SOUND WORKING ENVIRONMENTS

Optimizing the acoustic properties of open plan workspaces using parametric models

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PREFACE

Before you lies the final report; the result of my graduation project in the track of Building Technology at the Faculty of Architecture and the Built Environment, Delft University of Technology. This research project, dubbed *'Sound working environments'* brings together the topics of architectural acoustics, parametric modelling and optimization. Not only does the combination of these themes pose an interesting intellectual challenge, this study allowed for my freedom to operate on a strong personal belief that architecture, building design and related research – even technology in general – should seek to resolve issues relevant to everyday reality. The proposal of scientifically substantiated solutions challenging current building design practice is actively encouraged within this graduation studio. See this as my attempt at doing just that.

First of all, I would like to thank Arend van Waart for lending his coding skills to this project. As he coded a script paramount to the success of this project, it is safe to say that many of the results could not have been attained without his help. Also a thank you to my mentors Martin Tenpierik, Michela Turrin and Andy van den Dobbelsteen, for their knowledge and encouragement; and to everyone else I consulted, interviewed or involved in any other way in the process. Furthermore a big shout out to my friends, family, and colleagues from @Hok and the department of Design Informatics. And last but certainly not least, I especially want to thank mom and dad, and my sister Rebecca for all their love and support.

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CONTENTS

SUMMARY

Problem statement

Over the last two decades, there has been an increase in Europe in modern non-territorial offices with large open work environments. Past research has shown that a large number of workers in these offices suffer from lack of privacy and from noise. Noise is identified as a root cause of these problems and often poses the most severe indoor environment problem in open offices. Optimizing the acoustic environment of an open plan office is a complex task due to the large number of design parameters that must be considered. In current practice, acoustic analysis – even in a simplified form – is not naturally integrated into the design process of office spaces. The transition between geometric modelling programs and analysis software is a time consuming affair preventing seamless and hands-on iteration of design proposals. Hence, it is difficult for design team members to evaluate the specific influences of design changes with respect to acoustic characteristics of a room.

Research method

The following research question is formulated:

- *"How can a (parametric) performance-driven design method help in improving the acoustic quality of an open plan working environment and to what extent will said improvements be noticed (and regarded positively) by office workers in terms of acoustic comfort?"*

The hypothesis is as follows:

- Performing basic acoustic analysis via a parametric model will help in reducing sound propagation between workstations in an open space. The changes brought forth by (automated) parametric search are significantly large to be noticeable.

This research was subdivided into three phases. These are:

- Data acquisition – Two distinct open workspaces serve as case studies. These are each investigated through the use of employee questionnaires and two types of acoustic measurements;
- Development phase – A ray tracing definition was developed within Rhino / Grasshopper and coupled to Octopus to optimize the acoustics of an open office environment, utilizing a 3-D model from one of the case studies. This optimization is validated by a full detailed analysis in CATT-Acoustic;
- Feedback – The results were shared with respondents previously involved in the questionnaire to assess the proposal with regards to end user perception.

Results

Though both investigated case studies rooms are very different in their workplace layout and the make-up of the research populations, the main concerns brought forth in the questionnaires show remarkable similarities. As a whole, noise caused by speech and general the behavior of colleagues, exacerbated by large crowds of people occupying the same space (and the accumulation of noise as a result of that) are viewed as a great source of nuisance for both cases. The findings from these inquiries seem to corroborate past research.

Both case studies were measured and found to underperform in terms of sound decay relative to target values recommended by the ISO/NEN 3382-3:2012 standard.

A ray tracer was initially made in Grasshopper relying on a network of default components without custom code. Though it turned out to be technically possible, such a definition is highly unpractical in use due to extremely long calculation times associated with that setup. As a result of this finding a second definition was coded and subsequently tested on several simple models. Several models were also exported to CATT-Acoustic for comparison and validation. In these tests the results given by the Grasshopper definition turned out to be accurate in most cases, deviating in its measurements from analysis in CATT-Acoustic by ≤ 1 dB (less than the just-noticeable difference for human hearing). Having validated the definition it was then used to map the solution space of a few parametric models. Here the effect of sound energy scattering was made visible.

Finally the developed script was coupled to Octopus and used to perform three multi-objective optimization runs. Results of all runs indicated that the best performing design configurations employed a combination of screens and increased wall absorption. The configurations in the final run, that had either of these objectives minimized, displayed insufficient acoustic performance.

Conclusions

During this research it was observed that the computational optimization of open office environments is possible by integrating principles of acoustic simulation in a parametric model. Said model needs further development to become a viable and accessible tool in the arsenal of an architect or building physics consultant. The developed ray tracing algorithm is a very simple implementation of acoustic analysis with parameterization capabilities and provides a basic framework that can be built further upon. A correct application and interpretation of the methods and the script require significant knowledge on the designer’s behalf concerning parametric design and acoustics.

A parametric improvement of acoustics parameters does not necessarily equate positive reviews by office workers. In a feedback session several respondents had reservations with regards to the architectural implications of an acoustic improvement proposed as a result of the optimization process.

1 INTRODUCTION

1.1 RESEARCH TOPICS

Defining acoustics

Acoustics is the science of sound. The field of architectural acoustics generally deals with sound in the built environment (Cowan, 2000, p. 3). In particular this research focuses on room acoustics of open plan offices, covering issues related to the physical propagation of sound and the way people perceive and deal with noise in their working environment. Sound is interpreted by people's brains through sense of hearing. This interpretation, which in itself is open to personal subjectivity, partially dictates the extent in which we are able to properly communicate within a space.

New Way of Working

Often cited as a driving force for the increasing prevalence of open plan offices, 'Het Nieuwe Werken' is presented as a managerial vision in which knowledge workers – enabled by recent developments in ICT – have more freedom to choose how, when and where they do their work (Bijl, 2009, p. 27). The general idea is that people will be more satisfied with their job if they can chose to work in a setting they desire, that is suitable for their current activities. An added aspect is the train of thought that the solutions they come up with will be more creative if they work together: the workplace should facilitate and encourage people to interact. As personnel is less dependent of time and place, and with the amount of people in an office workforce rapidly and constantly changing, it is deemed no longer efficient to assign every single person their own desk. Hence a work environment is needed that facilitates said change, which is why a growing amount of organizations move away from cellular offices into more flexible open and mixed variants.

Regarding the move to open planning as a purely positive development would be a gross misconception. Although effectively these types of offices are initially cheaper to make, they are also noisier. This will be further discussed in the next chapter.

Open plan offices

The open plan office is typically defined as a workplace in which multiple people who work together are located in the same indoor space. This broad term encompasses a range of varying office layouts characterized by their lack of full-height partition walls separating different work areas. Instead, work groups may be partitioned using movable screens, cabinets or other types of furniture. Categorizations have been made, for example based on the number of partitions or a measure of openness, though with each different classification made to fit the purpose of its respective study (Brennan et al., 2002, p. 280).

Present-day offices in the Netherlands commonly offer a mix of different spaces aimed at facilitating diverse activities. Besides open areas for collaboration these typically include concentration rooms, which are small enclosed spaces designed with the intention to be used by a single person to work in silence; and meeting rooms, in which a small group of people should be able to have a confidential conversation. This study primarily focuses on sound propagation in shared workspaces.

Parametric design

By the definition of Barrios (2005, p. 394) parametric design is the process of designing with parametric models or in a parametric modelling setting. Parametric modelling is the process of making a geometrical representation of a design with components and attributes that have been parameterized.

In a broad sense of the term, parameters are features or measurable factors that help in defining a system. Looking at office spaces, quantifiable properties like room dimensions, amount of objects in the room, materialization, etc. are all examples of parameters which can be included in a model. Here we consider a digital model which not only contains a geometric representation of our physical room, but also prominently describes the hierarchical relationships between relevant components and their attributes. By definition a parametric model contains elements with fixed attributes, plus elements with attributes that are subject to change (variables). Which components of a model vary and how the variation occurs is determined by parameterization. In other words, the parameterization process determines the attributes subject to parametric transformations and includes a set of rules that is followed by which said attributes may be altered (Barrios, 2005, p. 394; Turrin, 2014, p. 173). This process yields a consistent hierarchical logic defining the way solutions are created when input variables are changed. Different solutions represent design alternatives. Each alternative is called an instance; all instances together make up the solution space. Solutions will therefore be described by their common fixed features and their variable features. The numerical quantification of these variable features are referred to as the design parameters (Méndez Echenagucia, 2014, p. 20).

The creation of a large set of design configurations is a core potential of parametric modelling. As stated by Woodbury & Burrow (2006, p. 74), the ability to make rapid changes along a limited range of variation is the primary argument for parameterization. A broad range of alternative design solutions can be explored and compared using parametric models. In turn, a selection can be made based on predetermined design criteria (Turrin, 2014, p. 175), aiding the search for a definitive solution. When we use parametric models for search processes, the extents of the search space are determined parameters and domains. Parameters are typically confined to domains of variation, meaning they are only allowed to take values inside a domain defined by the designer (Méndez Echenagucia, 2014, p. 20). As a whole, parametric design encompasses the criteria by which a design is selected, the logic upon which it is generated and the definition of parameters that ultimately define and affect the outcome.

This study questions the viability and practicality of parametric modelling with respect to the definition and (re)design of the acoustic environment in open workspaces. Parametric models are made, in which a combination of geometric objects, material properties and acoustic descriptors serve as parameters.

1.2 PROBLEM STATEMENT

General issues of open plan offices

Prior research and case studies point towards an increase of user complaints with the application of open planning in their workspace. Compared to small enclosed offices people generally experience a loss of privacy and tend to be distracted more easily, in large open workspaces that they share with colleagues, making it harder for them to concentrate on the task at hand (Banbury & Berry, 2005, p. 30; Brunia et al., 2011, p. 26; Hedge, 1982, p. 521). Noise – unwanted sound propagating freely due to the openness of the space – is identified as a root cause of these problems and often poses the most severe indoor environment problem in open offices. The sound sources that are reported to generally be considered the most distracting include other people's conversations and the sound of phones left ringing (Cristensson, 2009, p. 3; Keränen et al., 2008, p. 46; Sundstrom et al., 1994, pp. 206-207); and to a lesser extent it also includes noise stemming from the use of office equipment and HVAC systems. Pinpointing any particular source of nuisance differs per case as both acoustic properties and activities will varies for each different office.

Design implications

Optimizing the acoustic environment of an open plan office is a complex task due to the number of design parameters that must be considered (Bradley, 2003, p. 23). The very concept of open office planning itself already invites some level of acoustical compromise, since the conflicting requirements of good speech communication and good speech privacy are asked to co-exist in a single physical environment (Banbury & Berry, 2005, p. 25; Rychtáriková et al., 2004, p. 6). The extent to which a good balance can actually be achieved is even questioned sharply by Nijs (2014) who rightfully points out that achieving absolute confidentiality in an open space is impossible. It is also argued that direct person-to-person speech transmission can be lowered by placing screens, the effectiveness of which increases with their size: essentially acoustic performance will improve the closer you get to a cell-type office. Altogether this poses a predicament which is deemed too complex for most architects and is thus left to specialists who get consulted in later stages of the design process. Consequently acoustics is rarely given special consideration in office design and often comes second to other climate aspects and practical design challenges. This is further aggravated by the fact that implementing good acoustics does not always align with concepts for indoor climate and architecture; as, for instance, is the case for office buildings employing thermal capacity of the structure mass to provide thermal comfort (Chigot, 2010, p. 1; Peperkamp & Bruggema, 2012, p. 539).

The relation between acoustic performance criteria and building properties is described and assessed using terms such as reverberation time, which are typically expressed in the form of mathematical equations. A point of contention can be made that most architects do not innately utilize such formulas; therefore a translation into geometric representation would be better suited for application in design practice. In other words, design team members could gain understanding for the implications of certain decisions if information on acoustic requirements is directly expressed in room shape and material properties (Bergeron-Mirsky et al., 2010, p. 130; Rychtáriková et al., 2004, p. 1). Architects lack an appropriate toolset to easily evaluate acoustic quality of their proposals in an interactive fashion. Though specialized acoustic analysis software packages do exist, these currently do not offer seamless interoperation with popular 3-D modelling programs. Their application in office design is also far from commonplace.

Human comfort and performance

Jahncke et al. (2001, p. 381), amongst others, indicate that working in a high noise environment has a significant negative impact on the general well-being and performance of employees. The alteration of workspace interior thus not only impacts sound properties of the room, but ultimately affects end user perception as well. The relation between perceived acoustic comfort and quantifiable parameters has been topic of extensive research. Upon review no simple, linear correlation is found between objective assessment methods and subjective experience of the effects of sound in office spaces (Chigot, 2005, p. 162). Attempts at predicting and classifying acoustic comfort are further complicated by the notion that people's expectations are influenced by factors like physical surroundings and location (Wilson & Nicol, 2003, p. 117). Lab studies, in which subjects are removed from their normal working environment, yield significantly different results compared to real world situations because of this.

Although financial aspects are not a main concern in the framework of this thesis, in practice it may be difficult to secure extra budget to meet a higher standard for speech privacy. For reasons stated earlier the exact costs and benefits for the needed acoustic measures cannot be accurately assessed. As Bradley (2003, p. 29) puts it, the main argument favoring open plan offices is the expected reduced cost relative to closed offices. These savings are however offset in the long run by the costs of decreased performance by distracted workers; and that at least points to the need for good acoustical design.

Problem statement

In current practice, acoustic analysis – even in a simplified form – is not naturally integral to the design process of office spaces. The transition between geometric modelling programs and analysis software is a time consuming affair preventing seamless and hands-on iteration of design proposals. Hence, it is difficult for design team members to evaluate the specific influences of design changes with respect to acoustic characteristics of a room. End user response also cannot be accurately predicted.

2 RESEARCH QUESTION

Research question

“How can a (parametric) performance-driven design method help in improving the acoustic quality of an open plan working environment and to what extent will said improvements be noticed (and regarded positively) by office workers in terms of acoustic comfort?”

The main research question is subdivided into three general topics that will be subsequently dealt with in this study. This is further outlined in *chapter 3 Research method*. The following sub-questions are formulated:

- How do people generally experience acoustics in their workspace?
- How can parametric optimization be implemented in room acoustics design?
- Will the results of said design method have significance for the end user?

Goal

The goal of this study is to determine whether parametric modelling techniques can provide a valid design tool to aid in testing and improving acoustic performance of open plan workspaces. For the most part investigation will be aimed at figuring out the setup of a parametric model that produces meaningful results. The outcomes are considered significant when geometric alteration within the model is linked to a change in acoustic terms large enough to be noticed by a person (when the so called ‘just-noticeable difference’ for L_p ± 1 dB is exceeded).

Hypothesis

The underlying idea of this research is based on two assumptions. First is the notion that knowledge on room acoustics, relevant to the design process, can be made more accessible to design professionals if it is visualized directly in an architectural 3-D model. Second, it is presumed that acoustic design guidelines are too generalized to account for the intricacies of a specific project. This calls for the development of an acoustic analysis definition which is easy to use and can be rapidly implemented in the design workflow. This leads to the following hypothesis:

Performing basic acoustic analysis via a parametric model will help in reducing sound propagation between workstations in an open space. The changes brought forth by (automated) parametric search are significantly large to be noticeable.

Research limitations

Primarily this research focuses on the physical adaptation of the building interior, be it in a computer simulation. Even though organization structure, management and study of human behavior all play a part in the described issue, these subjects are outside the scope of this project. It also needs to be clarified that this study does not aim to financially quantify improvement in productivity or reduction of absenteeism as a result of improving the acoustic properties of an office.

3 RESEARCH METHOD

This chapter outlines methods and reasoning applied throughout the research process beyond literature review. Matching the sub-questions defined in the previous chapter, the complete study is categorized in three phases, which are described below. Two existing open plan workspaces have been selected to serve as case studies. Specific details for these buildings are given in *chapter 4 Case studies*.

3.1 PHASE 1: DATA ACQUISITION

- How do people generally experience acoustics in their workspace?

The first phase centers around identifying problems people experience with respect to sound in their workplace. In both case study buildings a survey was performed in conjunction with acoustic measurements. By means of questionnaires employees and students were asked to give their opinion on noise in their respective workplaces. The findings from these questionnaires are cross-referenced with the measurements, in order to pinpoint sound sources which are perceived as a nuisance. This also provides an indication as to whether the issues in these particular cases line up with theory and guidelines found in scientific literature.

Survey

Participating office workers and students in both case studies were given similar questionnaires consisting of up to 29 multiple-choice questions, plus an open question for personal remarks. The questionnaire is divided into the following 3 segments:

- General questions – to filter people by gender, age and their general disposition;
- Workspace – to determine how much time a person spends in the investigated space, as well as asking for their opinion on aesthetics and practicality of the room;
- Acoustics – inquiry on satisfaction with working conditions in relation to noise levels, speech communication and pinpointing noise sources.

The questionnaires have been collected and the responses are tallied. IBM SPSS Statistics 22 software package is used for easy further case selection and data analysis (encompassing the cross-tabulation of specific sets of answers, comparison of means and standard deviations plus the calculation of correlations).

Note: the questionnaire is included in *appendix A*.

Background noise measurements

A Norsonic Nor140 sound meter is placed in the workspace at several representative listening spots to measure sound level in occupied situation, during working hours. Each measurement taken has a total duration of 5 minutes with a polling interval of 10 seconds. The sound meter stores values for each interval, as well as an average for the entire duration of the measurement. Said values are then plotted in graphs to show fluctuation of sound pressure over time. Two parameters are specified:

- $L_{A,eq}$ is a measurement of sound levels with an A-weighting, which means that the measurement is filtered and weighted to be similar to the response of the human ear, covering the full audible audio range from 20 Hz to 20 kHz. $L_{A,eq}$ gives a single number value per set time interval;
- $L_{f,eq}$ is the sound pressure level equivalent per frequency. This returns a number value per set time interval for 5 octave band frequencies: 125 Hz; 250 Hz; 500 Hz; 1,0 kHz and 2,0 kHz.

Impulse response measurements

This is a test to determine the acoustic characteristics of an indoor space. It is performed (preferably) in an empty room. A sound source – the omnidirectional loudspeaker – is placed in a fixed position, at a chosen workstation. The loudspeaker is mounted to a tripod with its center at a height of 1,28 m off the ground. The sound meter is placed at a fixed distance and in a straight path from the sound source for each measurement: in succession the distance between speaker and microphone is 1 m; 2 m; 4 m; 8 m; 16 m and 6 m; 12 m. By plotting the distance against measured sound strength at each position, spatial decay DL_2 is calculated. A detailed description on the determination of spatial decay is given in the ISO/NEN 14257:2001 standard.

The measuring equipment for this test was provided by the Faculty of Architecture and the Built Environment, chairs of Building Physics and Building Services. The experimental setup for the sweep measurements is as follows:

1. Laptop with MATLAB software;
2. Behringer UCA222 USB-interface between USB-port and microphone / loudspeaker;
3. Norsonic Nor280 power amplifier;
4. Norsonic Nor276 dodecahedron loudspeaker + tripod;
5. Norsonic Nor140 sound analyzer as microphone + microphone stand;
6. Cables to connect the equipment.

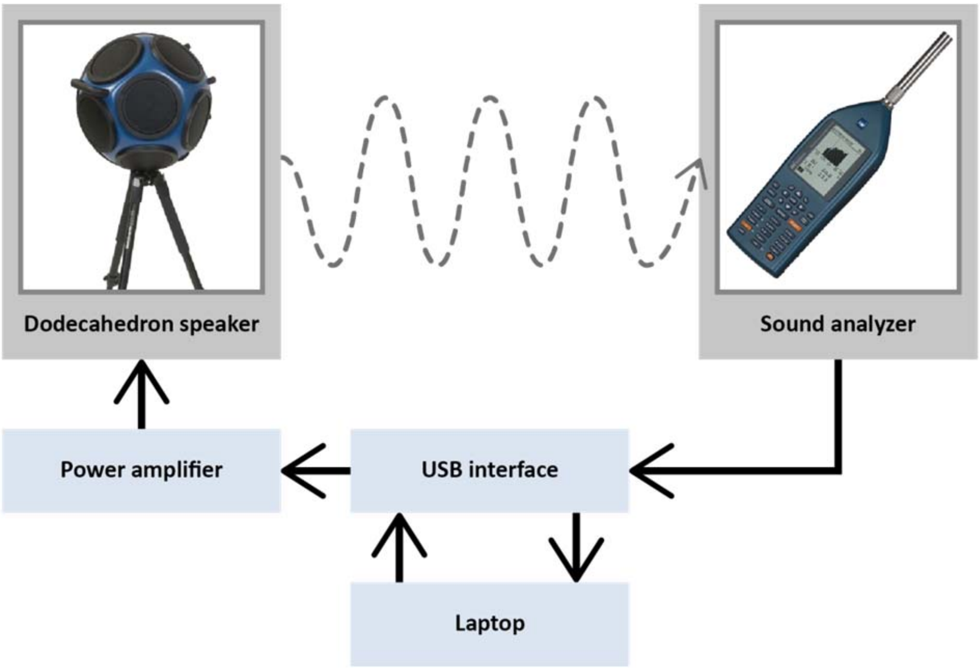


Figure 1. Equipment setup

Figure 1 shows how all instruments are connected. For this study the laptop generates 4 (+2) logarithmic sine wave sweeps per microphone position. The sweep sound is transmitted into the room by an omnidirectional speaker, where it is then recorded by the microphone and returned to the laptop. The signal is then processed by a MATLAB-based routine, which calculates and plots room impulse response, then returns the results expressed in acoustic parameters such as reverberation time, sound strength G and STI.

3.2 PHASE 2: DEVELOPMENT

- How can parametric optimization be implemented in room acoustics design?

The previous findings will serve as input for the development phase which will focus on improving and optimizing acoustic properties of said offices using computer models. For both case study buildings a basic geometric model is made in Rhinoceros 5. Grasshopper (visual scripting plugin) serves as the environment for parametric investigation and optimization. The goal is to develop a routine which aids in searching acoustic improvements by adaptation of ceiling and wall properties. Relevant models are also exported to CATT-Acoustic v8.0g in order to assess the accuracy of the results.

Grasshopper model

Grasshopper is a graphical editor for algorithmic modelling that integrates with the 3-D modelling environment of Rhinoceros. Here its components are used to define the logic of a basic acoustic ray tracer. Furthermore the capabilities of existing definitions are reviewed and compared. A parametric model is set up, applying the principles from geometrical acoustics theory, to investigate sound levels at predefined receiver positions.

Verification

In-depth acoustic analysis will be performed with CATT-Acoustic. Modelled surface geometry is converted to polylines and then exported from Rhino in *.DXF file format. In corresponding model files material properties are matched manually. The results that are generated from Grasshopper definitions and CATT analysis are compared. An indication of the validity of the parametric routine can be given accordingly.

3.3 PHASE 3: FEEDBACK

- Will the results of said design method have significance for the end user?

Possibilities for feedback are entirely dependent on the results of previous phases and the time frame of the research. CATT-Acoustic provides auralization capabilities, which is the technique of creating audible sound files on the basis of computer data (Vorländer, 2008, p. 3); in this case 3-D models of office interiors with and without proposed adaptations. Should parametric optimization prove to be valid and successful, sound clips resulting from auralization will be taken back to the surveyed students and employees for a short feedback survey. They will be asked to compare a control sample (a simulation of the existing situation) and one clip simulating a proposed change. This should lead to insight into the extent to which people are capable of judging and noticing virtualized changes in sound, whether these changes are regarded as positive, and the added value (or lack thereof) yielded by better integration of acoustics in the design process.

4 CASE STUDIES

4.1 CASE 1: BT STUDIO

The first case is the atelier assigned to students of the Building Technology studios at the Faculty or Architecture, Delft University of Technology. The room, mainly chosen for its accessibility, represents a radical case of open planning. While its layout and usage differ from a typical modern Dutch office environment, it is interesting from an acoustical standpoint for a number of reasons. The space is shared by students in different stages of their studies whom thus engage in different activities: at any given moment teacher consults, presentations, group projects, individual work and model making can be taking place at the same time.

Figure 2. BT Studio, picture taken 20 March 2015

The 'BT Studio' has a floor area of 400 m^2. In total there are 13 big desks, each shared by up to 8-10 students, totaling over 100 regular seats. Furthermore there are 24 dedicated computer workstations in the back of the room. Besides a few open metal cabinets, there are no partitions or other types of furniture separating the desks.

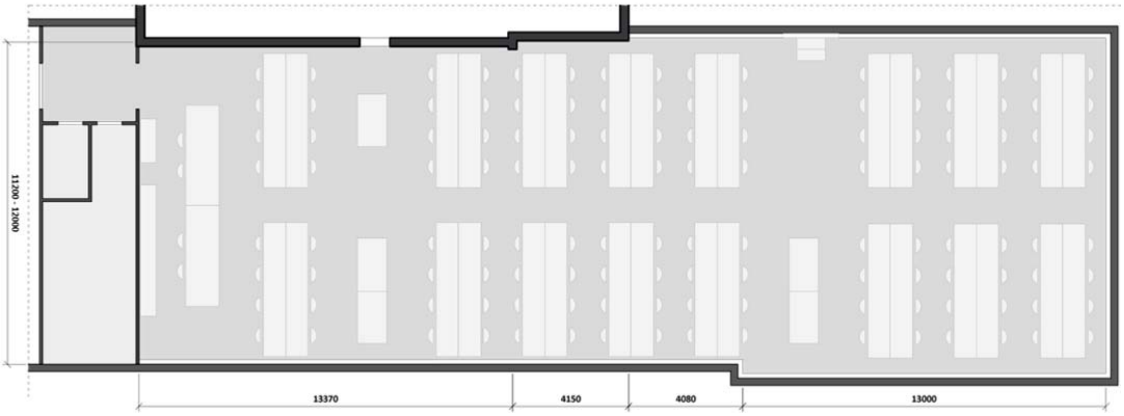


Figure 3. BT Studio floor plan

4.2 CASE 2: OFFICE A

The second case is a wing of an office building in the Netherlands (depicted in figure 4) which, for purposes of anonymity, will be referred to as 'office A' from here on out. This workspace exemplifies a typical Dutch office by its layout and activities. Tasks performed in this place are mostly individual and administrative in nature: these include paperwork, processing digital forms, archiving, making phone calls, writing e-mails, etc.

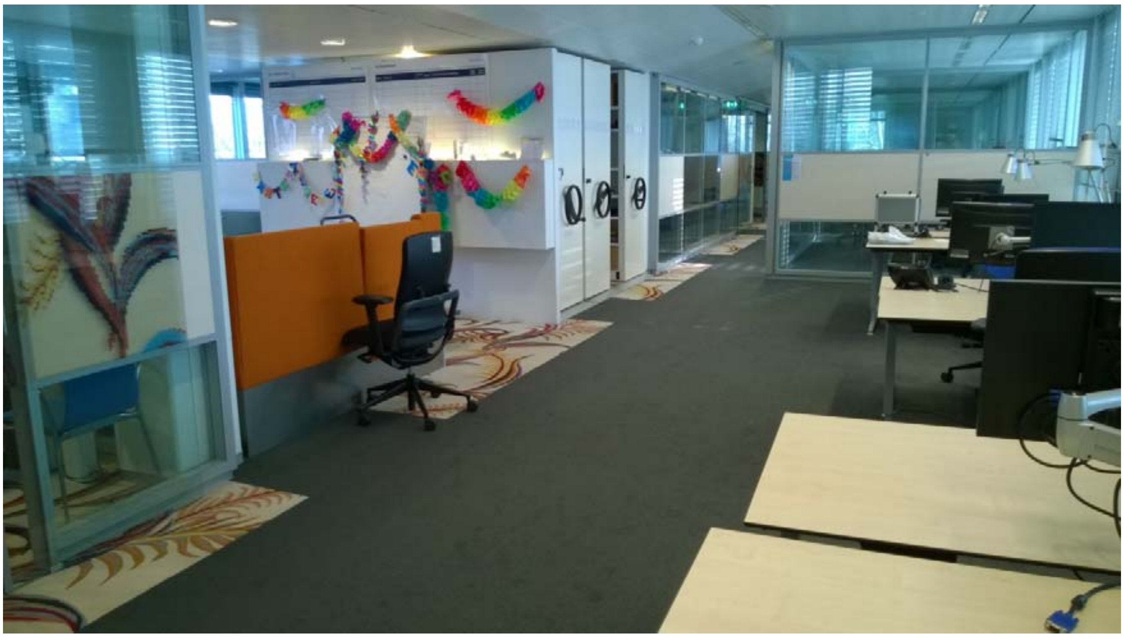


Figure 4. Picture of office A

This office wing has a total floor area of 340 m^2 and is divided into an open workspace and several 2-person workrooms. There are 27 single desks in total in the examined wing. The open space (area of 125 m^2) is emphasized in this study. On both sides of the room desks are arranged in two rows of 6, separated in the middle by a small conference room, an open meeting area and a filing cabinet. From the looks of it, the perforated metal ceiling seems to be the only acoustic absorption applied to this space.

Figure 5. Office A floor plan

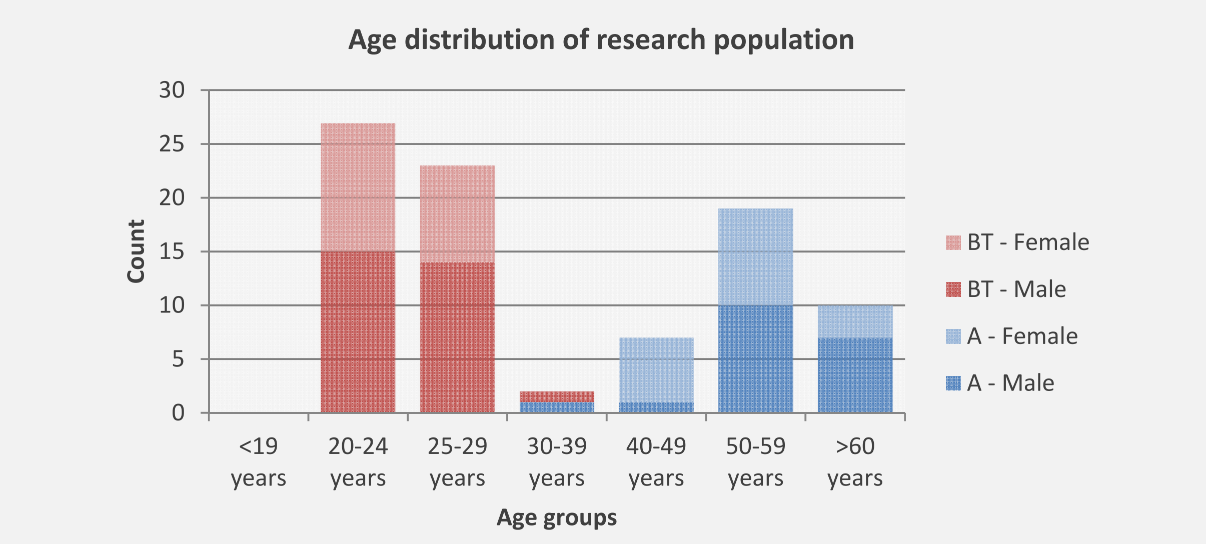
4.3 PRELIMINARY COMPARISON

When compared it is apparent that the two case studies significantly differ on three aspects (see table 1). Besides that both buildings are different, so is the way in which they are utilized. The BT Studio hosts a much wider variety of activities in contrast to office A, often involving group work, some of which are also not naturally found in the workplace of most knowledge workers.

