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Application of a Calibrated Room Acoustics Model for Retrofit Support

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ABSTRACT

Building performance simulation has been widely adopted in research and for consulting purposes for more than a decade now. This study outlines the use of performance simulation within the framework of a case study pertaining to room acoustics.

The results of the study contribute to the discussion concerning the effectiveness of acoustical simulation applications and the extent of necessary simulation calibration efforts in modeling the acoustical conditions in existing spaces and prediction of the implications of acoustical retrofit measures.

The target of the study is an office area within a university, consisting of closed and open spaces for different functions (workstations, seminar, service spaces). Certain indicators of the room acoustical performance of this office area were obtained based on both measurements and simulations. Subsequently, the simulation models were calibrated using the measurement results. The calibrated simulation models facilitated the prediction of the implication of acoustical retrofit measures. Upon the implementation of such a measure (installation of acoustical absorbers), measurements and simulations were conducted again and the results were compared. Moreover, occupants' subjective evaluation of the acoustical conditions before and after the acoustical retrofit measures were explored as well using appropriate questionnaires.

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1. INTRODUCTION

1.1. Motivation

As a part of Building Performance Simulation; Computer Aided Acoustical Modeling, has become widely used over more than a decade and is drawing increasing attention depending on their benefits.

The potential benefits of a simulation-aided approach to building design and retrofit have been widely discussed in the past (see, for example, Hensen and Lamberts 2011, Sieben 1986 and Sieben 1999). The basic idea is to evaluate design intentions a priori using simulation, such that they can be improved and fine-tuned before realization.

Currently, the potential of this simulation-aided design support strategy is not being fully exploited. The reasons are multi-faceted. Thereby, usability and reliability concerns with respect to performance simulation applications may play a role. Hence, it would be useful to collect, discuss, and evaluate actual experiences pertaining to the practical cases of simulation deployment in building design, retrofit, and operation.

In this context, the present contribution circles around the use of performance simulation within the framework of a case study pertaining to room acoustics. The relevant area of the study is an office area within a university, occupying closed and open spaces for different functions (workstations, seminar, and service spaces). Certain room acoustics performance indicators; Reverberation time (RT) and sound distribution patterns were captured via in-situ acoustical measurements as well as simulations. RT is considered to be the most important parameter and is used as a reference in the model calibration. Model calibration is executed via tuned absorption coefficients of virtual surfaces through measurement results. Calibrated simulation models are used for the retrofit design. After realization of retrofit (installation of acoustical absorbers), measurements were re-conducted and simulations were re-performed for both calibrated case and non-calibrated case and results were compared. Furthermore, by performing a subjective study before and after retrofit, it was attempted to estimate the degree of enhancement in acoustical comfort. The results were processed, comparatively evaluated (pro-after retrofit), and discussed.

The results of the case study are relevant in view of a number of questions:

- How effective are acoustical simulation applications in modeling the existing conditions?
- What are the likely sources of uncertainty in simulation? What is the extent of the calibration needed?
- Can a calibrated simulation model reliably predict the implications of retrofit measures?

The results allow, in addition, the exploration of possible change in the occupants' subjective evaluations of the acoustical conditions as a consequence of the executed retrofit measures.

1.2. Background

1.2.1. Room acoustic metrics

Reverberation time:

In the project, reverberation time (RT) and sound distribution patterns were taken as room acoustic indicators. RT was considered to be the most important parameter and was used as a reference in the model calibration. Furthermore it was taken as acoustic design criteria of studied spaces.

The reverberation time is one of the most important quantities in room acoustics. It can be measured with good accuracy, and the available formulas predict it with reasonable accuracy (Crocker 1997). There are four generally accepted methods for calculating reverberation time. In this paper, it was used Sabine equation (Sabine 1927) which is probably the most widely used method. The reverberation time (T_{60}) is the time taken for sound to decay by 60 dB (A) (See Figure 1).

$$T_{60} = 0{,}163\frac{V}{A}(s) \qquad \text{where;} \qquad \textit{(Eq. 1)}$$

V = Volume of the room in cubic meter

A = Total area of absorption in the room

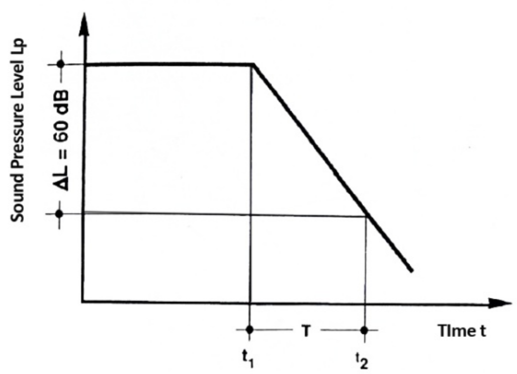


Figure 1 Sound decay and definition of the reverberation time (Fasold and Veres 2003)

Sound pressure level and sound distribution:

Figure 2 shows the decrease of sound pressure level from a sound source in a roughly cubic room. Sound pressure level is decreasing due to increase of equivalent absorption area. In larger distances exists a constant sound pressure level due to diffuse sound field which is developed by reflections.

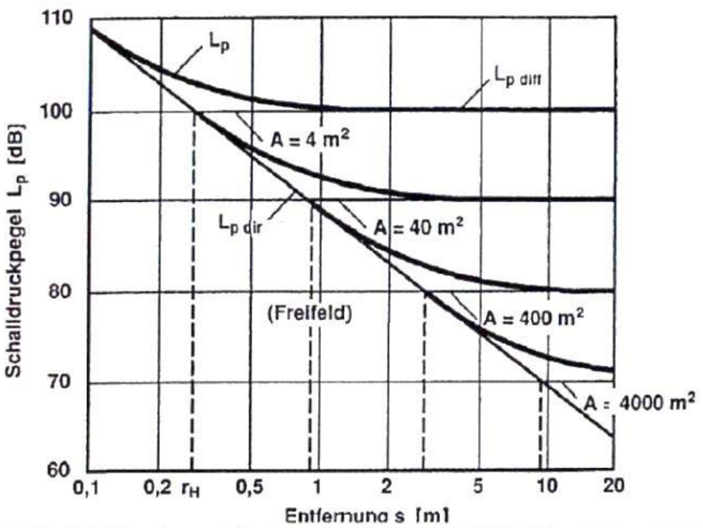


Figure 2 Sound pressure decrease level in the diffuse sound field (Fasold and Veres 2003)

$$Lp\ diff = Lw - 10lg\frac{A}{4}dB$$ where; *(Eq. 2)*

Lpdiff = Constant sound pressure level

LW = Sound power level

A = Equivalent absorption area

1.2.2. Design considerations for seminar room(SR)

In the design of classrooms, speech intelligibility is crucial. The architectural components of these rooms such as size, shape, surface orientation, and materials, as well as the background noise level influence intelligibility (Long 2006). There are several fundamental requirements in the design of rooms for speech (Doelle 1972), each of which contributes to achieving a high signal-to-noise level at the receiver:

1. There must be an adequate loudness.

2. The sound level must be relatively uniform.

3. The reverberation characteristics of the room must be appropriate.

4. There must be a high signal-to-noise ratio.

5. Background noise levels must be low enough to not interfere with the listening environment.

6. The room must be free from acoustical defects such as long delayed reflections.

In general, the more speech content to the sound is the lower the ideal reverberation time. For classrooms and small lecture halls reverberation times at or below one second are preferred (Long 2006).

In small classrooms (< 50 seats) the direct field, along with support from the walls, provides sufficient loudness and control of reverberant noise using an absorptive ceiling as the normal choice (Long 2006). In absorptive ceiling use, it is also crucial not to block useful reflection surfaces. There are three examples of efficient and inefficient use of sound absorbers (seen in Figure 3). In *option a*; useful reflection surfaces have been blocked. In *option b* and *option c* useful reflection surfaces are in use. A similar treatment like *option b* has been realized for seminar room (SR).

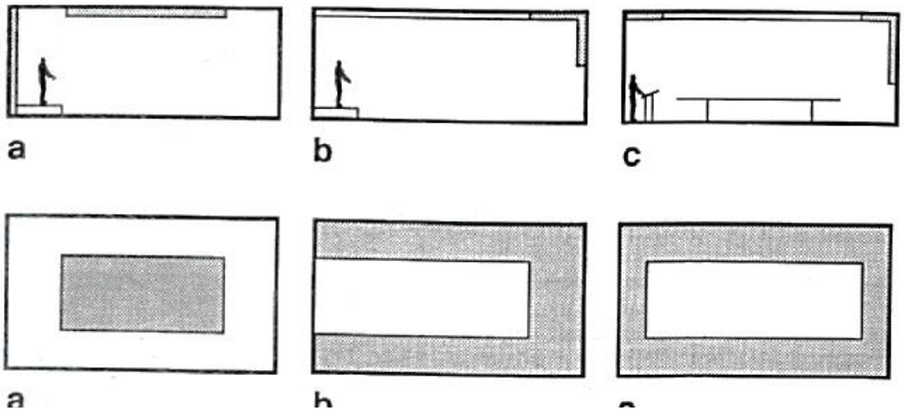


Figure 3 Inappropriate and appropriate distribution of broadband sound absorbers (Fasold and Veres 2003)

1.2.3. Design considerations for open plan office(OP)

In acoustical design of open-plan offices; ceiling treatment, use of screens, workstation distance and orientation, masking noise are the main practices (Toy 1998).

In OP sound absorptive treatment was practiced, since it was not possible to apply all aforementioned practices.

Sound absorptive treatment of the rooms to reduce interior noise level is effective if the room does not have much sound absorption already. In such a case, a reduction of 9 to 10 dB can be achieved through absorptive treatment. In fact, 10 dB is usually the upper limit of reduction possible through sound absorptive treatment. If sufficient absorption is already present in the room, noise reduction obtained by treating the room is small usually 2 to 4 dB. Although 2 to 4 dB seems a small improvement, it may be worthwhile if the noise levels are high while 3 dB reductions is a perceptible reduction (Metha et al. 1999).

Note that absorptive treatment reduces only reverberant sound; it is beneficial to occupants who are away from the source. It does not help an occupant who is close to the source since he/she gets most of the noise as direct sound. In a large room with a high ceiling, space absorbers are commonly recommended, since they can be hung from the ceiling and brought close to the source/s (Metha et al. 1999).

Figure 4 illustrates two absorptive treatment examples. In a room with a low ceiling (left case), ceiling absorption is effective since it is close to noise sources. In a room with high ceiling (right case), use of space absorbers bring absorption close to the noise sources

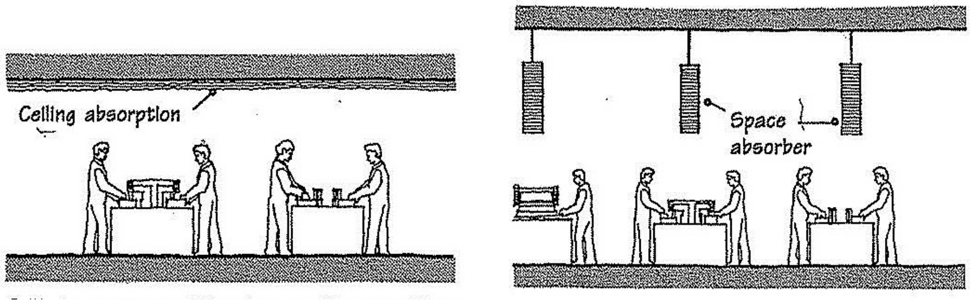


Figure 4 Use of space absorbers in rooms with high ceiling (Metha et al. 1999)

Suspended baffles yield more absorption per unit area of than regular use of same material. Baffles are more absorbent because both the front and back sides of each baffle is exposed to the sound field (Figure 5).One of the absorber elements which is used for retrofit has the possibility for both implementations; suspended use and regular acoustical ceiling coating. For office space (OP) suspended use of the element is preferred considering the facts that are mentioned above.

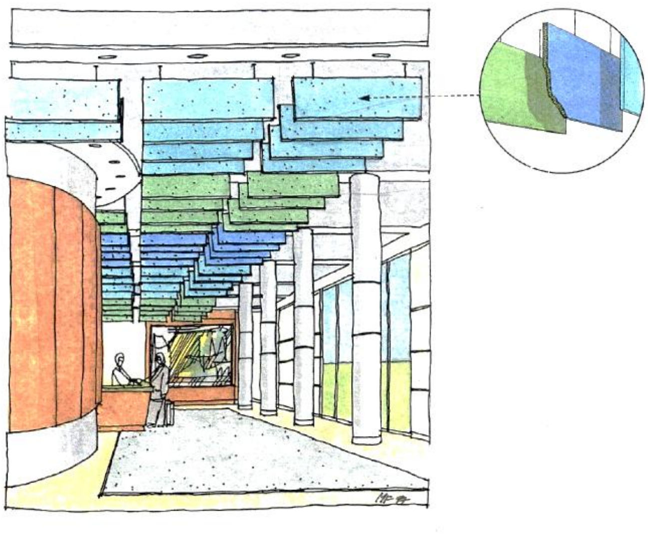


Figure 5 Suspended acoustical baffles (Schwind 1998)

The total absorption provided by a group of suspendent absorbers is not simply a product of the number of absorbers in a space and the absorption provided by each unit. Figure 6 illustrates a few alternative arrangements of suspended baffles in plan. Figure 7 illustrates a few of several possible space absorber profiles. For office space (OP) a pattern is used similar to the one on the left side (see Figure 6) with combination of cubic space absorbers.

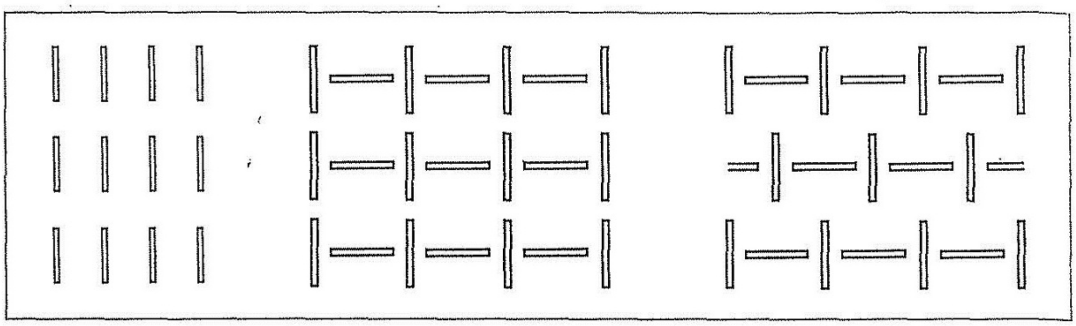


Figure 6 Alternative arrangements of suspended baffles in plan (Metha et al. 1999)

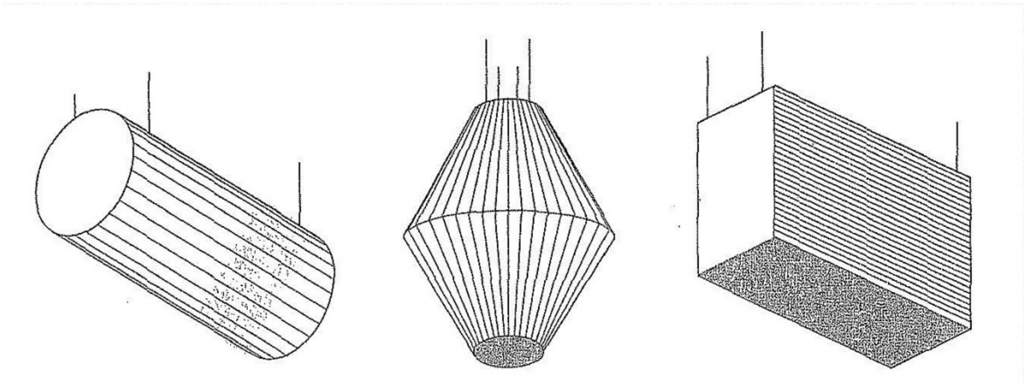


Figure 7 Space absorber profiles (Metha et al. 1999)

1.3. Structure

This thesis has six main sections. In introduction section right after brief explanation of motivation, room acoustics metrics that are used and retrofit design considerations of studied spaces; SR and OP are given in background.

Methodology section starts with a comprehensive overview. This is followed by the sections; *description of the office*, *questionnaire*, *measurements* and *simulation*.

In the *office description* section, two different spaces that are involved to the study called as seminar room (SR) and open plan office area (OP) were introduced. And spatial dimensions of these spaces were documented.

In *questionnaire* section, the information about participant and distribution-collection dates of questionnaire sets was given. Moreover, the design considerations of forms were explained.

In *measurements* section, after a short information about measurement equipment, settings and procedure; RT and sound distribution measurements were explained. In addition to that additional measurements were described which took place in reverberation chamber. It may be important to underline that additional measurements are not directly related with the place of the study (BPI office) but just to provide accurate input data for the simulation.

Similar to the *measurement* section; *simulation* section was also started with information about the tool, settings and the procedure. Then, room acoustics models of BPI were introduced with material assumptions. Afterwards, the calibration process of room acoustics models was explained. Moreover details were given about virtual absorbers. In section *design and realization of retrofit project*, selected acoustical absorbers were introduced and acoustic properties of these absorbers were explained.

