56	0.69	0.81	0.78	0.78
Walls		396.2	I	painted plaster surface	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
			II, III	plaster, gypsum or smooth finish on lath		0.14	0.14	0.10	0.06	0.04	0.04	0.03	0.03
Walls (retrospectively closed openings)		55.2	I, II, III	concrete block, painted	0.05	0.10	0.10	0.05	0.06	0.07	0.09	0.08	0.08
Ceiling		442.6	I	painted plaster surface	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
			II, III	plaster, gypsum or smooth finish on lath		0.14	0.14	0.10	0.06	0.04	0.04	0.03	0.03
Sliding Garage Door		34.6	I, II, III	painted plaster surface	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Side Doors		18.0	I, II, III	painted plaster surface	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Windows		66.8	I, II, III	single pane of glass 3mm	0.05	0.08	0.08	0.04	0.03	0.03	0.02	0.02	0.02
Skylight Windows		51.7	I, II, III	single pane of glass 3mm	0.05	0.08	0.08	0.04	0.03	0.03	0.02	0.02	0.02
Skylight Panel Element		3.9	I, II, III	painted plaster surface									
Beams		426.1	I, II, III	smooth concrete, painted or glazed	0.05	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Overhead Crane		129.1	I, II, III	painted plaster surface									
Canopy (shading element)		47.82	I, II, III	curtains, cotton cloth (0,33 kg/m²)	0.6	0.07	0.07	0.31	0.49	0.81	0.66	0.54	0.54
Stored Material		16.7	I, II, III	smooth concrete, painted or glazed	0.3	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Ventilation System		248.1	I, II, III	painted plaster surface	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

2.5.4 Simulated Audience Acoustic Simulations (Iteration III)

Final acoustic performance simulations, Iteration III, based on the simulated Iteration II models of the three selected repurposed learning environments, Aufbaulabor, Project Room Panigeltrakt EG, and TVFA Halle were conducted. These final simulations performed in both Odeon and Pachyderm simulation environments include occupied audience areas within the spaces. Moreover, these areas were defined using a standard audience material (audience on wooden chairs, one person per m²) which is found in the Odeon materials library. This material replaced the unoccupied wooden audience seating material used in the previous iterations.

Table 2.8 highlights this material change to an occupied audience which was used in all Iteration III simulations. The other surface materials used in these simulations match those used in the corresponding Iteration II simulations and the individual surface materials can be found in the previous subsections.

Table 2.8: Audience surface material used in Iteration III simulations

Surface		Area [m²]	Iteration	Material Description	Scatter	sound absorption coefficients by frequency [α]							
						63 [HZ]	125 [HZ]	250 [HZ]	500 [HZ]	1000 [HZ]	2000 [Hz]	4000 [Hz]	8000 [Hz]
Audience Zone	unoccupied	var. per room	I, II	wooden chairs, unoccupied	0.30	0.05	0.05	0.05	0.05	0.10	0.10	0.15	0.15
	occupied		III	audience on wooden chairs, 1 per sq.m		0.16	0.16	0.24	0.56	0.69	0.81	0.78	0.78

Additionally, calculations were performed in Microsoft Excel to estimate the reverberation times of the evaluated multifunctional spaces as if there had been an audience present. In other words, approximate the RT values if the spaces were in an occupied state as the on-site measurements were conducted. Thereby, the reverberation equation developed by Sabine and represented in Equation (1.1) was transformed to solve for the total equivalent absorption area (A). Furthermore, the volume of each room was divided by the corresponding on-site measured reverberation times per frequency. Next the maximum number of occupants per room was multiplied by the frequency dependent total absorption area of one seated person defined in (Fasold & Veres, 2003). Table 2.9 shows the frequency related sound absorption area used for this calculation.

Table 2.9: Total absorption area of 1 seated person (Fasold & Veres, 2003)

total absorption area of 1 seated person

frequency	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
absorption area	0.18 m²	0.40 m²	0.46 m²	0.46 m²	0.51 m²	0.46 m²

These calculated audience absorption areas were then added to the total equivalent absorption areas calculated in step one. Finally, using the Sabine equation, the reverberation times were determined to estimate the RT (with an audience) based on the on-site measured values at an unoccupied state.

In addition, the reverberation times based on the Sabine equation, Equation (1.1), were calculated for each simulation iteration, Iteration I, Iteration II, and Iteration III, and compared to the simulated and measured reverberation time values. Moreover, the areas of the individual building components per room and the used surface materials' frequency dependent sound absorption coefficients, that are listed in the surface materials tables in the previous section, were used for these calculations.

3 RESULTS

3.1 Overview

The results presented below in this section infer the acoustic performance of the individual spaces evaluated in this thesis.

As follows, the findings, which are presented below in graphs and tables, include, evaluated, calculated, and simulated reverberation times per octave band per room, sound distribution respective to the distance between sound sources and receivers, surface area and their sound absorption coefficients at each frequency.

Thereby, the derived results in this section have been subdivided into the following sections: On-Site Measurement Results, Simulation Results of Calibrated Models, and Simulation Results of Audience Models.

Following the results, section 4 Comparison and Discussion of this thesis, elaborates upon the findings to provide a conclusive report. In addition, a comparison of the results between Odeon and Pachyderm Acoustical Simulation can be found. Furthermore, the adaptability of the simulated models, acoustic parameters, and the usability of the used simulation tools are evaluated and discussed.

3.2 On-Site Measurement Results

The on-site acoustic measurements were performed in three selected repurposed learning spaces, Aufbaulabor, Project Room Panigeltrakt EG, and TVFA Halle (institute building, Erzherzog-Johann-Platz) at the TU Wien.

3.2.1 Aufbaulabor

Reverberation Time

The reverberation times (RT) per frequency were obtained from on-site acoustic measurements performed in an unoccupied state in the Aufbaulabor. Thereby, the reverberation times were recorded at the following receiver positions (1.1; 2.2; 4.1; and 4.3) using sound source S1 and receiver positions (1.1; 2.2, and 4.1) using sound source S2. The measured T_{30} values per frequency from each sound source were averaged together to obtain mean RT values which are presented in Table 3.1 and Figure 3.1. The frequency-based RT values are relatively close to each other, ranging from 0.85 s to 1.09 s. Whereby, the longest reverberation time, 1.09 s, occurred at 125 Hz and the shortest reverberation time, 0.85 s, occurred at 500 Hz.

Table 3.1 on-site measured average RT values per frequency in unoccupied Aufbaulabor

Aufbaulabor	RT by frequency [s]					
	125 [Hz]	250 [Hz]	500 [Hz]	1000 [Hz]	2000 [Hz]	4000 [Hz]
On-Site Measured	1.09 s	0.86 s	0.85 s	0.88 s	0.98 s	0.94 s

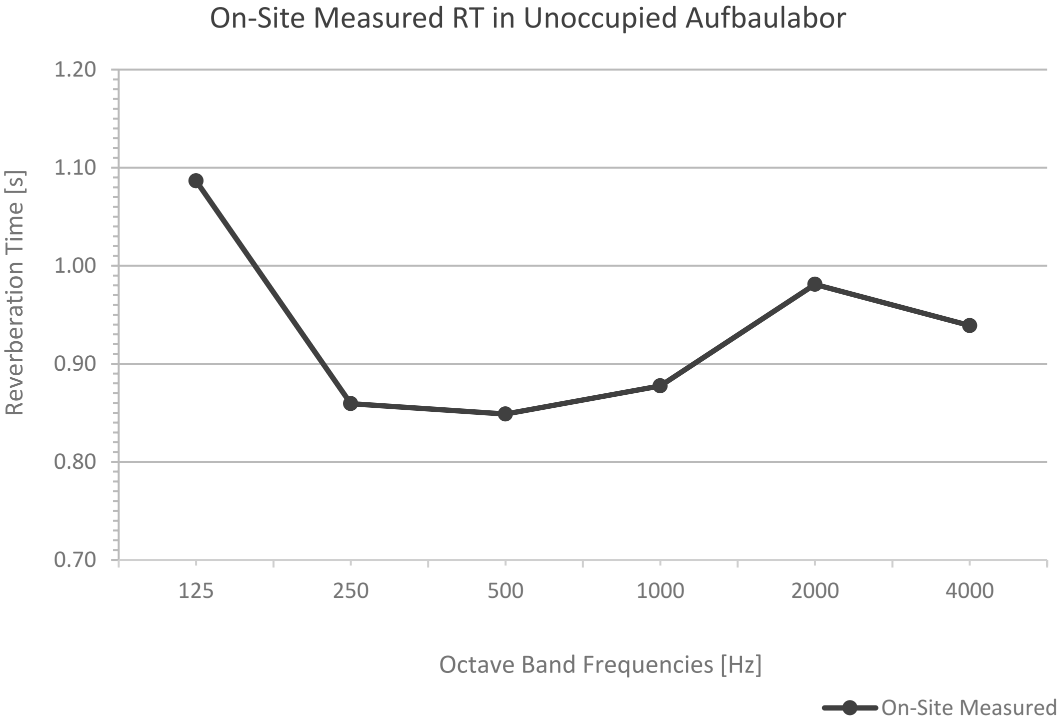


Figure 3.1:On-site measured RT in unoccupied Aufbaulabor

Sound Distribution

To effectively determine how the sound pressure level decreases with respect to the distance of the receiver to the sound source, a reference receiver position, naturally the position nearest to the sound source (position 1.2) and, therefore, the highest SPL, was defined. Moreover, the relative distances as well as the relative sound pressure level differences between the individual receiver positions and the reference receiver were calculated. Figure 3.2, arranged according to the increase of distance, expresses the relative reduction of the A-weighted SPL(A) as a function of distance. Moreover, since on-site measurements were not performed using sound source S2, the sound distribution of the receivers corresponding to S2 will be exempted from the results of the on-site measurements of the Aufbaulabor. Nevertheless, once the simulated model has been calibrated sound source S2 will be used to compare SPL results between the two acoustic simulation models.

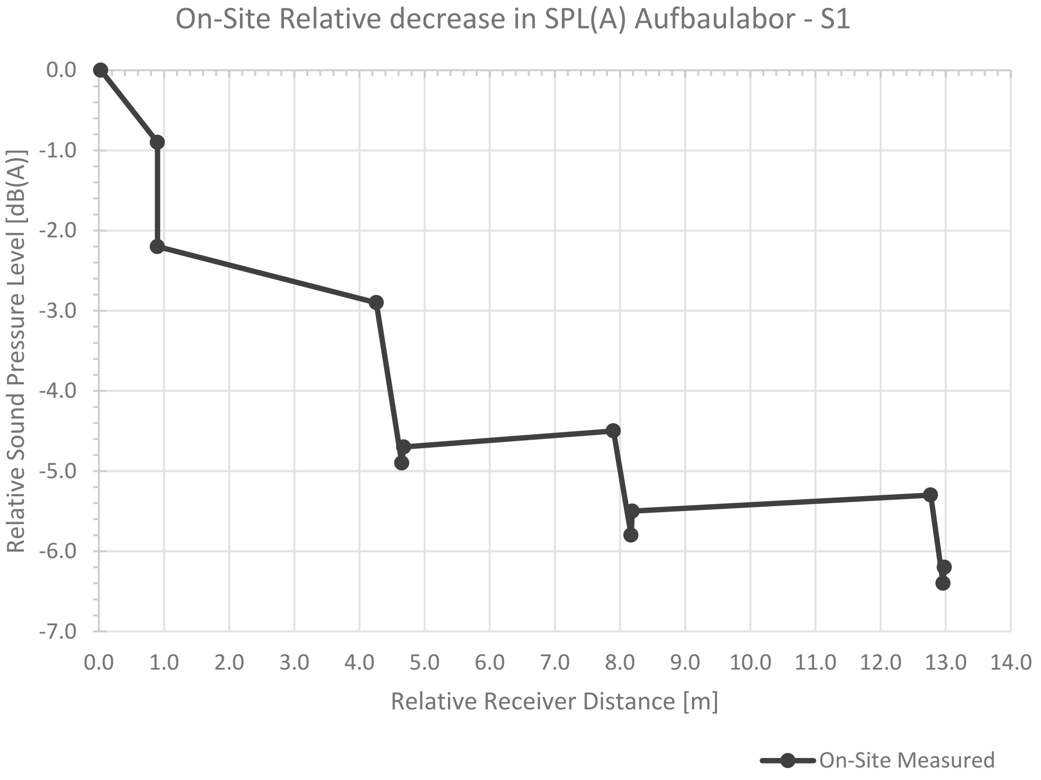


Figure 3.2: Relative decrease in SPL(A) of on-site measured Aufbaulabor SPL(A)s for S1

3.2.2 Project Room Panigltrakt EG

Reverberation Time

The reverberation times per frequency were obtained from on-site acoustic measurements performed in an unoccupied state in the Project Room Panigltrakt EG. Thereby, the reverberation times were recorded at the following receiver positions (1.1; 1.2; 1.3; 2.1 and 2.3) using sound source S1. The measured T_{30} values per frequency were averaged together to obtain mean RT values that are presented in Table 3.2 and Figure 3.3. The frequency-based RT values are much higher than those from the Aufbaulabor. However, the values remain close to one another, ranging from 1.42 s to 1.87 s. Whereby, the longest reverberation time, 1.87 s, which occurred at 1000 Hz and the shortest reverberation time, 1.42 s, occurred at 4000 Hz.

Table 3.2: on-site measured average RT values per frequency in unoccupied Panigltrakt

Project Room Panigltrakt	**RT by frequency band [s]**					
	125 [Hz]	**250 [Hz]**	**500 [Hz]**	**1000 [Hz]**	**2000 [Hz]**	**4000 [Hz]**
On-Site Measured	1.75 s	1.61 s	1.73 s	1.87 s	1.79 s	1.42 s

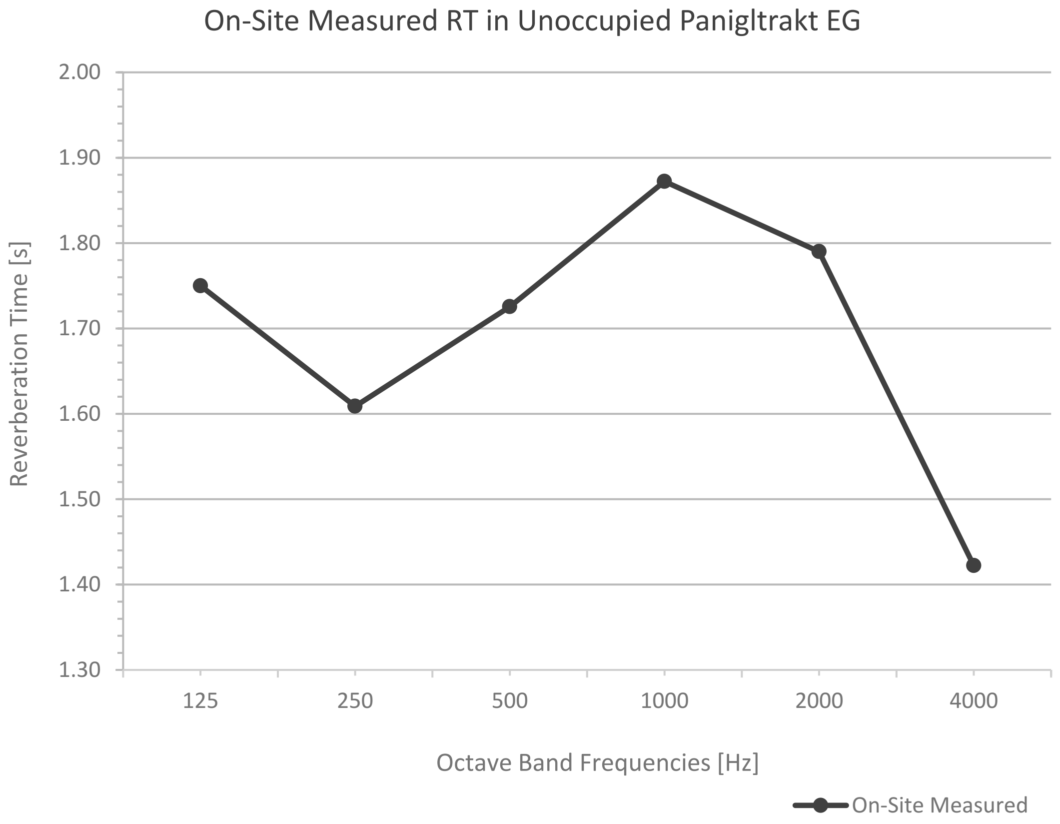


Figure 3.3:On-site measured RT in unoccupied Project Room Panigltrakt EG

Sound Distribution

The relative distances as well as the relative A-weighted sound pressure level differences between the individual receiver positions and the reference receiver were calculated and are presented in Figure 3.4, arranged according to the increase of distance. These were determined at five receiver positions using sound source S1 in relation to their distance to the sound source. Due to the small size of the room, only one sound source, S1, was used to perform acoustic measurements.

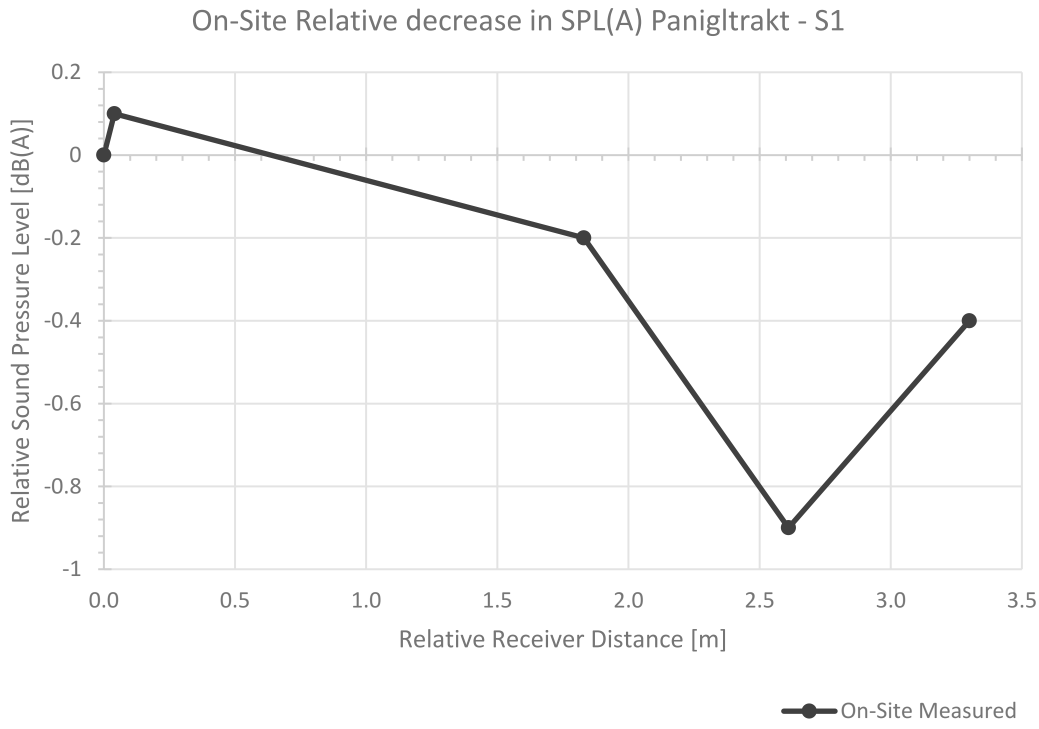


Figure 3.4: Relative decrease in SPL(A) of on-site measured Panigltrakt SPL(A)s for S1

3.2.3 TVFA Halle

Reverberation Time

The measurement results of the RT values per frequency were obtain from on-site acoustic measurements performed in an unoccupied state in the TVFA Halle. Thereby, the reverberation times were recorded at the following receiver positions (1.2; 2.1; 3.1; 3.2; 4.1; and 4.3) using sound source S1 and receiver positions (1.2; 2.1; 2.3; 3.2; and 4.1) using sound source S2. The measured T_{30} values per frequency were averaged together to obtain mean RT values which are presented in Table 3.3.and Figure 3.5 The frequency-based RT values are widely ranged, ranging from 1.69 s to 4.89 s. Whereby, the longest reverberation time, 4.89 s, occurred at 125 Hz and the shortest reverberation time, 1.69 s, occurred at 4000 Hz.

Table 3.3 on-site measured average RT values per frequency in unoccupied TVFA Halle

TVFA Halle	RT by frequency band [s]					
	125 [Hz]	250 [Hz]	500 [Hz]	1000 [Hz]	2000 [Hz]	4000 [Hz]
On-Site Measured	4.89 s	3.42 s	3.03 s	2.87 s	2.47 s	1.69 s

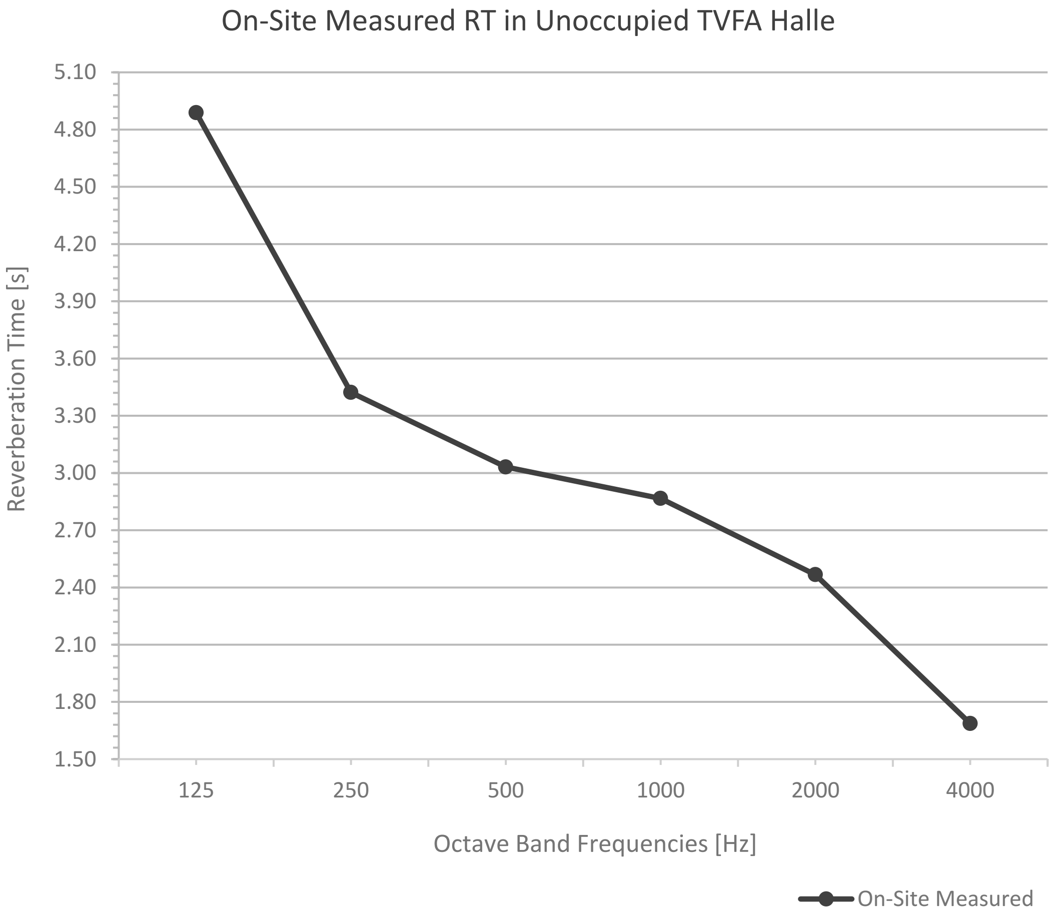


Figure 3.5:On-site measured RT in unoccupied TVFA Halle

Sound Distribution

The relative distances as well as the relative A-weighted sound pressure level differences between the individual receiver positions and the reference receiver were calculated and are presented in Figure 3.6, which corresponds to sound source S1, and Figure 3.7, which corresponds to sound source S2. These graphs are arranged according to the increase of distance. Moreover, since receiver position 1.3 does not conform to the minimum distance to the sound source, according to DIN EN ISO 3382-2, it has been excluded in the calculations relating to sound source S1. Therefore, eleven receiver positions using sound source S1 and twelve receiver positions using sound source S2 were assessed.