	BT Studio	**Office A**
Users	Students, age 20-30	Full time employees, age 50-60
Activities	Varying activities	Purely administrative
Workspace	Open space (34,4 x 12,4 m)	Mixed plan with open space (11,8 x 10,6 m)

Table 1. Research variables for case study buildings

Specifically looking at the makeup of the research population, the groups in both buildings are distinctly different when it comes to age, working hours and general attitude. The students of Building Technology are expected to have basic prior knowledge on the topics of acoustics and building physics. They tend to have preconceived ideas on office design as a result of their background in architectural studies, which is something that might affect their answers in the survey. This is not the case for the employees of office A.



Gender	<19	20-24	25-29	30-39	40-49	50-59	>60	Total
A - Female	-	-	-	-	6	9	3	18
A - Male	-	-	-	1	1	10	7	19
BT - Female	-	12	9	-	-	-	-	21
BT - Male	-	15	14	1	-	-	-	30
Total	0	27	23	2	7	19	10	88

Graph 1. Research population

5 THEORY

5.1 BASICS OF ACOUSTICS

Explaining sound waves

Explanations on the basics of acoustics and underlying physical mechanisms for propagation of sound are given by Begault (1998a); Cowan (2000); van der Linden & Zeegers (2006). When dealing with room acoustics of open plan offices we mostly consider airborne sound propagation of speech from a talking person – the source – to another person hearing said speech – the receiver. Sound consists of longitudinal pressure oscillations in air, which get meaning upon interpretation by human hearing. The sound wave is described by its wavelength and amplitude, which correlate to perceived pitch and loudness respectively.

$$f = \frac{c}{\lambda}$$

f = frequency [Hz]
λ = wavelength [m]
c = propagation speed of sound = 343 m s^{-1}

The frequency of sound determines the height of its tone. High frequency corresponds to a high tone, while low tones have low frequencies. In reality sounds are nearly always composites built up of many tones occurring at once. Human speech, for instance, contains frequencies in the range from 200 Hz to 5 kHz (Begault, 1998a, p. 29).

Sound measurements, are generally performed using an internationally standardized system of octave bands, with each band being designated by their middle frequency: in order 63 Hz, 125 Hz, 250 Hz, 500 Hz, and so on. The distribution of sound energy across a spectrum can be accurately characterized by taking measurements in this fashion (van der Linden & Zeegers, 2006).

The decibel

Sound pressure describes small positive and negative pressure variations in relation to atmospheric pressure we normally experience. The human ear can detect an extremely wide range of pressure variations. Its lower limit, i.e. the ‘limit of hearing’, is at $2 \cdot 10^{-5}$ Pa. This is a factor 10^{7} lower than the upper limit or ‘pain threshold’ at 200 Pa, which of itself is still 500 times smaller than atmospheric pressure (van der Linden & Zeegers, 2006, p. 148). To cope with such a wide range of values a logarithmic scale is introduced: the sound pressure level. The following expression is used to determine SPL:

$$L_p = 10 \log \left(\frac{p_{eff}^2}{p_0^2} \right)$$

L_p = sound pressure level [dB]
p_{eff} = effective sound pressure [Pa]
p_0 = reference sound pressure = $2 \cdot 10^{-5}$ Pa

Its unit, the decibel (dB), is also used to logarithmically express acoustic power and intensity. In all cases it needs to be noted that decibel values are not additive. If multiple sound levels are to be added, SPL values need to be converted to actual pressure before addition:

$$L_{p;tot} = 10 \log \left(10^{\frac{L_{p1}}{10}} + 10^{\frac{L_{p2}}{10}} + \ldots \right)$$

$L_{p;tot}$ = resulting sound pressure level [dB]
L_{p1} = SPL of source 1 [dB]
L_{p2} = SPL of source 2 [dB]

A doubling of sound pressure equals an increase of 6 dB. To get a grasp of sound pressure and SPL, some key values are given in table 2.

	Sound pressure [Pa]	SPL [dB]	Example sound source
■	200,0	140	Threshold of pain
■	20,0	120	Near a jet aircraft engine
■	2,0	100	Near a jackhammer
■	0,2	80	Typical factory
■	0,02	60	Normal speech level
■	0,002	40	Quiet living room
■	0,0002	20	Quiet recording studio
	0,00002	0	Threshold of hearing

Table 2. Comparison of sound pressure and SPL for typical sources (Begault, 1998a, p. 32)

Human hearing, A-weighting

Humans can hear sounds with frequencies between 20 Hz and 20 kHz. Our ears are however not equally sensitive to all tones within this range: we are most susceptible to sounds with frequency components between 500 Hz and 4 kHz, which corresponds to the most dominant range generated by the human voice (Cowan, 2000, p. 5). The relation between loudness and frequency is illustrated by the contour lines in figure 6.

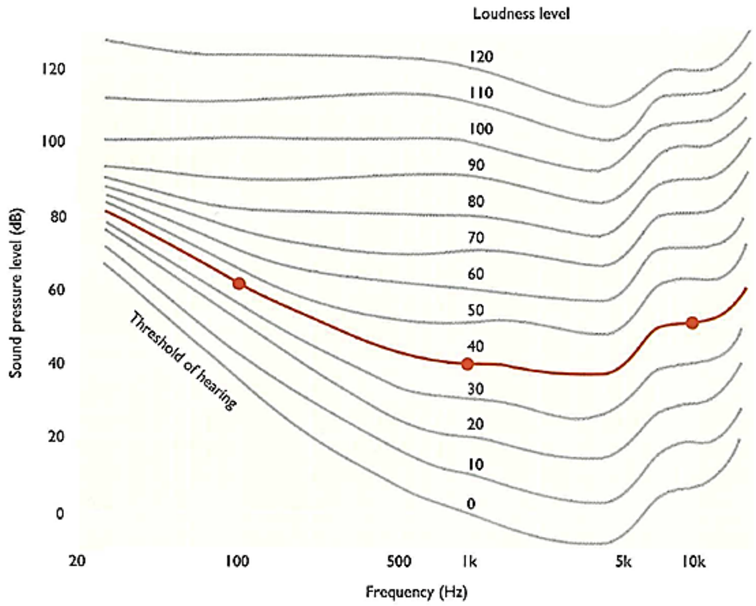


Figure 6. Equal loudness contours; Fletcher-Munson graph (Begault, 1998b, p. 40)

In evaluating a sound spectrum sensitivity of the human ear to sounds in each octave band need to be considered. A-weighting is a correction introduced in measurements to account for human hearing. Sound levels measured in this manner are designated L_A and are expressed in dB(A).

The sensitivity of the ear to changes in loudness somewhat varies with frequency and sound level. For low tones and low levels a much larger change needs to occur to be detected by our hearing, than is the case for high levels. For the most important frequencies the smallest detectable change, or ‘just-noticeable difference’, lies in the order of 1 dB (Everest & Pohlmann, 2001, p. 54; Fastl & Zwicker, 2007, p. 175).

5.2 BEHAVIOR OF SOUND IN AN OFFICE ENVIRONMENT

Absorption

When a sound wave encounters a structure part of its energy is absorbed, part is reflected and the rest is transmitted through the structure (figure 7). To put it even simpler we consider transmission and absorption as one, combining the portion of sound energy which does not return to the room.

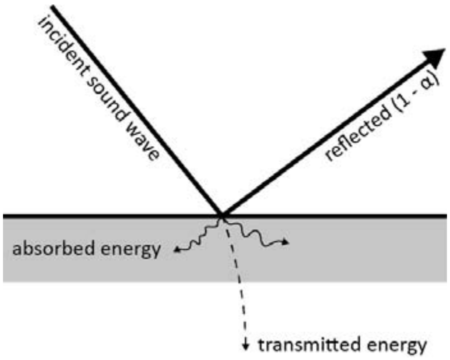


Figure 7. Reaction of a sound wave to interaction with a structure (Cowan, 2000, p. 24)

The amount of sound which is absorbed is firstly dependent on material. The effectiveness in which a material can absorb sound is described by the absorption coefficient:

$$\alpha = 1 - r$$

α = absorption coefficient [-]
r = reflection coefficient [-]

Hard materials such as concrete reflect nearly all sound. Porous surfaces absorb more sound. The absorption coefficients for several common building materials are given in Kennisbank Bouwfysica (2013, pp. 18-20). An open window is considered the perfect absorber since all energy passing through disappears to the outside. The total amount of absorption in a room is expressed as an equivalent of open window area, which is calculated as follows:

$$A = \sum_{i=1}^{n} \alpha_i \; S_i = \alpha_1 \cdot S_1 + \alpha_2 \cdot S_1 + \ldots$$

A = total amount of absorption [m^2 sabin]
α = absorption coefficient [-]
S = surface area [m^2]

Reflection

The direction in which sound energy is reflected off a structure depends on wavelength of the sound in question on one hand; and the shape, roughness and materialization of the surface on the other hand. Two types of reflection are distinguished:

- Specular reflections – Essentially the behavior of sound bouncing off a smooth and hard surface is similar as light being reflected by a mirror. The angle of incidence is equal to the angle of reflection in this case;
- Scattering – In practical cases room surfaces mostly have an irregular texture. When a sound wave encounters a convex or rough surface a distinct portion of the reflected energy is scattered evenly, instead of being limited to a singular specular direction.

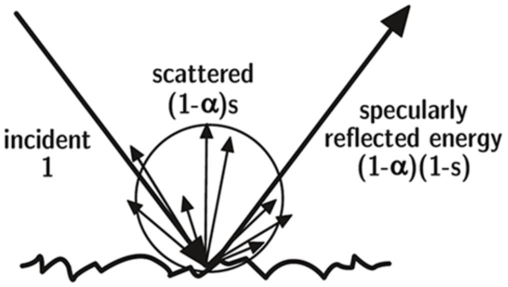


Figure 8. Specular and diffuse reflection from a rough surface (Vorländer, 2008, p. 45)

If the wavelength is very large relative to the irregularities of a surface, that surface can be considered smooth. The portion of reflected energy that is scattered in non-specular directions is expressed by the scattering coefficient:

$$s = 1 - \frac{E_{spec}}{E_{refl}}$$

s = scattering coefficient [-]
E_{spec} = energy reflected in specular direction
E_{refl} = total reflected energy

Diffraction

Obstacles can cause sound, which normally travels in a straight line, to change direction. The behavior of sound bending around objects is called diffraction and is most apparent for low frequency tones (Everest & Pohlmann, 2001, p. 107). Particular for open plan offices, diffraction limits the effectiveness in which partitions can reduce sound propagation. As sound will also reflect from the ceiling nearby sound reduction of a barrier is further compromised (Cowan, 2000, p. 42; Nijs, 2014).

Characterizing sound propagation indoors

Sound propagation in the free field (an outside environment without any nearby obstacles to stop sound from travelling unhindered) follows the inverse square law: sound intensity will decrease exponentially as distance from the source increases. Sound energy emitted from a point source will expand spherically under these conditions. In terms of decibels this equates to a decrease of 6 dB every time the distance relative to the source is doubled (Begault, 1998a, p. 34). Inverse square law does not apply indoors, where sound waves quickly collide with the surrounding structure. In a closed room sound will build up due to repeated reflections, resulting in an increase of sound levels in comparison to outdoor situations. This collection of reflected sound is called reverberation and is quantified by the reverberation time parameter (see *paragraph 5.3*). Reverberation is an acoustic characteristic of an indoor space which can be changed by altering the room size, shape and by changing the amount of absorptive materials to eliminate unwanted reflections.

The sound pressure level in a room can be analytically approximated using Barron's corrected version of the Sabine-Franklin-Jaeger formula:

$$L_p = L_w + 10 \log \left(\frac{Q}{4 \pi r^2} + \frac{4 (1 - \bar{\alpha})^{\frac{r}{mfp}}}{A} \right)$$

with 'mean free path':

$$mfp = \frac{4 V}{S_{tot}}$$

L_p = sound pressure level [dB]
L_w = sound power level of source [dB]
r = distance from source [m]
Q = source direction factor = 1 (omnidirectional) [-]
A = total amount of absorption [m^2 sabin]
$\bar{\alpha}$ = average absorption coefficient [-]

V = volume of the room [m^3]
S_{tot} = total surface area in room [m^2]

The SFJ theory is most precise when applied to a cubic room with evenly distributed absorption materials. This is not the case in open plan offices, which often have a complex room shape, plus many objects and obstacles not covered by the theory (Nijs, 2014). Noise levels will decrease more sharply, as a function of distance, due to placement of scattering elements such as irregular wall surfaces or furniture in office spaces. To account for scattering effects the following equation is derived by Nijs (2014):

$$L_p = L_w + 10 \log \left[\frac{Q}{4 \pi r^2} - \frac{4}{6 V^{\frac{2}{3}} \cdot \left(1 - \frac{\bar{s}}{2}\right) \cdot \ln(1 - \bar{\alpha})} \left\{ (1 - \bar{\alpha}) \left(1 - \frac{\bar{s}}{2}\right) \right\}^{\frac{r}{mfp_{eq}}} \right]$$

$\bar{s}$ = scattering coefficient [-]

= remaining terms unchanged

with:

$$mfp_{eq} = \frac{4\,V}{S_{eq}} = \frac{4}{6}\,V^{\frac{1}{3}}$$

5.3 ACOUSTIC PARAMETERS

A thorough evaluation of the acoustic performance of an open plan office includes following parameters, as described in ISO 3382-3:2012 plus stated sources.

(A-weighted) sound pressure level, $L_{p,A,S,4m}$ and $L_{p,A,B}$ [dB(A)]

Sound sources are distinguished in the measurement of sound pressure levels:

- $L_{p,A,S,4m}$ refers to nominal A-weighted sound pressure level of normal speech at a distance of 4 m from the sound source**.** Its value is either measured directly or obtained through linear regression on measurement results for spatial distribution of speech**;**
- $L_{p,A,B}$ signifies the sound pressure level of background noise. This refers to all continuous sounds observed at a workstation (HVAC systems, office equipment and traffic noise, for example) not caused by people.

Spatial decay rate of speech, DL_2 or $D_{2,S}$ [dB]

DL_2 and $D_{2,S}$ are parameters indicating the decrease of sound with distance from the sound source. To be more precise, spatial decay is measured per distance doubling. Either parameter can be used yielding comparable results. Target values for spatial decay depend on the activity, where tasks requiring high amounts of concentration will obviously lead to more stringent requirements.

- DL_2 is measured along a straight path, parallel to the ground with a free line of sight between source and receiver. Sound levels are measured at set point on the measurement path. The relative difference in sound levels between points, indicate amount of spatial decay. DL_2 is a constant value and can be determined separately for each octave band (ISO/NEN 14257:2001).
- $D_{2,S}$ is an application of DL_2 which uses the spectrum of normal speech and A-weighting over the whole frequency range. The spatial decay is thus not determined for individual octave bands. $D_{2,S}$ measurement paths can include obstacles. Sound decay between different points can vary (ISO/NEN 3382-3:2012).

In either case we aim for spatial decay to be as high as possible. A description of the measurement setup for this study is previously given in *chapter 3 Research method.*

Reverberation time, T_s [s]

Reverberation time is defined as the time that elapses from the moment a sound source is switched off, until the point at which the sound pressure level has decreased by 60 dB (van der Linden & Zeegers, 2006, p. 159).

Sabine's equation:

$$T = \frac{55{,}3\ V}{c_0\ A} \approx \frac{1}{6} \cdot \frac{V}{A}$$

Eyring's definition (Image Source Model):

$$T = -\frac{55{,}3\ V}{c_0\ S_{tot}\ \ln(1 - \bar{\alpha})} \approx -\frac{1}{6} \cdot \frac{V}{S_{tot}\ \ln(1 - \bar{\alpha})}$$

T = reverberation time [s]
V = volume of the room [m^3]
c = propagation speed of sound = 343 m s^{-1}
A = total amount of absorption [m^2 sabin]

$\bar{\alpha}$ = average absorption coefficient [-]
S_{tot} = total surface area in room [m^2]

Reverberation time is perhaps one of the most direct ways in which acoustic quality of a room is assessed. For open plan offices this variable alone is not sufficient to judge whether a space will perform adequately, and must therefore be supplemented with other descriptors. Reverberation time was originally invented to express musical quality. It does not describe noise levels. Furthermore RT is not at all suitable for overall room acoustic description in open plans since it varies per position, depending on the distance from the sound source (Rychtáriková et al., 2004, p. 4; Svensson & Nilsson, 2008, pp. 2, 4).

In real measurements a sound decay of 60 dB practically never occurs due to background noise. Instead reverberation time will be based on the decay rate for 20 dB or 30 dB (denoted as T_{20} and T_{30} respectively) which is then extrapolated to the value for 60 dB decay.

Speech transmission index, STI [-]

STI is a physical quantity representing the transmission quality of speech with respect to intelligibility.

Several other parameters exist to objectively measure speech communication properties of indoor spaces. These include articulation loss of consonants (AL_{cons}), speech interference level (SIL), speech intelligibility index (SII), articulation index (AI), among others. STI is however the most widely used parameter in Europe, this study being no exception. STI calculations can be directly performed with commercially available measurement equipment, plus the results seem to relate well to subjective experience of listeners. As such it is particularly suitable for assessing speech intelligibility at the workplace (NPR 3438:2007, p. 8).

Open plan offices pose a peculiar predicament in that speech intelligibility and privacy need to be considered for the same space:

- Speech intelligibility is defined as the percentage of spoken words that are understood correctly by a listener. It depends on the speaker (vocal effort and articulation), the listener (ear sensitivity) and the transmission channel, i.e. the room (reverberation and background noise) (Cauberg, 2005, p. 1).
- Speech privacy refers to conditions where our ability to understand some speech sounds is reduced. Speech privacy may be desired because we want a conversation to remain confidential and not be understood by others. In other cases we may want speech privacy because the conversations of others are an unwanted disturbance (Bradley, 2007, p. 1).

STI [-]	Intelligibility qualification	Privacy qualification
> 0,75	Excellent	Bad
0,60 - 0,75	Good	Poor
0,45 - 0,60	Fair	Fair
0,30 - 0,45	Poor	Good
< 0,30	Bad	Excellent

Table 3. STI qualifications for speech intelligibility (Eijdems & Nieman, 2011, p. 67)

Using the STI, speech intelligibility is rated on a five-point scale given in annex F of ISO/NEN 9921:2003 (p. 20). Speech privacy is regarded the direct inverse of speech intelligibility. The same rating is used in reverse order to give a qualification for privacy.

Distraction distance, r_D [m]

Distance from speaker where the speech transmission index falls below 0,50. According to ISO/NEN 3382-3:2012 concentration and privacy start to improve rapidly when the distraction distance is exceeded. In light of findings by Bradley (2007) it is questionable whether distraction and privacy distances are set correctly in the ISO standard.

Privacy distance, r_P [m]

Distance from speaker where the speech transmission index falls below 0,20. Above the privacy distance, concentration and privacy are experienced very much the same as between separate office rooms. STI values less than 0,20 are difficult to achieve in offices with poor speech privacy or small volume.

5.4 STANDARDS AND GUIDELINES

Design rules of thumb

Some generalized design tips are given in literature. A summary:

- Minimize sound propagation – In order to eliminate unwanted reflections, building elements should help to absorb or scatter sound (Persoon & de Kruijff, 2011, p. 27). An absorbing ceiling is necessary and pretty much standard. Propagation of direct sound is decreased when placing screens (the larger, the better). Screens are especially effective in reducing sound transmission over large distances (Nijs, 2014);
- Sound masking – Unwanted speech sounds can effectively be masked or covered up by increasing background noise. Doing this is important as irrelevant speech is considered to be much more disturbing than relatively constant levels of neutral sounds such as typical ventilation noise (Smith-Jackson & Klein, 2009). The sound level of background noise needs to be limited however, as it will become a source of annoyance otherwise and will cause people to talk louder, hence speech privacy would not be improved (Bradley, 2003, pp. 23-24; Persoon & de Kruijff, 2011, p. 27);
- Acoustic behavior – Colleagues should have a clear set of agreements on noise producing behavior, basically encouraging talking quietly and relocating discussions involving several people to closed meeting rooms. (Bradley, 2003, p. 28; Cristensson, 2009, p. 5; Persoon & de Kruijff, 2011, p. 24);
- Zoning – People with similar tasks who benefit from collaborating and hearing each other in their work should be put close together. Activities need to be taken into account in furnishing the workplace. The design distance between working groups can be reduced if their tasks are similar (Cristensson, 2009, p. 4; Vellenga-Persoon & Höngens, 2014, p. 41).

Parameter target values

The target values for previously given acoustic parameters have been collected and are shown in table 4. Following values are advised by indicated standards, articles and research papers:

	Parameter	Target value	Source
Average absorption			
	$\bar{\alpha}$	20 - 25 %	Rychtáriková et al. (2004)
Noise levels			
	$L_{p,A,B}$	≤ 45 dB(A)	Bradley (2003) Persoon & de Kruijff (2011)
▪ high task concentration		35 - 45 dB(A)	NPR 3438:2007
	$L_{p,A,S,4\ m}$	≤ 48 dB(A)	ISO/NEN 3382-3:2012
Spatial decay			
	$D_{2,S}$	≥ 7 dB	ISO/NEN 3382-3:2012
▪ between similar activities		≥ 5 dB	Persoon & de Kruijff (2011)
▪ between different activities		≥ 11 dB	Eijdems & Nieman (2011)
Reverberation time			
	T_{max}	≤ 0,8 s	Rychtáriková et al. (2004)
▪ open workspace		≤ 0,5 s	Eijdems & Nieman (2011)
▪ small concentration rooms		≤ 0,4 s	Vellenga-Persoon (2013)
Speech intelligibility			
▪ acceptable speech privacy	STI	< 0,50	Eijdems & Nieman (2011)
	AI	< 0,15	Bradley (2007)
Distraction distance			
	r_D	≤ 5 m	ISO/NEN 3382-3:2012

Table 4. Parameter target values as given in literature

6 DIGITAL SIMULATION OF ACOUSTICS

6.1 DIGITAL SIMULATION METHODS

Geometrical acoustics

Sound wave theory, though correct from a physical point of view, is not deemed to be beneficial when it comes to dealing with practical issues in architectural acoustics. Computer simulations are instead typically based on the principles of geometrical acoustics: herein the concept of a wave is replaced by the concept of a sound ray (Kuttruff, 2009, p. 101; Vorländer, 2008, p. 183). Analogous to light rays in optics, a sound ray is seen as a straight line along which a small portion of sound energy travels. Where sound in reality travels through a room from one person to another, rays in a simulation propagate from a defined source point to a receiver, interacting with the geometry of the room model along the way. The task in geometrical acoustics is to find the paths of sound connecting the source and the receiver (Pelzer et al., 2014, p. 116). Wave phenomena like diffraction and interference are typically neglected. Wavelength or frequency of sound is also not inherent to ray-based simulation models (Rindel, 2000, p. 219). Ultimately geometric acoustics provides an approximation of the acoustical environment in a room. Its application is however justified if the dimensions of the room and its walls are large compared with the wavelength of sound (Kuttruff, 2009, p. 101). According to Pelzer et al. (2014, p. 116) ray models are superior due to significantly faster computation time, while yielding results which are in no less accurate than the results gained from wave acoustic theory.

Ray tracing vs. Image source model

For the simulation of sound in large rooms two geometrical methods are generally distinguished: ray tracing and image source model. Below these approaches are briefly described and compared.

In ray tracing a large number of rays are emitted from a source point in various directions. Each ray carries a portion of the initial sound energy. Rays encountering the room boundary (walls) are subject to energy loss by absorption and will reflect and scatter as described in the previous chapter. With each hit, rays lose energy according to the absorption coefficient of the wall. Tracing continues until a ray has no significant amount of energy left or a certain distance is reached. Counting volumes, usually spheres, are used as receivers to record energy and elapsed time for every intersecting ray.

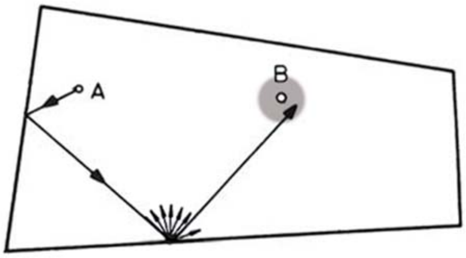


Figure 9. Principle of ray tracing (Kuttruff, 2009, p. 319)

Image source models construct specular reflection paths by mirroring the source in the plane of wall surfaces (Rindel, 2000, p. 220). The original source point is first mirrored at each wall to create so called mirror sources. These mirror sources are subsequently also mirrored, to create sources representing sound paths with multiple wall reflections. That procedure, which is illustrated in figure 10, is repeated a certain amount of times. Finally a validity test is carried out to check which image sources are relevant to a receiver point. This is done by back-tracing a ray from the receiver to the original source along a chain of mirror sources.

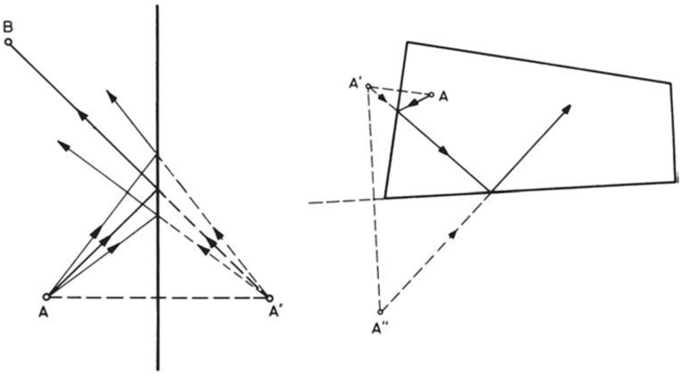


Figure 10. Construction of image sources (Kuttruff, 2009, pp. 104, 105)

The total sound field is composed by the contributions of all valid mirror sources in accordance with inverse distance law. This is in contrast to ray tracing, which relies on counting rays for its energy detection. Further differences between the two methods are outlined in table 5.

	Energy representation	Detectors	Early reflections	Late reflections	Scattering
RT	Stochastic by counting	Volumes	Decent	Good	Possible
ISM	Deterministic by distance	Points	Good	Slow	No

Table 5. Comparison of ray tracing and image source methods (Siltanen et al., 2010, p. 387; Vorländer, 2008, p. 176)

The image source method is particularly efficient for modelling early reflections. The number of image sources quickly explodes with increasing reflection order (Siltanen et al., 2010, p. 382), leading to a dramatic increase in calculation time for late reflections. For similar reasons this method also has difficulties coping with complex geometries. Most importantly, scattering cannot be modelled using image sources. It is for these reasons the development of ray tracing logic in a parametric model is pursued in this research.

For the implementation of ray tracing it is important to be aware of its inherent uncertainties and limitations. The level of detail of a geometric model needs to correspond to the frequencies of the simulated sound. Using highly detailed CAD models will lead to unnecessary long computation times, without producing a more accurate acoustic analysis (Dalenbäck, 2010, p. 1; Vörlander, 2010, p. 3). The amount of rays also needs to be sufficiently large, as does the volume of receivers to detect the rays. The intricacies and application of ray tracing are dealt with in more detail in *paragraphs 9.1 and 9.2*.

Hybrid models

The contradictory (dis)advantages of ray tracing and image source methods have spawned the development of hybrid models that seek to combine the best features of both methods. Ray tracing can either be used to model late reflections to overcome increasing calculation time of image sources, or used as a test to find valid image sources (Pelzer et al., 2014, p. 118; Rindel, 2000, p. 220). Commercial acoustic analysis software is typically based on variations of hybrid models. Two notable examples are CATT-Acoustic and ODEON:

- CATT-Acoustic (Dalenbäck, 1996) combines image sources with algorithms based on the diffuse radiation of energy from the surfaces of the room. High order reflections are accounted for with cone tracing (a form of ray tracing using cones instead of thin lines);
- ODEON (Naylor, 1993) uses image sources for early reflections, then switches to ray tracing with randomized reflection directions for late reflections. Ray tracing is utilized here for the construction of 'secondary sources' on the points where rays collide with a surface. Each of these sources is considered to radiate a small portion of energy onto the receiver (provided they are within line of sight).

Since CATT-Acoustic is available to students of Building Technology, it is chosen in this study to perform acoustic analysis for purposes of benchmarking and validating other models.

6.2 ACADEMIC PRECEDENCE

The discrepancy between digital acoustic simulation and its incorporation in the architectural design process is acknowledged in several recent academic papers. These studies share a principal aim to overcome the limited interoperability between commonly used CAD programs and acoustics software, often done by developing their own tools with the intent of making acoustic analysis more accessible to designers (Bergeron-Mirsky et al., 2010; Pelzer et al., 2014, pp. 121-129). A few examples, specifically dealing with acoustic issues using parametric models, are further elaborated below.

Palma et al. (2013) present a parametric form finding process for a sound reflective shell, to be located outdoor for musical performances. The design criterion here was to find the best shape of a parameterized double curved surface to achieve uniform distribution of sound energy across an audience area. The study is performed entirely within the Rhino software platform. A simple ray tracer was used on the setup of figure 11 to evaluate ray distribution on the receiving surface, to accordingly change the shape of the reflective shell. A small selection of shell shapes then underwent detailed acoustic analysis using the Pachyderm acoustics plugin.

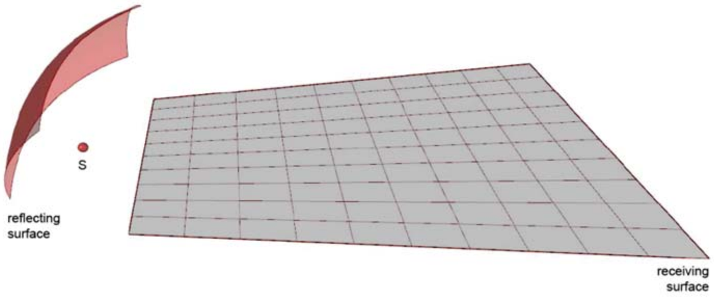


Figure 11. Model setup used in study by Palma et al. (2013)

A series of studies by Peters et al. (2013) uses the design of a semi-enclosed meeting room prototype, located in a larger open plan work setting, as a test case for the development of design workflows integrating acoustic simulation. A combination of acoustic performance plus geometrical and fabrication constraints related to constructing hyperboloid geometry, are cited as the main drivers for the design of the prototype. Several workflows are outlined, both for the evaluation of room acoustic performance, as well as the visualization of scattering properties of surfaces. Grasshopper was used to generate the complex geometry. Acoustic analysis was performed parallel to this modelling process, resorting to ODEON to map parameters such as STI, and Pachyderm for reverberation time calculations.

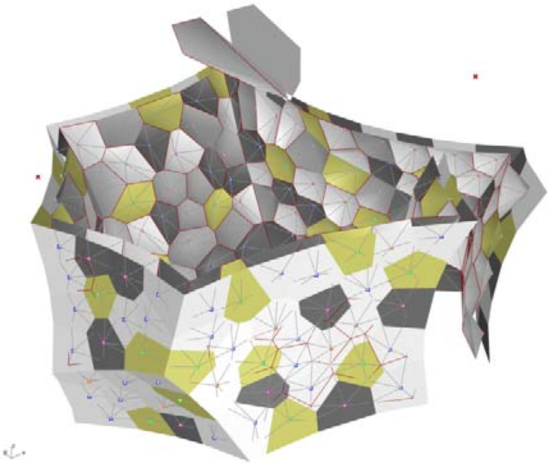


Figure 12. Geometric generation of meeting room prototype (Peters et al., 2013)

Bergeron-Mirsky et al. (2010) reports on the creation of a ray tracing tool for Grasshopper. Their implementation of ray tracing assumes specular reflections only, ignoring scattering and edge diffraction. A field of spheres of equal size are used as receivers, in their case to visualize an audience in a model of a lecture room. A revision of this tool was later applied in a follow-up study by Lim (2011), to parametrically alter the shape and absorption of the ceiling in a 'shoebox' auditorium, using a signal marking process. Unfortunately the tool seems to be outdated and does not work in recent versions of Grasshopper and is – to my knowledge – no longer actively maintained.