Consequently results were presented. It was followed by discussion where calibration process and effectiveness of retrofit were separately evaluated.Paper finalized by conclusions.

2. METHODOLOGY

2.1. Overview

The study involved the following steps:

i) The existing spaces were documented in view of geometry and material properties.

ii) Basic acoustical measurements – pertaining to reverberation time and sound distribution were conducted to capture the existing acoustical conditions.

iii) Occupants were interviewed with respect to their perception of the acoustical conditions.

iv) Office spaces were modeled in an advanced room acoustics simulation program (ODEON 2009). Note that a documentation of the acoustical room surface properties (absorption coefficients) did not exist. An in-situ measurement of such properties was also not possible. Thus, assumptions were made based on the surface material types (e.g., plaster, glass, wood) and available general absorption coefficient data in literature and the simulation application's database. (Note that one exceptional measurement conducted in reverberation chamber to obtain absorption coefficient of upholstered office seats.)

v) The simulation model was calibrated using the measurement data. The calibration was based on the comparison of the measured and simulated reverberation times and was realized in terms of virtual surfaces distributed in the office spaces.

vi) Existing acoustical conditions were compared with applicable criteria.

vii) Acoustical improvement measures – in this case, additional absorption – were conceived and modeled with the simulation tool.

The additional absorption was introduced in the office spaces in terms of panels attached to and suspended from the ceilings, as well as suspended cubical elements.

viii) The acoustical improvement measures were realized.

ix) Post-retrofit measurements and simulations were performed and compared.

x) Occupants were interviewed again in view of the modified acoustical conditions.

xi) The results were processed, analyzed, and discussed.

Figure 8 shows the general structure of the study.

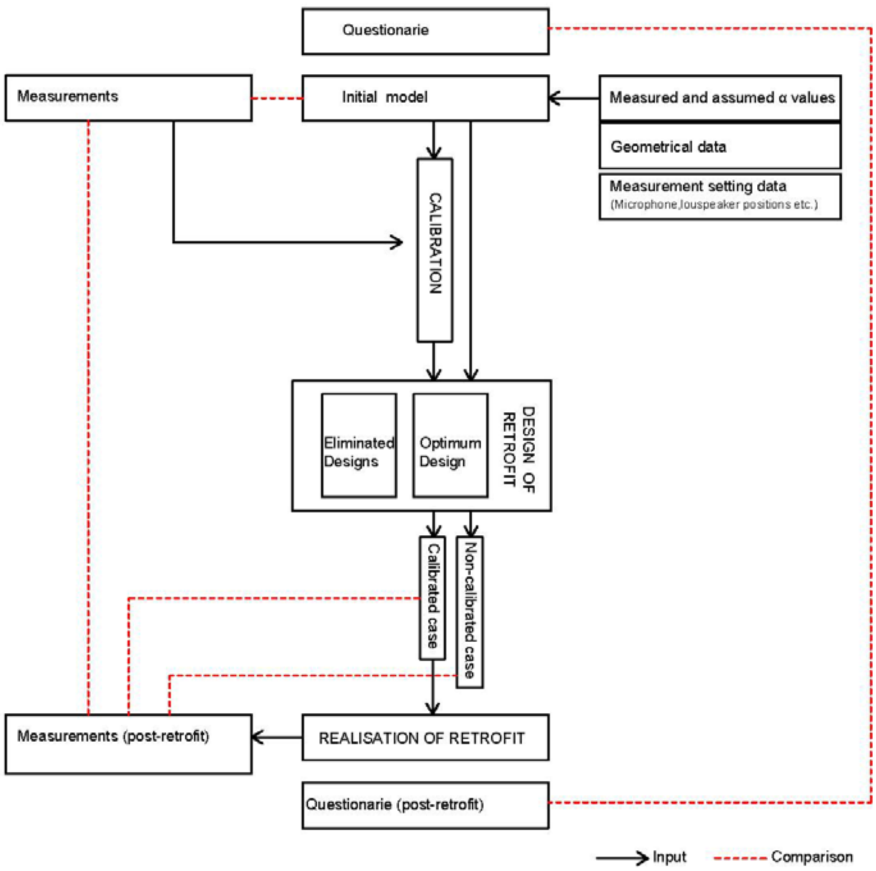


Figure 8 General structure of the study

2.2. Description of the office

Building Physics and Building Ecology Department (BPI) is located in the middle section of main building of Vienna University of Technology. The total area of the department is 243 m^2, including 56 m^2 seminar room, 37m^2 enclosed personal room of professor, 14.5 m^2 service area (restroom facility). Except the enclosed parts which are mentioned above, the rest part is utilized as, bullpen type offices for assistants, a secretary office and a service area (kitchenette) in a whole volume. Figure 9 displays the schematic plan of BPI. The study focuses on two volumes, namely seminar room (SR) and open plan office area (OP). Figures 10 and 11 show existing conditions in OP and in SR respectively. As seen in Figures, room surfaces are covered with hard materials that have high sound reflectance acoustic characteristics. The areas of room elements are shown in Table 1.

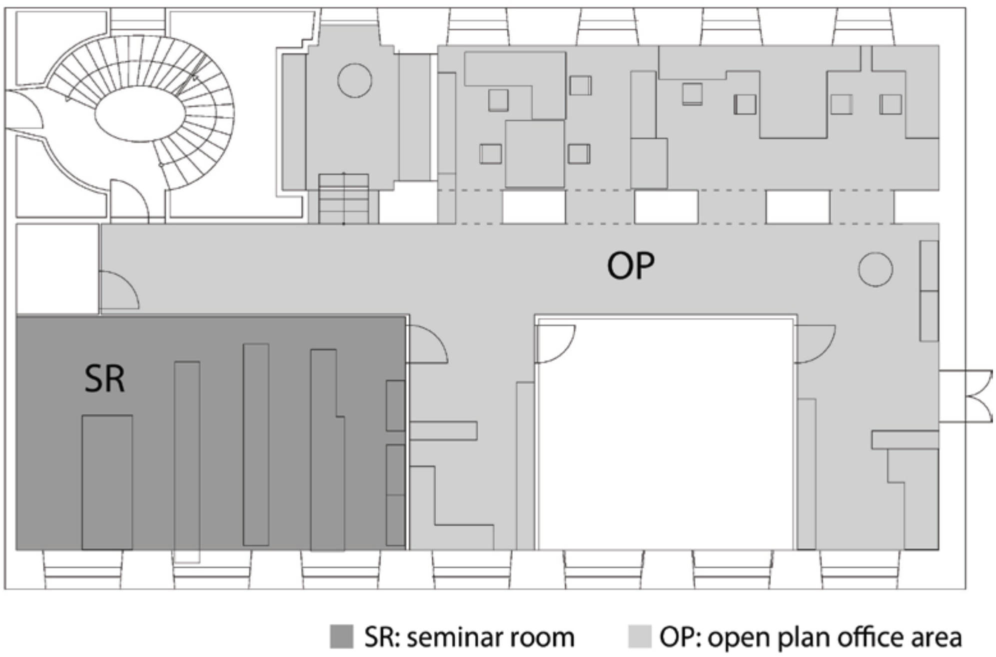


Figure 9 Schematic plan of the office area (SR: seminar room; OP: open-plan office area)

Figure 10 Existing conditions in OP

Figure 11 Existing conditions in SR

Table 1 Areas of room elements

ROOM ELEMENTS (SR)	**SURFACE AREA**
Ceiling	54,05 m^2
Floor	54,05 m^2
External wall (brick)	45, 89 m^2
Internal wall (gypsum)	30, 63 m^2
Window	13,89 m^2
Window frame (wood)	18, 33 m^2
Door	2, 15 m^2
Glass door	27, 90 m^2
Furniture	39, 94 m^2
SURFACE TYPE(OP)	**SURFACE AREA**
Ceiling OP	88,98 m^2
Ceiling Corridor	38, 69 m^2
Floor	154, 87 m^2
External wall	60, 6 m^2
Internal wall (brick)	239, 85 m^2
Internal wall (gypsum)	90, 40 m^2
Window	25, 11 m^2
Window frame (wood)	44, 73 m^2
Door (wood)	11, 56 m^2
Glass door+ other glass elements	37, 91 m^2
Furniture (wood)	123,22 m^2
Chairs	3, 41 m^2

Documentation of the building was obtained from TU GUT (Gebäude und Technik) including plan, some details and construction period Acoustical properties of the building elements were not documented.

2.3. Questionnaire

For the subjective part of the study, a questionnaire was designed (Appendix 1). Particular attention was paid to questionnaire design. Questionnaire was comprised of 21 questions. Different question types were used like multiple choice questions and 5-point rating scale questions. Rating labels were specified carefully, from low to high (Oppenheim 2001). Short answer text box was also used for additional comments, problems, and ideas.

Questionnaire was structured in two parts. Here part 1 was consisted of questions about participant and part 2 was consisted of questions about mainly acoustical comfort within the questions about overall indoor environmental quality (thermal comfort, lighting conditions, air quality etc.). Even the main tread was the evaluation of acoustic comfort; questionnaire was named as '*office environment assessment'* and questions about acoustic comfort was not highlighted but was embedded in the questionnaire. The reason behind this embedment was the prevention of biases and the consideration of possible correlation of the other office comfort parameters on acoustic comfort.

Questionnaires were applied to BPI occupants before and after retrofit. The first set of questionnaires were collected In February 2012 and the second set of them were collected in May 2012. (The questionnaire which was designed interactively was distributed and was collected via e-mail.)

Comparative evaluation of questionnaire results (between pre and post-retrofit case) was proceeded to show the expected acoustical comfort improvement.

Table 2 gives general information about participants who took part in the questionnaires. 2 Administrative staff, 12 researcher/scientific staff and 3 students took part in survey. 59% of the occupants are working in the office more than a year, working hours diverse from 0-10 hours to more than 60 hours.

Table 2 General information about participants

	CATEGORY	NUMBER OF PARTICIPANTS
Gender	Female	6
	Male	11
Occupation	Administrative staff	2
	Researcher/Scientific staff	11
	Student	3
	Other	1
Working time in BPI	Less than 6 months	3
	6-12 months	3
	More than a year	10
	Visiting time to time	1
Average hours/week	0-10 Hours	4
	11-20 Hours	2
	21-30 Hours	4
	31-40 Hours	4
	41-50 Hours	2
	51-60 Hours	0
	More than 60 Hours	1

2.4. Measurements

2.4.1. Measurement equipment and procedure

For reverberation time and sound distribution measurements following hardware and software components were used in Table 3. Measurement configuration can be seen in Figure 12. Further information about the equipment can be found in (NORSONIC 2009).

Table 3 List of measurement equipment components

WIRELESS BUILDING ACOUSTIC MEASUREMENT SYSTEM
2 x Sound analyzer Nor140
2 x Nor515 Building Acoustic Cases
1 x Nor514 Control Station
Calibrator Nor1251
Loudspeaker: Nor270
Power Amplifier: Nor280
Software: CtrlBuild Nor1028/3

Measurements were conducted in BPI. Additional measurements took place in reverberation chamber of building physics laboratory. All measurements were conducted in compliance with ÖNORM standards.

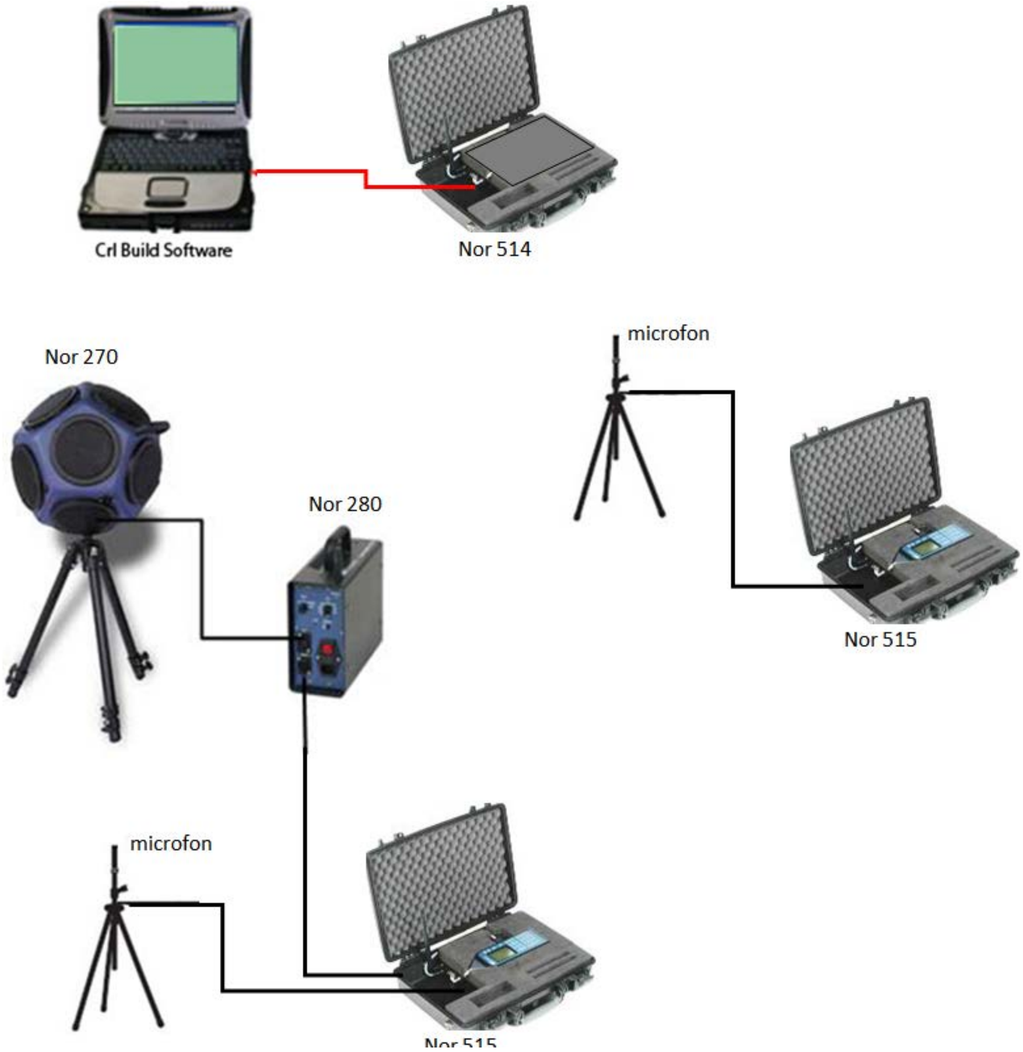


Figure 12 Measurement configuration (Lechleitner 2009)

2.4.2. RT measurements in BPI

Reverberation times were measured, according to the standard (ÖNORM 3382-2 2009) in empty (non-occupied) conditions. For OP; 3 different loudspeaker positions; LP1, LP2, LP3 and 5 to 6 microphone positions were used for each LP position (Figures 13, 14 and 15). Again, 2 different loudspeaker positions; LP4, LP5 and 4 microphone positions (for each LP position) were used for SR which was relatively smaller than OP (Figures 16 and 17). Results were obtained in 1/3 octave bands. In all measurements, the loudspeakers were located at 1.4 m, and microphones were located at 1.2 m above the floor. Spatial averaging was proceeded both for SR and OP. The spatial average was given by taking the mean of the individual reverberation times for all the independent source and microphone positions.

