TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

MASTER THESIS

Application and accuracy of computer simulation for the room acoustical improvement of gastronomic facilities: a case study

for the purpose of obtaining the degree of Diplom-Ingenieur

supervised by

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Vienna, May 2016

KURZFASSUNG

Die Atmosphäre in einem Restaurant ist ausschlaggebend für das Wohlbefinden des Gastes und somit auch für den Erfolg des Gastronomen. Viele Parameter haben Einfluss darauf, dazu zählt unter anderem auch die Raumakustik. Geschlossene Räume mit hoher Besucherdichte benötigen genaue akustische Planung, um dann entsprechend dem gastronomischen Konzept auch zum Erfolg zu führen. Mit der vorliegenden Fallstudie werden anhand eines Restaurantumbaus die Möglichkeiten der akustischen Simulation für die Planung untersucht. Hierfür wurden vor Ort Nachhallzeiten vor dem Umbau gemessen, dann wurde ein digitales Model erstellt, welches als Grundlage für die Simulation diente. In einem weiteren Schritt wurde die akustische Simulation durchgeführt und schließlich das Modell mithilfe der Messergebnisse kalibriert. Dieses Modell wurde für die Planung der akustischen Maßnahmen verwendet. Nach der Umsetzung der vorgeschlagenen Maßnahmen wurden erneut Messungen vorgenommen und somit das Model überprüft. Schlussendlich wurden die Ergebnisse analysiert und Vorschläge für eine erfolgreiche akustische Planung mit zu Hilfenahme von Simulation formuliert.

Schlagwörter

Raumakustik, Gastronomie, Nachhallzeit, ODEON, Kalibrierung

ABSTRACT

The atmosphere in a restaurant is crucial for the economic success of such an establishment. One of the parameters that has great influence on the perception of a space is the acoustics. The present case study investigates the usability and accuracy of acoustics simulation software based on the acoustical improvement of a restaurant characterised by high reverberation times. The restaurant space was modelled in a CAD tool. Subsequently, sound simulations on the basis of ray tracing were conducted. The simulated values were compared to the measured reverberation times and made subject to calibration. The initial simulations showed large deviations from the measured values. These occurred mainly due to the uncertainties of input data such as absorption properties of the used materials. Satisfactory values were obtained after three calibration iterations. Both the calibrated and the non-calibrated computer models were later used for the elaboration of a proposal for the acoustical improvement. After the implementation of the suggested measure new reverberation time measurements were carried out. The target value set for the reverberation time was largely achieved. The measured values were compared with the results from both simulations (non-calibrated and calibrated). The simulation based on the calibrated model proved to be the more accurate one.

Keywords

Room acoustics, gastronomy, reverberation time, ODEON, calibration

ACKNOWLEDGMENTS

Firstly, I would like to express my sincere gratitude to my supervisor Univ.-Prof. Dipl.- Ing. Dr.techn. Ardeshir Mahdavi for the support of my mater thesis, the guidance and his immense knowledge.

Besides my advisor, I would like to thank Mr. Josef Lechleitner for his patience, advices and for helping me with the sound measurements. My sincere thanks also go to DI Dr.techn. Kristina Kiesel and DI Dr.techn. Ulrich Pont for their insightful comments, encouragement and motivation.

I thank PORTfoods D.O.C. Wine & Foods GmbH for allowing me to conduct this master thesis, for their support and trust in my research.

Special thanks go to Mr. Hugo da Silva for his support and motivation during the highest highs and lowest lows.

Last but not the least, I must express my very profound gratitude to my friends and my family: my parents and my sister Una for supporting me spiritually throughout my studies. Without their support and unconditional love the realization of this master thesis would not have been possible.

CONTENTS

1 INTRODUCTION

The present work is divided in 5 sections. After a short description of the motivation for choosing the topic, background information is presented regarding room acoustics with a special focus on gastronomy facilities. Current research dealing with this topic is then presented to describe the state of the art in the field. Additional an insight into room acoustics simulation is presented.

A detailed description of the case in point is then provided in the methodology section, including details about the measurements and also the calibration process of the simulation model.

Subsequently the results are presented and discussed.

1.1 Motivation

A lot of attention is given to the design of restaurants as the perception is crucial for the economic success. Unfortunately in many cases the importance of the acoustic environment of these spaces is overlooked or its impact underestimated. Acoustics in restaurants are influenced on one hand by the environment including the spatial design, surfaces and materials as well as the furnishing. On the other hand the noise in this spaces plays a major role. This includes not only the noise coming from conversations, but also from the kitchen, the service staff, appliances and music (Rindel 2012, Pozsogar 2015, Resonics 2016a).

The lack of attention on this topic is even more striking if one takes into consideration todays possibilities to support the design process with acoustic simulation tools. Moreover, the acoustical planning and adaptation costs come up to decimal values of the overall investment costs or additional refurbishment costs induced by bad acoustical conditions (Pozsogar 2015).

Previously mentioned simulations for sound distribution in closed environments have been used since the late 1960s and refined ever since (Fasold and Veres 2003), offering overall accurate forecasts on the acoustical qualities of a room. First models are made to evaluate design intentions through simulation and subsequently adapted and improved before implementation. Tugrul (2012) states the potential of simulation-supported design is not being fully exploited. Usability and reliability of these software vary tremendously, hence it is important to compare and evaluate the simulations from case to case.

In this context, the present contribution seeks to compare the use of acoustic simulation and in-situ sound measurements within the framework of a case study for a restaurant. The usability and reliability of acoustics simulation software is investigated in the context of the improvement of an existing restaurant. Thoughts about common causes of inaccuracy in simulations are presented and the extent of calibration required for reliable prediction is investigated.

1.2 Background

In this chapter an overview on room acoustics and phenomena relevant for the study is presented. Subsequently, psychological and physiological effects of noise in eating establishments are presented and research done in this field is summarised. Additionally, an overview on up to date acoustics simulation software is presented. Special attention is paid to the accuracy of the programmes and sources of possible uncertainties.

1.2.1 Room acoustic metrics

The acoustical performance of a room is measured defined by certain acoustical parameters as presented in Table 1. For the present study the reverberation time was chosen as the determinant parameter, being one of the first known and most significant parameters to describe the acoustical conditions of a room (Fasold and Veres 2003).

Table 1 Room acoustical parameters (ISO 3382-1, 2009 cited on ODEON 13 Manual 2015)

Parameter	**Definition**
T_{30} (s)	Reverberation time, derived from –5 to – 35 dB of the decay curve
EDT (s)	Early decay time, derived from 0 to – 10 dB of the decay curve
D_{50} (%)	Definition, early (0 - 50 ms) to total energy ratio
C_{80} (dB)	Clarity, early (0 – 80 ms) to late (80- ∞) energy ratio
Ts [ms]	Centre time, time of first moment of impulse response or gravity time
G (dB)	Sound level related to omni-directional free field radiation at 10 m distance
LF (%)	Early lateral (5 – 80 ms) energy ratio, $\cos^2$ (lateral angle)
STI (RASTI) (%)	Speech Transmission Index

1.2.1.1 Reverberation time (RT)

The reverberation time describes the time it takes for the sound pressure level to decay by 60 dB after the source has stopped producing the sound (Figure 1). The most commonly used reverberation equation is the Sabine equation (1) (Fasold and Veres 2003).

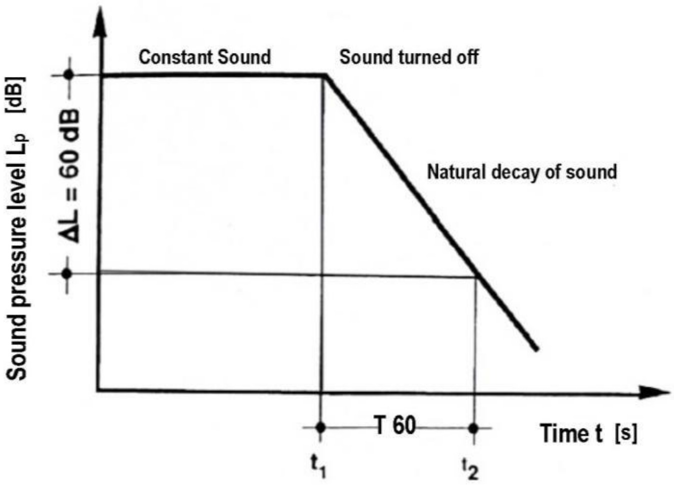


Figure 1 Reverberation process of the sound pressure level (based on Fasold and Veres 2003)

$$T_{60} = 0.163 \frac{V}{A} [s] \quad (1)$$

V = Room volume [m³]
A = Effective absorption area [m²]

Rooms with high RT are characterised by echo, since the sound travels long distances, being reflected repeatedly and not being absorbed. Generally, sound absorption is the most effective method to prevent sound reflection. This way it is directly with problems of excessive noise and reverberation (Resonics 2016b).

1.2.1.2 Sound pressure level and sound distribution

In an approximately cubic room the sound pressure level L_p is decaying in dependence on the equivalent absorption area, as presented in equation (2). In bigger distances from the sound sources a constant sound pressure level $L_{p\ diff}$ (diffuse sound field) is established due to sound reflections (Fasold and Veres 2003). Figure 2 shows the sound pressure level decrease in diffuse sound fields.

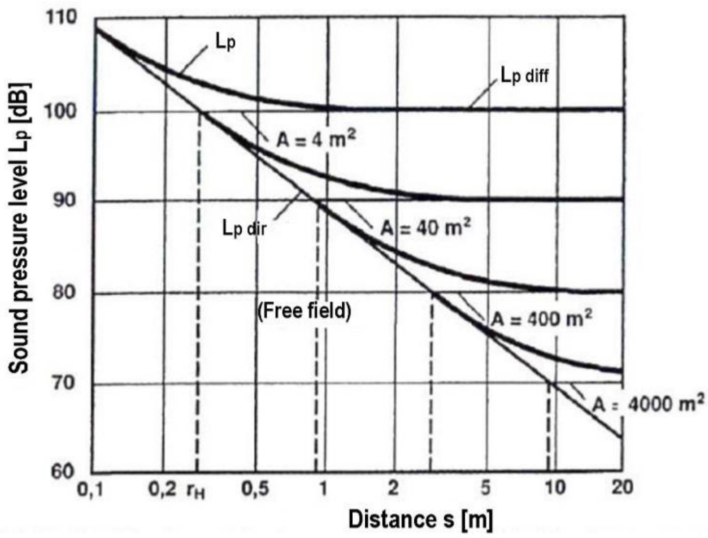


Figure 2 Sound pressure level decrease in diffuse sound fields in dependence of different equivalent absorption areas A (based on Fasold and Veres 2003)

$$L_{P\ Diff} = L_W - 10 \lg \frac{A}{4} \ \ [dB] \qquad (2)$$

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

1.2.1.3 Vocal effort and the Lombard effect

The effort given to vocalize words is *"characterized by the equivalent continuous A-weighted sound pressure level of the direct sound in front of a male speaker in a distance of 1 m from the mouth"* (Rindel 2012). ISO 9921 provides a description of the vocal effort in steps of 6 dB (Table 2). It shows that a normal vocal effort is required at a sound pressure level (SPL) of approximately 60 dB. In environments with a SPL above 72 dB, it can be more demanding to communicate than at lower levels.

Table 2 Vocal effort at various speech levels (ISO 9921 - 2003)

Decibels (dB)	Vocal Effort
54	Relaxed
60	Normal
66	Raised
72	Loud
78	Very Loud

At the beginning of the 20th century French otolaryngologist Étienne Lombard observed that people with normal hearing abilities tend to speak louder when exposed to noise. This phenomenon was later named the Lombard effect and is well known especially in restaurants and similar environments: Many people talking at the same time produce a high SPL, which again provokes them to raise their voices even more. This spiral leads to a snowballing overall noise level (Rindel 2010).

The ratio between speech level and ambient noise level is called the Lombard slope. It has been summarised in ISO 9921. According to Lazarus (1986) it does not describe a specific value but a possible range.

The Lombard effect has been observed to set in at an ambient noise level of approximately 45 dB and a speech level of 55 dB. The speech level can be expressed with the following equation (3) if a linear progress for noise levels above 45 dB is assumed (Lazarus 1986):

$$L_{S,A,1m} = 55 + c \cdot (L_{N,A} - 45) \quad [\text{dB}] \qquad (3)$$

$L_{N,A}$ = Ambient noise level [dB]
c = Lombard slope [dB/dB]

Numerous studies have been conducted dealing with the Lombard effect and the findings have increasingly been used in to design spaces with reduced noise level and improved intelligibility of speech in closed environments.

For instance, Tang et al. (1997) studied the Lombard effect by measuring the noise level variation in a university staff canteen. Their research dealt with the prediction of sound-pressure level in occupied enclosures. According to their observations, the occupants started raising their voice as the noise level surpassed 69 dB. Based on examinations of basic characteristics of conversation intelligibility in dining spaces, Kang (2002) suggested a computer model and a radiosity method for prediction of noise levels. He assumed a constant sound power from all speakers and studied e.g. the effect of increasing absorption area per person. Other studies (Hodgson et al. 2006, Rindel 2010) also described computer models for sound level predictions, taking into consideration different parameters such as the Lombard slope, the absorption per person or the number of people per group. Rindel (2010) concluded that the SPL increases by 6 dB when doubling the number of occupants. Furthermore, his research predicts a 6 dB reduction of the noise level, if the equivalent absorption area is doubled. Another model (Svensson et al. 2014) sought to introduce additionally subjective influences, e.g. annoyance, intelligibility or privacy in the prediction of the noise levels.

In a later study Rindel (2012) introduced the concept of acoustical capacity in eating establishments, which describes the allowed number of occupants for obtaining sufficient quality of verbal communication in a room. He also deduced a minimum of 3-4 m^2 equivalent absorption area per person for sufficient conditions and 6-8 m^2 for satisfactory conditions. Additionally, a volume per person of at least T·20 m^3 is proposed. As shown in Figure 3, a limited number of visitors can be calculated using the following equation (4):

$$N_{max} = \frac{V}{20 \cdot T} \qquad (4)$$

N_{max} = Number of persons
V = Room volumen [m^3]
T = Reverberation time [s]

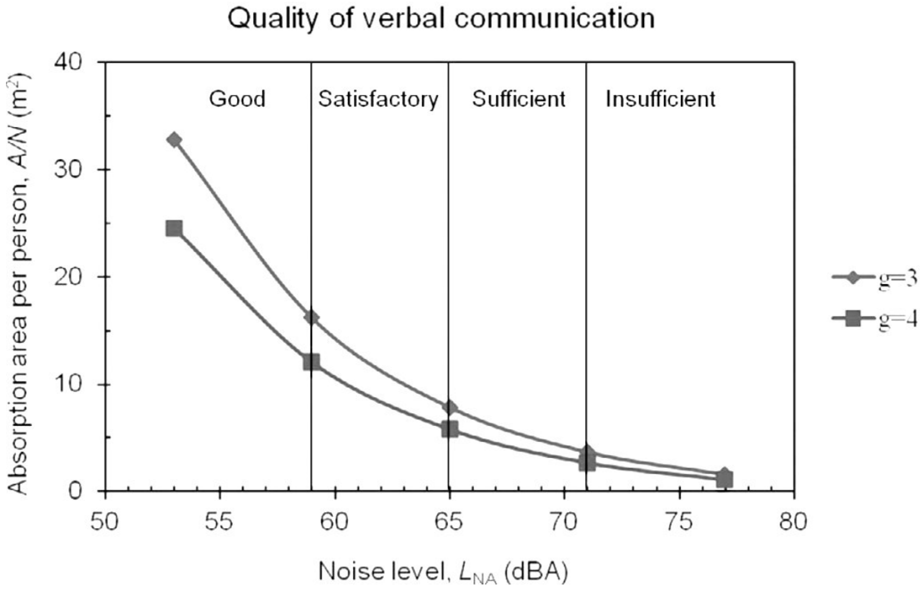


Figure 3 Relationship between the absorption area per person and the ambient noise level compared with groups of 3 and 4 persons (Rindel 2012)

1.2.2 Room acoustics in eating establishments

Both leisure and retail facilities increasingly use light and sound design strategies to raise their profit. British acoustics consultant Resonics believes that sales in a retail shop could increase by 5-10% through acoustic improvement measures (Resonics 2016c). Desired RTs can be set depending on the concept, with lower RTs in intimate atmospheres and higher ones in lively night bars and pubs. Resonics suggests a RT of <1 s for eating establishments. Due to the concept of lively dining of the restaurant in this study, a benchmark of 1 s was set for the upper limit. A tolerance range of up to -30% was defined.

