DIPLOMARBEIT

Acoustical Measurements and Simulation: A Case Study of a Complex Office Area

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KURZFASSUNG

Gebäudeerweiterungs- und Umbauprojekte können hinsichtlich der Lebenszyklus-Performance eine potenziell attraktive Option für Neubauprojekte sein. Manche Aspekte (z. B. Akustik) können dabei vernachlässigt werden, obwohl bei solchen Projekten der thermischen Sanierung und der Energieeffizienz große Aufmerksamkeit geschenkt wird. Schallschutz- und Sprachschutzkriterien spielen einen großen Einfluss auf den Komfort und die Leistungsfähigkeit der Bewohner und Büronutzer. In diesem Zusammenhang werden in dieser Masterarbeit die Ergebnisse einer aktuellen akustischen Analyse eines kürzlich fertiggestellten rund 350 m2 großen Büroerweiterungsprojekts in Wien, Österreich, vorgestellt. Es verfügt über einen Besprechungsraum, ein Großraumbüro und einige private Büros. Eine Galerie verbindet die einzelnen Bereiche mit dem größeren offenen Büroraum. Die Studie umfasste die Erstellung eines digitalen Modells des Büros, die Abschätzung der akustisch relevanten Eigenschaften der relevanten architektonischen Elemente, die Umsetzung eines Messplans zur Ermittlung der Werte akustischer Leistungsindikatoren (insbesondere Schallpegelunterschiede zwischen Bürozonen, Nachhallzeiten in unterschiedlichen Büroräumen/-bereichen), Bewertung empirisch bewerteter akustischer Bedingungen in den Büroräumen, Erstellung von akustischen Simulationsmodellen, Kalibrierung des Simulationsmodells und Überprüfung von möglichen akustischen Verbesserungsmöglichkeiten (z. B. Trennwände, schallabsorbierende Elemente). Die Ergebnisse dieser Fallstudie, die für andere Gebäudeaus- und Umbauprojekte relevant sein können, weisen darauf hin, dass die akustischen Bedingungen in den Büroräumen nicht den geltenden Vorschriften entsprechen. Aus diesem Grund untersuchte die Studie die Nutzbarkeit des zuvor erwähnten kalibrierten Simulationsmodells für die virtuelle Erforschung möglicher Lösungen zur akustischen Verbesserung.

Keywords

Acoustical Simulation, Room acoustics, Open-plan office, Acoustical Room Performance, Odeon

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ABSTRACT

Building extension and conversion projects can be a potentially appealing option to new construction projects in terms of life-cycle performance. Some aspects of building performance (e.g., acoustics) are sometimes disregarded in the process, while other aspects such as thermal upgrading and energy efficiency receive a lot of attention in such projects. Noise protection and speech privacy criteria play a major influence on the comfort and productivity of occupants. In this regard, the results of a recent in-depth acoustic analysis of a recently finished around 350 m2 large office extension project in Vienna, Austria, are presented in this master thesis. It has a meeting room, an open-plan office space, and some private offices. A gallery connects the individual areas to the larger open-plan office room. The study included the creation of a digital model of the office, estimation of the acoustically relevant properties of the relevant architectural elements, implementation of a measurement plan to obtain the values of key acoustic performance indicators (specifically, sound level differences between office zones, reverberation times in different office rooms/areas), evaluation of empirically assessed acoustic conditions in the office spaces, creation of acoustic simulation models, calibration of the simulation model, and a review of prospective acoustic-improvement options (e.g., partitions, sound-absorbing elements). The findings of this case study, which may be relevant to other building extension and conversion projects, indicate that the acoustic conditions in the office space are not in compliance with applicable regulations. As a result, the study looked into the usability of the previously mentioned calibrated simulation model for the virtual exploration of possible acoustic improvement solutions.

Keywords

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1 INTRODUCTION

1.1 Overview

Creative ideas and concepts are always required to meet the expectations of the modern world. After the industrial revolution, the technologies improved and adapted to our needs at a speed that is not easy to follow. In architecture could not be different. New technologies require new concepts, and building science needs to be aligned with them to avoid negative building performance. Ecological aspects have also a big impact on the new concepts, and to meet the ecological requirements, the interior and exterior buildings geometry have to be evaluated as well.

There are simulation tools in acoustics that are used to analyze existing rooms and future projects. In simple rooms with easy geometry, the usage of a simulation tool is not always required because the experience with other similar projects is enough to design and choose materials that will result in a good acoustical performance. The challenge is to design complex areas and be sure to achieve acoustical quality. For these situations, an acoustic tool is fundamental to enable positive room performance. The simulation tool used in this study was Odeon (Odeon A/S, 2020).

TU Wien has an office area that is not satisfying the people who work there. They are having issues with noise protection and speech privacy, interfering in their comfort and productivity. There are glass walls to separate the rooms but not extended until the ceiling, so the colleagues in their single rooms are not fully private. They want to have more privacy, and to achieve their expectations or at least provide an improvement suggestion, a case study was conducted.

The case study included creating a digital model of the office, estimating the acoustically relevant properties of the relevant architectural elements, implementing a measurement plan to obtain the values of key acoustic performance indicators (specifically, sound level differences between office zones, reverberation times in different office rooms/areas), creating acoustic simulation models using a commercially available simulation tool, calibrating the results and analysis of potential acoustic improvement.

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1.2 Motivation

Building Science is a gap between the studies of civil engineers and architects, and often those professionals do not have the experience to analyze building performance using the appropriate tools. Sometimes simulation tools used in the analysis of thermal, acoustics, and visual aspects do not have many bibliographies and studies involved, and consequently not much is documented enough to learn those tools without proper education. Companies are normally interested in hiring professionals that present reliable results of building performance, so they can invest in something promising. It is important to do case studies using simulation tools to evaluate existing buildings and be able to analyze future projects providing good results. In the case of acoustics performance, the same approach is applied to have effective analysis.

People spend most of their daily time in the work environment. There are many difficult decisions to choose the right job and the right field of study. Once this decision is made and the expected job appears, not only the work itself matters, but also the environment, the colleagues, and what the company has to offer. Room acoustics plays an important role in terms of comfort, and if this domain has no quality, it can negatively impact the performance of employees and their life quality. Owners of buildings and designers often do not take this factor into account. When issues in room acoustics are explored, and often proved that this problem occurs very often, it can open the eyes of professionals from this field and it can bring value with findings that can support them in future.

1.3 Background

Architecture and acoustics have mutual influence but often just the room design is taken into consideration, while the acoustics is overlooked. (Trocka-Leszczynska and Jablonska, 2021). Therefore, the studies in the field of room acoustics are sometimes done in existing office rooms where the issue already exists. Figure 1 illustrates the result of a survey in an office center which shows neutral acoustic quality according to the occupants.

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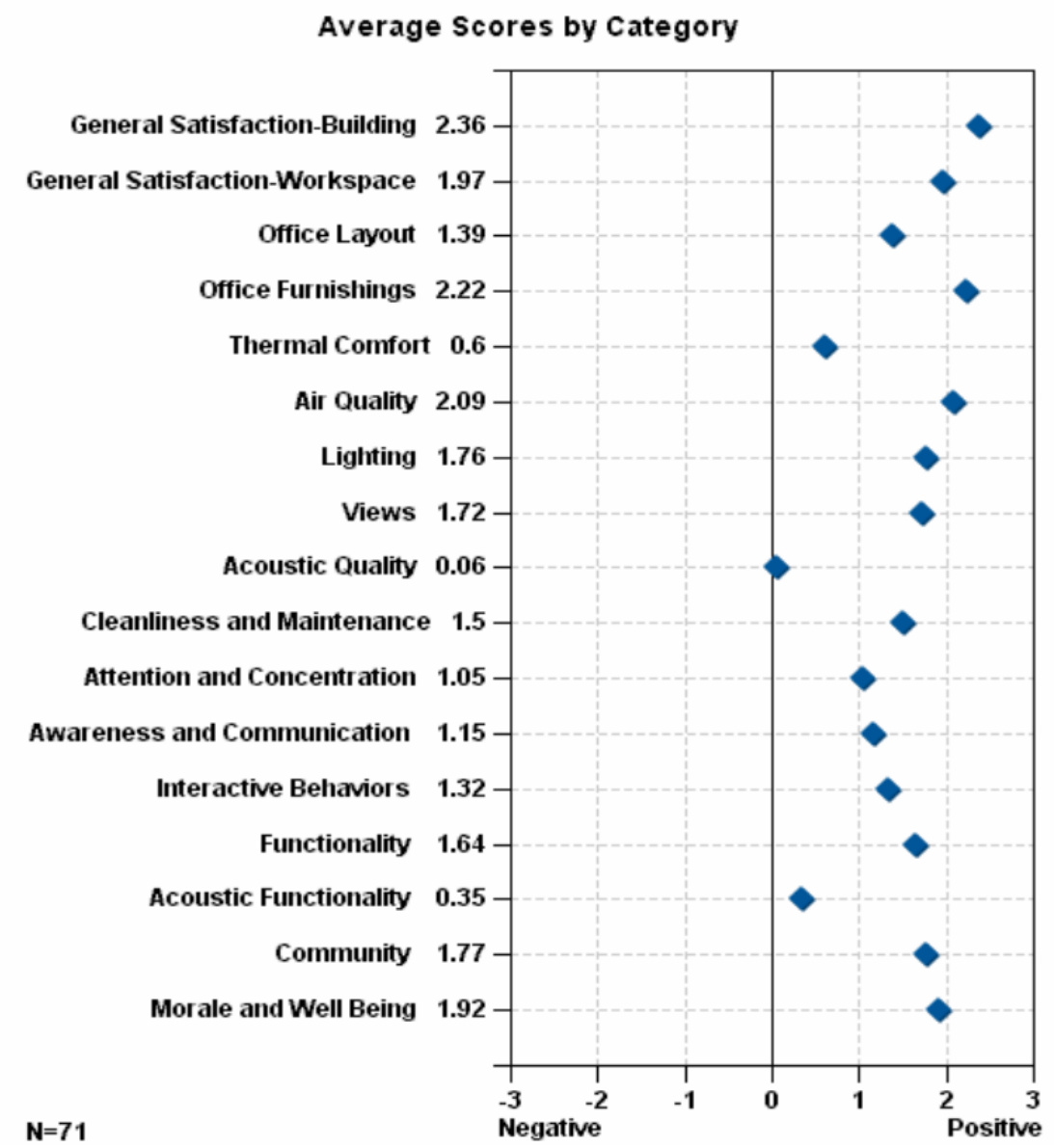

Figure 1: Survey responses about the Merrill Center building (source: Heerwagen, J and Zagreus, Leah 2005)

The field of acoustics known as room acoustics examines how a diffuse sound field made up of direct and reflecting sound propagates in a closed or semi-closed environment. As a result, room acoustics tries to describe a space's acoustic performance and indicate an optimized perception of the fullness of sound or clarity that corresponds to the space's intended purpose. (Willems et al., 2018)

The acoustic condition of a room is determined by the geometry of the space, sound absorption qualities, and the location of surface material present in the room, as well as the positions of sound sources and point receivers. (Fasold & Veres, 2003). These

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characteristics determine a space's acoustic quality, which indicates a room's suitability for a specific purpose according to DIN 18041: 2016.

Simulations can be done during the design phase or post-occupancy. When it is done in existing rooms, either the intention is to compare the simulation results with the measurements and have a reliable simulation model to suggest an improvement or it is an area difficult to evacuate and be able to do the measurements, like a hospital. In the case of an office area, it is normally not a problem to have the necessary conditions to do the measurements. The occupants cannot be in the office, and it can be easily done on weekends.

The analysis can be objective when measurements or simulations are conducted, or subjective when questionnaires are applied to the occupants. The second analysis is normally done in this field of study because the occupant's perception is very important. The consequences of the neglected study impact directly their work efficiency, health, and comfort (Trocka-Leszczynska and Jablonska, 2021). The noise in the office can come from outside the building because the construction is old or lack insulation or its source is the objects and people inside the office. The materials and machines produce sounds that can distract people or interrupt their production when the sound level is too high. According to Trocka-Leszczynska. and Jablonska (2021), the sound level can reach up to 70 dB in an office area, a value that is above 40 dB which is considered the limit in the Polish Norm PN-B-02151-2:2018-01-Building Acoustics - Protection from noise in a building.

Another consequence of bad insulation is also the vibration that some construction elements and surfaces may suffer due to the noise – i.e. phone ringing, movement of people, materials, and objects. Those noises are called background noise. There is also reverberation, which can be distracting in addition to the background noise. Excessive noise disturbances and long reverberation times reduce speech clarity.

Reverberation is the propagation of sound that continues after the sound was emitted. According to Sabine equation, the RT 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 [m^3]

A = total area of absorption in room [m^2]

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The sound emitted can overlap the current sound, which can be a speech issue. It is not the same as an echo. The sound reflects the surface, just like in the case of reverberation, but it does not occur in small distances where the source and surface are close to each other.

Studies were done in office areas and there are suggestions of what can be improved to improve the acoustic performance: use absorbing and diffusing divisions to separate the spaces, use absorbing materials on the building components – i.e. walls, ceiling, and floor, use absorbing solutions and materials, and allocate equipment or machines that produce sound, like printers, in a separated area (Trocka-Leszczynska and Jablonska, 2021). Those changes can drop the reverberation and bring more life quality for the employees and consequently increase their production.

According to the research done by Artan Ilter et al. (2019), the noise level and acoustic privacy are the worst for the majority who work at the office. The noise which disturbs them the most is the conversation. People talking can easily distract others, so they cannot perform their work efficiently. Other sounds are included in the noise level like footsteps, equipment, and ventilation. Privacy is another point that most people complained about. In the work environment is important to have privacy because not all topics are shared openly. When employees do not have acoustic privacy, information can leak and compromise the company.

Other studies in acoustics of office-space areas were conducted by Kaarlela-Tuomaala et al. (2009). A book “Office Buildings” by Pranab Kumar Nag (2019) presents indoor quality in office buildings, including acoustic characteristics and how acoustic issues can influence in people’s health and producitivity.

More surveys analyzed offices area which acquired similar results. Jensen et al. (2005) analyzed the data collected by the Center For The Built Environment (CBE) to make a post-occupancy evaluation regarding acoustical quality. Their findings were similar to the research before: acoustic privacy followed by noise level are the two mains complain. The more dissatisfied people are the ones who do not have their rooms, rather have their workstations in cubicles as shown in Figure 2.

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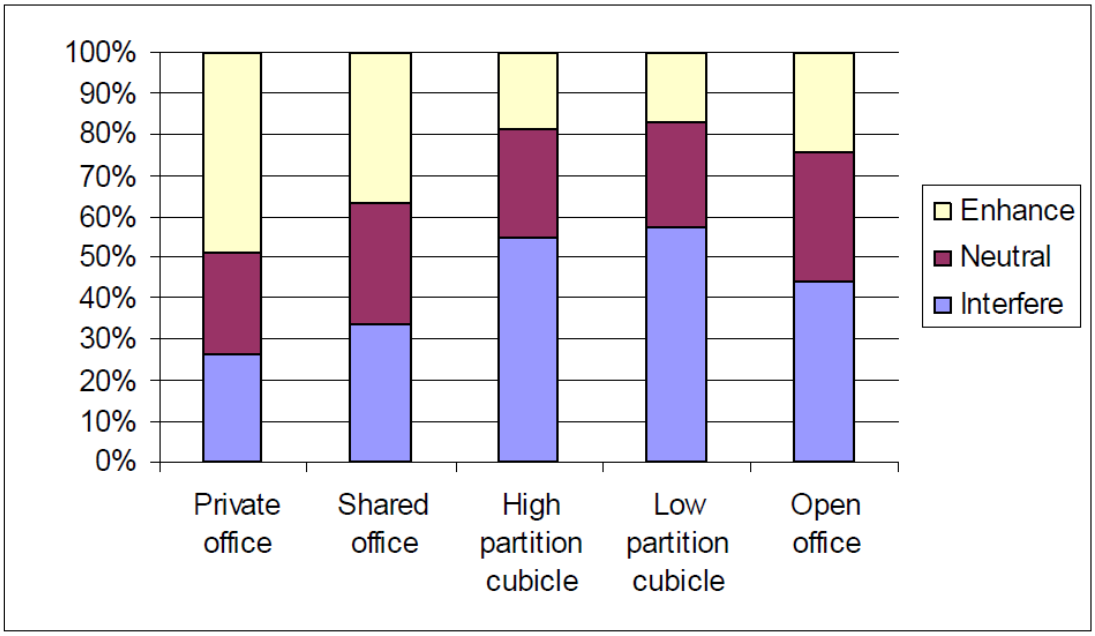

Figure 2: Percentage of employees who consider that acoustic quality either enhances, interferes or has no impact on their capability to have their work done. (source: Artan et al. 2019)

The employees in the open office area are used to hearing noises and conversations. However, they interfere with their ability to do their job. Open office spaces do not necessarily have a lack of acoustic privacy and noise level. It all depends on how the area was designed and which measures were applied to give people more privacy in their workspace.

Kim, J., & Dear, R. de (2013) analyzed as well the database of the CBE to differ the responses of occupants of different office layouts. On the perceptions of privacy, acoustics, and proxemics, there was a significant difference between occupant groups in private and open-plan offices. The main causes of workplace discontent in open-plan office design were identified as noise distraction and loss of privacy.

A post-occupancy evaluation was done by Heerwagen, J. and Zagreus, L (2005), of the Philip Merrill Environmental Center at Annapolis, MD. During the evaluation, they interviewed the occupants to know how they consider that ambient conditions enhance or interfere in their ability to get their job done. Figure 3 illustrates that 30% consider that noise and speech privacy interfere in their work and the same percentage think that acoustics can enhance their ability to do their work.

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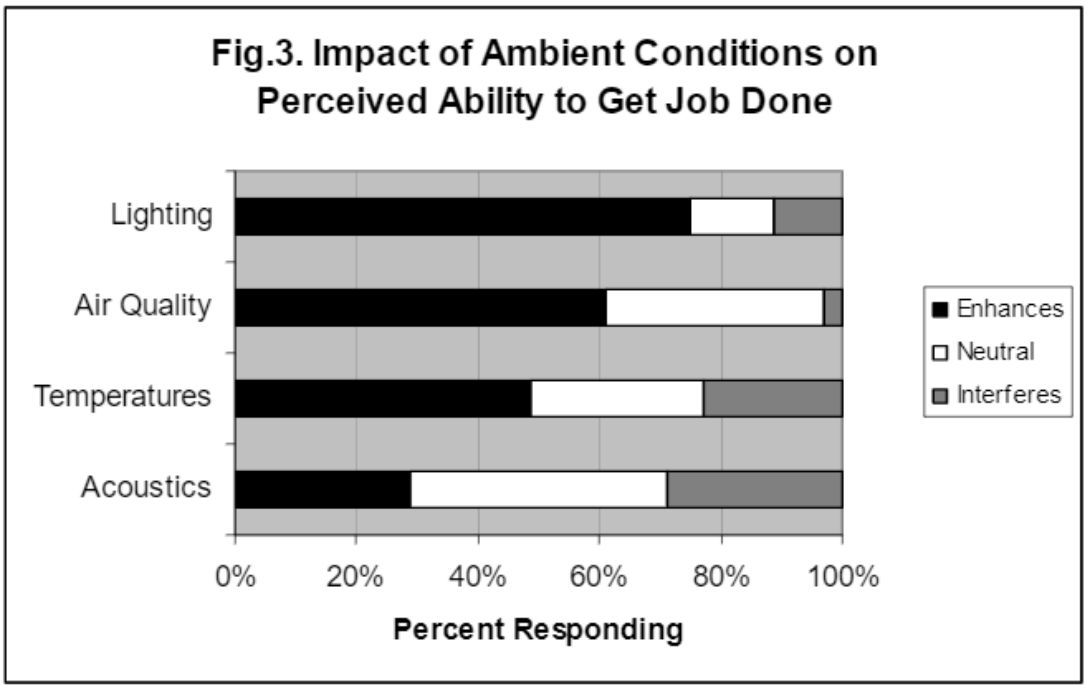

Figure 3: Impact on perceived work effectiveness (source: Heerwagen, J and Zagreus, Leah 2005)

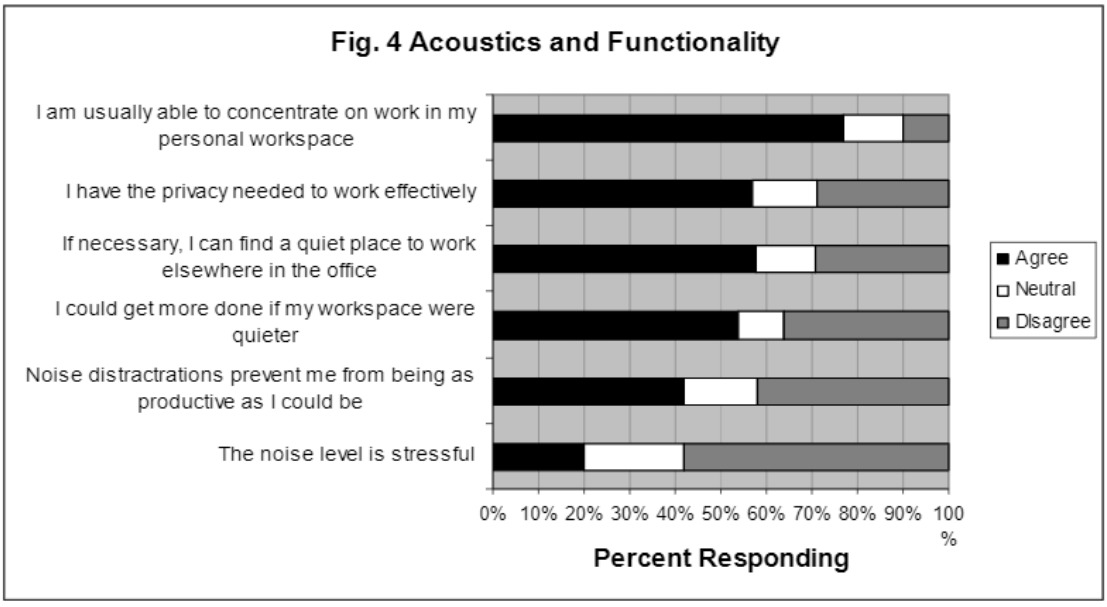

Figure 4: Questions on acoustical functionality and the occupant's answers (source: Heerwagen, J and Zagreus, Leah 2005)

Questions about acoustical functionality and concentration were also applied during the survey, as Figure 4 shows, and the majority consider that they can concentrate and find a good quiet place, in case they need it. The interesting part is that even

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though they think the acoustics do not interfere so much in their work, approximately 55% were not satisfied with the speech privacy and 30% with the noise levels. The problems regarding acoustics, according to the occupants of the survey, include people talking nearby or on the phone, and no privacy.