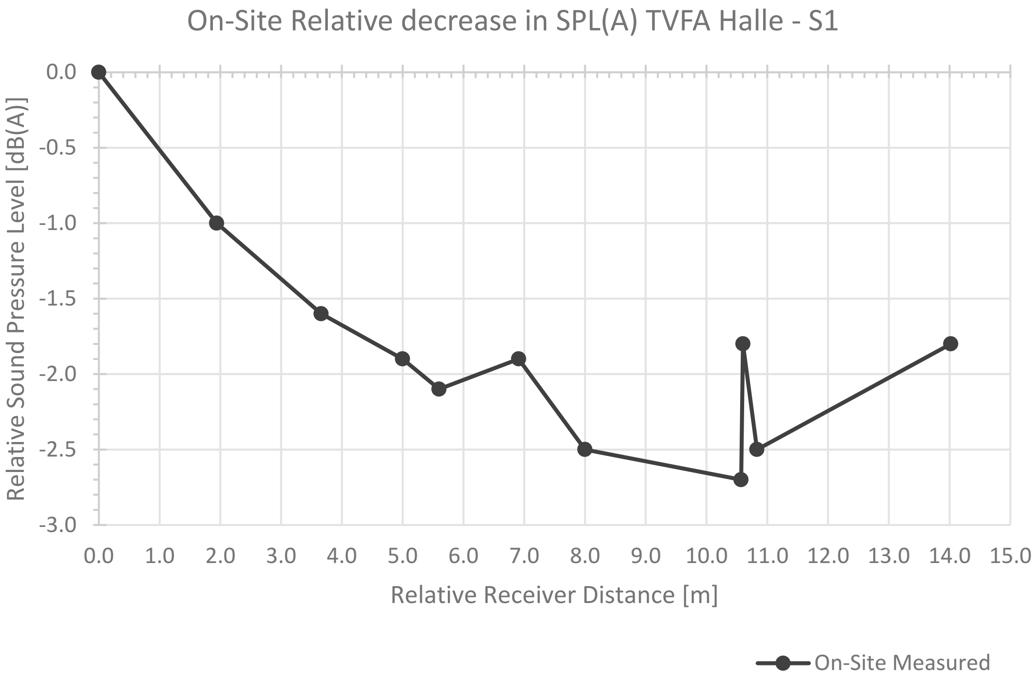


Figure 3.6: Relative decrease in SPL(A) of on-site measured TVFA Halle SPL(A)s for S1

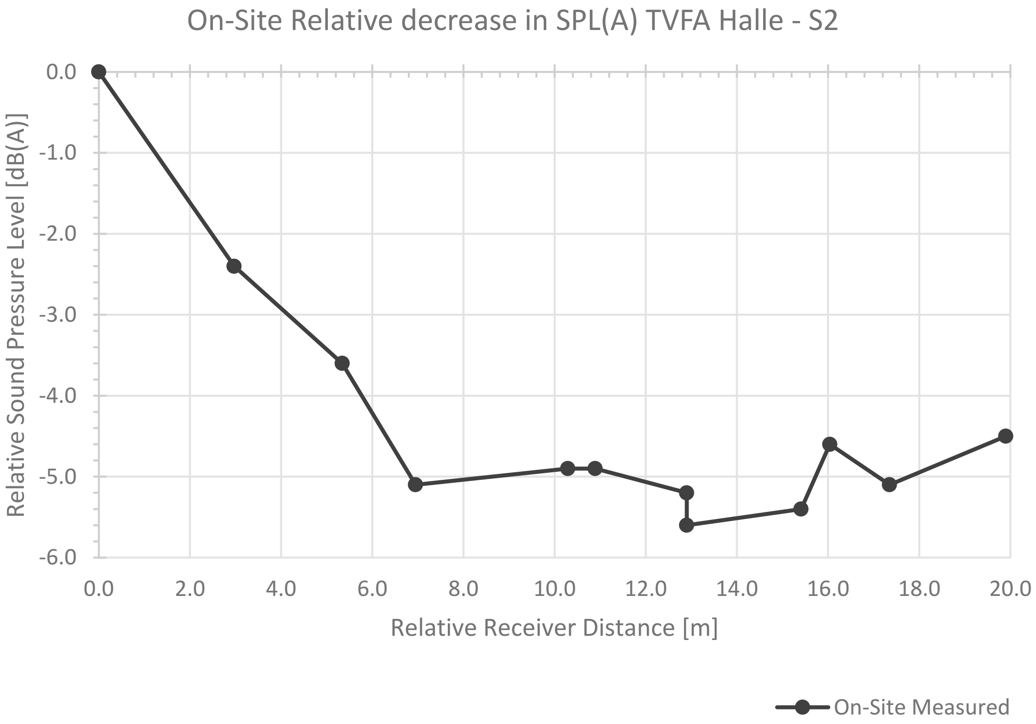


Figure 3.7: Relative decrease in SPL(A) of on-site measured TVFA Halle SPL(A)s for S2

3.3 Simulation Results of Calibrated Models

3.3.1 Aufbaulabor

Reverberation Time

The simulated frequency dependent RT values were obtained from the acoustic simulated models of the Aufbaulabor in an unoccupied state. Thereby, the reverberation times were recorded at the same receiver positions (1.1; 2.2; 4.1; and 4.3) like the on-site measurements using sound source S1 and at receiver positions (1.1; 2.2; and 4.1) using sound source S2. The simulated T_{30} values per frequency were averaged together from both configurations to obtain averaged RT values per iteration which are presented in Table 3.4 and Figure 3.8. Furthermore, the tables and graphs contain the data from the previous section 3.2 On-Site Measurement Results to easily compare the simulated results to the on-site measurements.

Table 3.4 measured and simulated average RT values per frequency in unoccupied Aufbaulabor

Aufbaulabor	RT by frequency band [s]					
	125 [Hz]	250 [Hz]	500 [Hz]	1000 [Hz]	2000 [Hz]	4000 [Hz]
On-Site Measured	1.09 s	0.86 s	0.85 s	0.88 s	0.98 s	0.94 s
Odeon Simulated (Iteration I)	1.24 s	1.22 s	1.14 s	1.03 s	1.02 s	0.90 s
Pachyderm Simulated (Iteration I)	2.17 s	2.35 s	2.45 s	2.49 s	2.56 s	2.47 s
Odeon Simulated (Iteration II)	1.02 s	1.01 s	1.01 s	0.93 s	0.90 s	0.67 s
Pachyderm Simulated (Iteration II)	1.64 s	1.71 s	1.69 s	1.82 s	1.78 s	1.74 s

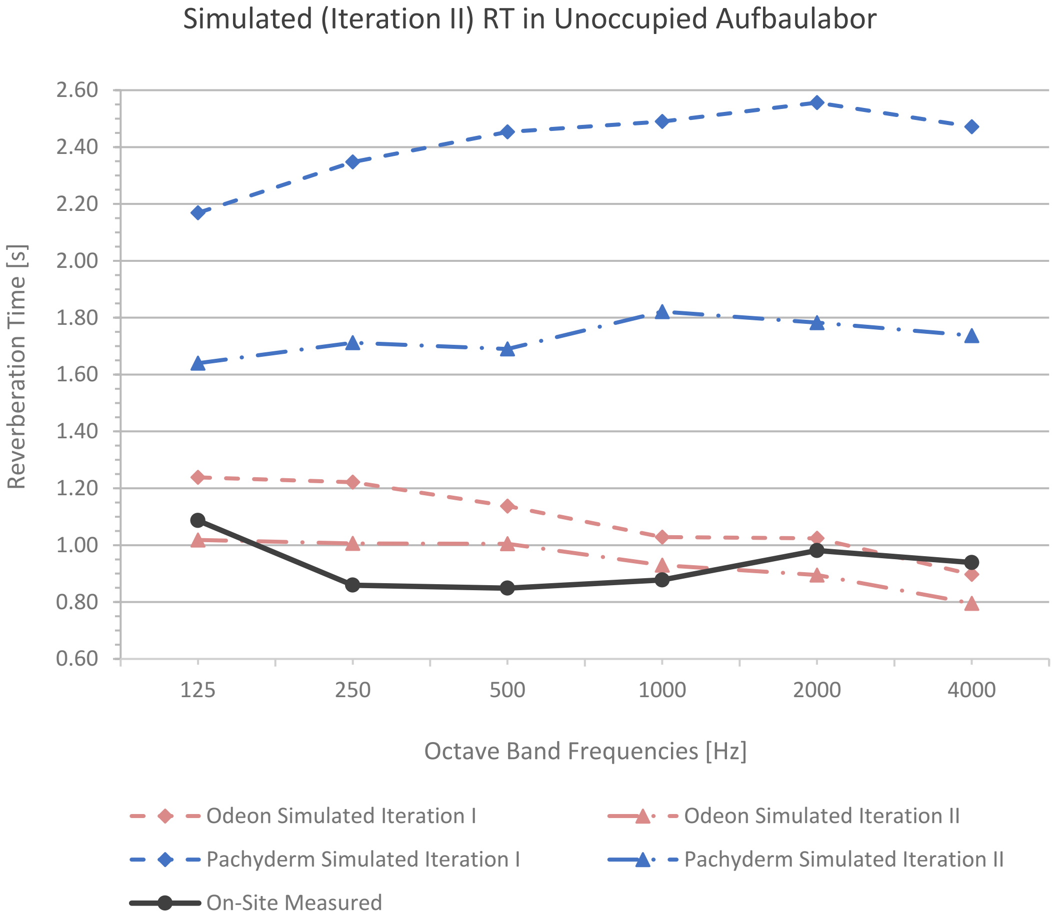


Figure 3.8:Simulated RT in unoccupied Aufbaulabor

Sound Distribution

The graphs below show how the sound pressure level decreases with respect to the distance of the receiver to the sound source. To show this comparison, reference receiver position 1.2, which is the nearest to sound source S1 and reference receiver position 3.3, which is nearest to sound source S2, were used to calculate the relative distances as well as the relative sound pressure level differences between the individual receiver positions and the reference receivers. Figure 3.9, arranged according to the increase of distance from the receivers corresponding to sound source S1, and Figure 3.10, arranged according to the increase of distance from the receivers corresponding to sound source S2, express the relative reduction of the A-weighted SPL(A) as a function of distance using the results from Iteration II.

Additional graphs comparing the results of all iterations can be found in Appendix B.

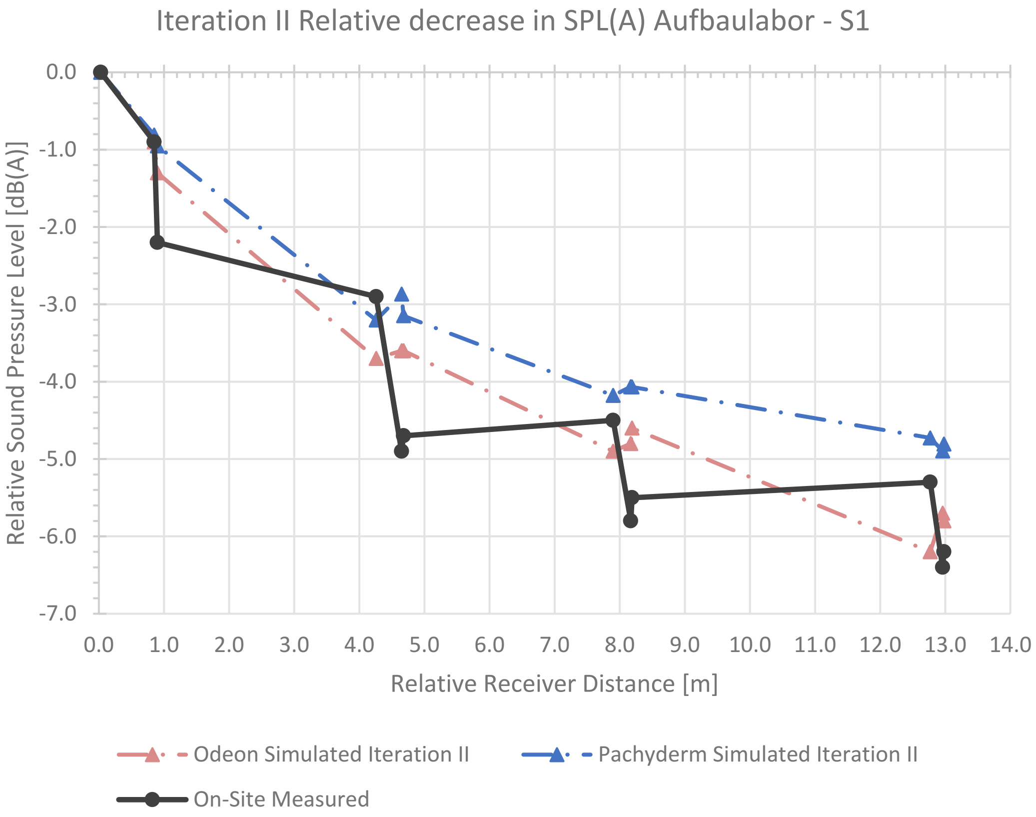


Figure 3.9: Relative decrease in SPL(A) of Iteration II Aufbaulabor SPL(A)s for S1

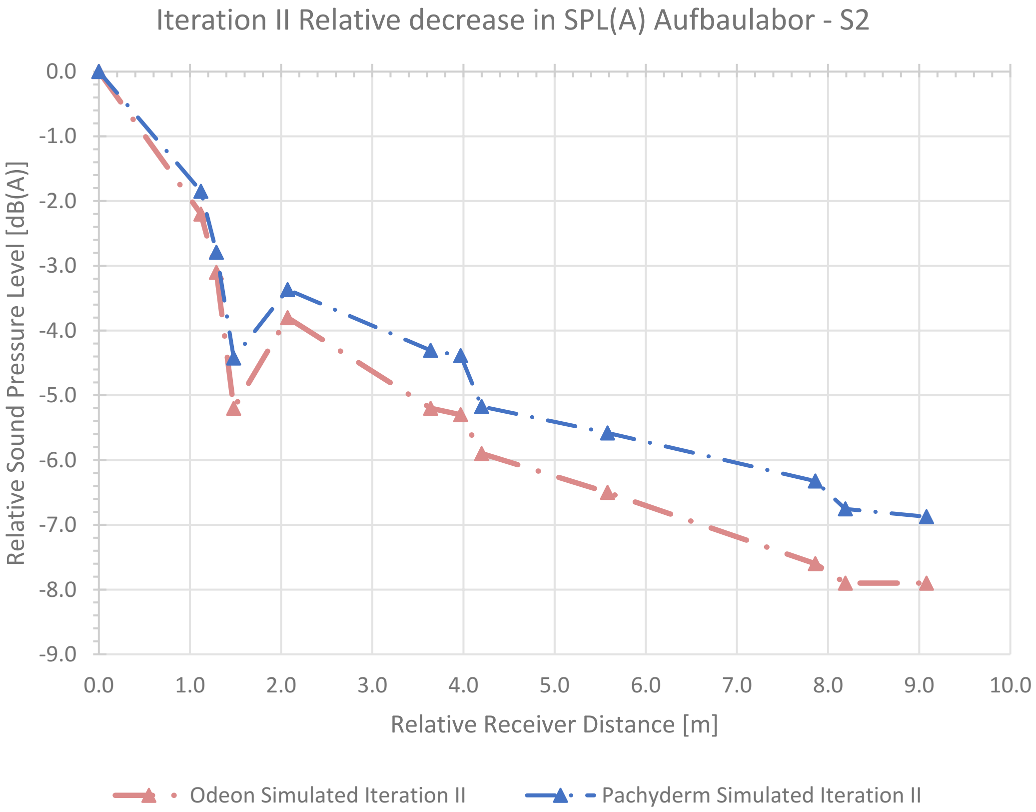


Figure 3.10: Relative decrease in SPL(A) of Iteration II Aufbaulabor SPL(A)s for S2

3.3.2 Project Room Paniglträkt EG

Reverberation Time

The simulated frequency dependent RT values were obtained from the acoustic simulated models of the Panigltrakt in an unoccupied state. Thereby, the reverberation times were recorded at the same receiver positions (1.1; 1.2; 1.3; 2.1; and 2.3) like the on-site measurements using sound source S1. The simulated T_{30} values per frequency were averaged together to obtain averaged RT values per iteration which are presented in Table 3.5 and Figure 3.11. Furthermore, the tables and graphs contain the data from the on-site measurements to easily compare the simulated results to the on-site measurements.

Despite the great differences between the RT results of Iteration I and the on-site measurements, Iteration II for both Odeon and Pachyderm acoustic simulations show significantly improved results that near the on-site measured reverberation times.

Table 3.5 measured and simulated average RT values per frequency in unoccupied Project Room Panigltrakt EG

Project Room Panigltrakt	RT by frequency band [s]					
	125 [Hz]	250 [Hz]	500 [Hz]	1000 [Hz]	2000 [Hz]	4000 [Hz]
On-Site Measured	1.75 s	1.61 s	1.73 s	1.87 s	1.79 s	1.42 s
Odeon Simulated (Iteration I)	5.97 s	6.34 s	6.18 s	5.05 s	4.14 s	2.158
Pachyderm Simulated (Iteration I)	5.05 s	5.58 s	5.85 s	5.30 s	5.24 s	4.34 s
Odeon Simulated (Iteration II)	1.63 s	2.02 s	2.41 s	2.46 s	2.10 s	1.41 s
Pachyderm Simulated (Iteration II)	1.49 s	1.88 s	2.22 s	2.29 s	2.08 s	1.92 s

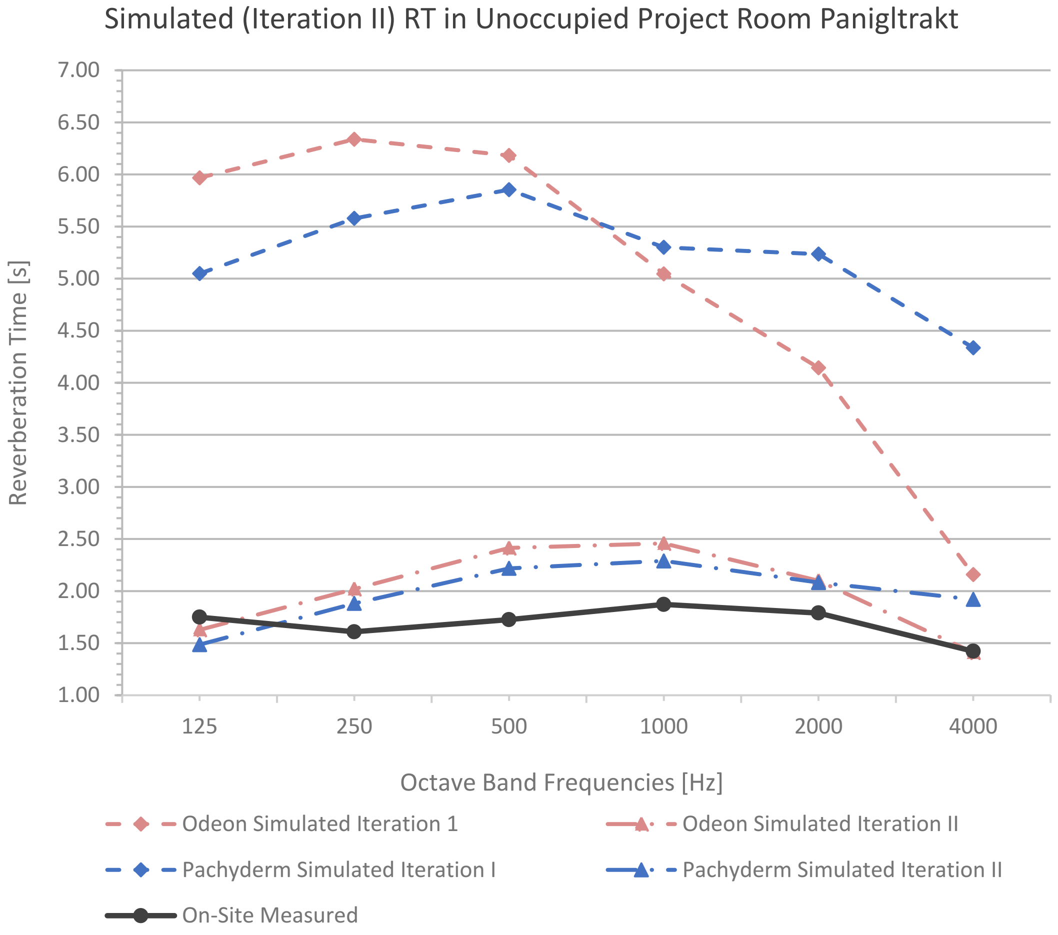


Figure 3.11:Simulated RT in unoccupied Project Room Panigltrakt EG

Sound Distribution

The graph below shows how the sound pressure level increases about 1 dB(A) before dropping again even with respect to the increase in distance of the receivers to the sound source. This comparison reference receiver position 2.3, which is the nearest to sound source S1, was used to calculate the relative distances as well as the relative sound pressure level differences between the individual receiver positions and the reference receiver. Figure 3.12 which is arranged according to the increase of distance from the receivers corresponding to sound source S1, expresses the relative decay of the A-weighted SPL(A) to the distance using the results from Iteration II.