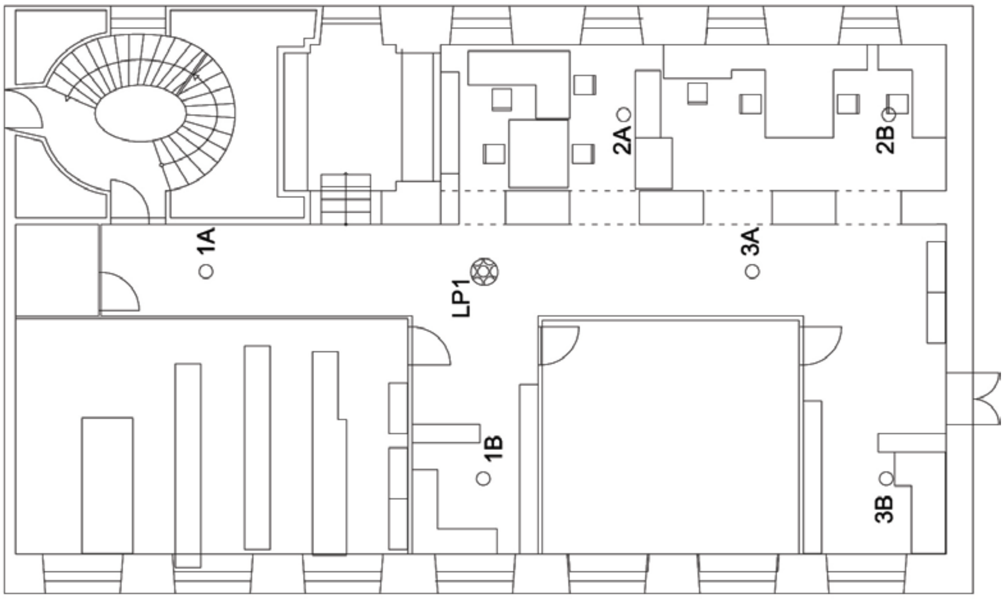


Figure 13 Speaker LP1 and relative microphone placements

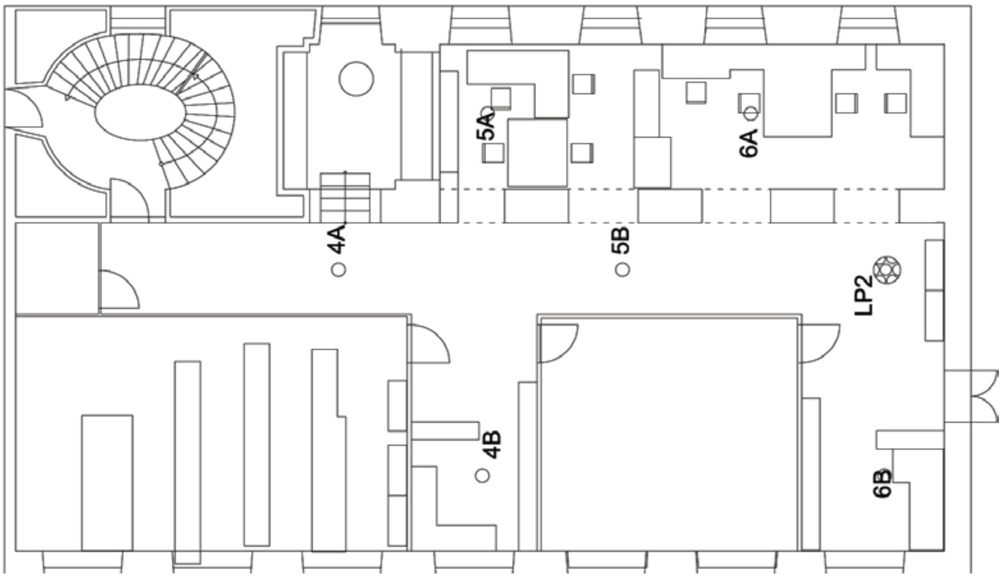


Figure 14 Speaker LP2 and relative microphone placements

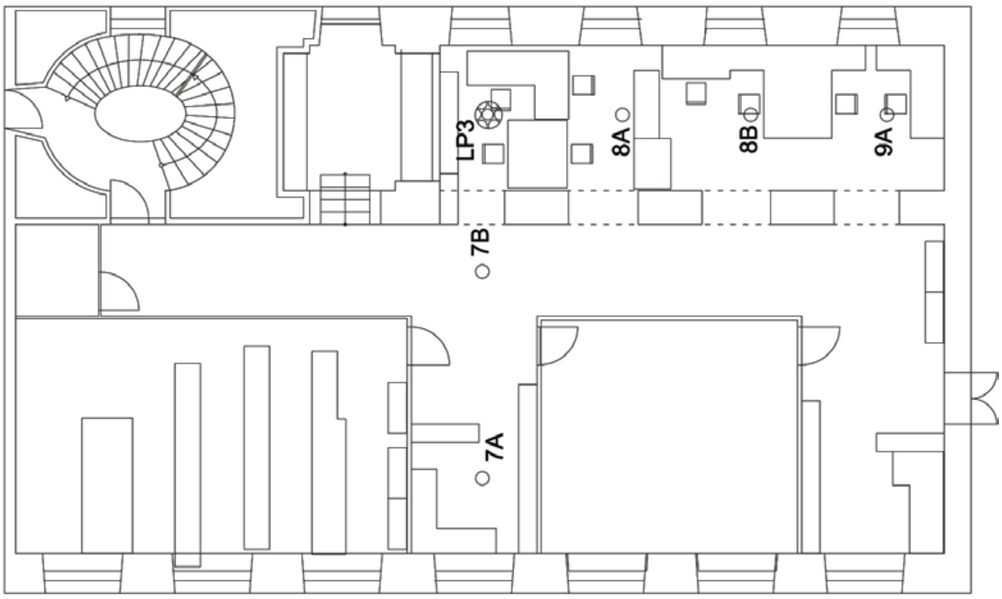


Figure 15 Speaker LP3 and relative microphone placements

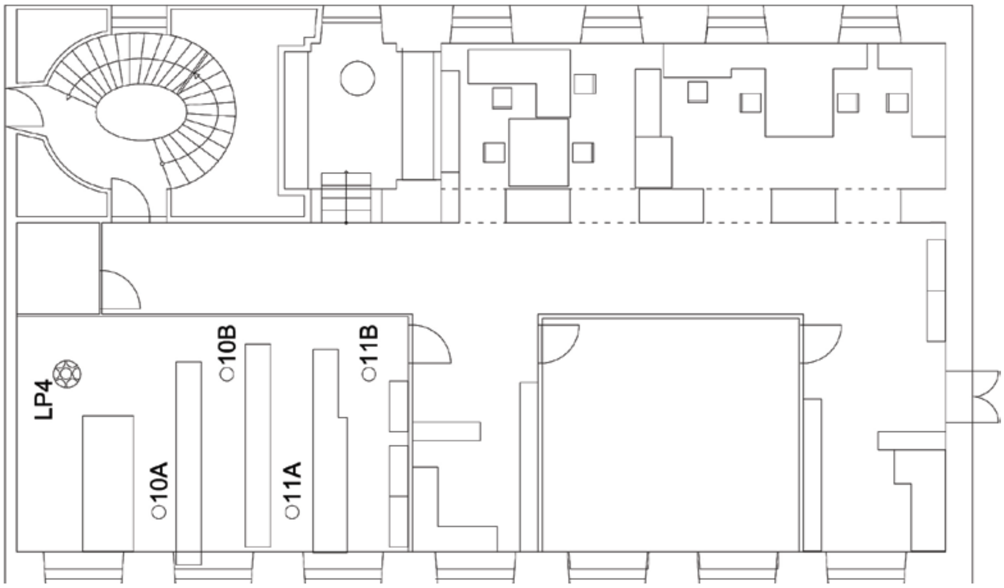


Figure 16 Speaker LP4 and relative microphone placements

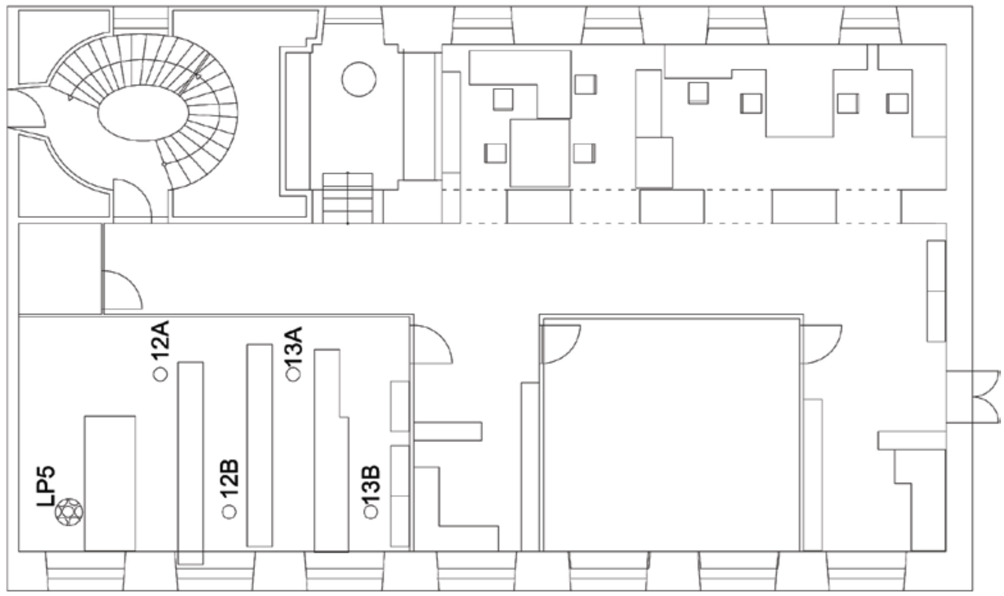


Figure 17 Speaker LP5 and relative microphone placements

2.4.3. Sound distribution measurements in BPI

Measurements were conducted in empty (non-occupied) conditions. For sound level distribution measurements, one loudspeaker position and a grid of microphone positions were considered (Figure 18). In all measurements, the loudspeaker was located at 1.4 m, and microphones were located at 1.2 m above the floor. Measurements were conducted in 10 sets. Sound pressure levels (SPL) were captured in 1/3 octave bands.

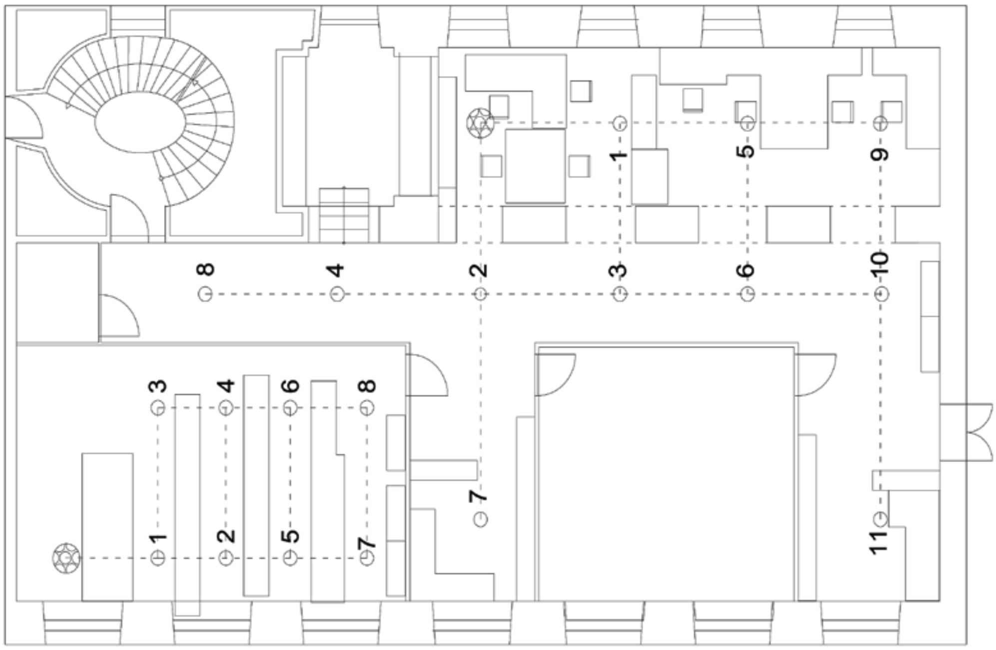


Figure 18 Speaker and microphone placements for sound level distribution measurements

Obtained values were converted to A-weighted sound pressure level. It was applied A-weighting correction values to unweighted octave-band sound pressure levels, then was derived the overall dBA level. Table 4 shows applied correction values. A weighting was intended to represent the varying sensitivity of the ear to sound at sound pressure levels ranging between 40 and 60 dB (Crocker 1997).

Table 4 Sound pressure level correction values of the frequency weighting curves (Fasold and Veres 2003)

FREQUENCY[HZ]	**SOUND PRESSURE LEVEL CORRECTION ΔL**
	CURVE A[Db]
16	-56.7
20	-50.5
25	-44.7
31,5	-39.4
40	-34.6
50	-30.2
63	-26.2
80	-22.5
100	-19.1
125	-16.1
160	-13.3
200	-10.9
250	-8.6
315	-6.6
400	-4.8
500	-3.2
630	-1.9
800	-0.8
1000	0
1250	0.6
1600	1
2000	1.2
2500	1.3
3150	1.2
4000	1
5000	0.5
6300	-0.1
8000	-1.1
10000	2.5
12500	-4.3
16000	-6.6
20000	-9.3

2.4.4. Additional measurements in reverberation chamber

Apart from the place of the study, two additional measurements were conducted in reverberation chamber of BPI laboratory to provide information for the simulation process.

First measurement was conducted to provide an input data for the material library of the simulation. Absorption coefficient of office chairs was required, due to the lack of a proper definition both in acoustic software's database and in the literature. To obtain this data, two reverberation time measurements were conducted in reverberation chamber; one with empty case and another with 10 office chairs. Figure 19 shows the latter case. As seen on the picture seats were distributed homogeneously.

Figure 19 Absorption coefficient measurements of office seats in reverberation chamber

Since the volume of the space and additional volumes of the chairs were known, the equivalent absorption area was derived for each frequency by using Sabine formula and absorption coefficients were calculated by dividing them to real absorption areas. Measurements were conducted in compliance with measurement standard of sound absorption in a reverberation room (ÖNORM 354 2003).

Second measurement was conducted to obtain SP (sound power) of loudspeaker which was in-use for the measurements. In empty reverberation chamber, measurement equipment was placed and reverberation time (RT) and sound pressure level in diffuse case ($L_{p\ dif}$) were measured. After this step; it was derived to sound power (L_w) of loudspeaker.

Both measurements were conducted to provide the accurate input data for the simulation.

2.5. Simulation

2.5.1. Simulation tool and procedure

A number of computer software programs are commercially available to predict sound propagation in rooms. The prediction models used for rooms are based on geometrical acoustics, partly combined with statistical concepts to include scattering effects. There are two basic methods; the ray-tracing and the image source method. There exist hybrid types combining principles from ray-tracing and image source modeling (Vigran 2008).

ODEON Room Acoustics Program version 9.1 (industrial, auditorium, and combined editions) was chosen as commercially available room acoustical simulation and auralisation tool (ODEON 2008).In this software, Responses from point sources are calculated using a hybrid calculation method: While the early reflections are computed using a combination of image source model and ray-tracing, the late reflections are calculated using a special ray-tracing process that generates secondary sources (Christensen 2008).

Formerly the three dimensional (3D) geometry of office (in the DXF format) was created in a CAD application (AUTOCAD 2012). Later this 3D geometry was imported to ODEON Software. Although there was the possibility of creating models in the software itself, model exchange was preferred because of the simplicity.

Circular geometries like vault ceiling of OP and some furniture were simplified to polygons to import them easily to ODEON.

Material assumptions were determined for the room surfaces. For these assumptions beside application’s library, literature was also reviewed. In case of deficiency of data; measurements were conducted in reverberation chamber to obtain necessary data.

The default value 0.05 was taken for scattering coefficients. Temperature and humidity levels were also left default.

As a last step, measurement settings were repeated one after another in virtual conditions. Extra attention was paid to come close as possible to the reality. Virtual sound source and microphones were positioned like the real ones in the measurements. Sound power was assigned to the virtual loudspeaker which was ascertained in laboratory conditions.

Eventually, simulations were carried on. Precision mode was chosen for calculation settings which required the longest calculation time for high accurate calculations. Impulse response length was set to the longest reverberation time or higher which was calculated with quick estimate function.

Results of RT were obtained in octave bands. The overall dBA level was calculated automatically by software.

2.5.2. Simulation and calibration of room acoustics model

Figures 20 and 21 show 3D models of OP and SR respectively which were exported to ODEON. In wireframe display mode, black lines represent exterior boundary and blue lines represent interior geometry. As seen in the Figures geometry was simplified as much as possible. The thicknesses of some furniture were ignored and they were assumed two dimensional to reduce calculation loads. The superiority of simplified geometrical models to high fidelity geometrical models was proved in many studies (see, for example, Rindel et al. 1999 and Shiokawa & Rindel 2007).