The complaints are frequently the same in different offices. However, the occupants do not always agree that noise and speech privacy interfere with their ability to work. It can depend on the type of business. Some business environments are more dynamic and people are used to noises, in general - i.e. sound of voices, phone ringing, and footsteps. Some offices are quieter and people need to be very focused, so any noise can be a distraction. It is important to consider the business type.

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2 METHOD

2.1 Overview

The literature and standards used for the analysis of the measurements and simulation results were always based on the acoustics of office areas and open-plan offices.

The first step is the measurements when the occupants are not in the office. Any sound caused by people can deviate from the precision of the measurements. The speaker (source) and the receivers were placed in each office room. Figures 5 and 6 show the location where all the speakers and receivers were placed during the measurements.

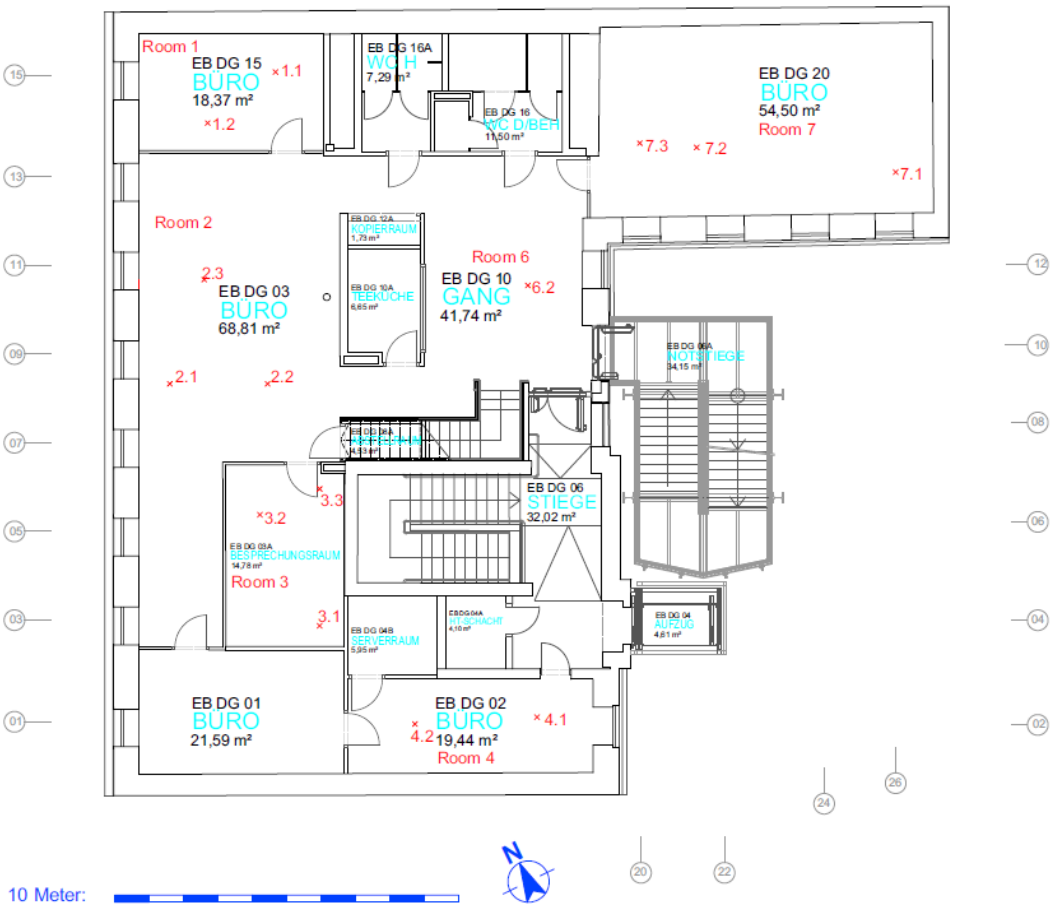

Figure 5: Location of speakers and receivers on the first floor of the office

Each point has a number that represents the room or area, and the speaker or receiver, respectively. The speaker is always the number 1, and the receiver is

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number 2 or more. Room 2, for example, has 3 points: 2.1, 2.2, and 2.3. The first point, 2.1, is where the speaker is allocated in room 2. Points 2.2 and 2.3 are where the receivers are allocated in room 2.

The rooms are enumerated and only from 1 until 7 are part of the analysis.

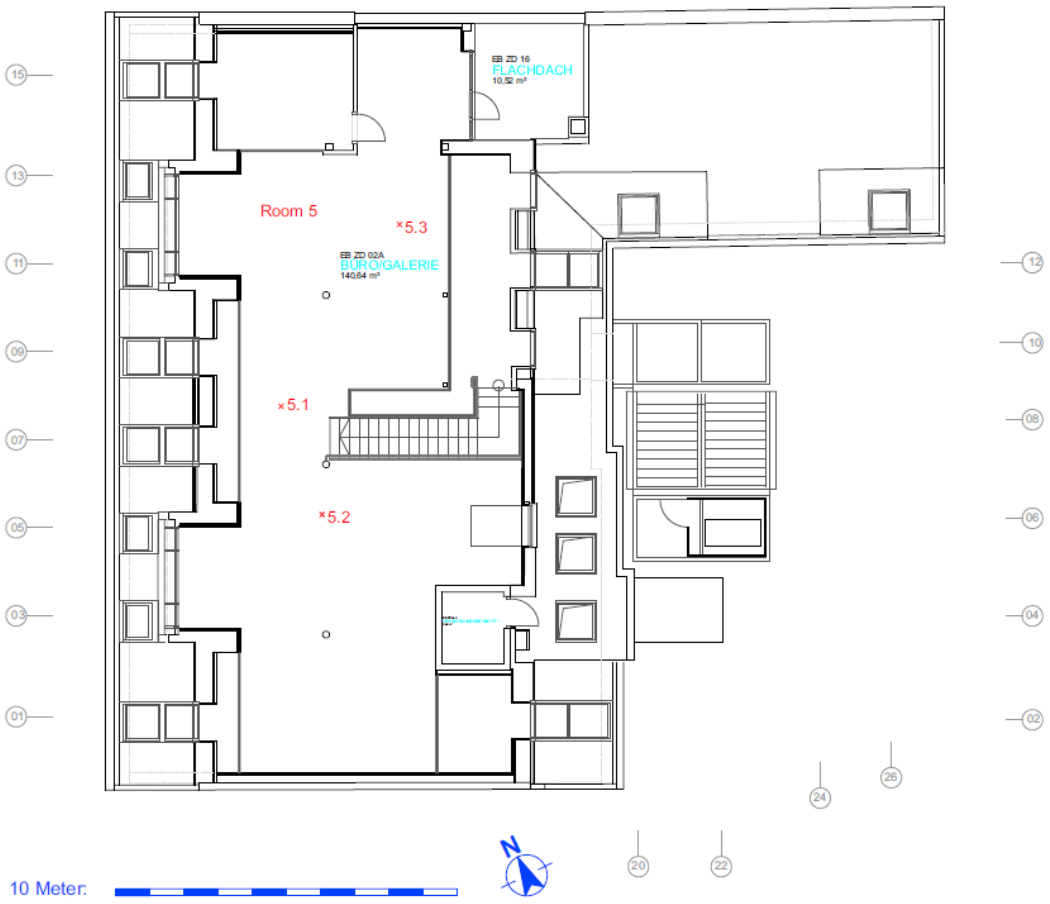

Figure 6: Location of speakers and receivers at the gallery

The measurements on-site had the purpose to identify the reverberation time, sound pressure level distribution, and background noise levels.

The simulations were conducted with Odeon 11.0, that is an acoustic software and the design was modeled in Sketchup 2017. The materials used from Odeon's library were chosen according to the estimation of the acoustically relevant properties of the pertinent architectural elements. The second simulation had to be done to calibrate the simulation model based on measured data.

The receiver and speaker were in the same position in the simulation and on-site.

The reverberation time from the simulation was averaged in rooms 2, 5, and 7 because there were two receiver positions with two different reverberations in each

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room. The reverberation is per room. Thus, the average had to be done to have a single value in each room.

Moreover, an interview took place with some occupants that are harmed by the acoustics issues. The interview provides information regarding acoustics comfort and how the acoustics aspects are perceived by the occupants at the current state. The information gathered during the interview is relevant to know where the crucial places are which shall be evaluated to be improved and to have a better understanding of how they feel to be able to suggest an appropriate improvement.

Finally, the utilization of the calibrated simulation model toward modeling and evaluation of potential acoustic improvement measures. The proposed solution is based on the final simulations, which the responsibles for the office space can choose to accept or find another solution to improve the acoustic quality in their office.

2.2 Hypothesis

Some materials have a low absorption index which often results in acoustic issues. In this case study, the materials used on the surfaces are possibly not the best ones considering that the rooms are not fully closed. Figure 7 is room number 4 where the occupants claim to hear the people from another extremity, like from room 1. The sound propagates easily because there are no barriers that absorb it.

Figure 7: Office room number 4

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2.3 Case Study

The case study is an office area in Vienna, Austria, that was recently finished and covers around 350 m^2. It has a meeting room, an open-plan office space, and some private offices. A gallery connects the individual areas to the larger open-plan office room., as shown in Figures 8, 9, and 10. The occupants started to work recently in the office and are having acoustic quality issues. Even though there are glass compartments to separate the rooms, the occupants are still able to listen to each other because those compartments are not extended until the ceiling, so the sound can propagate without the interference of walls.

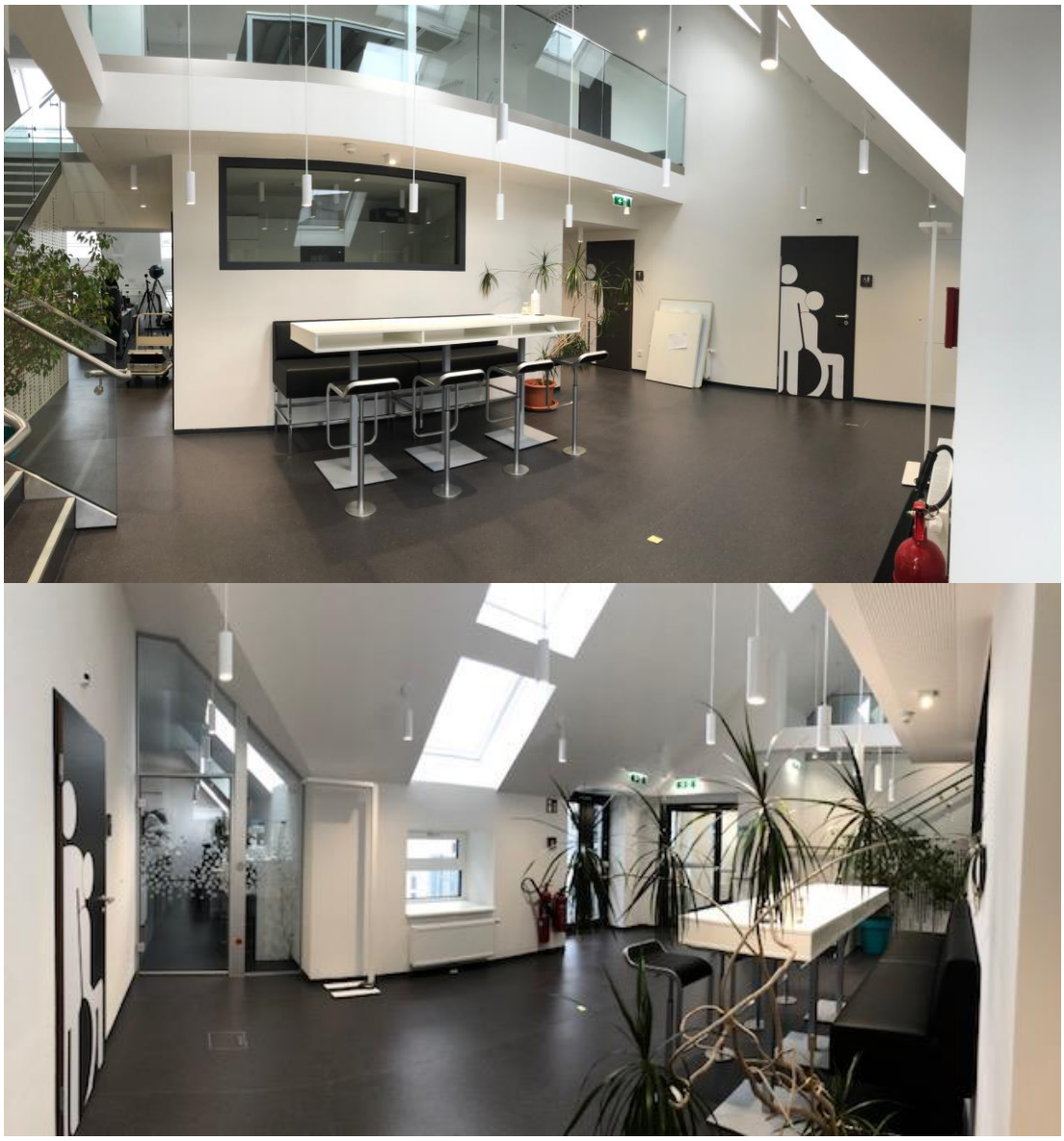

Figure 8: Entry Hall of the office where the measurements were conducted (TU Wien Faculty of Architecture and Planning)

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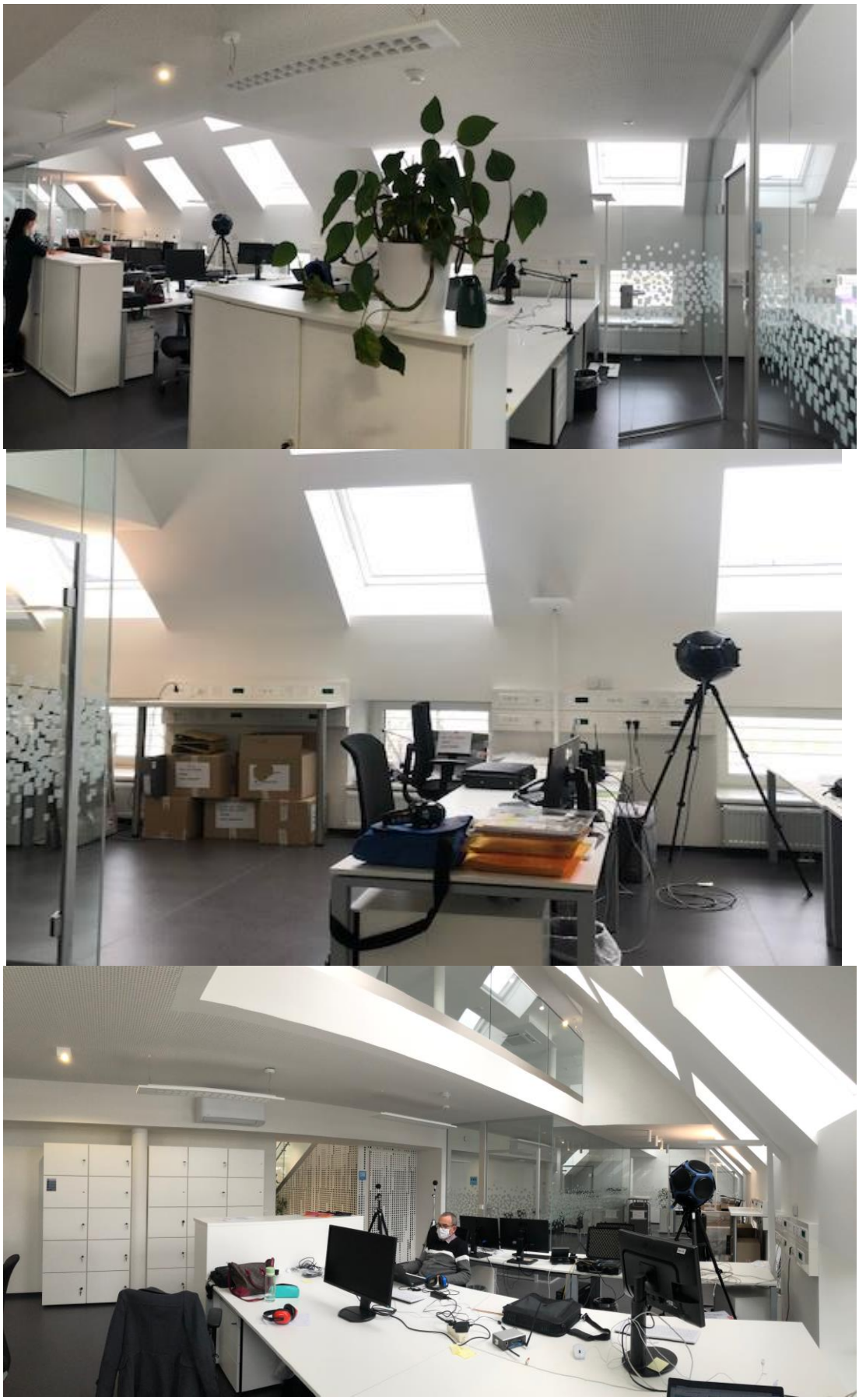

Figure 9: Open office where the measurements were conducted (TU Wien Faculty of Architecture and Planning))

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Figure 10: Attic of the office where the measurements were conducted (TU Wien Faculty of Architecture and Planning)

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2.3.1 Interview with occupants

The people selected to answer the interview were the occupants that have their workstations in the office area. Thereby, it is possible to have a better understanding of how the occupants are affected according to where they work. Each participant received an email with the questionnaire which was developed according to standards and based on Figure 4 from Heerwagen, J. and Zagreus, L (2005), to be able to compare the results with other scientific papers.

2.3.2 Acoustical Measurements

The measurements were done during the morning on a week day where the occupants were aware that we would need the office empty. One technician was responsible for the measurements and the equipment necessary, while two people were collecting the data moving the receiver and speaker accordantly. The speaker was the Dodecahedron Loudspeaker Nor276 from Norsonic and the power amplifier is the Nor280, also from Norsonic. The duration to conduct the measurements of the background noise and the sound pressure level shall be specified in the sound analyzer. The duration was 20 seconds.

The location of the speakers was according to where the noise source comes from. Those places are where the people have their workstations or where they have meetings. Room 7 was analyzed individually because it is not connected to the other rooms. There are pieces of furniture used to divide the room into three areas and give more privacy to the occupants, as Figure 11 shows.