Additional graphs comparing the results of all iterations can be found in Appendix B.

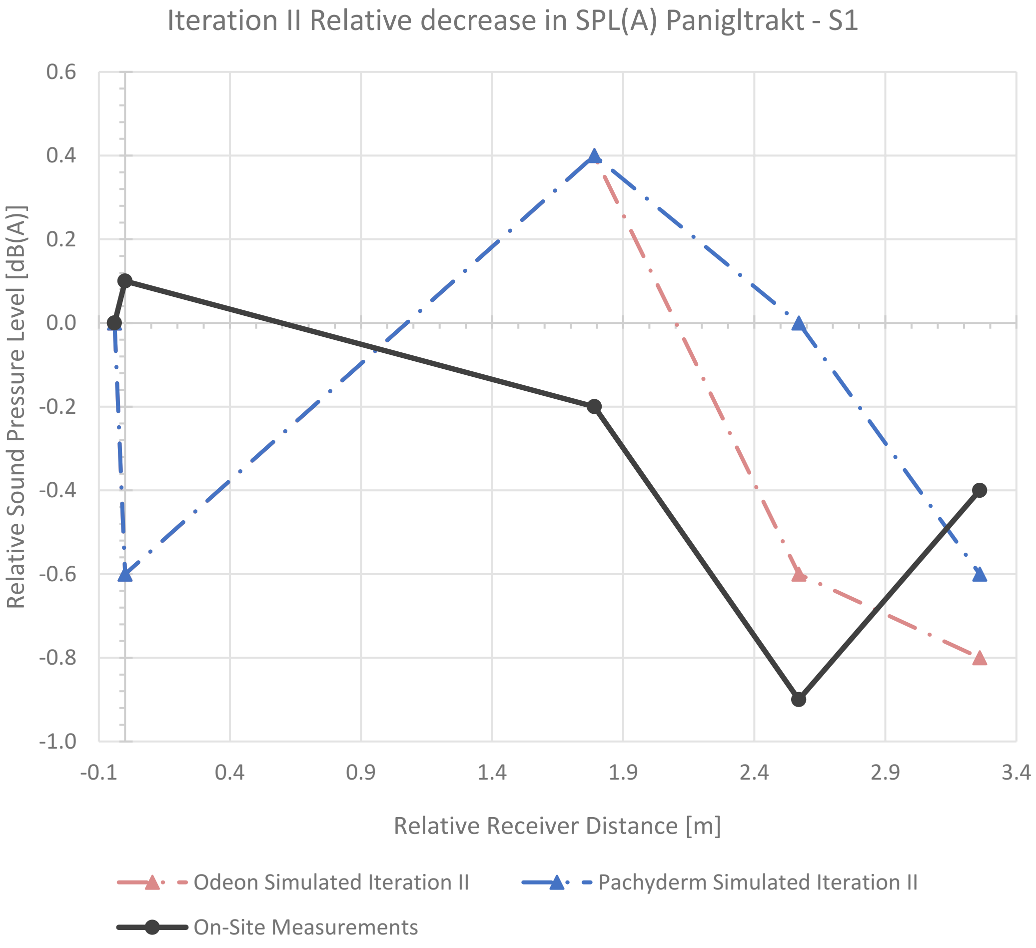


Figure 3.12: Relative decrease in SPL(A) of Iteration II Panigltrakt SPL(A)s for S1

3.3.3 TVFA Halle

Reverberation Time

The simulated frequency dependent RT values were obtained from the acoustic simulated models of the TVFA Halle in an unoccupied state. Thereby, the reverberation times were recorded at the same receiver positions (1.2; 2.1; 3.1; 3.2; 4.1; and 4.3) as in the on-site measurements using sound source S1 and at receiver positions (1.2; 2.1; 2.3; 3.2; and 4.1) using sound source S2. The simulated T_{30} values per frequency were averaged together from both configurations to obtain averaged RT values per iteration which are presented in Table 3.6 and Figure 3.13. Furthermore, the tables and graphs contain the on-site measurements to easily compare the simulated results to the on-site measurements.

Table 3.6: measured and simulated avg. RT values per frequency in unoccupied TVFA Halle

TVFA Halle	**RT by frequency band [s]**					
	125 [Hz]	**250 [Hz]**	**500 [Hz]**	**1000 [Hz]**	**2000 [Hz]**	**4000 [Hz]**
On-Site Measured	4.89 s	3.42 s	3.03 s	2.87 s	2.47 s	1.69 s
Odeon Simulated (Iteration I)	9.81 s	7.56 s	6.16 s	4.32 s	3.67 s	2.168
Pachyderm Simulated (Iteration I)	11.41 s	10.09 s	9.10 s	7.16 s	7.03 s	6.21 s
Odeon Simulated (Iteration II)	3.63 s	3.77 s	4.15 s	3.71 s	3.11 s	1.89 s
Pachyderm Simulated (Iteration II)	4.51 s	4.74 s	5.94 s	6.13 s	5.81 s	5.26 s

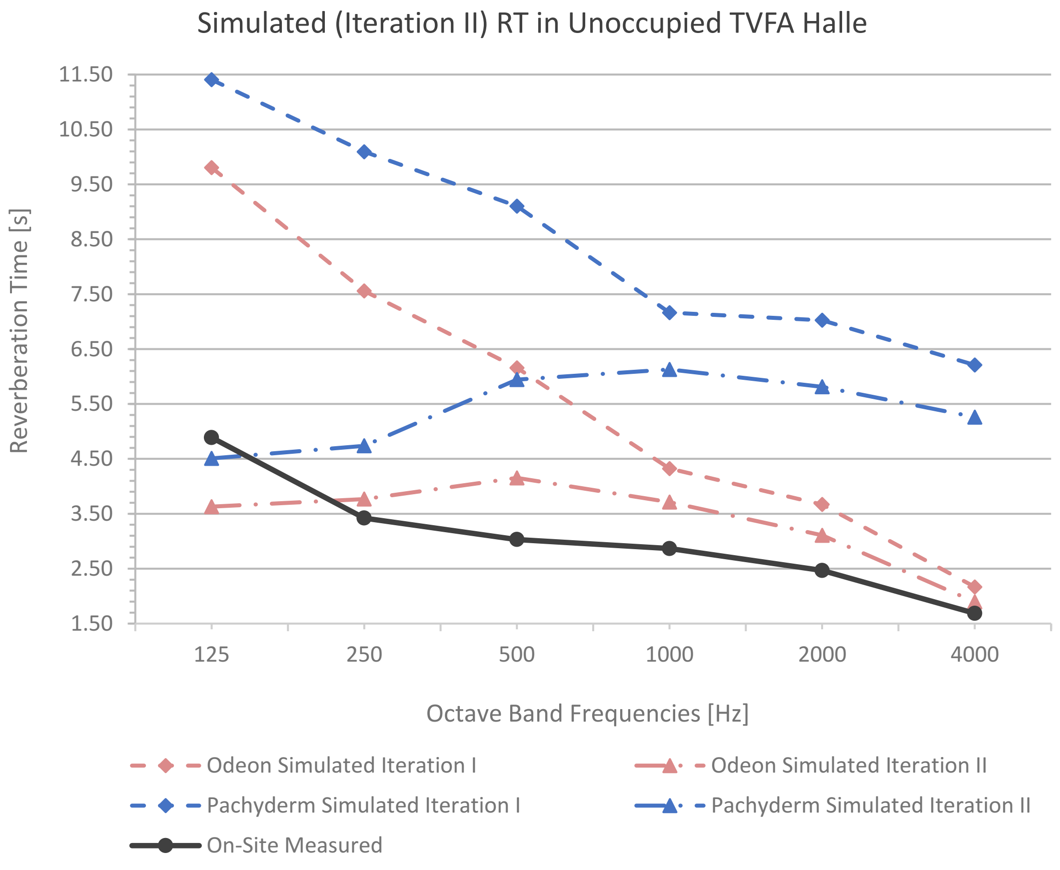


Figure 3.13:Simulated RT in unoccupied TVFA Halle

Sound Distribution

The graphs below show how the sound pressure level decreases with respect to the distance of the receiver to the sound source. To show this comparison, reference receiver position 2.3, which is the nearest to sound source S1 with exception to receiver position 1.3 since it does not conform to the acoustic measurement standards, and reference receiver position 4.3, which is nearest to sound source S2, were used to calculate the relative distances as well as the relative sound pressure level differences between the individual receiver positions and the reference receivers. Figure 3.14, arranged according to the increase of distance from the receivers corresponding to sound source S1, and Figure 3.15, arranged according to the increase of distance from the receivers corresponding to sound source S2, express the relative reduction of the A-weighted SPL(A) as a function of distance using the results from Iteration II.

Additional graphs comparing the results of all iterations can be found in Appendix B.

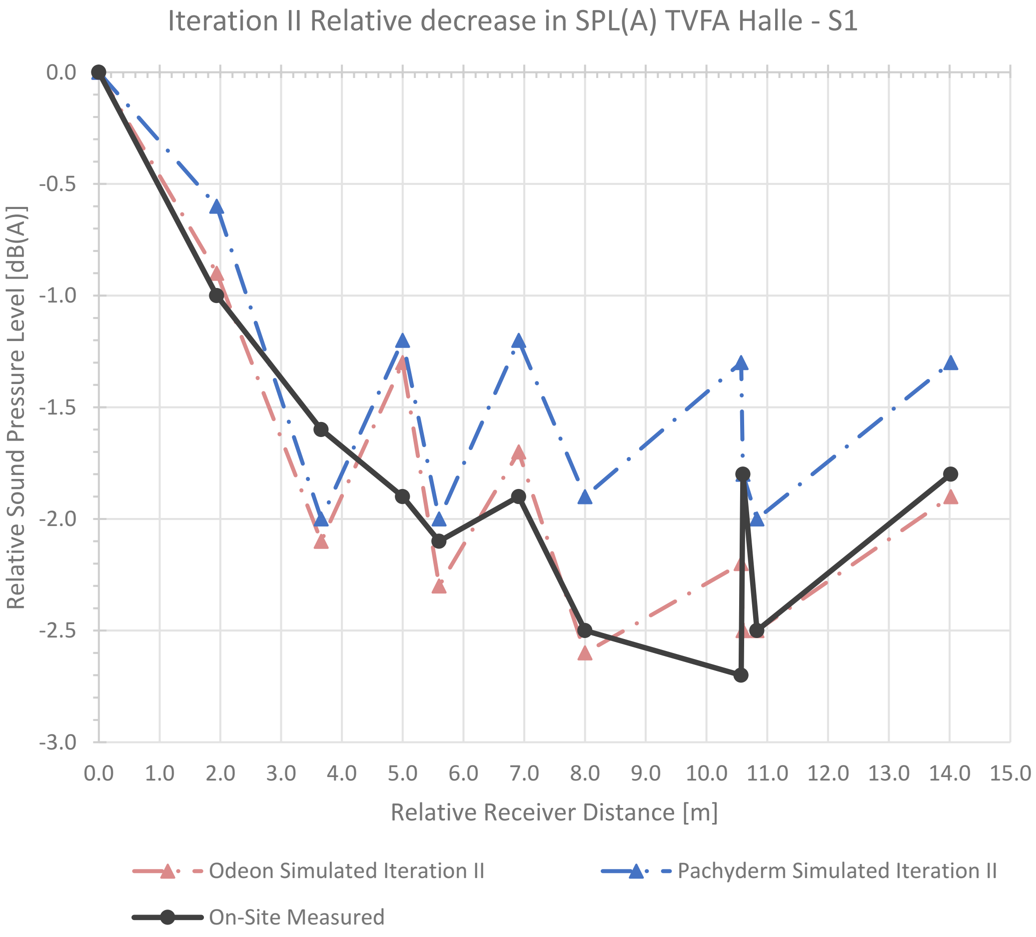


Figure 3.14: Relative decrease in SPL(A) of Iteration II TVFA Halle SPL(A)s for S1

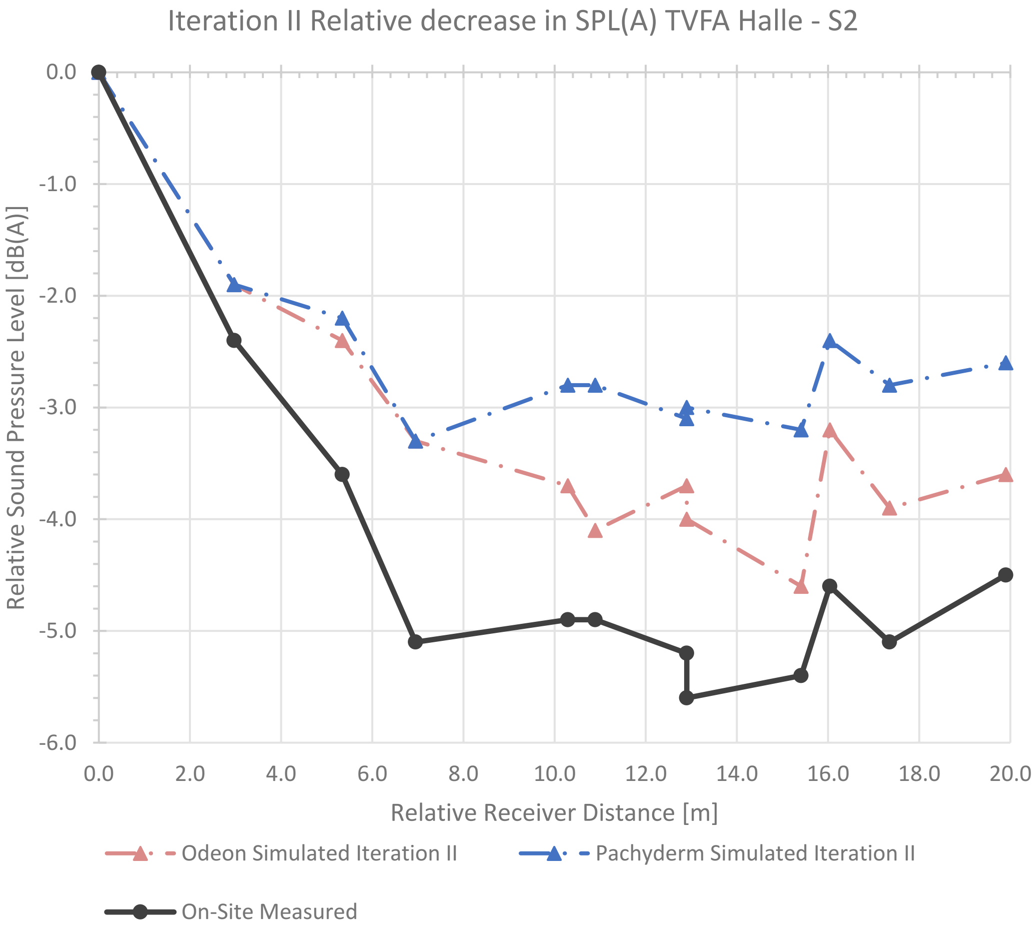


Figure 3.15: Relative decrease in SPL(A) of Iteration II TVFA Halle SPL(A)s for S2

3.4 Simulation Results of Audience Models

The reverberation time graphs presented below only contain the following reverberation time results: On-Site Measured, On-Site Estimated RT (Audience), Odeon Simulated (Iteration I, Iteration II, and Iteration III, also defined as Audience), Pachyderm Simulated (Iteration III, also defined as Audience), and the Sabine Calculation III which is based on the surface materials used in the Iteration III (Audience) simulations.

Additional graphs containing all simulated and calculated reverberation time results can be found in Appendix B.

3.4.1 Aufbaulabor

Reverberation Time

The RT values were obtained from the Iteration III (Audience) acoustic simulated model of the Aufbaulabor in an occupied state. Thereby, the reverberation times were recorded at the same receiver positions used for the on-site measurements and calibration simulations. Table 3.7 and Figure 3.16 compare the above-listed reverberation time results for the Aufbaulabor. Furthermore, tables and graphs containing all simulated and calculated reverberation time results can be found in Appendix B

Table 3.7: Average measured, simulated, and calculated RT for the Aufbaulabor

Aufbaulabor	**RT by frequency band [s]**					
	125 [Hz]	**250 [Hz]**	**500 [Hz]**	**1000 [Hz]**	**2000 [Hz]**	**4000 [Hz]**
On-Site Measured	1.09 s	0.86 s	0.85 s	0.88 s	0.98 s	0.94 s
On-Site Estimated RT (Audience)	0.98 s	0.72 s	0.70 s	0.72 s	0.77s	0.76 s
Odeon Simulated (Iteration I)	1.24 s	1.22 s	1.14 s	1.03 s	1.02 s	0.90 s
Odeon Simulated (Iteration II)	1.02 s	1.01 s	1.01	0.93 s	0.90 s	0.80 s
Odeon Simulated (Audience)	0.99 s	0.97 s	0.94 s	0.93 s	0.91 s	0.79 s
Pachyderm Simulated (Audience)	1.53 s	1.63 s	1.59 s	1.74 s	1.69 s	1.65 s
Sabine Calculation III (Iteration III Simulated Audience)	1.04 s	1.00 s	0.93 s	0.76 s	0.78 s	0.80 s

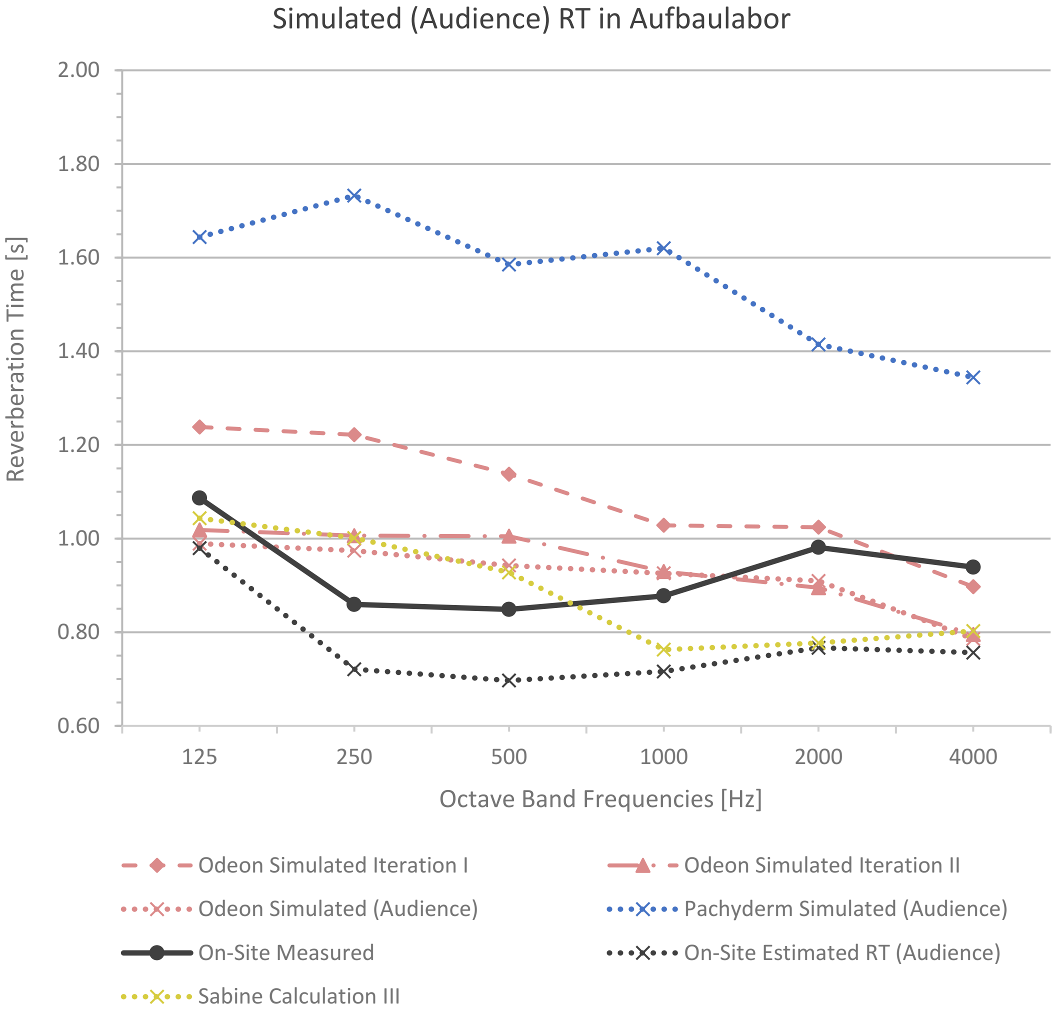


Figure 3.16: Average measured, simulated, and calculated RT for the Aufbaulabor

3.4.2 Project Room Panigltrakt EG

Reverberation Time

The RT values were obtained from the Iteration III (Audience) acoustic simulated model of the Panigltrakt in an occupied state. Thereby, the reverberation times were recorded at the same receiver positions used for the on-site measurements and calibration simulations. Table 3.8 and Figure 3.17 compare the above-listed reverberation time results for the Panigltrakt, whereby the RT results for the Odeon Iteration I simulation are exempted from Figure 3.17 since they are outlying from the audience related reverberation times. Furthermore, tables and graphs containing all simulated and calculated reverberation time results can be found in Appendix B.