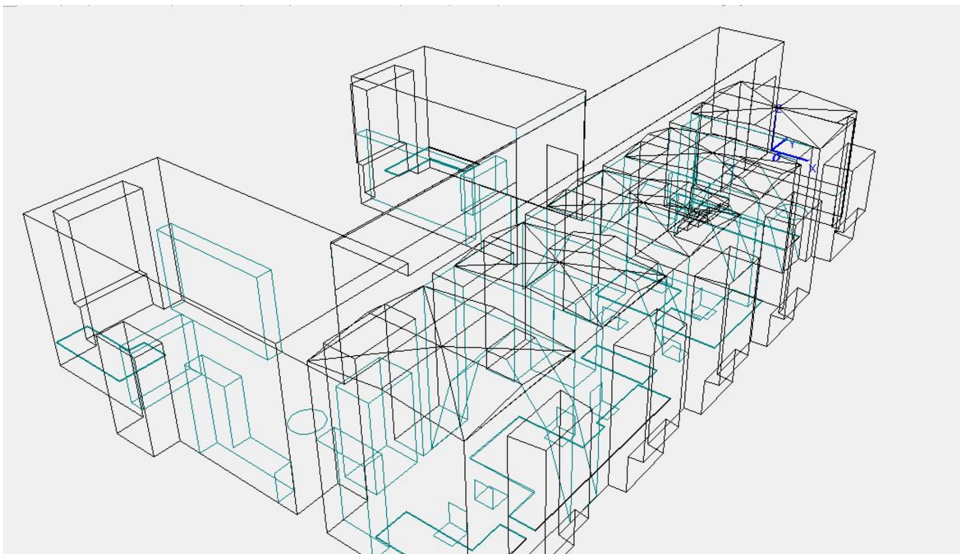


Figure 20 3D model of OP (empty case)

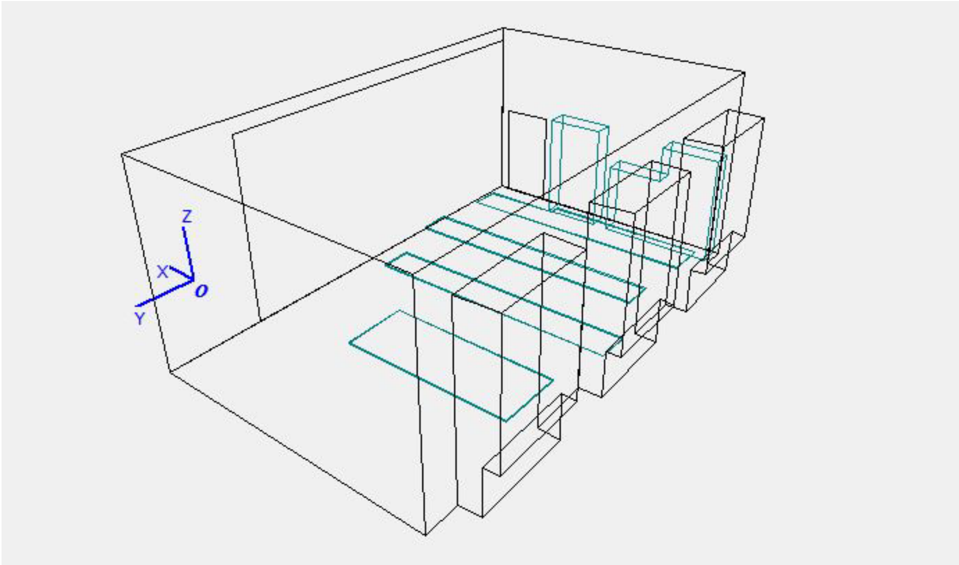


Figure 21 3D model of SR (empty case)

The main room elements of both SR and OP are listed in Table 5 with their representative reference numbers and absorption coefficients of the improved material assumptions in frequency range 125Hz to 4000Hz. In Table 5, e.g. reference number 2468 is given in Table 6 as the material definition and its reference.

Table 5 Absorption coefficients of improved material assumptions

		FREQUENCY [HZ]					
ELEMENT	**REFERENCE NUMBER**	**125**	**250**	**500**	**1000**	**2000**	**4000**
Floor (wood)	2468	0.04	0.04	0.07	0.06	0.06	0.07
Ceiling (corridor)	2294	0.20	0.15	0.10	0.08	0.04	0.02
Ceiling (OP)	2475	0.02	0.02	0.03	0.04	0.05	0.05
Ceiling (SR)	2475	0.02	0.02	0.03	0.04	0.05	0.05
Ex. wall (Brick)	2475	0.02	0.02	0.03	0.04	0.05	0.05
Int. wall-(Brick)	2475	0.02	0.02	0.03	0.04	0.05	0.05
Int. wall (Gyps. boa.)	2476	0.28	0.14	0.09	0.06	0.05	0.01
Window, door (Glass)	2479	0.25	0.15	0.10	0.05	0.03	0.03

Win. frame (Wood)	2471	0.04	0.04	0.05	0.06	0.06	0.06
Door, Cupboard, Desk (wood)	2478	0.20	0.12	0.10	0.07	0.05	0.05
Chairs	2467	0.11	0.35	0.53	0.63	0.64	0.57

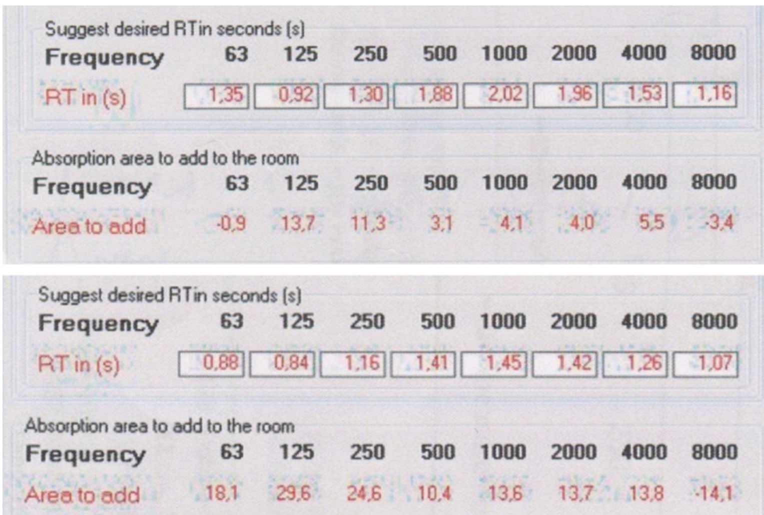
Table 6 Reference of absorption data

REFERENCE NUMBER	**MATERIAL DEFINITION IN REFERENCE**	**REFERENCE**
2468	Parkett auf Estrich	(Mahdavi and Orehounig 2011)
2294	Ceilings, plasterboard ceiling on battens with large air-space above	(Application's database)
2475	Ziegelmauerwerk mit Kalkzemenputz	(Mahdavi and Orehounig 2011)
2476	Gipskartonplatten mit 100mm Luftabstand zu Wand oder Decke ; im Hohlraum Mineralwolle	(Mahdavi and Orehounig 2011)
2479	Glass	(Fasold et al. 1987)
2471	Holz oder Spanplatte vor festem Untergrund	(Mahdavi and Orehounig 2011)
2478	Holzpanplatte, 19 mm, 913.5 kg/m², 12 cm	(Fasold and Veres 2003)
2467	-	(Measured)

2.5.3. Calibration of room acoustics model

After obtaining the first outcomes of the simulation, reverberation times were compared with the measured values. Consequently it was observed that initial material assumptions which were based on application's database were shown a significance disagreement with measurement values. The first attempt was the literature review to overcome disagreement. Alternative materials were searched in the literature and were replaced with the previous ones to obtain closer results to measurement data. For SR material assumptions were upgraded 4 times (excluding calibration) and for OP, the latest assumptions of SR were used and furthermore another upgrade was done (Appendix 2). The results could be improved up to a point with the help of literature review. After a point, no further improvements could be achieved. At that point calibration was realized. Calibration process was needed to be actualized by virtual surfaces equally distributed in the volume. In this sense, it was preferred to use existing surfaces (desks) instead of creating new ones considering the possible obstruction effect of the intended extra geometry.

Estimate area function of the software was used to determine absorbance confidents of virtual absorbers. By entering a RT value of choice, this function estimates the necessary area to be added. Figure 22 shows RT entry of measurement values, and additional absorption needed.


Suggest desired RTin seconds (s)

Frequency	63	125	250	500	1000	2000	4000	8000
RT in (s)	1,35	0,92	1,30	1,88	2,02	1,96	1,53	1,16

Absorption area to add to the room

Frequency	63	125	250	500	1000	2000	4000	8000
Area to add	-0,9	13,7	11,3	3,1	4,1	4,0	5,5	-3,4

Suggest desired RTin seconds (s)

Frequency	63	125	250	500	1000	2000	4000	8000
RT in (s)	0,88	0,84	1,16	1,41	1,45	1,42	1,26	1,07

Absorption area to add to the room

Frequency	63	125	250	500	1000	2000	4000	8000
Area to add	18,1	29,6	24,6	10,4	13,6	13,7	13,8	-14,1

Figure 22 Additional absorptions needed for calibration (above for SR and below for OP)

Absorption effect of tables was excluded from simulation and measured RT values were entered as desired value. Additional absorption needed was obtained as a result of it. Absorbance coefficients of virtual absorbers were calculated with the formula below;

$$A = \sum_{i=1}^{n} (\alpha_i \cdot S_i) \qquad \text{(Eq.3)}$$

A = Equivalent absorption area [m^2]

α = Sound absorption coefficient of material

S = Surface of the material [m^2]

Calculated sound absorption coefficients of virtual absorbers are given in Table 7 for SR and OP respectively.

Table 7 Assumed absorption coefficients of virtual absorbers

	FREQUENCY [HZ]					
ELEMENT	**125**	**250**	**500**	**1000**	**2000**	**4000**
Virtual absorb. (SR)	0.50	0.42	0.11	0.15	0.15	0.20
Virtual absorb. (OP)	0.68	0.57	0.24	0.31	0.31	0.32

2.5.4. Design and realization of retrofit project

Calibrated acoustics model was used for design of retrofit project. Existing conditions were compared with desired acoustical criteria by considering the function of the spaces.

For the seminar room as a place of listening RT was targeted 0.9. The goal of effortless perception of speech must have been achieved for each listener and reverberation echo and flutter must have been controlled. For open plan office, RT was targeted as 0.7 to decrease distractions caused by noise.

Alternative solutions were discussed considering the size and the treatment availability of room surfaces and it was decided to conduct a treatment with combination of two types of acoustical absorbance elements.

Baffle amount was needed and possible design options were investigated with the software to derive the optimum option. After evaluation of several design options optimum solution was chosen not only acoustical aspect, but also spatial design scheme. Lighting was also taken into design consideration. A particular importance was given to the placement of acoustical absorbers to avoid possible obstruction of the daylight and artificial light.

In this paper, only the selected optimum design is presented. Figure 23 and 24 illustrate introduced additional absorption to SR and OP respectively.

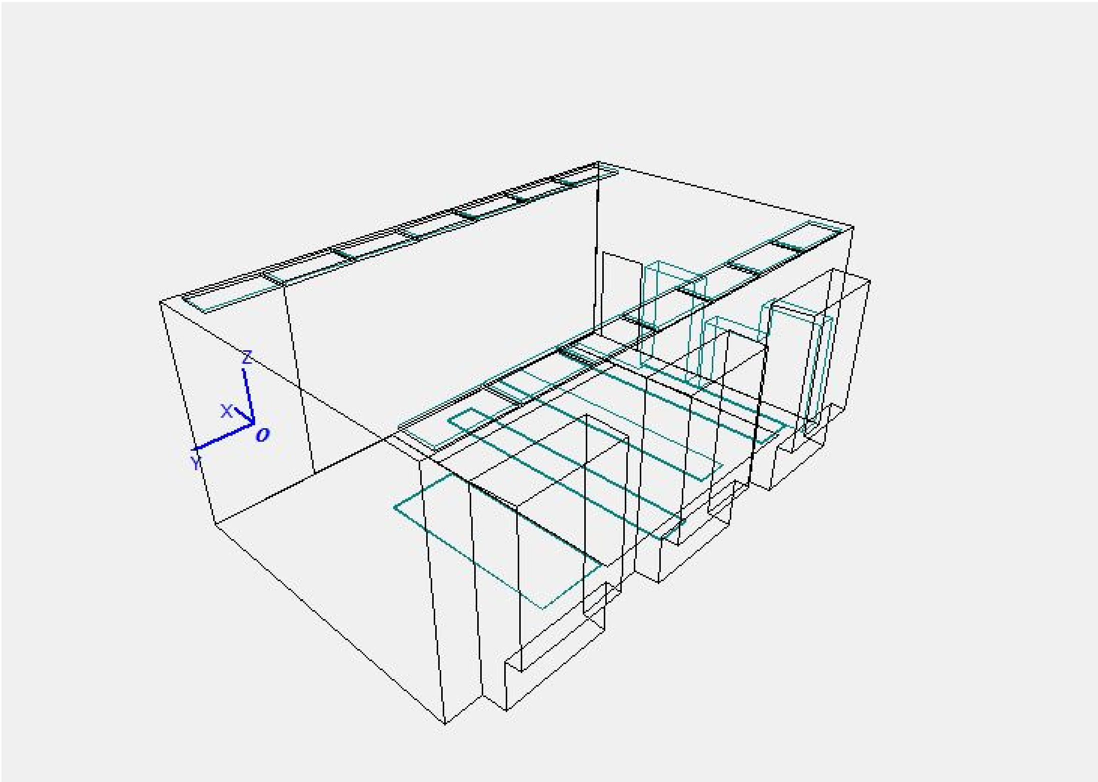


Figure 23 Introduced additional absorption to SR

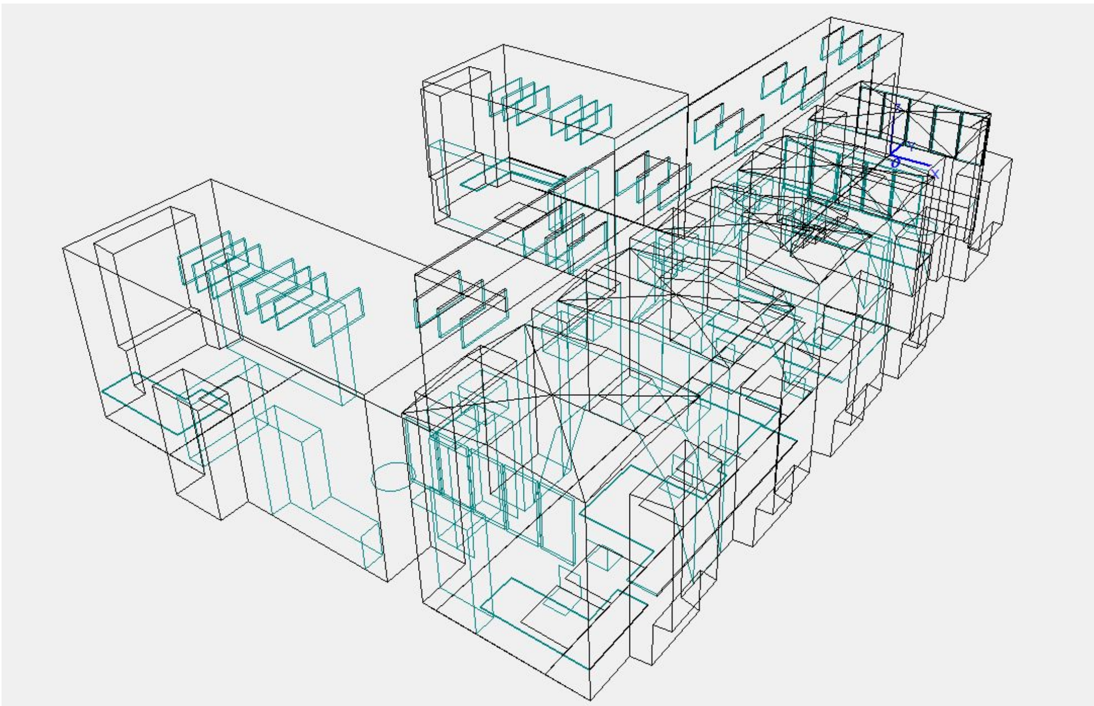


Figure 24 Introduced additional absorption to OP

Two kinds of absorber elements were used for the project namely; PF Cube and PF Plano. Figures 25 and 26 are taken from product data sheet which illustrate some reference work for PF Cube and PF Plano respectively.

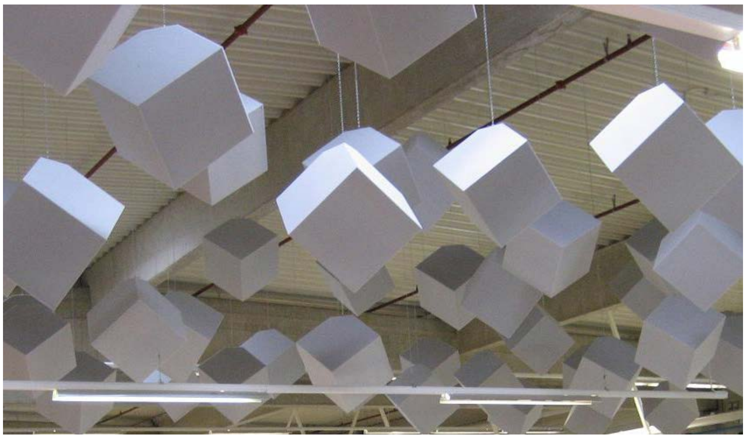
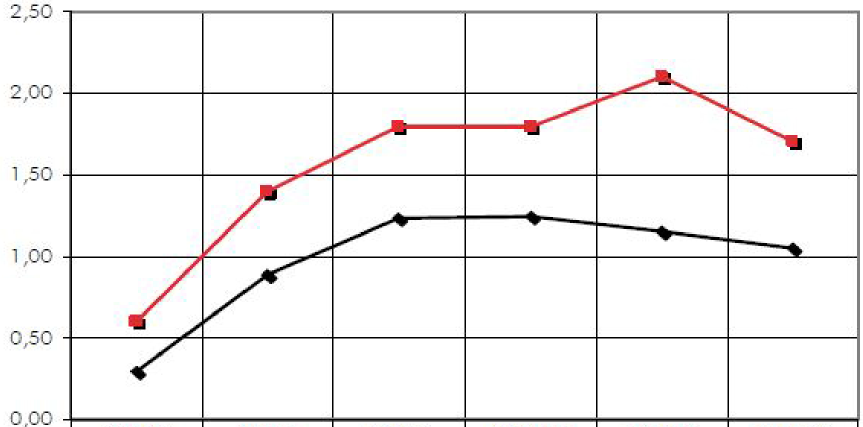


Figure 25 PF Cube element

Figure 26 PF Plano element

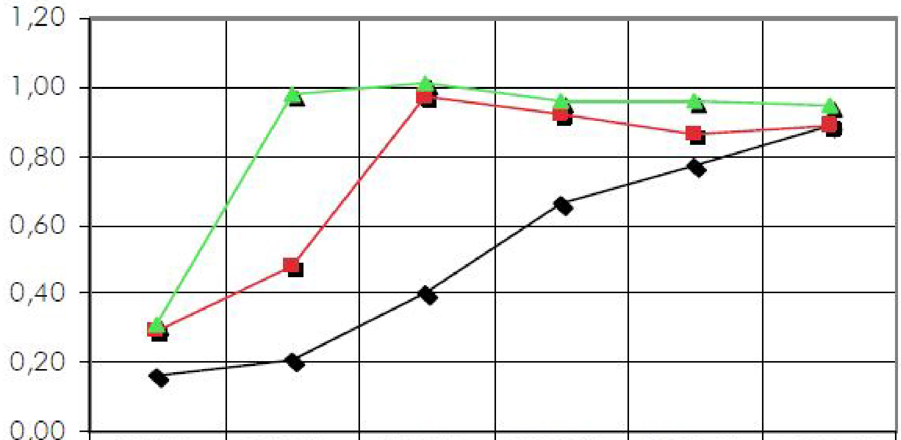
16 *PF Cube* elements and 60 *PF Plano* elements were used for the entire project. Both *PF Cube* and *PF-Absorber Plano* elements were used uncoated in white color. The size 480 x 480 x 480 mm was chosen for the cubical elements. The size 1.230 x 615 x 50 mm was chosen for the planar elements. Both of them had Class B1 (flame resistant) certificate according to DIN 4102, ÖNORM B3800: B1, Q1, Tr1.