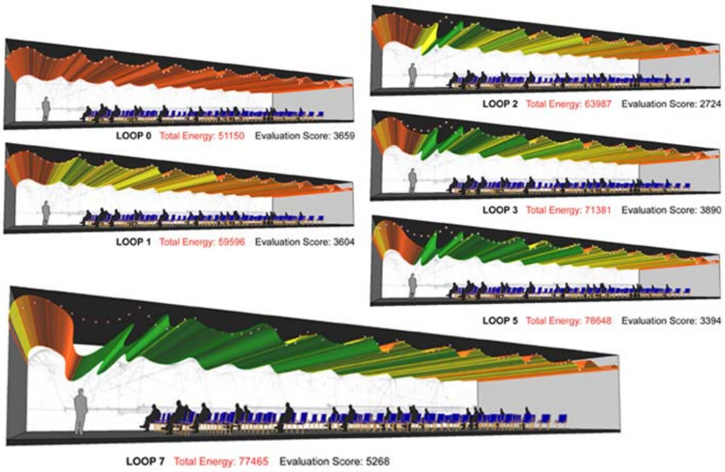


Figure 13. Form finding process for the ceiling of an auditorium by Lim (2011)

6.3 AVAILABLE EXTENSIONS AND DEFINITIONS

Acoustic Shoot

Acoustic Shoot is a simple ray tracing definition written by Guillaume Meunier (2012), built around a VB.NET scriptable component in Grasshopper. The latest version implements outdated code and components, but remains somewhat functional for the time being. From a given source point specular ray tracing is performed on surface geometry. Absorption coefficients are taken into account, with the script returning all collision points and the energy values at each point. This information is used to provide a basic visualization of colored particles. The ability of this script is to describe acoustic environments is limited as the definition does not handle scattering. It also returns false collisions when using trimmed geometry.

Pachyderm

Pachyderm is an acoustical simulation plugin for Rhino by Arthur van der Harten (2015). The program, which has been open-sourced since March 2015, utilizes a hybrid model for the purposes of acoustic prediction and auralization. As previously mentioned, Pachyderm has been used in a few form finding studies to perform acoustic analysis. Frequency-dependent absorption and scattering are assigned to geometry per model layer, via a separate interface. Results can be expressed in several acoustic parameters including reverberation time and noise levels. The parameterization of geometry is supported through an included Grasshopper extension. Absorption and scattering coefficients cannot be directly altered on the Grasshopper canvas, meaning that parameterization of material properties requires a workaround by cycling through layers with preassigned materials.

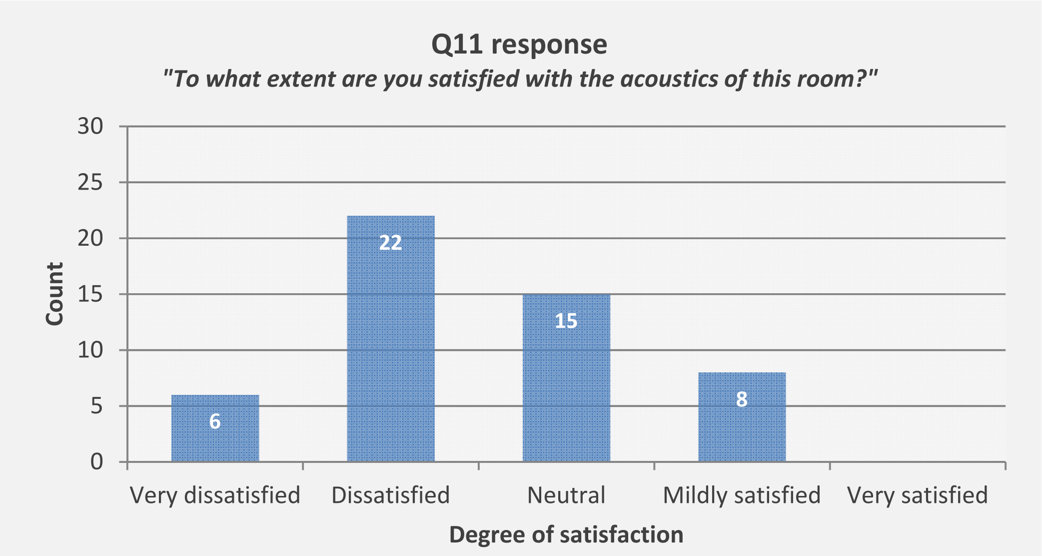
7 QUESTIONNAIRES

7.1 BT STUDIO

Students present in the studio during the afternoon on 9 July 2015 were given a printed questionnaire, which has been fillet out to completion by a total of 51 students, 21 of whom were female. The research population included both Dutch and non-Dutch speaking international students, practically all in the age range of 20-29 years. Neither age, gender nor nationality of a respondent seems to be of significant influence to a given response.

Summary

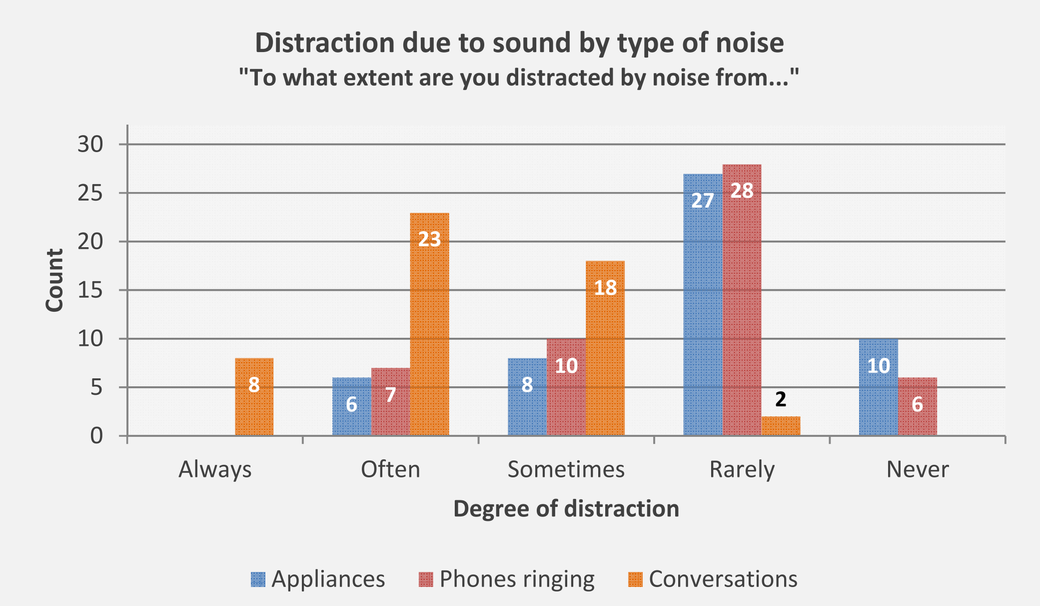
When questioned about the acoustics of the room in general the population as a whole tended to rate this aspect as slightly dissatisfactory. However, as this particular question generalizes the issue we cannot deduce from this response alone whether this negative tendency is caused by the room itself or rather the people occupying it.



Mean	St.dev.	Range
-0,51	0,903	-2 to 2

Graph 2. Students' degree of satisfaction with the acoustic properties of the BT Studio

Clarification may be given on the basis of the response given to the statement illustrated in graph 3. When asked to rate different noise types with respect to the degree they cause distraction to a student, other people's conversations clearly stands out as the main cause of nuisance in this room.



	Mean	St.dev.	Range
Appliances	-0,80	0,895	-2 to 2
Phones ringing	0,65	0,868	-2 to 2
Conversations	-0,73	0,777	-2 to 2

Graph 3. Students' rating of the degree at which each noise type causes distraction, BT Studio

Open questions

Respondents were asked for general remarks on their personal experience with sound in their workspace in a final open question: 24 out of 51 respondents provided an answer.

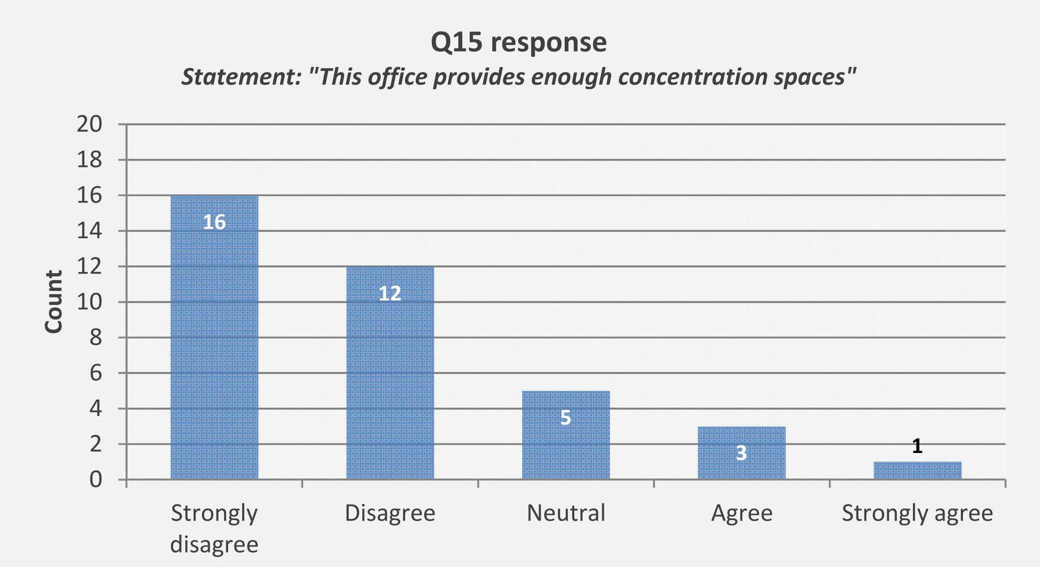
In most cases by far students remarked that they tended to be distracted by tutoring sessions taking place, as the room will be very crowded at these times with said groups producing a lot of noise (14x). The Bucky Lab and EXTREME courses, which happen to be fairly large groups of people, are often singled out as culprits. A conflict of activities between graduate students working individually and group course participants is often stated as a main reason. Several students cited a lack of concentration spaces within the faculty for graduate students (4x), with some even stating that they avoid coming to the faculty altogether whenever they need to make a presentation or write a report (4x). Furthermore a few respondents specifically find the space to be overcrowded during busy moments (3x). Other answers include general remarks on the unsuitability of the room for individual work (3x), students using headphones to avoid being distracted (2x) and a single respondent considering heat in terms of room temperature a larger issue than acoustics.

7.2 OFFICE A

An online questionnaire was taken for office A over a three week period between 2 March and 20 March 2015. It has been filled out to completion by a total of 37 employees. The research population consisted of a near equal amount of male and female respondents, most of whom have indicated to be between 50-59 years of age. For this group particularly, neither age nor gender of a respondent seems to significantly influence the way in which he or she was likely to answer a question.

Summary

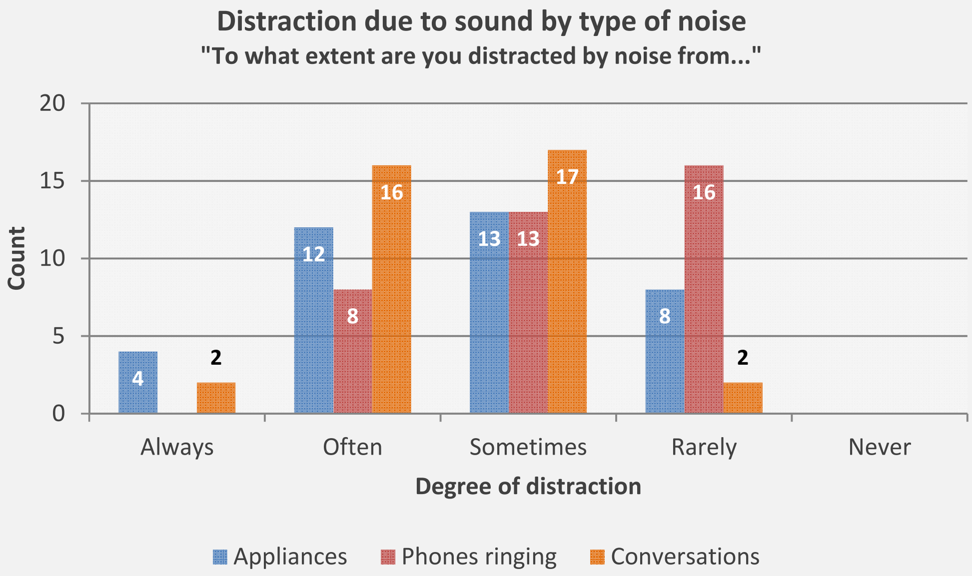
The most striking negative response found in the questionnaire concerned the lack of spaces that are found suitable to perform tasks which require concentration. Respondents were asked to which extent they agree with the following statement: “There are enough rooms available in this office that are suitable for working in a concentrated fashion.” As shown in graph 4, most respondents tended to strongly disagree with this statement.



Mean	St.dev.	Range
-1,05	1,079	-2 to 2

Graph 4. Lack of concentration spaces in office A

In the case of office A, besides other people’s conversations, appliances are also considered a significant cause for distraction. The category of appliances may refer to coffee machines, photocopiers and rubber stamps, all of which are available in the room and frequently used.



	Mean	St.dev.	Range
Appliances	-0,32	0,944	-2 to 2
Phones ringing	0,22	0,787	-2 to 2
Conversations	-0,49	0,692	-2 to 2

Graph 5. Employees' rating of the degree at which each noise type causes distraction, office A

Open questions

Respondents were asked for general remarks on their personal experience with sound in their workspace in a final open question: 13 out of 37 respondents provided an answer.

Most of the remarks concerned noise caused by overcrowding of the space during busy days (8x). Furthermore, several people forcefully indicated that propagation of speech noise bothered them (6x). Whether sound insulation between work rooms is sufficient is questioned repeatedly, as well as the researched office wing being seen as unfit by many for the purpose of confidential (phone) conversations. Other answers to the open inquiry include remarks on the office layout (3x) – namely the lack of concentration spaces – and the building being seen as outdated (2x).

8 MEASUREMENTS

8.1 BT STUDIO

Noise level measurements

The following figures and tables show the setup and results of noise level measurements, which have been conducted during a fairly busy afternoon on Thursday 9 July 2015. In this case questionnaires were taken at the same time as the measurements. During this time tutoring sessions were taking place in this room for the EXTREME course (the place of which is indicated in figure 14 by the orange tables).

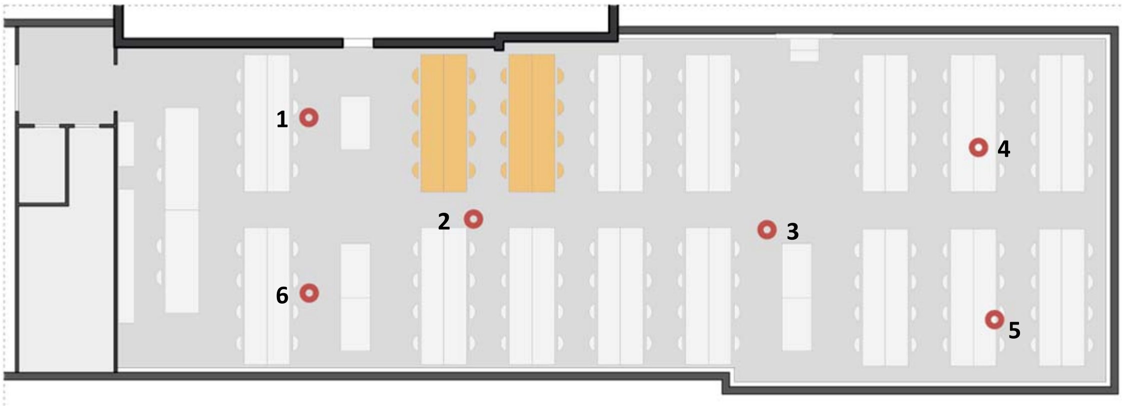
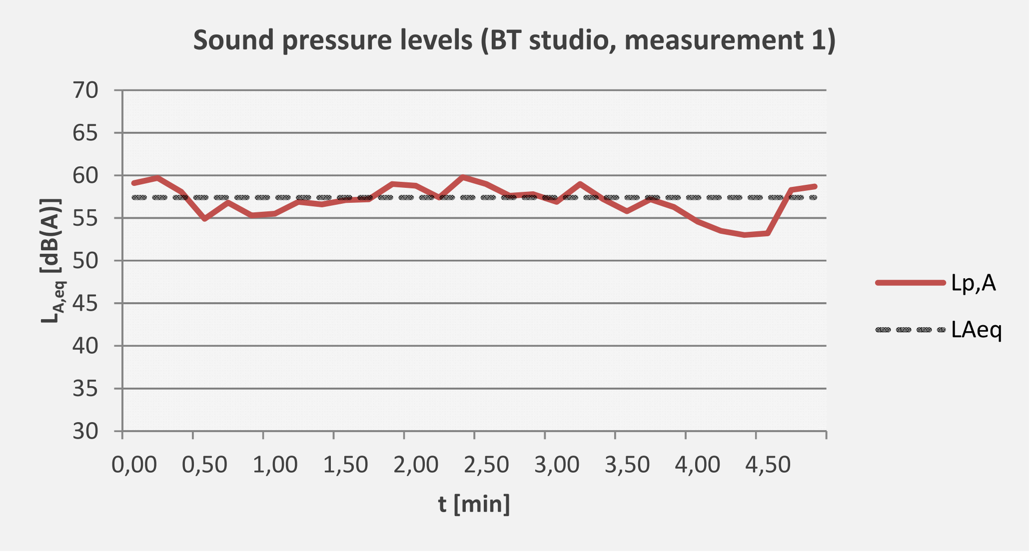


Figure 14. Noise level measurement positions, BT Studio (9 July 2015)

	1	2	3	4	5	6
Time	14:56 h	15:03 h	15:09 h	15:17 h	15:25 h	15:44 h
$L_{A,eq}$ [dB(A)]	57,4	59,8	56,3	55,2	53,8	59,2

Table 6. Average SPL over 5-minute measurement, BT Studio (9 July 2015)

The following graph shows an example of one of the sound level measurements taken. It is characterized by fairly constant levels over the duration of the measurement (a similar trend was observed in other positions as well).



Graph 6. Example of measurement, equivalent A-weighted SPL over all frequency bands

Note: graphs for all other sound level measurements conducted, both for this case as for the results for office A, are included in *appendix 0*.

Impulse response measurements

The positions for the impulse response measurements are indicated below. One line is taken diagonally along which impulse response is measured at fixed distances. From the results sound decay is calculated manually. Two extra positions were also measured, one at 14 m distance from the source across the room and another at 4 m distance in opposite direction.

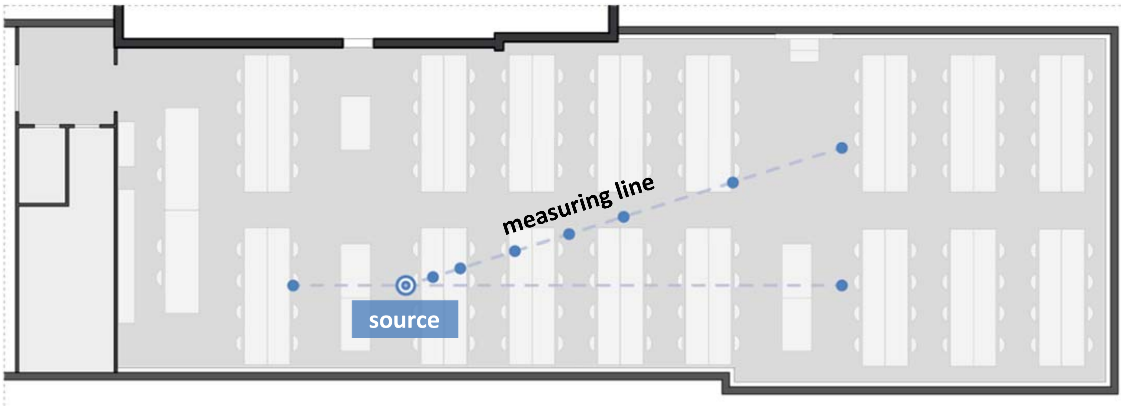


Figure 15. Impulse response measurement positions, BT Studio (20 February 2015)

At each position sound strength is measured. Sound strength G – not to be confused with SPL – indicates the contribution of a room to the measured sound or noise level from a sound source. More specifically it is defined as the logarithmic ratio of the measured impulse response to that of the response measured in a free field at a distance of 10 m from the sound source (ISO/NEN 3382-1:2009, p. 31), expressed by the following equations:

$$G = L_p - L_{p,10}$$

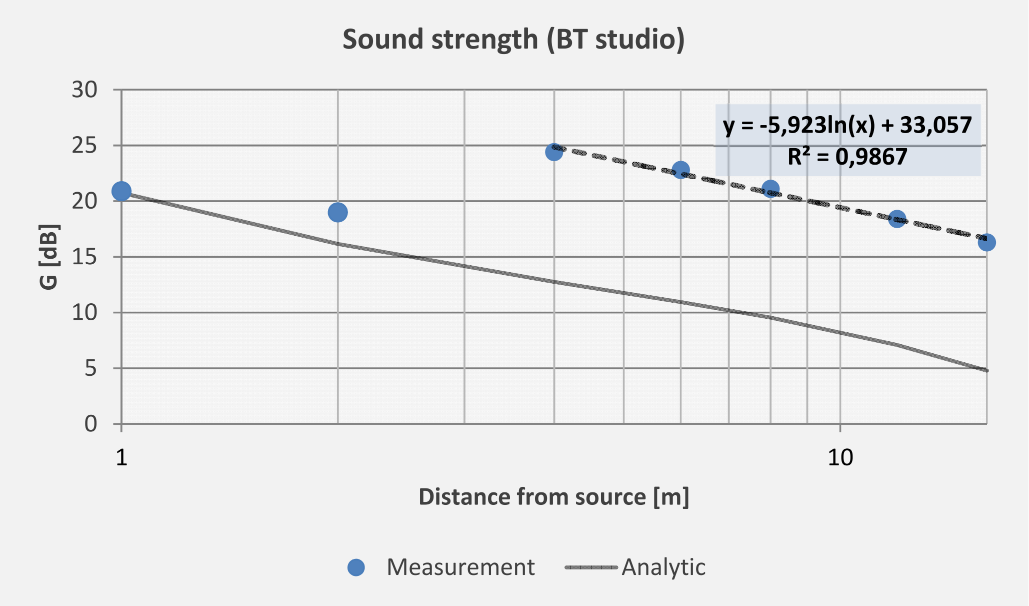
and:

$$G = L_p - L_W + 31$$

$G =$ sound strength [dB]
$L_p =$ SPL at each measured point [dB]
$L_{p,10} =$ SPL measured at 10 m distance in a free field [dB]

$L_W =$ sound power level of sound source [dB]

On the next page in graph 7, the relation between sound strength and the distance at which a measurement was taken is represented by the blue dots. The gray line is an analytic prediction made for the room by plotting the formula of (Nijs, 2014) given on *page 29*. In the measurements there is an unexpected jump between 2 m and 4 m, possibly due to faulty post-processing settings. The further trend does however not seem to be out of the ordinary.



Graph 7. Results of impulse response measurement with decay trend, BT Studio (20 February 2015)

DL_2 is determined here from a regression from 4 m to 16 m distance from the sound source. This is done for a broadband signal, as well as separately for the 500 Hz octave band. The latter is used later on to compare the measured values with simulation models.

	1 m	2 m	4 m	6 m	8 m	12 m	16 m	DL_2 [dB]
G_{linear} [dB]	20,9	19,0	24,4	22,8	21,1	18,4	16,3	4,1
$G_{500\ Hz}$ [dB]	21,8	17,6	26,0	22,0	19,6	18,3	16,0	4,7

Table 7. Measured sound decay DL_2, BT Studio

8.2 OFFICE A

Noise level measurements

The setup and results of noise level measurements, conducted on Friday 20 March 2015 in the afternoon, are shown below. During the measurement only half of the workstations were occupied.

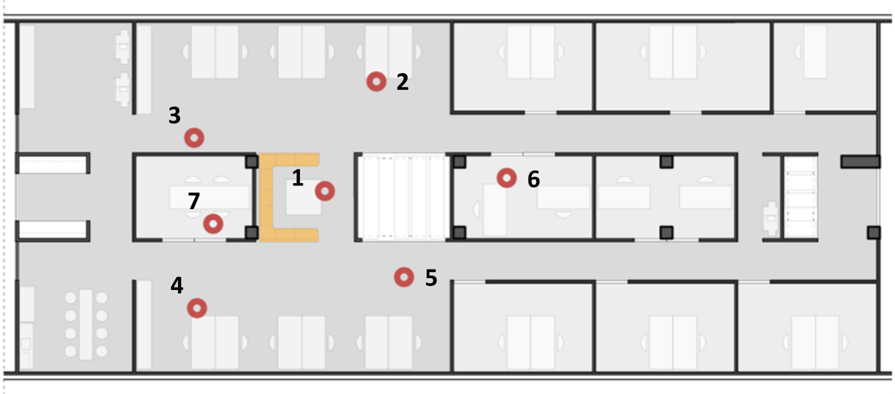
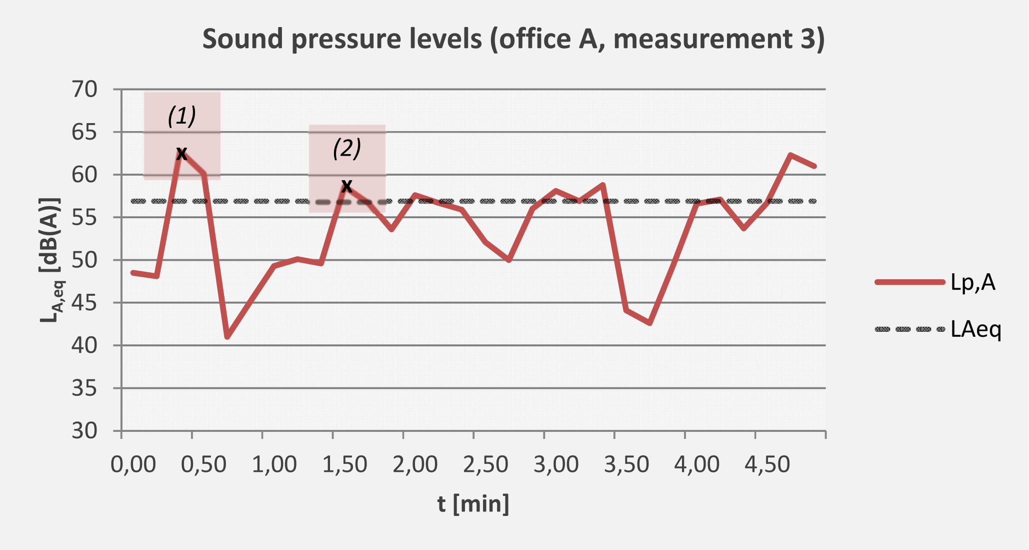


Figure 16. Noise level measurement positions, office A (20 March 2015)

	1	2	3	4	5	6	7
Time	12:34 h	12:44 h	12:52 h	13:01 h	13:18 h	13:30 h	13:42 h
$L_{A,eq}$ [dB(A)]	49,8	50,6	56,9	53,6	53,8	44,9	47,5

Table 8. Average SPL over 5-minute measurement, office A (20 March 2015)

Sound levels in office A are characterized by large fluctuations (over the course of the measurement), which can probably attributed to the fact that the measurements took place while the space was only half occupied. Peaks in sound level will more easily occur, which is for example observed in the measurement given in graph 8. The first peak is caused by an employee loudly hitting a stack of papers onto a desk in a quiet room (1). At t = 1,5 min a conversation started which took place at approximately 2 m distance from the microphone (2).



Graph 8. Example of measurement, equivalent A-weighted SPL over all frequency bands

For impulse response measurements two decay lines were measured. The results produced for the ´first line´ turned out to be the most trustworthy, and are thus presented further on.

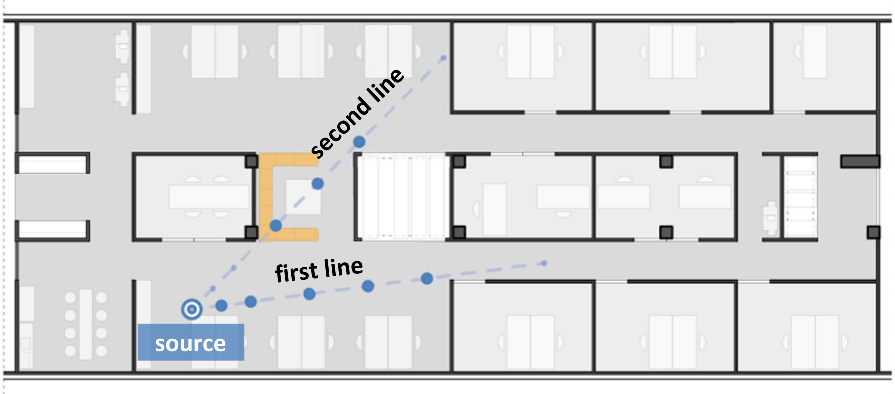
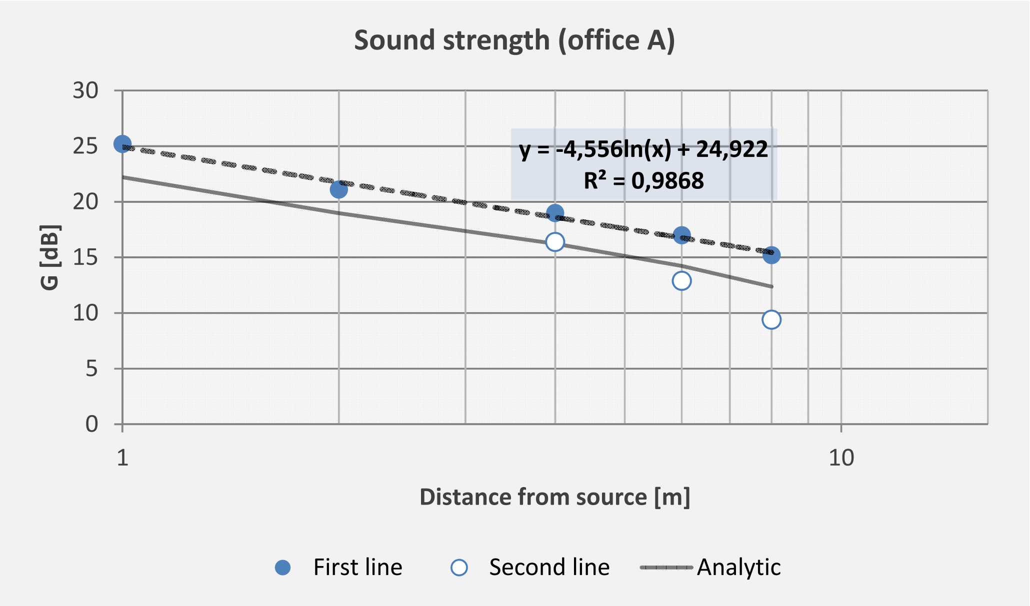


Figure 17. Impulse response measurement positions, office A (20 March 2015)



Graph 9. Results of impulse response measurement with decay trend, office A (20 March 2015)

DL_2 is determined in the range of 2 m to 8 m for both broadband signal and 500 Hz octave band.