Table 3.8: Average measured, simulated, and calculated RT for the Panigltrakt

Project Room Panigltrakt	**RT by frequency band [s]**					
	125 [Hz]	**250 [Hz]**	**500 [Hz]**	**1000 [Hz]**	**2000 [Hz]**	**4000 [Hz]**
On-Site Measured	1.75 s	1.61 s	1.73 s	1.87 s	1.79 s	1.42 s
On-Site Estimated RT (Audience)	1.51 s	1.22 s	1.23 s	1.31 s	1.23 s	1.07 s
Odeon Simulated (Iteration I)	5.97 s	6.34 s	6.18 s	5.05 s	4.14 s	2.16 s
Odeon Simulated (Iteration II)	1.63 s	2.02 s	2.41 s	2.46 s	2.10 s	1.41 s
Odeon Simulated (Audience)	1.54 s	1.80 s	1.64 s	1.59 s	1.37 s	1.09 s
Pachyderm Simulated (Audience)	1.43 s	1.72 s	1.71 s	1.65 s	1.49 s	1.45 s
Sabine Calculation III (Iteration III Simulated Audience)	1.78 s	2.13 s	2.08 s	2.03 s	1.83 s	1.93 s

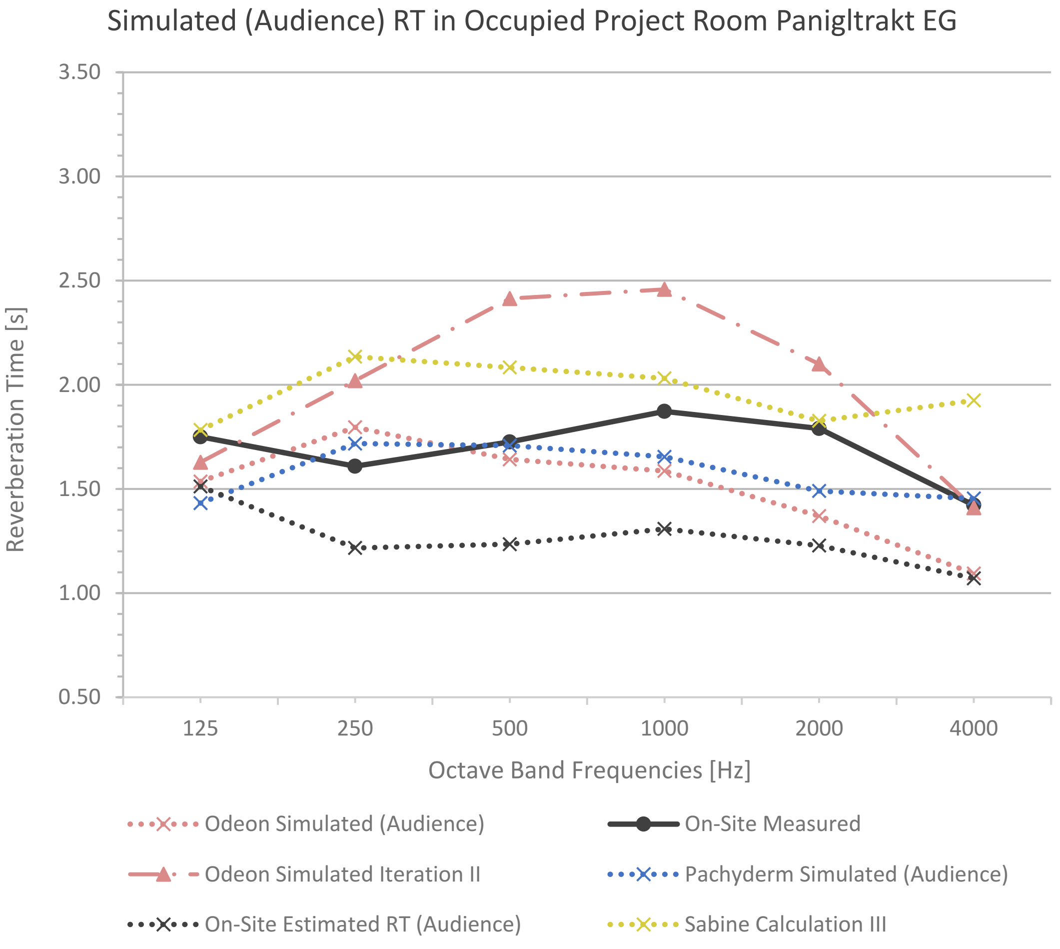


Figure 3.17: Average measured, simulated, and calculated RT for the Panigltrakt

3.4.3 TVFA Halle

Reverberation Time

The RT values were obtained from the Iteration III (Audience) acoustic simulated model of the TVFA Halle in an occupied state. Thereby, the reverberation times were recorded at the same receiver positions used for the on-site measurements and calibration simulations. Table 3.9 and Figure 3.18 compare the above-listed reverberation time results for the TVFA Halle. Furthermore, tables and graphs containing all simulated and calculated reverberation time results can be found in Appendix B.

Table 3.9: Average measured, simulated and calculated RT for the Panigltrakt

TVFA Halle	**RT by frequency band [s]**					
	125 [Hz]	250 [Hz]	500 [Hz]	1000 [Hz]	2000 [Hz]	4000 [Hz]
On-Site Measured	4.89 s	3.42 s	3.03 s	2.87 s	2.47 s	1.69 s
On-Site Estimated RT (Audience)	3.84 s	2.40 s	2.11 s	2.03 s	1.77 s	1.36 s
Odeon Simulated (Iteration I)	9.81 s	7.56 s	6.16 s	4.32 s	3.67 s	2.17 s
Odeon Simulated (Iteration II)	3.63 s	3.77 s	4.15 s	3.71 s	3.11 s	1.89 s
Odeon Simulated (Audience)	3.41 s	3.32 s	3.00 s	2.69 s	2.31 s	1.63 s
Pachyderm Simulated (Audience)	3.89 s	4.51 s	5.16 s	5.47 s	5.18 s	4.72 s
Sabine Calculation III (Iteration III Simulated Audience)	5.69 s	6.43 s	6.61 s	6.10 s	5.89 s	5.97 s

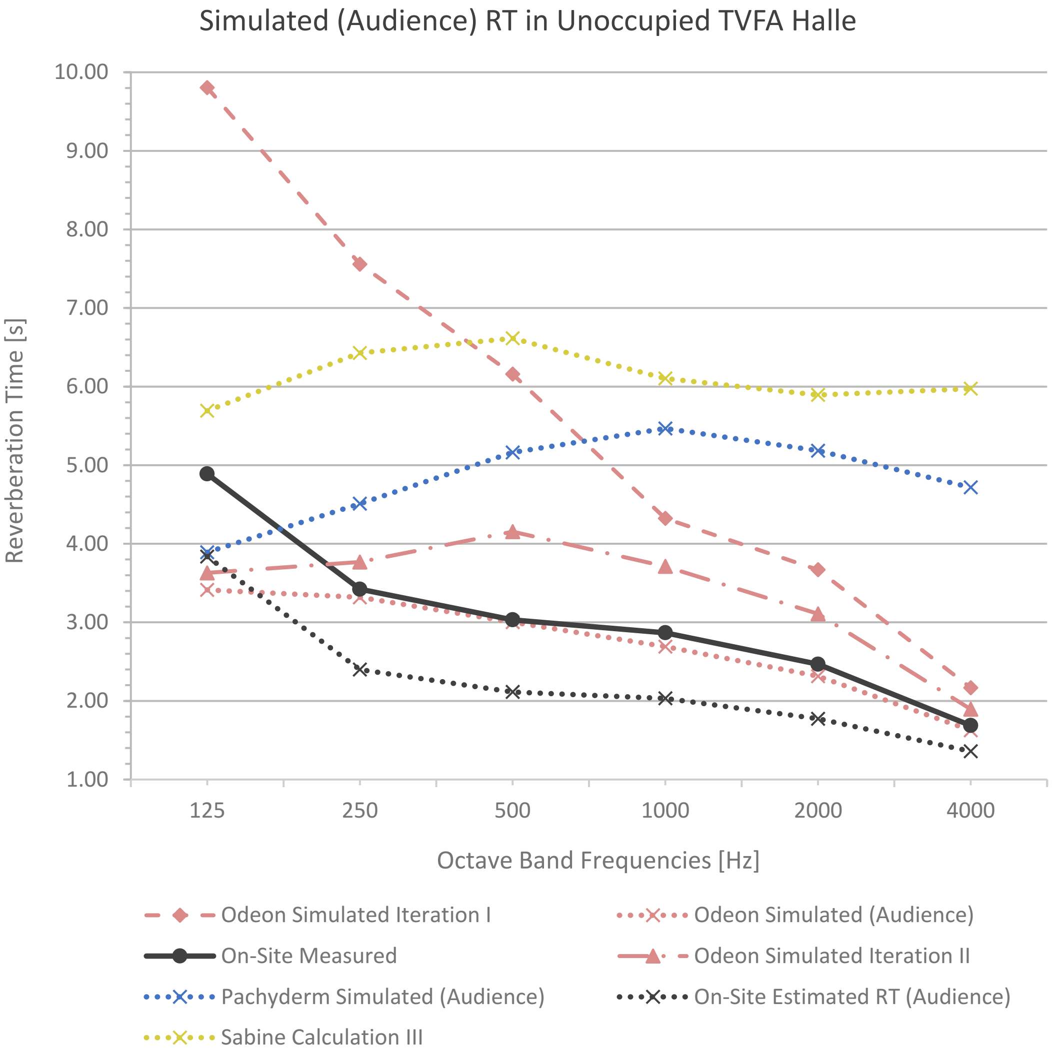


Figure 3.18: Average measured, simulated, and calculated RT for the TVFA Halle

4 COMPARISON AND DISCUSSION

In the following, the results presented in section 3 Results, which include the on-site measurement results, simulation results, and calculation results, are compared and reviewed. Notable materials used in the simulation models and adjustments made for each iteration are elucidated. Moreover, important simulation settings applied to both room acoustics simulation programs, Odeon and Pachyderm Acoustical Simulation, are outlined. Accordingly, the effects these parameters had on the final results are discussed.

Furthermore, the reverberation time results are compared to the target optimal reverberation times corresponding to volume and functional use per space according to DIN 18041 and ÖNORM B 8115-3 as outlined in section 1.3.3.1 Reverberation Time (RT). Thereby, the results for the octave center frequency band at 500 Hz in a maximum occupied condition were used for this comparison.

Following, an assessment of the implemented room acoustics simulation software is performed.

4.1 Comparison of Results

4.1.1 Aufbaulabor

The first results of the simulated Odeon iteration, Iteration I, of the Aufbaulabor show slightly overestimated reverberation time results (see: Figure 3.8), particularly in the lower frequency range, compared to the on-site measurements. Though, for the first iteration, this outcome was satisfactory and consequently, the surface material assumptions were fairly accurate and only needed to be slightly adjusted. Moreover, before conducting Iteration II, one crucial surface material adjustment was made applied a more absorbing, especially in the lower frequencies, plaster-like material to the walls. In addition, a marginally better, more sound absorbing mineral fiber material was selected for the middle section of suspended ceiling (see: Figure 4.1). These improvements are reflected in the results of Iteration II.

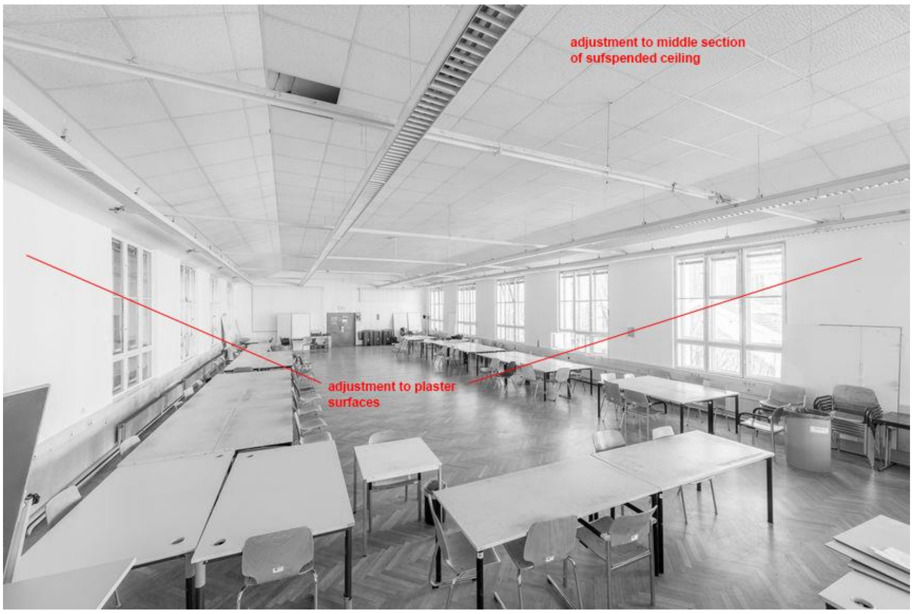


Figure 4.1: Aufbaulabor iteration adjustments adapted from source:
(TU Wien, 2020a)

At this point the Aufbaulabor Odeon Iteration II simulation model was considered to be calibrated to the on-site measurements. Thus, the Odeon simulation settings and surface materials used in the simulated Odeon Iteration I and Iteration II were applied to the Pachyderm Acoustical Simulation plugin environment. As presented in Figure 3.8, it can be seen that the simulation results between the two room acoustics programs greatly differ, whereas the Pachyderm reverberation time results for both iterations are significantly longer compared to those from the Odeon iterations.

Even though the same surface materials used in the Odeon iterations were created and applied to the Pachyderm simulation model surfaces, a few simulation calculation settings were changed. In particular, the defined reflection order of 2 used for the image source calculation section in Odeon was lowered to a reflection order of 1 in Pachyderm. Additionally, the internal Rhino / Pachyderm setting, indicating the depth of the spatial partition of the system, which determines how the geometry will be subdivided for acoustic simulations, was lowered to 5 rather than the default value of 7. In other words, the higher the reflection order and spatial partition settings are set, the more accurate the simulation results will be and the longer the calculation time will take, whereas the lower these settings are the less accurate the results will be and the shorter the simulation time will take. Without adjusting these settings, the approximated simulation time in Pachyderm for Iteration I and Iteration II was estimated to take three to four hours compared to around one hour to simulate Iteration I and II using the lower settings. In comparison, regardless which room was simulated, the Odeon simulations took approximately two minutes to simulate accurate results.

Furthermore, a final iteration, Iteration III (Simulated Audience), where the simulated models contained an audience, was conducted in both simulation tools. It is important to note that, as mentioned above, Iteration III was nearly identical to Iteration II, except that the simulated space was defined to be occupied. Moreover, in the case of the Pachyderm Iteration III (Simulated Audience) simulation, the simulation settings were improved to closely match those used in the Odeon simulations while keeping the simulation time as short as possible. The audience material, seen in Table 2.8 and defined in the final acoustic simulations, was changed to be more absorbing, to agree with the sound absorption properties of a live audience. The audience is often a crucial parameter for a sufficient acoustic performance of a space since the frequency dependent reverberation times in a room can fluctuate greatly depending on the number of occupants and how evenly distributed the occupants are.

Moreover, since the acoustic performance of the evaluated spaces were not able to be measured with a live audience, the on-site measurements were implemented in the Sabine equation, as described in section 3.4 Simulation Results of Audience Models, to calculate estimated reverberation times as if the rooms were occupied during the on-site measurements. Also, as presented in section 3.4, the Sabine equation was used to estimate the reverberation times using the simulated material absorption coefficients corresponding to the surfaces on which they were applied based on each simulated iteration, Iteration I, Iteration II, and Iteration III (Simulated Audience).

An overview of all the measured, calculated, and simulated reverberation time results for the Aufbaulabor can be found in Appendix B, whereby, in the case of the Aufbaulabor, the Odeon Simulated Audience (Iteration III) results and the estimated Sabine Calculation III, which is based on the surface materials used in the Iteration III simulations, most closely approximate the actual reverberation times when the Aufbaulabor is occupied.

4.1.2 Project Room Panigltrakt EG

The results of the first simulated Odeon iteration, Iteration I, of the Panigltrakt show significantly overestimated reverberation time results at all frequencies compared to the on-site measurements (see: Figure 3.11). The overcalculated results of the first iteration were likely caused by the considerable amount of surface area that was inaccurately defined in the first material assumption as a highly reflective plaster material and because there are few surfaces in this space which are assumed to effectively be able to absorb sound that could have possibly counterbalanced this error. Moreover, it is thought that because the concaved form of the vaulted ceiling in this space naturally focuses the sound energy, the reverberation times will generally be higher. Therefore, to further calibrate the simulation model, the surface materials and their corresponding absorption coefficients were adjusted before conducting the simulation, Iteration II.

The new material assigned to the plaster-like surfaces was the same material used in Aufbaulabor Iteration II, which was used to improve sound absorption qualities of the plaster-like surfaces. The acoustic properties of this material are more absorbing, especially in the lower frequencies, compared to the first used plaster-like material for the walls, vaulted ceiling, and supporting beams. In addition, a considerably better, more sound absorbing mineral fiber material was added to the Odeon materials library and applied to the pin board surfaces. Added to these adjustments, an adaptation to the model geometry, particularly the surfaces of the lockers and ventilation unit, was made. Since these room fixtures are tall, the simplified object representations on the floor were changed to the adjacent wall surface to more accurately approximate the sound propagation in the room (see: Figure 4.2).

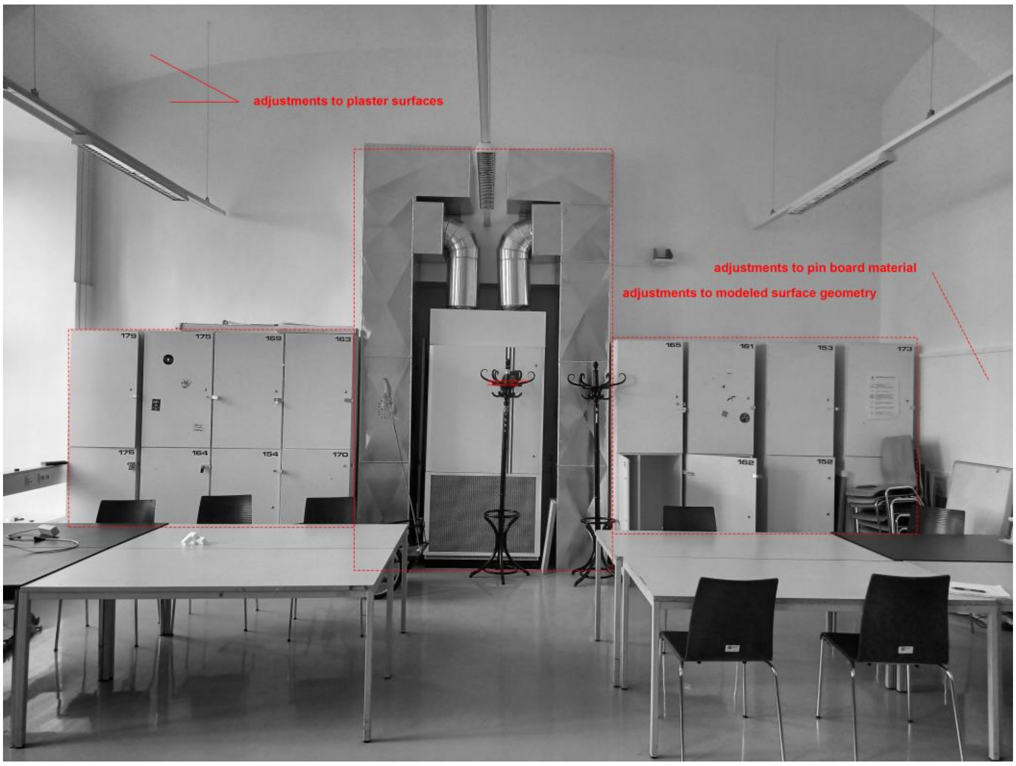


Figure 4.2: Paniglitrakt iteration adjustments (source: from author)

Altogether, these improvements are reflected in the results of Iteration II, which can be seen in Figure 3.11. As a result, the Panigltrakt Odeon Iteration II simulation model was considered to be calibrated to the on-site measurements. Thus, the Odeon simulation settings and surface materials used in the simulated Odeon Iteration I and Iteration II were applied to the Pachyderm Acoustical Simulation plugin for Rhinoceros and Grasshopper. As presented in Figure 3.11, unlike the results of the Aufbaulabor, it can be seen that the simulation results between the two simulation programs are relatively similar, whereas the Pachyderm reverberation times, especially for Iteration II, are slightly shorter compared to those from the Odeon Iteration I. Overall, these iteration changes greatly shorten the simulated reverberation time results, thus, making them in better agreement to the on-site measurements.

Moreover, the same surface materials that were used in the Odeon iterations were created and applied to the Pachyderm simulation model surfaces and simulation calculation settings were match to those used in Odeon. The defined reflection order of 2 which was used for the image source calculations in the Odeon simulations was also used For the Panigltrakt Pachyderm simulations. Additionally, the internal Rhino / Pachyderm setting, indicating the depth of the spatial partition of the system, was set the default value of 7.

Even though the calculation time required for the Pachyderm simulations remains significantly longer than the Odeon simulations, the Pachyderm simulation results for each iteration were generated in roughly 40 minutes with better accuracy, which is reflected in the reverberation time result graphs. This is considerably faster compared to the Aufbaulabor Pachyderm simulations. Therefore, it is postulated that spaces with a greater room volume tend to take more time to simulate in Pachyderm.

Furthermore, a final iteration, Iteration III (Simulated Audience), where the simulated models contained an audience, was conducted in both simulation tools. It is important to note that, as mentioned above, Iteration III was nearly identical to Iteration II, except that the simulated space was defined to be occupied. The audience material defined in the final acoustic simulations was changed to be more absorbing, to agree with the sound absorption properties of a live audience. Moreover, the results of the simulated models with a defined audience material, seen in Table 2.8, indicate the magnitude in which an audience can positively affect the reverberation times of a space.

Like with the Aufbaulabor, since the acoustic performance of the Panigltrakt could not be measured with a live audience, the on-site measurements were implemented in the Sabine equation, as described in section 3.4 Simulation Results of Audience

Models, to calculate estimated reverberation times similar to if the room had been occupied during the on-site measurements.

The Sabine equation was also used to estimate the reverberation times using the simulated material absorption coefficients corresponding to the surfaces on which they were applied based on each simulated iteration, Iteration I, Iteration II, and Iteration III (Simulated Audience).

An overview of all the measured, calculated, and simulated reverberation time results for the Panigltrakt can be found in Appendix B, whereby, in the case of the Panigltrakt, the Odeon Simulated Audience (Iteration III) results and the Pachyderm Simulated Audience (Iteration III) results most closely approximate the actual reverberation times when the Project Room Panigltrakt is occupied.