Figures 27 and 28 summarize the sound absorption properties of these elements. These figures contain information about different sizes as well. Relevant size is highlighted with red color.



	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
PF - Cube 400	0,30	0,89	1,23	1,24	1,15	1,05
PF - Cube 480	0,60	1,40	1,80	1,80	2,10	1,70

Figure 27 Equivalent absorption area (m^2) of one cubical element (relevant is highlighted with red color) (Pernikl 2012)



	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
20 mm	0,16	0,21	0,40	0,66	0,77	0,89
50 mm	0,29	0,48	0,97	0,92	0,86	0,89
80 mm	0,31	0,98	1,01	0,96	0,96	0,95

Figure 28 Absorption coefficients (α) of one planar element (Relevant is highlighted with red color.) (Pernikl 2012)

Absorber elements were distributed to SR and OP. 14 of *Plano* elements were screwed to the ceiling of SR. The rest of the *planos* and all the *cubes* were used for OP. Apart from the previous process, this time some plano elements were suspended from the ceiling by using simple hook elements. A similar mounting detail is illustrated in Figure 29 (Lord and Templeton 1996). Rest of the *plano* elements were mounted to the walls with the help of a pipe system. Pipes were mounted to the walls and planos were suspended from the pipes. Figure 30 shows mounting process of suspended plano elements. Figure 31 shows SR after retrofit. Again Figures 32 and 33 show OP after retrofit.

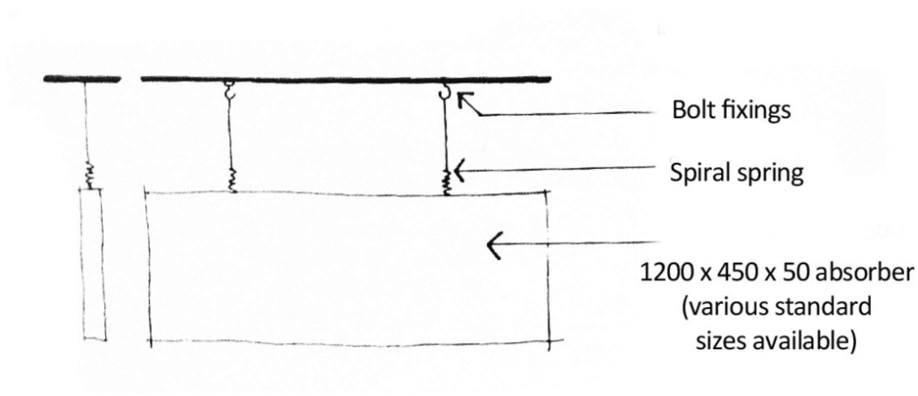


Figure 29 A sketch of mounting elements

Figure 30 Mounting process of absorber elements

Figure 31 SR after retrofit

Figure 32 OP after retrofit

Figure 33 OP after retrofit

3. RESULTS

As noted in the introduction and approach sections, the present research involved data collection pertaining to reverberation times and sound distribution in the office area as well as subjective evaluations by the office users before and after retrofit measures. Reverberation time graphs, regression analysis results, relative errors (%) in simulations, sound distribution pattern graphs, were illustrated. Afterwards subjective evaluation of office users was presented to find out the effectiveness of treatment project. RT and sound distribution results were presented separately for pre-retrofit and post-retrofit. In that way, calibrated and non-calibrated cases could be plotted together in the same graph to identify the effectiveness of calibration. Moreover some pre-post retrofit comparison graphs also illustrated the effectiveness of retrofit itself.

3.1. Improvements via literature search

Figures 34 and 35 show the measured values of the reverberation time together with improved simulation results via literature search. After a point, no further improvements could be achieved. At that point calibration was realized. Calibration range is depicted with gray color. As it is reflected in the Figures, measurement results were approximated in a considerable extend by means of literature search.

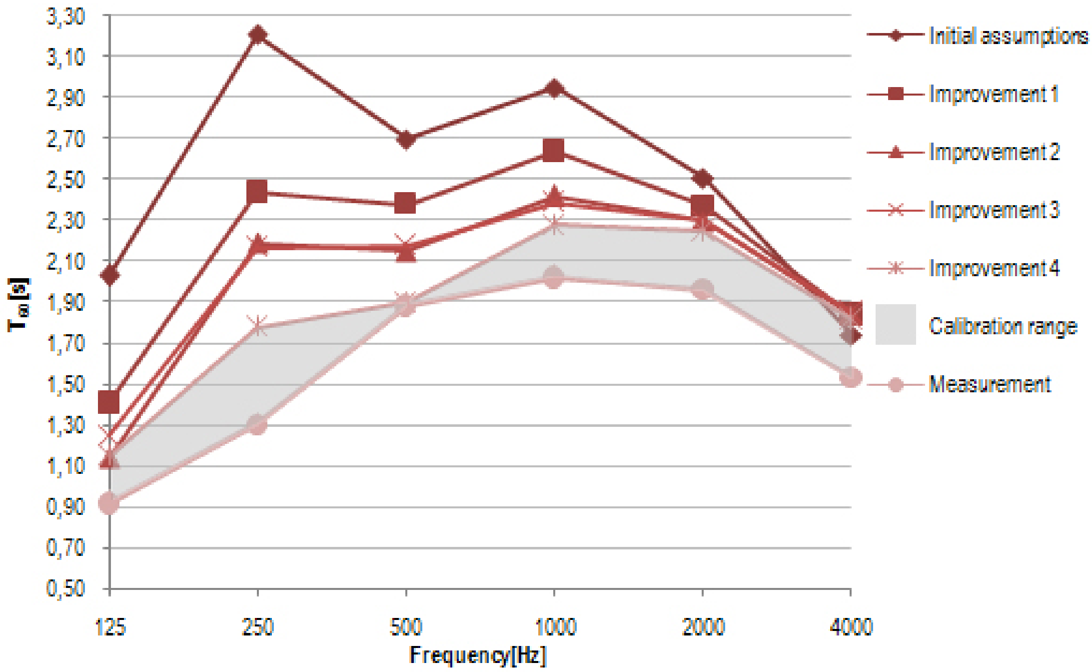


Figure 34 Improvements via literature search and calibration range of SR

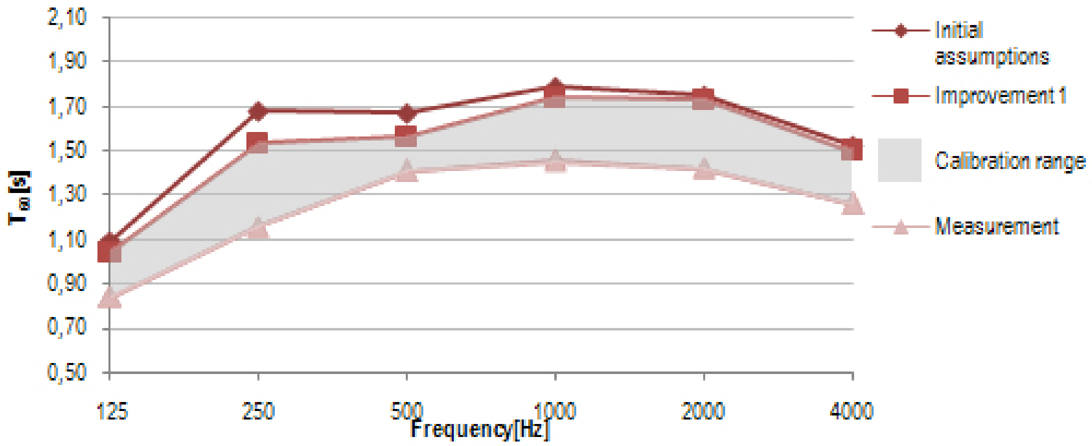


Figure 35 Improvements via literature search and calibration range of OP

3.2. Measured and simulated reverberation times

Figures 36 and 37 show for SR and OP respectively, the measured values of the reverberation time together with corresponding non-calibrated simulation results. Note that the calibrated simulation results almost exactly match the measurements are thus not explicitly plotted in Figures.

As these results show, the existing reverberation times were found to be too long for both SR and OP. Hence, it was concluded that the addition of sound absorbing elements could reduce the reverberation times and improve the room acoustics in the office area. Toward this end, acoustical panels were considered for SR, and a combination of acoustical panels and cubical elements for OP. A reverberation time of around 1.0 s was targeted for the SR (occupied setting). For OP, the targeted reverberation time was around 0.8 s.

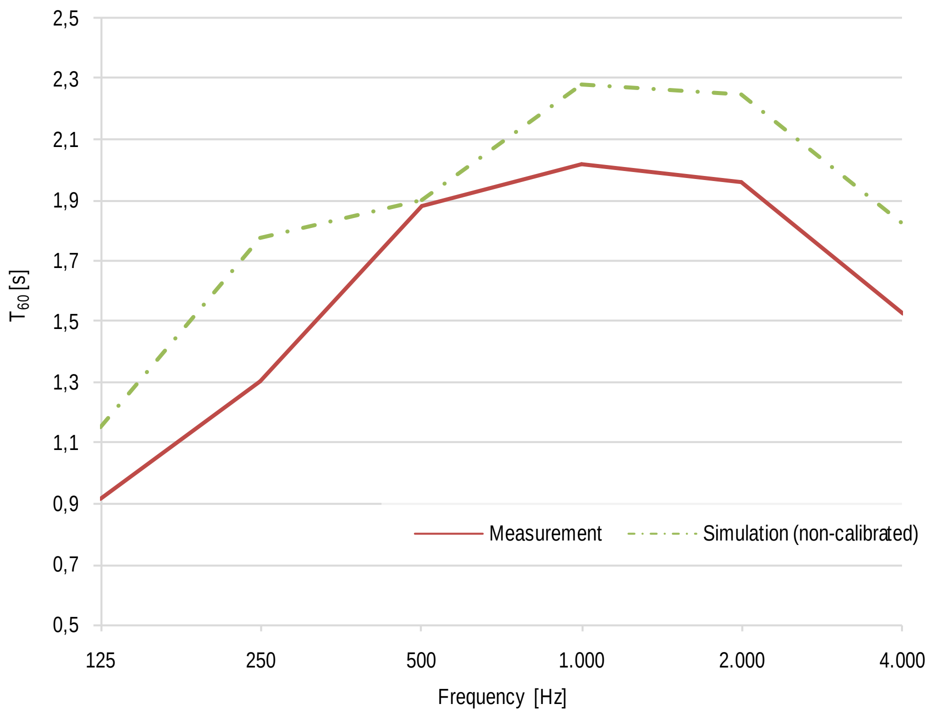


Figure 36 Measured and simulated (non-calibrated) pre-retrofit reverberation times in SR (non-occupied)

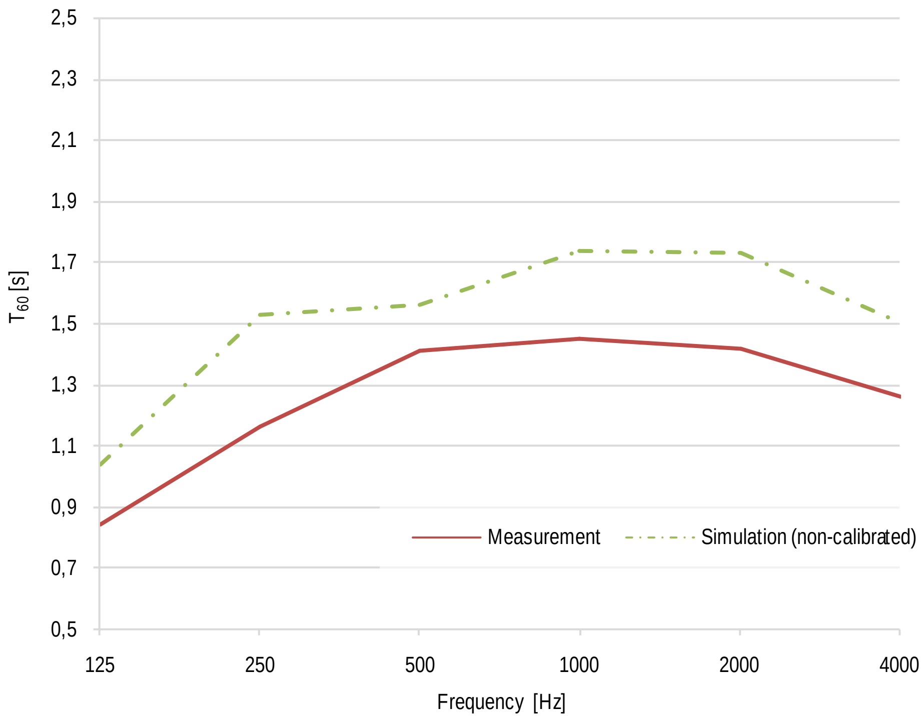


Figure 37 Measured and simulated (non-calibrated) pre-retrofit reverberation times in OP (non-occupied)

Figures 38 and 39 show, for SR and OP respectively, the measured and simulated post-retrofit reverberation time values. To illustrate the effect of calibration, these Figures include both non-calibrated and calibrated simulation results. To consider the effect of occupancy in SR, Figure 40 includes calibrated simulation results for the reverberation time under non-occupied and occupied (20 people) conditions.