1.2.2.1 Psychological and physiological effects of noise on dining experiences

A restaurant's noise environment can shape several aspects of the dining experience (Resonics 2016d). People often do not perceive the noise as disturbing but they feel uncomfortable in a loud surrounding. Besides the fact that our brain is being challenged to filter out the important information, noise raises levels of adrenaline, norepinephrine, and cortisols, resulting in the sensation of anxiety and even fear (McNamee 2014). These feelings can be intensified by further intake of alcohol and food. In addition, a 2010 study (Woods et al. 2011) wanted to find out whether background restaurant noise affected the people's perception of flavour. They found out that higher noise levels reduce the perception of the sweetness and saltiness of food. The higher a sound level a person is exposed to is, the less they will enjoy their food, as flavours and aromas are suppressed (Resonics 2016d).

1.2.2.2 Design and profit questions

Nowadays restaurants are often characterised by a sleek, minimalistic design, where reflective materials such as glass, wood, metal or tiles are applied. The problem with these materials is that they increase noise by being highly reflective. Open bars and kitchens are an additional source of noise. Even though restaurant visitors dine in order to socialize, often they end up not being able to communicate with their companions because it is very loud.

Hernandez (2014) describes that decibel levels in 8 restaurants in the Boston area were sampled, with results ranging from 66 dB (normal conversation) to 97 dB (nightclub). Therefore not surprisingly, noise is ranked number two among customer complaints from restaurants in the USA, only after service being ranked number one (Zagat Staff 2015). This fact even resulted in several restaurant-rating websites indicating noise levels as a rating criteria, introduced by *The San Francisco Chronicle* in 1998 (Resonics 2016a).

Even though on one hand bad acoustics in restaurants can seriously harm the business, on the other hand they can have a positive effect on the turnover: the crammed set up of tables and the elevated sound level make people drink more, eat faster and leave sooner (LeTrent 2010). For some people the noise does not represent a disturbance but rather an indicator for a lively and vibrant atmosphere. There are also restaurants that are too quiet in which customers feel uncomfortable because the conversation can be clearly understood at the next table. These places can be in the same way less appealing as extremely loud places.

1.2.3 Room acoustics simulation software

Before computer simulations were introduced in acoustics, reverberation time predictions were made by scale models where small microphones were placed inside. The computer-aided simulations have the advantage to be much more flexible in terms of geometry and acoustical parameters settings. Nowadays, updated results can be obtained within few hours or less, moreover they can be visualised and analysed better than with scale models (Rindel 2000).

Computer simulation for room acoustics have been used since the 60s and first applied by Krokstad for the prediction of acoustical quality of a concert hall (Vorländer 2010). There are two main classical geometrical methods for acoustical simulation: the Image source method and the Ray tracing method.

Image source method

The Image source method uses a specular reflection, which is geometrically constructed by mirroring the source in the reflecting surface and creating a virtual source. This method was considered very accurate when used for simple rectangular rooms or in cases where low order reflections are sufficient (Rindel 1995).

Ray tracing method

The Ray tracing method is based on the principle, that particles emitted from a source point are traced around the room. Every time a particle hits a surface, it loses energy according to the absorption coefficient assigned to that surface (Rindel 1995). After this method was introduced in acoustical simulations, it was proved to be very convenient because rays in acoustical software can both explore the geometry in order to find relevant reflective surfaces and transport energy (ODEON 2016a).

Hybrid method

The combined use of both methods (development of hybrid models) resulted in more reliable results and faster calculation, by exploiting each method's strengths (Figure 4). An example of a hybrid model programme is the ODEON Room Acoustics Software, which is used in this study (Version 11.0). It was created as a cooperation between the Technical University of Denmark and a group of consulting companies in 1984 (ODEON 2016b).

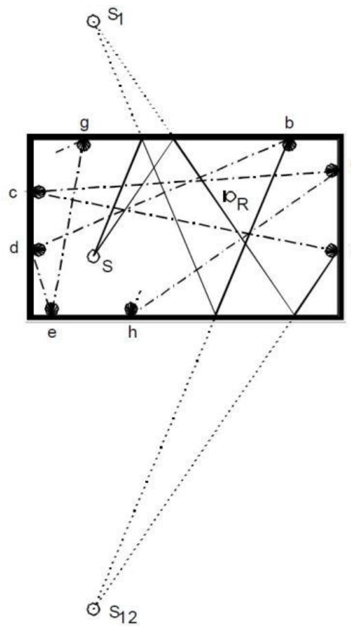


Figure 4 Principle of a hybrid model. The rays create image sources for early reflections and secondary sources on the walls for late reflections (Rindel 2000)

Scattering coefficient

Due to the wave nature of sound it has been necessary to simulate scattering effects in the models. Therefore the scattering coefficient s of a surface was introduced. It represents the ratio between reflected sound in non-specular directions and the total reflected sound. By assigning a scattering coefficient to a surface, reflection properties can be changed from a pure specular behaviour into an approximately diffuse behaviour (Figure 5). Although recent simulation software can implement the scattering in the calculations, it is difficult to define which scattering coefficients have to be used (Rindel 2000).

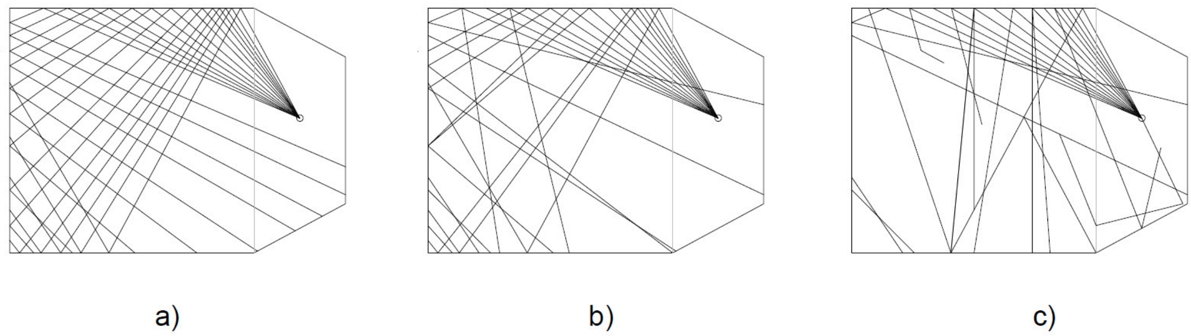


Figure 5 Reflections of rays with different scattering coefficients. a: s = 0, b: s = 0.2, c: s = 1 (based on Rindel 2000)

1.2.3.1 Accuracy of ray tracing based simulations

The reliability of simulation software has been largely discussed in several studies so far (Bork 2000, Bork 2005a, Bork 2005b, Vorländer 2010, Vorländer 2013). Quantitative data on uncertainties can be obtained through the application of the statistical method of error propagation. Another possibility is to analyse results from intercomparisons (so-called “round robins”), where the accuracy is being tested by modelling existing rooms and comparing the results with measurement results (Vorländer 2010 and 2013).

The first round robin on room acoustics simulation software was conducted by Vorländer and presented at the International Congress on Acoustics (ICA) in Trondheim 1995 (Vorländer 2010). Fourteen programmes were tested with the same 3D model of a single volume space (Bradley and Wang 2007). The first results were partially unsatisfactory. They showed a large scatter with a strong tendency to underestimate the absorption coefficients, which were selected individually. This resulted (Figure 6) in an overestimated reverberation time. In some cases the differences exceeded 50% (Vorländer 2010).

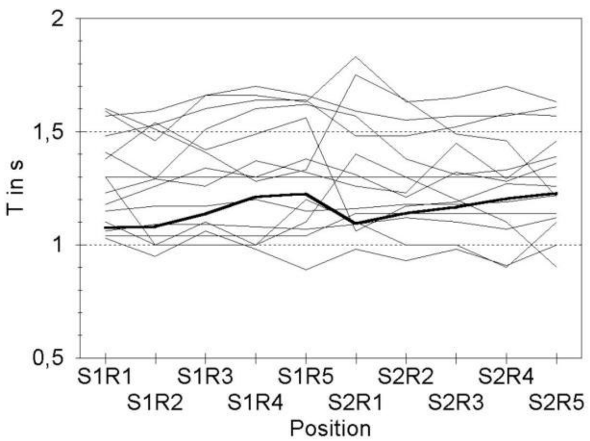


Figure 6 First round robin - Reverberation times predicted for the 1 kHz octave band in an auditorium. Thick line: average measurement result which has an uncertainty of 5% (±0.05 s) (Lundeby et al. 1995 cited on Vorländer 2010)

Vorländer concluded that the geometrical methods worked well, correct input data of boundary conditions such as absorption and scattering factors were, however, of great importance. The reliability of results depends at least partly on the quality of the numerical solver for geometrical models and of course on the skills of the user (Vorländer 2010 and 2013). Three programmes were found to produce the most accurate results, one of which was the ODEON Room Acoustics Software programme (Bradley and Wang 2007), used in the present case study.

In the following years two more round robins were conducted by Bork (2000, 2005a, 2005b). Even though in the former a common geometry model and information on absorption and diffusivity characteristics were given, *“differences between the calculation results (…) can scarcely be attributed to individual software properties.”* (Bork 2000). In the 2005 round robin the subject had to be modelled with an increasing number of geometrical details, which had little influence on the obtained results. Most programmes showed good coincidence with the measured data. Bork stated that higher calculation errors occurred for the low frequencies. Similar to Vorländer, he also concluded that accurate material absorption characteristics had a significant effect on producing reliable predicted results. Hybrid method programmes such as ODEON were found to deliver the most accurate data (Bork 2005a, Bork 2005b).

Naylor (1993) was the first to use the hybrid modeling of ODEON (version 1.5) for coupled volume rooms. He found that this version of the programme did not accurately predict coupled volume decay. Posterior versions of the ODEON programme, however, use a more advanced hybrid method. Hence, they are performing better at predicting the non-exponential decay in coupled rooms (Bradley and Wang 2007).

Also Bradley and Wang (2007) evaluated the reliability of computer simulations in comparison to in–situ measurements for a coupled volume concert hall. Their results showed a high level of accuracy for high frequency ranges. Lower frequency ranges showed less agreement between the computer model and the existing hall.

Nijs et al. (2002) investigated the reliability of the ray tracing programmes on three coupled rooms. The accuracy was found to be good, provided that the sound reflections on the walls were introduced as angle dependent. A careful choice of scattering factors of flat surfaces is advisable. Also they underlined the importance of the material absorption properties.

1.2.3.2 Uncertainties in acoustical simulations

Besides Bork (2000, 2005) and Rindel (1995, 2000), Vorländer (2010) describes uncertainties in acoustical simulations. He distinguishes between systematic and stochastic uncertainties. The systematic ones can occur due to shortcomings in the algorithms and the modelling approach. Sources of stochastic uncertainties are often introduced by uncertain input data, mainly by boundary conditions such as absorption and scattering coefficients. These data are often taken from software integrated databases, textbooks or other.

Furthermore he claims that "*it is not adequate to "calibrate" a computer model by adjusting input data so that, for instance, reverberation times or other damping effects are matched to measurement results. The objective for computer simulations should be to be independent of adjustment factors. It should be purely based on physical data and corresponding databases of input data (typically material properties)" (Vorländer 2010).* The algorithm itself can still cause systematic and stochastic. The calculation speed remains an interesting issue, certainly worth mentioning. He assumes that *"the rather large uncertainties in measured random-incidence scattering coefficients play only a little role in the overall acoustic impression."* (Vorländer 2010).

2 METHODOLOGY

In the following section an overview on the structure of the case study and the realised steps is given. It includes also a description of the case in point. Additionally tools and procedures for the reverberation time measurements are explained. The processes of the 3D modeling, the simulations and the needed calibration steps are presented. Furthermore the acoustical improvement measure is elaborated.