4.1.3 TVFA Halle

Considerably the largest of the three multifunctional university spaces evaluated in this thesis, the TVFA Halle has the longest measured reverberation times, ranging from 4.89 s at 125 Hz to 1.69 s at 4000 Hz. The sound propagation results imply that, even though the room volume is large, sound waves reflect many times off the room surfaces before completely decaying. The results of the first simulated Odeon iteration, Iteration I, of the TVFA Halle show significantly overestimated reverberation time results (see: Figure 3.13), particularly in the lower frequency range, compared to the on-site measurements. The overcalculated RT results of the first TVFA Halle simulation iteration, similar to the first Panigltrakt Iteration I, were likely caused by the considerable amount of surface area, walls and ceiling, that was inaccurately defined in the first material assumption as a highly reflective plaster material. Therefore, to further calibrate the simulation model, the surface materials and their corresponding absorption coefficients were adjusted before conducting the simulation, Iteration II.

The new material assigned to the plaster-like surfaces was the same material used in Aufbaulabor and Panigltrakt Iteration II, which was used to improve the sound absorption qualities of the plaster-like surfaces. The acoustic properties of this material are more absorbing, especially in the lower frequencies, compared to the first used plaster-like material for the walls and ceiling. In addition, a marginally better, more absorbing surface finish, rough concrete, was applied to the floor of the TVFA Halle (see: Figure 4.3). Overall, these iteration changes greatly shorten the simulated reverberation time results, thus, making them in better agreement to the on-site measurements.

Figure 4.3: TVFA Halle iteration adjustments adapted from source:
(TU Wien, 2020a)

Altogether, these improvements are reflected in the results of Iteration II, which can be seen in Figure 3.13. As a result, the TVFA Halle Odeon Iteration II simulation model was hence calibrated to the on-site measurements. Thus, the Odeon simulation settings and surface materials used in the simulated Odeon Iteration I and Iteration II were applied to the Pachyderm Acoustical Simulation plugin for Rhinoceros and Grasshopper. As presented in Figure 3.13, the simulation results between the two room acoustics simulation programs greatly differ, whereas the Pachyderm reverberation time results for both iterations are significantly longer compared to those from the Odeon iterations.

Even though the same surface materials used in the Odeon iterations were created and applied to the Pachyderm simulation model surfaces, a few simulation calculation settings were changed. Like in the Aufbaulabor Pachyderm simulations, the reflection order was set to 1. Additionally, the spatial partition setting was lowered to 5 rather than the default value of 7. In other words, the simulation settings were adjusted to reduce the total calculation time the TVFA Halle Pachyderm simulations. However, as a result to these changes, the accuracy of the simulation results was lowered. Nevertheless, if these parameters had not been adjusted, the approximated simulation time in Pachyderm for Iteration I and Iteration II III was estimated to have taken ten to twelve hours compared to around three to four hours to simulate using the lower settings. In comparison, regardless which room was simulated, the Odeon simulations took approximately two minutes to simulate accurate results.

Furthermore, a final iteration, Iteration III (Simulated Audience), where the simulated models contained an audience, was conducted in both simulation tools. It is important to note that, like the other evaluated spaces, Iteration III was nearly identical to Iteration II, except that the simulated space was defined to be occupied. The audience material defined in the final acoustic simulations was changed to be more absorbing, to agree with the sound absorption properties of a live audience as seen in Table 2.8. Moreover, the results of the simulated models with a defined audience material indicate the magnitude in which an audience can positively affect the reverberation times of a space.

Like with the other two multifunctional university spaces, since the acoustic performance of the TVFA Halle could not be measured with a live audience, the on-site measurements were implemented in the Sabine equation, as described in section 3.4 Simulation Results of Audience Models, to calculate estimated reverberation times similar to if the room had been occupied during the on-site measurements.

The Sabine equation was also used to estimate the reverberation times using the simulated material absorption coefficients corresponding to the surfaces on which they were applied based on each simulated iteration, Iteration I, Iteration II, and Iteration III (Simulated Audience).

An overview of all the measured, calculated, and simulated reverberation time results for the TVFA Halle can be found in Appendix B, whereby, in the case of the TVFA Halle, the Odeon Simulated Audience (Iteration III) results are nearly identical to the on-site measurements. These results for this simulation most closely approximate the actual reverberation times when the TVFA Halle is occupied. Additionally, it is predicted that the defined work / audience zones in the simulations amounts to roughly a quarter of the maximum occupancy. Therefore, if more occupants were to be in the TVFA Halle, the reverberation time would correspondingly decrease.

4.2 Comparison to Optimal Reverberation Time

As discussed in section 1.3.3.1 Reverberation Time (RT), the reverberation time is directly correlated to the volume of a room and the total equivalent absorption surface area within that space which together are the most crucial parameters that affect speech intelligibility and the perception of sound in a space.

Furthermore, the optimal reverberation time of a space, which is typically compared and considered at the middle frequency band 500 Hz, is dependent on the intended use of a room and pertains to a room that is at least 80% occupied according to DIN 18041:2016. This is further outlined DIN 18041:2016 and ÖNORM B 8115-3.

Moreover, Figure 4.4 , which is a simplified version of Figure 1.3,indicates the optimal reverberation time of a space at 500 Hz per intended use of space category. Though if the reverberation times for the frequencies 125 Hz to 4000 Hz over the recommended function dependent optimal reverberation times, also expressed as (RT/RT_{opt}), are within the 20% tolerance range, seen in Figure 1.5 and below in Figure 4.5, the space is then considered suitable for that particular purpose.

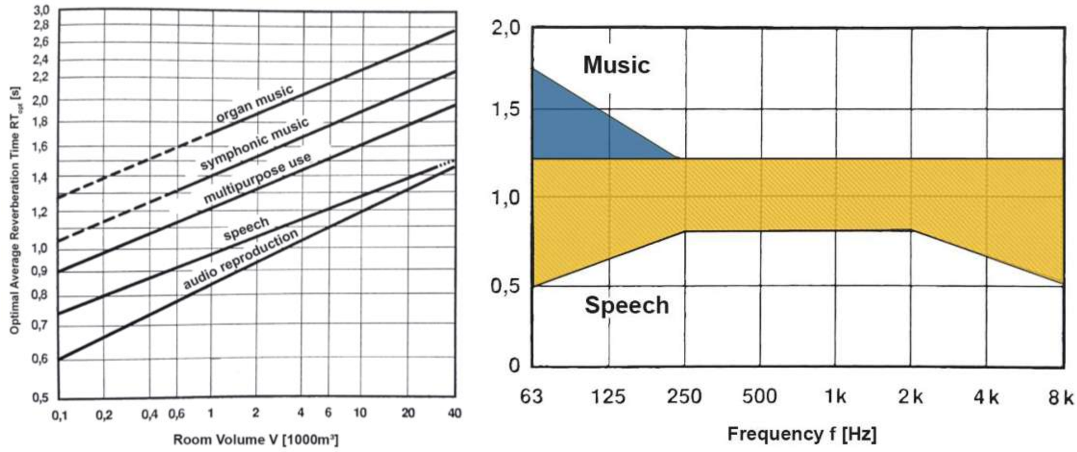


Figure 4.4 (left) and Figure 4.5 (right): (left) Optimal average reverberation times at 500 Hz for various room uses adapted from (Fasold & Veres, 2003)*; (right) Tolerance range of reverberation times as a function of frequency per room use adapted from* (Fasold & Veres, 2003)

Table is a summary of, maximum occupancy, volume, and middle frequency reverberation time results simulated in the Odeon Simulated Audience, Iteration III, and the On-Site Estimated RT (Audience) results of the three multifunctional university learning / working spaces evaluated in this thesis.

Table 4.1: Overview of the figures for the three evaluated case study spaces

Room	Max. Capacity	Volume	Volume/Seat	RT Odeon Simulated (Audience) at 500 Hz	On-Site Estimated RT (Audience) at 500 Hz
Aufbaulabor	120 p	1318 m^3	11.0 m^3/p	0.94 s	0.70 s
Panigltrakt	40 p	490 m^3	12.3 m^3/p	1.64 s	1.23 s
TVFA Halle	300 p	5910 m^3	19.7 m^3/p	3.00 s	2.11 s

The following graphs (see: Figure 4.6), based on Figure 4.4 use the volume of each room to determine the recommended reverberation time (RT_{opt}) according to one of the specified room functions, multi-purpose Figure 4.6 (left) or speech Figure 4.6 (right).

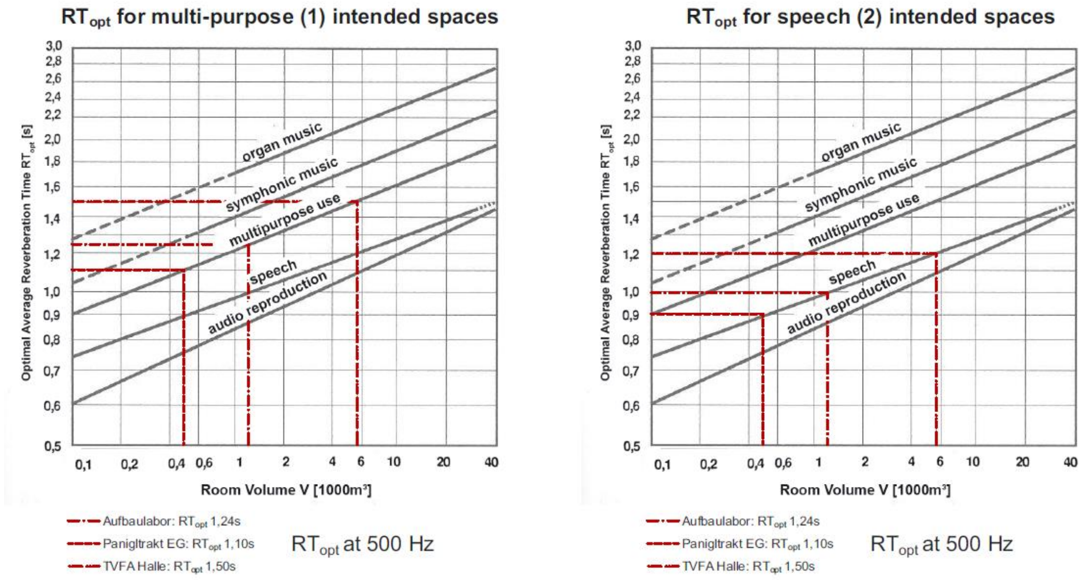


Figure 4.6: Case study optimal average reverberation times at 500 Hz for (left) multi-purpose spaces; (right) speech-oriented spaces adapted from source: (Fasold & Veres, 2003)

Table 4.2 provides an overview of the acquired optimal room use dependent reverberation times.

Table 4.2: Case study optimal average reverberation times at 500 Hz

Room	**RT_{opt} [s]**	
	Multi-Purpose Intended Spaces	**Speech Intended Spaces**
Aufbaulabor	1.24 s	1.00 s
Panigltrakt	1.10 s	0.90 s
TVFA Halle	1.50 s	1.20 s

The ratio between the simulated / calculated occupied space reverberation results to the corresponding optimal reverberation times is discussed below in the following subsections.

4.2.1 RT/RT_{opt} Aufbaulabor

Table 4.3 presents the RT/RT_{opt} ratios for the Aufbaulabor at the frequencies 125 Hz to 4000 Hz. Here the reverberation time results for the Odeon Simulated (Audience) simulation and the calculated On-Site Estimated RT measurements with an audience were compared to the acquired optimal use dependent reverberation times, 1.24 s for multi-purpose uses and 1.00 s for speech intended uses.

Table 4.3: RT/RT$_{opt}$ ratio for the Aufbaulabor corresponding to RT the Odeon Simulated (Audience) simulation results and the calculated On-Site Estimated RT measurements with an audience

Aufbaulabor	RT by frequency					
	125 [Hz]	250 [Hz]	500 [Hz]	1000 [Hz]	2000 [Hz]	4000 [Hz]
Odeon Simulated (Audience)	0.99 s	0.97 s	0.94 s	0.93 s	0.91 s	0.79 s
RT/Rtopt Multi-Purpose (1)	0.80 s	0.78 s	0.76 s	0.75 s	0.73 s	0.64 s
RT/Rtopt Speech (2)	0.99 s	0.97 s	0.94 s	0.93 s	0.91 s	0.79 s
On-Site Estimated RT (Audience)	0.98 s	0.72 s	0.70 s	0.72 s	0.77 s	0.76 s
RT/Rtopt Multi-Purpose (1)	0.79 s	0.58 s	0.56 s	0.58 s	0.62 s	0.61 s
RT/Rtopt Speech (2)	0.98 s	0.72 s	0.70 s	0.72 s	0.77 s	0.76 s

In addition, the RT/RT$_{opt}$ ratios presented in Table 4.3 are organized into a graph to determine whether the calculated RT ratios lie within the acceptable target range. Figure 4.7 indicates that the RT ratios using the Odeon Simulated (Audience) results are within the tolerance range. Moreover, according to these results, the space would be suitable for speech at all frequencies. Nevertheless, as seen in Figure 4.7, the remaining results are below the acceptable range, thus suggesting that the Aufbaulabor is inadequate for both multi-purpose and speech performances.

As defined in section 2.3.1 Aufbaulabor, the use of this space is varied, ranging from, but not limited to, computer-work, eating, listening to music, dancing, model building including the use of power tools, presenting projects, project discussions, reading, and studying.

Although the predominant use of the Aufbaulabor is speech-oriented and short reverberation times are typically desired, particularly since clarity and speech intelligibility are often enhanced, the calculated RT ratios are too short to be satisfactory, especially when the room is occupied at full capacity, which is the case most of the time. Furthermore, when the reverberation times are too short, the overall loudness and tonal balance are affected, resulting in a space that is “acoustically dead” (Fasold & Veres, 2003).

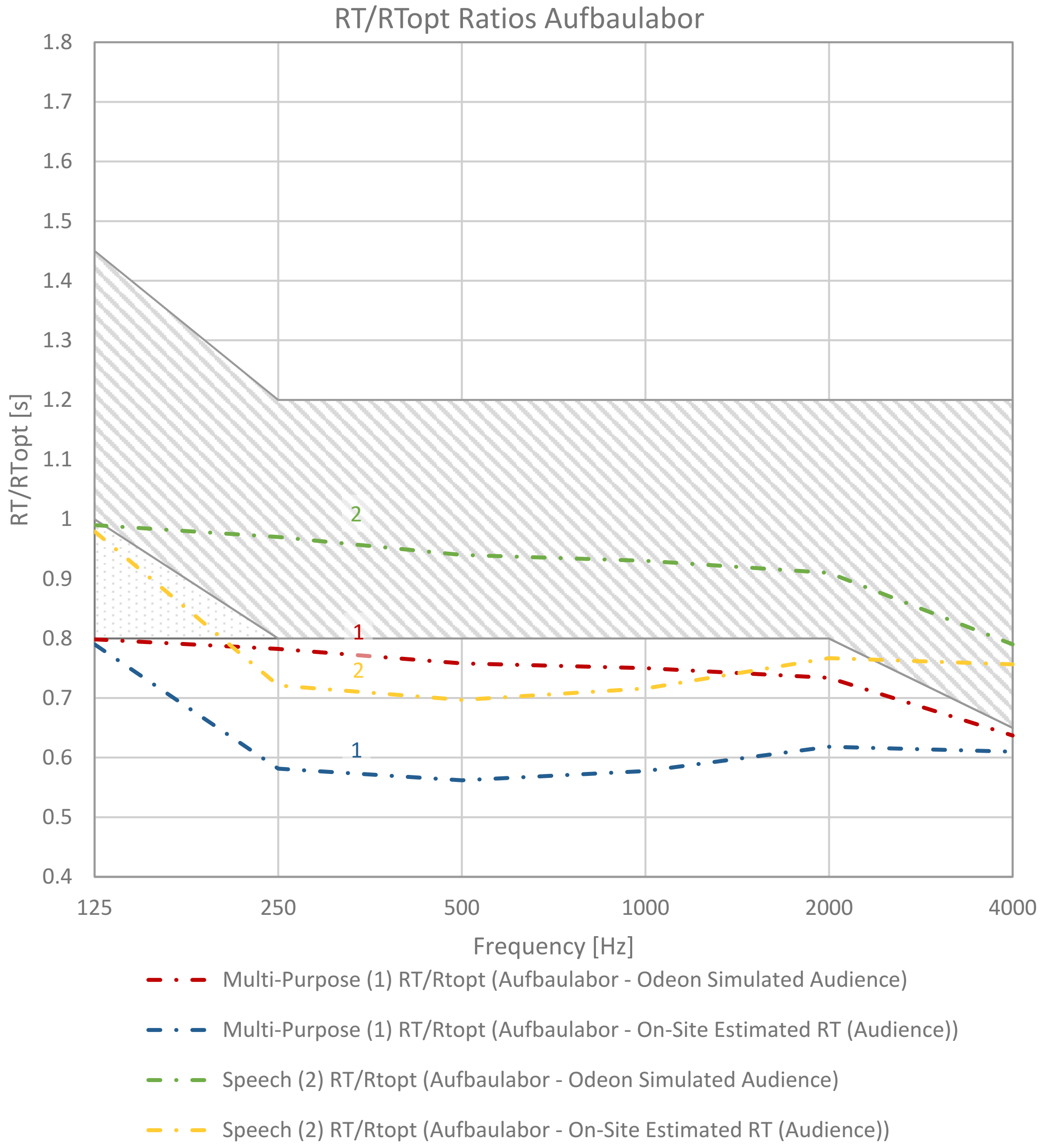


Figure 4.7: RT/RT$_{opt}$ ratio for the Aufbaulabor for multi-purpose and / or speech use

4.2.2 RT/RT$_{opt}$ Project Room Panigltrakt EG

Table 4.4 presents the RT/RT$_{opt}$ ratios for the Panigltrakt at the frequencies 125 Hz to 4000 Hz. Here the reverberation time results for the Odeon Simulated (Audience) simulation and the calculated On-Site Estimated RT measurements with an audience were compared to the acquired optimal use dependent reverberation times, 1.10 s for multi-purpose uses and 0.90 s for speech intended uses.

Table 4.4: RT/RT$_{opt}$ ratio for the Panigltrakt corresponding to RT the Odeon Simulated (Audience) simulation results and the calculated On-Site Estimated RT measurements with an audience

Panigltrakt	RT by frequency					
	125 [Hz]	250 [Hz]	500 [Hz]	1000 [Hz]	2000 [Hz]	4000 [Hz]
Odeon Simulated (Audience)	1.54 s	1.80 s	1.64 s	1.59 s	1.37 s	1.09 s
RT/Rtopt (1)	1.40 s	1.63 s	1.49 s	1.44 s	1.25 s	0.99 s
RT/Rtopt Speech (2)	1.71 s	2.00 s	1.82 s	1.76 s	1.52 s	1.22 s
On-Site Estimated RT (Audience)	1.51 s	1.22 s	1.23 s	1.31 s	1.23 s	1.07 s
RT/Rtopt Multi-Purpose (1)	1.37 s	1.11 s	1.12 s	1.19 s	1.12 s	0.97 s
RT/Rtopt Speech (2)	1.68 s	1.35 s	1.37 s	1.45 s	1.36 s	1.19 s

In addition, the RT/RT$_{opt}$ ratios presented in Table 4.4 are organized into a graph to determine whether the calculated RT ratios lie within the acceptable target range. Figure 4.8 indicates that the calculated On-Site Estimated RT (Audience) results are within the tolerance range. Moreover, according to these results, the space would be best suitable for multi-purpose uses at all frequencies. Nevertheless, as seen in Figure 4.8, the remaining results are considerably longer than those in the acceptable range, thus suggesting that the Panigltrakt is also inadequate for multi-purpose uses and undeniably inadequate for speech uses.

As defined in section 2.3.2 Project Room Panigltrakt EG, in addition to primarily being used as a conference room for weekly project reviews, lectures, mentoring lessons and presentations, the Project Room Panigltrakt EG has also been used for exams including board exams. Moreover, the space has been used for music related functions such as the backstage room for Popfest Karlsplatz, for a summer musical and English camp, and as a rehearsal space for the TU Wien Orchestra.

Since the main use of the Panigltrakt, specifically a conference room, is primarily speech-oriented, the results support that the reverberation times are too long. Thus, if the reverberation time is too long, speech intelligibility is drastically reduced. In worst cases and instances where speech is quickly spoken, a listener will simultaneously hear a mix of sounds, making the speech incomprehensible (Fasold & Veres, 2003).

On the contrary, a long reverberation time promotes fullness of sound and liveness within a space (Fasold & Veres, 2003). These qualities are often desired and suitable for music related activities, which promotes the blend of the music and assists for a more pleasing perception than a dead sound. Therefore, it is reasonable that such music related activities have taken place in the Project Room Panigltrakt EG.