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Figure 11: Office room number 7

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While the speaker is on, a very loud sound propagates in the whole office area. The receivers had to be allocated in different places according to Figures 5 and 6. The location of the receivers was the same for each speaker.

The speaker was approximately at the height of 1.70 meters and the receivers 1.20 meters.

Each time the receiver was placed in a different position, the sound level meter Nor140 from Norsonic was activated and the data were collected during the next 20 seconds. This value can change, and it was decided by the technician. The data is the sound level in decibel.

The first part of the measurements was the background noise, and the second part was the reverberation time. The reverberation time is measured using the computer, the appropriate acoustic software, speaker, and only one receiver. For this case study, the software was Norsonic CtrBuild. Again, a very loud sound is emitted through the power amplifier and when it stops, the software connected to one receiver collects how long it took to the sound level drop by 60dB. The measurements were conducted according to the position in Table 1.

Table 1: The position of speaker and receivers for the reverberation time measurement.

Room	Speaker and Receiver position
1	1.1 - 1.2
2	2.1 - 2.2 and 2.1 - 2.3
3	3.1 - 3.2
4	4.1 - 4.2
5	5.1 - 5.2 and 5.1 - 5.3
7	7.1 - 7.2 and 7.1 - 7.3

Both, background noise and reverberation time, are fundamental to analyzing the acoustic quality. Besides those two, there are more measurements that can be supportive and complement the acoustic analysis.

The third part of the measurements was the sound level distribution.

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2.3.3 Acoustic Simulations

The simulation part started with the design in SketchUp. The office area had to be designed separated from room 7. The surfaces had to be named according to each building component – i.e., walls, interior walls, floor, and roof. It was important because in Odeon the materials are assigned and without the names, it can take too long to know what each layer is. Figure 12 illustrates the design of the office area and where to name the surfaces.

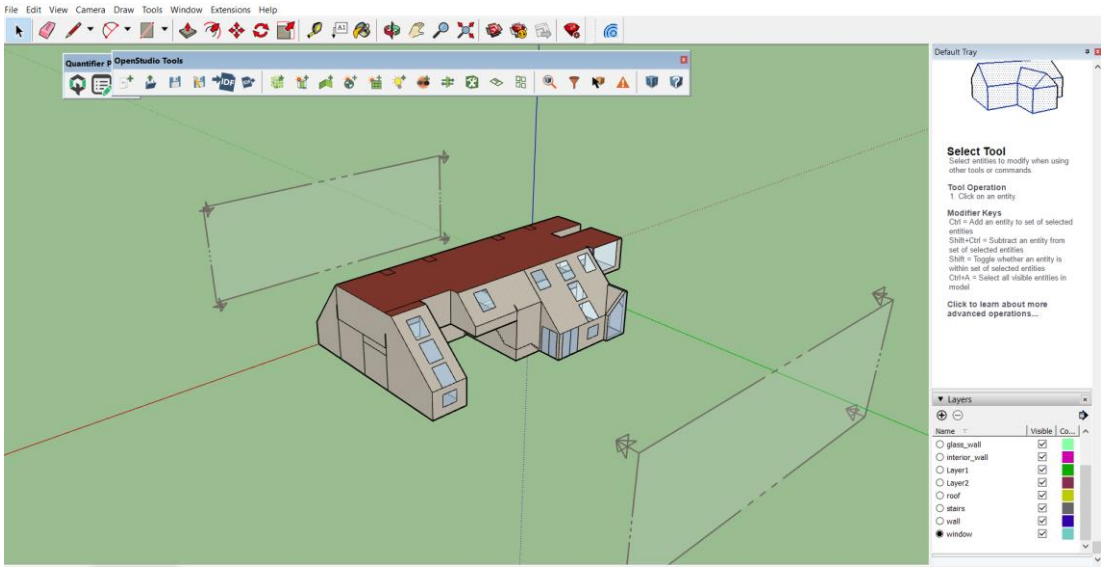

Figure 12: Office designed in SketchUp

The materials were assigned in SketchUp only for visualization purposes. It has to be done one more time in Odeon, so the materials do not have to be chosen before.

To import the file, the Odeon extension had to be installed.

The volume has to be calculated because in Odeon this information is sometimes not reliable. Therefore, the volume of Room 7 was collected from SketchUp and has 175.84 m^3. The volume of the office area is 988 m^3, excluding Room 7.

The first step in Odeon is to assign the materials according to Odeon's library. The list of materials chosen for each building component is listed in Table 2. The materials were chosen for the first simulation. In the second simulation, some materials changed in order to have similar values compared to the measurements. Table 3 illustrates the second list of materials and Table 4 the sound absorption coefficients by frequency.

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Table 2: List of materials assigned in Odeon for the first simulation

Building components	Materials
Security barrier	10001 - Single panel of glass
Glass wall	10005 - Glass, large panes of heavy plate glass
Interior glass door	10005 - Glass, large panes of heavy plate glass
Floor	6000 - Linoleum or vinyl stuck to concrete
Stairs	6000 - Linoleum or vinyl stuck to concrete
Interior wall	4036 - Plaster, gypsum, or lime, smooth finish on lath
Roof	4036 - Plaster, gypsum, or lime, smooth finish on lath
Exterior wall	4002 - Painted plaster surface (Kristenses, 1984)
Side of the stairs	4002 - Painted plaster surface (Kristenses, 1984)
Window	10004 - Double glazing 2-3 mm glass > 30 mm
External door	10004 - Double glazing 2-3 mm glass > 30 mm
Ceiling between 1st and 2nd floor	4050 - Plasterboard 9.5 mm with 6 mm o holes in square pattern with approx. 11% perforation. 100 mm from wall with 25 mm mineral wool at front of cavity (Kristensen, 1984)"

Table 3: List of materials assigned in Odeon for the second simulation

Building components	Materials
Security barrier	10001 - Single panel of glass
Glass wall	10005 - Glass, large panes of heavy plate glass
Interior glass door	10005 - Glass, large panes of heavy plate glass
Floor	6000 - Linoleum or vinyl stuck to concrete
Stairs	6000 - Linoleum or vinyl stuck to concrete
Interior wall	4036 - Plaster, gypsum, or lime, smooth finish on lath
Roof	4038 - Acoustic plaster (Kristensen, 1984)
Exterior wall	4036 - Plaster, gypsum, or lime, smooth finish on lath
Side of the stairs	4002 - Painted plaster surface (Kristenses, 1984)
Window	10004 - Double glazing 2-3 mm glass > 30 mm
External door	10004 - Double glazing 2-3 mm glass > 30 mm
Ceiling between 1st and 2nd floor	4050 - Plasterboard 9.5 mm with 6 mm o holes in square pattern with approx. 11% perforation. 100 mm from wall with 25 mm mineral wool at front of cavity (Kristensen, 1984)"

The glass walls of the meeting room (Figure 13) cannot be simply assigned like the other surfaces, otherwise, it is not possible to simulate the interaction of the meeting room with the other spaces.

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Figure 13: Meeting room (Room 3 according to Figure 5) (TU Wien Faculty of Architecture and Planning)

It happens because the materials are not set up to transmit sound waves, they only absorb. It means a room with no openings is fully insulated and the sound keeps only inside the room. The two glass walls of the meeting rooms had to be setup up to “Transmission” and the reduction indexes had to be specified for the different frequencies, as Figure 14 shows. The values were based on the technical bulletin of Pilkington United Kingdom Limited, 2021. Figure 15 illustrates the table for single glazing with reduction indexes for frequencies from 100Hz to 4000Hz. The values of the single glazing with the thickness of 6mm were selected to be used in this case. Odeon requires reduction indexes at more frequencies which were adapted.

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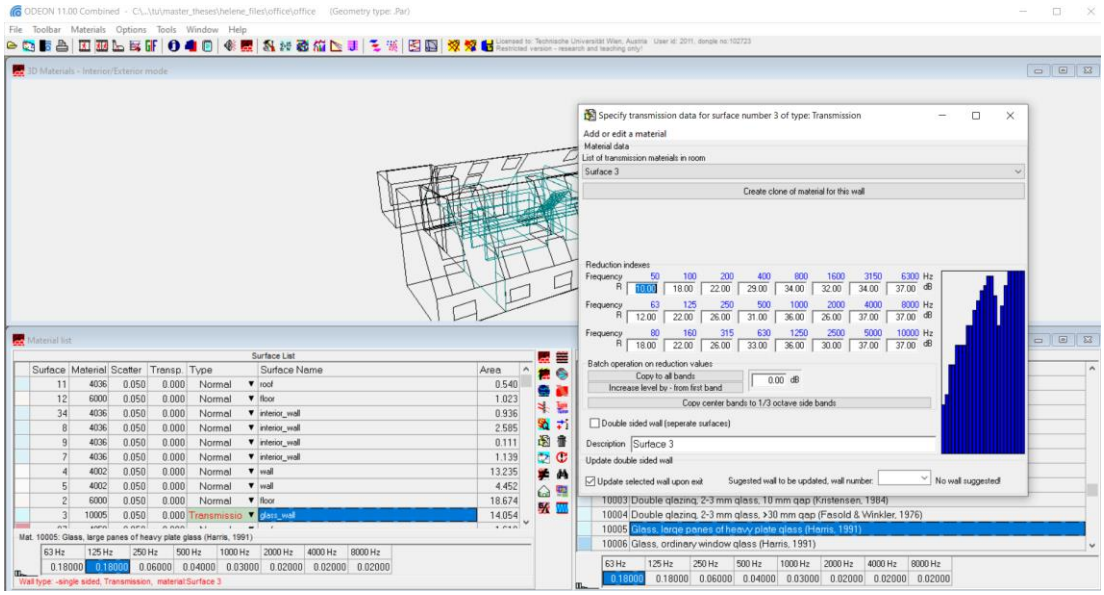

Figure 14: Reduction indexes for single glazing of 8mm

Table 4: List of materials assigned in Odeon for the second simulation with respective sound absorption coefficients by frequency

Materials assined in Odeon	sound absorption coefficients by frequency							
	63 Hz	125 Hz	250 Hz	500 Hz	1.000 Hz	2.000 Hz	4.000 Hz	8.000 Hz
10001 - Single panel of glass	0.18	0.18	0.06	0.04	0.03	0.02	0.02	0.02
10005 - Glass, large panes of heavy plate glass	0.18	0.18	0.06	0.04	0.03	0.02	0.02	0.02
6000 - Linoleum or vinyl stuck to concrete	0.02	0.02	0.02	0.03	0.04	0.04	0.05	0.05
4036 - Plaster, gypsum, or lime, smooth finish on lath	0.14	0.14	0.10	0.06	0.04	0.04	0.03	0.03
4038 - Acoustic plaster (Kristensen, 1984)	0.15	0.15	0.25	0.40	0.55	0.60	0.60	0.60
4002 - Painted plaster surface (Kristenses, 1984)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
10004 - Double glazing 2-3 mm glass > 30 mm	0.15	0.15	0.05	0.03	0.03	0.02	0.02	0.02
4050 - Plasterboard 9.5 mm with 6 mm o holes in square	0.08	0.08	0.20	0.50	0.40	0.40	0.35	0.35

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Thirdoctaveband Centre Frequency (Hz)	Sound Insulation (dB) for Glass Thickness (mm)									
	4		6		10		19		6.4 PVB	
100	17		18		24		25		18	
125	23	20	22	20	26	26	29	28	22	20
160	22		22		28		31		22	
200	21		22		26		31		22	
250	21	22	26	24	28	27	32	32	26	24
315	24		26		29		35		26	
400	26		29		32		36		29	
500	29	28	31	31	34	34	38	37	31	31
630	30		33		36		36		33	
800	32		34		37		35		34	
1000	34	33	36	35	36	35	38	37	36	35
1250	34		36		33		40		36	
1600	36		32		33		44		36	
2000	36	34	26	29	38	36	47	46	34	33
2500	31		30		41		50		31	
3150	25		34		43		52		35	
4000	31	28	37	36	44	44	55	54	39	38
R_m (dB)	27		29		33		37		30	
R_w (dB)	30		32		36		40		33	
R_{TRA} (dBA)	27		28		32		35		29	

Figure 15: Reduction indexes for single glazing of 8mm (Pilkington United Kingdom Limited, 2021)

The next step is to insert the sound sources and the receivers according to where they were located during the measurements. The sound source inputs are the position, the type of sound source, and the power of the sound. The type of sound source is omnidirectional radiation. The receivers just require the position.

Furthermore, it has to be set up the calculation parameters and air conditions. In calculation parameters, the impulse response length is the highest reverberation time collected previously. This value determines how many milliseconds the decay curves are calculated. The number of late rays is 16000 according to the suggestion of Odeon when PRECISON is chosen. This option is the most accurate because it has the longest calculation time. In case the decay curve is not smooth, the number of rays must be increased. The air condition was set up to 22 degrees for air temperature and 30% relative humidity. Those values are an estimation but necessary because they influence sound propagation. The other paraments remain the same.

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The last step, before running the simulation, is to define jobs, which means the relationship between source and receiver. Between rooms 1 until 6, all speakers were related to one receiver. Room 7 is the only one where the speaker (7.1) is related only to the receiver from the same room (7.2 and 7.3), as was done during the measurements. There are in total 47 jobs.

2.3.4 Improvement Simulations

The implemented room acoustical changes were to increase room absorption and close the openings of private rooms.

The first improvement simulation was geometry-related change. The openings that connect the individual office spaces were closed. The glass material is the same used for the glass walls of the meeting room, and the same reduction indexes.

The second improvement simulation had not only the geometry-related change from the previous simulation but also the material-related change. A material with a higher absorption index from Odeon's library was added to the flat and sloped part of the ceiling. The material chosen is the 13003 (100 mm thick wood-wool against ceiling).

Table 5: Sound absorption coefficients of material used for improvement in Odeon

Materials assined in Odeon	sound absorption coefficients by frequency							
	63 Hz	125 Hz	250 Hz	500 Hz	1.000 Hz	2.000 Hz	4.000 Hz	8.000 Hz
13003 - 100 mm thick wood-wool, against ceiling	0.58	0.58	0.69	0.96	0.97	0.99	0.91	0.91

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3 RESULTS

3.1 Results of the current state simulation and measurements

The sound pressure level difference from the measurements and the simulation, and the speech transmission index values from the simulation are illustrated in Figure14. Only the results of the second simulation were considered because it was calibrated.

Speaker Position	Receiver Position	SPL speaker position dB(A) (=receiver closest to speaker)		SPL receiver position dB(A)		SPL Difference dB(A)		Speech transmission index STI
		Measurement	Simulation	Measurement	Simulation	Measurement	Simulation	Simulation
1.1	1.2-5.3	107.1	81.6	97.0	67.3	10.1	14.3	0.5
1.1	1.2-5.2	107.1	81.6	93.8	62.3	13.3	19.3	0.5
1.1	1.2-6.2	107.1	81.6	92.4	63.4	14.7	18.2	0.4
1.1	1.2-2.2	107.1	81.6	85.3	60.5	21.8	21.1	0.4
1.1	1.2-4.2	107.1	81.6	84.8	54.0	22.3	27.6	0.4
1.1	1.2-2.3	107.1	81.6	84.3	59.4	22.8	22.2	0.3
1.1	1.2-3.2	107.1	81.6	65.2	33.2	41.9	48.4	0.3
2.1	2.2-2.3	102.2	78.1	101.5	78.2	0.7	-0.1	0.5
2.1	2.2-6.2	102.2	78.1	95.5	71.4	6.7	6.7	0.4
2.1	2.2-5.2	102.2	78.1	95.2	65.5	7.0	12.6	0.5
2.1	2.2-5.3	102.2	78.1	93.8	66.3	8.4	11.8	0.5
2.1	2.2-1.2	102.2	78.1	86.9	58.5	15.3	19.6	0.3
2.1	2.2-4.2	102.2	78.1	85.3	57.3	16.9	20.8	0.4
2.1	2.2-3.2	102.2	78.1	82.0	51.2	20.2	26.9	0.4
3.1	3.2-2.2	109.0	81.1	81.2	51.2	27.8	29.9	0.4
3.1	3.2-2.3	109.0	81.1	78.2	50.9	30.8	30.2	0.4
3.1	3.2-6.2	109.0	81.1	72.5	44.5	36.5	36.6	0.4
3.1	3.2-5.3	109.0	81.1	70.6	39.2	38.4	41.9	0.4
3.1	3.2-5.2	109.0	81.1	70.4	38.0	38.6	43.1	0.4
3.1	3.2-1.2	109.0	81.1	64.4	31.9	44.6	49.2	0.3
3.1	3.2-4.2	109.0	81.1	63.1	29.1	45.9	52.0	0.3
4.1	4.2-1.2	106.4	82.9	85.6	53.8	20.8	29.1	0.4
4.1	4.2-6.2	106.4	82.9	90.0	58.9	16.4	24.0	0.4
4.1	4.2-5.2	106.4	82.9	97.2	67.5	9.2	15.4	0.5
4.1	4.2-5.3	106.4	82.9	91.5	59.8	14.9	23.1	0.5
4.1	4.2-2.2	106.4	82.9	84.1	57.9	22.3	25.0	0.3
4.1	4.2-2.3	106.4	82.9	84.4	57.5	22.0	25.4	0.3
4.1	4.2-3.2	106.4	82.9	71.5	29.4	34.9	53.5	0.3
5.1	5.2-5.3	103.1	72.3	101.5	69.9	1.6	2.4	0.7
5.1	5.2-6.2	103.1	72.3	99.4	69.2	3.7	3.1	0.5
5.1	5.2-1.2	103.1	72.3	94.7	64.6	8.4	7.7	0.5
5.1	5.2-2.2	103.1	72.3	94.6	70.4	8.5	1.9	0.5
5.1	5.2-2.3	103.1	72.3	94.3	70.5	8.8	1.8	0.5
5.1	5.2-4.2	103.1	72.3	93.6	65.4	9.5	6.9	0.5
5.1	5.2-3.2	103.1	72.3	73.2	43.2	29.9	29.1	0.4

Figure 16: STI and SPL difference in the office area according to measurement and simulation

The SPL difference of measurements are also illustrated in the graphs below. The simulation results are in the Appendix.