2.1 Approach

This study was carried out upon following steps (Figure 7):

I) Documentation of the geometry and material properties of the existing restaurant

II) Compilation of requirements imposed by the municipal authorities, operator expectations and architectural proposal

III) Reverberation time measurements according to ÖNORM EN ISO 3382-2 and subsequent evaluation of measured values

IV) 3D modelling of the existing space in SketchUp 2015 and export to ODEON 11.0

V) Sound simulation in ODEON 11.0

VI) Comparison of the measured and simulated reverberation times and calibration

VII) Proposal for acoustical improvement

VIII) Simulation of the non-calibrated 3D model including the architectural proposal and the acoustical improvement measure

IX) Simulation of the calibrated 3D model including the architectural proposal and the acoustical improvement measure

X) Application of the material during the reconstruction

XI) Reverberation time measurements according to ÖNORM EN ISO 3382-2 of the space after renovation and subsequent evaluation of measured values

XII) Comparison of the measured and simulated (calibrated and non-calibrated) reverberation times

XIV) Analysis and discussion of the results and the conducted improvement measures

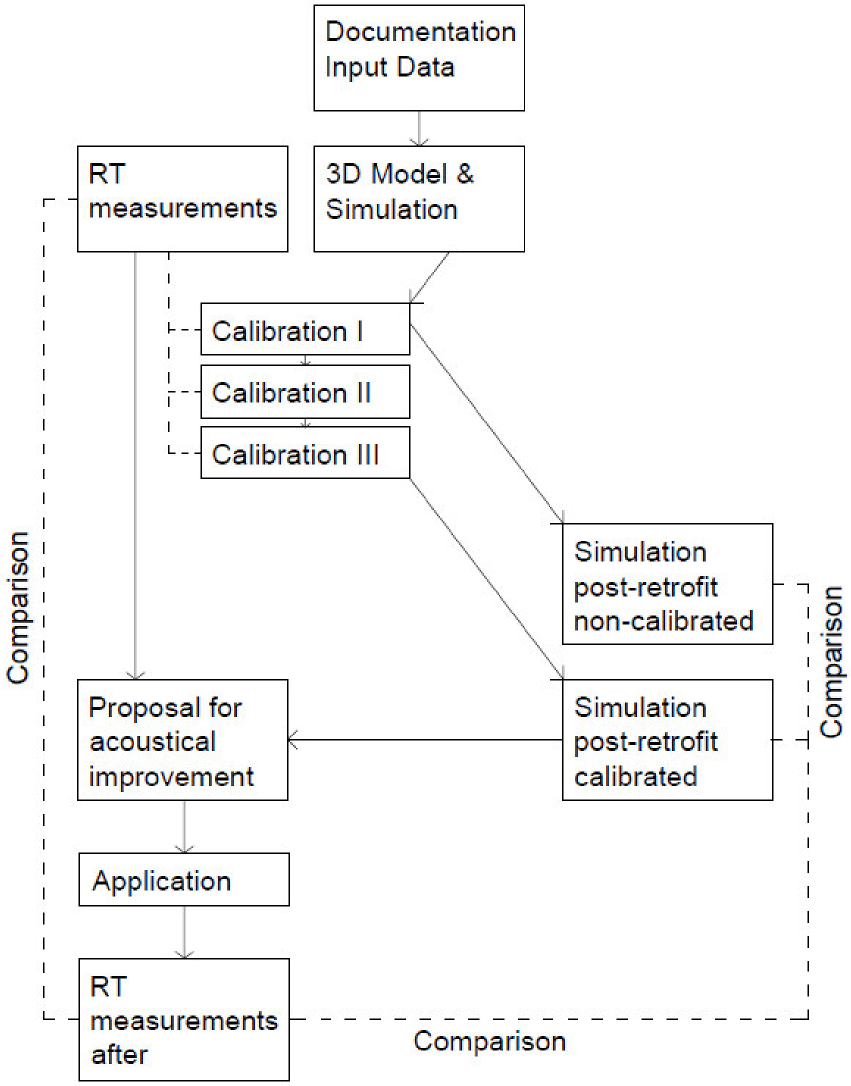


Figure 7 Structure of the study – realised steps

2.2 Case in point

For the detailed examination of room acoustical improvement measures the Portuguese restaurant *Lisboa Lounge* (Mühlgasse 20, 1040 Vienna) was used as a study case. Already during the first visits on the location in summer 2015 the operators PORTfoods D.O.C. Wine & Foods GmbH had detected the inadequate acoustical properties of the place. Subsequently, it was decided to take a closer look at acoustics and suggest an improvement measure to be included in the upcoming reconstruction.

2.2.1 Description of the restaurant

The 200 m² big, already for gastronomy purposes adapted space is divided into 3 levels: a ground floor bar area is facing the street; a few steps higher a split level accommodates the dining area, the kitchen and an office facing the inner courtyard., a multifunctional room, toilets, storages and the ventilation room can be found in the basement (Figures 8 and 9). Table 3 shows the geometrical properties of the three main rooms where measurements and simulations where conducted. The kitchen and the toilets anteroom have been featured as well, since they are inseparably coupled with the previous ones. A more detailed list of surface areas and materials can be found in the appendix.

Table 3 Geometrical properties of the coupled spaces

	Bar area	**Dining area**	**Kitchen**	**Basement area**	**Toilets anteroom**
Area [m²]	49,30	34,20	13	49,30	4,35
Height [m]	5,10	4,10	4,10	2,50 (max.)*	2,70
Volume [m³)	251,40	140,20	53,30	123,25	11,75

*measured at the highest arch apex

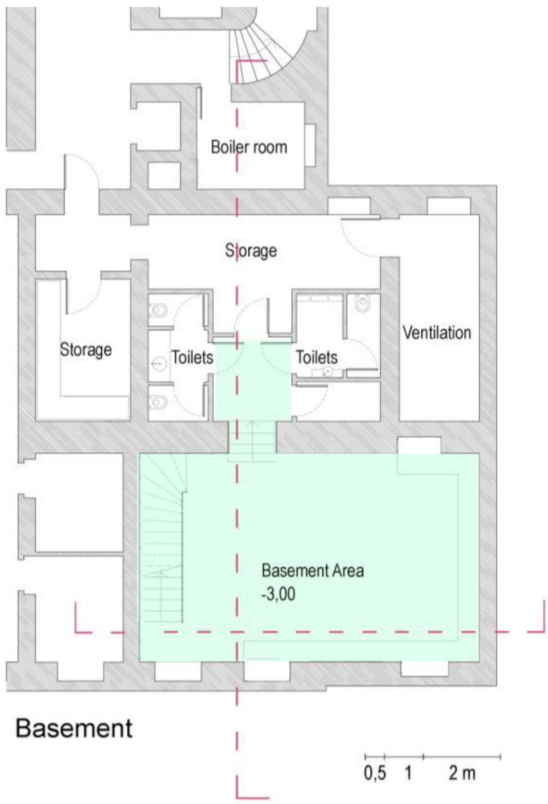
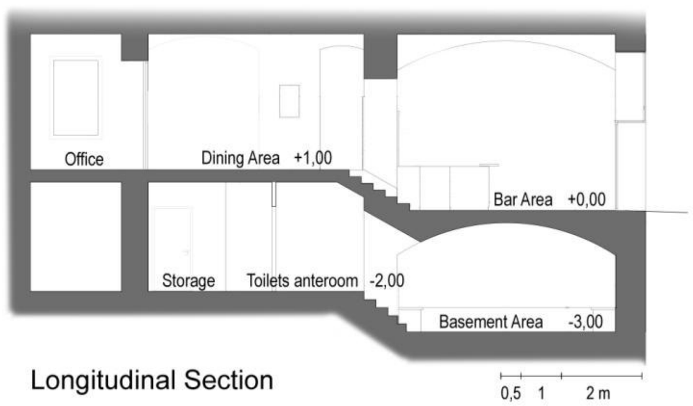


Figure 8 Ground floor and basement – simplified plans



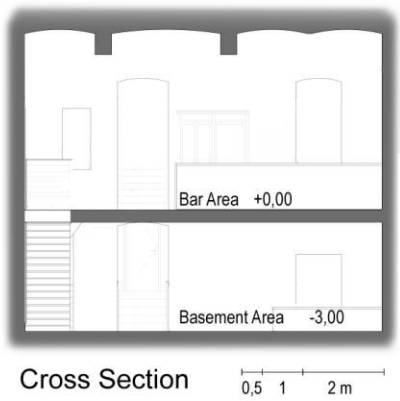


Figure 9 Sections – simplified plans

The restaurant is located in a building from the beginning of the 20th century. The solid construction features materials typically used for Viennese housing projects of that time: brick walls with a classical lime plaster and also plastered brick vault ceilings. Parts of the walls were found unplastered though. Besides a stone floor close to the entrance, the floors in the bar area and the dining area are wooden. The stone floor is repeated in the basement area, whereas epoxy resin is used for the floor in the toilets anteroom. The bar area is characterised by huge glass windows which cover roughly 10% of the overall surface area in this room. Figures 10-13 show the restaurant prior to reconstruction.

Figures 10-13 Pictures before reconstruction – Exterior; Bar area; Dining area; Basement area

2.2.2 Architectural proposal

The architectural proposal by *s3 arquitectos* did not include any changes of the space configuration. It was mostly based on the use of new materials for the surfaces. Pine wood cladding was suggested along the walls in the dining area, parts of the basement walls and along the bar and the reeling in the bar area. The latter was also characterised by a ceramic tile stripe along the walls. Wood and metal was used for the tables and chairs, which were positioned by the operators not according the architects' plan (Figure 14). The renderings presented (Figures 15-17) show the first proposal, nevertheless the suggested ceramic tiles surface was finally reduced to a 1.30 m stripe along the wall. Figures 18-20 show the restaurant after implementing the design proposal.

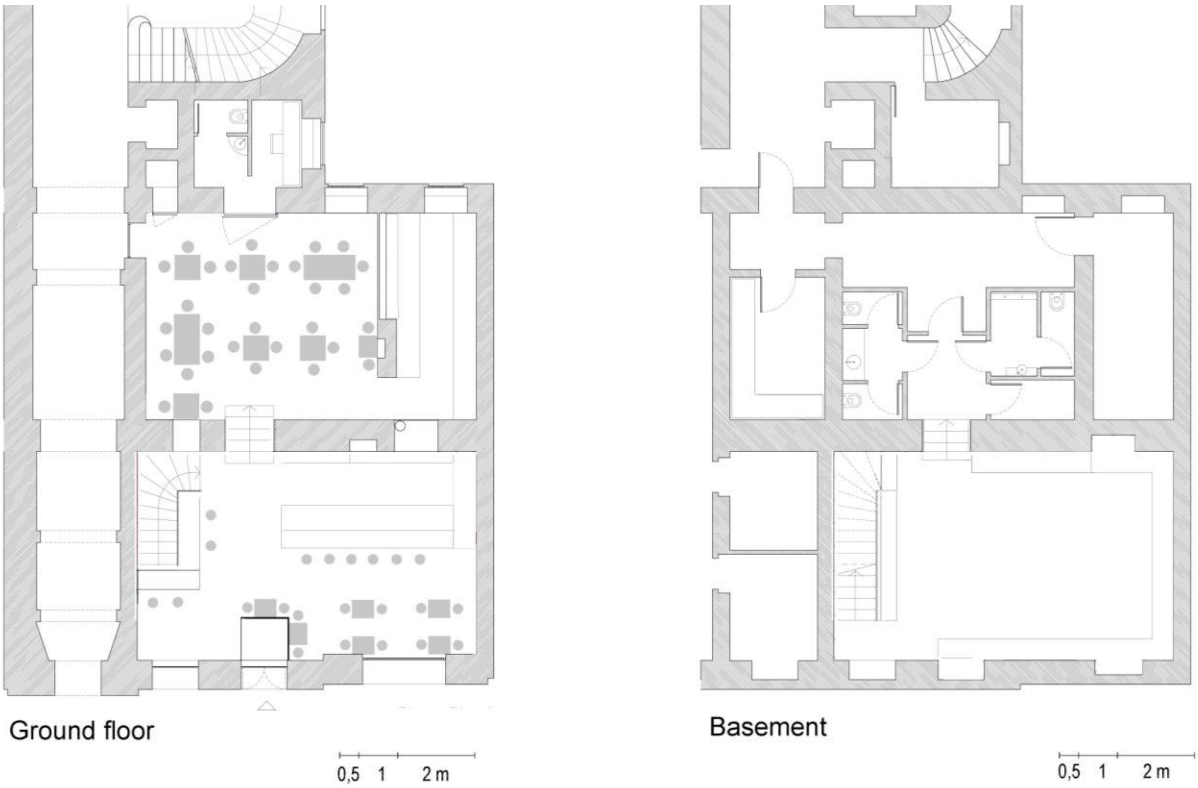


Figure 14 Actual set-up of the tables

Figures 15-17 Renderings - Bar area; Dining area; Basement area (s3 arquitectos 2015)

Figure 18 Bar area (PORTfoods GmbH 2015)

Figure 19 Dining area (PORTfoods GmbH 2015)

Figure 20 Basement area (PORTfoods GmbH 2015)

2.2.3 Room acoustical challenges

Reflective Surfaces

The subject presented acoustical challenges of different types. As previously described, in all the rooms hard, highly reflective surfaces were found, which have a detrimental effect on the acoustics. Also the adopted design proposal is characterised by the use of hard surfaces: pine wood cladding, ceramic tiles and furniture made of metal and wood. The architects suggested an application of a thin sound insulating material in order to inhibit the sound transmission through the construction. Nevertheless, this would not have had a significant impact on the room acoustics since the wood cladding mounted on top would have presented a plane hard surface and reflected the sound waves. No further considerations regarding the room acoustics were discussed in the architects' proposal.

High Ceilings

Another challenge for the room acoustics are the high ceilings. Especially in the bar area, they contribute to a bigger room volume. Thus, sound is lost in the 'dead space' above our heads, resulting in higher reverberation times because the sound has to travel long distances before the waves are reflected by a hard surface (Resonics 2016c).

Multiple noise sources

As described in the chapter 1.2.2., multiple noise sources in social settings such as restaurants can lead to massive noise disturbance. It is commonly a result of verbal communication, human activity, music or the equipment. In a coupled space like the given example, it was expected that the noise gets distributed even more easily due to the continuous movement of the people.

2.3 Before reconstruction

Prior to the reconstruction of the restaurant, reverberation time measurements were conducted. A 3D model of the space was created and simulations were performed. Subsequently the model was calibrated and the measured and simulated results were compared. The calibrations of the model sought to provide a ground for simulations of an acoustical improvement measure.

2.3.1 Measurements

Reverberation time measurements prior to the reconstruction were conducted according to ÖNORM EN ISO 3382-2 (2009) in unoccupied conditions. Used components of the NORSONIC wireless building acoustics measurement system are listed in Table 4 and presented in Figure 21.

Table 4 List of the NORSONIC measurement equipment

Dodecahedron Loudspeaker	Nor276
Power Amplifier	Nor280
Sound Analyzer (incl. microphone)	Nor140
Wireless Building Acoustic System	Nor1516B
Software	Control-Build and Nor-Build
Building Acoustic Case	Nor-515
WLAN router Moxa	

Figure 21 Measurement equipment components (Based on NORSONIC Catalogue)

The measurements were conducted with the loudspeaker in two different locations in each of the three rooms. For the measurement with the loudspeaker position 1 in the bar area 4 different sets of microphone position were conducted. For all other loudspeaker positions the microphone was placed in 3 different spots. The source-receiver distance according to ISO

3382-2 (2009), presented in equation 5, was respected in all the cases (Bar area > 1 m; Dining area > 1 m; Basement area > 1 m).

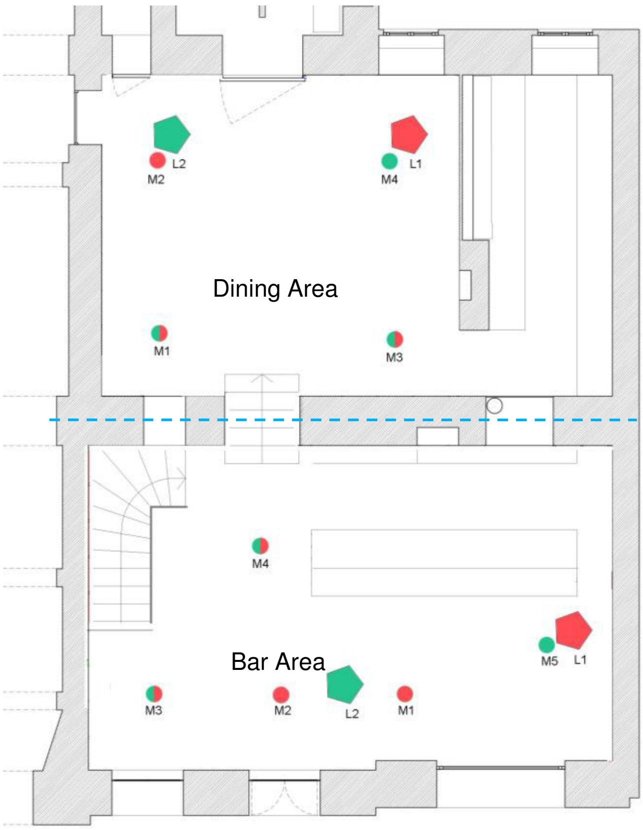
$$d_{min} = 2 \cdot \sqrt{\frac{V}{c \cdot T}} \quad [m] \qquad (5)$$

V = Room volume [m³]
c = Speed of sound [m/s]
T = Estimate of the expected RT [s].