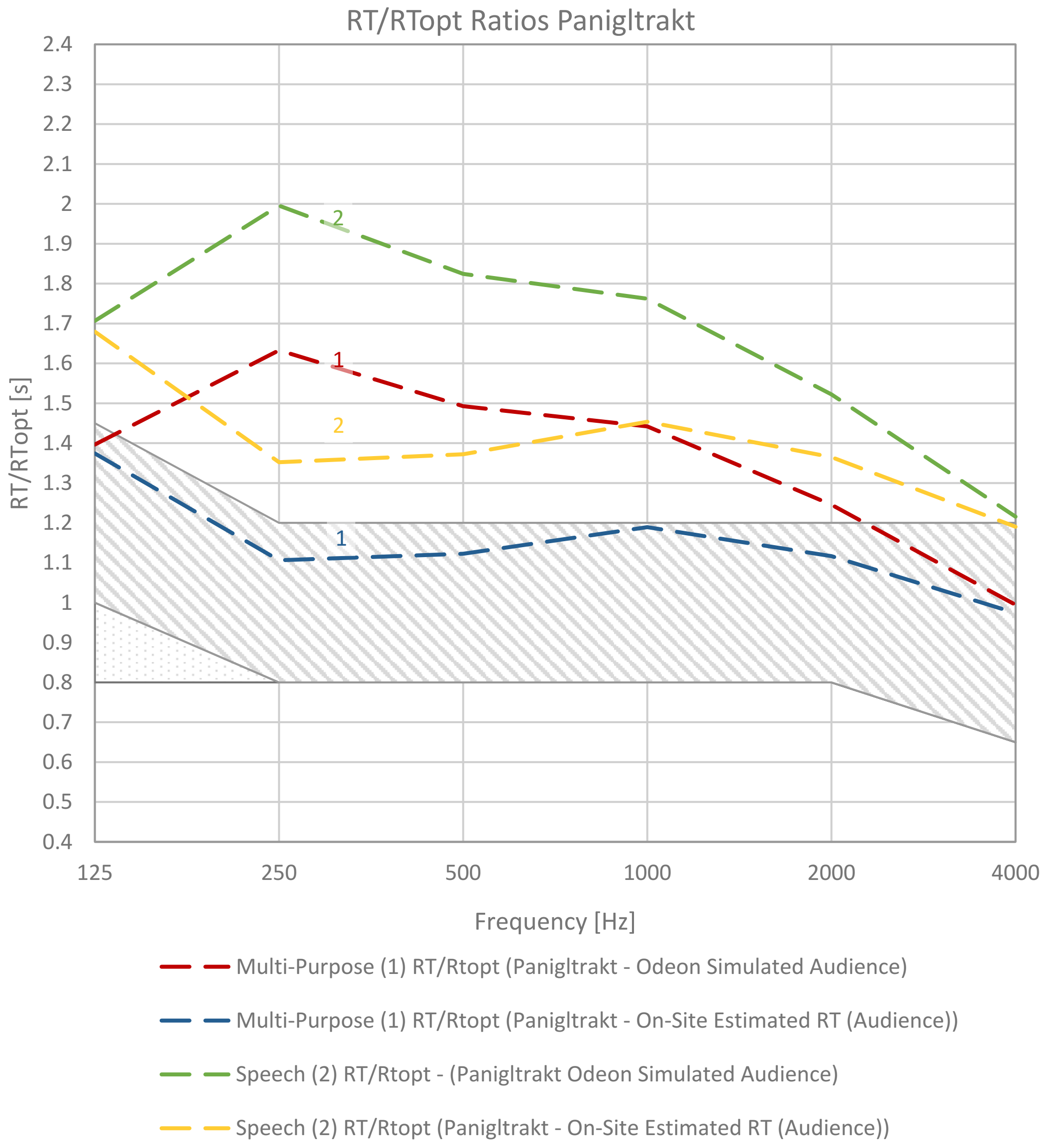


Figure 4.8: RT/RT$_{opt}$ ratio for the Panigltrakt for multi-purpose and / or speech use

4.2.3 RT/RT$_{opt}$ TVFA Halle

Table 4.5 presents the RT/RT$_{opt}$ ratios for the TVFA Halle at the frequencies 125 Hz to 4000 Hz. Here the reverberation time results for the Odeon Simulated (Audience) simulation and the calculated On-Site Estimated RT measurements with an audience were compared to the acquired optimal use dependent reverberation times, 1.50 s for multi-purpose uses and 1.20 s for speech intended uses.

Table 4.5: RT/RT_{opt} ratio for the TVFA Halle corresponding to RT the Odeon Simulated (Audience) simulation results and the calculated On-Site Estimated RT measurements with an audience

TVFA Halle	**RT by frequency**					
	125 [Hz]	**250 [Hz]**	**500 [Hz]**	**1000 [Hz]**	**2000 [Hz]**	**4000 [Hz]**
Odeon Simulated (Audience)	3.41 s	3.32 s	3.00 s	2.69 s	2.31 s	1.63 s
RT/Rtopt Multi-Purpose (1)	2.28 s	2.21 s	2.00 s	1.79 s	1.54 s	1.08 s
RT/Rtopt Speech (2)	2.84 s	2.77 s	2.50 s	2.24 s	1.93 s	1.36 s
On-Site Estimated RT (Audience)	3.84 s	2.40 s	2.11 s	2.03 s	1.77 s	1.36 s
RT/Rtopt Multi-Purpose (1)	2.56 s	1.60 s	1.41 s	1.35 s	1.18 s	0.91 s
RT/Rtopt (2)	3.20 s	2.00 s	1.76 s	1.69 s	1.48 s	1.13 s

As defined in section 2.3.3 TVFA Halle, this space is primarily used by students as a place for general computer-work, presentations, studying, and building models. Because of its large floor space, the hall is often used for large workshops and design studios. In addition, since the TVFA Halle is mainly used for large events, optimal RT values for multi-purpose uses are desired.

In addition, the RT/RT_{opt} ratios presented in Table 4.5 are organized into a graph to determine whether the calculated RT ratios lie within the acceptable target range. Figure 4.9 indicates that the calculated On-Site Estimated RT (Audience) results are not within the tolerance range. Moreover, according to these results, the TVFA Halle is not suitable for multi-purpose uses or speech-oriented uses. Nevertheless, as seen in Figure 4.9, the RT results are considerably longer than those in the acceptable range. Furthermore, though the simulated Odeon simulation only considered an audience size of about a quarter the maximum capacity, which is approximately the typical number of occupants use this space, the calculated estimated audience results considered the space to be occupied at full capacity. Even so, the RT ratios lie outside the acceptable tolerance range.

The results in the RT ratio graph below support that the reverberation times are too long. Thus, as explained above, if the reverberation time is too long, speech intelligibility is drastically reduced. Like the Panigltrakt, this hall has also been used as a rehearsal space for the TU Wien Orchestra. This use of the space is assumed to have been an appropriate fit due to the long reverberation times. Nevertheless, in the usual conditions in which the TVFA Halle is used, it does not display an optimal acoustic performance for multi-purpose or speech involved uses.

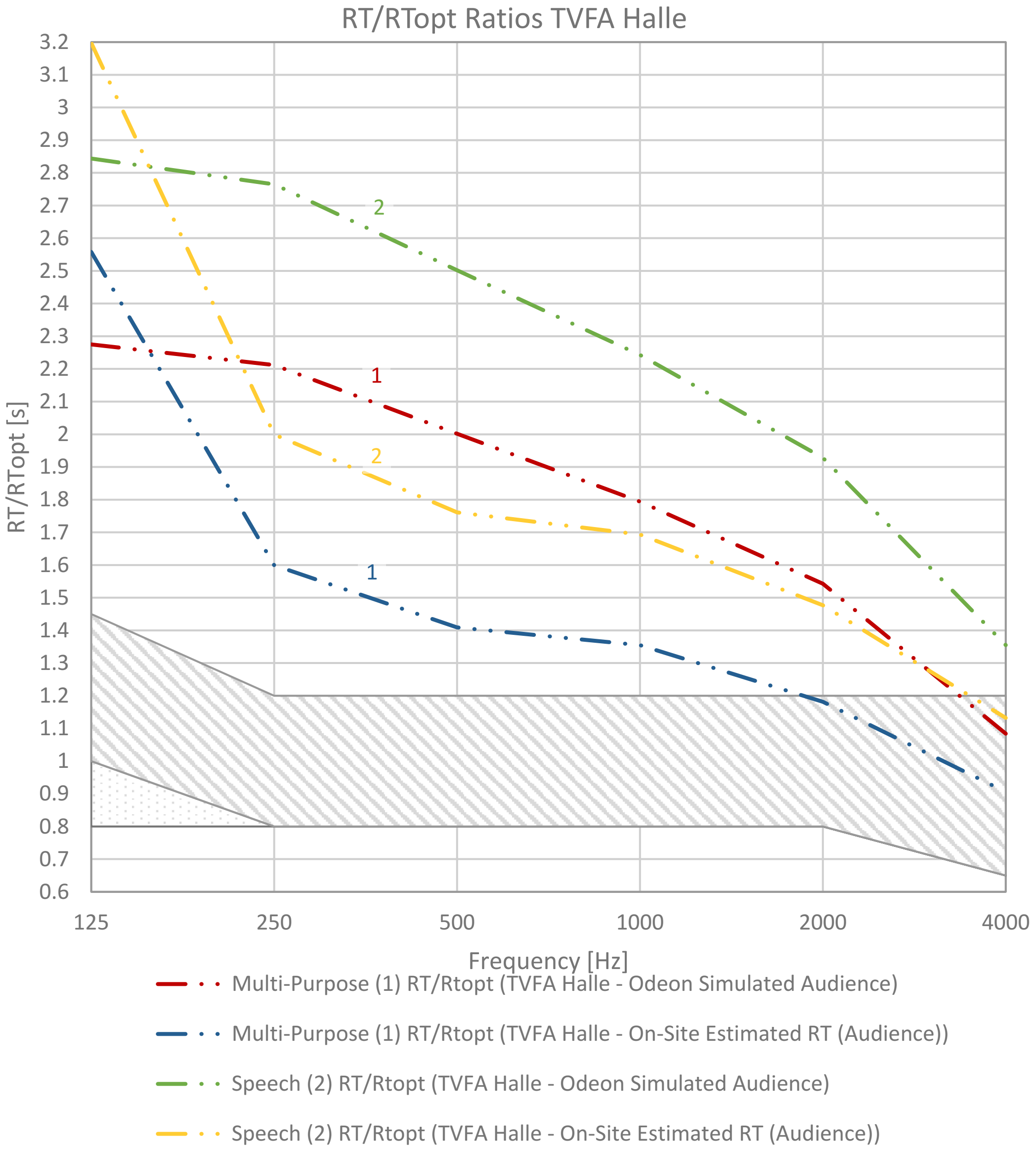


Figure 4.9: RT/RT$_{opt}$ ratio for the TVFA Halle for multi-purpose and / or speech use

4.3 Comments on Sound Pressure Levels

The relative sound pressure level decay diagrams in section 3 Results and in Appendix B generally correspond to how sound pressure levels are distributed (see: Figure 1.7) in relation to distance and total equivalent absorption areas.

In instances where the recorded relative SPL(A) values increase though the receiver position is further away from the sound source, the amplification is typically no more than 3 dB. Therefore, it is expected that these differences are not perceptible to the human ear and do not disrupt from obtaining constant sound pressure level distribution.

4.4 Assessment of Acoustic Simulation Software

The integration of room acoustic simulations to assess the acoustic performance of a space in the planning stages of a design are not new; this evaluation process is, however, often implemented at the final design phases (Peters, 2015). Though this unmethodical workflow has been practiced by architects for decades, considering the first use of acoustic simulation software, room acoustic performances could potentially improve if these assessments were already integrated in early design stages rather than being a “last-minute” consideration.

One reason why this unmethodical workflow might be so commonly practiced might be because the most widely used architectural design tools do not effectively incorporate acoustic parameters so that acoustic simulations can be performed (Peters, 2015)

Even though conventional, well-established hybrid room acoustics simulation tools such as Odeon, are frequently used, however, simply stated, integrating such a room acoustics program in a design workflow requires that the room geometry is exported from the designers preferred drafting tool and imported into the simulation program. More times than not, the exported geometry is often too complex and contains unwanted data that is not needed for the simulation. Therefore, rework to is required to simplify the model so that it can run smoothly in an acoustic simulation.

This section discusses and compares the acoustic simulation programs, Odeon and Pachyderm Acoustical Simulation, whereby Pachyderm is integrated in the 3D modelling software McNeel Rhinoceros (Rhino) and Grasshopper, which was used for this case study. Furthermore, major differences in the individual simulation results are also outlined.

Evaluation of Features

Table 4.6 provides an overview, based on the user’s experience with both programs, of the key performance features and limitations of each room acoustics simulation tool used to evaluate the case study rooms. Moreover, comments to the features as well as unique aspects of the programs are presented below.

Table 4.6: Software evaluation based certain key features and limitation

	Software Evaluation		
	Feature	**Acoustic Simulation Software**	
		Odeon	**Pachyderm Acoustical Simulation**
general	stand alone software	applies	does not apply
	affordable	does not apply	applies
	application bugs	does not apply	somewhat applies
	user guide / supportive community	applies	somewhat applies
	user-friendly interface	applies	applies
	intuitive implementation	applies	somewhat applies
geometry related	import 3D CAD files	applies	applies
	allowed "gaps" in geometry	somewhat applies	applies
	adjustments to geometry in simulation environment	somewhat applies	applies
	curved / complex surfaces	somewhat applies	applies
	parametric optimization	does not apply	applies
simulation settings	compatibility with multiple sources	applies	applies
	compatibility with multiple receivers	applies	applies
	definable material absorption coefficients	somewhat applies	applies
	custom/ complex material designer	does not apply	applies
	application of scatter coefficients	somewhat applies	applies
results	comprehensive simulation results	applies	applies
	accurate results	applies	somewhat applies
	quick simulation time	applies	somewhat applies

General

Perhaps the biggest drawback associated with Odeon, is its price. The basic Odeon edition commercially costs at a starting price of about €4,500 for a single license and can exceed €18,000 for a full-featured license, as of 2021 (Odeon A/S, 2021b). In comparison, Pachyderm is an open-source plugin for Rhino and Grasshopper that is still in development which can be acquired at no charge. Nevertheless, with the expensive price of Odeon comes a well-established / well-known, world leading and reliably accurate acoustic simulation program, which has a supportive community of experts who can answer possible simulation related questions. Moreover, many tutorials and much documentation can be found to learn how to fully exploit the potential of this tool.

Conversely, since Pachyderm is continually under development, limitations and bugs have not been fully resolved. In addition, the few tutorials and documents available online for Pachyderm are a bit outdated and thus, make the learning curve for this program rather steep. However, the intuitiveness of both programs is quite high, whereas it is slightly better in the Odeon environment mainly because it is a fully developed tool. Though it must be stated that without prior knowledge and experience with the Pachyderm plugin, the simulations were able to be quickly set up due to a similar settings environment like in other room acoustics simulation tools.

Geometry Related

Furthermore, it is possible to import 3D geometries into both programs. This can be extremely practical particularly for Odeon in which the 3D editing / constructing tool in the simulation environment is principally text based that is dependent on a list of the surface vertices of the 3D geometry. Therefore, it can be rather difficult to quickly model or adjust the room geometry and especially very cumbersome if applied to early design stage, as the original 3D model must repetitively be imported into the Odeon environment.

Also, in situations where complex surfaces are present, Odeon subdivides the curved surfaces into planar sections to approximate the original surface. Additional inspections to the simplified surfaces should be made to determine whether the surface will reflect the sound rays in a similar manner. For example, as with the vaulted ceiling in the Project Room Panigltrakt, the concave surfaces naturally focus the sound energy. Therefore, it was necessary to ensure that these surfaces acted accordingly, rather than creating additional surfaces for which the sound rays can reflect off. In comparison, Pachyderm can perform acoustic simulations with models containing complex surfaces. Instead of approximating these surfaces with planar subdivision, Pachyderm uses meshes and non-uniform rational B-Splines (NURBS), which are native to the 3D Rhino modelling environment, to better approximate any complex geometry.

Moreover, it is important that an Odeon model is watertight or has at least a bounding box so that the simulated sound rays remain in the interior space for acoustic calculations to be performed. For Pachyderm acoustic simulations can be performed even if the 3D model is open and has leaks. Thus, the user must check if a meaningful geometry is used and if the results are plausible.

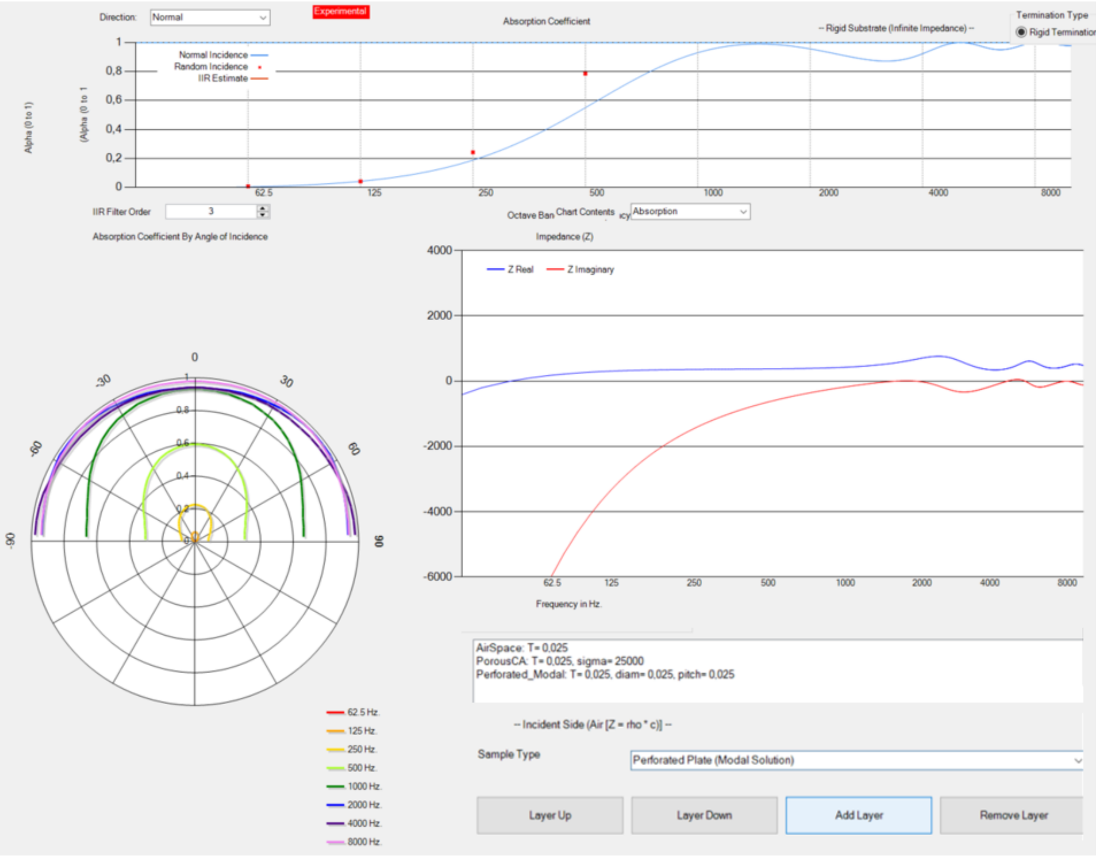
Alternatively, because Pachyderm is integrated into the widely used 3D modeling program, Rhino, it is straightforward and allows for ‘real-time’ modeling and adjustments to be made to the 3D geometry in this environment. Moreover, since both 3D design model and room acoustics simulation model are, in this case, one and the same, acoustic simulations can be rather intuitively and effectively incorporated in a planner’s workflow. In particular, when various adjustments to the geometry of the space, such as in the preliminary design / conceptional phases, and their resulting effects to the acoustic performance shall be examined, they can be directly assessed in Rhino / Pachyderm using the original 3D model.

In addition, though not implemented in this case study, it is possibly to perform acoustic simulations in a fully parametric manner using Pachyderm in the Grasshopper environment, whereby, for example, room dimensions and various parameters can effortlessly be altered at the click of the mouse.

Simulation Settings

Both Odeon and Pachyderm support simulations with multiple sound sources and point receivers. Results for each setup can be obtained after a simulation which can be useful when performing a room acoustics assessment.

Furthermore, though materials can be added to the Odeon and Pachyderm materials library and surfaces can be assigned specific sound absorption coefficients, a particular unique feature included in the Pachyderm simulation tool is that it is possible to create custom multi-layered material compositions to determine the sound absorption properties of the said material. Figure 4.10 displays this material designer that can be used in Pachyderm.



Direction: Normal

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Chart Contents Absorption

Termination Type ● Rigid Terminatio

AirSpace: T= 0,025
PorousCA: T= 0,025, sigma= 25000
Perforated_Modal: T= 0,025, diam= 0,025, pitch= 0,025

Sample Type Perforated Plate (Modal Solution)

Figure 4.10: Pachyderm custom material designer

Resuls

As mentioned in section 4.1 Comparison of Results, the Odeon and Pachyderm simulation results, specifically the results of simulated Iteration I and Iteration II for the Aufbaulabor and TVFA Halle, greatly differ; whereas the Pachyderm reverberation time results for both iterations are significantly longer compared to those from the Odeon iterations.

An explanation for these differences is most certainly connected to the lower simulation settings used in Pachyderm to perform these simulations. Outlined before in 4.1 Comparison of Results, adjustments to the Pachyderm settings were made to shorten the overall simulation time. In other words, the higher the reflection order and spatial partition settings were defined in Pachyderm, the more accurate the simulation results were and the longer the calculation time was corresponding to the room size.

This is true for the simulated Pachyderm results for the Paniglitrakt. For these simulations, the settings were set to match those used in the corresponding Odeon simulation iterations. Since the Panigltrakt is significantly smaller in size, the overall simulation time was not greatly affected when using higher simulation settings. Thus, more accurate and comparable results were obtained.

In addition and directly correlated to the accuracy of the simulation results, the simulation times varied significantly. Nevertheless, the simulation times for the Pachyderm simulations ranged from 40 minutes to 4 hours. In comparison, regardless which room was simulated, the Odeon simulations took less than two minutes to simulate accurate results for multiple receiver positions.

As such, the appropriateness of which simulation tool to use is largely dependent on the intended use. Moreover, it must be stated that generally uses in the early design phases of a project do not necessarily require detailed results; but instead benefit on the principles and trends the results might exhibit. Additionally, the specifications of the user's operating system used to run the programs can also greatly affect the processing time of each simulation program.

Ultimately, it should be added that such parametric acoustic simulation tools like Pachyderm are not intended to replace the well-established existing hybrid acoustic simulation programs. Alternatively, they should be integrated to the design phases and research areas where simulation programs like Odeon can often not effectively be used.

5 CONCLUSION

This thesis examined the acoustic performance of repurposed university learning spaces at the TU Wien which are presently being used as multifunctional learning / workspaces. Moreover, the rooms selected, Aufbaulabr, Project Room Panigltrakt EG, and TVFA Halle, have been assessed in a case study, whereby the acoustic indicators, reverberation time and sound pressure level distribution, were used to compare the acoustic performance of each space.

On-site measurements, simulated models in Odeon and Pachyderm Acoustical Simulation, and calculations using the Sabine equation, were used to produce comparable results. Major deviations in the simulation results, particularly in the results of the simulated Odeon Iteration I simulations, were caused by the lack of information on the actual surface materials including their sound absorption coefficients present in the rooms. Thus, these inaccurate surface material assumptions were adjusted along with other acoustical parameter settings in further iterations to better calibrate the simulation models to the on-site measurements. Furthermore, the settings, material definitions, and other various simulation parameters were set almost identically in both Odeon and Pachyderm so that the accuracy of the results could be identified.

Once the simulation models had been calibrated a defined audience was simulated to best approximate the actual reverberation times within the spaces since an audience can greatly shorten reverberation times. Furthermore, an estimated audience absorption area was added to the on-site reverberation time results using the Sabine formula since the on-site measurements could not be performed with the rooms in an occupied state. Accordingly, these results were compared to the simulation results in which an audience was simulated.