	1 m	2 m	4 m	6 m	8 m	12 m	16 m	DL_2 [dB]
G_{linear} [dB]	25,2	21,1	19,0	17,0	15,2	-	-	3,2
$G_{500\ Hz}$ [dB]	24,8	21,7	20,3	16,6	14,7	-	-	3,2

Table 9. Measured sound decay DL_2, office A

8.3 Discussion

Going purely by the results of the impulse response measurements, both investigated rooms fall short by any standard given in *paragraph 5.4* in terms of sound decay. Furthermore, the noise levels returned by the 5-minute measurements greatly exceed the stated SPL target values for performance of tasks which require a certain degree of concentration. In light of these findings the general responses from both questionnaires are far from surprising. Neither room is seen as particularly suitable for carrying out individual tasks. Though both rooms are very different in their layout and the make-up of the research population also greatly differs between both cases, the main concerns brought forth show remarkable similarities. As a whole, noise caused by speech and general the behavior of colleagues, exacerbated by large crowds of people occupying the same space (and the accumulation of noise as a result of that) are viewed as a great source of nuisance across the board.

Response in the questionnaires seem to line up best with the acoustic measurements on the specific questions. Generalized inquiries usually do not cover important intricacies in the discussion of managing acoustics within open plan workspaces. For example, when asked whether respondents were generally satisfied with the room acoustics of their workspace, BT students turned out to be more critically negative on the issue while office A employees remained more neutral as a group. Office A, however, scored lower in one of the sound decay measurements compared to the BT Studio. Simply asking respondents to grade their workspace on a scale of 1-10 also produces a far too generalized description of the situation, since other external factors also come into play when people assign their grades. Such factors include, but are not limited to behavior of colleagues, building physics aspects (such as thermal comfort and lighting), architectural appeal and practicality of the office design and layout.

Particularly the final open questions provide far more relevant information which, especially in the case of office A, help explain some of the observations in the acoustic measurements. Noise nuisance caused by appliances (mainly photocopiers and rubber stamps) are examples which are more unique to office A, and some of these also clearly stand out in as peaks in the graphed sound level measurements. Said uniqueness is somewhat logical considering the BT Studio in its layout and population is essentially not directly comparable to a typical modern-day administrative office. Noise nuisance due to conflicting activities is far more like to occur there, and is a complaint brought forth exclusive to that case.

While the sound levels in office A fluctuated more during each measurement compared to the BT Studio, this occurrence is easily explained when the relatively poor sound decay is taken into account, next to the fact that the measurements were taken in a semi-occupied situation. It is not unthinkable that the measured sound levels would turn out higher and show a more constant course during a more busy moment in the work week.

9 DEVELOPMENT PHASE

In order to answer whether and how parametric optimization can be useful in room acoustics design, a ray tracing definition was developed in Grasshopper during this project. This chapter deals first with the general logic of acoustic ray tracing and details its implementation within Grasshopper. The issues encountered during the development of this definition are also specified.

9.1 APPLICATION OF RAY TRACING IN GRASSHOPPER

Defining logic in Grasshopper

Grasshopper is a graphical programming interface editor that enables designers to create and explore parameterized shapes. Instead of writing a script, logic is defined through the use of visual components containing predefined sets of code, which serve as building blocks for a model. Each component is applied following the same principle concept.

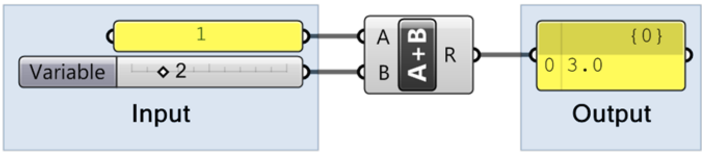


Figure 18. Basic input-output scheme of a Grasshopper component

A component performs an operation on one or more inputs and generates output accordingly. The type of action that is executed varies per component. Grasshopper by default includes components to generate and manipulate geometry, perform math operations and to solve projection and intersection events, amongst others. The output of one component can be used as input for another. By stringing components together in this manner, a network of dependent operations is created. As such, the interrelation between parts of the created network represents itself visually as a block scheme on the canvas of Grasshopper.

Implementing principles of the ray tracing routine

The process of software acoustical simulation consists of three subsequent elements (Alpkocak & Sis, 2010, p. 505):

- Source conception – deals with how the sound is emitted;
- Modelling method of the room – comprises the definitions of the geometric model and tracing procedure, paramount to obtaining the correct parameters;
- Modelling of the receiver.

As shown in table 10, the digital simulation follows a standard communication model resembling that of an acoustic measurement, which in turn mimics person-to-person speech propagation in a room.

	Source	Medium	Receiver
Real situation	Person	Airborne sound, room	Person
Measurement	Dodecahedron speaker	Airborne sound, room	Microphone
Digital simulation	Omnidirectional source	Rays, geometric model	Counting sphere

Table 10. Communication models in acoustic assessment

The process of ray tracing yields a large data set, including sound paths and a record of energy attenuation , related to the material properties and geometry used as input. This data is interpreted at the receiver, where it is filtered to leave only relevant information which is then converted to a single number parameter (sound pressure level in this particular case). The processed output of one or more receivers, along with other quantified characteristics of the modelled configuration, are used as a scoring mechanism to drive an automated process of optimization. Dependent on the outcome of acoustic analysis, geometry and material properties are changed, then re-analyzed (see figure 19).

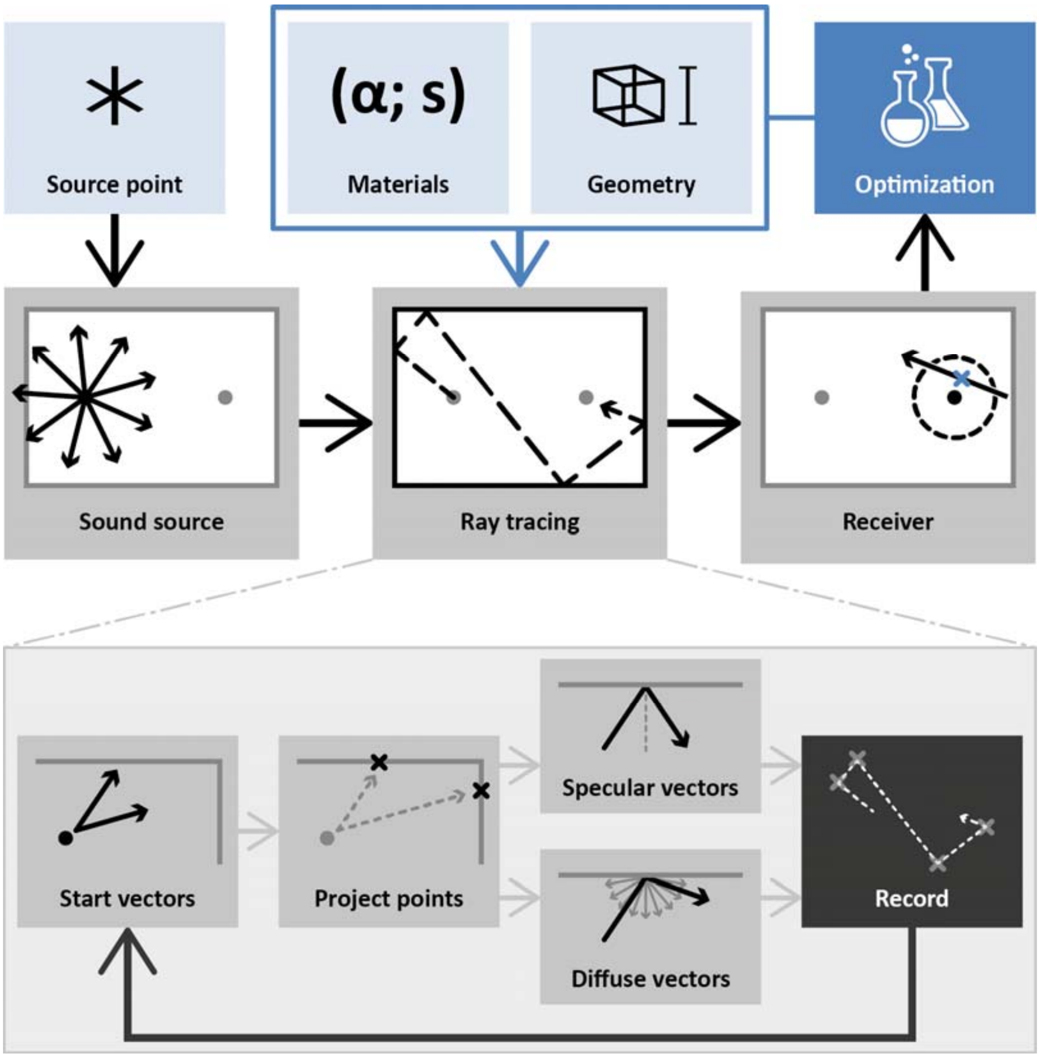


Figure 19. Ray tracing routine

9.2 RAY TRACING COMPONENTS EXPLAINED IN DETAIL

Source conception

Similar to acoustic measurements in reality, an omnidirectional sound source is used in the computer model. The source is represented as point emitting a large number of rays in all directions. The radiation of rays from the source point needs to be as spherically uniform as possible. Essentially, modelling an omnidirectional sound source poses the mathematical problem of evenly distributing many points on the surface of a sphere. Several different methods to model ray generation are given in literature. For starters, Vorländer (2008, p. 182) states spherically uniform radiation is achieved by evenly distributing azimuth angles in a spherical coordinate system, followed by applying the formula below for the distribution of polar angles.

$$\theta = \begin{cases} \arccos z \\ \arccos z + \frac{\pi}{2} \end{cases}$$

θ = polar angle distribution
z = random or regular number sequence between 0 - 1

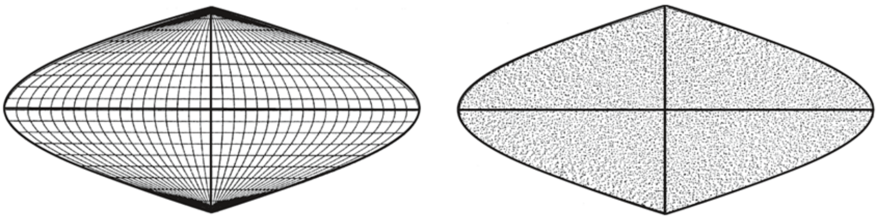


Figure 20. Uniform random distribution of points in a spherical coordinate system (Vorländer, 2008, p. 182)

Another method is described by Farina (1995, p. 112) in which a sphere is subdivided in 400 facets of equal area (see figure 21), followed by a random distribution of points on each of these facets.

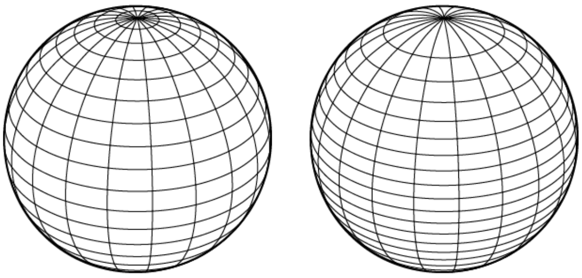


Figure 21. Default subdivision (left) vs. equal area partitioning (right)

Grasshopper contains a component to populate geometry with a set number of points, which can thus be used to distribute points on the surface of a sphere. The points are however added in a pseudo-random fashion, meaning there is no way to initially control the homogeneity of the resulting point distribution, regardless of the way in which the sphere may have been subdivided. A near uniform distribution can be achieved if all points are regarded as charged particles that repel each other (Saff & Kuijlaars, 1997, pp. 6-7). This behavior can be simulated within Grasshopper using the Kangaroo physics engine plugin (Piker, 2015). In this case a Kangaroo simulation will maximize the distance between all points until a state of equilibrium is reached (when all relative distances are roughly the same). The main advantage of this method is that the number of rays used can be set precisely. The speed by which rays are generated is limited by geometry population, which seems to slow down drastically when the amount of points to be added is in the order of 10K.

Keeping in mind the limitations imposed by Grasshopper, the source generation method that is implemented in this study follows a process described by Tenenbaum et al. (2007, p. 212). The triangular faces of a regular icosahedron are split into four new triangles, and this process is repeated several times. All intersection points are then projected outwards from the center of the source, as shown in figure 22. The number of rays can be calculated with the following equation:

$$N_R = 2 + 10 \cdot 4^n$$

N_R = total number of rays [-]
n = amount of subdivisions

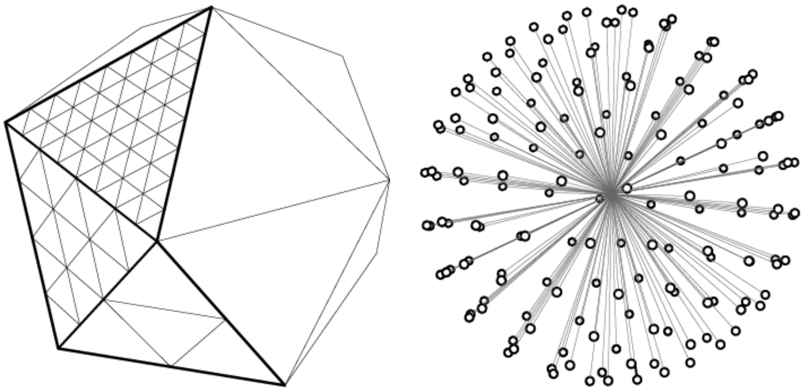


Figure 22. Using subdivided icosahedra (Tenenbaum et al., 2007, p. 212) to generate starting rays

The icosahedron method is chosen as, out of all tested methods, it provides the best trade-off between the homogeneity criterion, ease of implementation and the speed in which rays are generated. This comes at the expense of precisely controlling the amount of rays used.

Reflection modelling

The tracing process is comprised of a repeating series of projection operations determining the interaction of rays with the modelled geometry. Points are projected along the starting rays, which are given by the sound source, until a room boundary surface or an obstacle within the room is encountered. Upon intersection of a ray with geometry, the following actions are performed in quick succession:

- Point of intersection is given;
- The angle and direction of the surface is evaluated at the intersection point;
- Reflection coefficient of said surface is stored for future reference.

In accordance with theory given in *paragraph 5.2*, the directions for specular and scattering reflections are constructed for each ray. Since the angle of incidence equals the angle of reflection for specular rays, only a straightforward mirroring action is required for the construction of specular reflections. In 3-D space this is most easily accomplished by reversing the incident vector, then rotating it 180 degrees using the surface normal as rotation axis. This method works regardless of whether an incident ray strikes the front or back side of a surface.

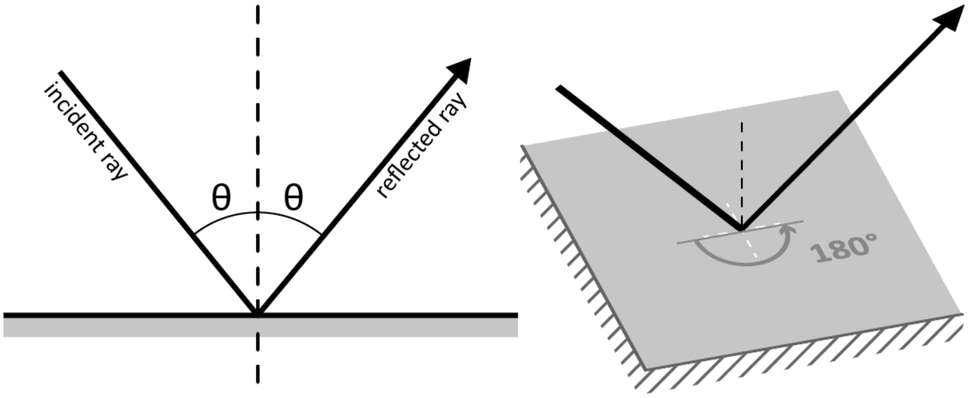


Figure 23. Construction of specular reflection vector

The distribution of scattered sound energy follows Lambert's cosine law. This roughly comes down to the reflection of energy in all directions, the intensity of which is highest at a reflection angle perpendicular to the surface. The intensity of sound scattered in the direction of a certain reflection angle is given with the following equation (Kuttruff, 2009, p. 122; Vorländer, 2008, p. 46):

$$\left|\bar{I}\,(\vartheta)\right| = B_0\ dS\ \frac{\cos\vartheta}{\pi\, r^2}\ (1 - \alpha)$$

I = intensity of sound scattered in defined direction [W]
B_0 = irradiation strength on the wall [W m^{-2} s^{-1}]
dS = area element of the wall [m^2]
ϑ = scattering angle of reflection
r = measuring distance from wall [m]
α = absorption coefficient [-]

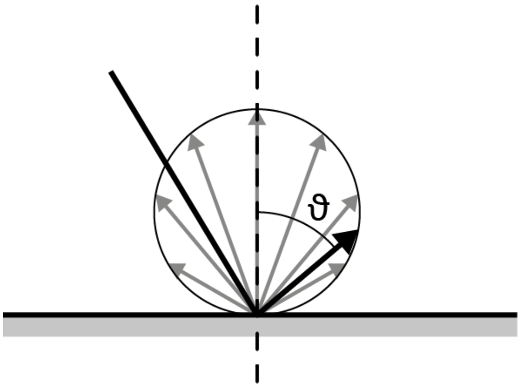


Figure 24. Lambert distribution of diffuse reflected sound energy

From a computational perspective, generating new rays at each reflection point to model scattering is not feasible, as it would lead to an explosion of calculation time, even more so if several angles are to be considered. For application in a computer model, one scattering angle is instead chosen for each reflection at a time according to Lambert distribution. This is done by generating two random numbers from which the polar and azimuth angle of the new direction are calculated (Kuttruff, 2009, p. 319):

$$\theta = \arccos \sqrt{z_1}$$

$$\varphi = 2\,\pi\, z_2$$

θ = polar angle
φ = azimuth angle
z = random numbers between 0 - 1

Schröder & Pohl (2013, p. 3) identify two commonly applied scattering implementations in acoustic simulations:

- Hybrid reflectance – sound reflection is strictly decomposed in specular and diffuse energy portions, which are then handled separately;
- Vector mixing – in this case a single reflection direction is determined by directly combining specular and diffuse reflections through weighted vector addition (Christensen & Rindel, 2005, p. 2).

The Grasshopper definition was initially developed based on hybrid reflectance. The separate handling of both reflection types allows us to visually inspect the functionality of the script during its development. Scattering is implemented in a manner described by Kuttruff (2009, p. 319). A fraction of all sound rays arriving at a boundary undergo diffuse reflection. The percentage of rays sent in non-specular directions for a given surface is determined by the scattering coefficient assigned to it. A few extra operations are thus needed to ensure scattering reflections are constructed correctly, and the logic by which this is done is always the same relative to the incoming direction of a ray. The incident ray is first projected onto the intersected surface. The resulting projected vector is then used to set up a plane (denoting a local coordinate system) upon which the reflected vector is constructed going by polar and azimuth angles (figure 25).

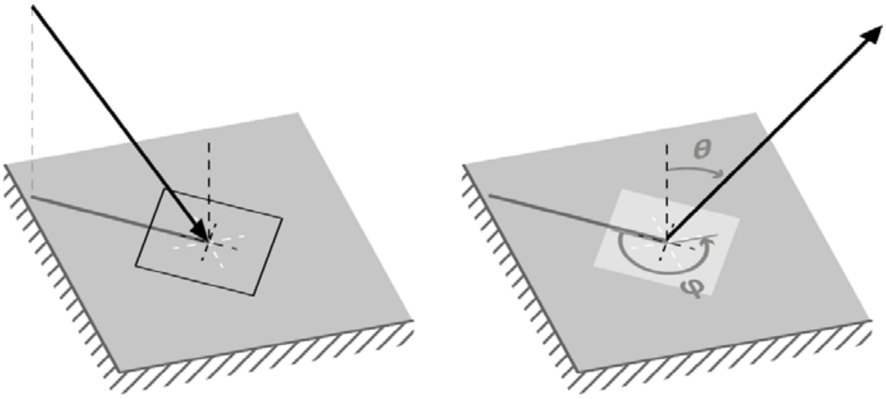


Figure 25. Construction of scattered reflection vector

The normal direction of the intersected surface is important to take into account upon construction of the local plane. If an incident ray projects onto the backside of a surface, the normal needs to be flipped in that particular instance to prevent the reflection vector from being constructed on the wrong side of the surface, resulting in rays passing through walls.

When all reflections are constructed, the previously described operations in the tracing process are repeated. The intersection points are projected along the reflected rays to find the next intersection, where the subsequent reflection is determined, and so on.

Issues found in the tracing process

After the initial projection from the sound source, each iteration in the tracing process uses the found intersections as starting points. The next projection should yield a new intersection somewhere else on the modelled geometry. It is observed however that this projection will return a false result, since the starting points already coincide with a surface in the set of target geometry. The precision with which projection and intersection operations are executed in Grasshopper are reliant on the units and tolerances set in Rhino. This characteristic generally applies to other 3-D modelling software as well. If a point is on or near a possible target surface within a certain tolerance, the nearest point on the surface will be returned as the result of projection, as shown in figure 26 (a). To deal with this issue the surface in question could be temporarily excluded as a target. However, with a several thousand rays intersecting different geometry, multiple geometric configurations would have to be handled simultaneously. Correct tracing can also be enforced by nudging a point off the surface in the reflection direction, for a small distance exceeding the unit tolerance (b). This approach is much simpler to implement since no geometric alterations are required for it to work. In the first developed definition each point is pre-moved by $5 \cdot 10^{-3}$ units before it is projected further.

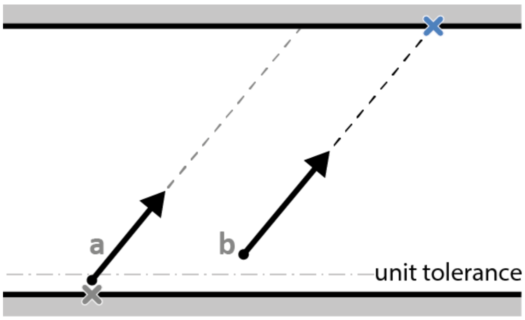


Figure 26. Relation of point projections and model unit tolerance

Systematic errors occur when rays are cast into concave corners (figure 27). Since the single evaluated surface normal in these cases falls in line with another surface, specular reflections especially run the risk of escaping the room boundaries (a). Theoretically this can be addressed if the normals of both surfaces making up the corner are averaged (b), which is certainly a correct approach from a purely geometric standpoint.

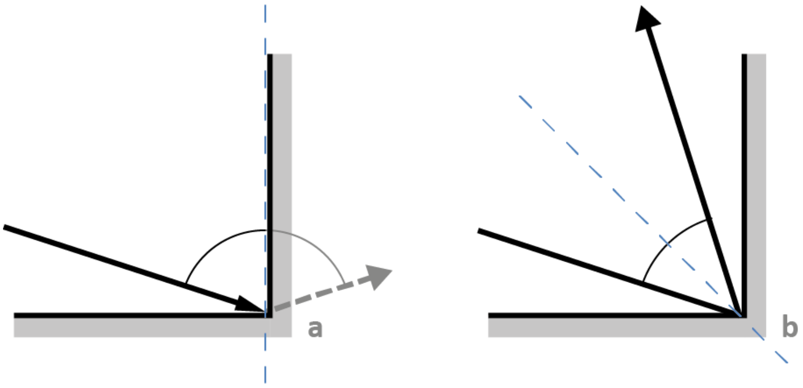


Figure 27. Construction of reflections for rays projected into corners

In practice implementing this solution turns out to be computationally expensive in terms of calculation time. First, the distance of each intersection to the edge of a surface needs to be evaluated, which requires closest point projection. The adjacency of all surfaces is checked for the corner edges in question. Only then can the relevant normals be found and averaged. The domain within which a scattering reflection can be generated also needs to be limited to the inside angle of the corner, again to prevent rays from escaping the room boundary.

Receiver modelling

The conversion of data generated during the tracing process into quantifiable acoustic parameters, is handled by the receiver. Great attention must thus be given to the model of the receiver, particularly regarding its shape and size, as these determine whether ray tracing data is interpreted correctly. As a general rule, a traced ray must meet a detection condition at the position of the receiver in order to contribute to the impulse response of the room. The probability of detection occurring is a function of the detector size (Lehnert, 1993, p. 208). With this in mind, point receivers can be ruled out from the get-go, because the chance that an infinitely thin ray will hit a point is practically nil. Several suggestions are given for plane and volume receivers in literature. Savioja (1999, p. 20) points out that using a sphere is usually the best choice in practice since it provides an omnidirectional sensitivity pattern and is easy to implement. In other words, the cross-section of a sphere is a circle of constant size for all directions. They are not subject to complicated directional characteristics observed in cubic and planar detectors.

The size of spherical receivers to be used poses a far from trivial problem. Lehnert (1993, pp. 208-210) found that the use of receivers of constant size leads to systematic errors. Instead the use of spheres with a changeable radius is proposed based on the following formula, which is derived in order to achieve a constant density of rays across the solid angle of the receivers:

$$r = l_{max} \cdot \sqrt{\frac{2\pi}{N}}$$

r = radius of spherical receivers [m]
l_{max} = maximum length of a ray [m]
N = total number of rays [-]

The formula above does not account for the size of the room. Furthermore it is a function of ray length, meaning the receiver size will be different for each ray, which in turn drastically increases computation time. For this reason Xiangyang et al. (2003, p. 436) derive the following equation for the volume of a receiver as function of room size and receiver distance:

$$V_{rec} = \omega \cdot d_{SR} \cdot \sqrt{\frac{4}{N}},$$

with:
$$\omega = \log(V_r)$$

V_{rec} = volume of the receiver [m^3]
ω = weight factor dependent on room volume [-]
d_{SR} = distance from source to receiver [m]
N = total number of rays [-]
V_r = volume of the room [m^3]

The latter definition for receiver size is applied. As illustrated in figure 28, the amount of rays detected at each receiver will vary with its size. Simply taking the average energy reaching each receiver will lead to inconsistent results. Tenenbaum et al. (2007, p. 214) states that this inconsistency can be solved with a conversion from energy or sound power to sound intensity, implicitly bringing the receiver size into the equation.

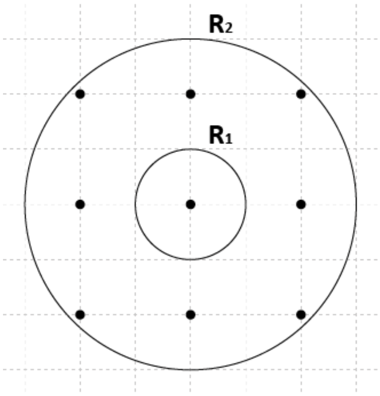


Figure 28. Different detection rates with variable receiver size (Tenenbaum et al., 2007, p. 214)

The detector is considered in this case as a circular plate which rotates around its center, so an incoming ray is always perpendicular to the receiver. This, in fact, comes down to the same as the cross-section of a sphere with similar radius. For the implementation in Grasshopper the detection condition is when a ray intersects with a receiver sphere (intersection events are handled with a default component). In all, the steps outlined in figure 29 are taken in the calculation of SPL at the receiver position, from a given source pressure level and the ray tracing process that follows:

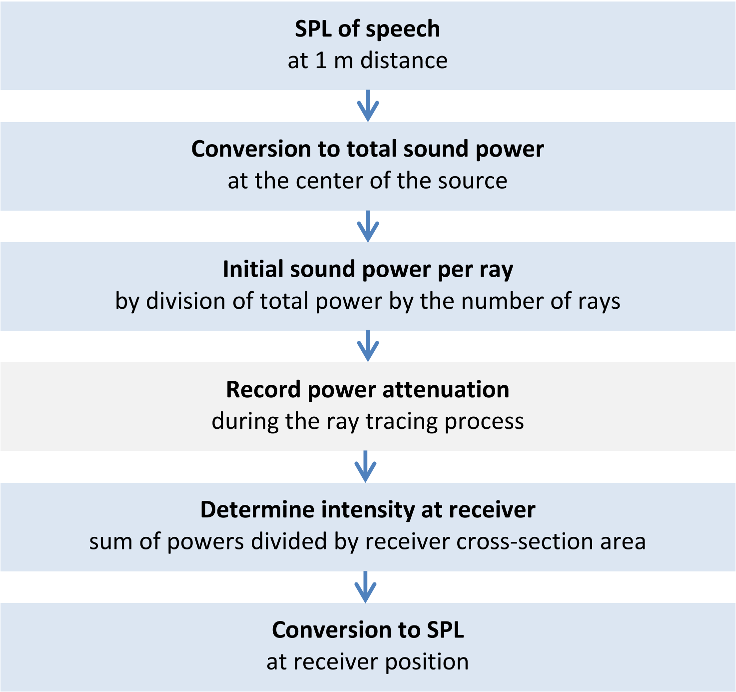


Figure 29. Steps taken for the calculation SPL at receiver

The mathematical elaboration for this routine is given. The SPL is assumed as 60 dB for starters, which is the sound level of typical speech noise at 1 m distance. This value is then recalculated to sound power level at the center of the source using the formula below, which returns 71 dB as its result:

$$L_w = L_p - 10 \log\left(\frac{Q}{4 \pi r^2}\right)$$

L_p = SPL of speech at 1 m distance = 60 dB
L_w = sound power level of source [dB]
Q = source direction factor = 1 (omnidirectional) [-]
r = distance from source = 1 m

The sound power left in each ray by the time it reaches the receiver is calculated with the next formula. In plain English it states that the starting power of a ray is multiplied with the reflection coefficients of each wall that is encountered in its path from source to the receiver. The equation also includes a factor for air absorption e^{-mL}, which is neglected in the final Grasshopper definition:

$$W_i = \frac{W_s\, Q}{N}\, e^{-mL} \prod_{j=1}^{J} (1 - \alpha_j)$$

with:

$$L_w = 10 \log\left(\frac{W_s}{W_0}\right) \Rightarrow W_s = W_0 \cdot 10^{0{,}1\, L_w}$$

W_i = sound power carried by ray ‘i’ [W]
W_s = sound power of source [W]
W_0 = reference sound power = 10^{-12} W
Q = source direction factor = 1 (omnidirectional) [-]
N = total number of rays [-]
m = air absorption coefficient [-]
L = travel distance of ray ‘i’ from source to receiver [m]
J = amount of reflections involved in the sound path [-]
α_j = absorption coefficient of the wall at reflection ‘j’ [-]

The power of all detected rays are summed, then divided by the area of the cross-section of the respective receiver (a circle with radius r):

$$I_r = \frac{\sum_i W_i}{\pi r^2}$$

I_r = sound intensity at the receiver [dB]
W_i = sound power carried by ray ‘i’ [W]
r = radius of the receiver [m]

Finally, sound intensity is reconverted to sound pressure level:

$$L_{p,r} = 10 \log\left(\frac{\rho\, c \cdot I_r}{p_0^2}\right) \approx \left(\frac{I_r}{I_0}\right)$$

$L_{p,r}$ = sound pressure level at the receiver [dB]
$\rho\, c$ = acoustic impedance ≈ 400 - 410 Pa s m^{-1}
p_0 = reference sound pressure = $2 \cdot 10^{-5}$ Pa
I_r = sound intensity at the receiver [dB]
I_0 = reference sound intensity = 10^{-12} W m^{-2}

Still, the receivers may pick up rays that are invalid in terms of the geometric model due to their finite size. Examples of this are depicted in figure 30. According to Lehnert (1993, pp. 209-210) the first two detection problems, namely when a sound source is shaded (a) or when the reflection point is not located within the wall (b), can be viewed as rough models of diffraction and diffuse reflections. These can be tolerated as such. The error caused by receivers detecting rays on the backside of a wall (c) needs to be avoided at all cost. For this study this is taken care of manually. No measuring points are taken where a receiver may intersect with geometry. In the case that this occurs a receiver will be moved to a different position or not be considered at all.