The exact set up is presented in Figure 22 and in Table 5. Loudspeaker heights were adjusted to approx. 1.80 m and microphone heights to approx. 1.50 m above the floor. For each measurement position a white noise of overall power of Lw = 120 dB was emitted twice for 10 sec. Even though it comprehends frequencies from 50 Hz to 5000 Hz (third-octave bands) which are evaluated by the software, the lowest and the highest frequencies (63 Hz and 8000 Hz) could not be measured or they provided incomprehensive values. Thus they were not taken into consideration for further evaluation. The third-octave bands values were averaged to octave bands arithmetically.

Table 5 Loudspeaker positions and the corresponding microphone positions

Room	L1	L2
Bar	M1 / M2 / M3 / M4	M3 / M4 / M5
Dining	M1 / M2 / M3	M1 / M3 / M4
Basement	M1 / M2 / M3	M1 / M3 / M5



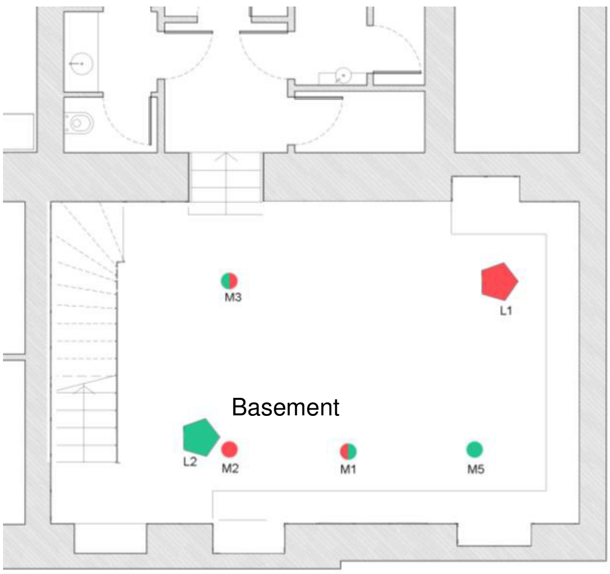


Figure 22 Loudspeaker and microphone positions in the three rooms

Figures 23 and 24 show the measurements in the bar area and the dining area.

Figure 23 RT measurements in the bar area

Figure 24 RT measurements in the dining area

2.3.2 3D modelling and simulation

The ODEON Room Acoustics Program version 11.0 (ODEON 2011) was chosen for the sound simulations. A room can be generated in two different ways: either by the input of coordinates in ODEON itself or by creating a CAD model and importing it to ODEON. Because of the complexity of the geometry, the model was created in SketchUp (SketchUp 2015) and imported via ODEON plug in for SketchUp (ODEON 2011) (Figures 25 and 26). Based on existing layout documents, a closed model was created dividing the surfaces in layers to be assigned with different material properties. Circular geometry like vault ceilings and arches have been approximated by polygonal shapes. The functions 3D OpenGL and 3D investigate rays were used to check the geometry. No overlapping surfaces or holes in the model were detected.

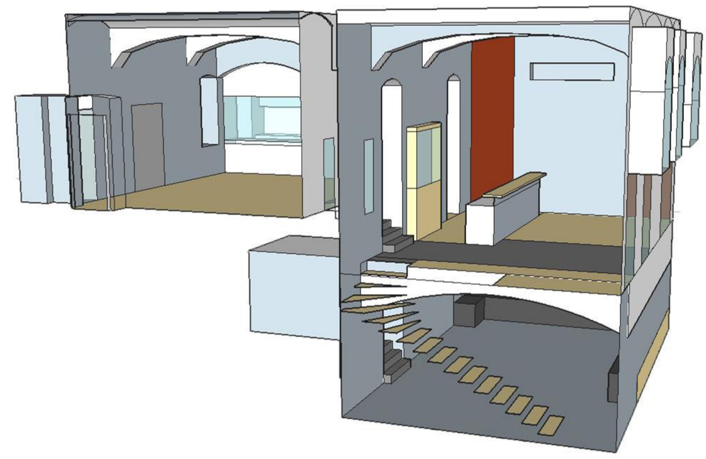


Figure 25 Model created in SketchUp

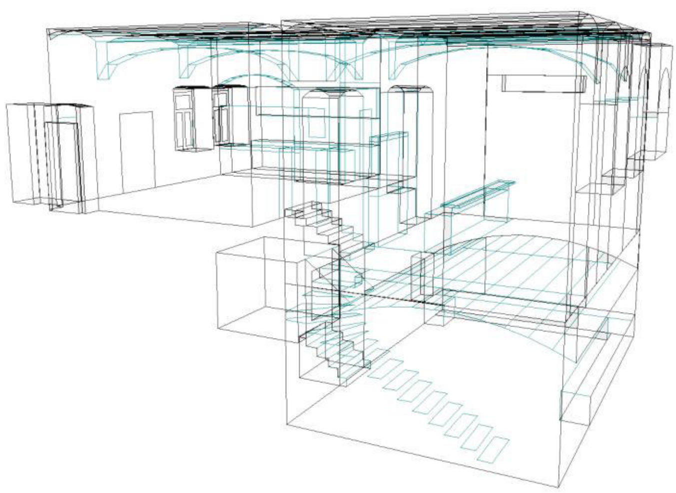


Figure 26 Model exported to ODEON

Each surface had to be assigned by a material which is characterised by the sound absorption coefficient α in the frequency range of 63 to 8000 Hz. α represents the ratio of the non-reflected (absorbed) sound energy to the impact sound energy. Complete reflection means α = 0, whereas total sound absorption is described as α = 1 (Fasold and Veres 2003). First material assignments were based on the software's material library, further literature and assumptions. A simplified overview is given in Table 6.

Table 6 Material list for simulation (non-calibrated) - Before reconstruction / unoccupied

Non-calibrated	Absorption Coefficient α									
Layer	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**αw**	**m²**
Floor – Wood	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07	**0.06**	**64**
Floor – Stone	0.01	0.02	0.02	0.03	0.04	0.05	0.05	0.06	**0.04**	**58**
Glass - Windows	0.35	0.35	0.25	0.18	0.12	0.07	0.04	0.04	**0.18**	**23**
Glass – Other	0.18	0.18	0.06	0.04	0.03	0.02	0.02	0.02	**0.07**	**9**
Wood – Other	0.14	0.14	0.10	0.06	0.08	0.10	0.10	0.10	**0.10**	**19**
Plastered brickwork	0.02	0.02	0.02	0.03	0.04	0.05	0.05	0.05	**0.04**	**457**
Metall *	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	**0.01**	**12**
Exposed brickwork	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.03	**0.02**	**38**
Other reflective *	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07	**0.06**	**15**
Doors *	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07	**0.06**	**3**

** Assumption*

The measured RTs were taken as objective criteria to compare the results of the non-calibrated simulation. Due to the fact that the room volumes and the measured RTs were known, the existing equivalent absorption area could be easily calculated with the equation (6) to give a first estimation (Table 7). It should be pointed out that regardless of the coupled nature of the rooms first estimations on each room's characteristics were calculated with Sabine's formula, which describes the RT in closed spaces. The equivalent absorption area is also calculated with equation (7) by multiplying the room surfaces with their corresponding absorption coefficient. This means that the equivalent absorption area (A) is equal to the area of the absorbing surface (S) if the absorption coefficient is 1.

$$A = \frac{V}{T} \cdot 0.163\ [m^2] \qquad (6)$$

A = Equivalent absorption area [m²]
V = Room volume [m³]
T = Reverberation time [s]

$$A = S_i \cdot \alpha_i\ [m^2] \qquad (7)$$

A = Equivalent absorption area [m²]
S = Absorbing surface [m²]

Table 7 Existing equivalent absorption area and the one to be achieved for RT = 1s. Room volumes have been rounded up.

	Volume [m³)	RT [s]	**A [m²]**	RT new [s]	**A new [m²]**
Bar area	250	1.56	**26.1**	1	**40.8**
Dining area	140	1.55	**14.7**	1	**22.8**
Basement area	120	1.37	**14.2**	1	**19.6**

Default scattering factors of 0.05 were used. Also temperature and humidity settings were set on default.

The same measurement settings were used for all microphone and loudspeaker positions which were placed as accurate as possible to the positions defined in reality. Loudspeaker heights were set to approx. 1.80 m and microphone heights to approx. 1.50 m above the floor. Also the overall gain power of the loudspeaker was set according to the power used for the measurements. The Impulse response length was adjusted to 3000 ms and the transition order to 0. Out of 16 000 used rays, 0.3% were lost. The precision mode settings were chosen for the RT calculation which resulted in the longer calculation times. The RT values were obtained in octave bands.

2.3.3 Calibration

After carrying out the first simulation, the data was compared with the measurements. Extreme disagreement was observed especially in the bar area and the dining area, where the simulated RTs reached almost the double of the measured values. Interestingly, peaks of the simulated RTs where at low frequencies, whereas the measured RTs for the same frequencies were the lowest of all values. It was assumed that this discordance is mainly rooted in the wrong material assignments due to missing absorption information of existing materials.

Three calibration iterations were performed. The first one included an adjustment of the plastered brickwork which represented the biggest percentage of the surfaces. Slightly higher absorption coefficients were chosen. Erroneously, the wooden floor in the bar area was previously assumed to be a wood parquet in asphalt on concrete. It was replaced by wood mounted on counterfloor, as given in reality. The wooden benches along the wall in the basement have a metal grille and accommodate the ventilation pipes. An overall $\alpha = 0.6$ was assigned to the metal grille for the first simulation. These coefficients were adapted to more realistic non-uniform values. ODEON's Quick Estimate tool was used to obtain the first RT estimations. The impulse response length was subsequently set to 2500 ms which represented the highest estimated RT. The Transition Order remained default. Due to the coupled geometry, it was recommended by ODEON support to increase the number of late rays so that more rays could be safely transferred between rooms and keep the reflection density high enough to calculate the parameters accurately. After applying these changes significant improvement was observed. An overview on the changes in the first calibration is given in Table 8. Original values can be seen in Table 6.

Table 8 Changes in first calibration - Before reconstruction / unoccupied

Calibrated I	Absorption Coefficient α									
Layer	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**α_w**	**m^2**
Floor - Wood *	0.2	0.2	0.15	0.1	0.1	0.05	0.1	0.1	0.13	30
Plastered brickwork	0.02	0.03	0.04	0.04	0.04	0.05	0.05	0.05	0.04	457
Metal grille	0.6	0.5	0.5	0.4	0.3	0.3	0.3	0.2	0.2	7

** Change applied only for the bar area*

The second calibration step included an additional fine-tuning of the plastered brickwork properties. The material wood mounted on counterfloor was assigned also to the wooden floor in the dining area. Changes are represented in Table 9.

Table 9 Changes in second calibration - Before reconstruction / unoccupied

Calibrated II	Absorption Coefficient α									
Layer	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**αw**	**m²**
Floor - Wood *	0.2	0.2	0.15	0.1	0.1	0.05	0.1	0.1	0.13	34
Plastered brickwork	0.025	0.035	0.045	0.05	0.05	0.05	0.05	0.05	0.04	457

** Change applied also for the dining area*

The third calibration step showed satisfactory results in comparison to the measured values. Wooden floor and plastered brickwork values were adapted again. Additionally, the absorption of the double glazed windows was slightly raised. Due to the distance between the glass panes the windows act like vibrating panels, hence better absorption coefficients were assigned. Table 10 shows the changes made during the last calibration process.

Table 10 Changes in third calibration - Before reconstruction / unoccupied

Calibrated III	Absorption Coefficient α									
Layer	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**αw**	**m²**
Floor - Wood	0.2	0.2	0.25	0.25	0.2	0.1	0.1	0.1	0.18	64
Plastered brickwork	0.025	0.035	0.045	0.05	0.05	0.05	0.05	0.05	0.04	457
Floor - Stone	0.02	0.05	0.05	0.04	0.05	0.05	0.05	0.05	0.05	58
Glass - Windows	0.35	0.35	0.25	0.18	0.16	0.1	0.04	0.04	0.18	23

On the basis of Table 7 additional absorption area to be added was calculated for an aimed RT of 1 s with the Quick Estimate Tool. Figure 27 shows the required areas according the simulation and the last calibration step.

Figure 27 Additional absorptions areas needed – according simulation and final calibration

Complete material lists, with the corresponding absorption properties and the changes made can be found in the appendix.

2.4 Suggested improvement measures

Due to the remaining uncertainties in the simulation and the fact that the architectural proposal did not suggest the use of drastically different surfaces and did not include absorbing materials, the influence of other important factors was taken into consideration for the final material choices for the acoustical improvement (Figure 28). Subsequently, simulations based on the non-calibrated and the calibrated model were conducted, including the suggested measures.

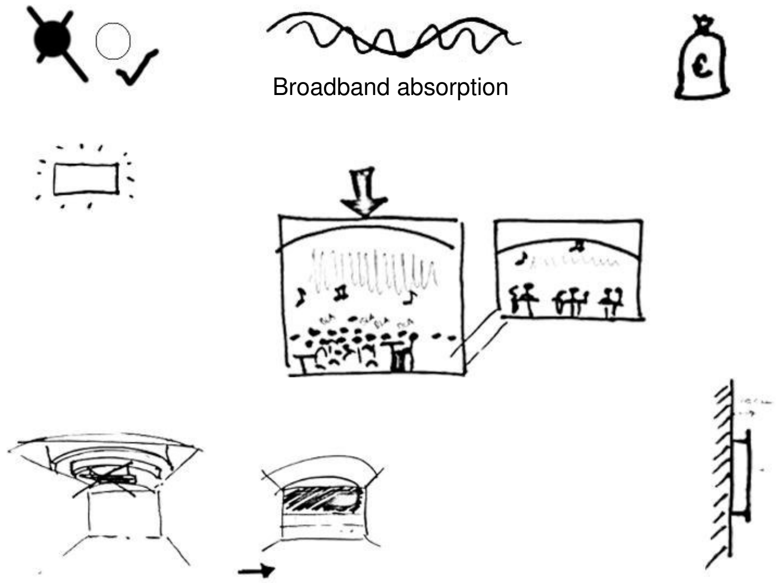


Figure 28 Criteria for the material choice

In order to fit to the interior, it was agreed to select a plane, white material with homogenous aspect to be mounted along a room surface. Ideally it should be a broadband absorber to cover the whole range of frequencies. Nevertheless, special attention was paid to the high frequencies which showed the highest measured RTs. The improvement measures were concentrated to the bar area, as this was seen as the centre of action and therefore the most important space. It was also the room that was characterised by the longest average RTs and with the subjectively perceived worst acoustic conditions. The bar area is also the welcome area facing the street. Additionally, the living room and the bedroom of the neighbour above the restaurant is located exactly over the bar area. That was another reason to reduce the RTs and therefore the sound pressure level. The operators agreed on not suspending any panels and on maintaining the visual qualities of the vault ceilings. Hence, the two opposite cross walls were taken into consideration for the application of absorbers. Since the architectural proposal included a 1.30 m high stripe of ceramic tiles along these walls, the surfaces above could be used. These surfaces had an area of 26 m^2. The tile stripe was planned to be mounted on a Rigips plasterboard with a 10 cm total distance from the wall. This meant that the absorber placed above also should not have a construction thickness of more than 10 cm.