To summarize, the performance results of the repurposed multifunctional spaces were compared by the acoustic indicators, reverberation time and sound pressure level distribution. Overall, this analysis disclosed the significance individual acoustic parameters have on corresponding simulation / iteration results. The results, particularly the reverberation times, were then compared to spatial use dependent optimal RT values in relation to the room volume as outlined in DIN 18041:2016.

Conclusively, the three assessed repurposed multifunctional university spaces were proven to be acoustically inadequate for speech and multi-purpose uses. Thus, further research questions arise such as how to acoustic performance of these spaces can be optimized and suitable for their varied spatial uses.

6 INDEX

6.1 List of Abbreviations

RT	Reverberation time
RT_m	Mid-frequency reverberation time at 500 Hz
RT_{opt}	Recommended RT at 500 Hz
SPL	Sound pressure level
SPL(A)	Sound pressure level (A weighted)
STI	Speech transmission index

6.2 List of Figures

6.3 List of Tables

6.4 List of Equations

7 LITERATURE

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8 APPENDIX

A. Site Plans

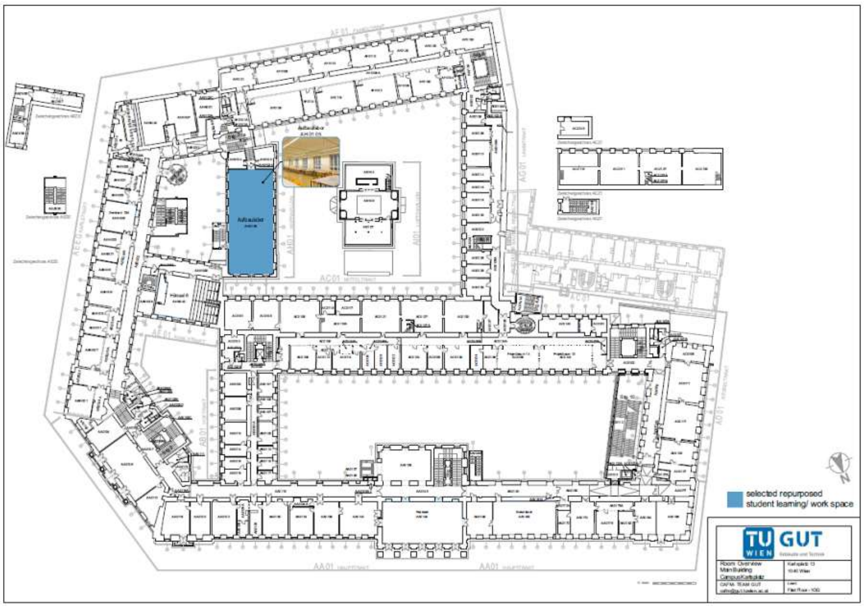

Figure 8.1: Location of Aufbaulabor in the building Campus Karlsplatz at the TU Wien adapted from (TU Wien, 2020a)

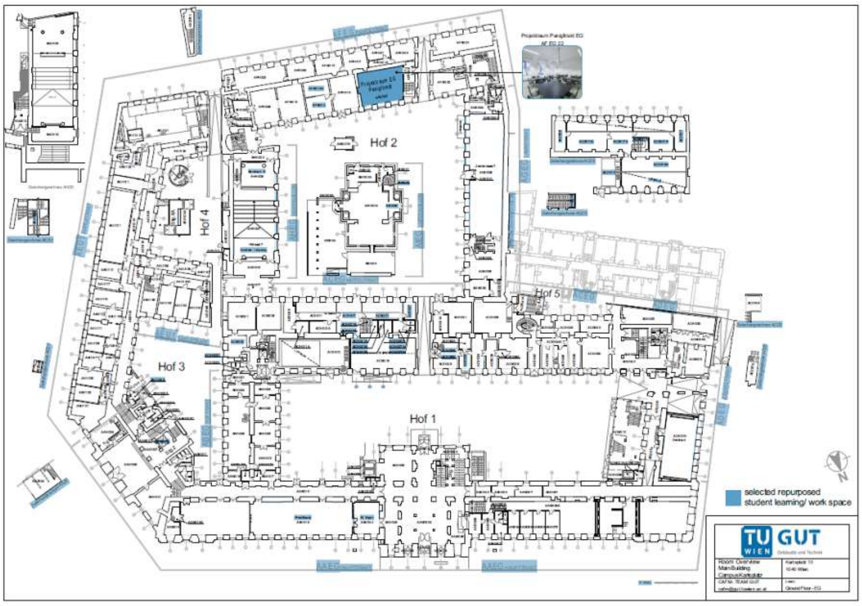

Figure 8.2: Location Panigltrakt in the building Campus Karlsplatz at the TU Wien adapted from (TU Wien, 2020a)

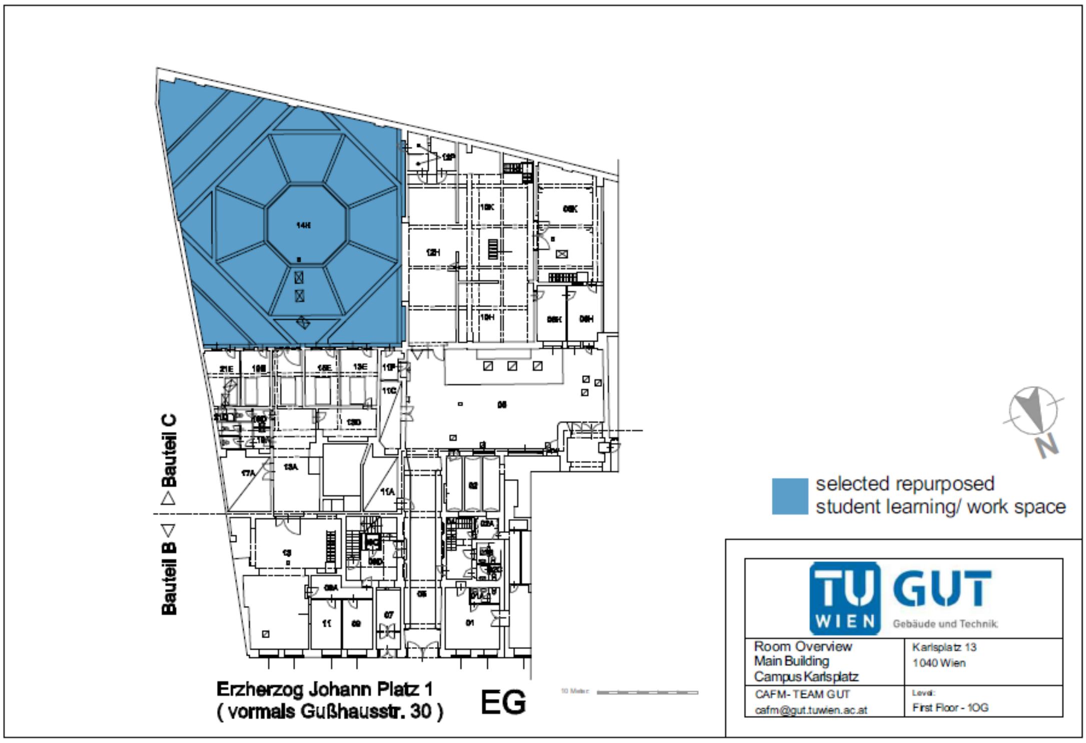

Figure 8.3: Location TVFA Halle in institute building, Erzherzog-Johann-Platz at the TU Wien adapted from (TU Wien, 2020a)

B. Figures

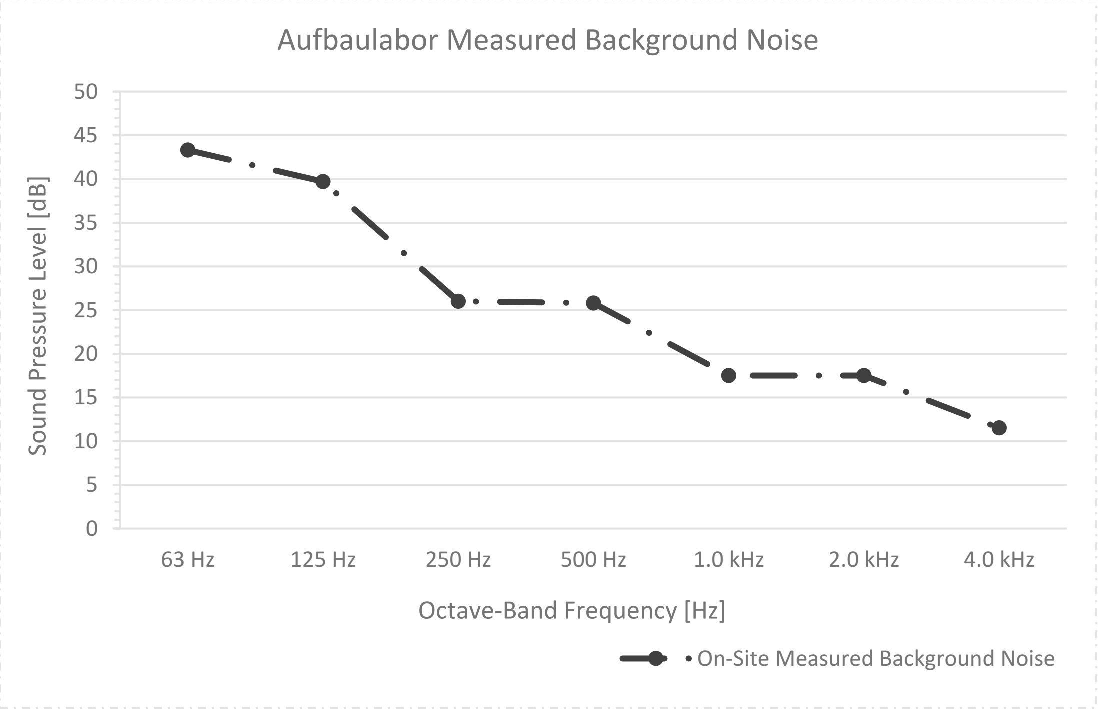

Figure 8.4: On-site measured background noise for the Aufbaulabor

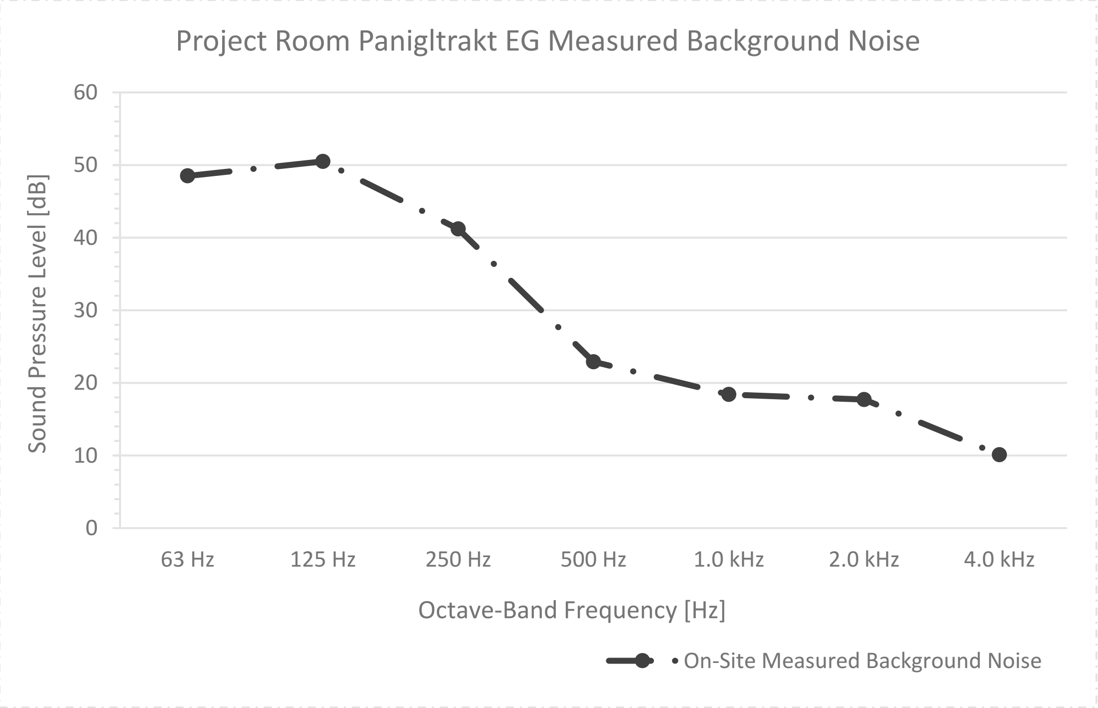

Figure 8.5: On-site measured background noise for the Panigltrakt

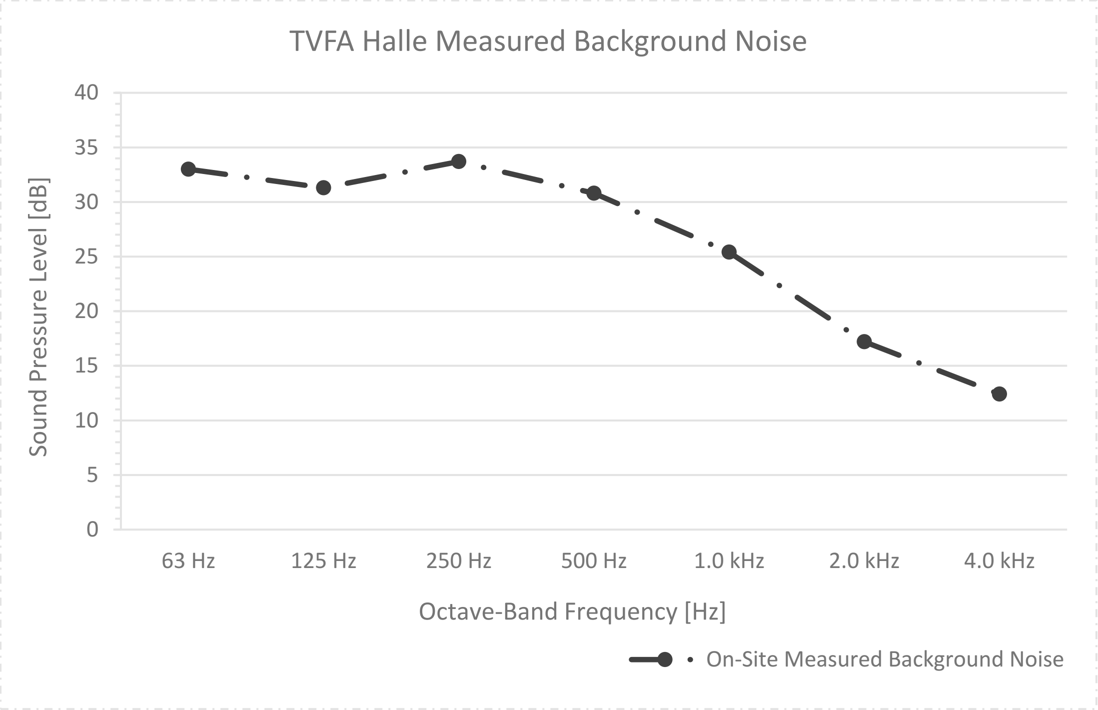

Figure 8.6: On-site measured background noise for the TVFA Halle

Figure 8.7: Calculated, Measured, and Simulated RT results for the Aufbaulabor

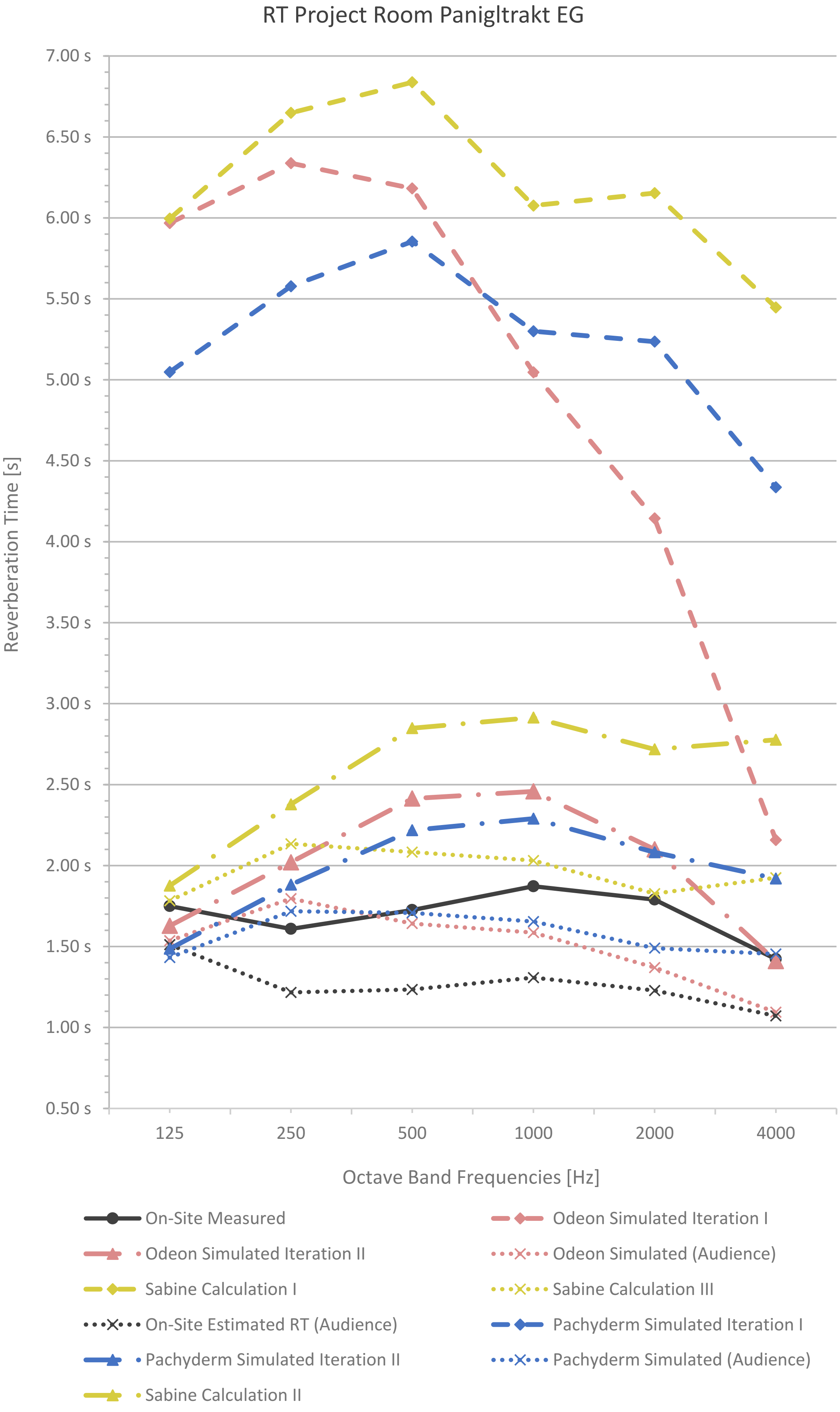

Figure 8.8: Calculated, Measured, and Simulated RT results for the Panigltrakt

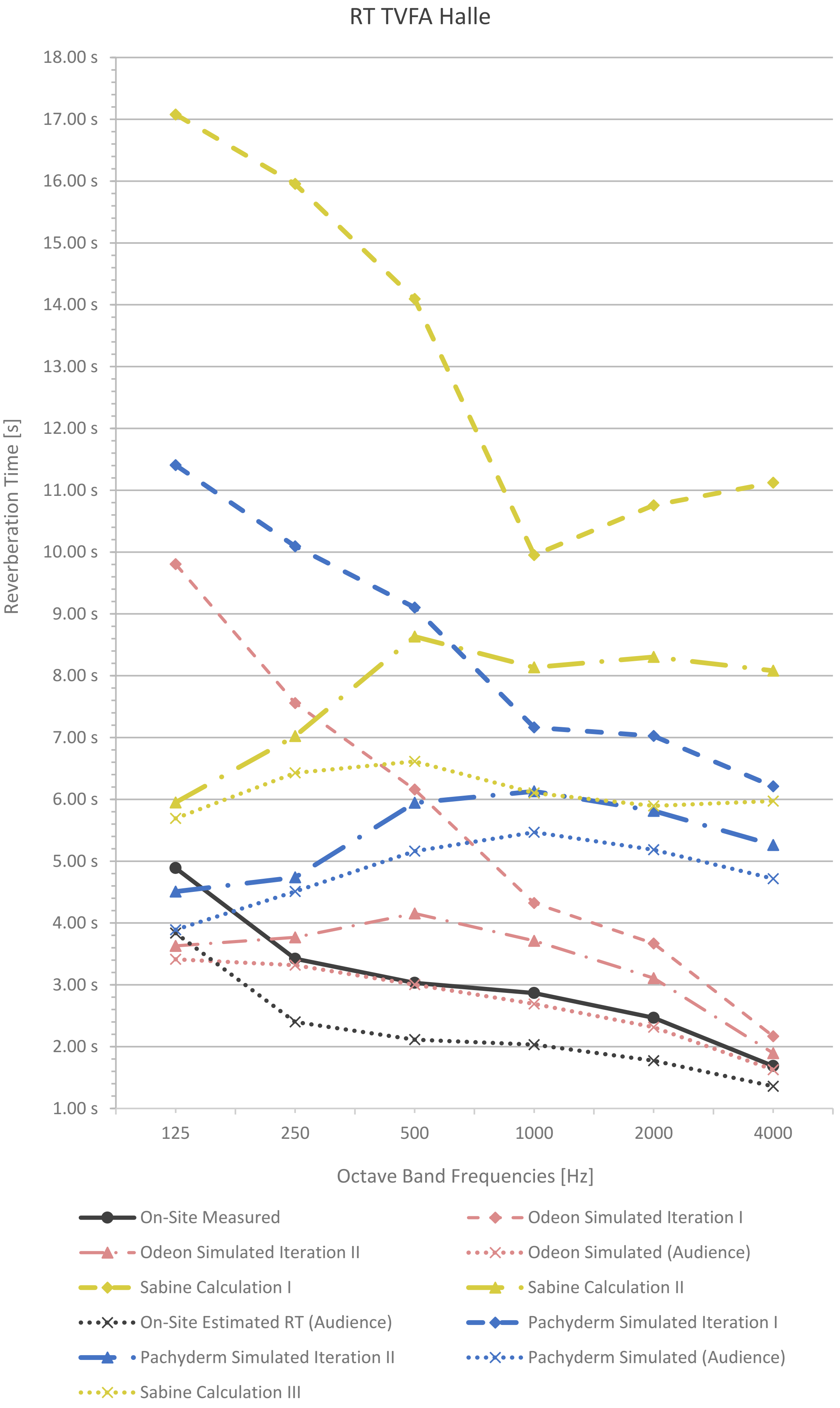

Figure 8.9: Calculated, Measured, and Simulated RT results for the TVFA Halle

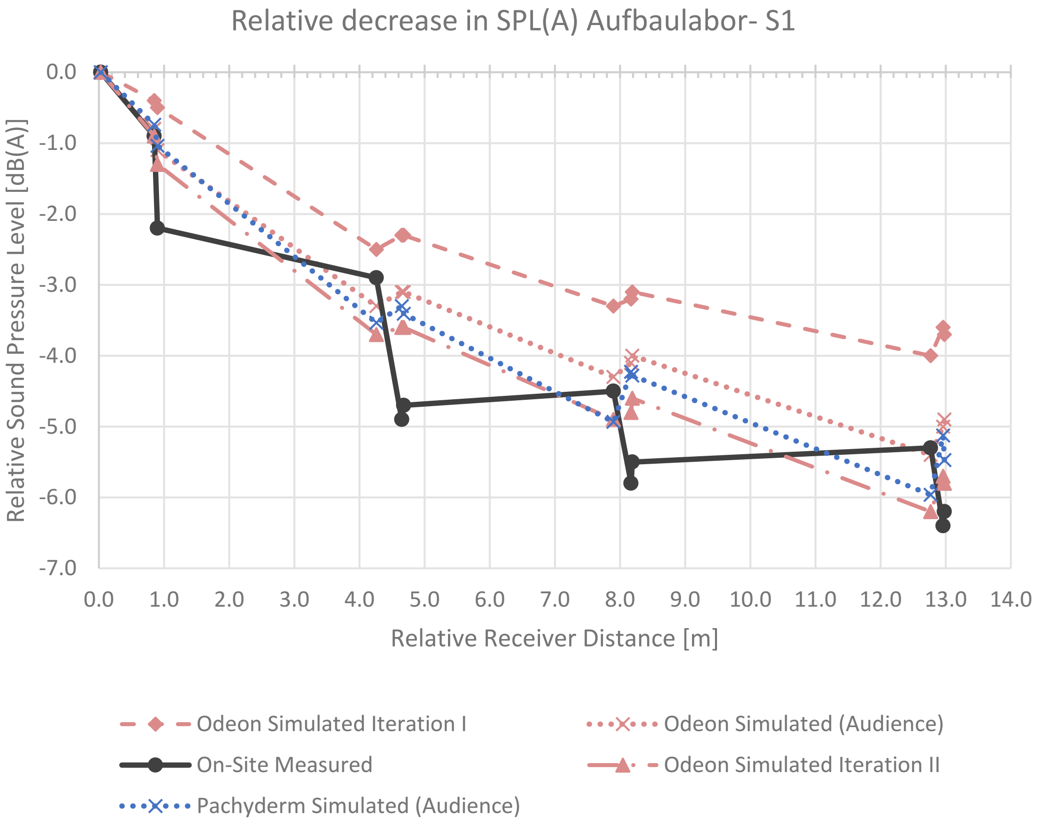

Figure 8.10: Measured and Simulated relative SPL(A) decay results for S1 in Aufbaulabor