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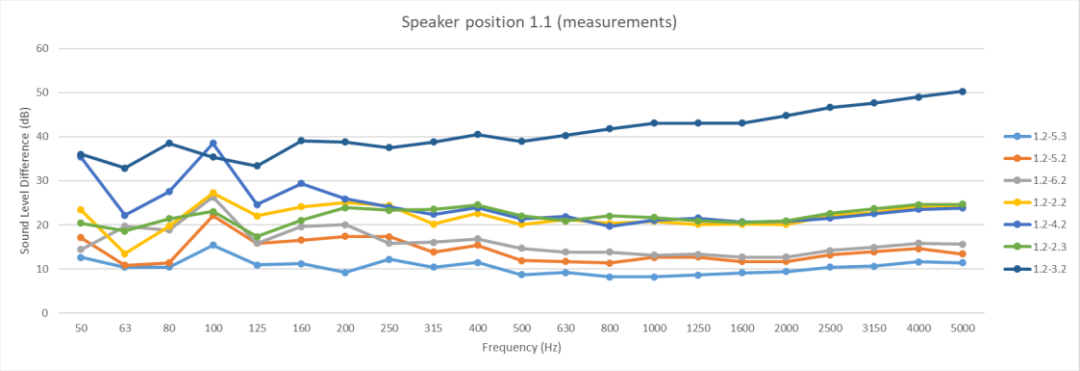

Figure 17: Sound pressure level difference (dB) for speaker in Room 1 according to measurements on site

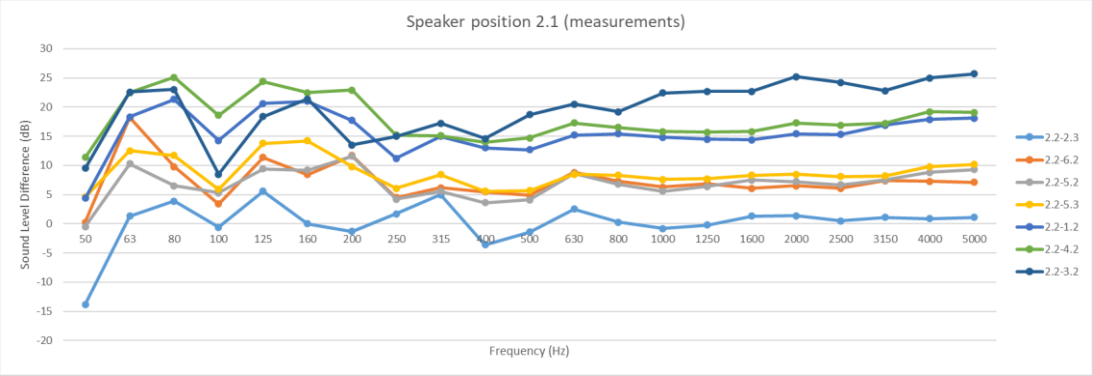

Figure 18: Sound pressure level difference (dB) for speaker in Room 2 according to measurements on site

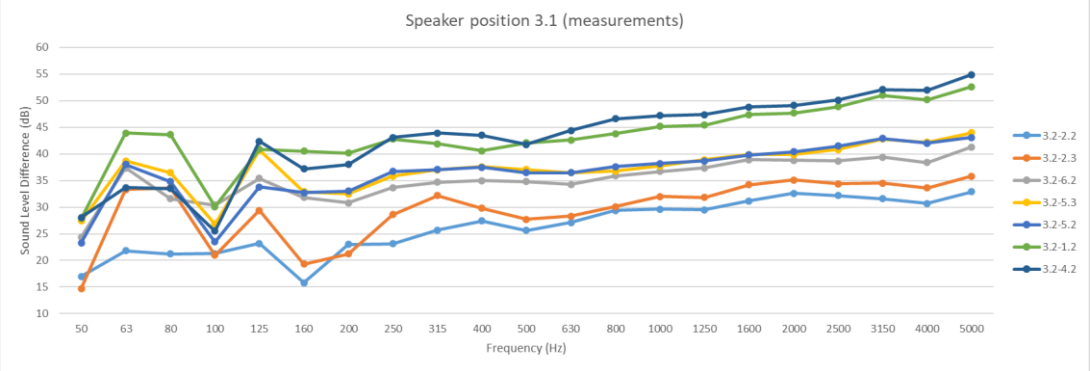

Figure 19: Sound pressure level difference (dB) for speaker in Room 3 according to measurements on site

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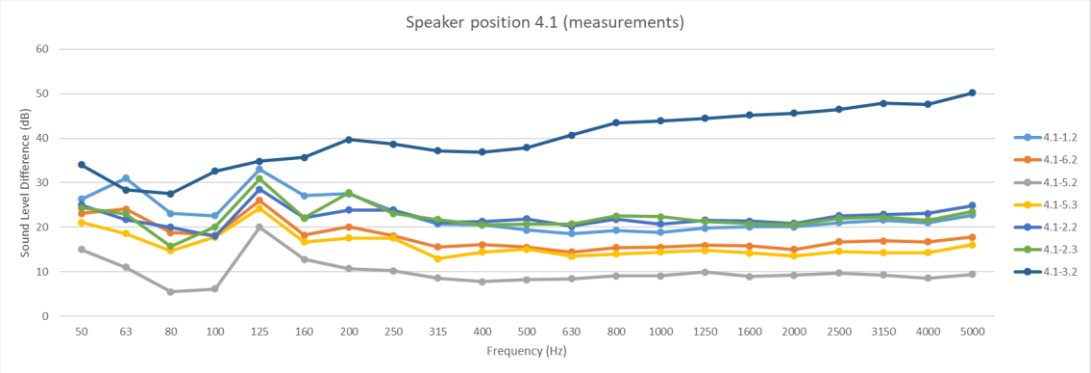

Figure 20: Sound pressure level difference (dB) for speaker in Room 4 according to measurements on site

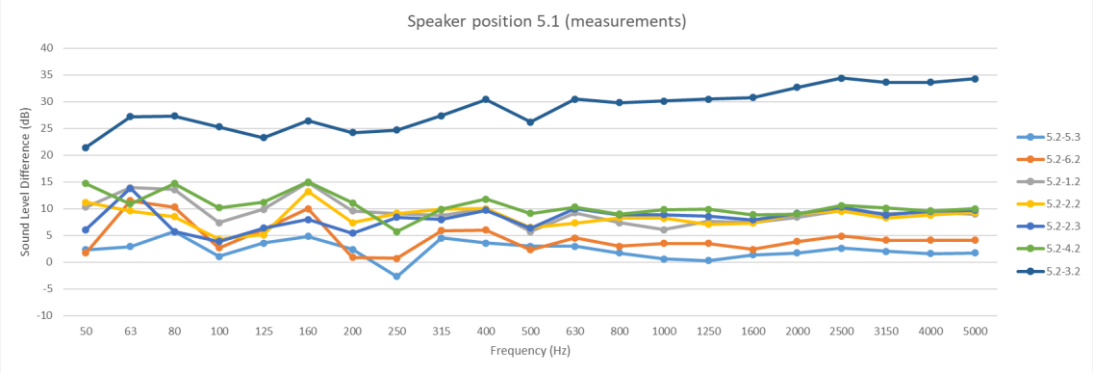

Figure 21: Sound pressure level difference (dB) for speaker in Room 5 according to measurements on site

When the distance between the source and receiver is higher than 8 meters, the reverberation is not applied (VDI 2569, 2019). Therefore, the reverberation time has to be analyzed for each room.

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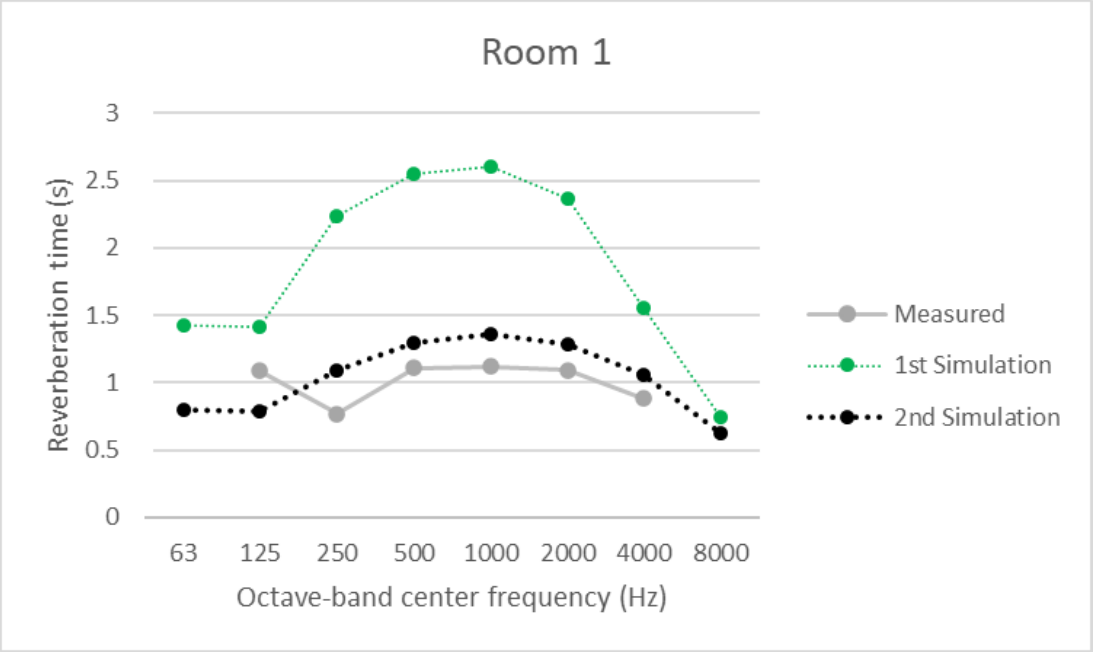

Figure 22: Reverberation TIme - Room 1

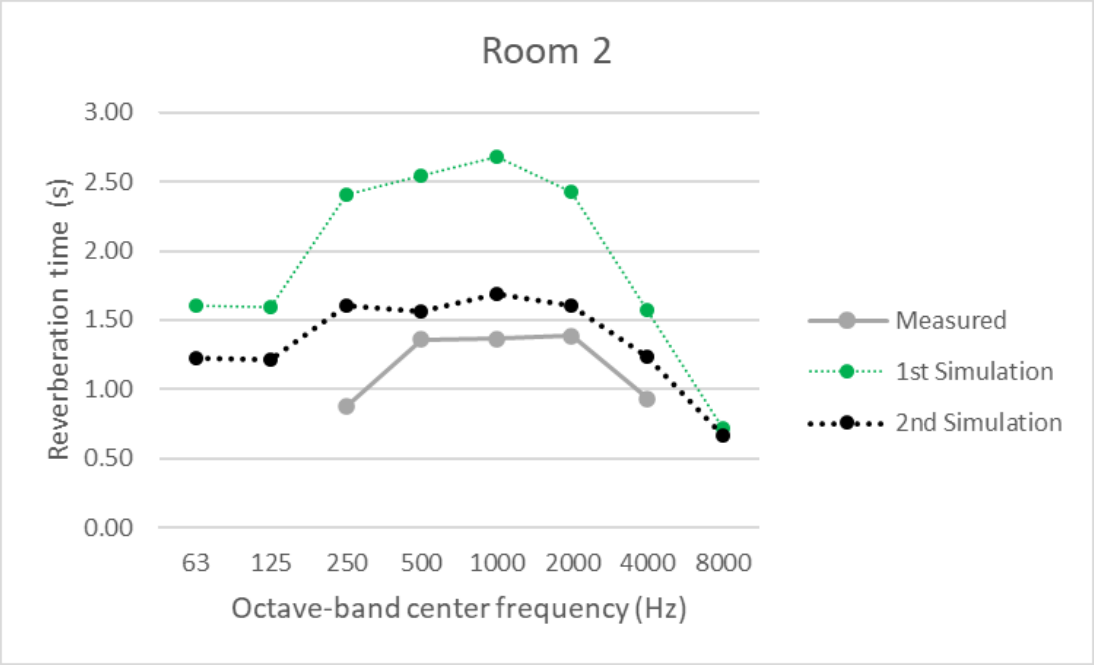

Figure 23: Reverberation Time - Room 2

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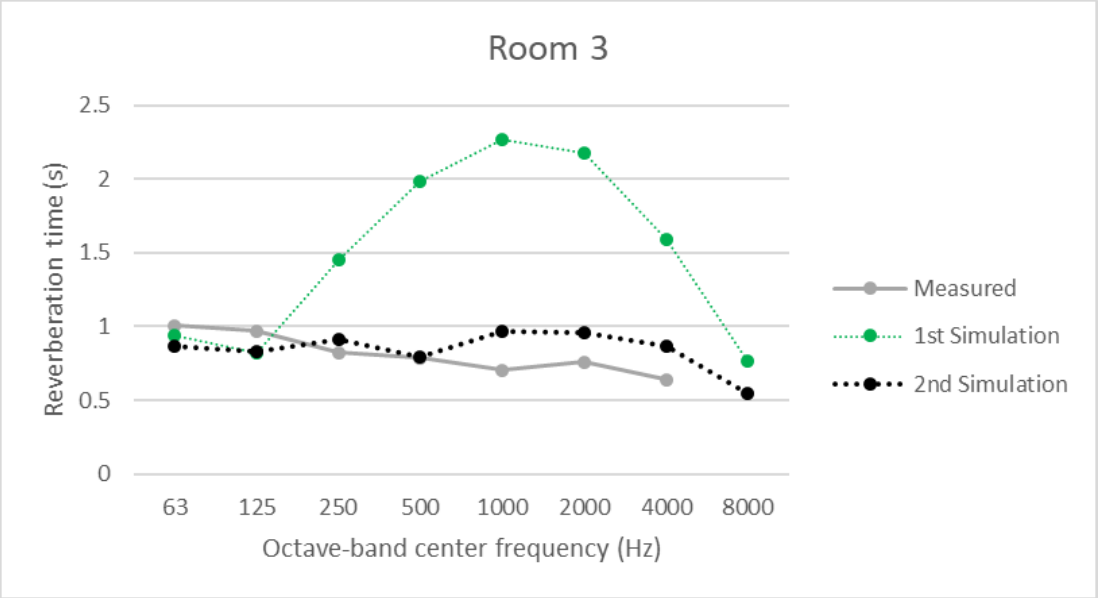

Figure 24: Reverberation Time - Room 3

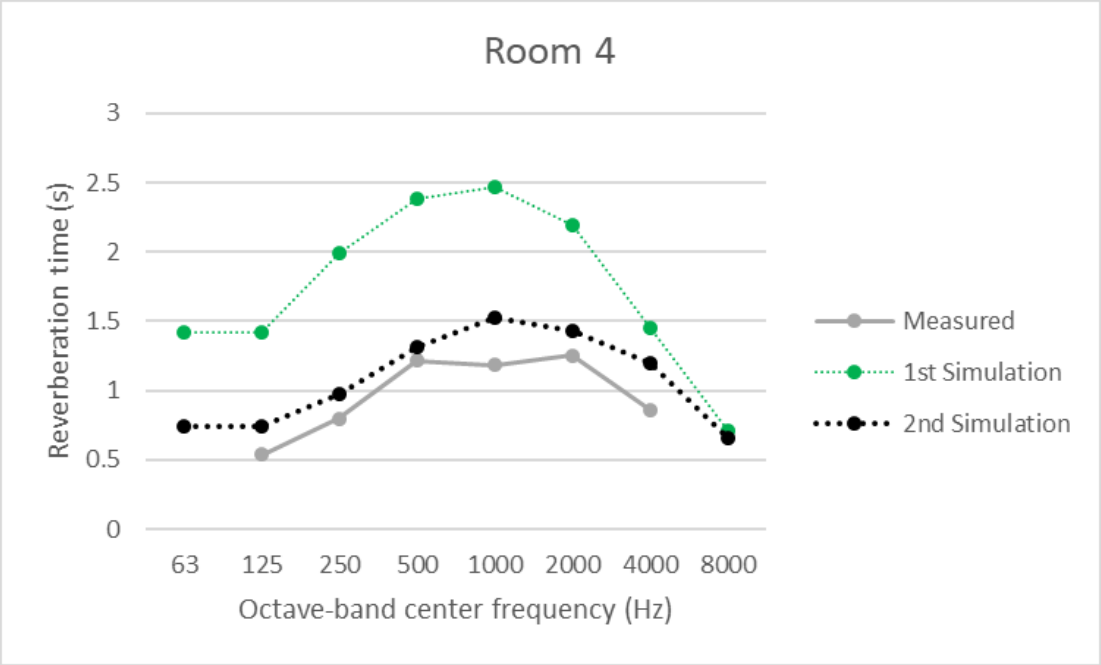

Figure 25: Reverberation Time - Room 4

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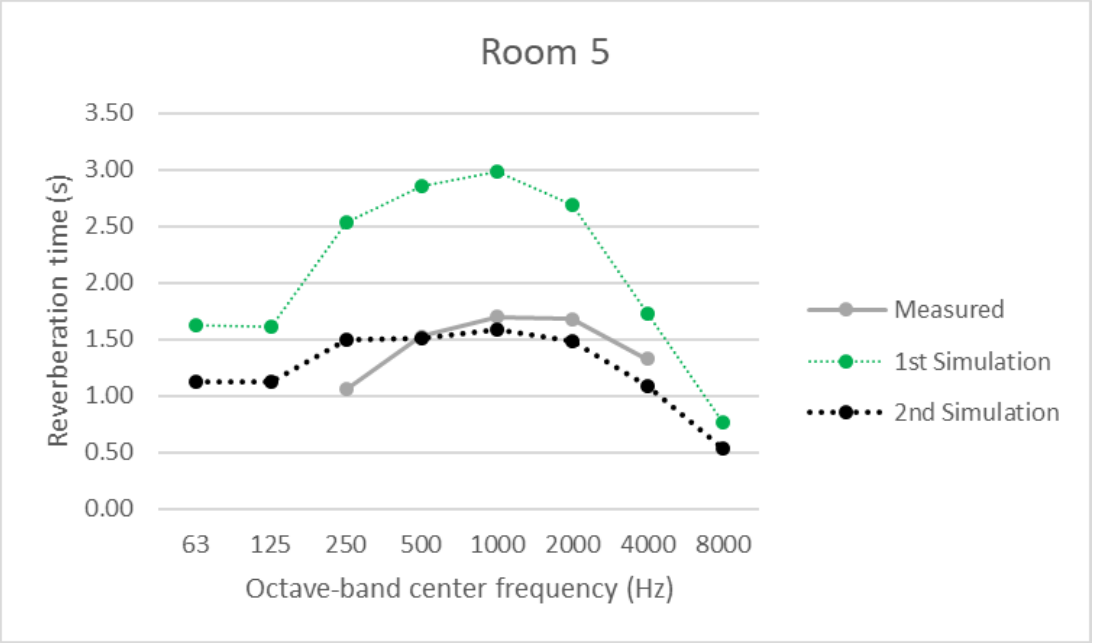

Figure 26: Reverberation Time - Room 5

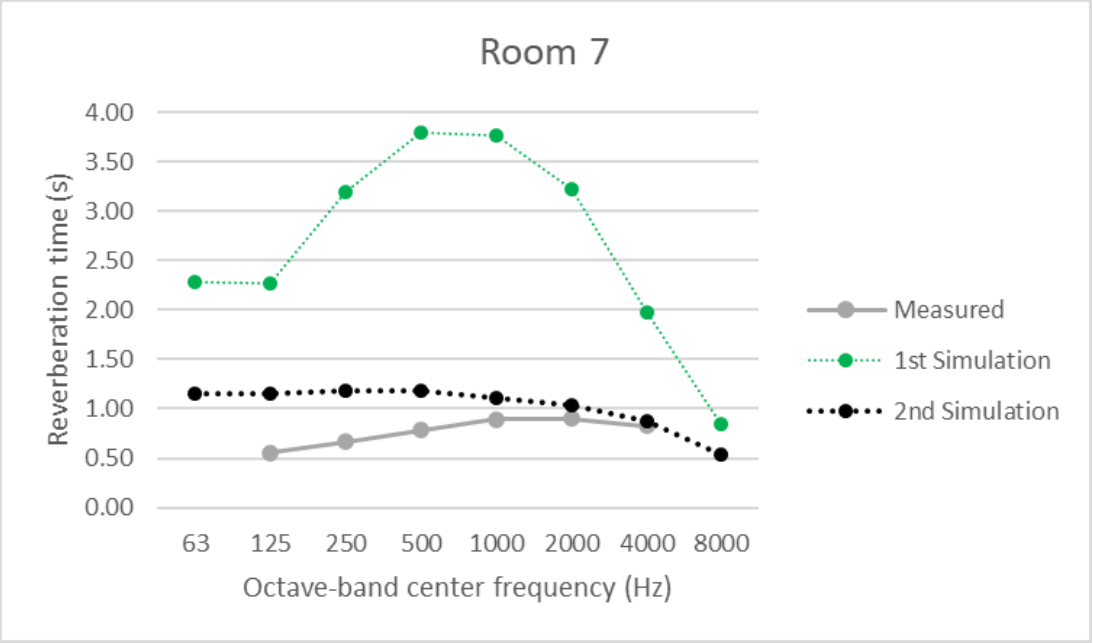

Figure 27: Reverberation Time - Room 7

The background noise is the sound in the ambient that does not include the sounds of humans. It's normally the sounds produced by electronic devices, water, traffic, and any other sound that can be heard even when is silent. It was the first measurement and the results for each frequency are the following ones:

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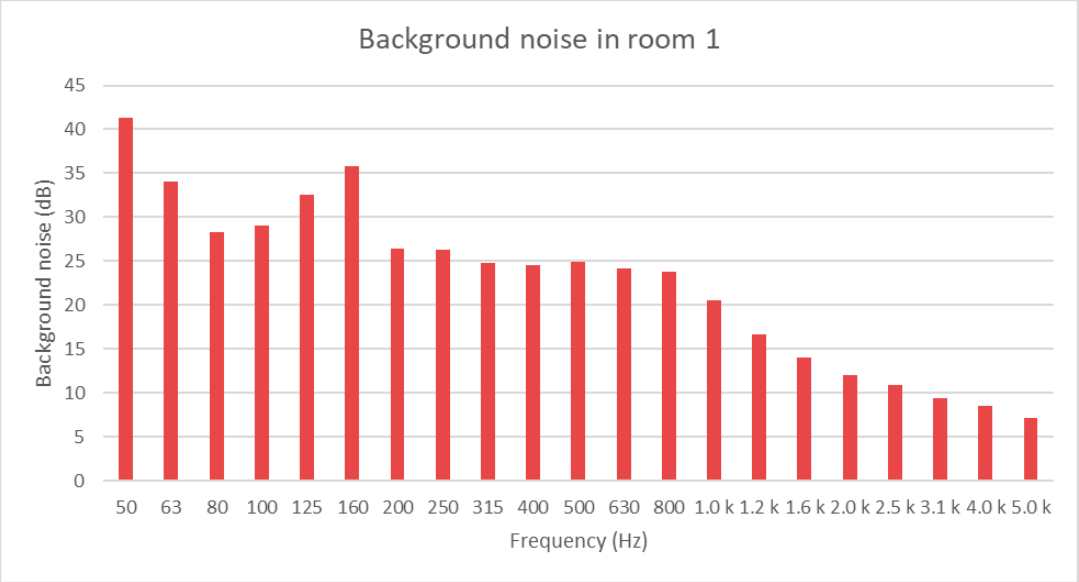