Very few companies were found to produce absorbers with these properties. It was mostly because there were no construction systems to have a maximum thickness of 10 cm and perform well, so the choice was reduced to two possibilities. The first was an acoustical wall system by Rigips, the Rigiton Air 8/18 Q (Figure 29). It is a jointless system with 20% square perforations (8 x 8 mm). According to the drywall builder company Schreiner, who was engaged for the installation, the Rigiton system could have been mounted with a 5 cm cavity filled with mineral wool. Unfortunately, absorption coefficients were known only for a standard system with 5 cm distance and empty cavity. The properties listed in Table 10 are based on assumptions.

The second option was the Akusto Wall C system by Ecophon with invisible joints (Figures 30 and 31). These panels were manufactured from third generation glass wool. The back of the panel is covered with glass tissue. The visible surface is available as a glass fibre fabric (Texona), an impact resistant glass fibre fabric (Super G) or a painted surface (Akutex™ FT). The total construction thickness is 4.3 cm. The glass wool core was tested and classified as non-combustible according to EN ISO 1182 (Akusto Wall C Catalogue 2015). Because of its room acoustical performance (Figure 32) and the homogenous aspect Akusto Wall C with the painted surface was chosen. Table 11 presents the absorption properties of both systems.

Table 11 Absorption coefficients **α** of properties of Rigiton Air 8/18 Q and Akusto Wall C Akutex FT

	Absorption Coefficient α								
Acoustical System	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**αw**
Rigiton Air 8/18 Q	0.2	0.25	0.35	0.8	1	0.85	0.7	0.7	**0.6**
Akusto Wall C Akutex FT	0.25	0.25	0.75	1	1	1	1	1	**0.8**

Figure 29 Rigiton Air 8/18 Q (Rigips 2014)

Putting these average absorption coefficients of both systems in the equation (7), an equivalent absorption area of 15.6 m² for Rigiton and 20.8 m² for Akusto Wall was obtained.

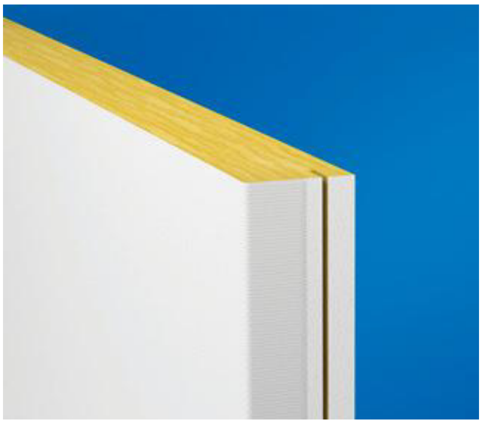


Figure 30 Akusto Wall C Panel (Ecophon 2015)
Figure 31 Akusto Wall C Joint (Ecophon 2015)

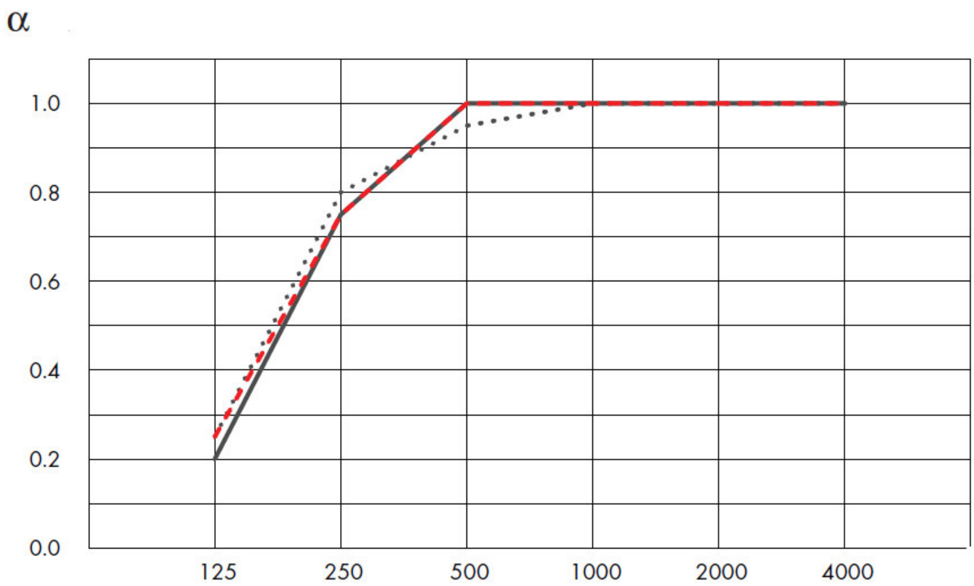


Figure 32 Akusto Wall C Absorption coefficients (Ecophon 2015)

2.5 Simulation of suggested measures

After suggesting an acoustical improvement measure, both the first non-calibrated and the final calibrated pre-retrofit models were used to predict the acoustical performance of the post-retrofit conditions. The obtained RT values would serve for the latter examination of the accuracy of the models.

2.5.1 Simulation based on the non-calibrated model

The first post-retrofit simulation was based on the non-calibrated model of the existing space. The geometry was adapted and new materials were introduced according to the architectural proposal and the suggested acoustical improvement (Figures 33 and 34). Also in this case, first material assignments were based on the software's material library, further literature and assumptions. A simplified overview is given in Table 12.

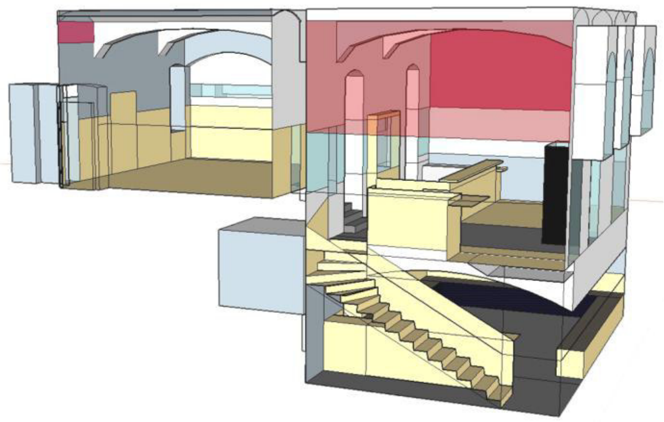


Figure 33 Absorber position in new SketchUp Model

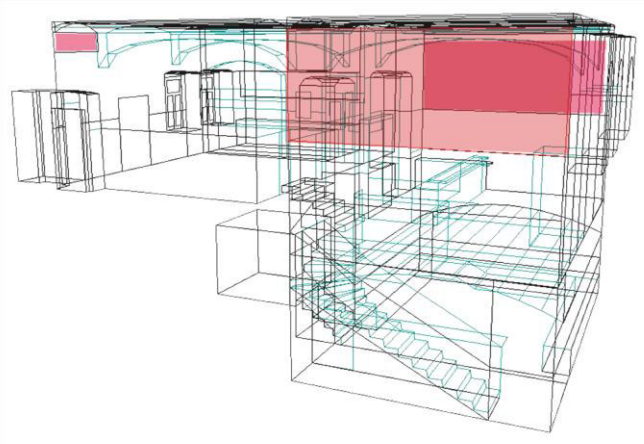


Figure 34 Absorber position in new ODEON Model

Table 12 Material list for simulation (non-calibrated) – after reconstruction / unoccupied

Non-calibrated	Absorption Coefficient α									
Layer	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**αw**	**m²**
Absorber	0.25	0.25	0.8	0.95	1	1	1	1	0.78	26
Floor - Wood	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07	0.06	64
Floor - Stone	0.01	0.02	0.02	0.03	0.04	0.05	0.05	0.06	0.04	58
Fibre cement panels	0.08	0.08	0.11	0.05	0.03	0.02	0.03	0.03	0.05	16
Glass - Windows	0.35	0.35	0.25	0.18	0.12	0.07	0.04	0.04	0.18	23
Glas - Sonstiges	0.18	0.18	0.06	0.4	0.03	0.02	0.02	0.02	0.07	8
Wood – Pine cladding	0.42	0.42	0.21	0.1	0.08	0.06	0.06	0.06	0.18	80
Wood - Other	0.14	0.14	0.1	0.06	0.08	0.1	0.1	0.1	0.10	27
Ceramic Tiles	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.01	20
Leather	0.37	0.4	0.5	0.58	0.61	0.58	0.5	0.47	0.50	6
Plastered brickwork	0.02	0.2	0.02	0.03	0.04	0.05	0.05	0.05	0.04	370
Metal *	0.01	0.1	0.01	0.01	0.01	0.02	0.02	0.02	0,01	12
Rigips plasterboard	0.5	0.5	0.12	0.06	0.04	0.07	0.1	0.1	0.19	5
Other reflective *	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07	0.06	15
Doors *	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07	0.06	3
Curtain	0.15	0.15	0.45	0.96	0.91	1	1	1	0.70	2

** Assumption*

Same parameters were set as for the first simulation of the existing conditions. Also microphone and loudspeaker positions were repeated according to the measurements.

2.5.2 Simulation based on the calibrated model

High RTs were obtained in the simulation based on the non-calibrated model, even though the absorber was applied. Peaks were mainly at mid-frequencies whereas short RTs were calculated for the low frequencies. Since the chosen material is characterised by very good absorption properties from 500 Hz to 8000 Hz, it could be expected to have the peaks at low frequencies. In order to examine the efficiency of calibration, another simulation was run based on the calibrated model. Absorption properties are presented in Table 13.

Table 13 Material list for simulation (calibrated) – after reconstruction / unoccupied

Calibrated	Absorption Coefficient α									
Layer	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**αw**	**m²**
Absorber	0.25	0.25	0.8	0.95	1	1	1	1	0.78	26
Floor - Wood	0.2	0.2	0.25	0.25	0.2	0.1	0.1	0.1	0.18	64
Floor - Stone	0.02	0.05	0.05	0.04	0.05	0.05	0.05	0.05	0.05	58
Fibre cement panels	0.08	0.08	0.11	0.05	0.03	0.02	0.03	0.03	0.05	16
Glass - Windows	0.35	0.35	0.25	0.18	0.16	0.1	0.04	0.04	0.18	23
Glass - Other	0.18	0.18	0.06	0.4	0.03	0.02	0.02	0.02	0.07	8
Wood – Pine cladding	0.42	0.42	0.21	0.1	0.08	0.06	0.06	0.06	0.18	80
Wood - Other	0.14	0.14	0.1	0.06	0.08	0.1	0.1	0.1	0.10	27
Ceramic Tiles on Rigips	0.08	0.08	0.11	0.05	0.03	0.02	0.03	0.03	0.05	20
Leather	0.37	0.4	0.5	0.58	0.61	0.58	0.5	0.47	0.50	6
Plastered brickwork	0.025	0.035	0.045	0.05	0.05	0.05	0.05	0.05	0.04	370
Metal *	0.01	0.1	0.01	0.01	0.01	0.02	0.02	0.02	0,01	12
Metal grille	0.6	0.5	0.5	0.4	0.3	0.3	0.3	0.2	0.2	7
Rigips plasterboard	0.5	0.5	0.12	0.06	0.04	0.07	0.1	0.1	0.19	5
Other reflective *	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07	0.06	15
Doors *	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07	0.06	3
Curtain	0.15	0.15	0.45	0.96	0.91	1	1	1	0.70	2

* *Assumption*

Impulse Response Length set to 2500 ms
Transition Order: 2
All late rays

After conducting the simulation based on the calibrated model, a significant decrease of RTs could be observed. The following step would include the RT measurements after the renovation, in order to prove which of the two simulations was the more accurate one.

2.5.3 Realization of the improvement measures

The Akusto Wall panels were mounted with Ecophon’s aluminium connect profiles. During the application of the panels (Figures 35 and 36) a gradual improvement of the acoustical conditions was observed.

Figure 35 Ecophon Akusto Wall C Akutex FT Panels

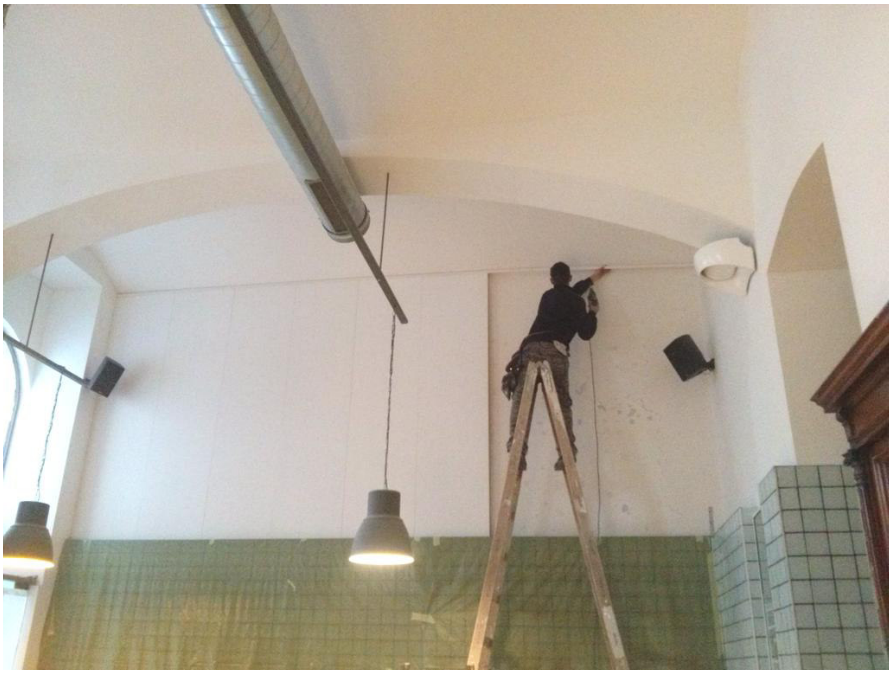


Figure 36 Installation process

2.5.4 Reverberation time measurements

After the reconstruction and the opening of the restaurant in December 2015, reverberation times were measured one more time according to ÖNORM EN ISO 3382-2 (Figure 37). Loudspeakers and microphones were placed the same way as during the first measurements. It should be noted that this time the restaurant was fully furnished, which was assumed to have an impact on the scattering of the rays. After comparing the measured and simulated values, the scattering coefficients of the floors in the bar area and the dining area were changed from the default value of 0.05 to 0.3. Since these alterations did not have a significant impact on the simulations, these adaptations were not included into further discussions. Another difference presented also the wooden swinging door, which was loosely mounted at the entrance of the kitchen in contrast to the open passage from the state before the refurbishment.