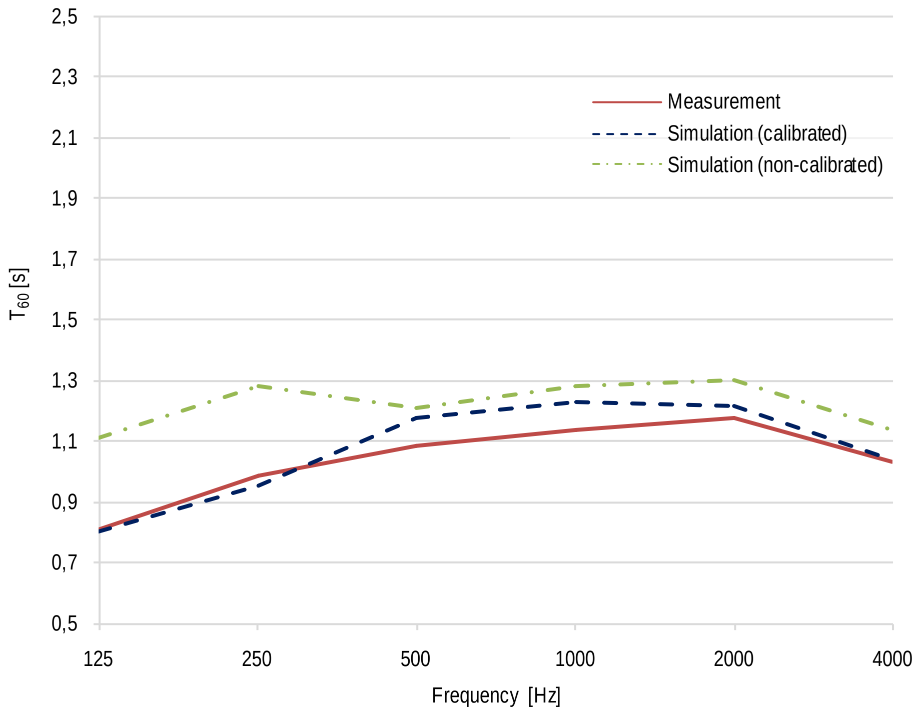


Figure 38 Measured and simulated (non-calibrated and calibrated) post-retrofit reverberation times in SR (non-occupied)

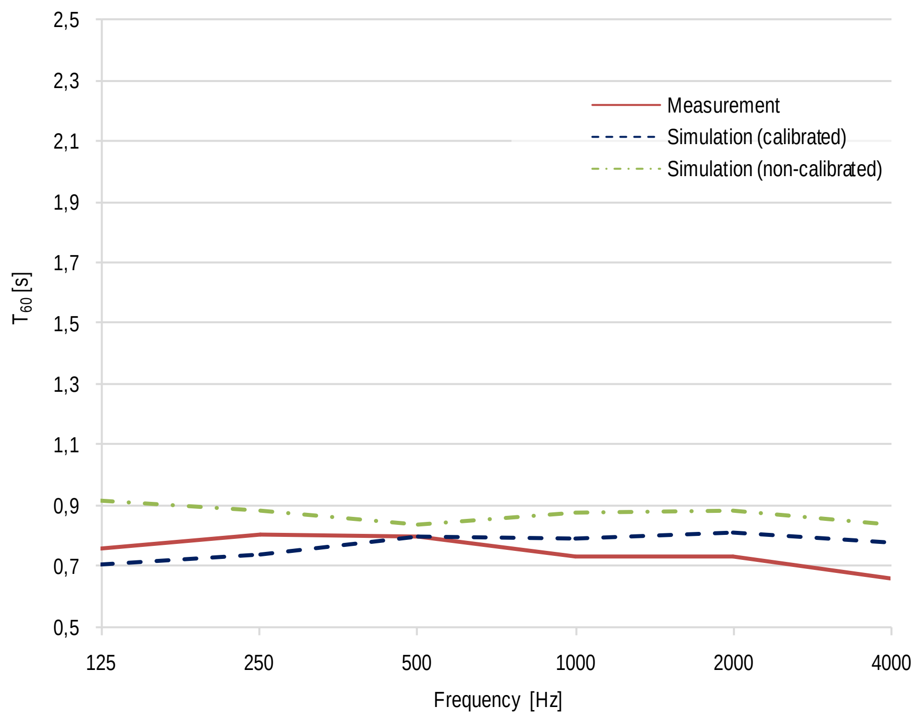


Figure 39 Measured and simulated (non-calibrated and calibrated) post-retrofit reverberation times in OP (non-occupied)

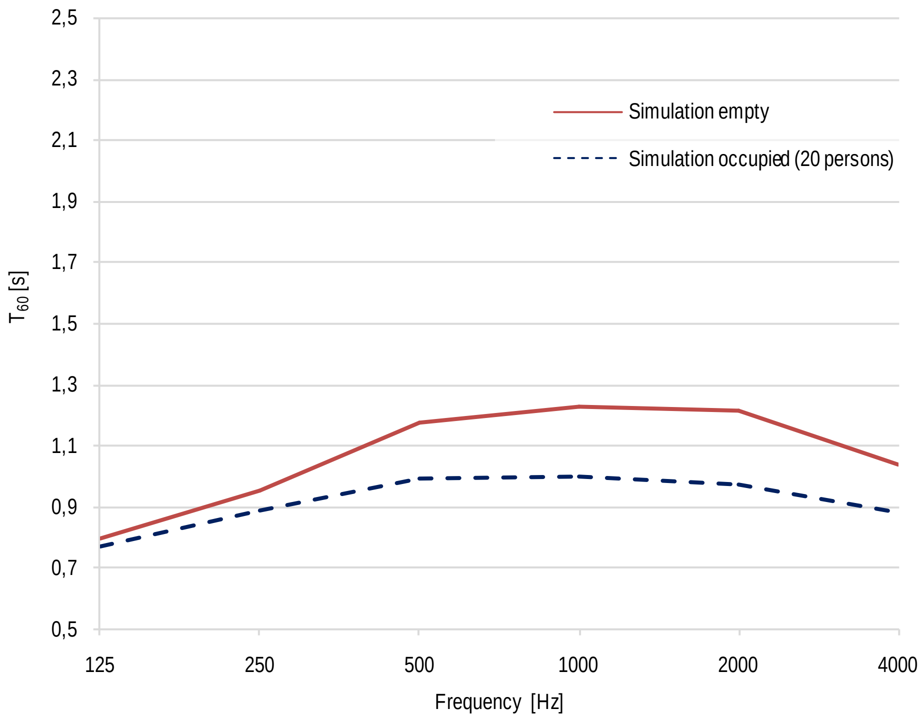


Figure 40 Simulated (calibrated) post-retrofit reverberation times in SR under non-occupied and occupied (20 people) conditions

3.3. Measured and simulated sound distribution patterns

Figure 41 displays sound distribution in OP (measured values) for both pre and post-retrofit cases. Figures 42 and 43 show measured and simulated (non-calibrated and calibrated) sound distribution in OP for pre and post-retrofit cases respectively. All graphs represent non-occupied conditions.

Note that sound distribution of SR is not presented due to relative small size of the room and homogeneity of sound distribution.

The microphone positions which were represented in numbers took place on a virtual grid which can be read on Figure 18. Microphone positions were labeled according to the distance to sound source. When there was an obstruction between sound source and the microphone; the closest path from sound source to the microphone was taken as a distance. In normal conditions, as a result of the distance, a constant decrease is expected in SPL. However, in spatial conditions where many obstructions exist like OP, it can be expected that positions which are directly exposed to the sound source (positions 5 and 9) have relatively higher SPL values than indirectly exposed ones (positions 4 and 8). In case of post retrofit, high deviations are observed in the positions 4, 5, 8, 9.

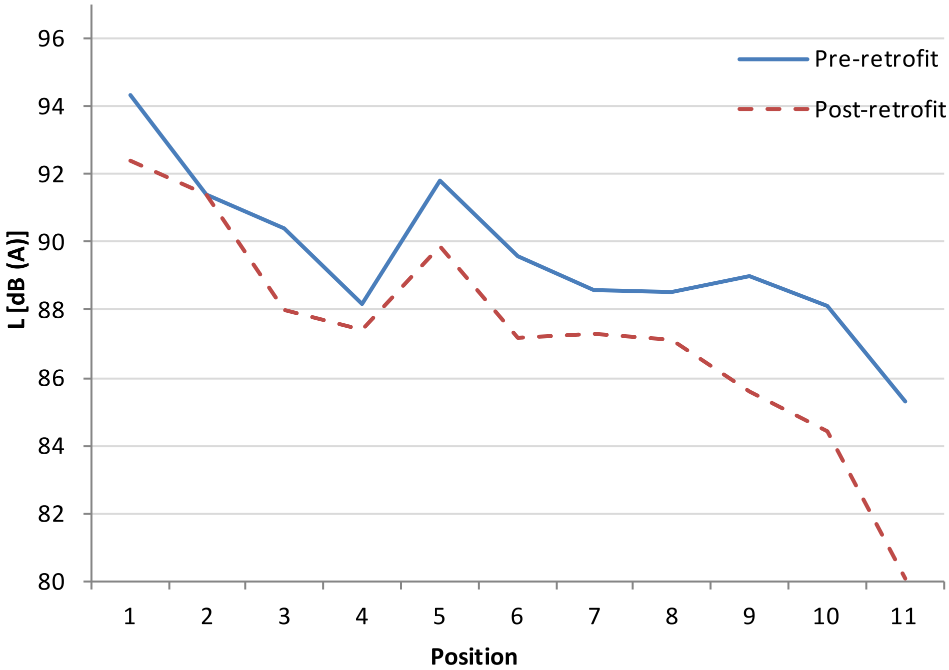


Figure 41 Pre and post retrofit measured sound distribution in OP

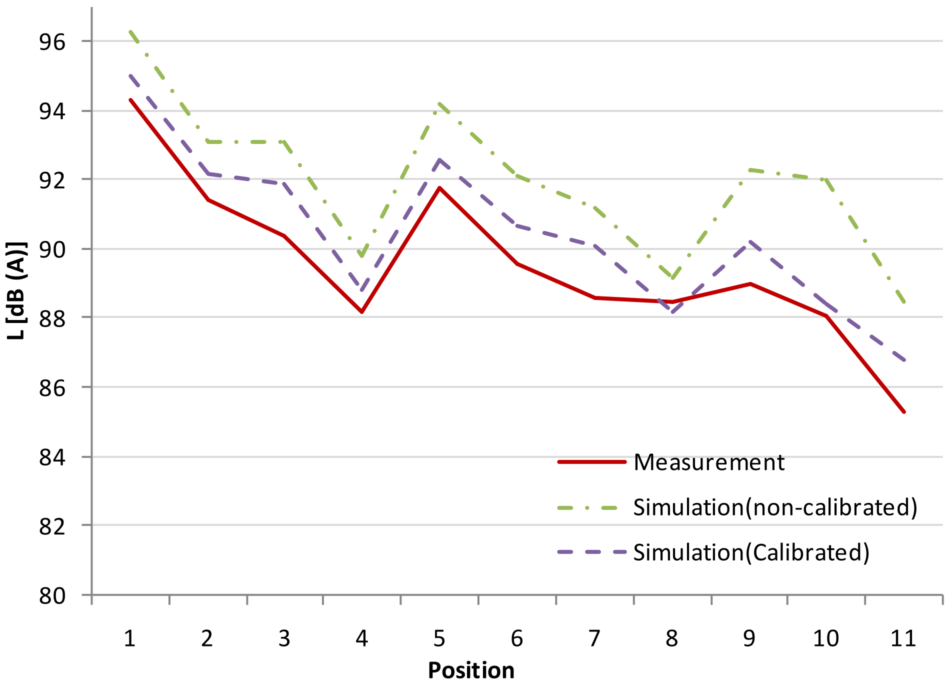


Figure 42 Pre-retrofit-measured and simulated (non-calibrated and calibrated) sound distribution in OP

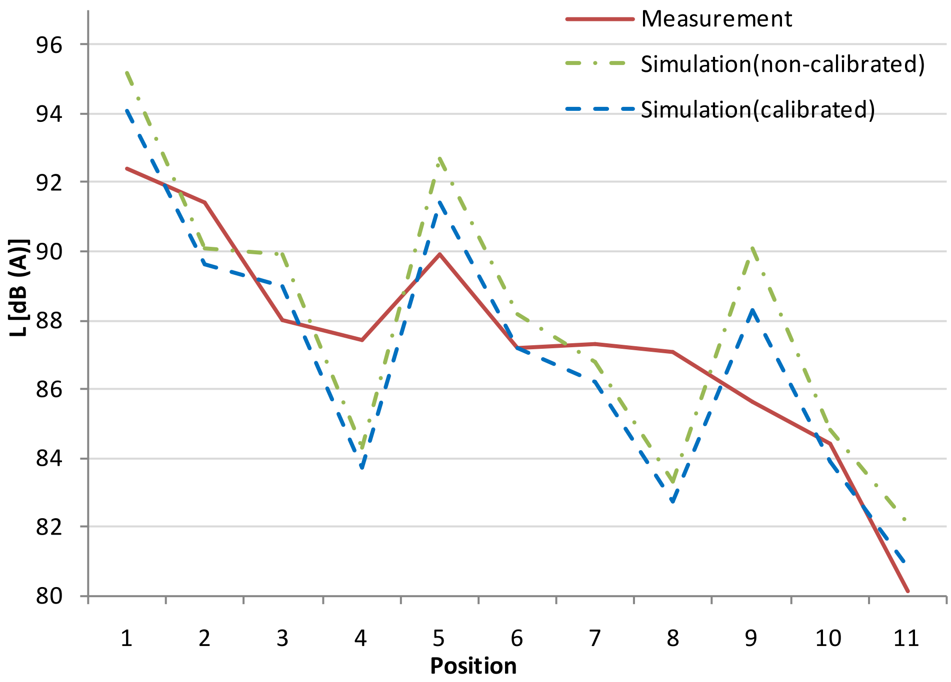


Figure 43 Post-retrofit-measured and simulated (non-calibrated and calibrated) sound distribution in OP

3.4. Measured vs. simulated reverberation times and relative error in simulations

Simple linear regression analysis was also performed for purpose of showing the efficiency of calibration. Figures 44 and 45 show simulated versus measured reverberation times (all frequencies) of SR for calibrated and non-calibrated case respectively. Figures 46 and 47 belong to OP. R^2 value of seminar room increased from 0,838 to 0,962, and R^2 value of open plan office increased from 0,811 to 0,883. Results are seemed to prove the efficiency of calibration. Both for SR and OP, R^2 values increased considerably.

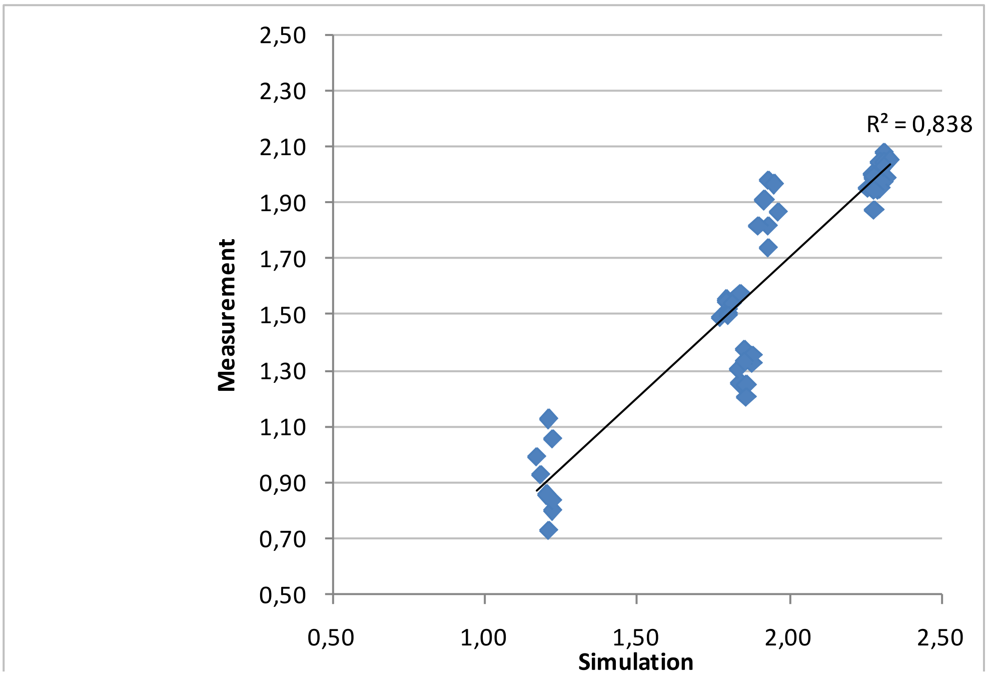


Figure 44 Non-calibrated-simulated versus measured reverberation times in SR (All frequencies)

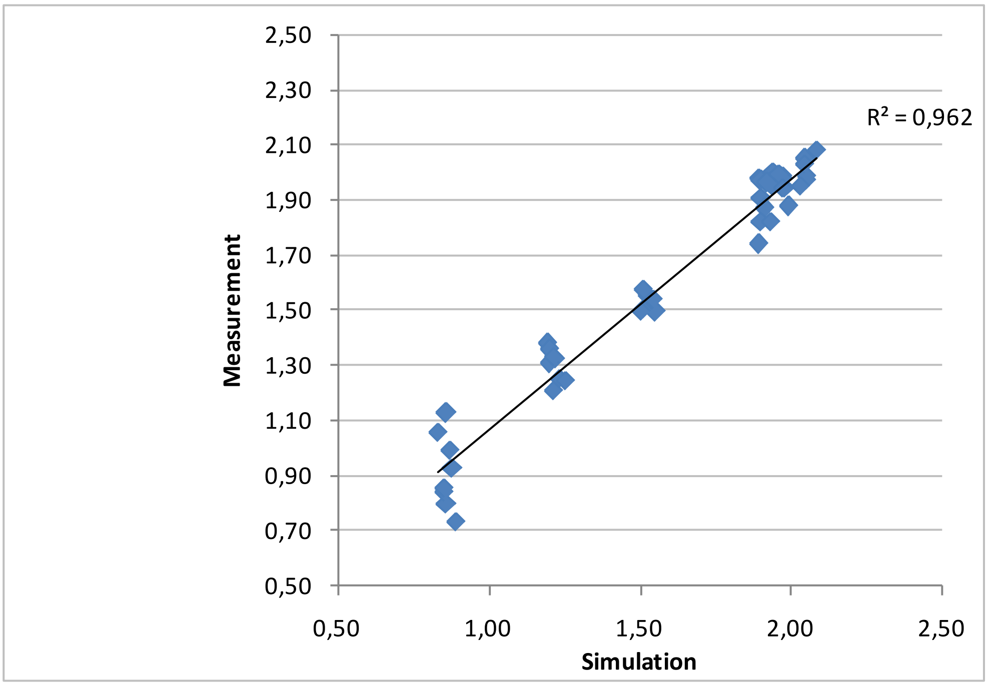


Figure 45 Calibrated-simulated versus measured reverberation times in SR (All frequencies)