Figure 28: Background noise in Room 1 measured on site

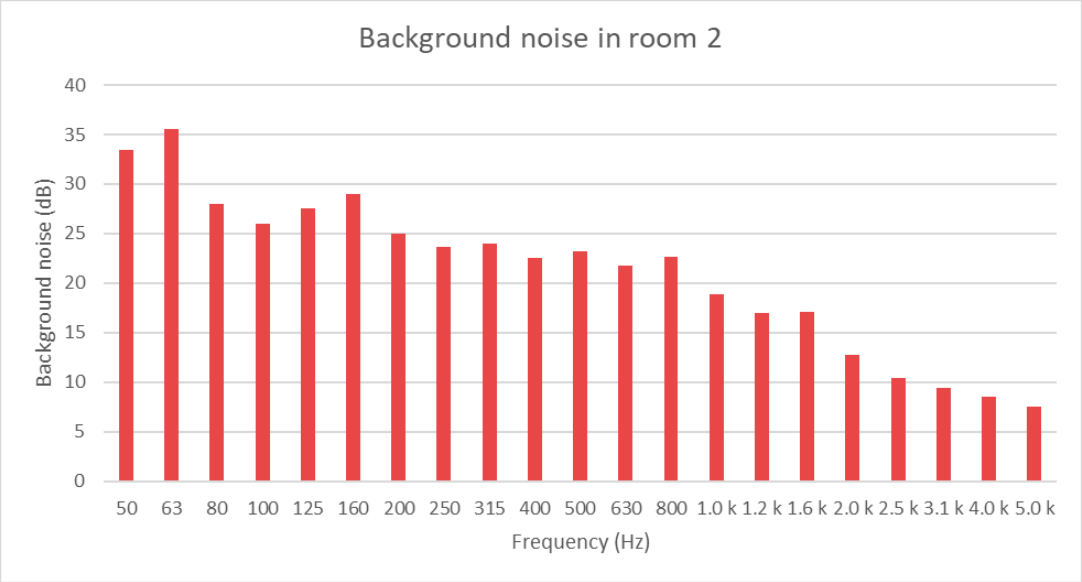

Figure 29: Background noise in Room 2 measured on site

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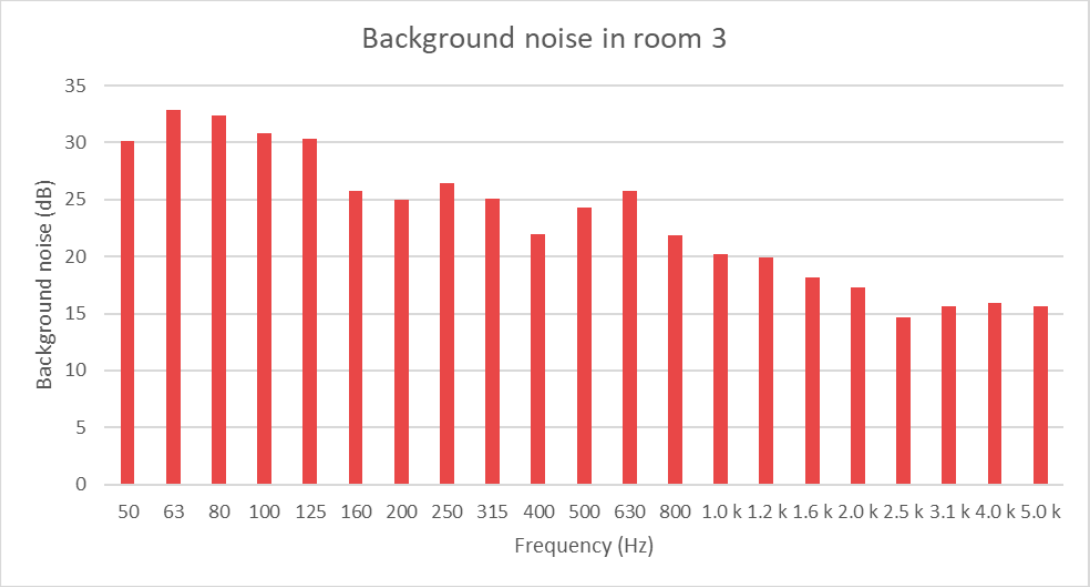

Figure 30: Background noise in Room 3 measured on site

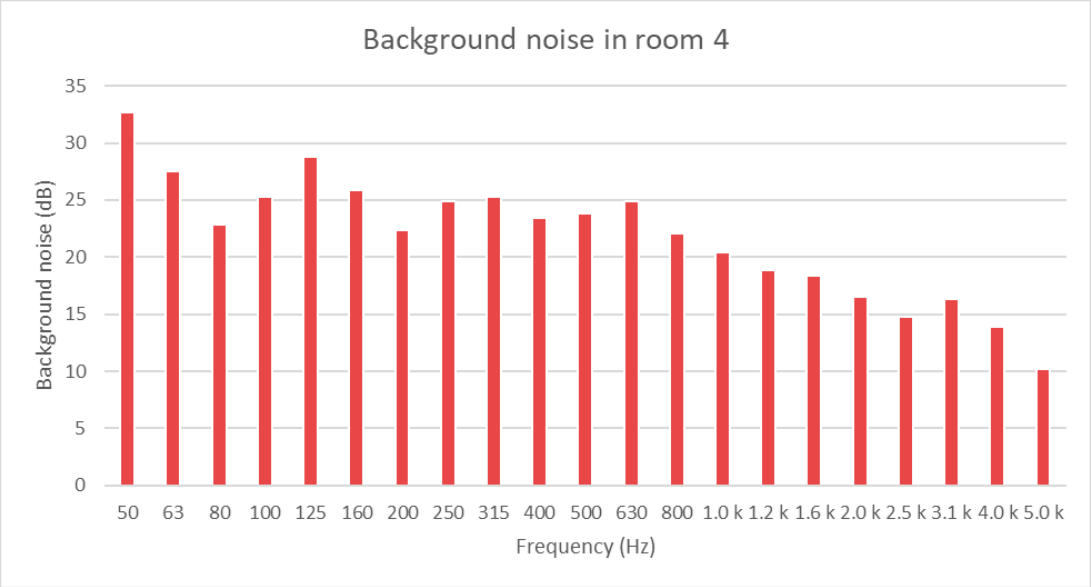

Figure 31: Background noise in Room 4 measured on site

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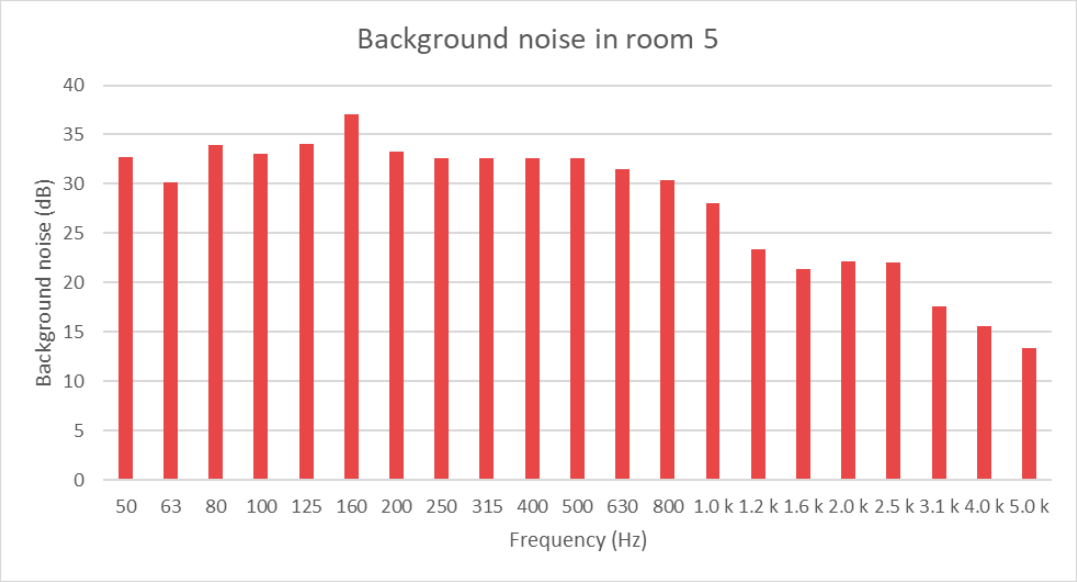

Figure 32: Background noise in Room 5 measured on site

The L_{Aeq} for each room is listed below:

- Room 1: 31.1 dB
- Room 2: 29.4 dB
- Room 3: 31.3 dB
- Room 4: 20.7 dB
- Room 5: 37.9 dB

3.2 Results of the improvement simulation

The improvement simulation considered the material and geometry-related changes. Before, a simulation only with the geometry-related change was conducted in order to compare the efficiency of each action to improve the room acoustics of the office space.

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Speaker Position	Receiver Position	SPL Difference dB(A)		
		Current state	Geometry-related change simulation	Improvement simulation
1.1	1.2-5.3	14.3	39.1	45.4
1.1	1.2-5.2	19.3	41.2	48.6
1.1	1.2-6.2	18.2	36.6	46.0
1.1	1.2-2.2	21.1	30.0	32.7
1.1	1.2-4.2	27.6	70.6	78.2
1.1	1.2-2.3	22.2	29.9	31.9
1.1	1.2-3.2	48.4	53.8	54.9
2.1	2.2-2.3	-0.1	-0.1	-0.7
2.1	2.2-6.2	6.7	6.6	10.0
2.1	2.2-5.2	12.6	12.4	19.3
2.1	2.2-5.3	11.8	11.6	18.6
2.1	2.2-1.2	19.6	27.9	29.4
2.1	2.2-4.2	20.8	46.7	59.3
2.1	2.2-3.2	26.9	27.1	27.2
3.1	3.2-2.2	29.9	30.0	33.2
3.1	3.2-2.3	30.2	30.5	33.5
3.1	3.2-6.2	36.6	36.7	44.5
3.1	3.2-5.3	41.9	42.0	53.4
3.1	3.2-5.2	43.1	43.4	54.0
3.1	3.2-1.2	49.2	54.0	58.9
3.1	3.2-4.2	52.0	72.9	87.1
4.1	4.2-1.2	29.1	74.4	90.0
4.1	4.2-6.2	24.0	50.2	63.8
4.1	4.2-5.2	15.4	41.8	47.4
4.1	4.2-5.3	23.1	49.3	56.8
4.1	4.2-2.2	25.0	50.6	65.8
4.1	4.2-2.3	25.4	50.9	64.3
4.1	4.2-3.2	53.5	73.1	88.4
5.1	5.2-5.3	2.4	2.3	4.4
5.1	5.2-6.2	3.1	2.9	10.8
5.1	5.2-1.2	7.7	28.0	37.8
5.1	5.2-2.2	1.9	1.7	6.9
5.1	5.2-2.3	1.8	1.8	8.4
5.1	5.2-4.2	6.9	33.6	38.8
5.1	5.2-3.2	29.1	29.0	32.0

Figure 33: SPL difference in the office space in the simulated current state and after two improvement simulation

The same applied to the reverberation time (RT). Two improvement simulations were conducted to know which change is more relevant to meet the RT requirements.

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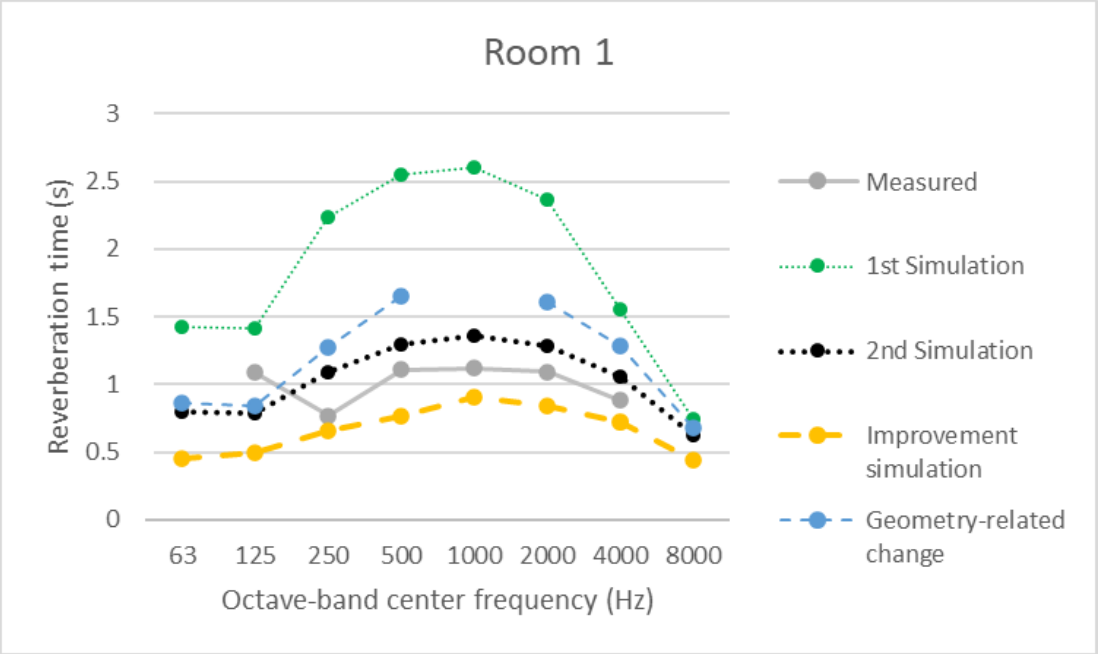

Figure 34: Reverberation Time after the improvement simulation - Room 1

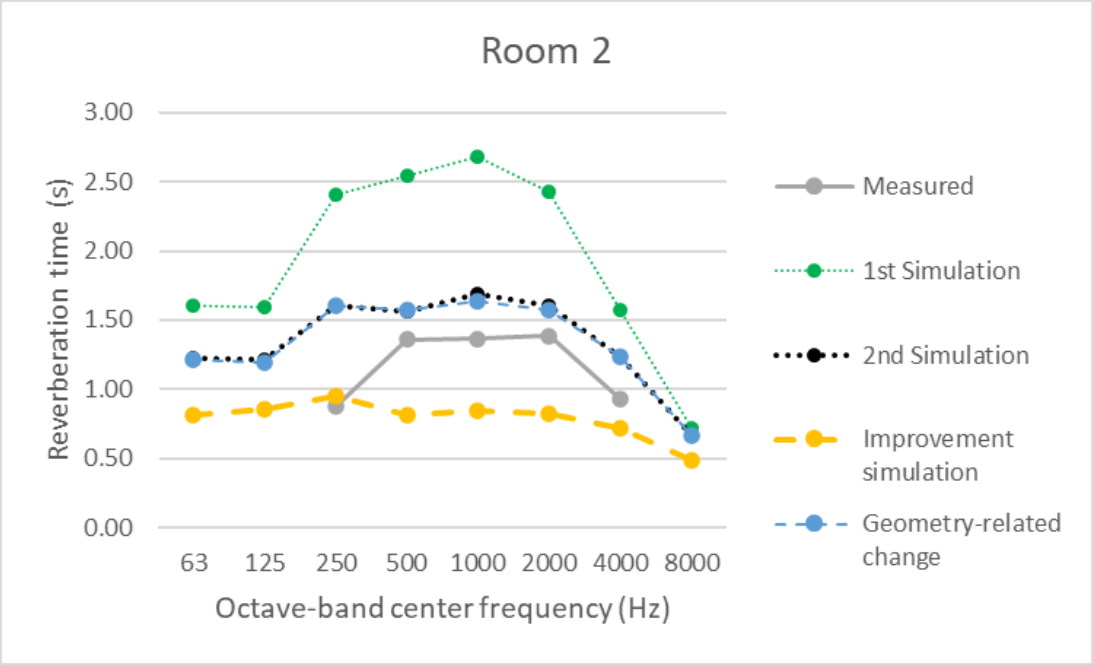

Figure 35: Reverberation Time after the improvement simulation - Room 2

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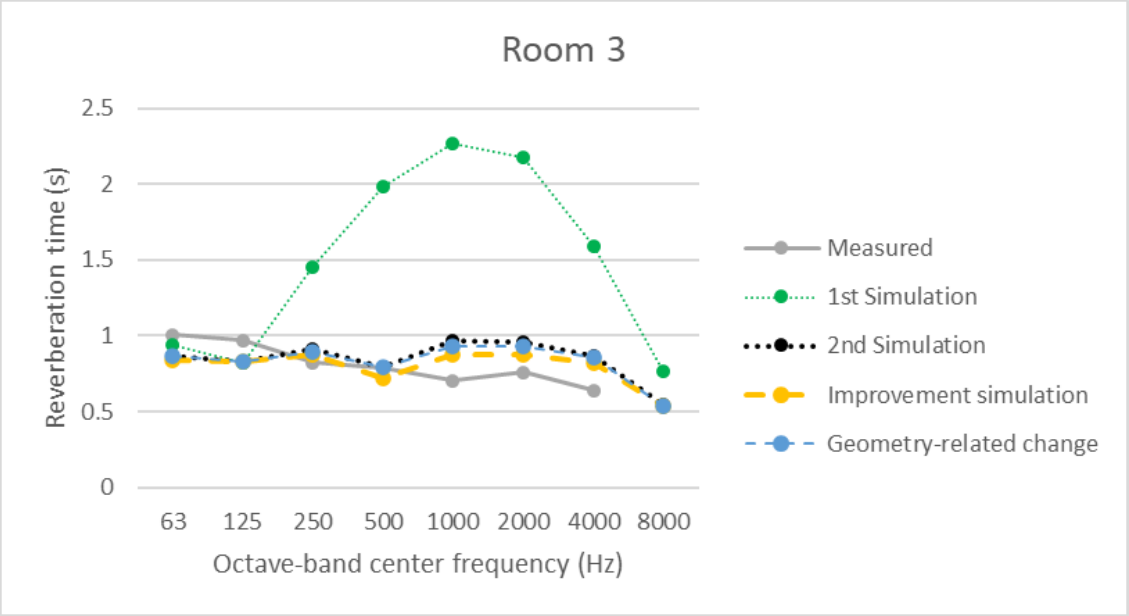