As expected the measured RTs were drastically lowered. Especially at high frequencies the target value of 1 s (upper limit) was largely achieved. All evaluated results were compared and are presented in the following section.

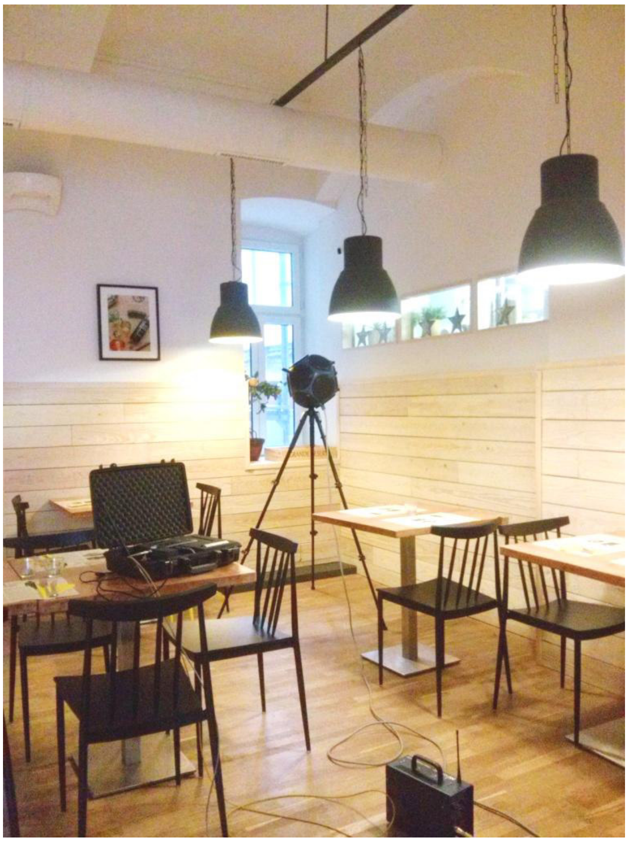


Figure 37 Measurements in the dining area

3 RESULTS

In this section the most significant results of this study are presented. Firstly, the state before reconstruction was analysed for the three rooms. The graphs present the measured values, the simulated, non-calibrated and calibrated RTs. Absolute RT values and relative deviations of the simulated values in comparison to the measured RTs are presented in tables. The graphs for the state after the refurbishment show the simulated values based on the non-calibrated and calibrated model, by contrast with the posterior RT measurements. The third overview compares the measured RTs before and after the reconstruction in order to depict the actual acoustical improvement. Furthermore the divergences of the measured values and the target RTs are shown. The evaluation of the data is presented in the chapter Discussion.

3.1 Measured and simulated reverberation times before reconstruction

Figures 38, 39 and 40 show the measured RTs in the three areas prior to the reconstruction versus simulated, non-calibrated values and the different calibration steps. After the third calibration no further improvements could be achieved. Table 14 presents the corresponding absolute values. Deviations of each calibration step regarding the measured values are shown in Table 15.

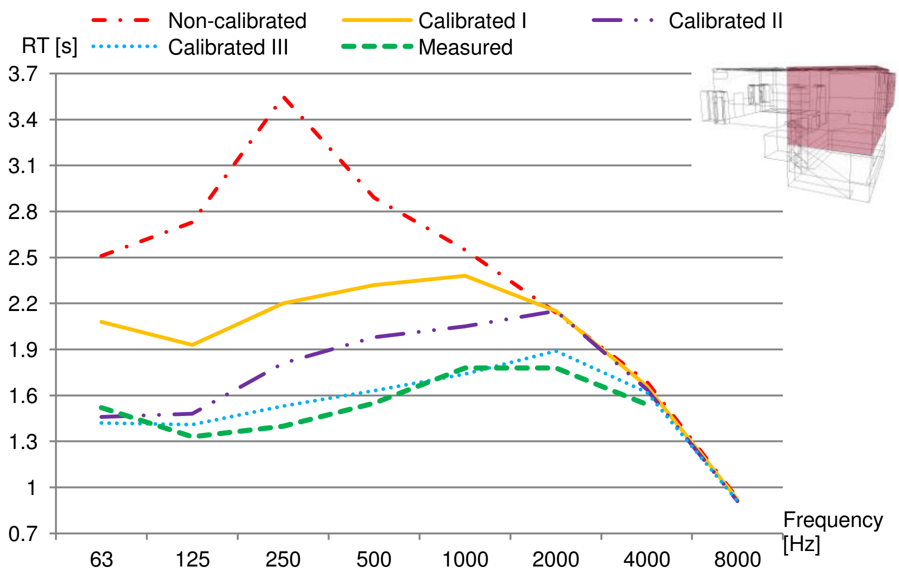


Figure 38 Measured and simulated (non-calibrated and calibrated) reverberation times in the bar area (before reconstruction)

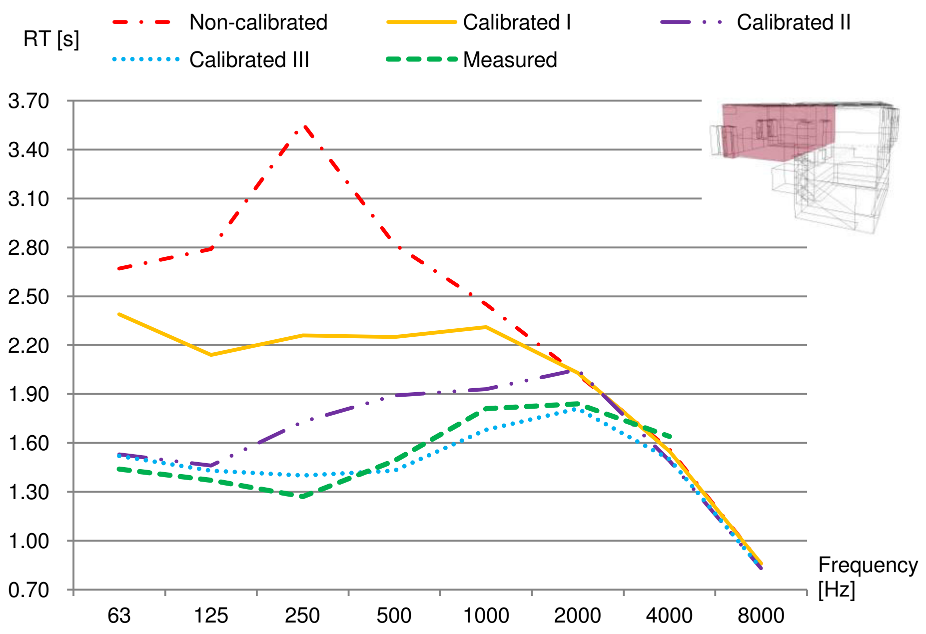


Figure 39 Measured and simulated (non-calibrated and calibrated) reverberation times in the dining area (before reconstruction)

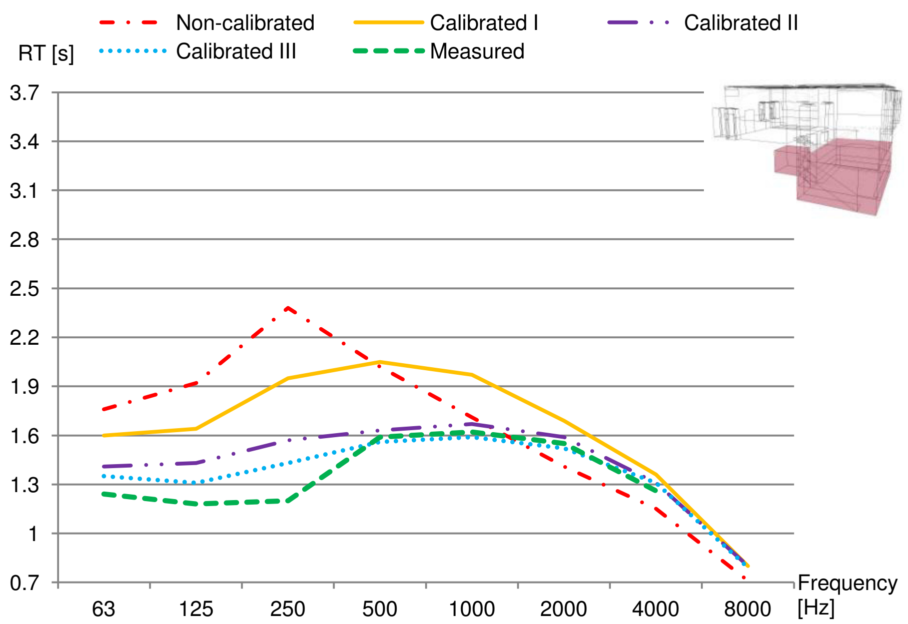


Figure 40 Measured and simulated (non-calibrated and calibrated) reverberation times in the basement area (before reconstruction)

Table 14 Measured and simulated reverberation times - absolute values [s] – before reconstruction

			Frequency [Hz]							
			63	125	250	500	1000	2000	4000	8000
Before Reconstruction	Bar area	Measured	1.52	1.33	1.4	1.55	1.78	1.78	1.54	
		Non-calibrated	2.51	2.73	3.55	2.89	2.55	2.14	1.69	0.93
		Calibrated I	2.08	1.93	2.2	2.32	2.38	2.15	1.66	0.92
		Calibrated II	1.46	1.48	1.81	1.98	2.05	2.15	1.64	0.91
		Calibrated III	1.42	1.41	1.53	1.63	1.74	1.89	1.62	0.91
	Dining area	Measured	1.44	1.37	1.27	1.49	1.81	1.84	1.64	
		Non-calibrated	2.67	2.79	3.56	2.82	2.45	2.02	1.56	0.86
		Calibrated I	2.39	2.14	2.26	2.25	2.31	2.03	1.55	0.86
		Calibrated II	1.53	1.46	1.73	1.89	1.93	2.05	1.49	0.83
		Calibrated III	1.52	1.43	1.4	1.43	1.68	1.81	1.5	0.83
	Basement area	Measured	1.24	1.18	1.2	1.59	1.62	1.55	1.26	
		Non-calibrated	1.76	1.92	2.38	2.02	1.71	1.41	1.15	0.71
		Calibrated I	1.6	1.64	1.95	2.05	1.97	1.69	1.36	0.8
		Calibrated II	1.41	1.43	1.57	1.63	1.67	1.59	1.31	0.8
		Calibrated III	1.35	1.31	1.43	1.56	1.59	1.52	1.31	0.79

Table 15 Relative deviations of simulations regarding the measurements – before reconstruction

			Frequency [Hz]							
			63	125	250	500	1000	2000	4000	8000
Before Reconstruction	Bar area	Non-calibrated	65%	105%	154%	86%	43%	20%	10%	-
		Calibrated I	37%	45%	57%	50%	34%	21%	8%	-
		Calibrated II	-4%	11%	29%	28%	15%	21%	6%	-
		Calibrated III	-7%	6%	9%	5%	-2%	6%	5%	-
	Dining area	Non-calibrated	85%	104%	180%	89%	35%	10%	-5%	-
		Calibrated I	66%	56%	78%	51%	28%	10%	-5%	-
		Calibrated II	6%	7%	36%	27%	7%	11%	-9%	-
		Calibrated III	6%	4%	10%	-4%	-7%	-2%	-9%	-
	Basement area	Non-calibrated	42%	63%	98%	27%	6%	-9%	-9%	-
		Calibrated I	29%	39%	63%	29%	22%	9%	8%	-
		Calibrated II	14%	21%	31%	3%	3%	3%	4%	-
		Calibrated III	9%	11%	19%	-2%	-2%	-2%	4%	-

3.2 Measured and simulated reverberation times after reconstruction

Figures 41, 42 and 43 show the measured RTs in the three areas after the reconstruction in comparison to the results of the calibrated and non-calibrated models. Absolute values are listed in Table 16. Relative deviations of the simulated values regarding the posterior measurements are presented in Table 17.

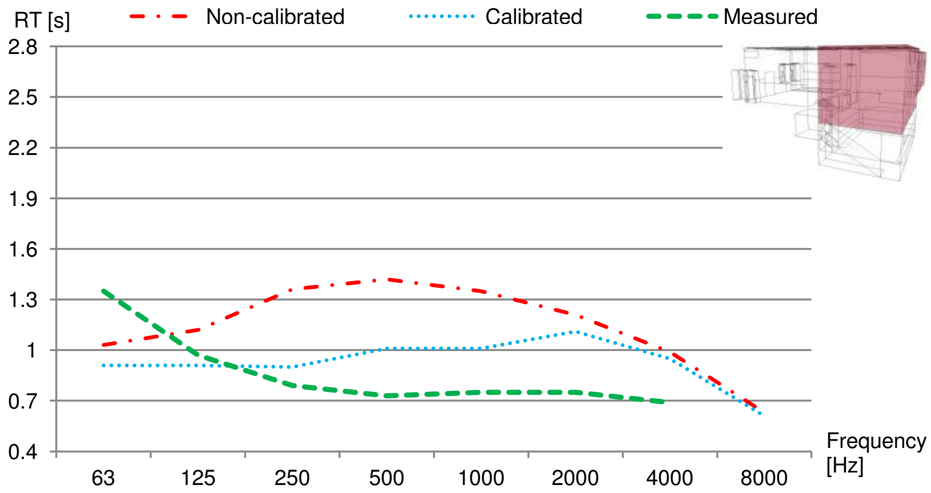


Figure 41 Measured and simulated (non-calibrated and calibrated) reverberation times in the bar area (after reconstruction)

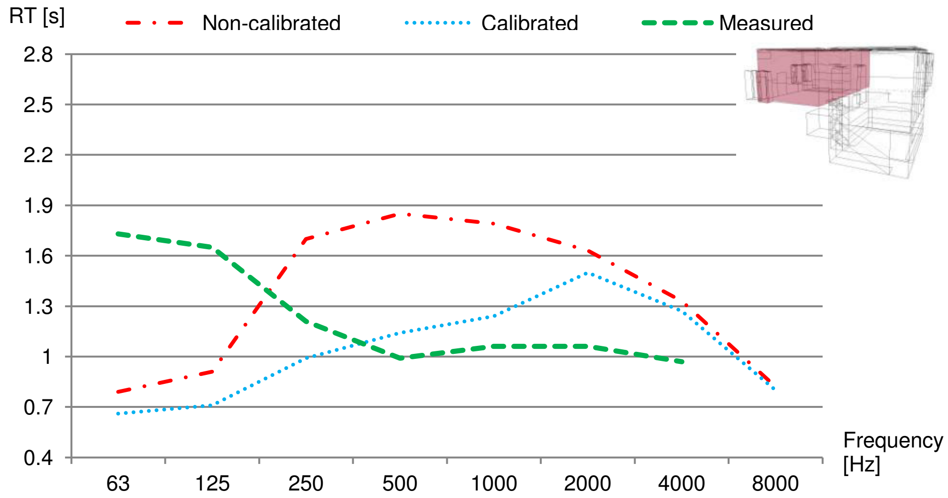


Figure 42 Measured and simulated (non-calibrated and calibrated) reverberation times in the dining area (after reconstruction)