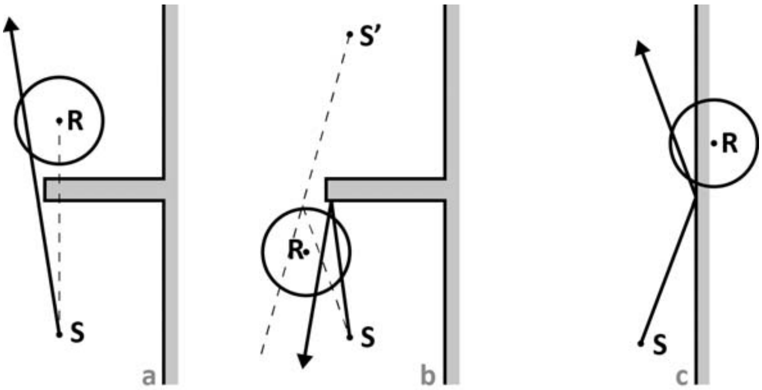


Figure 30. Invalid detections of volume receivers (Lehnert, 1993, p. 210)

9.3 DEFINITION 1: COMPONENT BASED LOGIC

The first definitions were initially made using standard components, following the logic outlined in previous paragraph. Figure 31 is an illustration of a completed network including all subroutines of the ray tracing process. For following definitions fixed geometry is defined by referencing a Rhino model. The example shown uses approximately 120 components from input to output.

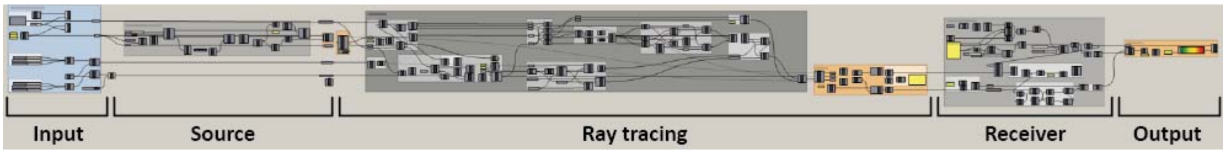


Figure 31. Grasshopper component network of 'definition 1'

Repetitive routines

Both source generation and the tracing process consist of routines that are repeated. Of itself, a loop operation cannot be defined using the standard Grasshopper components. This can be circumvented with custom code, however there are also several add-in components available online made specifically for this purpose. Table 11 shows a comparison between a few examples that were tested on the definition.

	Hoopsnake 0.6.7	Anemone 0.26	OctopusLoop 0.1
Can be triggered on-canvas	×	✓	✓
Takes downstream termination conditions	✓	×	✓
Works directly with evolutionary solvers	×	×	✓
Runs definition to completion	✓	✓	×

Table 11. Direct comparison of features between tested loop component add-ins for Grasshopper

In the tracing process presented here, reflection points, absorption coefficients at each reflection and vectors for the direction of continuation, are handled using separate matching data lists. Keeping that in mind, Hoopsnake was dismissed early on as a viable solution for this case. With Hoopsnake (Chatzikonstantinou, 2014) a single component is used to send the output of a set of components back to its input, resulting in a feedback loop. The upside of this method is that a termination condition for the looping process can be taken from anywhere downstream in the definition without limitation. However, Hoopsnake only handles a single data stream at once, which means aforementioned data lists would have to be combined, and later separated again, in order to be fed through the component. Furthermore the start of a looping process needs to be triggered manually in this case, ruling out the possibility to be used in conjunction with evolutionary solvers such as Galapagos and Octopus. In this regard, OctopusLoop (Vierlinger & Zimmel, 2015b) seems like a promising alternative, since the components included in the looping process are evaluated in a separate context, which in turn allows it to be used with aforementioned solvers. OctopusLoop, currently a work-in-progress first release, turned out to be an unstable solution when paired with the definition. The tracing process would either cease prematurely or cause Grasshopper to crash entirely. In the final versions of 'definition 1' Anemone (Zwierzycki, 2014) is used to create simple loops for source conception and ray tracing routines. The contents of these loops are defined with two components denoting their beginning and end. Looping is triggered manually with a Boolean toggle (although this could also be replaced with a routine that detects change of input) and repeats the given routine for a preset number of times. This number is determined by dividing sound propagation in the investigated time frame – 1 s (= 343 m) – by the mean free path length of the room.

Evaluation of features

The features and limitations of analysis software and scripts used up to this point in the study were tested by tracing at least 10.000 rays in a Rhino model of the BT Studio. The results are given in table 12. For CATT-Acoustic the same model is exported and the material properties are matched accordingly. A full detailed calculation is then performed, with the number of rays and truncation time set automatically by the program.

	CATT-Acoustic 8	**Pachyderm GH**	**Acoustic Shoot VB**	**Custom Definition 1**	**Custom definition 2**
Multiple sources	✓	✓	×	-	✓
Multiple receivers	✓	✓	-	-	✓
Multiple frequencies	✓	✓	×	×	×
Absorption	✓	✓	✓	✓	✓
Scattering	✓	✓	×	✓	✓
Trimmed surfaces	mesh	-	×	✓	mesh
Curved geometry		-	✓	✓	
Back-faces	✓	-	✓	✓	✓
Parametric optimization	×	-	✓	✓	✓
Time to solve >10K rays	4 min.	15 min.	6 min.	**1h. 15m.**	< 2 min.

Table 12. Comparison of features between tested programs and definitions

First of all it needs to be noted that both CATT-Acoustic and Pachyderm are hybrid models that are capable of taking multiple frequency bands into account in a single simulation run and, as a whole, are far more advanced (containing extra features which obviously add to calculation time) compared to the simple ray tracing definitions created within Grasshopper.

The most striking weak point of the custom definition developed for this study is its excruciatingly slow calculation time. The modularity of Grasshopper becomes a big disadvantage in terms of computation time as vast amounts of data need to be sent from one component to another. Considering several hundred-thousand reflections may be calculated, the entire operation is bottlenecked by this transfer of data. To have any chance of creating a workable solution the amount of components used should thus be limited. Though the creation of a ray tracer relying on a network of default components without custom code is technically possible, such a definition is highly unpractical in use even when limited to this study.

9.4 DEFINITION 2: C# CODED RAY TRACER

Changes in comparison to model 1

A faster definition has been created for this study to replace the first one. The entire tracing portion and part of the receiver modelling are condensed into two C# scriptable components with code based on RhinoCommon libraries:

- Tracing process – Takes starting rays and room geometry as input. Amongst other data, returns traced rays and remaining energy at each reflection point;
- Ray history interpreter – Checks which segments of every ray cross a receiver (basically a selection of relevant data). Outputs the amount of energy left for crossing rays and their distance to the center point of a receiver.

The applied logic is overall similar to the first definition, however differs in its implementation in a few details. First off, scattering is modelled according to vector mixing or ‘vector based scattering’, as the method is referred to by Christensen & Rindel (2005, p. 2). Specular and scattering reflections are both generated, with the latter being picked at random from a Lambert distribution. The scattering coefficient determines the weighting between the two, with a coefficient of 0 equating to pure specular reflection; 1 equals purely random scattering. The resultant ray is constructed according to figure 32.

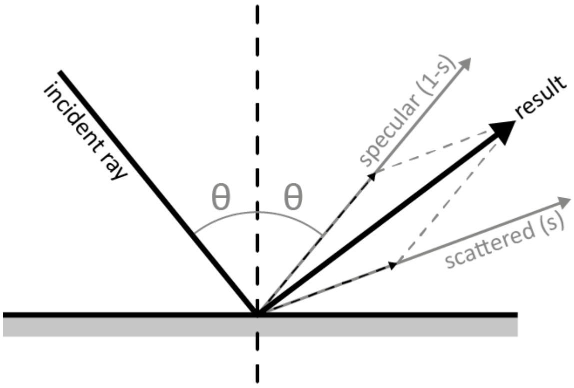


Figure 32. Scattering included through vector addition (Christensen & Rindel, 2005)

A second difference, and a main advantage of custom code, is the relative ease in which termination conditions are defined. The capabilities of aforementioned loop components are limited in this respect, what mostly comes down to repeating operations a discrete number of times. Rays will be traced for an unnecessarily long time and distance, plus they will also greatly differ in length. Describing a better termination condition is beneficial, since most of the needless information will not be generated in the first place, which in turn causes a significant increase in calculation speed for late reflections. The termination conditions are applied here as such that the tracing process will discontinue for a certain ray when:

- Its remaining energy falls below a 10^{-12} fraction of the initial energy;
- Path length exceeds 343 m (= 1 s).

Modelling geometry

The description of geometry in CAD modelling plays an important factor in acoustic simulation. Here, two types of geometric construction are distinguished and briefly discussed:

- Using NURBS ('non-uniform rational b-splines') – With NURBS free-form surfaces are accurately described through curves which are mathematically defined by their order, a set of weighted control points and a knot vector (Burry & Burry, 2010, p. 263).
- Using meshes – A mesh is described as a collection of points, or vertices, arranged into basic elements called faces. These faces are bounded by polygons, which are figures that consists of a sequence of straight line edges (Pottmann et al., 2007, pp. 381, 716).

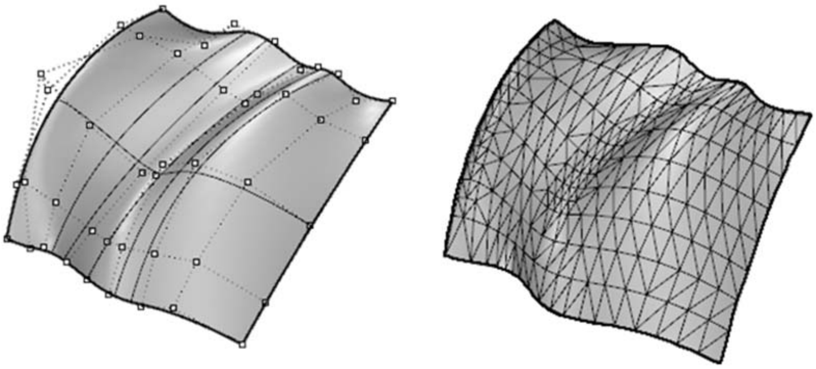


Figure 33. The same surface in Rhino described using NURBS (left) and mesh geometry (right)

Meshes mainly differ from NURBS in that smooth surfaces are roughly approximated. A curved surface described as a mesh is, strictly speaking, not smooth. At an architectural scale smooth free-form geometry is usually not economically feasible, especially in the case of typical offices. Approximation by meshing can thus hardly be seen as a drawback. Rhino, though capable of interpreting and manipulating mesh geometry, is primarily a NURBS modeler. As the same applies for parameterization in Grasshopper, most of its definitions take NURBS surfaces as their input. The latest definition takes mesh geometry as input for the ray tracing process, which is in line with commercial acoustic simulation software like CATT-Acoustic, as shown in table 12. To be more specific, NURBS geometry is converted on the canvas of Grasshopper to a single closed mesh consisting of triangulated planar faces. Information on surface absorption and scattering is temporarily stored as mesh colors. Geometry and material properties are thus fed into the ray tracer at once. As a whole this setup showed a drastic improvement in calculation time compared to previous definitions.

Functionality and limitations

In its current form ‘definition 2’ offers limited abilities to assess and visualize acoustic performance at a room scale. As of now, strictly sound pressure levels at receiver positions are evaluated for a single frequency band at a time. The way in which SPL is calculated, as previously explained in *paragraph 9.2*, neglects air absorption. Results from the tracing process can only be expressed in parameters which can be directly derived from SPL, such as strength G or sound decay DL_2. STI for example, requires analysis across all frequencies in the speech spectrum since each octave band is weighted separately.

Upon interpretation of ray history, the elapsed time and remaining energy of each ray crossing a receiver are stored. When sorted this information can be used to plot energy-time curves and subsequently calculate reverberation time. However, this is currently not included in the definition.

Finally, as this definition is purely based on ray tracing, the general limitations of geometrical acoustic techniques apply. Wave phenomena such as interference and edge diffraction are not considered in the script. The validity of the results given by this model thus do not extend to studying sound propagation at very low frequencies, since the wavelengths in those regions cannot be considered negligibly small compared to the size of an office. This is also something that generally needs to be taken into account when creating the geometric models to be used in acoustic simulation, this definition being no exception. Furthermore the normals of all surfaces in the modelled geometry need to manually checked, ensuring that all are pointing towards the interior of the space (to the same side as where the source is positioned). As of this writing the scripted definition does not handle back-faces. Internal partition walls and obstacles thus need to be modelled as volumes.

10 BENCHMARKING

10.1 VALIDATION OF THE CUSTOM DEFINITION

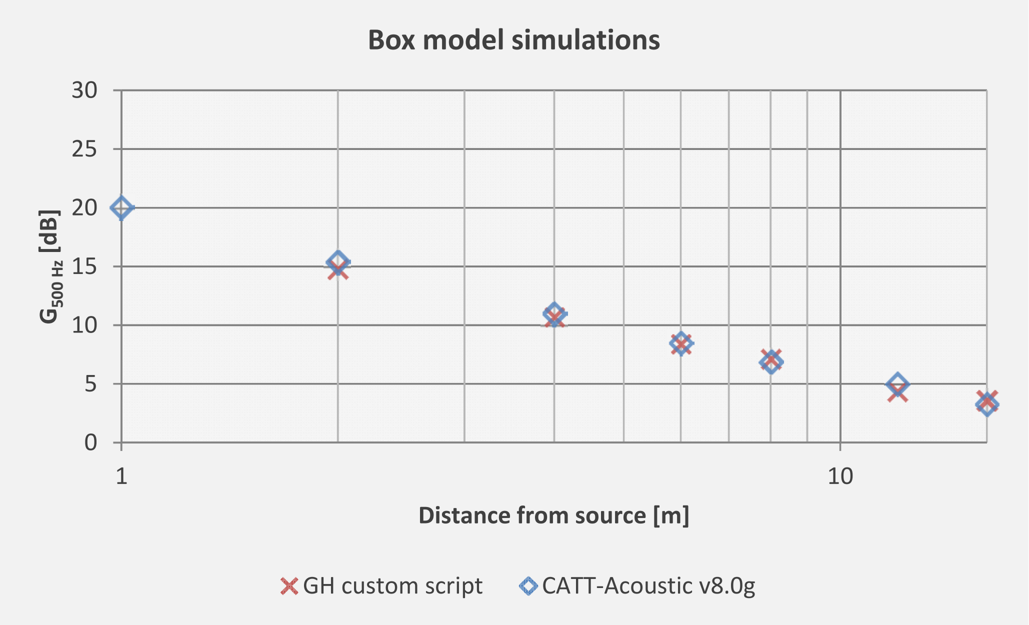
Box model

In order to validate the accuracy of the developed definition, its results are compared to those of a full detailed simulation run performed in CATT-Acoustic. This is done firstly for a simple shoebox model without any doors or windows. Dimensions are 34,6 x 12,1 x 3,9 m (similar dimensions as the BT Studio). The material properties are set as indicated in table 13.

	α [-]	s [-]
Floor	0,60	0,60
Walls	0,20	0,10
Ceiling	0,80	0,60

Table 13. Material properties of box model

Below the direct comparison is shown of the results given for analysis of the same model by CATT and Grasshopper. The highest deviation between any two measurements is 0,6 dB. This is below just-noticeable difference for human hearing. DL_2 is nearly identical.



Graph 10. Sound strength returned by simulations for box model

	1 m	2 m	4 m	6 m	8 m	12 m	16 m	DL_2 [dB]
CATT	20,1	15,4	11,0	8,5	6,9	5,0	3,3	4,3
GH script	20,0	14,8	10,7	8,4	7,1	4,4	3,6	4,2

Table 14. DL_2 calculation from G-values [dB] for box model simulations

BT Studio

Similar comparisons have also been made for a Rhino model of the BT Studio (figure 34). This was done for both an empty room, plus a room with furniture. The results are given for the furnished situation.

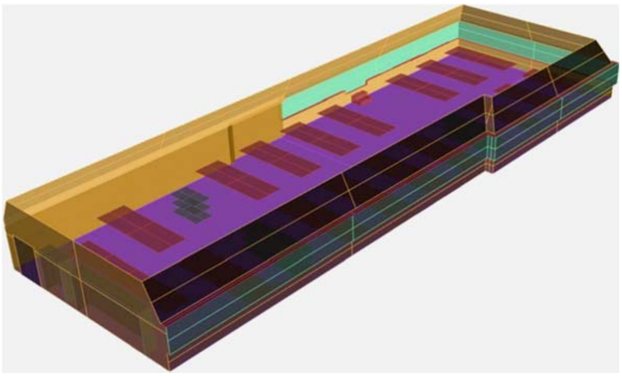
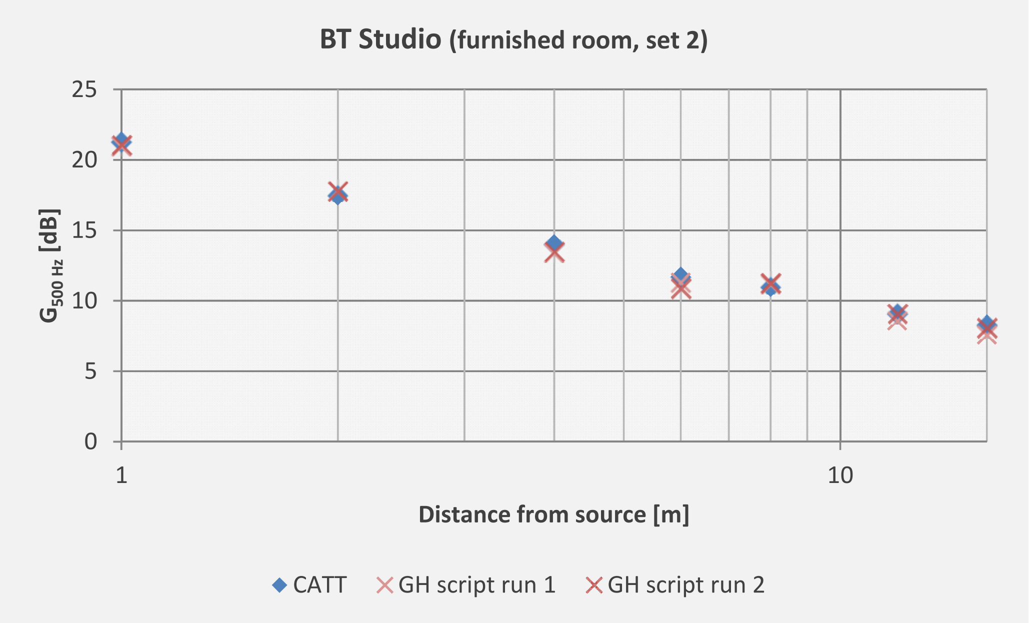


Figure 34. Rhino model of BT Studio

The Grasshopper script is run twice in this case. The highest deviation between CATT and Grasshopper measurements is 0,8 dB. This is below just-noticeable difference for human hearing. DL_2 is again practically identical with differences smaller than the margin of error of the calculation itself.



Graph 11. Sound strength returned by simulations for BT Studio model

	1 m	2 m	4 m	6 m	8 m	12 m	16 m	DL_2 [dB]
CATT	22,8	17,5	14,0	11,7	11,0	9,1	8,3	3,1
GH run 1	21,0	17,8	13,4	11,3	11,2	8,6	7,6	3,3
GH run 2	21,1	17,8	13,5	10,9	11,3	9,1	8,1	3,1

Table 15. DL_2 calculation from G-values [dB] for BT Studio simulations

Office A

Finally the script is validated for the open space in office A as well using the model shown in figure 35. The receiver positions are the same as used in the impulse response measurements for this case (outlined on page 46).

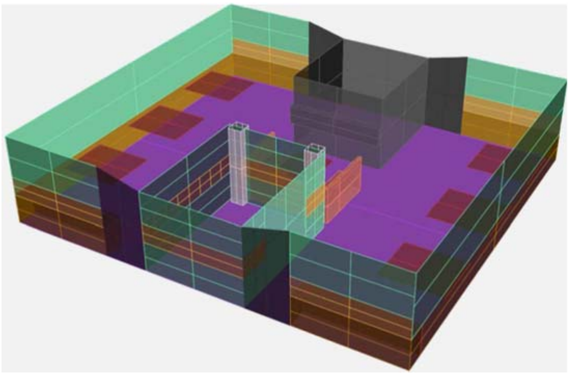


Figure 35. Rhino model of office A

At two receiver positions deviations are observed between CATT and Grasshopper measurements which exceed just-noticeable differences. Upon inspection these receivers turned out to be intersecting with geometry, thus suffered the detection problem illustrated in figure 30c. This was corrected in another run by moving the measuring line 0,3 m upwards. As shown below, the differences for both SPL and DL_2 fall within the margin of error of the calculation in the corrected runs.

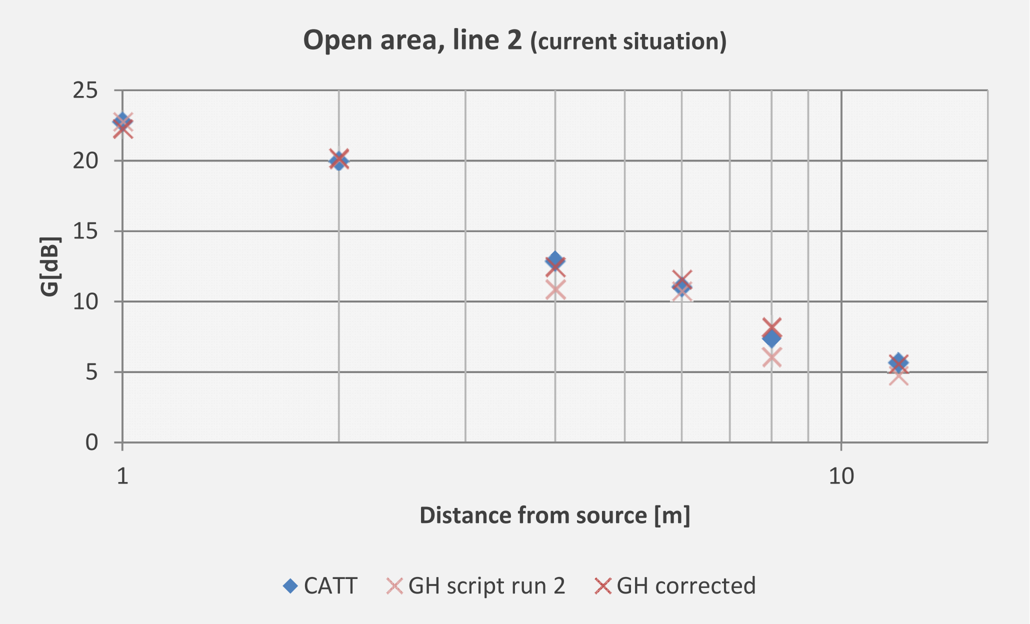


Figure 36. Sound strength returned by simulations for office A model

	1 m	2 m	4 m	6 m	8 m	12 m	16 m	DL_2 [dB]
CATT	22,8	20,0	12,9	11,1	7,4	5,7	-	6,0
GH run 2	22,8	20,1	10,9	10,8	6,1	4,8	-	6,5
GH corrected	22,3	20,2	12,5	11,6	8,2	5,6	-	5,8

Table 16. DL_2 calculation from G-values [dB] for office A simulations

10.2 STATISTICAL RUNS

Simulation setup

To get a feel for the magnitude of changes brought about in the acoustic properties of a room when a design configuration is altered, different parameterized box models have been evaluated. These are 3 simple and predictable cases designed to initially validate the parametric search runs using the Galapagos evolutionary solver.

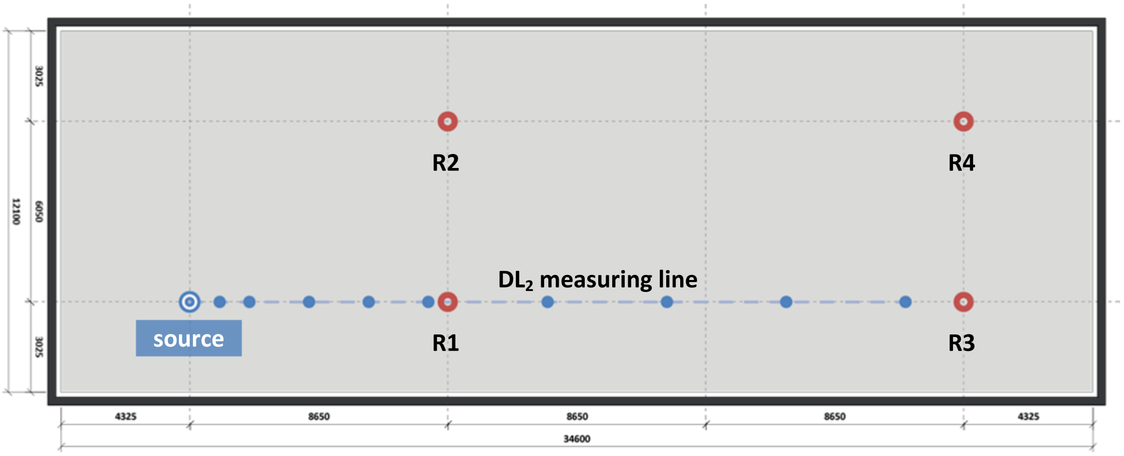
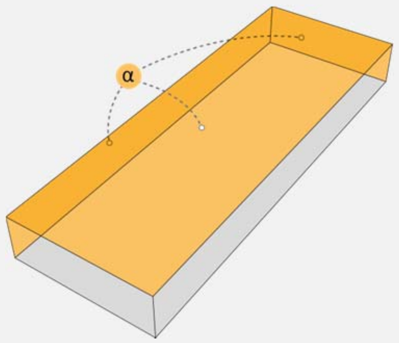


Figure 37. Measurement setup for analysis and single-objective optimization

Two measurements are performed in the simulations described in this paragraph. The setup firstly consists of a straight line of receivers to determine DL_2 in the range from 1 m to 24 m distance from the source. The receivers are in order placed at 1 m, 2 m, 4 m, 6 m, 12 m, 16 m, 20 m and 24 m. A second setup considers just sound pressure given at the positions denoted by R1-R4 in figure 37. The SPL measured across these four positions is then averaged to a single value.

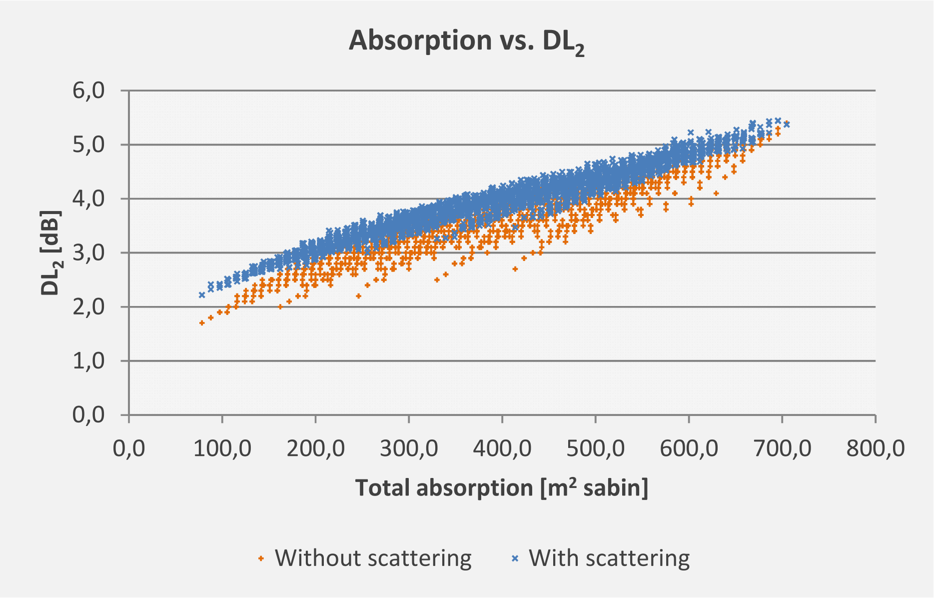
Model 1: changing wall and ceiling absorption

In this instance a simple box is taken. The absorption coefficient of the walls and ceiling are parameterized. Each can assume a value out of 5 possible choices (0,10; 0,30; 0,50; 0,70 or 0,90). Scattering coefficients are kept constant at 0,10 for all parameterized surfaces and 0,60 for the floor. This leads to a grand total of 3125 different configurations for the model. All instances are cycled through one-by-one. This process is performed twice: the second time scattering is taken out of the equation. The total amount of absorption applied in the room is calculated and recorded, as are SPL and DL_2.



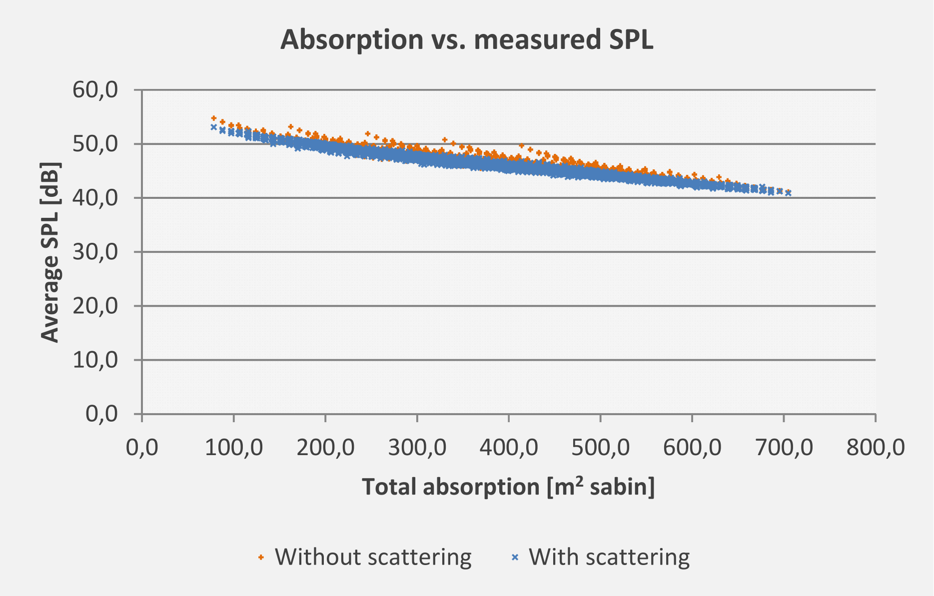
	α [-]	s [-]
Floor	0,20	0,60
Walls	variable	0,10
Ceiling	variable	0,10

Figure 38. Parameterized surfaces on box model



Graph 12. DL_2 calculated for each instance of box model with parameterized surface properties

A clear relation between spatial decay of sound and the amount of absorption applied to the room can be observed. Graph 12 also displays the effect of scattering. In the run with scattering the worst set of outcomes score higher in DL_2 (as expected). All results in that case end up closer together. The trend is also not purely linear. The absorption is returned as a single number for the entire room, not accounting for how the absorption is distributed across the surfaces. In other words, two configurations with different distribution of absorbing materials along the boundary surfaces of the room can score the same in terms of total absorption. This could also possibly explain why the graph shows multiple relations fitting different curves.