Figure 36: Reverberation Time after the improvement simulation - Room 3

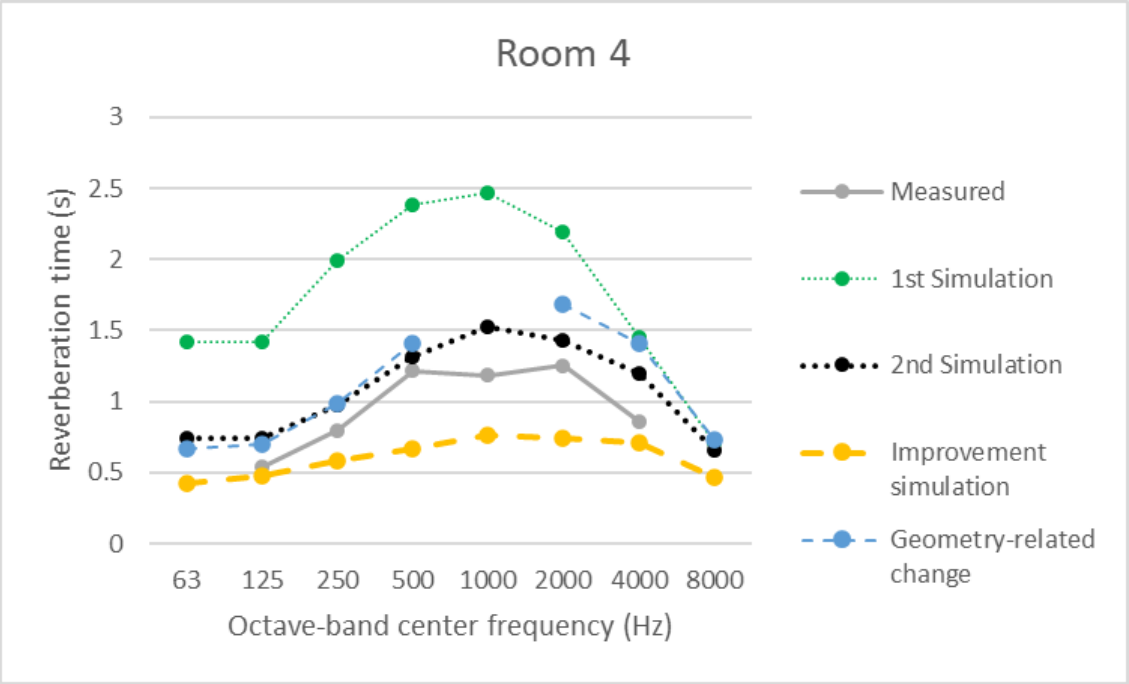

Figure 37: Reverberation Time after the improvement simulation - Room 4

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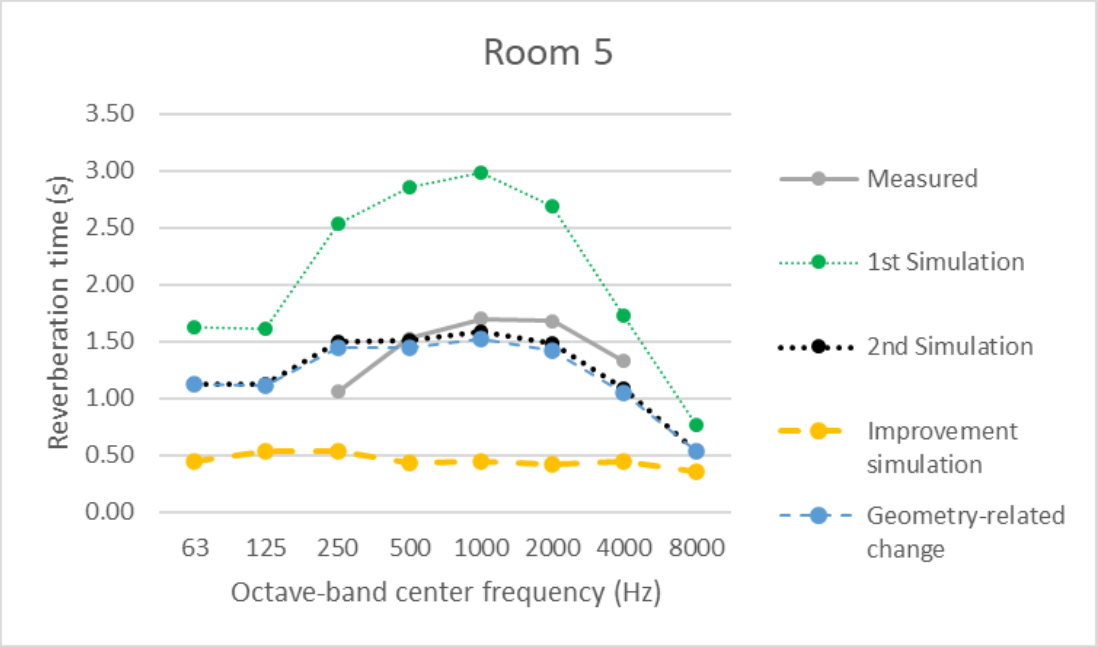

Figure 38: Reverberation Time after the improvement simulation - Room 5

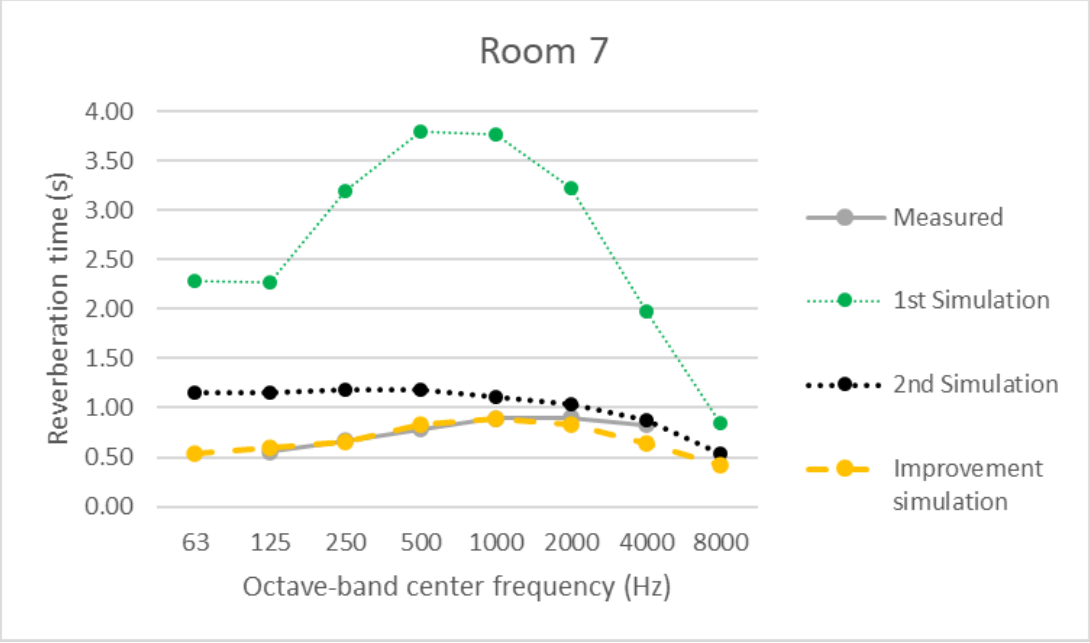

Figure 39: Reverberation Time after the improvement simulation - Room 7

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3.3 Results of the interview

Three people participated in the interview. At the present moment, the offices are not fully occupied so there were not many people available to participate.

3.2.1 Interview with Participant 1

1. **Where is your workstation located? Please mark it in the office plan.**

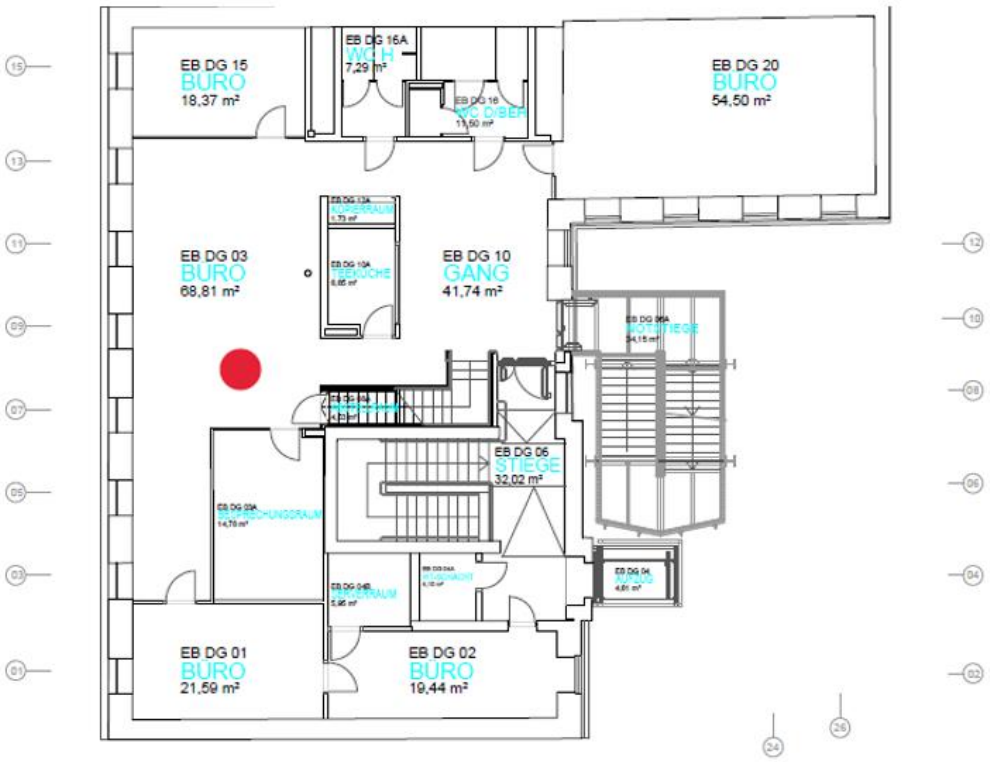

Figure 40: Interview with participant 1 (1/4)

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2. How often do you go to the office?

Once a week or twice a month

3. How do you evaluate the overall quality of your office space?

a) Excellent	
b) Good	
c) Fair	x
d) Poor	

4. How do you rate the overall acoustic quality of your office?

e) Excellent	
f) Good	
g) Fair	
h) Poor	x

Figure 41: Interview with participant 1 (2/4)

5. I am able to concentrate on work in my workplace.

Full agree	If I am alone yes
Somewhat agree	
Somewhat disagree	
Totally disagree	If people interacting

6. I have the privacy needed to work effectively.

Full agree	
Somewhat agree	x
Somewhat disagree	
Totally disagree	

7. If necessary, I can find a quiet place to work elsewhere in the office.

Full agree	
Somewhat agree	
Somewhat disagree	
Totally disagree	x

Figure 42: Interview with participant 1 (3/4)

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8. I could get more done if my workspace were quieter.

Full agree	
Somewhat agree	x
Somewhat disagree	
Totally disagree	

9. Noise distractions in my office disturb my concentration.

Full agree	
Somewhat agree	x
Somewhat disagree	
Totally disagree	

10. The noise level in my office is stressful.

Full agree	
Somewhat agree	x
Somewhat disagree	
Totally disagree	

Figure 43: Interview with participant 1 (4/4)

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3.2.2 Interview with Participant 2

1. Where is your workstation located? Please mark it in the office plan.

Figure 44: Interview with participant 1 (4/4)

2. How often do you go to the office?

During Corona – 2-3 times/week,
Normally 5 days/week

3. How do you evaluate the overall quality of your office space?

a) Excellent	
b) Good	
c) Fair	X
d) Poor	

4. How do you rate the overall acoustic quality of your office?

e) Excellent	
f) Good	
g) Fair	
h) Poor	X

Figure 45: Interview with participant 2 (2/4)

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5. I am able to concentrate on work in my workplace.

Full agree	
Somewhat agree	
Somewhat disagree	X
Totally disagree	

6. I have the privacy needed to work effectively.

Full agree	
Somewhat agree	
Somewhat disagree	X
Totally disagree	

7. If necessary, I can find a quiet place to work elsewhere in the office.

Full agree	
Somewhat agree	
Somewhat disagree	
Totally disagree	X

Figure 46: Interview with participant 2 (3/4)

8. I could get more done if my workspace were quieter.

Full agree	X
Somewhat agree	
Somewhat disagree	
Totally disagree	

9. Noise distractions in my office disturb my concentration.

Full agree	X
Somewhat agree	
Somewhat disagree	
Totally disagree	

10. The noise level in my office is stressful.

Full agree	X
Somewhat agree	
Somewhat disagree	
Totally disagree	

Figure 47: Interview with participant 2 (4/4)

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3.2.3 Interview with Participant 3

1. Where is your workstation located? Please mark it in the office plan.

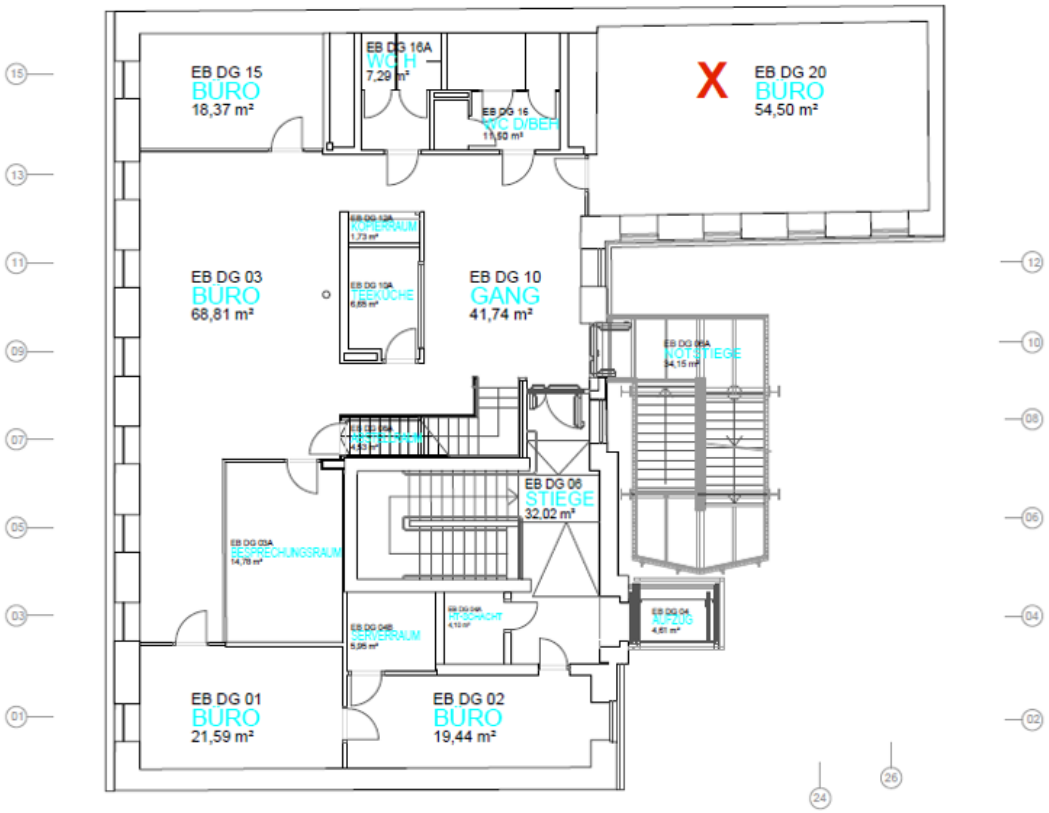

Figure 48: Interview with participant 3 (1/4)

2. How often do you go to the office?

One-two days per week

3. How do you evaluate the overall quality of your office space?

a) Excellent	
b) Good	x
c) Fair	
d) Poor	

4. How do you rate the overall acoustic quality of your office?

e) Excellent	
f) Good	
g) Fair	
h) Poor	x

Figure 49: Interview with participant 3 (2/4)

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5. I am able to concentrate on work in my workplace.

Full agree	
Somewhat agree	x
Somewhat disagree	
Totally disagree	

6. **I have the privacy needed to work effectively.**

Full agree	
Somewhat agree	
Somewhat disagree	x
Totally disagree	

7. If necessary, I can find a quiet place to work elsewhere in the office.

Full agree	
Somewhat agree	x
Somewhat disagree	
Totally disagree	

Figure 50: Interview with participant 3 (3/4)

8. I could get more done if my workspace were quieter.

Full agree	x
Somewhat agree	
Somewhat disagree	
Totally disagree	

9. Noise distractions in my office disturb my concentration.

Full agree	
Somewhat agree	x
Somewhat disagree	
Totally disagree	

10. The noise level in my office is stressful.

Full agree	
Somewhat agree	x
Somewhat disagree	
Totally disagree	

Figure 51: Interview with participant 3 (4/4)

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4 DISCUSSION

4.1 Current State

Acoustic privacy is very important in the offices and can be poor or good. The analysis of acoustic privacy in the office areas is based on how audible and intelligible the conversations are (Stout, 2015). Speech intelligibility and Sound Transmission Index (STI) are correlated. According to Hongisto et al. (2016), the standard speech source is played at the position of the speaker, while the STI is measured in the position of the listener. The STI scale ranges from 0.0 (no intelligibility) to 1.0 (high intelligibility). In order to have the desired acoustic privacy, the STI has to be the minimum possible, resulting in low speech intelligibility.

Table 6: Sound Transmission Index for acoustic privacy. source: Stout, 2015.

STI	Quality	Acoustic Privacy
0.0-0.3	Bad	Excelent
0.3-0.45	Poor	Good
0.45-0.6	Fair	Fair
0.6-0.75	Good	Poor
0.75-1.0	Excelent	Bad

The STI in the office according to the simulation results (Figure 16) varies between 0.3 and 0.6. The gallery has a higher STI than the floor below and has fair acoustic privacy, while the other areas of the office space have good acoustic privacy.

A normal background noise limit in a mechanical ventilated unoccupied space of 40 – 45 dB L_{Aeq} is advised for open-plan workplaces, and a typical background noise limit of 30 – 35 dB L_{Aeq} is recommended for private offices and meeting rooms. (Field, Dr. Chris. 2010). According to the results of the measurements, the background noise is meeting the recommendations.

SPL is the effect of sound waves causing pressure fluctuations in the air, which is measured in decibels (dB) and weighted to link sound level to human hearing and pain thresholds. The lower the overall sound pressure level in a space, the greater the corresponding sound absorption area. When sound is evenly dispersed throughout an area, it produces excellent room acoustics. The loudness and directivity of the source, as well as the surface material properties and the geometry of the

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space, are important because 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.

Figure 16 shows how the sound pressure levels are distributed in relation to the distance from speakers to receivers. The SPL difference changes considerably from one location to another, especially when the distance between source and receiver decreases. The SPL is lower when the sound absorption area is higher, as illustrated in Figure 52.

The values from simulation and measurements are similar or at least following the same pattern, showing that the simulation was calibrated, and the materials assigned to the surfaces in Odeon represent the real absorption index of the materials in the office area. There are a few outliers, but they can be accepted.

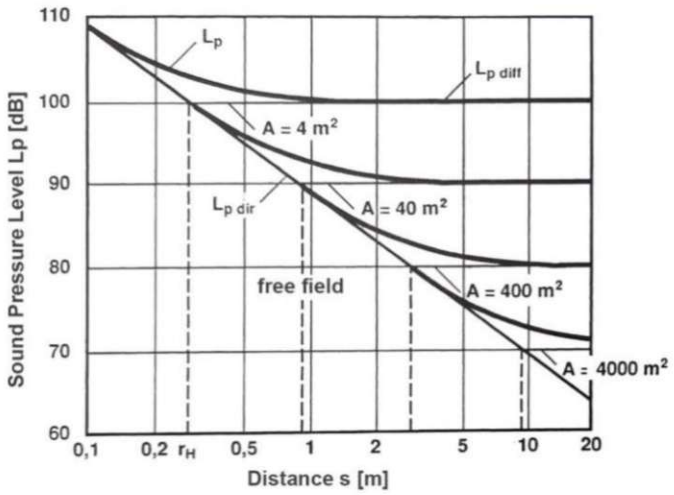

Figure 52: Sound pressure level in function of distance and absorption area. (Oldland K., 2021 p.11)

4.1.1 Reverberation time

The reverberation time is also very important to determine the acoustic comfort in room acoustics. According to Abd Jalil et al. 2013, in ISO 11690-1: 1996 I18] the recommended reverberation time range in an open-plan office with a volume between 200 m^3 and 1.000 m^3 is 0.8 s – 1.3 s. The office area has 988 m^3 and Room 7 has almost 200 m^3, so the range given suits both. Moreover, the Finnish room acoustic regulations from 2018 recommend reverberation time below 0.6 s for open offices. (Renz, 2019).

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The standard VDI 2569 recommends maximum reverberation time for multi-person office space according to the room acoustics class. For this standard, two workstations or more are considered multi-person office. A distinction is made between small and big multi-person offices. In small multi-person offices, the distance between the farthest workstations is less than 8 m, whereas, in large multi-person offices, the distance is greater than 8 m. Therefore, Rooms 2, 4, 5, and 7 are considered small multi-person offices, and Room 1 is a single office.

In order to know the recommended reverberation time for each room in the office, they have to be classified according to the usage and the planning/construction efforts, as Table 7 shows.

Table 7: Room acoustics class depending on the usage and the planning/construction efforts Source: VDI 2569 (2019)

Room acoustics class	Planning and constructio-nal efforts	Description	Recommendations depending on usage
A	high	Room acoustics class A requires very extensive and highly effective room acoustical measures for room attenuation and reduction of sound propagation. An improvement of the acoustic conditions that goes beyond room acoustics class A is not possible while maintaining an open office structure.	well suitable for call centres and rooms with communication intensive usage
B	medium	Room acoustics class B requires extensive and effective room acoustical measures for room attenuation and reduction of sound propagation.	well suitable for rooms for sales, construction, administration; suitable for call centres
C	low	Room acoustics class C requires effective acoustic measures for room attenuation and reduction of sound propagation.	suitable for rooms for sales, construction, administration

The office should be classified as B according to its usage.

The reverberation time in the simulation is longer than the results from the measurements. A contribution factor could be that no furniture was considered during the simulations. The furniture as all materials has reflectance and absorption properties influencing the acoustics in the environment. Longer reverberation times are linked to larger spaces and/or larger areas of reflected surfaces, whereas shorter reverberation times are linked to smaller spaces and/or smaller areas of reflective surfaces.