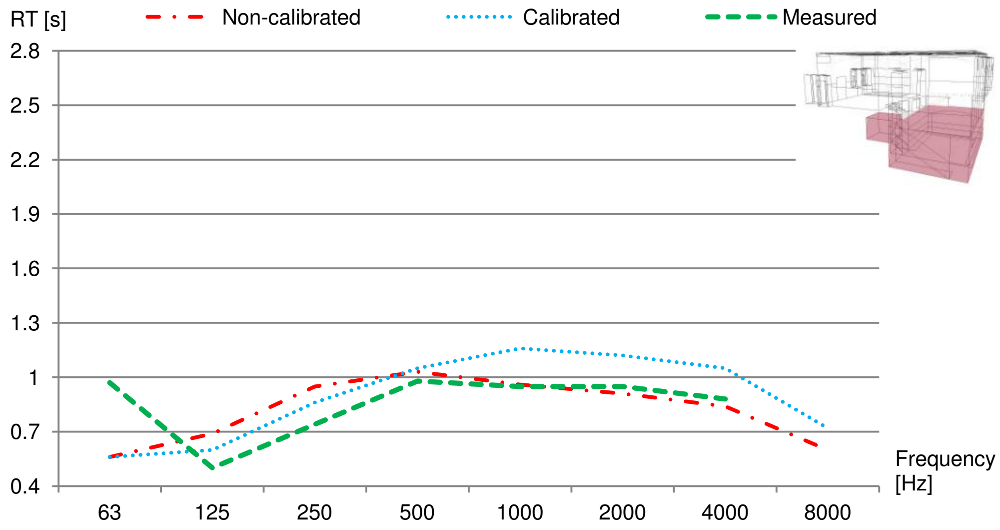


Figure 43 Measured and simulated (non-calibrated and calibrated) reverberation times in the basement area (after reconstruction)

Table 16 Measured and simulated reverberation times - absolute values [s] – after reconstruction

			Frequency [Hz]							
			63	125	250	500	1000	2000	4000	8000
After Reconstruction	Bar area	Measured	1.35	0.97	0.79	0.73	0.75	0.75	0.69	-
		Non-Calibrated	1.03	1.12	1.36	1.42	1.35	1.21	0.99	0.63
		Calibrated	0.91	0.91	0.9	1.01	1.01	1.11	0.95	0.61
	Dining area	Measured	1.73	1.65	1.21	0.99	1.06	1.06	0.97	-
		Non-Calibrated	0.79	0.91	1.7	1.85	1.79	1.63	1.33	0.82
		Calibrated	0.66	0.71	0.99	1.14	1.24	1.5	1.27	0.8
	Basement area	Measured	0.97	0.5	0.74	0.98	0.95	0.95	0.88	-
		Non-Calibrated	0.56	0.69	0.95	1.03	0.96	0.91	0.84	0.6
		Calibrated	0.56	0.6	0.86	1.05	1.16	1.12	1.05	0.72

Table 17 Relative deviations of simulation steps regarding the measurements – after reconstruction

			Frequency [Hz]							
			63	125	250	500	1000	2000	4000	8000
After Reconstruction	Bar area	Non-Calibrated	-24%	15%	72%	95%	80%	61%	43%	-
		Calibrated	-33%	-6%	14%	38%	35%	48%	38%	-
	Dining area	Non-Calibrated	-54%	-45%	40%	87%	69%	54%	37%	-
		Calibrated	-62%	-57%	-18%	15%	17%	42%	31%	-
	Basement area	Non-Calibrated	-42%	38%	28%	5%	1%	-4%	-5%	-
		Calibrated	-42%	20%	16%	7%	22%	18%	19%	-

3.3 Measured reverberation times before and after reconstruction

The actual acoustical improvement can be deduced from the comparison of the measured RT values before and after the refurbishment, as shown in Figure 44-46 and Table 18. The relative deviations of the newly measured values in comparison to the maximum target RT of 1 s are presented in Table 19.

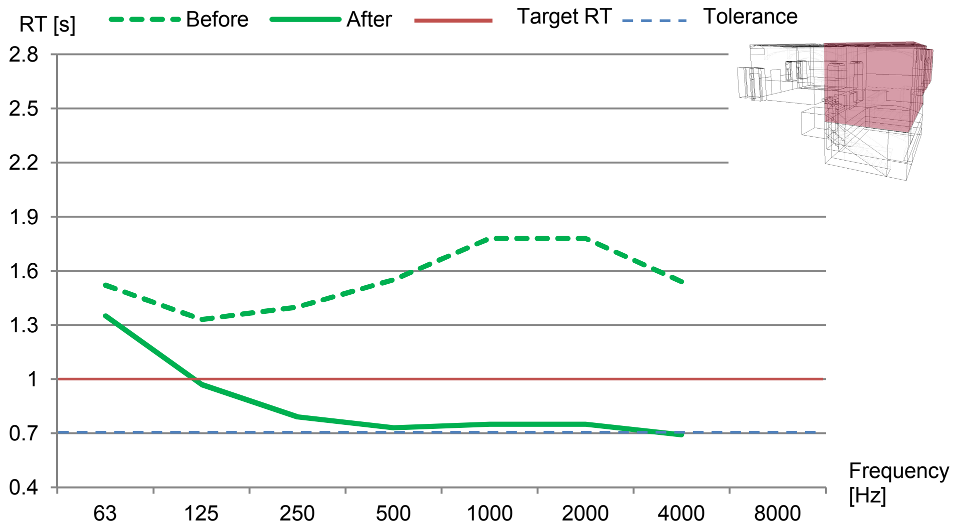


Figure 44 Measured reverberation times in the bar area (before and after reconstruction)

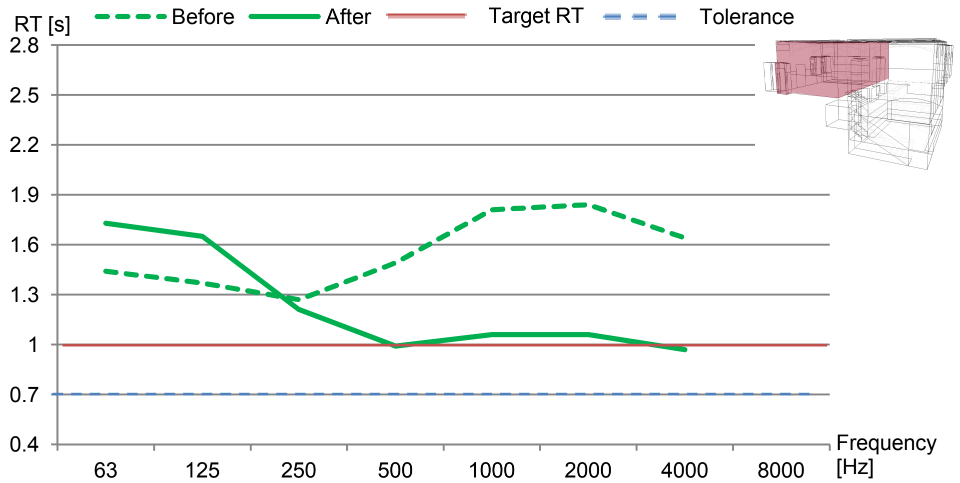


Figure 45 Measured reverberation times in the dining area (before and after reconstruction)

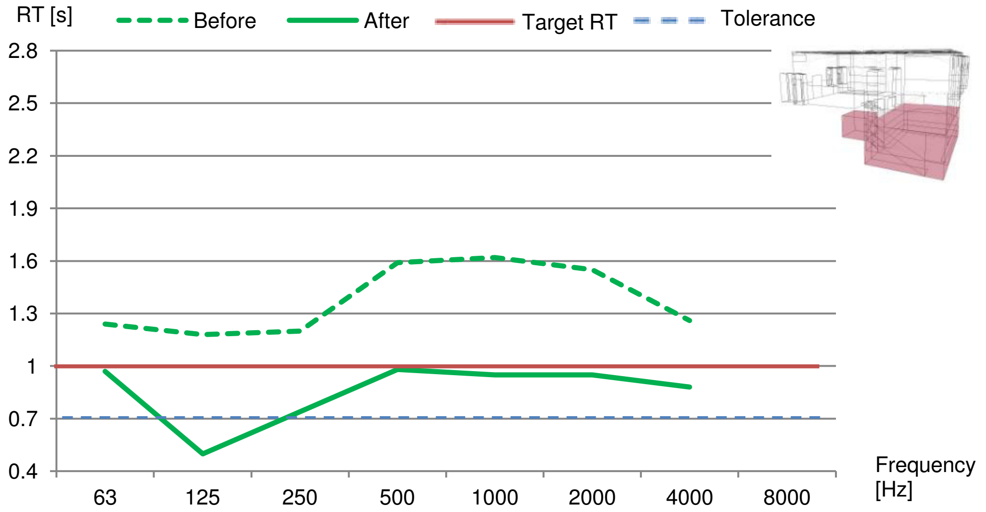


Figure 46 Measured reverberation times in the basement area (before and after reconstruction)

Table 18 Measured RTs before and after reconstruction - absolute values [s]

		Frequency [Hz]							
		63	125	250	500	1000	2000	4000	8000
Bar area	Before	1.52	1.33	1.4	1.55	1.78	1.78	1.54	-
	After	1.35	0.97	0.79	0.73	0.75	0.75	0.69	-
Dining area	Before	1.44	1.37	1.27	1.49	1.81	1.84	1.64	-
	After	1.73	1.65	1.21	0.99	1.06	1.06	0.97	-
Basement area	Before	1.24	1.18	1.2	1.59	1.62	1.55	1.26	-
	After	0.97	0.5	0.74	0.98	0.95	0.95	0.88	-

Table 19 Relative deviations of measured RTs after reconstruction to target RT = 1s

	Frequency [Hz]							
	63	125	250	500	1000	2000	4000	8000
Bar area	35%	-3%	-21%	-27%	-25%	-25%	-31%	-
Dining area	73%	65%	21%	-1%	6%	6%	-3%	-
Basement area	-3%	-50%	-26%	-2%	-5%	-5%	-12%	-

4 DISCUSSION

4.1 Effectiveness of the simulations and calibrations

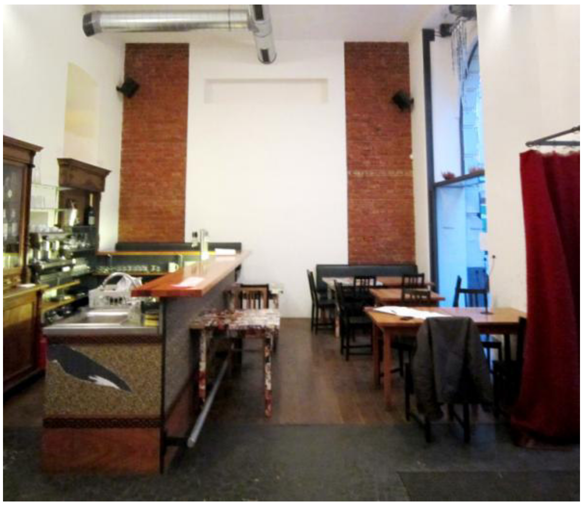
The non-calibrated simulation model of the un-refurbished rooms showed major deviations when compared to the values from the in-situ measurements (Figures 38-40, Tables 14-15). Measured RTs had their peaks at mid-high frequencies (1000, 2000 Hz), whereas the curve of simulated values starts with large deviations already at low frequencies, reaching its peak at 250 Hz. As observed in the aforementioned round robins (Bork 2000, Bork 2005a, Bork 2005b), these errors occurred most likely due to uncertainties related to the absorption coefficients of the existing materials. Since it was not possible to measure their absorption properties on-site, materials were applied according to ODEON’s material library, further literature research and personal assumptions. Discordance can also be rooted in the approach of dealing with the geometry. The 3D model was created as a hermetically closed coupled room.

The calibration process as described in chapter 2.3.3 led to a significant improvement of the model. After three iterations the final simulation results were close to the measured values. The plastered brick walls, for instance, were characterised by a rougher structure than primarily assumed, which is why the absorption factors were slightly raised. Because of these minimal alterations it was possible to significantly reduce the deviations. Furthermore, construction types such as the double glazed windows or the wooden floor with an empty cavity act like vibrating panels. This way they absorb better at low-mid frequencies and could contribute to reduce the RTs at that range.

The simulations of the refurbishment were run based on the non-calibrated and the calibrated model (Figures 41-43, Tables 16-17). The deviations from the measured values were generally not as high as the pre-refurbishment divergences. A reason for the overall better accuracy of the simulation results is the more reliable information on the implemented Akusto Wall absorbing properties. But also in this case the results of the simulation using the calibrated model corresponded more closely with the measurements. Particularly values for low frequencies showed some divergences, probably due to inadequate (to high) setting for the low frequencies absorption coefficients. Again it can be concluded that the deviations of the non-calibrated model occurred due to absorption properties uncertainties.

The final measurements were conducted in the fully furnished restaurant. Therefore, an additional test was made by changing scattering factors, in order to examine the impact of different scattering coefficients on the simulation values. The alteration of the scattering coefficient for the floors in the bar and dining area did not show significant impact on the values and were therefore neglected.

In both simulation cases – pre- and post- refurbishment - the uncertainties regarding absorption had a significant impact on the simulated values. It shall be noted that the latest version of ODEON (v.13) released in 2015 already includes a material optimization tool, which allows the user to calibrate the model directly in ODEON (ODEON 13 Manual 2015). The unreliability of results depends also on the skills of the person executing the simulations.



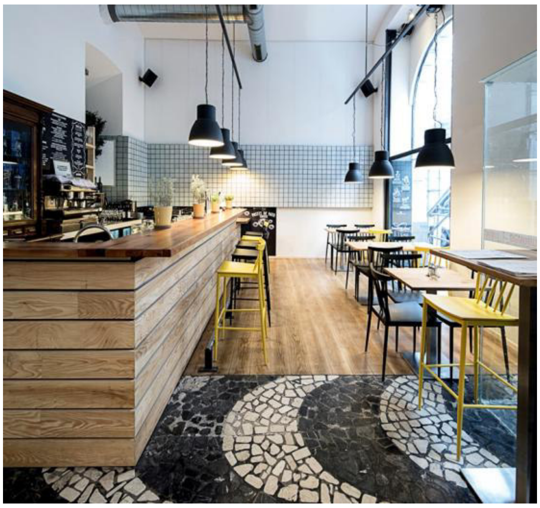


Figure 47 Bar area before reconstruction (PORTfoods GmbH 2015)

Figure 48 Bar area after reconstruction. Absorbers seen on the back (PORTfoods GmbH 2015)

4.2 Effectiveness of the acoustical improvement measure

The acoustical performance of the room was clearly improved by the refurbishment. Both the additional absorption materials as well as the design elements introduced by the architects led to this improvement. Even though the planned intervention was limited only to the bar area, significant improvement of the acoustical comfort was also observed in the other two rooms (Figures 44-46, Table 18). The intended RT of 0.7-1 s was achieved in the majority of cases. RT values of the bar area and the basement area are almost completely within this range. The exceptions are the RT value for 63 Hz in the bar area and the value for 125 Hz in the basement area. Although the acoustical conditions in the dining area improved, the RT values were still surpassing the 1 s benchmark.