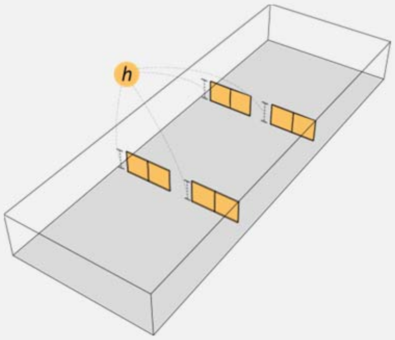


Graph 13. SPL calculated for each instance of box model with parameterized surface properties

Graph 13 shows the same multitude of relations in the run with scattering, but this time between the average SPL measured across the four receivers R1-R4 and the total amount of absorption material in the room.

Model 2: four height-adaptable screens

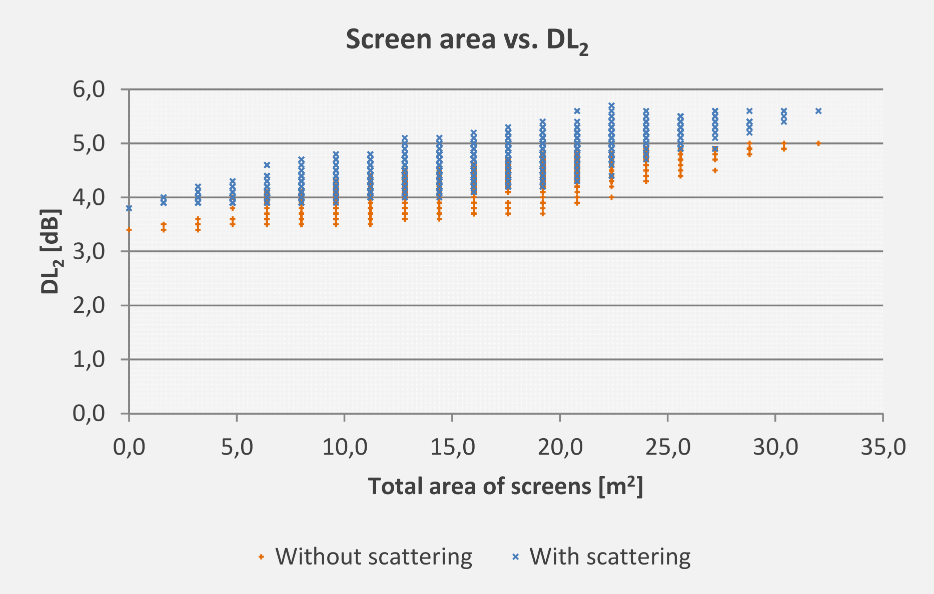
Four sets of partitions are placed on the ground in fixed locations within the room. The height of these barriers is made adjustable. Each screen can independently assume a height of 0,4 m; 0,8 m; 1,2 m; 1,6 m or 2,0 m or alternatively be removed completely. This leads to a total of 1296 unique configurations.



	α [-]	s [-]
Floor	0,20	0,60
Walls	0,30	0,10
Ceiling	0,80	0,10
Screens	0,30	0,10

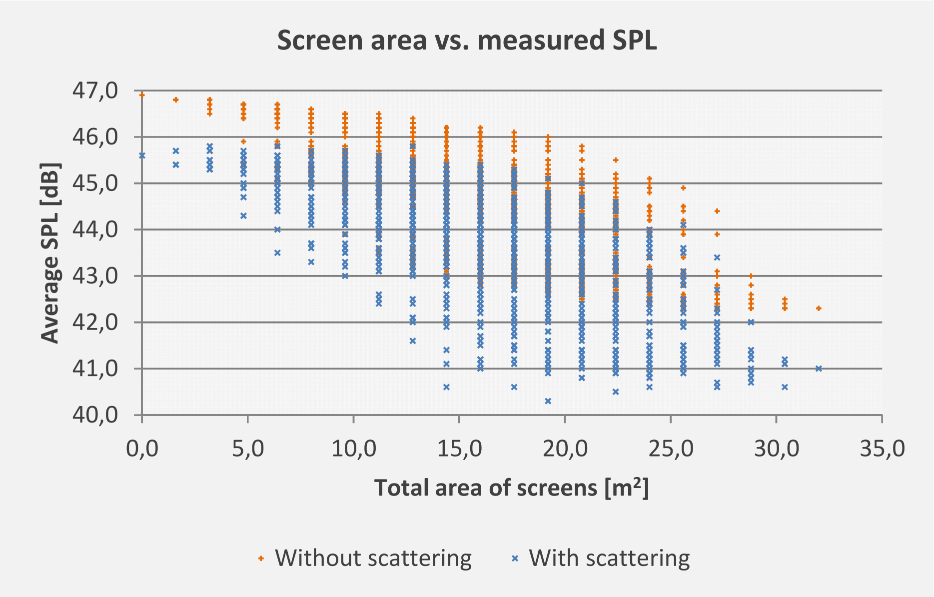
Figure 39. Placement of variable height screens

First off, the extent of which sound pressure and decay are lowered as a result of increasing screen size does not seem to be affected by whether or not scattering is taken into account. The results from the run with scattering are simply acoustically more favorable across the board.



Graph 14. DL_2 calculated for each instance of box model with parameterized internal screens

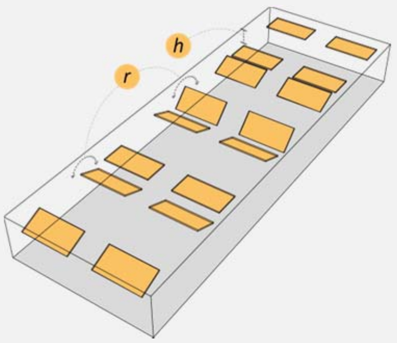
From 22 m^2 screen area and up acoustic performance is shown not to improve any further both in terms of increased sound decay (graph 14) or decrease of SPL (graph 15). The screen furthest from the source logically contributes the least to overall improvement since it only directly shields receiver R4. Especially when all other screens are raised to their maximum height, already blocking a large portion of propagated sound energy, the effect of adding this fourth barrier is minimal.



Graph 15. SPL calculated for each instance of box model with parameterized internal screen

Model 3: adjustable ceiling panels

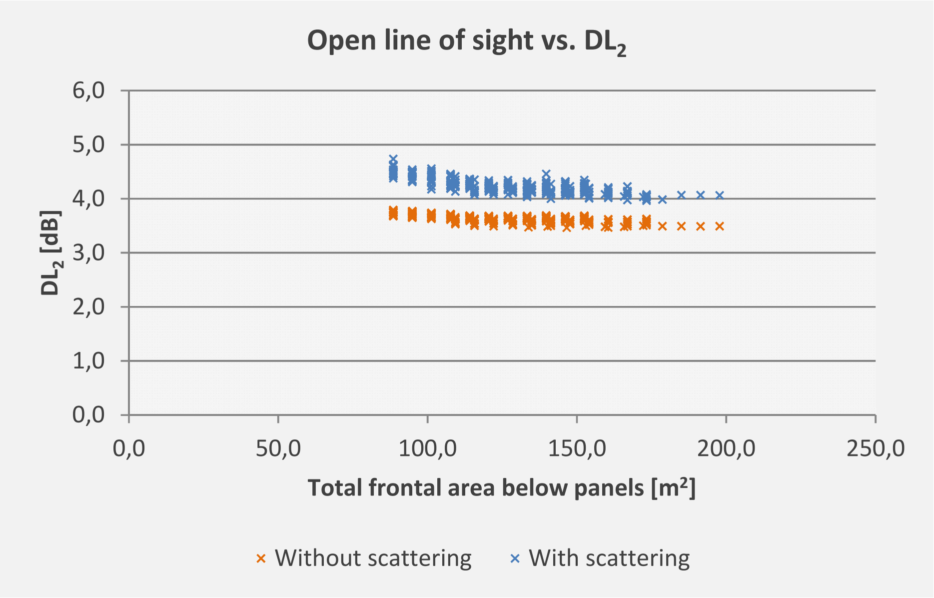
This model tests a slightly more radical solution using eight sets of two rotatable ceiling mounted panels. Each set can rotate 45 degrees to either side relative to horizontal position in increments of 22,5 degrees. The height of the entire ensemble is also variable, allowing for an adjustment between 0,8 m and 1,6 m distance from the ceiling with a 0,1 m increment. A total of 275 configurations are plotted. Rotation is in this case not assigned to each set independently, but is kept the same for every other row (one value for even rows; another for uneven rows).



	α [-]	s [-]
Floor	0,20	0,60
Walls	0,30	0,10
Ceiling	0,80	0,10
Panels	0,80	0,10

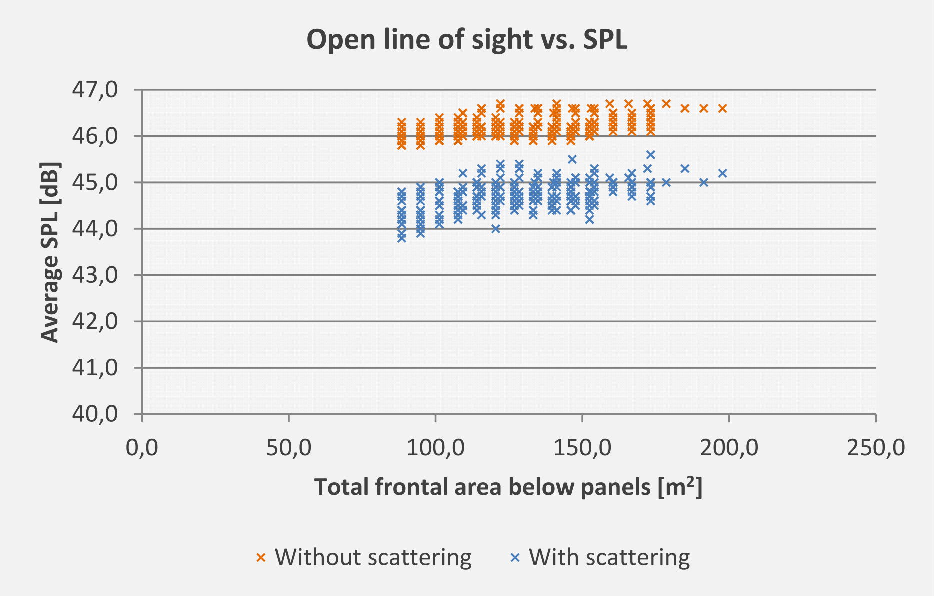
Figure 40. Positioning of ceiling mounted panels

In the following graphs each configuration is assessed by the amount of space left below the ceiling panels, the so called frontal area for open line of sight. A lower score for frontal area equates to panels being lower to the ground. The effect of this solution is minimal, to the point of the difference between the alternatives with the best and worst acoustic performance being barely unnoticeable for human hearing.



Graph 16. DL_2 calculated for each instance of box model with parameterized ceiling panels

The minimal deviation between configurations can be attributed to two factors. Firstly, the panels have the same absorption coefficient as the ceiling itself. De facto these panels have no effect on the absorption of sound energy in the room whatsoever. Instead a part of the early reflections is redirected, the effect of which as a whole is very small compared to direct sound propagation. The second factor has to do with the fact that none of the design configurations obstruct direct sound paths between the source and receivers. In order for a solution like this to yield significant improvements, these overhead panels would have to absorb a lot of energy and need to be suspended at an unpractically low height (which defeats the purpose of this solution).



Graph 17. SPL calculated for each instance of box model with parameterized ceiling panels

10.3 EVOLUTIONARY SOLVING

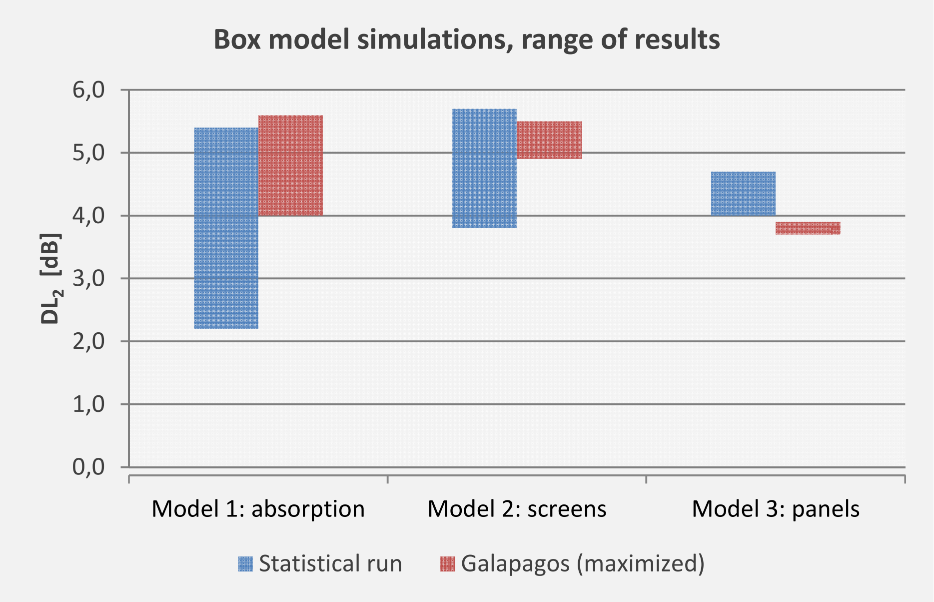
Approach of evolutionary solving

A series of simple tests have been conducted to evaluate the extents at which Galapagos is capable of interpreting and correctly operating on the models described in the previous paragraph. Included by default in Grasshopper, Galapagos is a single-objective evolutionary solver which connects to variable 'slider' inputs of a parametric model, and compares their values to a defined numeric output to assign a score to that same model. In this fashion the performance of a design configuration is linked to its properties, which enables the possibility to automatically iterate and improve on an overall design. Evolutionary algorithms – upon which Galapagos platform is based – are stochastic search methods that mimic the metaphor of natural biological evolution and / or the social behavior of species (Turrin, 2014, p. 314). These algorithms are generally used to solve optimization problems. The approach of evolutionary solving is characterized by the assessment of a pool or population of design solutions, rather than a single solution. Out of this pool, individual solutions are selected according to their adjustment to a fitness function (a formulaic description quantifying performance goals) and new solutions may be generated through mutations and crossovers of previous elites, which are those configurations displaying the most favorable traits with respect to the fitness criteria (Marin et al., 2008, p. 333).

It is not within the scope of this project to assess or develop upon the specifics of any evolutionary algorithm. The applicability of an evolutionary solving mechanism to the issue of acoustic optimization of office spaces is merely tested. *Chapter 0* deals with actual optimization of a case study. Below the results from the Galapagos benchmarks are briefly discussed.

Test results

Graph 18 shows a comparison between the statistical runs described in previous paragraph, and single-objective optimization performed on the same models using Galapagos. The bars represent the range of the answers found. The full bandwidth of possible outcomes is thus displayed by the statistical runs. DL_2 is maximized during the evolutionary solving runs. The series shown for Galapagos are those belonging to the first generation in which the highest performing instance of the entire run was found.



Graph 18. Range of values considered in Galapagos single-objective optimization on box models

Model 1, in which wall and ceiling absorption were parameterized and assessed, showed the biggest range of answers in the statistical run. It could be argue that in this case increasing absorption could constitute for the largest improvements, since its extremes are furthest apart. That conclusion is however entirely limited to the particular setups used in these models. If, for instance, all room boundary surfaces in the first model were made to fully absorb all incoming acoustic energy, at DL_2-value of 6 dB would be reached (sound decay in a free field condition). Only four walls were placed in model 2 at a distance of over 10 m apart from each other. Better performance in terms of sound decay is achievable when more and larger walls are placed within the confines of the space, possibly even exceeding the aforementioned 6 dB limit.

In principle, the maximum values found in the evolutionary solving process are expected to be the same as those of the statistical runs. A small deviation can be tolerated here, since all runs shown include scattering which introduces a slight randomness in the results. Models 1 and 2 performed in a predictable fashion with Galapagos finding solutions which approached the best alternatives in the solution space. The same cannot be said for the third model where the optimization run missed the benchmark entirely. This discrepancy may have been brought forth by a difference in settings used between both runs. The rotation of each set of ceiling panels could be assigned independently in the optimization. To limit the amount of cases to be calculated this was constrained in the statistical runs. Still, it is surprising that none of the solutions returned by Galapagos fall within the expect bandwidth. In any case the concept of model 3 was dismissed as a serious design alternative altogether, since the acoustic performance that could be attained was deemed insufficient.

On the applicability of EAs in acoustic optimization

The application of an evolutionary solving method in these tests exposed a few dilemmas of acoustic optimization. In general, when more variables are added to a parametric model, the solution space becomes larger which consequently increases the chance that the process may converge to a suboptimal solution. Including less variables and objectives inversely makes the outcome more predictable, which may ultimately defeat the purpose of automated solving entirely. Additionally it is found that random scattering in the ray tracing process (as explained on page 53) introduces variations in the measurements which, under the tested circumstances, are not negligibly small compared to the entire range of solutions. Negating scattering reflection altogether would however be physically incorrect.

11 OPTIMIZATION

11.1 SIMULATION SETUP

Multi-objective optimization

The process of optimization describes the synthetic search for the best state within a model, usually under a set of restrictions (Burry & Burry, 2010, p. 117). The role of optimization in a design system is to find the configuration in the feasible design space that best matches desired performance goals (Monks, 1999, p. 56). Negotiating the architectural implications associated with limiting sound propagation in open workspaces, by definition comprises a trade-off between diverse aesthetic and acoustic performance measures. Multi-objective optimization, which is the search for optimal values for two or more of such conflicting objectives, comes into play. The compromise between different performance aspects may be described with Pareto optimization, a state in which one thing can only improve at the expense of another (Burry & Burry, 2010, pp. 118, 262).

As a conclusion to the development phase of this study, multi-objective optimization is performed on a parametric model of the office A case study. For this purpose the Octopus plugin (Vierlinger & Zimmel, 2015a) for Grasshopper is used to assess this model across several runs. The overall process is aimed at finding a set of configurations in which a vast improvement of room acoustic characteristics is balanced with a limited degradation in the open appearance of the indoor space. The properties of Pareto optimal solutions found in this process are then compared before a final selection is made and elaborated.

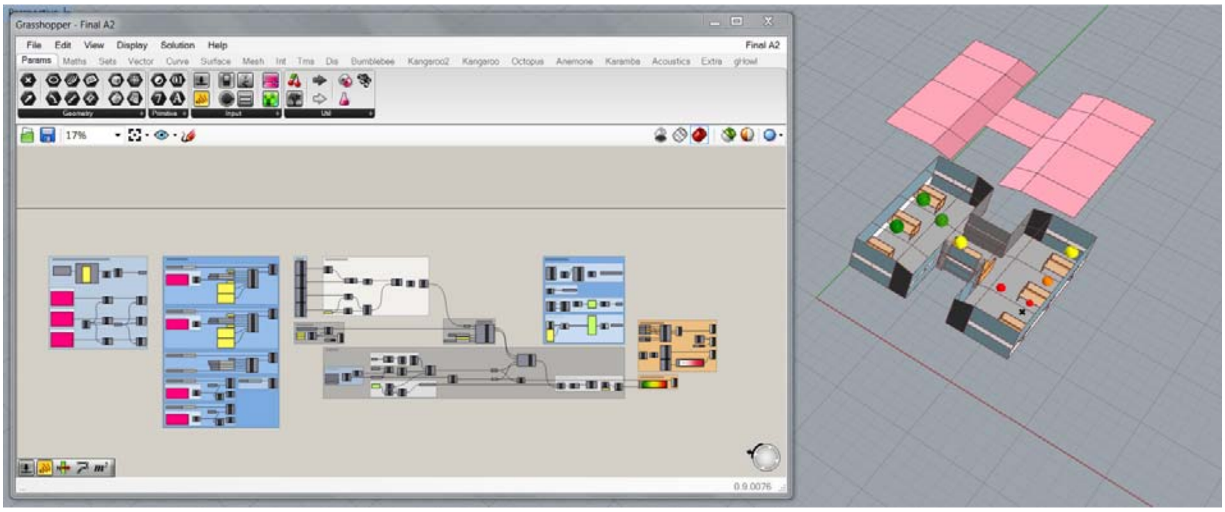


Figure 41. Screenshot of the final Grasshopper model for the multi-objective optimization of office A

Variables

The start point for the final model is the open space of office A in its current layout and material properties. The position of all the walls, the floor and ceiling, plus all furniture is fixed. The variables are as follows:

- Ceiling – The ceiling has been subdivided in 18 panels. These can have their absorption coefficient independently changed between 3 values (0,50; 0,70 or 0,90);
- Outer walls – The non-glazed portion of the façade is divided in 4 parts on each side according to the position of the desks. These parts can assume one of 3 values (0,10; 0,30 or 0,50) for its absorption coefficient. Glazed area remains unchanged;
- Internal walls – All of the glazed internal walls are parameterized. Every wall is divided over its height in three partitions. The middle portion is a closed panel with changeable absorption (0,10; 0,30 or 0,50), changeable dimensions and variable vertical position;
- Screens – Finally screens are placed in between and alongside the desks. Their height can vary in increments of 30 cm in the range of 0,9 m to 1,8 m. Their absorption coefficient is fixed to 0,30.

Parameters

All runs are performed utilizing the same experimental setup. A single source and a total of ten receivers are placed in the room model at fixed positions as indicated in figure 42, all at a height of h = 1,2 m. The sound pressure levels recorded at these positions are used to assess the acoustic performance of each instance.

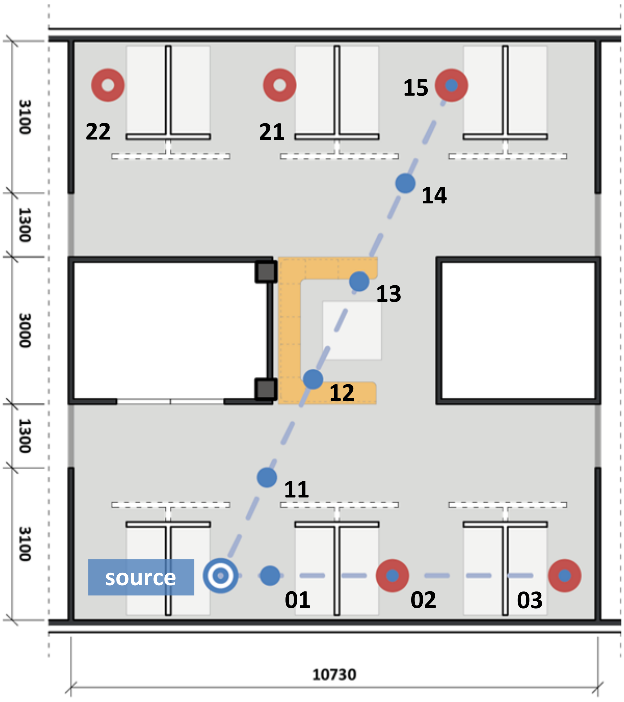


Figure 42. Measurement setup for multi-objective optimization

Receiver	01	02	03	11	12	13	14	15	21	22
Distance [m]	1,0	3,5	7,0	2,2	4,4	6,6	8,8	11,0	10,2	11,5

Table 17. Shortest distance between source and receivers

The specific goal of these runs is thus to maximize said acoustic performance at places in the room where people might work while, at the same time, satisfying the conflicting criteria of keeping the amount of added absorption and the size of placed screens to a minimum. The following parameters are defined:

- Amount of absorption (minimized) – Calculated for each instance by multiplying the area of the surface with its absorption coefficient. All of the results are then summed for a room total;
- Surface area of screens (minimized);
- SPL increase (minimized, initial runs only) – The sound pressure level is measured at 5 workstations in the room by receivers 02, 03, 15, 21 and 22. A control simulation is performed to get initial values. Each consecutive run is then compared to the control sample and the difference between the values at each receiver is recorded. Better performing options in terms of sound level will result in a negative increase, in other words a reduction in sound level. The measured reductions across all receivers are summed into a single value. This total difference should end up to be as big as possible;
- DL_2 (maximized, final run only) – Sound decay is measured across two lines of receivers. The first line is made up of receivers 01-03. The second line runs through receivers 11-15. Values returned from both measurements are averaged to a single value.

11.2 RESULTS

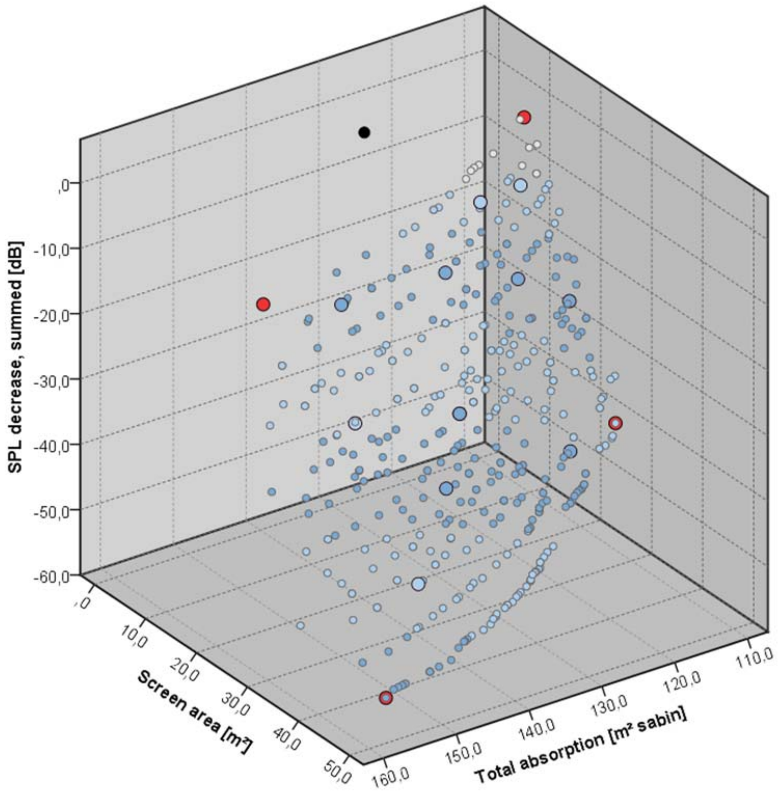
Settings

A total of three Octopus optimizations were performed on a custom built desktop computer fitted with an i7-5920K CPU clocked at 3,8 GHz. (calculations are single-threaded), each with a runtime of at least one week. The settings within Octopus were mostly kept to their defaults, applying HypE reduction and mutation. Population size has been set to 250 instances per generation, which results in a total combined amount of 88.000 evaluated solutions. More detailed statistics on the calculation runs are given in table 18.

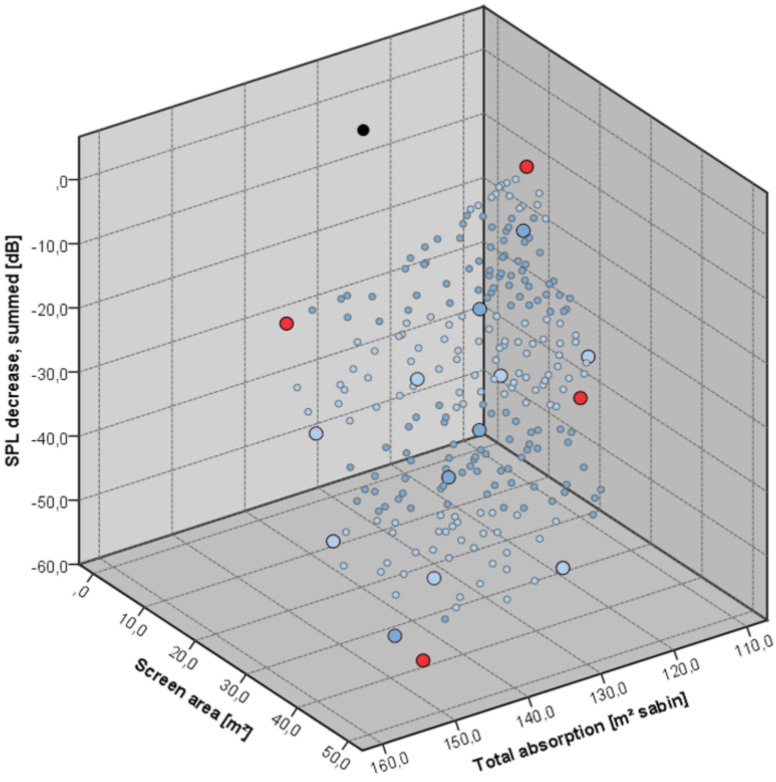
		Run 1	**Run 2**	**Final run**
Acoustic parameter		SPL	SPL	DL_2
Random scattering enabled		✗	✓	✓
Total runtime	[d]	7,3	7,4	10,7
Average evaluation time per instance	[s]	25,2	23,1	26,2
Amount of completed generations	[s]	100	111	141
Total number of evaluated instances	[-]	25.000	27.750	35.250
Pareto optimal solutions in final gen.	[-]	412	254	171

Table 18. Statistics of performed optimizations in Octopus

Findings from initial runs 1 and 2: optimization by SPL



run 1



run 2

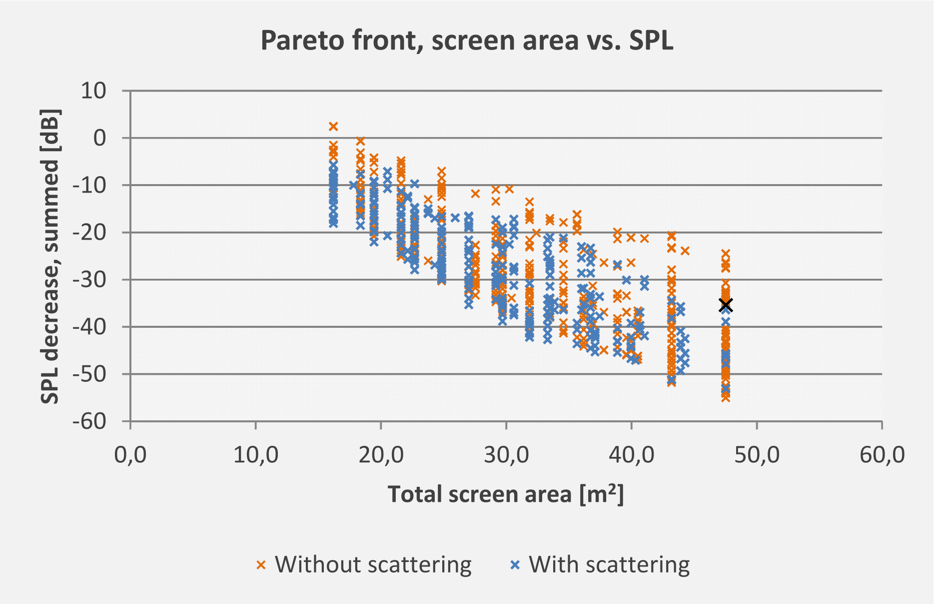
Graph 19 - 20. Final generation Pareto front solutions from SPL-based optimizations

The graphs to the left map the Pareto fronts from the last generations of the optimizations based on measurement of SPL. The 100th and 111th generations are shown for 'run 1' and 'run 2' respectively. Each objective is plotted on one of the axes. The further away from the origin a particular solution is drawn, the worse it performs with respect to the given objective. The red dots indicate extremes which are visualized further on in figure 43. It is shown that solutions which score best on acoustic measures – those drawn lowest on the vertical axis of these graphs – always employ a combination of added screens and absorption. It needs to be noted once more that the overall recorded improvement in SPL is an unweighted sum from 5 receivers. In order to find out which receivers contribute most to these outcomes, specific instances would have to be more closely examined.