Not all the values from the measurement could be considered because had high deviation and were not realistic. Nevertheless, the few values that were not considered did not harm the result, so it was easier to just exclude them.

The first simulation had higher values and was far from the measurements results because the materials chosen did not have absorption coefficients like the real

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materials. The estimations of the absorption coefficients were based on the material absorption databases.

Room 1 has the reverberation time (T30) between 0.62 s and 1.36 s in the simulation, while in the measurements the range is between 0.77 s and 1.01 s.

These values are considered good according to ISO 11690-1: 1996 I18], but much higher than the Finnish room acoustic regulations from 2018.

According to the standard VDI 2569, the reverberation time should be maximum of 1 s for a frequency of 125 Hz and below 0.8 s when the frequency is between 250 Hz and 4.000 Hz, as illustrated in Table 8. Thus, Room 1 has RT above the recommendation.

Table 8: Recommendation for the maximum RT and the maximum noise SPL of noise generated by building system in single offices. Source: VDI 2569 (2019)

Room acoustics class	T in octave bands		$L_{NA, Bau}$
	125 Hz	250 Hz to 4000 Hz	
A	≤ 0,8 s	≤ 0,6 s	≤ 30 dB
B	≤ 1,0 s	≤ 0,8 s	≤ 35 dB
C	≤ 1,2 s	≤ 1,0 s	≤ 40 dB

During the interviews, the occupant of Room 1 complained that all the office could hear her conversation on the phone. Even though there is a glass wall that separates Room 1 and Room 2, it is open to the gallery. Thus, there is no acoustic privacy for the occupant of Room 1.

Room 2 is a small multi-person office that should have RT below 0.7 s when the frequency is 125 Hz or 0.5 s for frequency between 250 Hz and 4.000 Hz, according to the standard VDI 2569, as shown in Table 9.

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Table 9: Recommendation for the RT and maximum SPL of construction noises in small multi-person offices. Source: VDI 2569 (2019)

Room acoustics class	T		$L_{NA, Bau}$
	125 Hz	250 Hz to 4000 Hz	
A	≤ 0,6 s	≤ 0,4 s	≤ 35 dB
B	≤ 0,7 s	≤ 0,5 s	≤ 40 dB
C	≤ 0,9 s	≤ 0,7 s	≤ 40 dB

The reverberation time in Room 2 is between 0.7 s and 1.7 s in the simulation, and 0.9 s and 1.4 s in the measurements on-site. Thus, the RT is not meeting the recommendations of standards and regulations above mentioned.

Room 3, the meeting room, has better values of reverberation because it is isolated by glass walls and there are no openings. The highest RT according to measurement and simulation is 1 s. It is still above the recommendation of the Finnish room acoustic regulation from 2018 but it has a better acoustic performance than the other rooms.

Room 4 and 5 have their maximum reverberation time at 1.5 s and 1.7, respectively, above the threshold values.

In the interview, the occupant of Room 4 mentioned that it is possible to clearly hear people from Room 1, even though the offices are far from each other and there is a big absorption area. Acoustic privacy and speech intelligibility are inverses proportional in the case of office spaces. The distraction caused by speech decreases as the sound level of speech and speech intelligibility decreases.

The reverberation time in Room 7 is between 0.5 s and 1.2 s. The measurement results are closer to the recommendation and the possible reason is the fact that furniture was taken into consideration. Moreover, the RT is not meeting the recommendations.

4.2 Improvement proposed

The first improvement is about closing the openings in Rooms 1 and 4. Figures 17, 20 and 21 illustrates the SPL difference between the gallery and the other rooms in

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the current state. The highest SPL difference is between the a room and the meeting room, which is the only room without any opening. Thus, closing the opening of Room 1 and 4 was the one of the improvements proposed.

The reverberation time did not have significant changes. Therefore, the openings are not the reason for having the RT above the recommendation of standards. On the other hand, the SPL difference changed significantly compared to the current state of rooms 1 and 4. The SPL decreased with the improvement, and consequently, the SPL difference increased. However, the SPL difference still vary when we compare the same speaker and different receivers. The sound coming from Room 1 and 4 is still perceived very differently in other rooms, but better than before the improvement. The SPL difference is higher when the receiver is in Room 1 and 4 because the SPL decreases.

The second improvement was to change the material from the ceiling to another one with higher sound absorption. The SPL difference is slightly higher in all the rooms, which is better for the human's welfare. The reverberation time improved and now is below or closer to the recommendation of standards.

A closer analysis of the reverberation time is done for each room.

- Room 1 is meeting the RT recommended in the standard VDI 2569, while
- Room 2 is slightly above the recommendation but performing better than before the improvement.
- Room 3 didn't have significant changes because the improvements did not affect the room directly.
- Room 4 has an RT of 0.4 s when the frequency is 125 Hz, but around 0.7 Hz when the frequency is higher. The reverberation time enhanced, even though is not fully meeting the recommendation of the standards.
- Room 5 has an RT around 0.5 s for all frequencies, meeting the requirements of VDI 2569 and the Finnish room acoustic regulations from 2018.
- The RT of Room 7 is similar to the RT in Room 1, but the recommendation is different according to the standard VDI 2569, because Room 1 is a single office, while Room 7 is a multi-person office. Therefore, the RT is above the recommendation for frequency from 250 Hz and higher but still considered good and better than before the improvement.

As mentioned previously, the furniture was not considered in the simulations, and perhaps resulted in longer reverberation than the measurements on-site.

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5 CONCLUSION

The interview reviewed the dissatisfaction of the occupants regarding the room acoustics. They agree that the noise can disturb their concentration and that they would be more productive if they would have a quieter place to work. Thus, an improvement solution is necessary to enhance their efficiency and satisfaction to work in the office.

The measurements gave the inputs necessary to calibrate the simulations in Odeon and to prove that in fact, the room acoustics is not meeting the recommendation values according to standards. The speech transmission index in the first simulations to analyze the current state of the open-office space reveals that in the gallery, the acoustic privacy is considered poor, and in the other rooms is good. In the interview, two of the three participants answered that somewhat they do not have the privacy needed to work, so even though the STI is considered good, something had to be done to improve the acoustic privacy. The background noise measurements were conducted on-site, and the results are meeting the recommendations. Therefore, nothing has to be done to improve the background noise.

Two improvement simulations were conducted, and both had good results. The reverberation time was above the recommendation and after the implementation of a material with higher sound absorption on the flat and sloped part of the ceiling, the RT decreased meeting the recommendation.

The sound pressure level difference improved with both improvement solutions. The openings in Room 1 and 4 were closed and automatically improved the SPL. The noise in those two rooms is less perceived by the occupants in different rooms, and now the occupants of Room 1 and 4 will be less affected by the noise in other rooms. Once the material of the ceiling is changed, the SPL is once more improved.

The meeting room was the only room that had no improvements because it meets already the room acoustics requirements, so no intervention was needed.

The acoustic improvement measures are a potential solution for the acoustic issues that the occupants are facing in the current state. To reach a positive acoustic quality in room acoustics, the reverberation time and sound pressure level have to be improved. Thus, this paper proposes the improvements above mentioned.

For the next studies in the field of room acoustics, the suggestion is to deepen the knowledge in objects and furniture that could improve the poor acoustic privacy of open office spaces.

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6.3 List of Equations

(1.1) Reverberation time according to Sabine formula

6.4 List of Abbreviations

RT Reverberation time

SPL Sound pressure level

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STI	Speech transmission index
L_{Aeq}	A-weighted Leq sound level

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8 APPENDIX

8.1 SPL difference – simulation of the current state

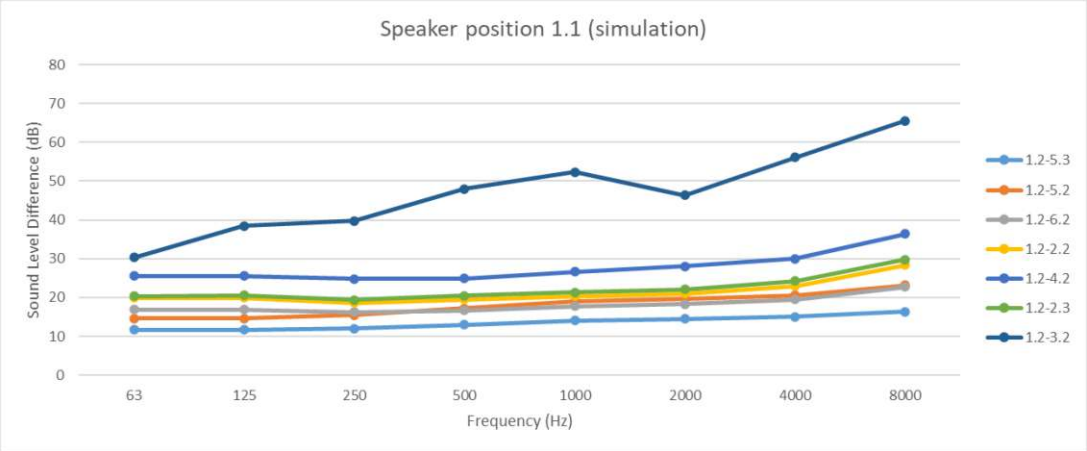

Figure 53: Sound pressure level difference (dB) for speaker in Room 1 according to simulation of the current state

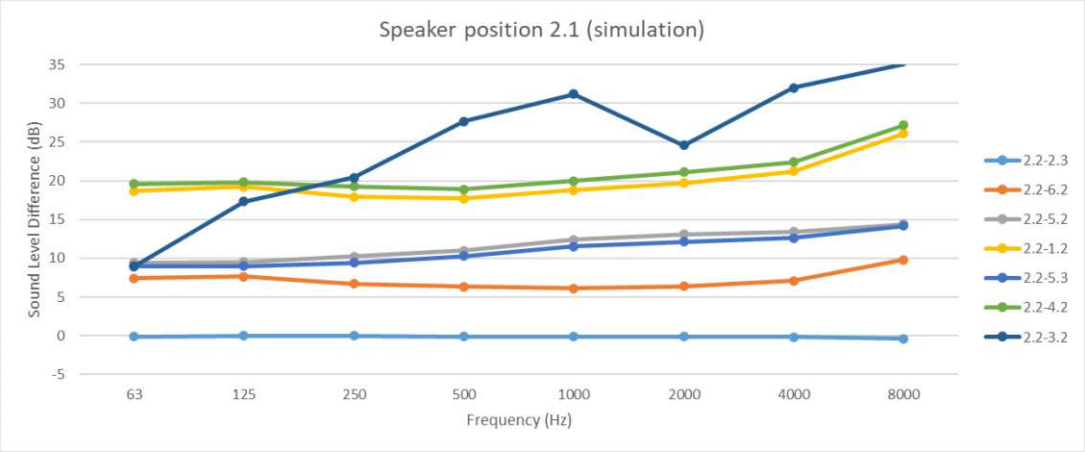

Figure 54: Sound pressure level difference (dB) for speaker in Room 2 according to simulation of the current state

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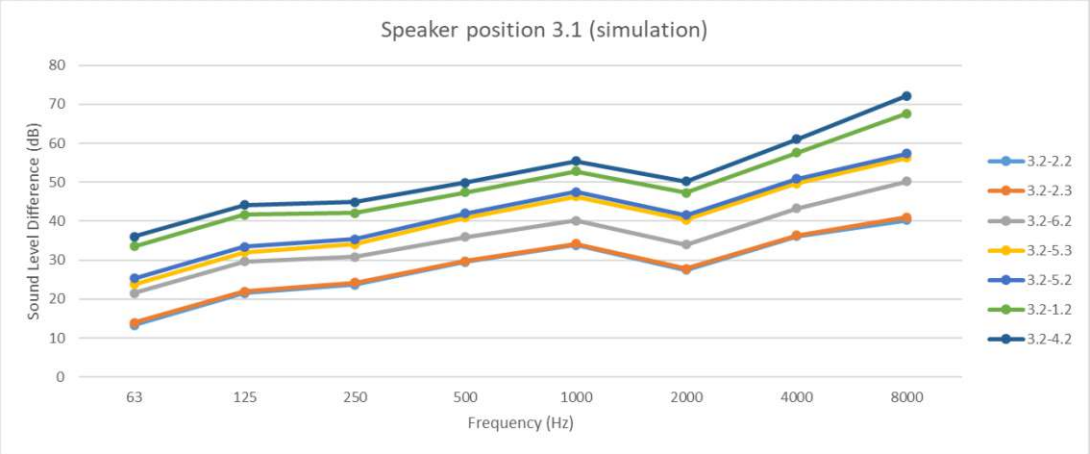

Figure 55:Sound pressure level difference (dB) for speaker in Room 3 according to simulation of the current state

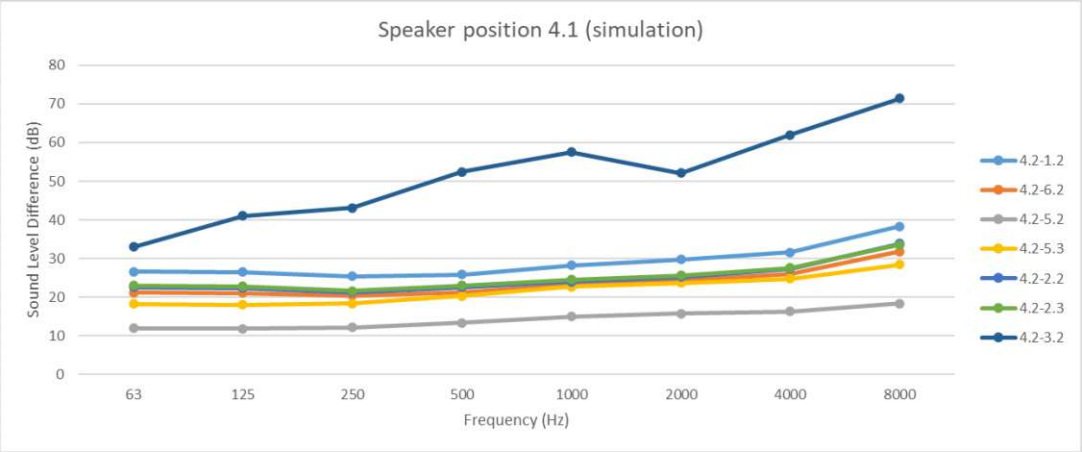

Figure 56: Sound pressure level difference (dB) for speaker in Room 4 according to simulation of the current state

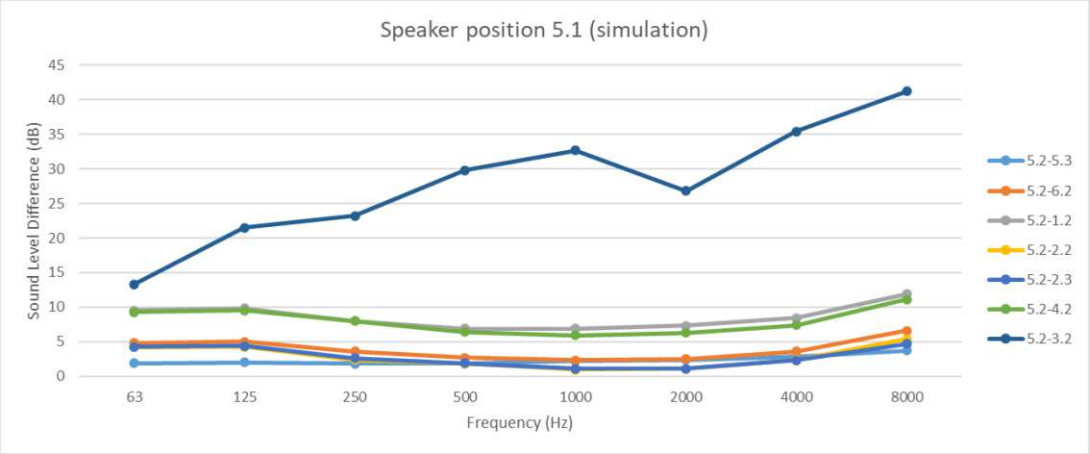

Figure 57: Sound pressure level difference (dB) for speaker in Room 5 according to simulation of the current state

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8.2 SPL difference – simulation of the current state and measurements on-site

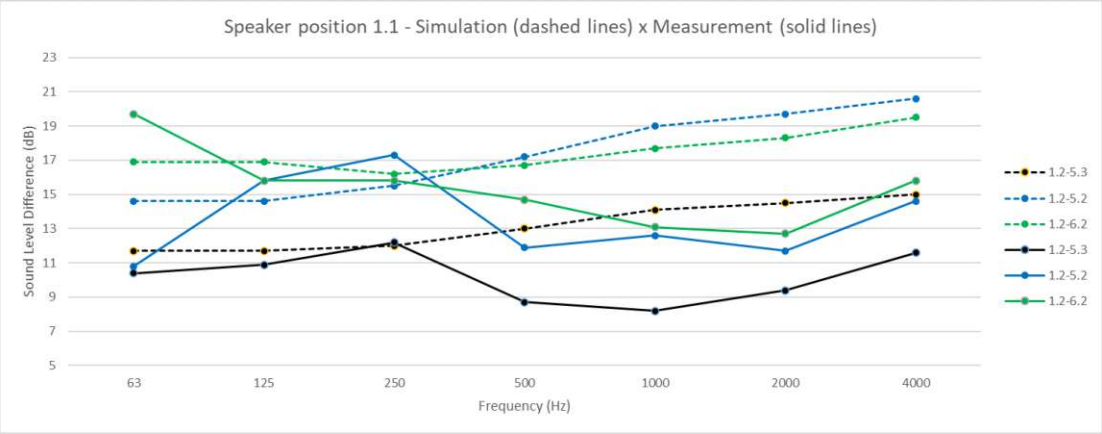

Figure 58: Sound pressure level difference (dB) for speaker in Room 1 according to simulation of the current state and the measurements on-site (1/2)

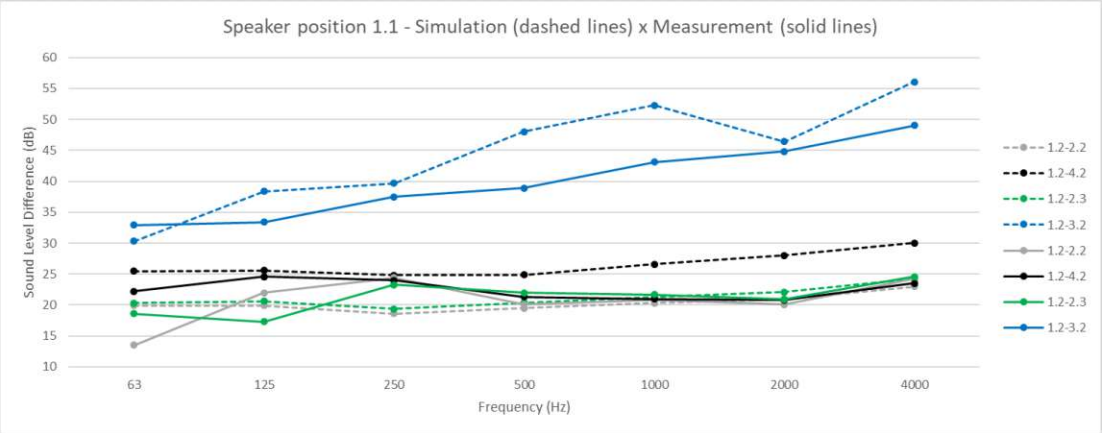

Figure 59: Sound pressure level difference (dB) for speaker in Room 1 according to simulation of the current state and the measurements on-site (2/2)

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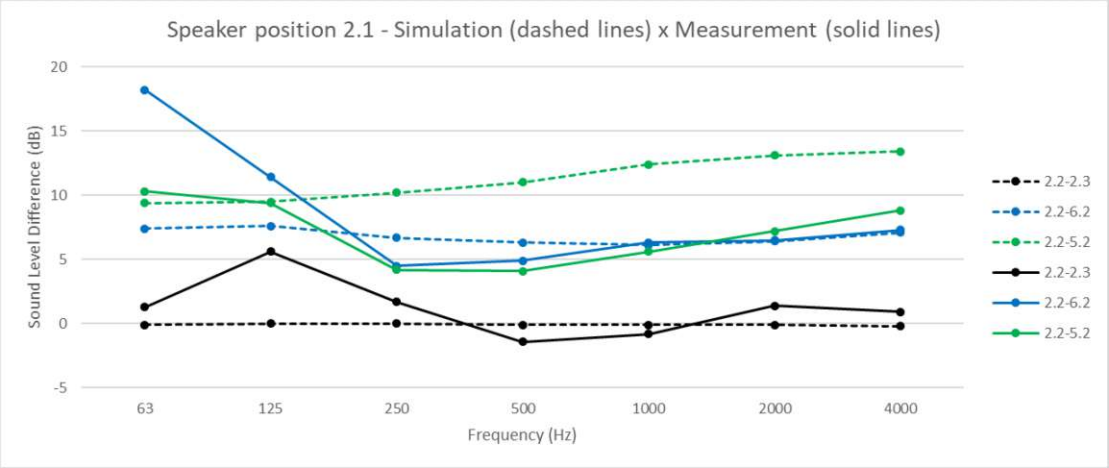