Additionally personal observations and customer feedback confirmed the findings: the bar area is preferred over the dining area as the costumers favour the acoustical comfort in this part of the restaurant.

5 CONCLUSION

The present study investigated the acoustical performance of the refurbishment of a restaurant using measurements and simulation. In this case study the criterion for acoustical quality was the reverberation time. The compared values regarding simulation and measurements showed major deviations which were mainly caused by the lack of information on absorption properties of the used materials. Through several calibration steps, satisfying values were obtained. Small adjustments resulted in a significant improvement of the simulated values. The first simulation model and the calibrated model were then used in order to evaluate improvement measurements along with the refurbishment of the restaurant. Predictions for the acoustical improvement which were based on the calibrated model showed more accurate values than the ones based on the non-calibrated simulation model when compared to the measurements. As a result it has been observed, that the information regarding the used materials and surfaces is crucial for the model quality and that a more comprehensive database on material properties is needed to deliver more accurate results. When comparing the acoustical performance of the restaurant before and after the refurbishment with regard to the measured data, the suggested modification led to significantly improved results. Overall it has to be noted that with sufficient calibration and reliable model input information acoustic simulation is a powerful tool for the evaluation and prediction of room acoustics. As ODEON now has improved its material database and also implemented an option for calibration, it would be very interesting to test this feature in future case studies on the topic. Furthermore such a study should also look at additional room acoustical parameters.

6 INDEX

6.1 List of figures

6.2 List of tables

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7 LITERATURE

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8 APPENDIX

A. TABLES

Materials used for the 3D model – before reconstruction

Material list for simulation (non-calibrated) - before reconstruction			Absorption Coefficient α										
Number	Layer	Material name	63	125	250	500	1000	2000	4000	8000	αw	m²	Source
3002	Floor - Wood	Wood parquet in asphalt on concrete	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07	0.06	64	Odeon
11200	Floor - Stone	Rough stone floor - Sandstone	0.01	0.02	0.02	0.03	0.04	0.05	0.05	0.06	0.04	58	schweizer-fn.de
10006	Glass - Windows	Glass, ordinary window glass	0.35	0.35	0.25	0.18	0.12	0.07	0.04	0.04	0.18	23	Odeon
10001	Glass - Other	Single pane of glass	0.18	0.18	0.06	0.04	0.03	0.02	0.02	0.02	0.07	9	Odeon
10007	Wood - Other	Solid wooden door	0.14	0.14	0.1	0.06	0.08	0.1	0.1	0.1	0.10	19	Odeon
4000	Plastered brickwork	Lime cement plaster	0.02	0.02	0.02	0.03	0.04	0.05	0.05	0.05	0.04	457	Odeon
18000	Metal	Metall	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.01	12	Assumpton
1003	Exposed brickwork	Brick, unglazed, painted	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.03	0.02	38	Odeon
19000	Other reflective *	Other	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07	0.06	15	Assumpton
20000	Doors	Doors	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07	0.06	3	Assumpton

Changes in first calibration - before reconstruction			Absorption Coefficient α										
Number	Layer	Material name	63	125	250	500	1000	2000	4000	8000	αw	m²	Source
3005	Floor - Wood	Wood mounted on counterfloor	0.2	0.2	0.15	0.1	0.1	0.05	0.1	0.1	0.13	30	Odeon
5000	Plastered brickwork	Lime cement plaster - modified	0.02	0.03	0.04	0.04	0.04	0.05	0.05	0.05	0.04	457	Assumpton
21000	Metal grille	Metal grille	0.6	0.5	0.5	0.4	0.3	0.3	0.3	0.2	0.2	7	Assumpton

Changes in second calibration - before reconstruction			Absorption Coefficient α										
Number	Layer	Material name	63	125	250	500	1000	2000	4000	8000	αw	m²	Source
3005	Floor - Wood	Woood mounted on counterfloor	0.2	0.2	0.15	0.1	0.1	0.05	0.1	0.1	0.13	34	Odeon
5000	Plastered brickwork	Lime cement plaster - modified	0.025	0.035	0.045	0.05	0.05	0.05	0.05	0.05	0.04	457	Assumpton

Changes in third calibration - before reconstruction			Absorption Coefficient α										
Number	Layer	Material name	63	125	250	500	1000	2000	4000	8000	αw	m²	Source
3010	Floor - Wood	Woood mounted on counterfloor - modified	0.2	0.2	0.25	0.25	0.2	0.1	0.1	0.1	0.18	64	Assumpton
5000	Plastered brickwork	Lime cement plaster - modified	0.025	0.035	0.045	0.05	0.05	0.05	0.05	0.05	0.04	457	Assumpton
11307	Floor - Stone	Rough stone floor - Sandstone	0.02	0.05	0.05	0.04	0.05	0.05	0.05	0.05	0.05	58	Assumpton
10017	Glass - Windows	Glass, ordinary window glass	0.35	0.35	0.25	0.18	0.16	0.1	0.04	0.04	0.18	23	Assumpton

Materials used for the 3D model – after reconstruction

Material list for simulation (non-calibrated) - after reconstruction			Absorption Coefficient α										
Number	Layer	Material name	63	125	250	500	1000	2000	4000	8000	αw	m²	Source
1150	Absorber	Akusto Wall Akutex FT	0.25	0.25	0.8	0.95	1	1	1	1.00	0.78	26	Ecophon
3002	Floor - Wood	Wood parquet in asphalt on concrete	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07	0.06	64	Odeon
11200	Floor - Stone	Rough stone floor - Sandstone	0.01	0.02	0.02	0.03	0.04	0.05	0.05	0.06	0.04	58	schweizer-fn.de
4042	Fibre cement panels	Plasterboard on frame, 13 mm boards, 100 mm empty cavity	0.08	0.08	0.11	0.05	0.03	0.02	0.03	0.03	0.05	16	Odeon
10006	Glass - Windows	Glass, ordinary window glass	0.35	0.35	0.25	0.18	0.12	0.07	0.04	0.04	0.18	23	Odeon
10001	Glass - Other	Single pane of glass	0.18	0.18	0.06	0.04	0.03	0.02	0.02	0.02	0.07	8	Odeon
3063	Wood - Pine cladding	Thin plywood paneling	0.42	0.42	0.21	0.1	0.08	0.06	0.06	0.06	0.18	80	Odeon
10007	Wood - Other	Solid wooden door	0.14	0.14	0.1	0.06	0.08	0.1	0.1	0.1	0.10	27	Odeon
2001	Ceramic Tiles	Marble or glazed tile	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.01	20	Odeon
11400	Leather	Leather	0.37	0.4	0.5	0.58	0.61	0.58	0.5	0.47	0.50	6	acoustic.ua
4000	Plastered brickwork	Lime cement plaster	0.02	0.02	0.02	0.03	0.04	0.05	0.05	0.05	0.04	370	Odeon
18000	Metal	Metal	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.01	12	Assumpton
17000	Rigips plasterboard	Rigips 12.5 mm, wall distance 100 mm	0.5	0.5	0.12	0.06	0.04	0.07	0.1	0.1	0.19	5	schweizer-fn.de
19000	Other reflective	Other	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07	0.06	15	Assumpton
20000	Doors	Doors	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07	0.06	3	Assumpton
11600	Curtain	Heavy Curtain	0.15	0.15	0.45	0.96	0.91	1	1	1	0.70	2	Odeon

Material list for simulation (calibrated) – after reconstruction			Absorption Coefficient α										
Number	Layer	Material name	63	125	250	500	1000	2000	4000	8000	αw	m²	Source
1150	Absorber	Akusto Wall Akutex FT	0.25	0.25	0.8	0.95	1	1	1	1.00	0.78	26	Ecophon
3002	Floor - Wood	Wood mounted on counterfloor	0.2	0.2	0.15	0.1	0.1	0.05	0.1	0.1	0.13	64	Assumpton
11200	Floor - Stone	Rough stone floor - Sandstone	0.02	0.05	0.05	0.04	0.05	0.05	0.05	0.05	0.05	58	Assumpton
4042	Fibre cement panels	Plasterboard on frame, 13 mm boards, 100 mm empty cavity	0.08	0.08	0.11	0.05	0.03	0.02	0.03	0.03	0.05	16	Odeon
10006	Glass - Windows	Glass, ordinary window glass	0.35	0.35	0.25	0.18	0.16	0.1	0.04	0.04	0.18	23	Assumpton
10001	Glass - Other	Single pane of glass	0.18	0.18	0.06	0.04	0.03	0.02	0.02	0.02	0.07	8	Odeon
3063	Wood - Pine cladding	Thin plywood paneling	0.42	0.42	0.21	0.1	0.08	0.06	0.06	0.06	0.18	80	Odeon
10007	Wood - Other	Solid wooden door	0.14	0.14	0.1	0.06	0.08	0.1	0.1	0.1	0.10	27	Odeon
2001	Ceramic tiles on Rigips	Plasterboard on frame, 13 mm boards, 100 mm empty cavity	0.08	0.08	0.11	0.05	0.03	0.02	0.03	0.03	0.05	20	Odeon
11400	Leather	Leather	0.37	0.4	0.5	0.58	0.61	0.58	0.5	0.47	0.50	6	acoustic.ua
4000	Plastered brickwork	Lime cement plaster	0.025	0.035	0.045	0.05	0.05	0.05	0.05	0.05	0.04	370	Assumption
18000	Metal	Metal	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.01	12	Assumpton
21000	Metal grille	Metal grille	0.6	0.5	0.5	0.4	0.3	0.3	0.3	0.2	0.2	7	Assumpton
17000	Rigips plasterboard	Rigips 12.5 mm, wall distance 100 mm	0.5	0.5	0.12	0.06	0.04	0.07	0.1	0.1	0.19	5	schweizer-fn.de
19000	Other reflective	Other	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07	0.06	15	Assumpton
20000	Doors	Doors	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07	0.06	3	Assumpton
11600	Curtain	Heavy Curtain	0.15	0.15	0.45	0.96	0.91	1	1	1	0.70	2	Odeon

B. Documents

Ecophon - Akusto Wall C Product Info

Ecophon Akusto™ Wall C

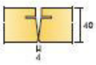
For use as wall absorbers together with a sound absorbing ceiling, to achieve excellent acoustic properties in the room. Ecophon Akusto™ Wall C has a concealed grid and the bevelled edges create a narrow groove between each panel. The system provides extensive design possibilities.

The system consists of Ecophon Akusto™ Wall C panels and Ecophon Connect profile systems with an approximate weight of 5 kg/m². The panels are manufactured from high density, 3rd generation glass wool. The visible surface has a glass fibre fabric (Texona) or an impact resistant glass fibre fabric (Super G), and is also available with a painted surface (Akutex™ FT). The back of the panel is covered with glass tissue. The edges are painted, and the front surface is partly covering the long edges. The Texona gamma version offers a reflecting surface, see absorption diagram.

For best performance and system quality, use Ecophon Connect profiles and accessories, which gives a lot of design possibilities. The profiles are manufactured from extruded aluminium.

Kliniken Maria Hill, Mönchengladbach, Germany

SYSTEM RANGE

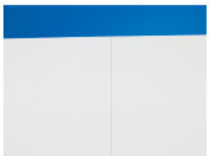


Size, mm	2700x600
Thinline Profile	•
WP Profile	•
Thickness	40
Inst. Diagr.	M354, M356, M355, M235, M303

Ecophon Akusto™ Wall C, Created: 2016-05-06

Ecophon - Akusto Wall C Product Info


Akusto Wall C

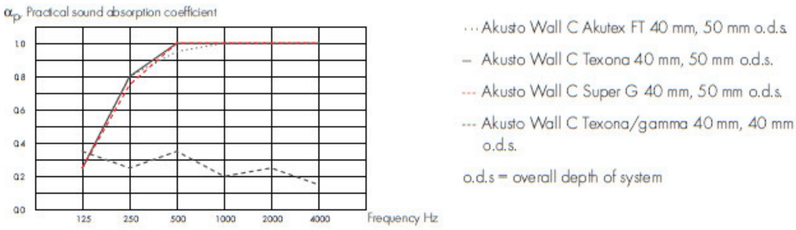

Section of Akusto Wall C System


Akusto Wall C system with Connect WP profile and external corner


Akusto Wall system with Connect Thinline profiles

Acoustic

Sound Absorption:
Test results according to EN ISO 354. Classification according to EN ISO 11654, and the single value ratings for Noise Reduction Coefficient, NRC and Sound Absorption Average, SAA according to ASTM C 423.



	THK mm	o.d.s. mm	α_p, Practical sound absorption coefficient						α_w	Sound absorption class
			125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz		
Akutex FT	40	50	0.25	0.80	0.95	1.00	1.00	1.00	1.00	A
Texona	40	50	0.25	0.80	1.00	1.00	1.00	1.00	1.00	A
Super G	40	50	0.25	0.75	1.00	1.00	1.00	1.00	1.00	A
Texona gamma	40	40	0.35	0.25	0.35	0.20	0.25	0.15	0.25	E

THK mm	AC(1.5) Articulation Class, ASTM E1111, ASTM E1110
40	240

Accessibility

The tiles are not demountable except in selected installation diagrams. See quantity specification for more information.

Cleanability

Daily dusting, vacuum cleaning and weekly wet wiping (Super G and Akutex FT surface). Weekly dusting and vacuum cleaning (Texona) as required.

Visual appearance

Akusto Wall in white has high light reflectance. Light reflectance and nearest NCS colour sample for all the different colours: See Ecophon Colours and surfaces.

Ecophon - Akusto Wall C Product Info

Influence of climate

The panels withstand a permanent ambient RH up to 95% at 30° C (Super G and Akutex FT surfaces) and RH up to 75% at 30° C (Texona) without sagging, warping or delaminating (EN 13964). Thermal resistance for the panels, Rp=1,0 m²° C/W. Since a wall absorber mounted on an external wall serves as additional insulation, the need for a vapour barrier should be investigated.

The tiles are also available for especially demanding hot and humid conditions. Please contact Ecophon for specifying your project.

Indoor Climate

Certificate / Label	
Finish M1	•
French VOC, A	•
Swedish Asthma and Allergy Association	•
Danish Indoor Climate Label	•

Environmental influence

Fully recyclable

Fire safety

Country	Standard	Class
Europe	EN 13501-1	A2-s1,d0

The glass wool core of the tiles is tested and classified as non-combustible according to EN ISO 1182.

Mechanical properties

M354 and M355 with Super G surface are tested according to EN 13964 annex D and DIN 18032 part 3 and fulfils the demands corresponding to class 1A. Please note: Where the panels are subjected to frequent blows and impacts e.g. behind goal mouths, protection in form of e.g restraining nets or wooden slats is required. No additional live load is allowed.

Installation

Installed according to installation diagrams, installation guides and drawing aid. For information regarding minimum overall depth of system see quantity specification. The systems should not be placed behind goals or similar areas where they are likely to be hit regularly. In such cases a protective net in front of the system is recommended.