Since both runs were performed using exactly the same model, constraints and assessment criteria, the effect of scattering on the simulation is once again made clear through comparison of both results. In the first run, where scattering is not included, several solutions turn out to perform worse than the existing office. These are marked with gray dots.

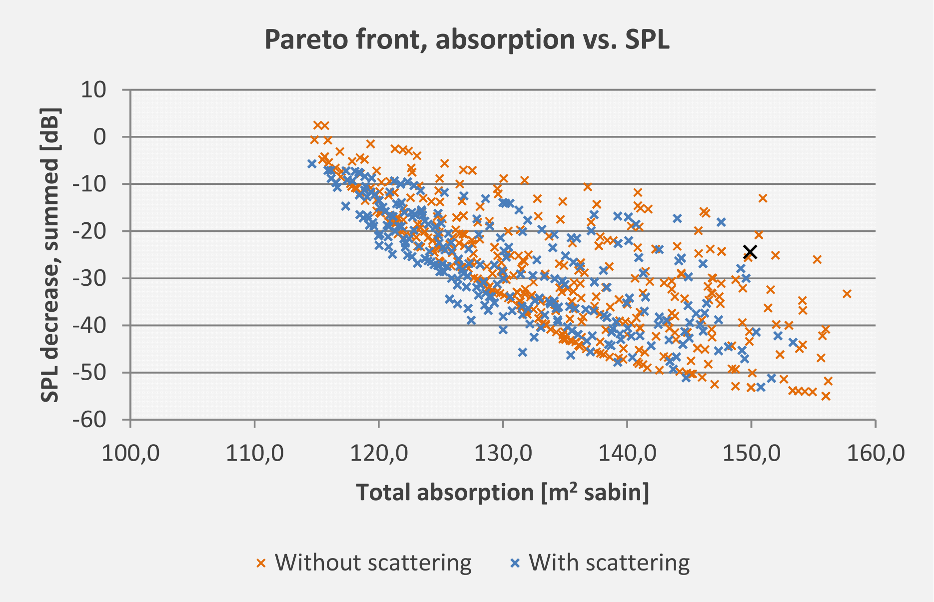
	Legend
●	Current situation
●	Visualized extremes
○	$SPL_i \geq 0$ dB
●●	$SPL_i < 0$ dB

Similar to the benchmarks from *paragraph 10.2*, the inclusion of random scattering in the simulation process evidently decreases the spread in the solutions that are produced. Graph 21 and 22 plot the same results given in graph 19 - 20 from both optimization runs.



Graph 21. Comparison of Pareto front solutions initial runs 1 and 2, screen area

These graphs also describe the limits found in the optimizations. Looking at graph 21 for example, it is shown that a maximization of screen area alone can, at best, cause a total decrease in measured SPL in the order of 30 dB for the entire model (solution marked in the group with scattering by the black **X**). Additional acoustic performance displayed by solutions lower on the y-axis is entirely attributed to an comparative increase of absorption applied in those instances. The same relation applies for graph 22, which displays absorption only accounts for a total decrease of up to 20 dB maximum.



Graph 22. Comparison of Pareto front solutions initial runs 1 and 2, absorption

Both runs find the same extremes for screen area. For absorption (see graph 22) this not entirely the case however. In the optimization without scattering several configurations have a higher total absorption than the most extreme case in the run with scattering. There are two factors that may explain this occurrence. The first has to do with the setup of the model. The amount of variables used to describe the absorption properties of different objects was larger than the amount describing the size and placement of screen elements. As such the number of unique distribution patterns for absorption is also far bigger than the amount of different screen layouts. Consequently there is an increased chance that certain configurations are not kept within Pareto front, or perhaps may have not even be considered at all over the course of the calculation. Secondly the consideration of random scattering causes randomness in the results. This means that if a certain design configuration is recalculated, the outcome might be different since scattering directions change in each ray tracing run. Also taking into account that the values of 5 measurements are summed, this randomness may be exaggerated in some cases. This is exemplified by the results given in table 19. The simulation is, separately from Octopus, redone for the indicated solutions. It is shown that the results from re-runs deviate from the optimization to varying degrees.

Evaluated instance id	001	063	098	126	228	253	254
Original value ‘run 2’	-5,7	-18,1	-23,0	-26,6	-42,2	-51,2	-53,1
Recalculation	-5,4	-14,3	-17,0	-23,5	-35,6	-42,4	-47,5
Absolute deviation	0,3	3,8	6,0	3,1	6,6	8,8	5,6

Table 19. Reproducibility of results when scattering is considered, SPL increase [dB]

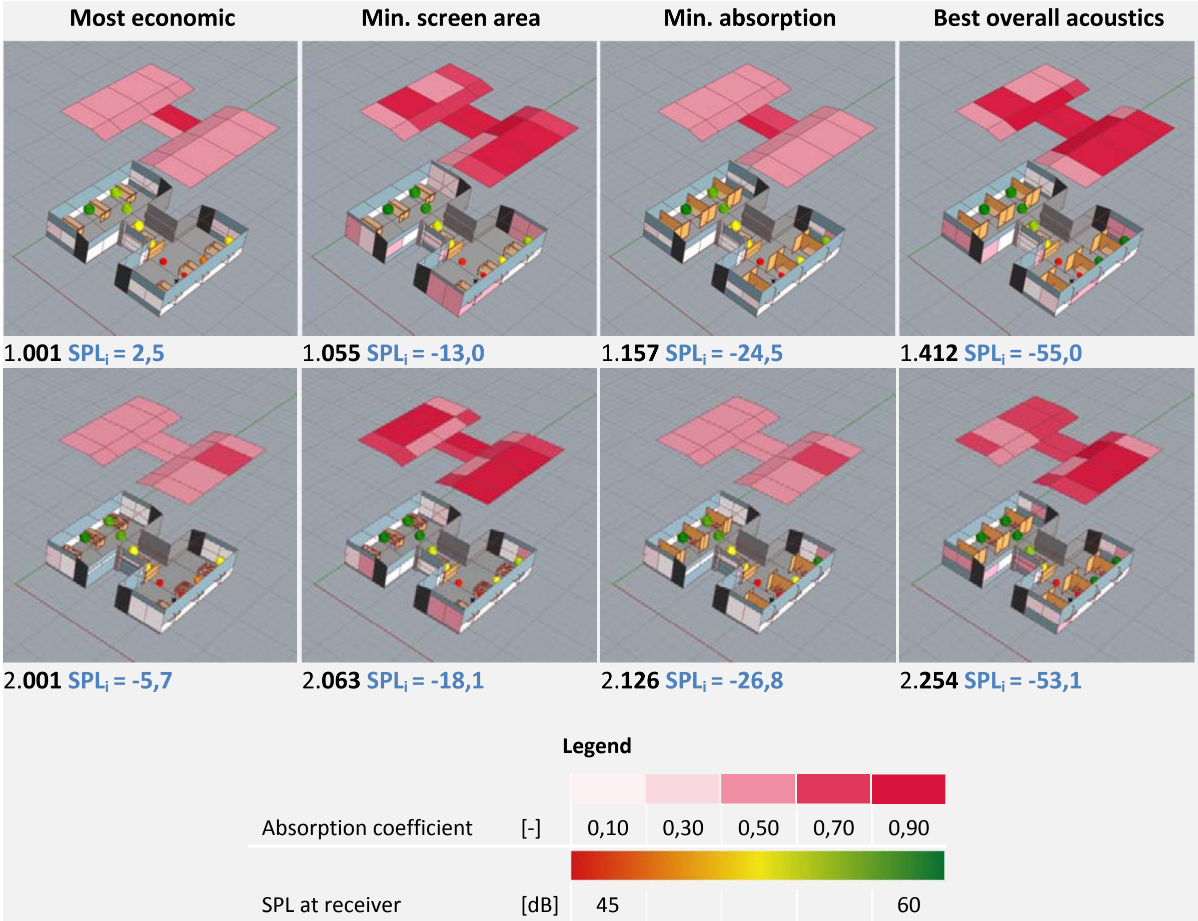


Figure 43. Extremes within Pareto front returned by optimization runs 1 (top row) and 2 (bottom row)

In order, the following extremes are visualized in figure 43:

- Most economic – This is the solution found in the optimization process that represents the configuration with the least amount of absorption and the smallest screens possible. Though this alternative may be viewed as architecturally the most pleasing, in any case it displays the worst acoustic performance out of all Pareto optimal solutions;
- Minimal screen area – The solution where recorded sound pressure is lowered the most, without increasing the size of screens placed within the room. Improvements to room acoustics are thus accomplished squarely by increasing absorption;
- Minimal absorption – Same as before, but in this case absorption is kept to a minimum. This solution thus solves acoustical issues through placement of larger screens;
- Best overall acoustics – Performs the absolute best out of all evaluated instances with regards to sound, but that comes at the total expense of the material objectives.

For reasons mentioned earlier both runs find slightly different extremes. Judging purely from observation, the solution with the best acoustical properties have in common that the ceiling panels nearest to the source have their absorption maximized. The differences found in the SPL totals between the extremes of both runs are relatively small considering these are summed values from multiple receivers. However, not all receivers contribute the same to this total.

Evaluated instance id	**001**	**063**	**098**	**126**	**228**	**253**	**254**
Receiver 03	-0,9	-3,4	-4,4	-4,8	-9,7	-9,8	-11,6
Receiver 15	-0,7	-2,7	-0,3	-0,2	-1,3	-1,8	-2,6
Receiver 22	-1,9	-2,1	-3,7	-6,2	-8,5	-10,4	-13,3

Table 20. Recorded SPL increase [dB] per receiver

Since receiver 15 is always in a clear line of sight to the source, even in the cases with the biggest screens, it is affected far less little by changes made to the configuration in comparison to the other receivers (figure 44).

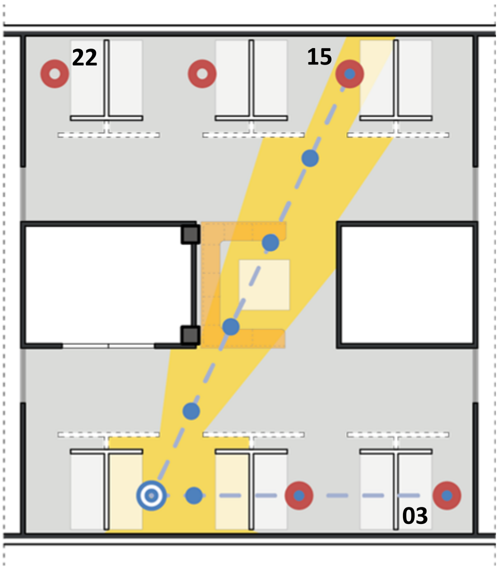
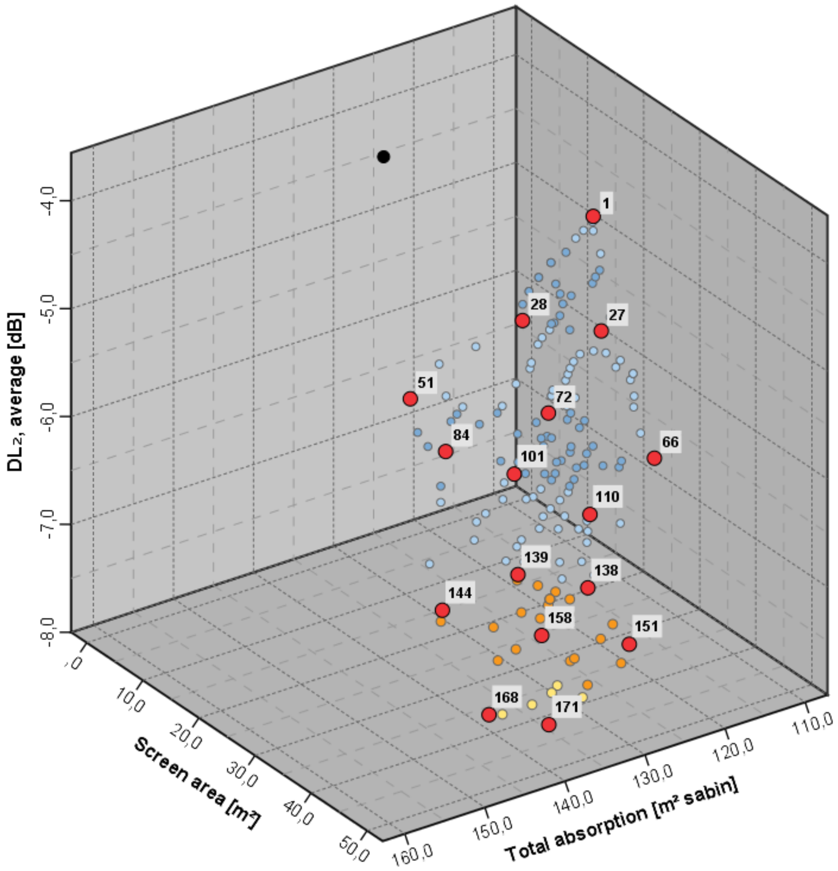


Figure 44. Line of sight from the source in cases with maximized screen area

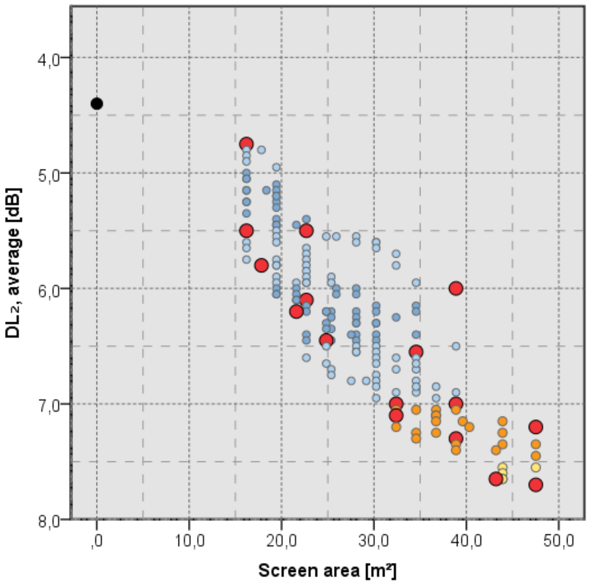
Final run: optimization by DL_2



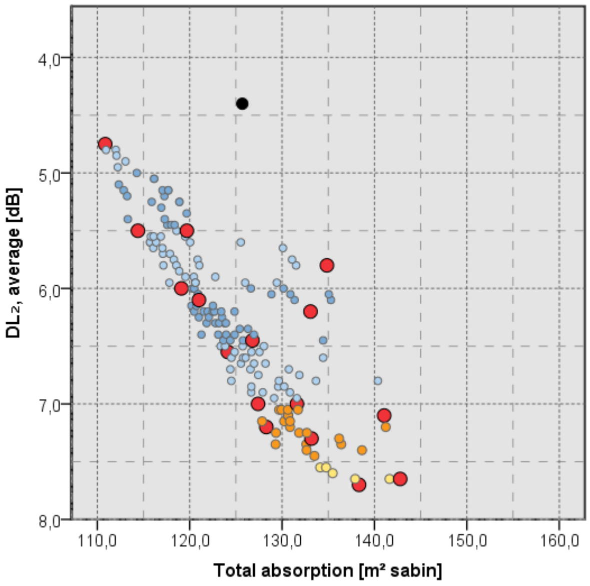
Graph 23. Final generation Pareto front solutions from final DL_2-based optimizations

The graph to the left maps all of the Pareto optimal solutions for the 141st generation of the final multi-objective optimization run. The numbered labels are the indices of the solutions corresponding to those visualized in figure 45. In comparison to the current office, practically all of the configurations on the Pareto front score better when it comes to sound decay. Office A in its current state has no screens whatsoever placed in between the desks. None of the optimized design instances approach this extreme due to the solution space being constrained in that regard.

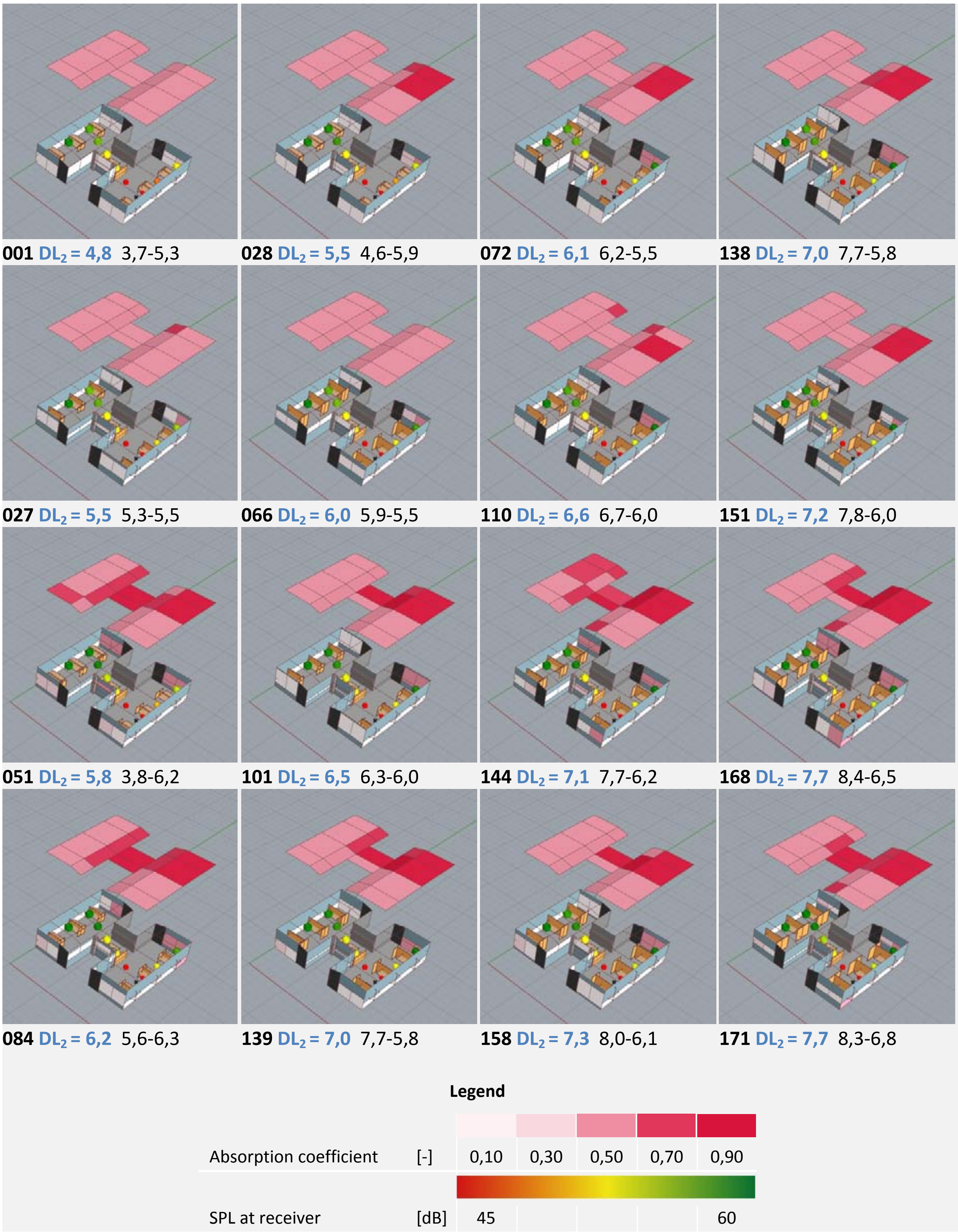
	Legend
●	Current situation
●	Visualized solutions
●●	$DL_2 \geq 7dB$
●●	$DL_2 < 7dB$



Graph 24. Pareto front of final optimization, screen area



Graph 25. Pareto front of final optimization, absorption



001 DL$_2$ = 4,8 3,7-5,3
028 DL$_2$ = 5,5 4,6-5,9
072 DL$_2$ = 6,1 6,2-5,5
138 DL$_2$ = 7,0 7,7-5,8

027 DL$_2$ = 5,5 5,3-5,5
066 DL$_2$ = 6,0 5,9-5,5
110 DL$_2$ = 6,6 6,7-6,0
151 DL$_2$ = 7,2 7,8-6,0

051 DL$_2$ = 5,8 3,8-6,2
101 DL$_2$ = 6,5 6,3-6,0
144 DL$_2$ = 7,1 7,7-6,2
168 DL$_2$ = 7,7 8,4-6,5

084 DL$_2$ = 6,2 5,6-6,3
139 DL$_2$ = 7,0 7,7-5,8
158 DL$_2$ = 7,3 8,0-6,1
171 DL$_2$ = 7,7 8,3-6,8

Figure 45. Examples of Pareto optimal design configurations returned by final optimization

A sample is taken from the Pareto front. This is presented in figure 45 with corresponding scores for measured DL_2 (in order these are the average, followed by recalculated values for receiver line 01-03 and receiver line 11-15 respectively). These scores show that sound decay over the first measurement line increases much more drastically between the extreme solutions, in comparison with the second line. This is, just like in previous optimizations, because all of the receivers in question are within an open line of sight from the source. Upon further inspection it is striking that the model instances with the highest DL_2 values have the absorption maximized for the ceiling panels closest to receivers 02 and 03. This is in contrast to the initial optimizations were absorption was placed close to the source first. Minimizing the sound pressure level at these positions, as a result of more energy being absorbed in the ceiling, would result in an increase of sound decay across the first line. The distribution of absorption in the room seems heavily dependent on the acoustic parameter being optimized and its corresponding method of measurement. Figuring out the exact relation between the used calculation method, applied parameters and the outcomes subsequently produced by the optimization process requires more in-depth (statistical) scrutiny of the dataset. One thing that can be said in favor of using DL_2 as main acoustic parameter is that its value slightly less subject to randomness in the results given by individual receivers (as is shown in table 21). On the other hand, it still remains questionable whether this method is a better representative for good acoustic design of offices compared to using raw SPL measurements. Since only one source is considered in this optimization, the outcome will likely differ significantly when the source is placed elsewhere in the room or multiple sources are considered at the same time.

Evaluated instance id	**001**	**051**	**066**	**084**	**138**	**144**	**171**
Original value 'final run'	4,8	5,8	6,0	6,2	7,0	7,1	7,7
Recalculation	4,5	5,0	5,7	6,0	6,8	7,0	7,6
Absolute deviation	0,3	0,8	0,3	0,2	0,2	0,1	0,1

Table 21. Reproducibility of results when scattering is considered in final optimization, DL_2 averages [dB]

11.3 FINAL SELECTION

For feedback purposes one design alternative is selected from the final run. Its characteristics have been studied and the model was exported to CATT Acoustic for comparison and auralization. The selection is made on the basis of ISO/NEN 3382-3:2012 which suggests a parameter target value of $D_{2,s} \geq 7$ dB. As this parameter is comparable to DL_2, the configuration is chosen which barely satisfies this criterion with the smallest amount of screen area obstructing sightlines. The solution that most closely this description is shown in the image below.

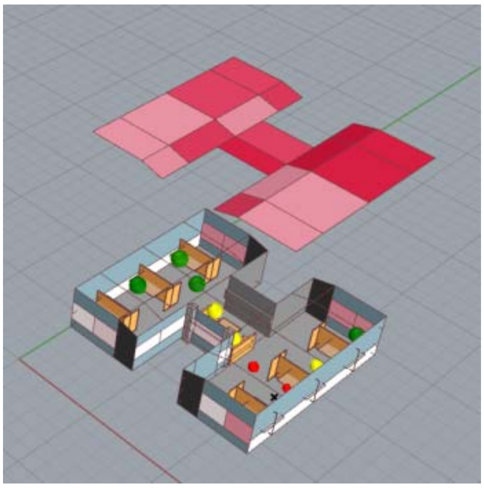
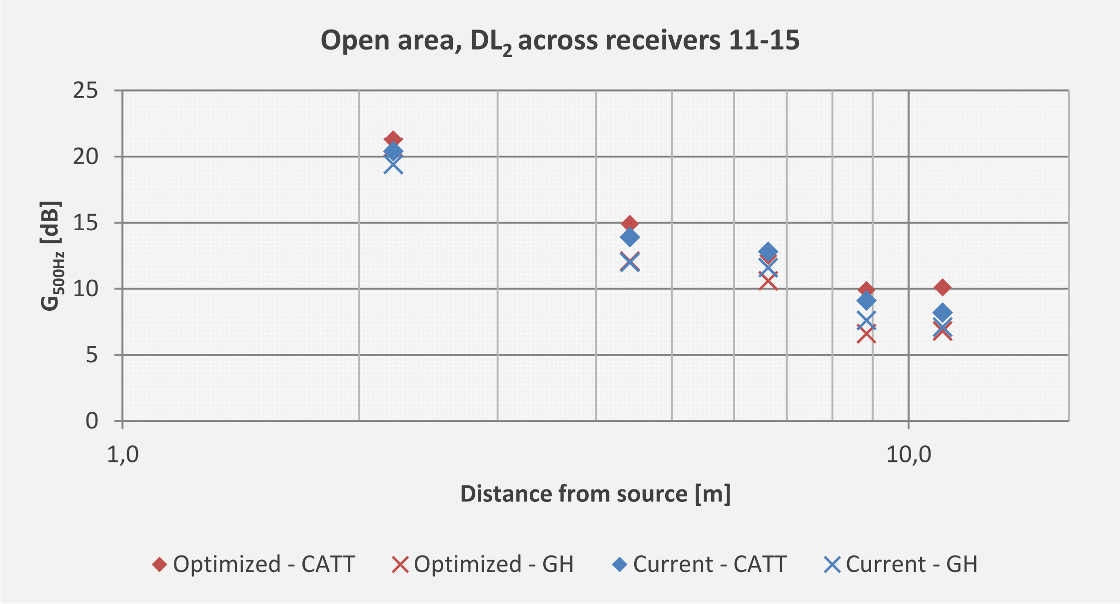


Figure 46. Selected alternative (Pareto front solution 144)

This configuration is firstly characterized by a screen height of h = 1,5 m. Keeping in mind that the source and receivers are placed at a height of h = 1,5 m; increasing screen height further (to 1,8 m) leads to configurations that outperform 'solution 144', although not by much. The effect of this increase is for instance far less evident than the same increase made between 1,2 m to 1,5 m screen height. Although seemingly coincidental, the size of the wall panels of the meeting room are unchanged from the current situation. The front and back walls have their glazed area decreased. The closed panel areas on the back walls nearest to receivers 03 and 15, have their absorption coefficient set to 0,30.



Graph 26. Sound strength recalculated for solution 144

		2,2 m	4,4 m	6,6 m	8,8 m	11 m	DL_2 [dB]
Current	CATT	20,4	13,9	12,8	9,1	8,2	5,2
	GH	19,4	12,0	11,6	7,6	7,1	5,2
	Deviation	-1,0	-1,9	-1,2	-1,5	-1,1	0,0
Optimized	CATT	21,3	14,9	12,5	9,9	10,1	5,0
	GH	20,7	12,1	10,6	6,6	6,8	6,2
	Deviation	-1,4	-2,8	-1,9	-3,3	-3,3	+1,2

Table 22. DL_2 calculation from G-values [dB] for solution 144

As illustrated by graph 26, the simulation is unfortunately not without error. A substantial discrepancy is found upon comparison between the results given for the optimized configuration, when it is in succession recalculated in Grasshopper and CATT-Acoustic. While the optimization routine claims to have improved DL_2 over the second line, a full detailed analysis in CATT-Acoustic does not show same effect, even getting slightly (though not significantly) worse when compared to the current situation. Somehow the sound pressure recorded at receivers furthest away from the source evens out, according to the CATT-Acoustic simulation. The definition in Grasshopper however continues the decay trend at these positions, causing it to overestimate sound decay.

Despite this minor upset the selected solution showed that SPL in all remaining receivers had significantly decreased in comparison to the current real life situation. These findings were corroborated by analysis in CATT.

11.4 IMPRESSIONS

Figure 47. Render of office A, current situation

Figure 48. Render of office A, alterations according to 'solution 144'

Disclaimer: these images were rendered in mental ray for Maya 2015 SP6 using a separate purpose-built model.

12 FEEDBACK

12.1 END USERS

On 27 November 2015 a feedback interview was conducted on small sample of office A employees, whom were previously involved in the questionnaires discussed in *paragraph 7.2*. This is mainly done with the goal of gaining first insight into the extent to which people are capable of noticing virtualized changes in sound, which are caused by a change in the office layout. The interview contained a series of simple tests in which respondents were asked to compare and judge sound clips generated using auralization in CATT-Acoustic. Though these recordings were in English, the respondents (whom all are Dutch) all indicated to be proficient in understanding the English language. Besides that, employees were questioned on their general stance on open office planning and were asked to give their personal opinion on the proposed changes. A total of 7 people participated in this interview session. The questions are included in *appendix D*. All listening tests were conducted using Sennheiser HD201 headphones.

The sound files used during these tests were generated by convolution of anechoic speech recordings taken from development data by Kayser & Anemüller (2008), made as part of SiSEC 2008. These files are available online under the terms of the *Creative Commons Attribution NonCommercial ShareAlike 2.0* license.

Judging distance from auralization

Respondents listened to two auralized recordings. The first recording was a single line of female speech at 1 m distance from the source. The second file consisted of several fragments of normal speech (both male and female) recorded at five different receivers (going one-by-one from receiver 11 to 15), placed in a single line, with the distance from the source increasing for each fragment. Respondents were asked to guess the distance at which they had supposedly arrived at the end of the second recording. The distance between the source and final receiver amounts to 11 m. All respondents underestimated this distance. Their guesses are shown in figure 49, marked as ✖.

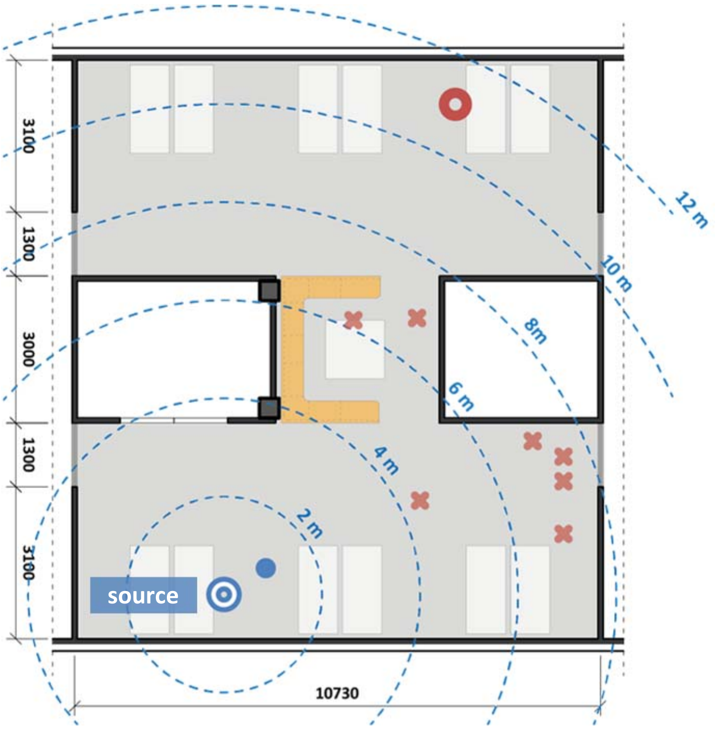


Figure 49. Position of receiver question 3, respondents' estimation vs. actual placement

A/B testing

Respondents were given two recordings to compare. One of them was made in an auralization on a model resembling the current situation. The other record is produced the same way, using the same source and receiver positions, but now using the optimized configuration. A total of 3 A/B-tests were performed in this fashion using 'before and after' recordings for receiver 03, 15 and 22. Table 23 shows the difference in sound pressure level for each of these tests, according to CATT-Acoustic. All these sound files were calibrated using a simulated measurement at 1 m distance from the source.