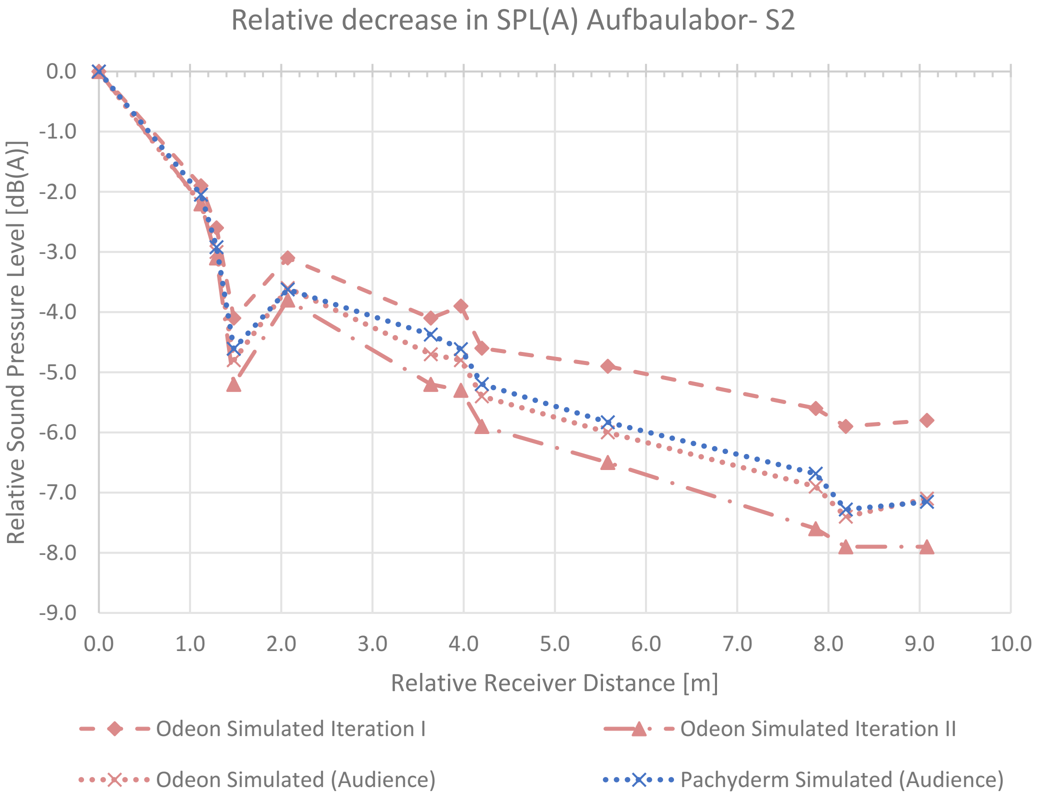

Figure 8.11: Measured and Simulated relative SPL(A) decay results for S2 in Aufbaulabor

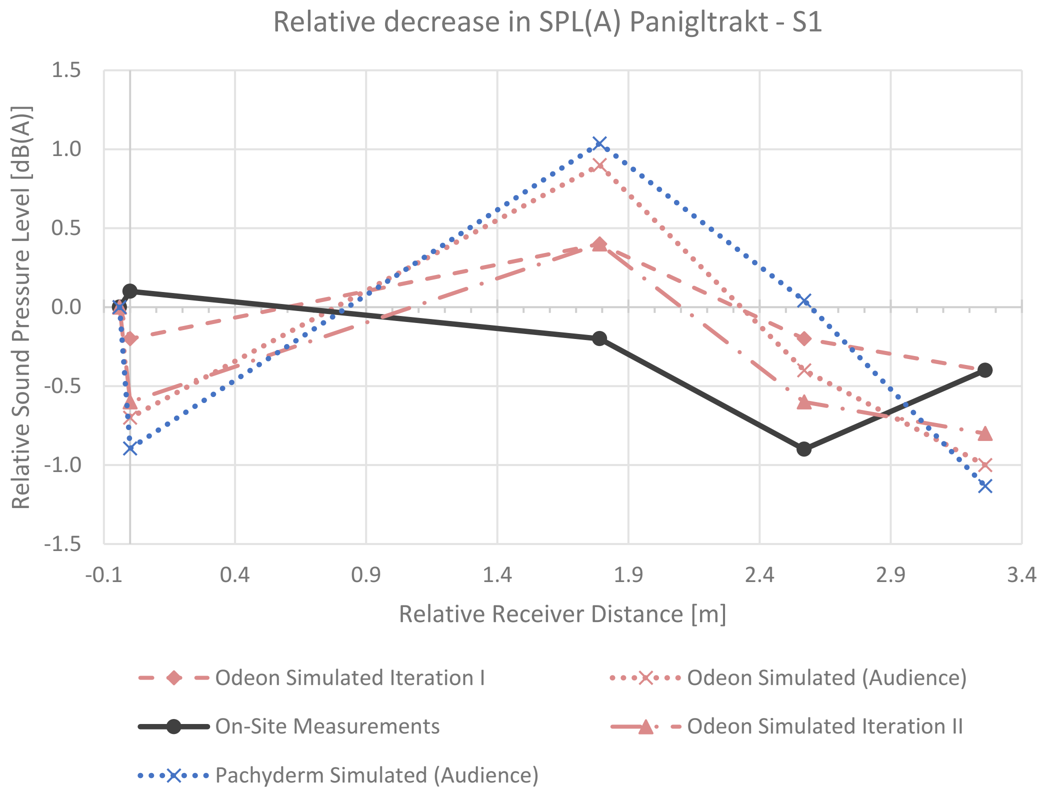

Figure 8.12: Measured and Simulated relative SPL(A) decay results for S1 in the Panigltrakt

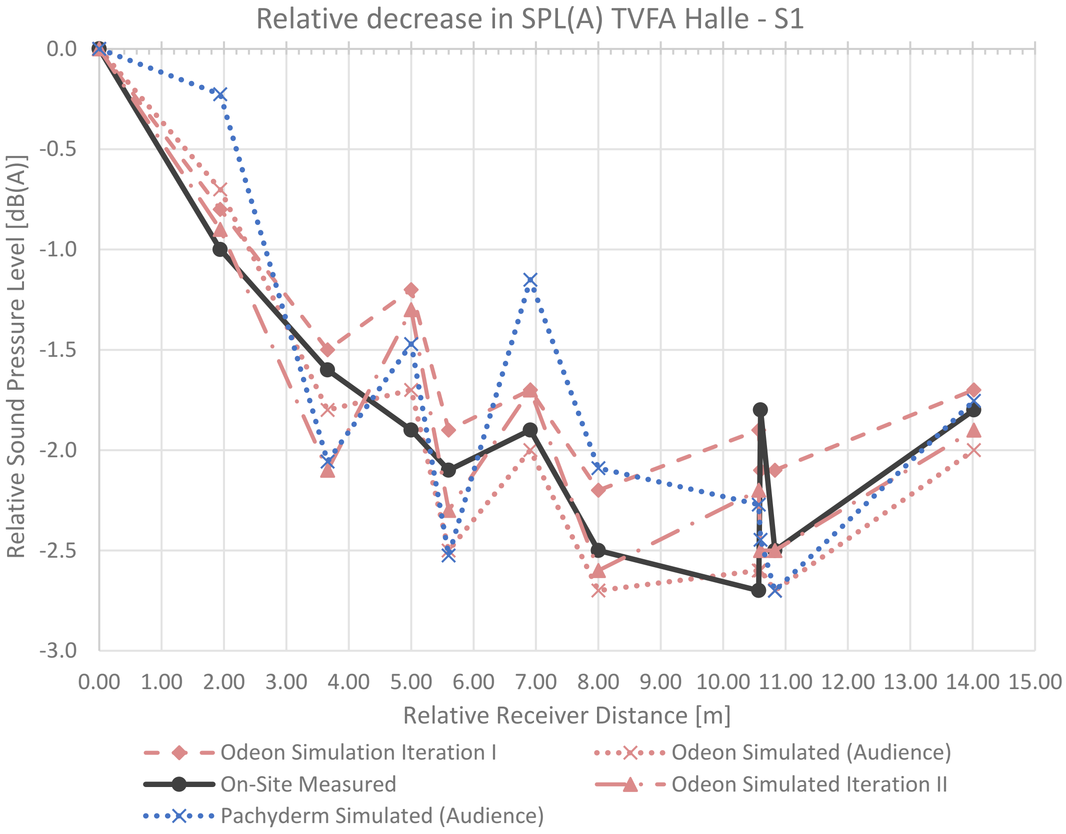

Figure 8.13: Measured and Simulated relative SPL(A) decay results for S1 in the TVFA Halle

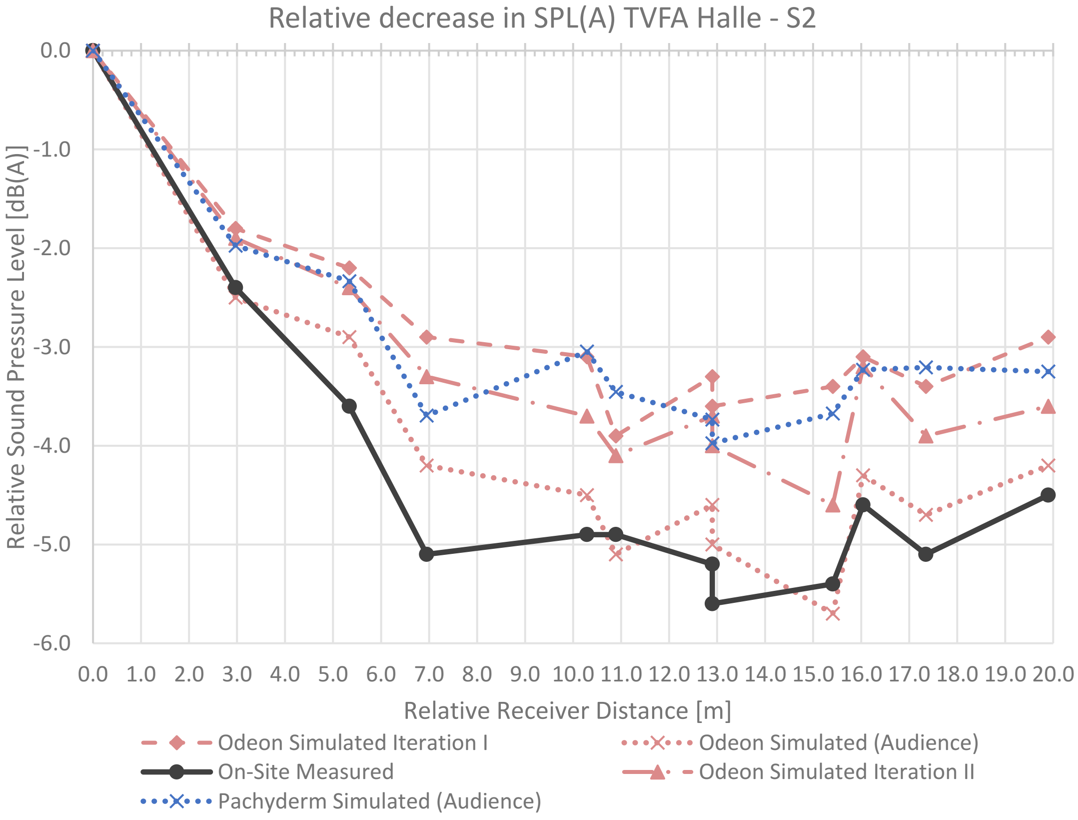

Figure 8.14: Measured and Simulated relative SPL(A) decay results for S2 in the TVFA Halle

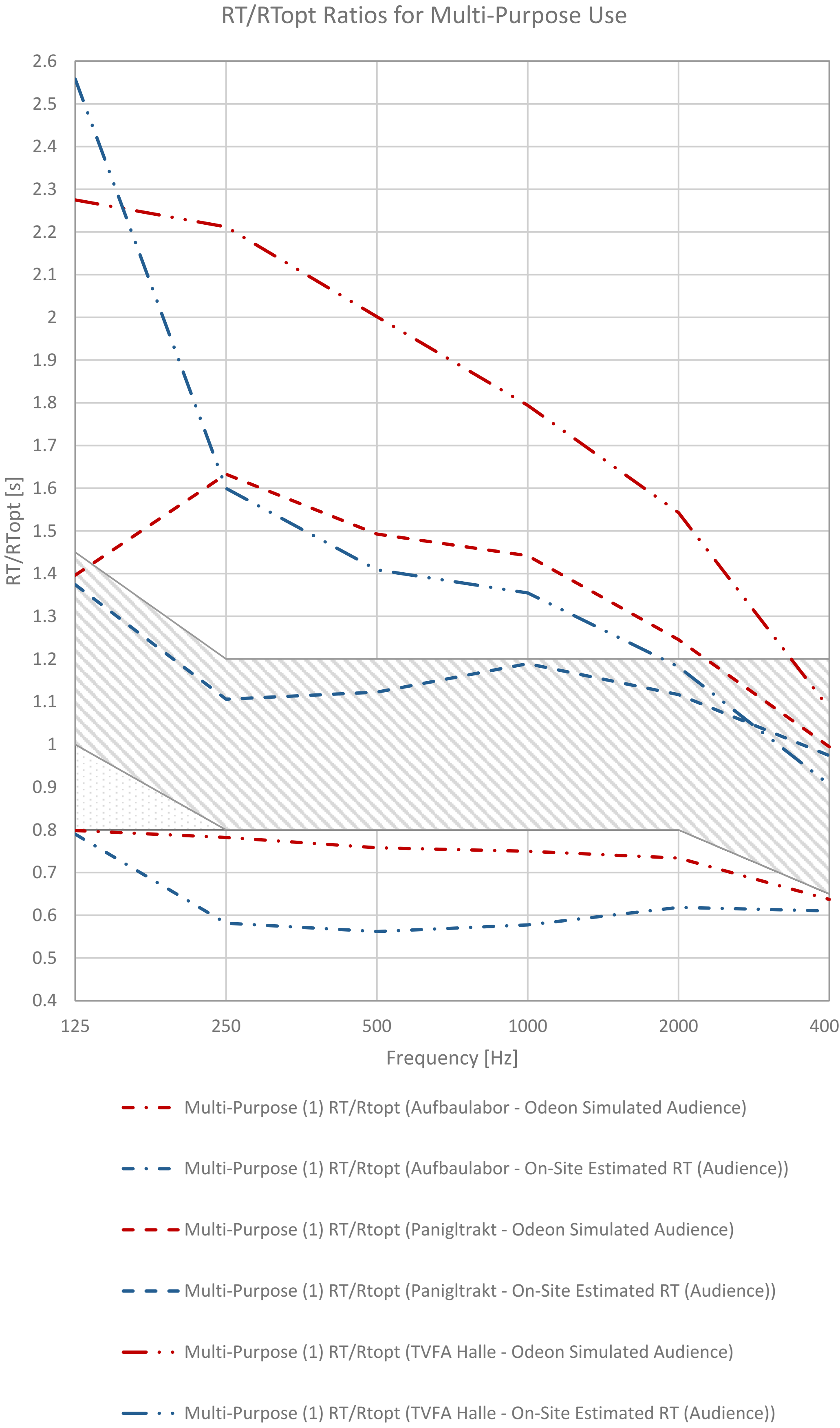

Figure 8.15: RT/RT$_{opt}$ ratio for all evaluated spaces for multi-purpose uses

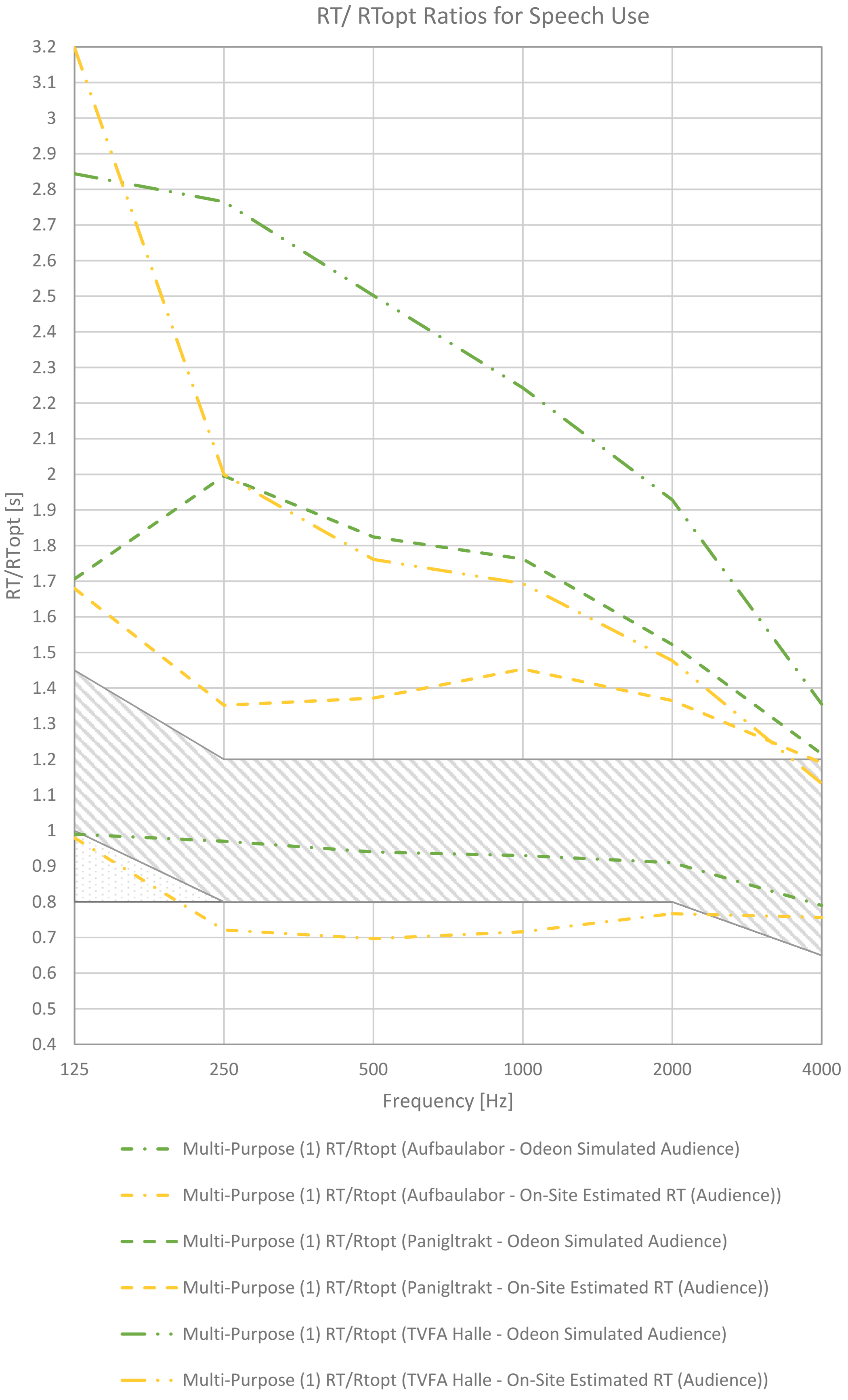

Figure 8.16: RT/RT$_{opt}$ ratio for all evaluated spaces for speech uses