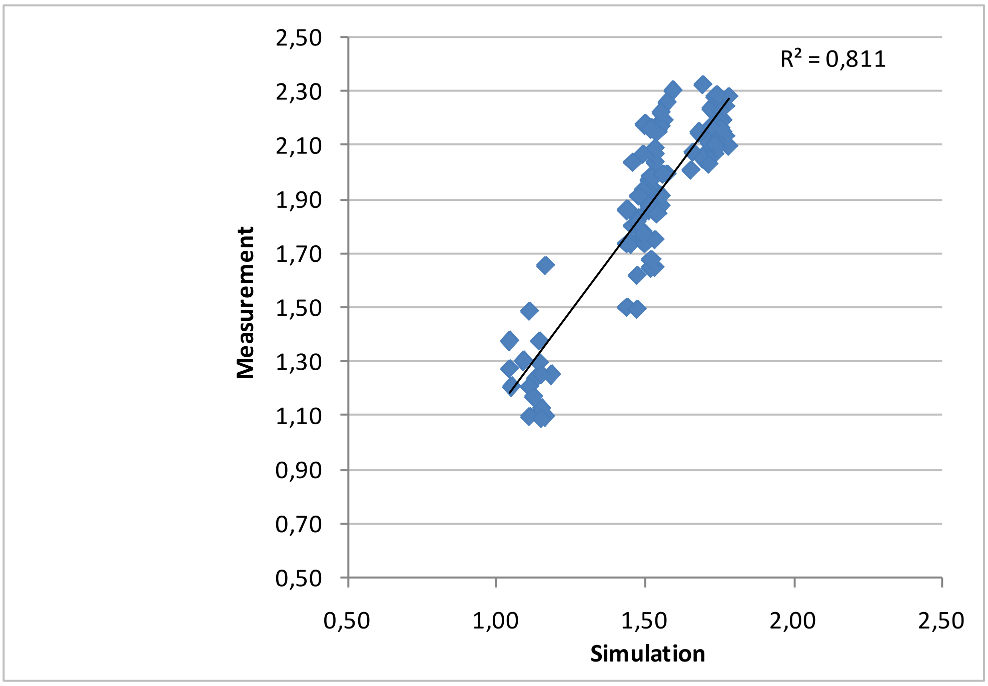


Figure 46 Non-calibrated-simulated versus measured reverberation times in OP (All frequencies)

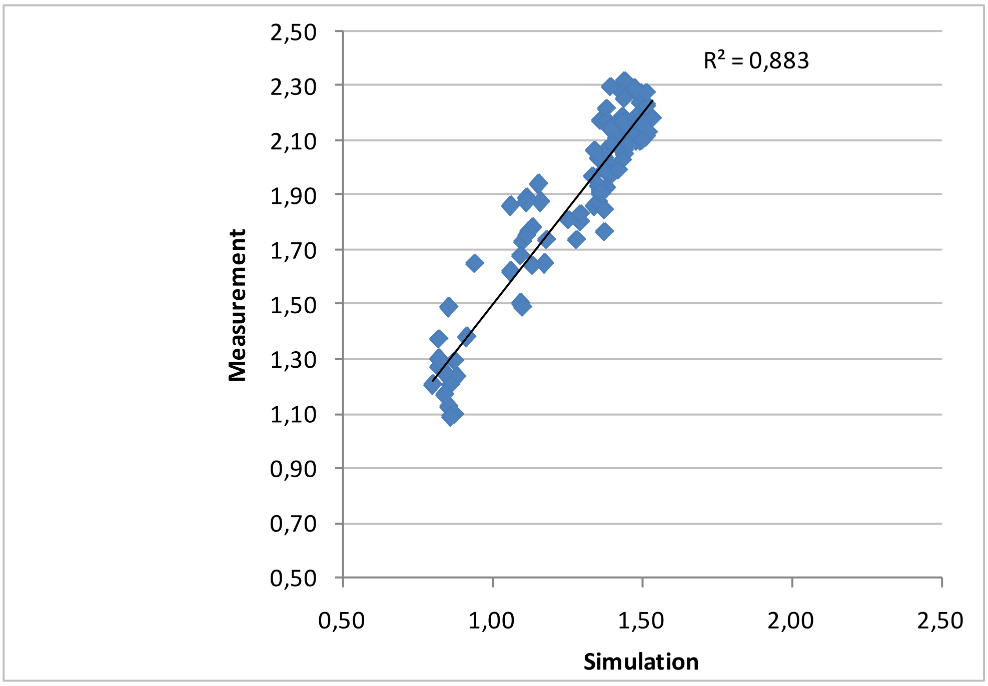


Figure 47 Calibrated-simulated versus measured reverberation times in OP (All frequencies)

Table 8 summarizes the deviations of simulation results from the respective measurements in terms of relative error. Relative error of (in %) simulations for various frequencies are illustrated in Table for calibrated and non-calibrated cases for both pre and post retrofit. The frequency dependent relative errors of non-calibrated simulations are higher than calibrated ones, for both pre and post retrofit cases.

Table 8 Frequency dependent relative error (in %) of simulations for non-calibrated and calibrated cases

			FREQUENCIES [HZ]					
			125	**250**	**500**	**1000**	**2000**	**4000**
PRE-RETROFIT	**SR**	Non-calibrated	30	42	2	14	16	18
		Calibrated	-7	-7	1	1	0	-1
	OP	Non-calibrated	23	19	1	10	13	10
		Calibrated	-6	-11	-8	-8	-3	-2
POST-RETROFIT	**SR**	Non-calibrated	37	29	11	13	11	11
		Calibrated	-1	-4	8	8	3	1
	OP	Non-calibrated	21	10	5	19	21	27
		Calibrated	-7	-8	0	8	11	19

3.5. Subjective evaluation

Participant information about questionnaires has already been given in methodology section. Thus; it is missed out the first 4 questions concerning participant information and is directly presented the second part; evaluations about overall indoor environment quality. Table 9 lists the content of questions. Answers are presented in two different styles; bar graphs (for multiple choice questions) and ratings on 5 point scale questions. Bar graphs show the results in percentage (%). Correspondingly on 5 point scales; linear line represents pre-retrofit and dashed line represents post-retrofit.

Table 9 List of questions

EVALUATIONS ABOUT OVERALL INDOOR ENVIRONMENT QUALITY
5) Evaluation of the general office environment of BPI
6) Evaluation of the thermal conditions of BPI
7) Evaluation of the lighting conditions of BPI
8) Evaluation of air quality of BPI
9) Evaluation of acoustical conditions of BPI
10) The items that are considered most important for an ideal working place
11) Items wanted to be improved in the workplace if it would be possible to improve (selected up to 3 items)
12) Annoyance level of noise from outside
Most intrusive noises (selected up to 2 items)
13) General annoyance level of noise from inside
Annoyance level of;
a) Office equipment, computers/faxes/printers
b) Noise from alarms rings and calls
c) Noise from adjacent spaces
d) Noise from conversations of co-workers
e) Noise caused by doors, windows, chairs, blinds
14) The level of acoustical privacy at workstation
15) The level of negative impact of current acoustical condition on ability to concentrate on work

Figure 48 shows evaluation of acoustical conditions with other office comfort parameters. After retrofit, a remarkable improvement in perceived acoustical conditions is observed (item 9) with a slight improvement in perceived general office environment (item 5).

As it is mentioned before, other comfort parameters related questions are also formed to reveal possible correlation of them with acoustic comfort. However change in lighting conditions (item 7) could not be interpreted since it is known that there is no correlation between lighting and acoustical condition. If the topic was thermal comfort parameter, only then the correlation of acoustic comfort parameter could be discussed. (For example, operation of windows could affect both thermal comfort and acoustical comfort.)

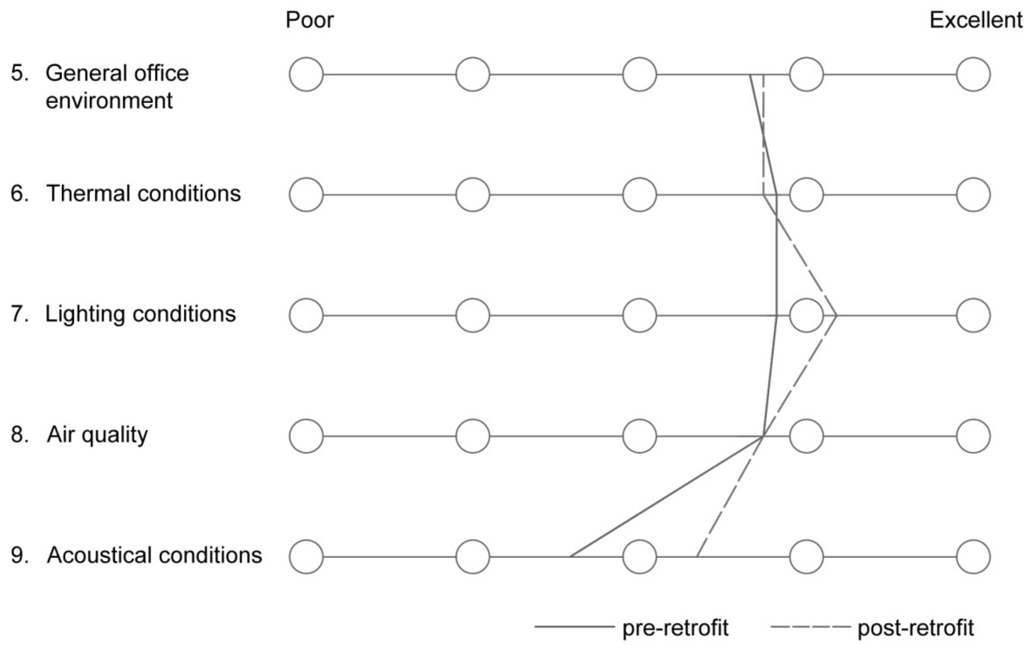


Figure 48 Evaluation of acoustical conditions with other office comfort parameters (question 5-9)

Figure 49 shows the perceived importance of working environment features. As seen in the Figure the level of significance of all these items was slightly changed after retrofit. Increasing importance of *privacy and calm* might be explained by rising attention towards the topic together with acoustic retrofit.

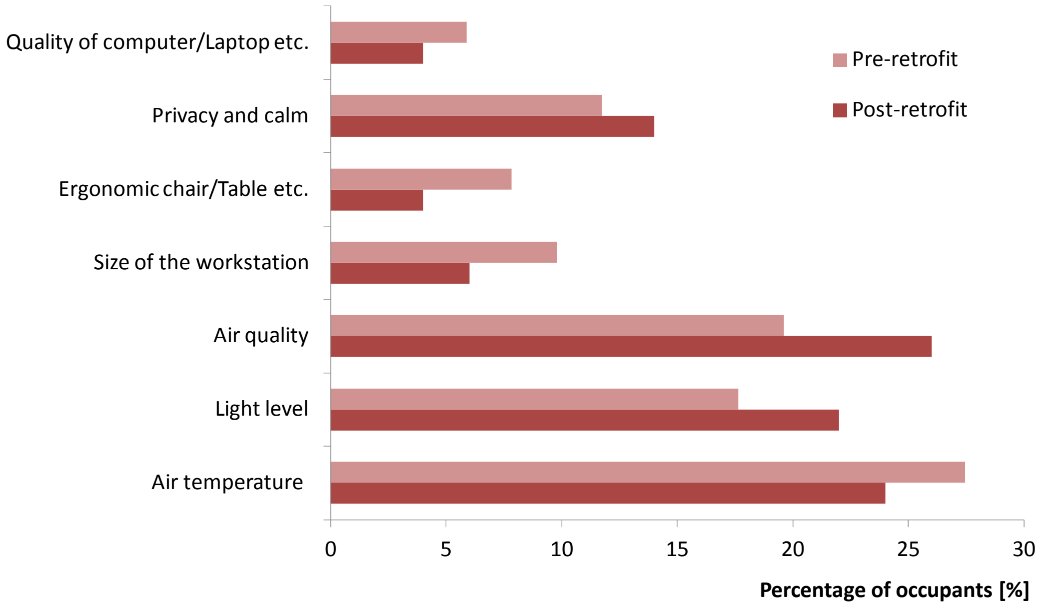


Figure 49 Perceived importance of working environment features (question 10)

Figure 50 shows the percentage of occupants who wished specific improvement measures. Before retrofit, acoustical conditions were the primary comfort parameters that were wanted to be optimized. After retrofit it was not a priority condition anymore. This also proved the increase in the acoustic comfort.

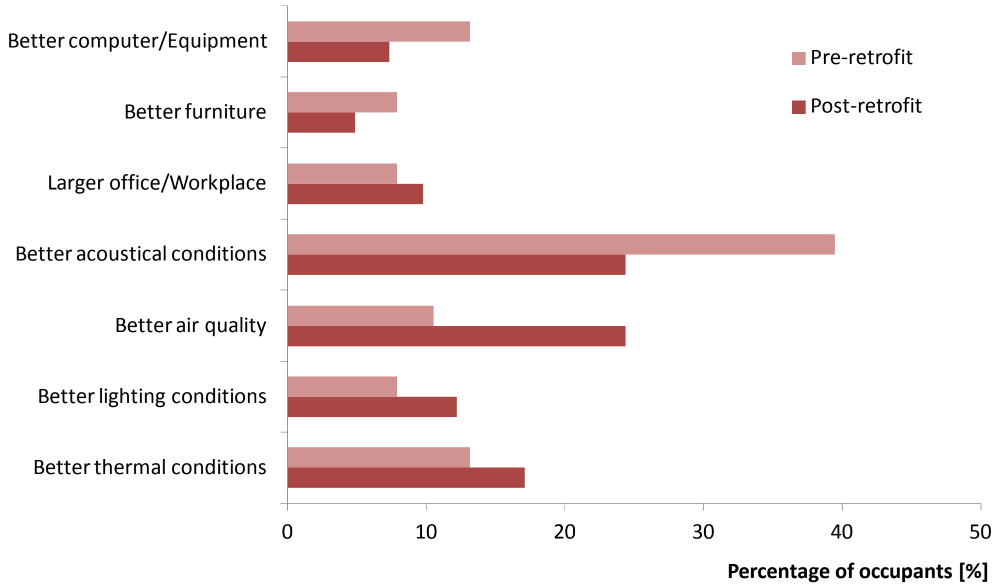


Figure 50 Percentage of occupants who wished specific improvement measures (question 11)

Figure 51 shows the change in annoyance levels (items 12-13) and negative impact level of current acoustical condition on concentration (item 15). A general decrease of annoyance levels from inside noises, as well as an increase of concentration on work observed.

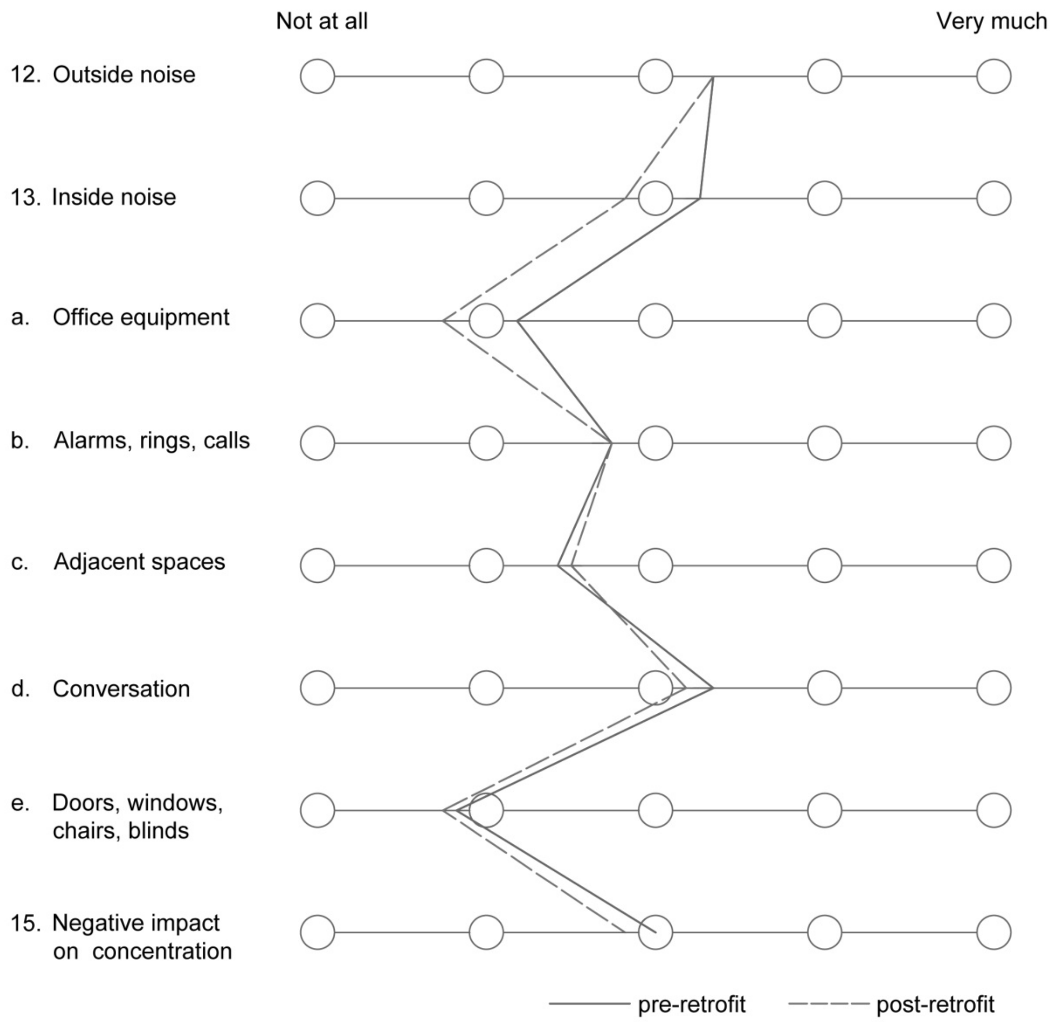


Figure 51 The change in annoyance levels (questions 12-13) and negative impact level of current acoustical condition on concentration (question 15)

Figure 52 shows the change in perceived intrusiveness of noise sources. The rise of intrusiveness from construction noise may be originating from open windows. The first set of questionnaires was collected in February (no windows were open as it was winter). The second set was collected in May (some windows were open). The rise of intrusiveness from people could not be interpreted.