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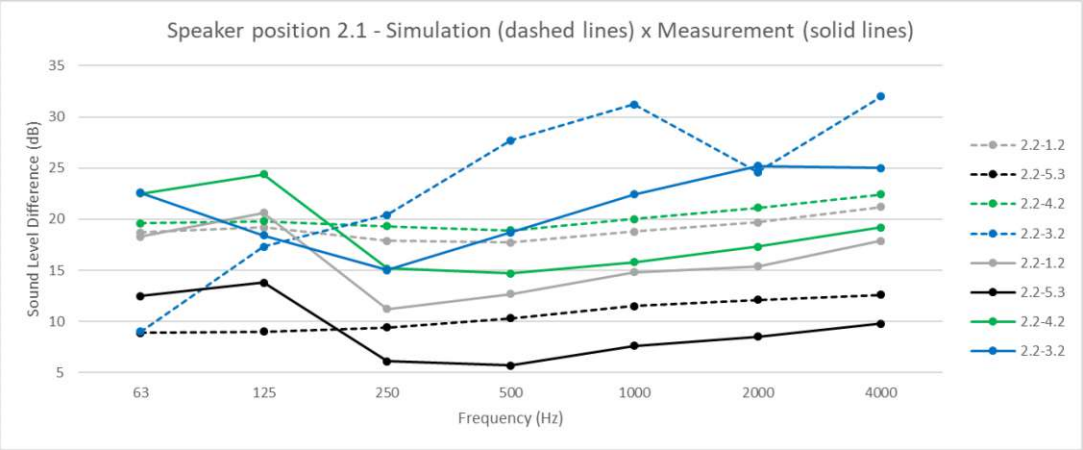

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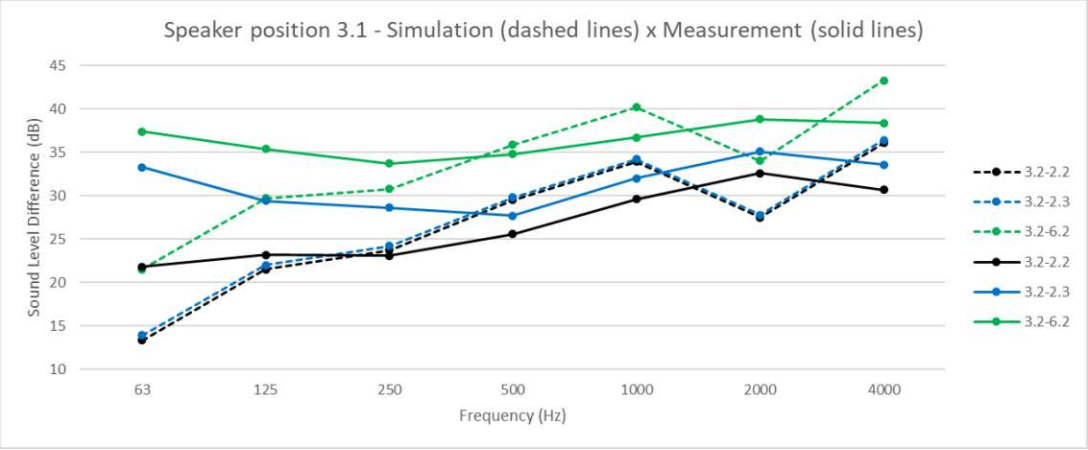

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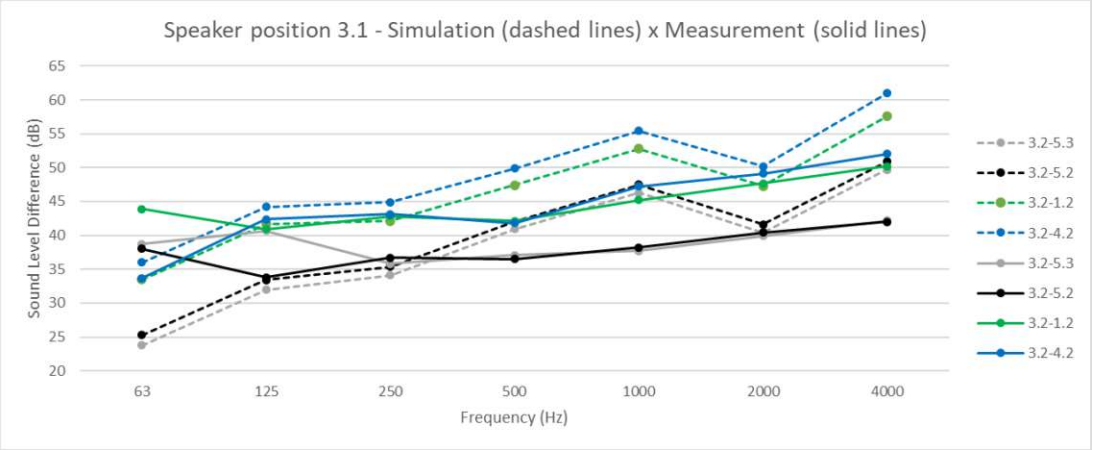

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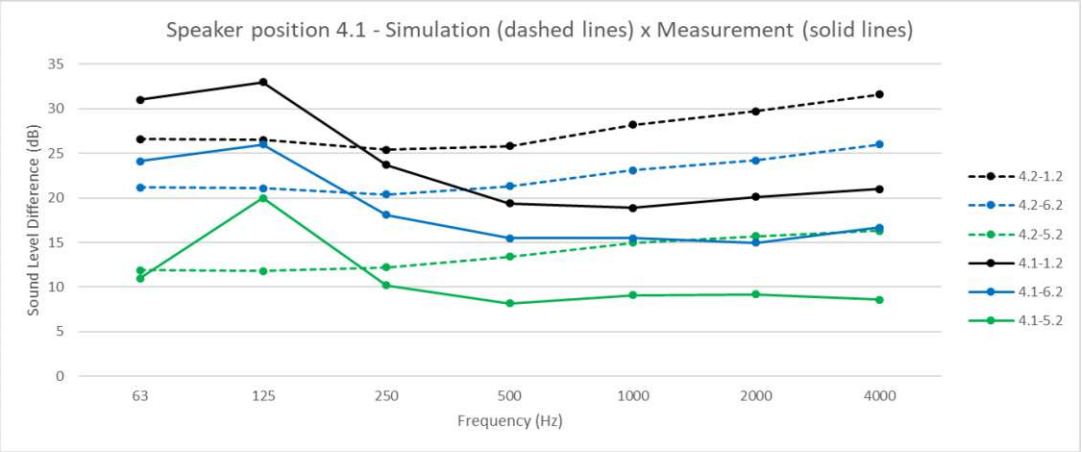

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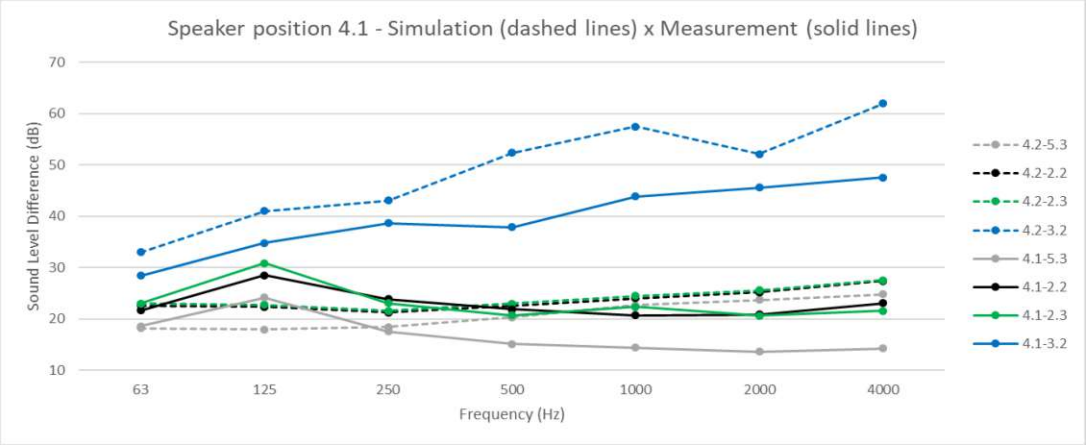

Figure 65: Sound pressure level difference (dB) for speaker in Room 4 according to simulation of the current state and the measurements on-site (2/2)

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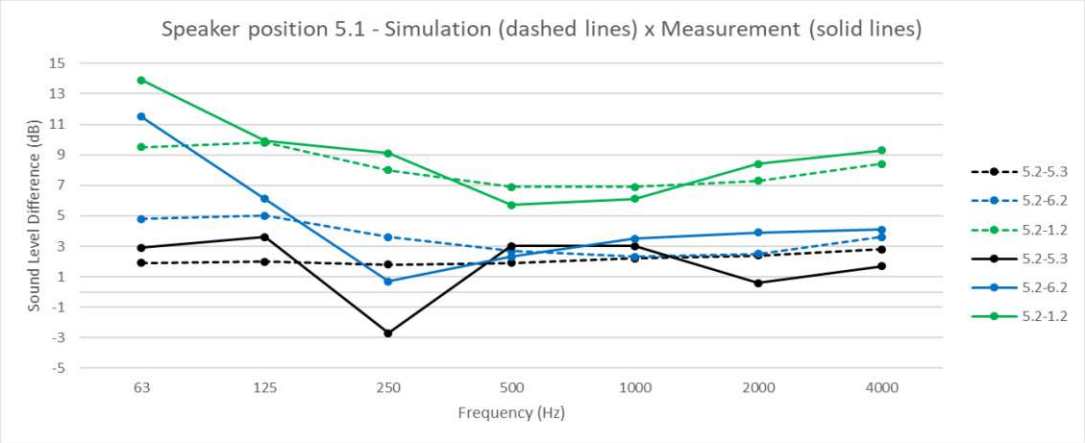

Figure 66: Sound pressure level difference (dB) for speaker in Room 5 according to simulation of the current state and the measurements on-site (1/2)

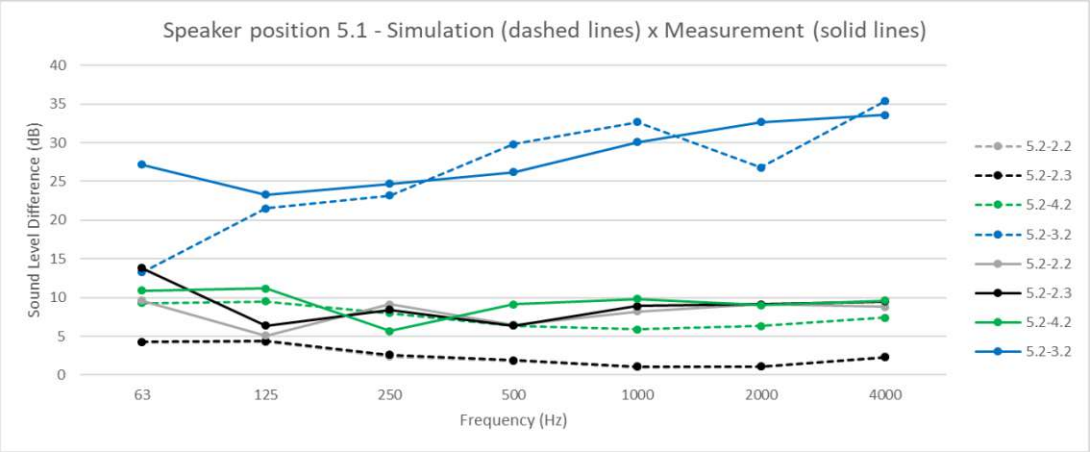

Figure 67: Sound pressure level difference (dB) for speaker in Room 5 according to simulation of the current state and the measurements on-site (2/2)

8.3 SPL difference – difference between simulation of the current state and measurements on-site

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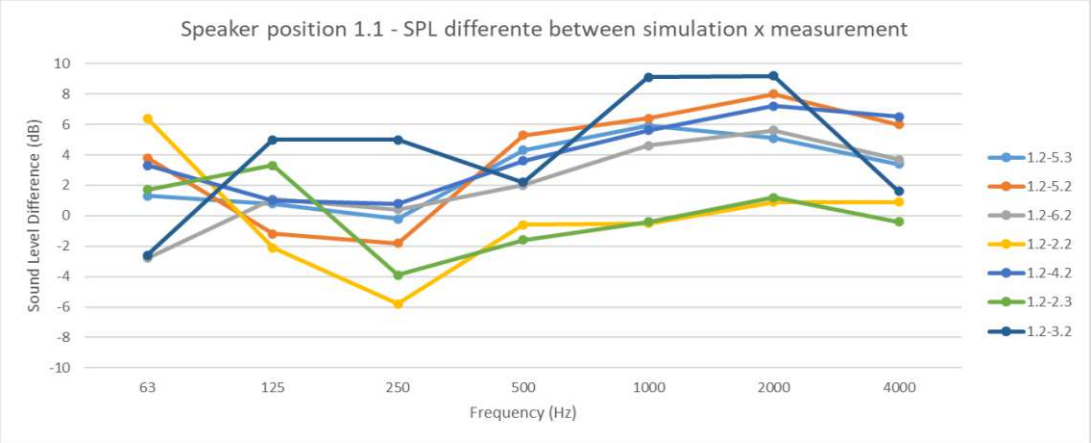

Figure 68: The difference between SPL difference (dB) of current state's simulation and the measurements on-site - Room 1

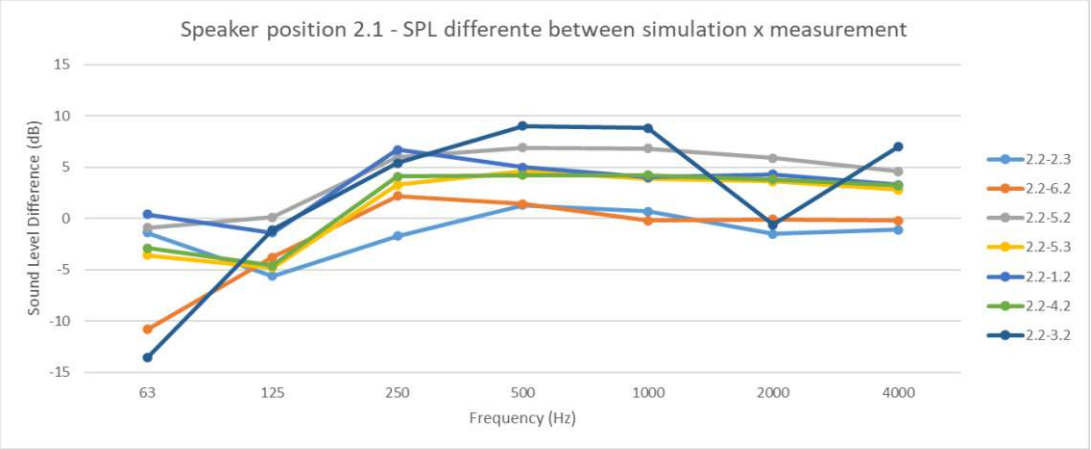

Figure 69: The difference between SPL difference (dB) of current state's simulation and the measurements on-site - Room 2

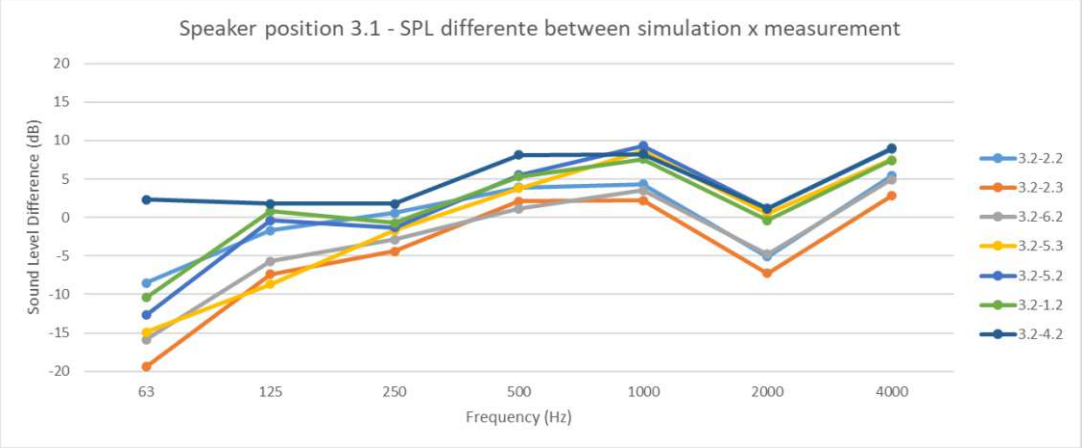

Figure 70: The difference between SPL difference (dB) of current state's simulation and the measurements on-site - Room 3

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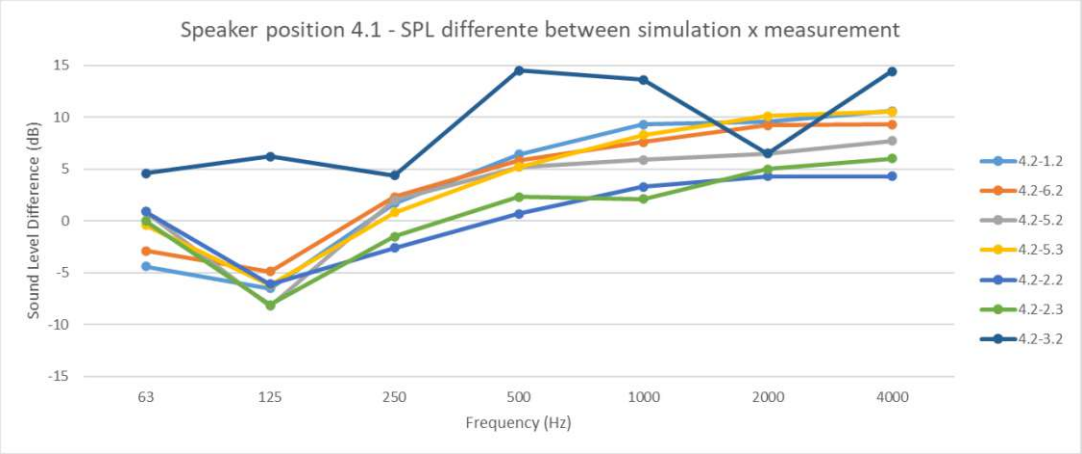

Figure 71: The difference between SPL difference (dB) of current state's simulation and the measurements on-site - Room 4

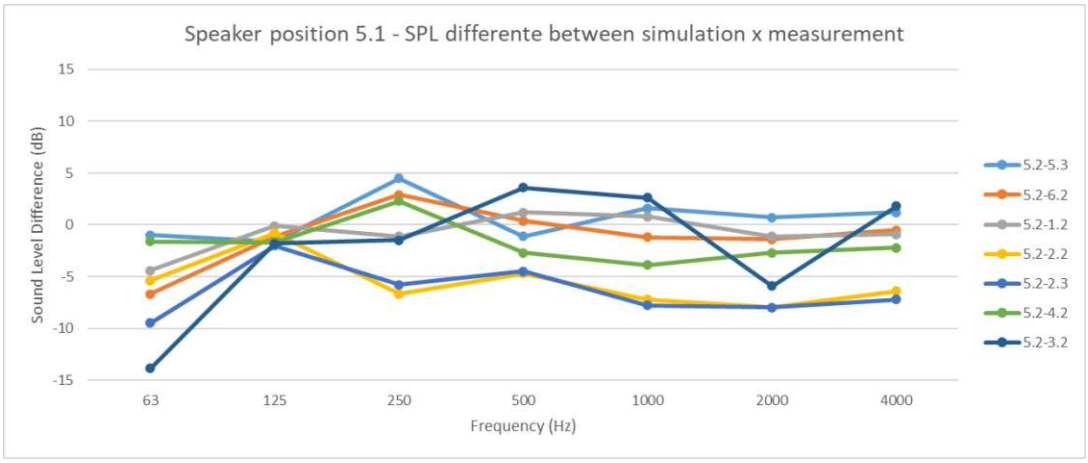

Figure 72: The difference between SPL difference (dB) of current state's simulation and the measurements on-site - Room 5

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