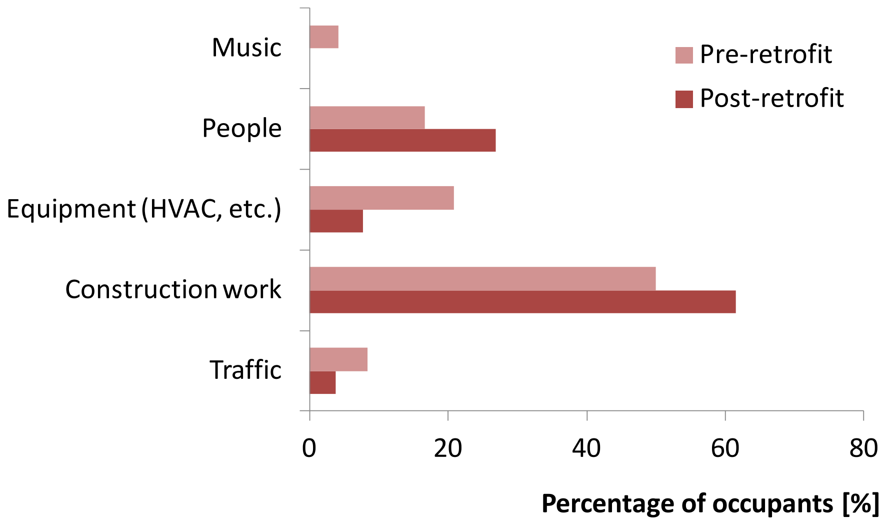


Figure 52 Perceived intrusiveness of noise sources (question 12)

4. DISCUSSION

4.1. Effectiveness of calibration

- Simulation results obtained via the non-calibrated simulation model display relatively large errors (see Figures 36 and 37). The errors are most likely due to the uncertainties associated with the assumptions pertaining to the sound absorption coefficients of the room surfaces (see also Mahdavi et al.2008 and Mahdavi 2011). As mentioned earlier, a documentation of these coefficients for the existing conditions was not available. Nor was it possible to conduct an in-situ measurement of the absorption coefficients. Default assumptions (based on literature, experience, and simulation application's database) may have thus deviated from the "true" surface properties, leading to the aforementioned errors.

- The calibration process with the virtual absorption elements appears to be quite effective in the trivial sense that, after calibration, simulation results closely match the measurements. Additionally the results of linear regression analysis are tend to prove this effectiveness. R^2 value of seminar room increased from 0,838 to 0,962 (Figures 44 and 45), and R^2 value of open plan office increased from 0,811 to 0,883 (Figures 46 and 47).

- The calibration process may be also viewed to be effective in a non-trivial sense: There is a relatively good agreement between simulation-based predictions (based on the calibrated model) and measurement results for post-retrofit conditions. This inference is clearly supported by the comparison between the predictions of calibrated and non-calibrated simulation models for the post-retrofit conditions. Predictions based on the non-calibrated model show significantly higher errors than those obtained from the calibrated model (see Figures 38 and 39). Correspondingly, the frequency dependent relative errors of non-calibrated simulations are higher than calibrated ones, for both pre and post retrofit cases. This supports the efficiency of the calibration as RT results and regression analysis (Table 8).

- With regard to sound distribution, there is also a relatively good agreement between calibrated model predictions and measurement results for pre-retrofit conditions (Figure 42). However, for post-retrofit conditions, high deviations are observed at certain positions (Figure 43). The simulation appears to underestimate the occlusion effect (e.g., positions 4 and 8) and overestimate direct exposure (e.g., positions 5 and 9).

4.2. Effectiveness of retrofit

The targeted RT values; around 1.0 s. for the seminar room - occupied setting - and around 0.8 s for the OP are achieved via retrofit (Figure 40 and Figure 39). Up to 5dB decrease in SPL is observed (Figure 41). Questionnaire results also indicate a certain improvement regarding to perceived acoustical conditions by the occupants (see item 9 in Figure 48).

5. CONCLUSIONS

The calibration of acoustical simulation models of existing spaces via measurement results can provide an effective way to improve the reliability of the simulation-based assessment of the implications of acoustic retrofit measures in buildings. Specifically, measures necessary to achieve the targeted values of the acoustical performance indicator (in this case, the reverberation times) could be realized and tested virtually using the calibrated simulation model, and implemented subsequently in reality.

A more comprehensive empirically obtained database of acoustical properties of architectural elements is necessary. Such a database could be incorporated in acoustical simulation tools in order to expedite the simulation and analysis process and thus make it more effective toward design support (Mahdavi et al, 2007).

Future acoustical studies should include an extended number of case studies pertaining to calibration efforts to better estimate the size of error on the material data as well as the impact of calibration on the simulated results.

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7. APPENDIX

7.1. Office environment assessment questionnaire

Office Environment Assessment

Please answer all the relevant questions.

Part 1) General Information about Participant
(Please click one of relevant options.)

1) Gender

☐ Female ☐ Male

2) Occupation *(Please click most relevant or state in 'other'.)*

☐ Administrative Staff
☐ Researcher/Scientific Staff
☐ Student
☐ Other:

3) How long have you been working in BPI?

☐ Less than 6 months
☐ 6-12 months
☐ More than a year
☐ Visiting time to time

4) How many hours in average do you spend per week in your current working place?

☐ 0-10 Hours
☐ 11-20 Hours
☐ 21-30 Hours
☐ 31-40 Hours
☐ 41-50 Hours
☐ 51-60 Hours
☐ More than 60 Hours

Part 2) Questions about Overall Indoor Environment Quality
(In the following five questions please rate relevant items on a 5 point scale.)

5) How do you evaluate the general office environment of BPI?

(Overall indoor environment quality refers to acoustical, thermal, visual comfort and air quality)

Poor ○—○—○—○—○ Excellent

6) How do you evaluate the thermal conditions in your work station?

Poor ○—○—○—○—○ Excellent

7) How do you evaluate lighting conditions in your work station?

Poor ○—○—○—○—○ Excellent

8) How do you evaluate air quality in your workstation?

Poor ○—○—○—○—○ Excellent

9) How do you evaluate acoustical conditions in your workstation?

Poor ○—○—○—○—○ Excellent

10) From the items in the following list, please <u>select up to 3</u> which you consider most important for an ideal working place.

- ☐ Air temperature
- ☐ Light level
- ☐ Air quality
- ☐ Size of the workstation
- ☐ Ergonomic chair/Table etc.
- ☐ Privacy and calm
- ☐ Quality of computer/Laptop etc.

11) If you could improve something in your workplace, what would it be? (Please choose from the following list <u>up to 3 items</u>.)

- ☐ Better thermal conditions
- ☐ Better lighting conditions
- ☐ Better air quality
- ☐ Better acoustical conditions
- ☐ Larger office/Workplace
- ☐ Better furniture
- ☐ Better computer/Equipment

12) Does noise from outside annoy you?

Not at all ○—○—○—○—○ Very much

If yes, which source of the noise is most intrusive? (Please select <u>up to 2 items</u>.)

- ☐ Traffic
- ☐ Construction work
- ☐ Equipment (HVAC, etc.)
- ☐ People
- ☐ Music

13) Does noise from inside the office annoy you?

Not at all ○—○—○—○—○ Very much

If yes, please indicate degree of annoyance in following 5 questions;

a) Does noise from office equipment, computers/faxes/printers annoy you?

Not at all ○—○—○—○—○ Very much

b) Does noise from alarms rings and calls annoy you?

Not at all ○—○—○—○—○ Very much

c) Does noise from adjacent spaces annoy you?

Not at all ○—○—○—○—○ Very much

d) Does noise from conversations of co-workers annoy you?

Not at all ○—○—○—○—○ Very much

e) Does noise caused by doors, windows, chairs, blinds annoy you?

Not at all ○—○—○—○—○ Very much

14) Do you have sufficient acoustical privacy at your workstation? (Ability to have conversations without your neighbours overhearing and vice versa)

No privacy at all ○—○—○—○—○ High level privacy

15) Does current acoustical condition have a negative impact on your ability to concentrate on your work?

Not at all ○—○—○—○—○ Very much

Please provide additional comments, problems, and ideas about your working environment:

Thanks for your Participation

7.2. Material improvements via literature search

Table 10 Initial material assumptions for SR

INITIAL MATERIAL ASSUMPTIONS (SR)									
ELEMENT	**REFERENCE NUMBER**	**REFERENCE**	**MATERIAL DEFINITION IN REFERENCE**	**FREQUENCY[H]**					
				125	**250**	**500**	**1000**	**2000**	**4000**
Floor (wood)	2468	Technischer Ausbau (Mahdavi and Orehounig 2011)	Parkett auf Estrich	0,04	0,04	0,07	0,06	0,06	0,07
Ceiling (SR)	2311	(Dalenbäck 2000)	Walls , hardsurfaces, average (brickwalls, plaster,hardsurfaces, etc.)	0,02	0,02	0,03	0,03	0,04	0,05
Ex. wall (brick)	2311	(Dalenbäck 2000)	Walls , hardsurfaces, average (brickwalls, plaster,hardsurfaces, etc.)	0,02	0,02	0,03	0,03	0,04	0,05
Int. wall-(brick)	2311	(Dalenbäck 2000)	Walls , hardsurfaces, average (brickwalls, plaster,hardsurfaces, etc.)	0,02	0,02	0,03	0,03	0,04	0,05
Int. wall (gyps. boa.)	2311	(Dalenbäck 2000)	Walls , hardsurfaces, average (brickwalls, plaster,hardsurfaces, etc.)	0,02	0,02	0,03	0,03	0,04	0,05
Door (glass)	2022	(Harris 1991)	Glass, large panes of heavy plate glass	0,18	0,06	0,04	0,03	0,02	0,02
Window (glass)	2466	Technischer Ausbau	Holzkastenfenster d=0.2 m	0,25	0,05	0,03	0,02	0,02	0,02

		(Mahdavi and Orehounig 2011)							
Win. frame (wood)	2468	Technischer Ausbau (Mahdavi and Orehounig 2011)	Parkett auf Estrich	0,04	0,04	0,07	0,06	0,06	0,07
Door, Cupboard, Desk (wood)	2469	(Fasold and Veres 2003)	Tür, Holz, Lackiert	0,10	0,08	0,06	0,05	0,05	0,05

Table 11 First material improvement for SR

IMPROVEMENT 1 (SR)									
ELEMENT	**REFERENCE NUMBER**	**REFERENCE**	**MATERIAL DEFINITION IN REFERENCE**	**FREQUENCY[H]**					
				125	**250**	**500**	**1000**	**2000**	**4000**
Ceiling (SR)	2475	Technischer Ausbau (Mahdavi and Orehounig 2011)	Ziegelmauerwerk mit Kalkzemenputz	0,02	0,02	0,03	0,04	0,05	0,05
Int. wall (gyps. boa.)	2476	Technischer Ausbau (Mahdavi and Orehounig 2011)	Gipskartonplatten mit 100mm Luftabstand zu Wand oder Decke ; im Hohlraum Mineralwolle	0,28	0,14	0,09	0,06	0,05	0,01

Table 12 Second material improvement for SR

IMPROVEMENT 2 (SR)									
ELEMENT	**REFERENCE NUMBER**	**REFERENCE**	**MATERIAL DEFINITION IN REFERENCE**	**FREQUENCY[H]**					
				125	**250**	**500**	**1000**	**2000**	**4000**
Ex. wall (brick)	2475	Technischer Ausbau (Mahdavi and Orehounig 2011)	Ziegelmauerwerk mit Kalkzemenputz	0,02	0,02	0,03	0,04	0,05	0,05
Int. wall-(brick)	2475	Technischer Ausbau (Mahdavi and Orehounig 2011)	Ziegelmauerwerk mit Kalkzemenputz	0,02	0,02	0,03	0,04	0,05	0,05
Door, Cupboard, Desk (wood)	2477	(Fasold and Veres 2003)	Holzpanplatte, 19 mm, 913.5 kg/m², **6** cm	0,25	0,12	0,10	0,07	0,05	0,05

Table 13 Third material improvement for SR

IMPROVEMENT 3 (SR)									
ELEMENT	**REFERENCE NUMBER**	**REFERENCE**	**MATERIAL DEFINITION IN REFERENCE**	**FREQUENCY[H]**					
				125	**250**	**500**	**1000**	**2000**	**4000**
Window (glass)	2022	(Harris 1991)	Glass, large panes of heavy plate glass	0,18	0,06	0,04	0,03	0,02	0,02
Win. Frame (wood)	2471	Technischer Ausbau (Mahdavi and Orehounig 2011)	Holz oder Spanplatte vor festem Untergrund	0,04	0,04	0,05	0,06	0,06	0,06

Door, Cupboard, Desk (wood)	2478	(Fasold and Veres 2003)	Holzpanplatte, 19 mm, 913.5 kg/m², **12** cm	0,20	0,12	0,10	0,07	0,05	0,05

Table 14 Fourth material improvement for SR

IMPROVEMENT 4 (SR)									
ELEMENT	**REFERENCE NUMBER**	**REFERENCE**	**MATERIAL DEFINITION IN REFERENCE**	**FREQUENCY[H]**					
				125	**250**	**500**	**1000**	**2000**	**4000**
Door (glass)	2479	(Fasold et al. 1987)	Glass	0,25	0,15	0,10	0,05	0,03	0,03
Window (glass)	2479	(Fasold et al. 1987)	Gass	0,25	0,15	0,10	0,05	0,03	0,03

Table 15 Initial material assumptions for OP

INITIAL MATERIAL ASSUMPTIONS (OP)									
ELEMENT	**REFERENCE NUMBER**	**REFERENCE**	**MATERIAL DEFINITION IN REFERENCE**	**FREQUENCY[H]**					
				125	**250**	**500**	**1000**	**2000**	**4000**
Floor (wood)	2468	Technischer Ausbau (Mahdavi and Orehounig 2011)	Parkett auf Estrich	0,04	0,04	0,07	0,06	0,06	0,07
Ceiling (corridor)	2294	(Dalenbäck 2000)	Ceilings, plasterboard ceiling on battens with large air-space above	0,20	0,15	0,10	0,08	0,04	0,02
Ceiling (OP)	2475	Technischer Ausbau	Ziegelmauerwerk mit Kalkzementputz	0,02	0,02	0,03	0,04	0,05	0,05

		(Mahdavi and Orehounig 2011)							
Ex. wall (brick)	2475	Technischer Ausbau (Mahdavi and Orehounig 2011)	Ziegelmauerwerk mit Kalkzemenputz	0,02	0,02	0,03	0,04	0,05	0,05
Int. wall-(brick)	2475	Technischer Ausbau (Mahdavi and Orehounig 2011)	Ziegelmauerwerk mit Kalkzemenputz	0,02	0,02	0,03	0,04	0,05	0,05
Int. wall (gyps. boa.)	2476	Technischer Ausbau (Mahdavi and Orehounig 2011)	Gipskartonplatten mit 100mm Luftabstand zu Wand oder Decke ; im Hohlraum Mineralwolle	0,28	0,14	0,09	0,06	0,05	0,01
Door (glass)	2022	(Harris 1991)	Glass, large panes of heavy plate glass	0,18	0,06	0,04	0,03	0,02	0,02
Window (glass)	2022	(Harris 1991)	Glass, large panes of heavy plate glass	0,18	0,06	0,04	0,03	0,02	0,02
Win. Frame (wood)	2471	Technischer Ausbau (Mahdavi and Orehounig 2011)	Holz oder Spanplatte vor festem Untergrund	0,04	0,04	0,05	0,06	0,06	0,06
Door, Cupboard, Desk (wood)	2478	(Fasold and Veres 2003)	Holzpanplatte, 19 mm, 913.5 kg/m², **12** cm	0,20	0,12	0,10	0,07	0,05	0,05
Chairs	2467		---	0,11	0,35	0,53	0,63	0,64	0,57

Table 16 First material improvement for OP

IMPROVEMENT 1 (OP)									
ELEMENT	**REFERENCE NUMBER**	**REFERENCE**	**MATERIAL DEFINITION IN REFERENCE**	**FREQUENCY[H]**					
				125	**250**	**500**	**1000**	**2000**	**4000**
Door (glass)	2479	(Fasold et al. 1987)	Glass	0,25	0,15	0,10	0,05	0,03	0,03
Window (glass)	2479	(Fasold et al. 1987)	Glass	0,25	0,15	0,10	0,05	0,03	0,03