		1m	**03**		**15**		**22**	
		SPL [dB]	SPL [dB]	T_{30} [s]	SPL [dB]	T_{30} [s]	SPL [dB]	T_{30} [s]
Current situation	A	61,1	51,2	0,39	44,9	0,39	41,7	0,40
Optimized	B	62,9	41,7	0,37	46,8	0,34	38,2	0,49
Deviation		+1,8	-9,5	-5%	+1,9	-13%	-3,5	+23%

Table 23. Results from CATT-Acoustic full detailed calculation for receivers used in auralization

First respondents were asked to rate the 1 m speech recording with respect to what they perceive as normal speech level: 6 out of 7 indicated that the recording sounded slightly louder over the headphones than a regular conversation. Next they were asked to compare two audio files, each pair containing the same short fragment of English speech. For receivers 03 and 22 all respondents unanimously correctly identified the sound file belonging to the optimized design as being clearly the less loud of the two. One of them even went as far as quantifying the improved situation as being half as loud as before. The judgements of receiver 15 were split, with 4 people indicating they did not hear a difference. The remaining participants thought clip B was slightly louder than A which, going purely by the numbers from CATT-Acoustic, would be incorrect. Though the population size is too small to draw scientific conclusion, for this group it seems that any acoustic improvement needs be fairly large in order to be noticed without hesitation. Finally respondents were given two more sound clips to compare, but this time the audio contained multiple fragments mixed together as to imitate multiple people talking at the same time. For the improved situation 6 out of 7 respondents found the clips recorded nearby far easier to distinguish from those recorded far away, compared to the same test for the current office layout.

Opinion on architectural implications

Finally the participants were shown the renders of figure 47 and 48 in succession. After being questioned on their stance on open offices in general, they were asked whether they personally found the proposed change acceptable in terms of architecture appeal and practicality in day-to-day use. Most of the respondents seemed rather undecided on the merits of open office planning, with 2 of them indicating being neutral on the issue and 4 more leaning towards a more positive demeanor with the side note that their experience is dependent on circumstances (mostly affected behavior of colleagues). Opinions were extremely divided when it came to the proposed changes: 4 out of 7 respondents judged the proposal as an overall improvement, while 2 of the remaining employees strongly opposed it. A primary complaint brought up by 5 respondents is that placement of screens between desks may be detrimental to the atmosphere of the room, judged by some as 'minder gezellig' in Dutch. The ability to see and interact with the person sitting across from your desk is mostly appreciated, but would be obstructed with these screens. One of the employees uttered to place the screens on the backside relative to each workstation as to not directly block forward view, deeming such placement more acceptable. Furthermore, 4 respondents proposed a use case that did not necessarily line up with their day-to-day activities, referring to the proposal, in some way or another, as a better place for confidential phone calls or individual work (these answers all involve an aspect of seclusion).

12.2 CONSULTATION PROFESSIONALS

To frame the applicability of the developed definition in design practice, and to get a general idea of professional workflow with regards to the use of acoustic simulations, several practicing building physics consultants were interviewed over the course of this project. They were questioned on the topics of their professional background, their general stance on contemporary office design and their knowledge on the principles of parametric design. Those interviewed in a late stage of this research were also given a demonstration of the definition, and were asked to give remarks based on what they were shown. The questions used as framework for these interviews are included in *appendix 0*. The people listed below took part in these consultation sessions:

- Marten Valk – consultant building physics, acoustics and fire safety at Deerns;
- Michiel Susebeek – consultant building physics, fire safety and sustainable building design at Deerns;
- Pieter Schepman – project leader building physics and fire safety at ZRi;
- Mark van der Bijll – project assistant building physics and engineering specialist at ZRi;
- Yvonne Wattez – project assistant building physics, acoustics and sustainable building design at ZRi.

All consulted practitioners operate in the wider field of building physics covering, amongst other topics, issues related to heat and moisture, lighting, ventilation and energy efficiency. Acoustics is in practice not viewed as a secluded topic, neither should it be, since all these aspects may adversely affect each other. A brief account is given for the events of all conducted interviews, categorized by company affiliation, with the inclusion of several interesting remarks.

Deerns

Both consultants were interviewed separately at different stages in the research. Marten Valk was consulted as early as 11 November 2014. At that time this project was still being set up, therefor this interview does not reflect on the developed work. Nevertheless he raised a few interesting points on design practice. First of all, he pointed towards budget constraints that need to be dealt with in practice. Acoustic simulation may be performed – in their case by using a Revit model as template for a *.DXF file exported to ODEON – but that is entirely dependent on the finances of the project at hand. Secondly, he also stated that investigating architectural improvements may not be the only or best way to deal with the acoustics in an office, since a lot of problems are a results of organizational difficulties rather than technical ones. On the whole he seemed rather positive on the proposal of more tightly integrating acoustic analysis with geometric modelling, however did raise doubt on whether it is really necessary to investigate thousands of solutions in a parametric search.

Michiel Susebeek was interviewed on 26 August 2015. He gave some insight on how computer modelling is used in his everyday practice. Mostly they use a Revit BIM to collaborate with other parties involved in a design project. Standard (acoustical) issues are mostly resolved doing calculations by hand. As of this moment, he states, there is no direct adjustment and feedback between building physics aspects and their architectural implications. A program that could quickly provide an inclusive feedback on multiple physical performance properties would be very much welcomed. When asked to which aspects of a parametric model would be most worthwhile for further development, it was really stressed that reliability of the calculation should be guaranteed above all, since inaccurate results are worthless and would totally defeat the point of acoustic analysis. Any inconsistencies in the calculation should be documented so, as consultants, they know when a model like this can be applied reliably. Having prior interest and experience with evolutionary solving and using Grasshopper during his own studies, he needed little convincing on the further potentials of this study. Finally Michiel enthusiastically iterated that visualizations, like the one in figure 50, could provide a very useful tool for communication with clients.

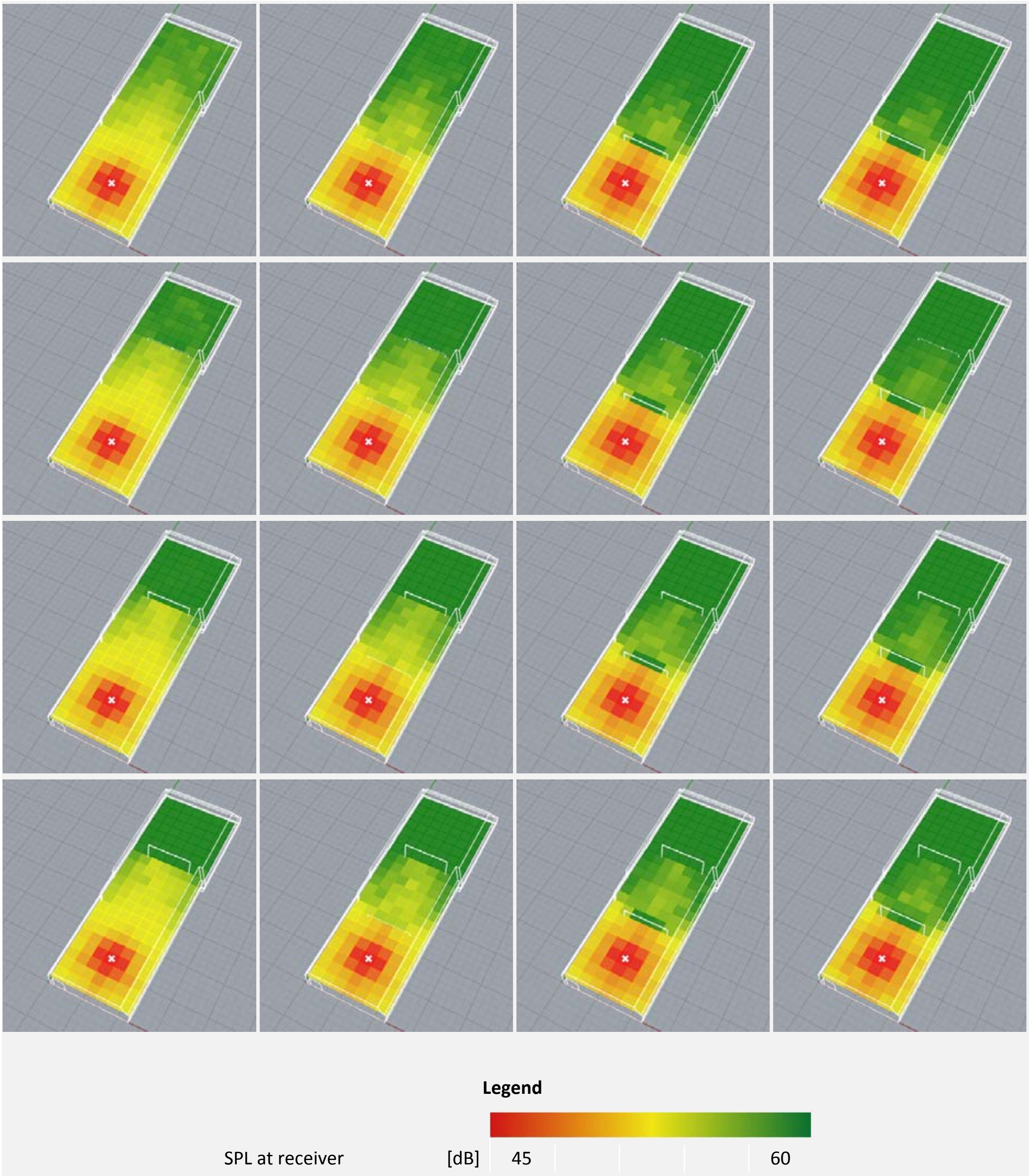


Figure 50. Gradient map visualization capabilities of the developed definition, BT Studio with two parameterized walls

ZRi

All participating consultants were interviewed in a single sitting on 16 September 2015. Practically all of the consultants at this firm cover several topics of building physics depending on whatever projects they may be working on. ZRi mostly gets involved, usually after the fact, with offices that have already been designed, built and sometimes are in use already. They indicated that simulations using acoustic analysis software is practically never performed when dealing with office spaces in their case, since budget constraints do not allow for it in those projects. Pieter Schepman, their project leader, expressed that a large part of his work involved articulating what clients are actually asking for, as they usually are not particularly well versed. Their daily activities mostly involve advising clients on how to deal with acoustics and other building physics aspects. Resolving acoustic issues involves, on their part, performing acoustic measurements and lots of manual calculations.

Proper and swift communication with their clients is paramount to their operations. This is reflected in the consultants' answers to the question of which aspects of a parametric model should be developed for them to see a direct use case in their practice. Ease of use of the definition is most greatly emphasized (and to a certain level this also ties into the speed at which such a model can be deployed). It is also seen as a considerable plus if a greater number of acoustic parameters could be calculated simultaneously, which would in turn help lessen the amount of calculations that need to be done separately. Finally, according to a statement made by Yvonne Wattez, office managers think in terms of office configuration and occupancy rather than acoustic parameters. Occupancy is currently not explicitly dealt with in the script, but could pose an interesting aim for future development.

13 CONCLUSIONS

13.1 GENERAL CONCLUSION

Answering the research question

- Research question: "How can a (parametric) performance-driven design method help in improving the acoustic quality of an open plan working environment and to what extent will said improvements be noticed (and regarded positively) by office workers in terms of acoustic comfort?"

Long story short, within this research it is observed that the computational optimization of open office environments is possible by integrating principles of acoustic simulation in a parametric model. Said model needs further development to become a viable and accessible tool in the arsenal of an architect or building physics consultant. The developed ray tracing algorithm is a very simple implementation of acoustic analysis with parameterization capabilities and provides a basic framework that can be built further upon. In its current form sound pressure levels (and other parameters derived from SPL) can be analyzed in a given closed space. Through alteration of geometric entities and material properties, measured sound levels can be lowered, which should bluntly equate to an improvement of acoustic quality in the space. This assumption was put to the test and validated through listening tests carried out on a small number of case study office workers.

- Hypothesis: "Performing basic acoustic analysis via a parametric model will help in reducing sound propagation between workstations in an open space. The changes brought forth by (automated) parametric search are significantly large to be noticeable."

In all, the hypothesis seems to hold true at least partially. However, some nuance is in order. The noticeability of changes brought forth by search are heavily dependent on how bad the start configuration performs in relation to all other instances available in the rest of the search space. Furthermore, based on the results generated by the parametric models alone it would not be correct to assume that an improvement of design parameters automatically leads to more positive reviews by office workers. In a feedback session several respondents had reservations with regards to the architectural implications of a proposed acoustic improvement. A correct application and interpretation of the methods outlined in this report thus require significant knowledge on the designer's behalf concerning parametric design and acoustics.

Potential impact on design practice

In a short term the tools and knowledge yielded from this study will likely be confined to academics. Parametric modelling is far from commonplace in architectural design, building engineering and consultancy. Though there is great interest in the potentials of parametric analysis, most practitioners in these fields of work tend not to be particularly well-versed in Grasshopper or similar programs. It does not help that parametric models are fairly time consuming to set up, plus the search algorithms often running overnight. A culture shift in design practice needs to be in order before parametric tools, such as the one outlined in this study, will be ordinary in use.

13.2 SPECIFIC IMPROVEMENTS ON THE SCRIPT

Areas of improvement

Six areas of improvement have been identified to improve the script used in this study. These are: support for wider range of programs, calculation speed, ease of use, reliability and accuracy, more visualization features and expanding the number of acoustic parameters. In further development priority should perhaps be given to increasing the reliability of the script and its results, creation of an easier interface and making the definition faster (both in use and in calculation time).

Reliability and speed

One major improvement for the reliability of the results would possibly be to evolve the script from a simple ray tracer into a hybrid model. As a result of such a change the definition will likely produce more accurate results in complex rooms. An issue to take into account is that adding too much complexity and features to a model may be detrimental to its calculation speed. The latter becomes extremely important when considering the ability to be used in parametric search, evolutionary or not, as one of the main goals of this definition. Every second lost on one solution will multiply itself by the amount of instances in the model you are willing to investigate.

Ease of use

Right now, operating the definition would require someone to be fairly experienced in using Grasshopper. A lot of components have also been added for the purposes of inspecting the functionality of the script. Finally all material properties are currently input manually with no way of saving or recalling these settings. A lot of components still left on the canvas of the definition can be made redundant with new code. A library to select and store material properties would also benefit usability a great deal. Finally the current script does not interpret back-faces, which means tabletops cannot be defined as flat surfaces, but have to be created as volumes. The inclusion of double sided geometry would allow the use of even simpler models.

13.3 FUTURE RESEARCH

During this study a large amount of design alternatives were created. The dataset produced as a result should be evaluated more closely, perhaps through in-depth statistical analysis, to truly uncover any relationships between the parameters and results of the parametric optimizations (assuming any such relation exists). Another suggestion for further study is to parametrically analyze the acoustic environment of more different types of offices in search of a common trend.

Research may be done in the automated conversion of complex 3-D models into simpler ones that have all acoustically irrelevant information removed. This could help alleviate the time consuming activity of importing and exporting files from one program to another.

14 REFLECTION

This chapter, written 1 November 2015 as required for admission to the P5 final assessment of this graduation project, serves as a personal account for the outcome of the research process. The aspects of planning, approach and the relation between research and design are briefly discussed below.

14.1 PLANNING AND APPROACH

As a result of a series of setbacks over the course of graduation, the final assessment was initially postponed on my accord. The extra time allowed me to reach a more substantial conclusion and far better technical understanding on the subjects of this study. The schedule proposed in the graduation plan, although seemingly realistic on paper, left very little room for error and subsequently turned out to be too tight. I already got delayed in a very early stage (the first few weeks after the P2 presentation). Arranging locations for case studies ended up being a long-winded and time consuming ordeal. Originally two different offices were proposed, but neither was used due to disagreement amongst involved parties. In the interest of saving time one of the case studies was thus performed at the faculty, so at least I had a room to model and investigate.

The bulk of the literature study performed prior to the case studies focused mostly on general theory of acoustics and design guidelines for open plan workspaces. Considering the inclusion of acoustic analysis in the design process is emphasized in this study, perhaps literature on simulation techniques should have been examined more thoroughly at an earlier stage. The planning was based on the assumptions that parametric search using acoustics as a driver could be performed utilizing available software and plugins. This however, as described in the report, turned out not to be the case. Several weeks were spent on building definitions with existing components, only to conclude that none of the explored options were considered to be either accurate enough or fit the purpose of the study. As such, I had to develop my own definition from scratch – an approach we tried to avoid altogether up to that point – which, ironically, makes up the main part of my research now.

As later phases of the study relied heavily on previously gathered results, late-stage activities were pushed back and my planning was obviously altered severely. For instance, the computer model optimizations were conducted in a relatively short time frame and continued until well after the P4. The same goes for the feedback interviews, which were taken just a week prior to the final presentation. As a result of those activities handing this report was done too uncomfortably close to the deadline for my liking. In hindsight, a planning based on serialized research phases may not have been the best idea time-wise, although what different approach would be more effective instead is honestly beyond me. Taking into account an entire design workflow needed to be built from the ground up, perhaps my initial plans were a bit over-ambitious for the allotted time of a graduation thesis. Whether that development could have been foreseen at the draft of the graduation plan remains speculation.

14.2 RELATING RESEARCH AND DESIGN

This study was not set up with the intent of producing an extensive architectural design in the classical sense, but rather to critically evaluate the concepts on which current office design practice is based. Scrutiny of the tools and methods we use in making design decisions is underlined throughout my project. By and large the conclusions regarding design guidelines I reached as a result of this study were unsurprising, although this is perhaps understandable considering the open plan workspace and the effects on its occupants has already been a topic of widespread scientific debate and research for several decades. The models I created help in quantifying the relation between acoustic parameters, geometric and material properties. These gained insights spawned a few wacky ideas on my part, which were mostly conceptual at best and neither very realistic nor practical. I opted to propose a sensible solution instead.

The final optimization purposely was kept simple in terms of form and architectural design, as adding complexity would only convolute the search process for a definitive solution. The tools and workflow need to be developed and improved upon further before we get to the point where more complex designs can truly be integrally driven by parametric processes, which is a point the report tries to get across. Though my research did not spawn any radically innovate solution in terms of architectural design guidelines, the gathered information could prove to be invaluable for future reference.

14.3 SOCIAL CONTEXT

The wider societal relevance of this project requires little elaboration. From the outset the underlying ideas of this study are grounded in addressing real issues related to open workspaces, their design and the way these environments affect human well-being. Said issues can be recognized by anyone who works in an open plan office. Feedback study was limited to a single interview session on a small sample of my initial research population. Though it was an insightful and fun addition to the late part of my graduation project, it is hardly enough material to make educated claims. Pursuing scientific substantiation of technical aspects clearly took precedence over the radical inclusion of end users opinions over the course of the study. Several external building physics consultants provided some excellent feedback on the developed script and the research in general. Framing the significance of this project for actual design practice definitely is a strong point in my view. I am certain that this is perhaps one of the best and most socially relevant projects that I have worked on in recent years; and most definitely a great way to conclude my studies at the Faculty of Architecture and the Built Environment.

Nick Vlaun

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Appendix A CASE STUDY QUESTIONS

Below are the questions used in the BT Studio survey. Participating employees in office A were given the same questions, with the exception of questions 11 and 21, which were omitted in their case.

General questions

1. What is your gender?
Wat is uw geslacht?

☐ Female
Vrouw
☐ Male
Man

2. What is your age?
Wat is uw leeftijd?

☐ <19 years
<19 jaar
☐ 20-24 years
20-24 jaar
☐ 25-29 years
25-29 jaar
☐ 30-39 years
30-39 jaar
☐ >40 years
>40 jaar

3. How do you feel in general?
Hoe goed voelt u zich doorgaans?

☐ Really good
Zeer goed
☐ Good
Goed
☐ Neutral
Neutraal
☐ Bad
Slecht
☐ Really bad
Zeer slecht

4. What time of day is it?
Wat is het tijdstip waarop u dit invult?

☐ Prior to 12:00 h
Voor 12:00 uur
☐ Between 12:00 – 16:00 h
Tussen 12:00 – 16:00 uur
☐ After 16:00 h
Na 16:00 uur

Workspace

5. With how many people are you currently sharing a table?
Met hoeveel mensen deelt u op dit moment een tafel?

☐ 0
☐ 1
☐ 2-4
☐ >5

6. How many hours a week do you currently spend on average working in this room?
Hoeveel uur per week werkt u gemiddeld in deze ruimte?

☐ <10 hours *<10 uur*
☐ 10-20 hours *10-20 uur*
☐ 20-30 hours *20-30 uur*
☐ 30-40 hours *30-40 uur*
☐ >40 hours *>40 uur*

7. For how long have you already been working in this room today?
Hoe lang werkt u vandaag in totaal al in deze ruimte?

☐ < 2 hours *<2 uur*
☐ 2-4 hours *2-4 uur*
☐ 4-6 hours *4-6 uur*
☐ 6-8 hours *6-8 uur*
☐ > 8 hours *>8 uur*

8. How do you like the way the interior of this workspace looks?
Hoe vindt u dat de inrichting van de ruimte eruit ziet?

☐ Beautiful *Heel erg mooi*
☐ Quite nice *Vrij mooi*
☐ Neutral *Neutraal*
☐ Quite ugly *Vrij lelijk*
☐ Hideous *Heel erg lelijk*

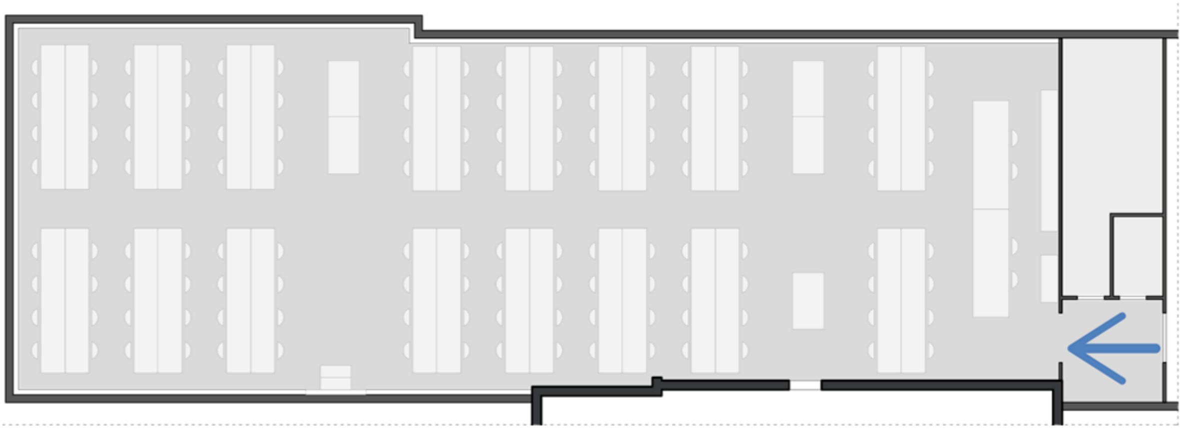
9. To what extent do you think the interior is also practical in its use?
In hoeverre bent u van mening dat de inrichting ook praktisch in gebruik is?

☐	Really practical *Zeer praktisch*
☐	Fairly practical *Redelijk praktisch*
☐	Neutral *Neutraal*
☐	Fairly unpractical *Redelijk onpraktisch*
☐	Really unpractical *Zeer onpraktisch*

10. Can you judge this workspace with a grade between 1-10?
Kunt u deze werkruimte beoordelen met een cijfer van 1-10?

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10

11. Can you indicate on the map below where in the room you are currently seated? Please draw a small ***X*** at your current position.
Kunt u op de onderstaande kaart aanduiden waar in de ruimte u nu zit? Teken a.u.b. een kleine X om uw huidige positie aan te geven.



← Indicates the entrance to the room
Geeft de ingang van de ruimte aan

Acoustics

12. To what extent are you satisfied with the acoustics this room?
In hoeverre bent u tevreden over de akoestiek van deze studio?

☐ Very satisfied
Zeer tevreden

☐ Satisfied
Redelijk tevreden

☐ Neutral
Neutraal

☐ Dissatisfied
Redelijk ontevreden

☐ Very dissatisfied
Zeer ontevreden

13. How noisy do you feel this studio is, generally speaking?
Hoe luid ervaart u het algemene geluidsniveau deze studio?

☐ Very quiet
Zeer rustig

☐ Fairly quiet
Vrij rustig

☐ Neutral
Neutraal

☐ Fairly noisy
Vrij Lawaaierig

☐ Very noisy
Zeer Lawaaierig

14. To what extent do you experience concentration problems due to noise when working this room?
In hoeverre heeft u moeite met concentreren tijdens het werk als gevolg van rumoer op deze werkplek?

☐ Never
Nooit

☐ Rarely
Zelden

☐ Sometimes
Soms

☐ Often
Vaak

☐ Always
Altijd

15. To what extent do you think, generally speaking, you are capable of working comfortably in a busy (public) environment? (e.g. in a train or lunchroom / cafeteria)
In hoeverre vindt u, in het algemeen, dat u in staat bent prettig te werken in een drukke (openbare) omgeving? (bijv. in de trein of een café)

☐ Very comfortable / takes little effort
Zeer prettig / weinig moeite

☐ Quite comfortable
Redelijk prettig

☐ Neutral
Neutraal

☐ Quite uncomfortable
Redelijk onprettig

☐ Very uncomfortable / takes a lot of effort
Zeer onprettig / moeizaam

16. To what extent do you agree with the following statement?
"The faculty provides enough rooms that are suitable for working in a concentrated fashion."
In welke mate bent u het eens / oneens met de volgende stelling?

"De faculteit voorziet genoeg in ruimtes die geschikt zijn om geconcentreerd te kunnen werken."

☐ Strongly agree
Volledig mee eens

☐ Agree
Een beetje mee eens

☐ Neither agree or disagree
Neutraal

☐ Disagree
Een beetje mee oneens

☐ Strongly disagree
Volledig mee oneens

17. To what extent are you distracted by background noise caused by appliances when working in this studio; phones not included? (e.g. coffee machine, computers, printers)
In welke mate vind u dat u afgeleid wordt van uw werk door geluid veroorzaakt door apparatuur; uitgezonderd telefoons? (bijv. koffieautomaat, computers, printers)

☐ Never
Nooit

☐ Rarely
Zelden

☐ Sometimes
Soms

☐ Often
Vaak

☐ Always
Altijd

18. To what extent are you distracted by noise from phones left ringing?
In welke mate vind u dat u afgeleid wordt van uw werk door gerinkel van onbeantwoorde telefoons?

☐ Never
Nooit

☐ Rarely
Zelden

☐ Sometimes
Soms

☐ Often
Vaak

☐ Always
Altijd

19. To what extent are you distracted by other people’s conversations?
In welke mate vind u dat u afgeleid wordt van uw werk door gesprekken van andere personen?

☐ Never
Nooit

☐ Rarely
Zelden

☐ Sometimes
Soms

☐ Often
Vaak

☐ Always
Altijd

20. To what extent do you to believe that someone at an adjacent table is able to clearly overhear one of your (phone) conversations? My conversation is…
Hoe eenvoudig denkt u dat de inhoud van een eigen gesprek op uw werkplek kan worden verstaan, door iemand anders die aan een naastgelegen tafel zit? Voor hem / haar ben ik…

☐ Unintelligible / inaudible
Niet te verstaan

☐ Relatively hard to overhear
Redelijk slecht verstaanbaar

☐ Neutral
Neutraal

☐ Relatively easy to overhear
Redelijk goed verstaanbaar

☐ Clearly understandable
Overduidelijk te verstaan

21. To what extent do you to believe that someone is able to clearly overhear one of your (phone) conversations from across the room; at a distance of at least 4 rows of tables? My conversation is…
Hoe eenvoudig denkt u dat de inhoud van een eigen gesprek op uw werkplek kan worden verstaan, door iemand die minstens 4 rijen tafels bij u vandaan zit? Voor hem / haar ben ik…

☐ Unintelligible / inaudible
Niet te verstaan

☐ Relatively hard to overhear
Redelijk slecht verstaanbaar

☐ Neutral
Neutraal

☐ Relatively easy to overhear
Redelijk goed verstaanbaar

☐ Clearly understandable
Overduidelijk te verstaan

22. To what extent do you agree with the following statement?

“My current workplace is perfectly suitable if I want to have a one-on-one conversation with someone else.”
In welke mate bent u het eens / oneens met de volgende stelling?

"Als ik met iemand één-op-één gesprek wil voeren kan dat prima op mijn huidige werkplek."

☐ Strongly agree
Volledig mee eens

☐ Agree
Een beetje mee eens

☐ Neither agree or disagree
Neutraal

☐ Disagree
Een beetje mee oneens

☐ Strongly disagree
Volledig mee oneens

23. To what extent do you experience noise from adjacent workstations when working in this room?
In welke mate merkt u bewust geluid afkomstig van naburige werkplekken op?

☐ Not at all
Niet

☐ A little
Weinig

☐ Neutral
Neutraal

☐ A lot
Veel

☐ Constantly
Constant

24. To what extent do you experience noise from outside the building?
In welke mate merkt u bewust geluid afkomstig van buiten op?

☐ Not at all
Niet
☐ A little
Weinig
☐ Neutral
Neutraal
☐ A lot
Veel
☐ Constantly
Constant

25. To what extent do you experience noise from HVAC systems?
In welke mate merkt u bewust geluid afkomstig van klimaatinstallaties op? (i.e. ventilatiesysteem)

☐ Not at all
Niet
☐ A little
Weinig
☐ Neutral
Neutraal
☐ A lot
Veel
☐ Constantly
Constant

26. Do you listen to music while working?
Luistert u wel eens naar muziek tijdens het werken?

☐ Yes
Ja
☐ No (go to question 28)
Nee (ga naar vraag 28)

27. What do you use to listen to music?
Wat gebruikt u om naar uw muziek te luisteren?

☐ Radio set
Aparte radio
☐ Computer speakers
Computer speakers
☐ Headphones
Koptelefoon
☐ Earbuds
Oordopjes

28. To what extent do you change your behavior in order to prevent being a nuisance towards fellow students?
In welke mate past u bewust uw gedrag aan om andere studenten niet tot last te zijn?

☐ Not at all
Niet

☐ A little
Een beetje

☐ A reasonable amount
Redelijk

☐ A lot
Veel

☐ Very much
Heel erg veel

29. To what extent do you think other students take their behavior into account to prevent nuisance?
In welke mate denkt u dat andere studenten hun gedrag aanpassen om anderen niet tot last te zijn?

☐ Not at all
Niet

☐ A little
Een beetje

☐ A reasonable amount
Redelijk

☐ A lot
Veel

☐ Very much
Heel erg veel

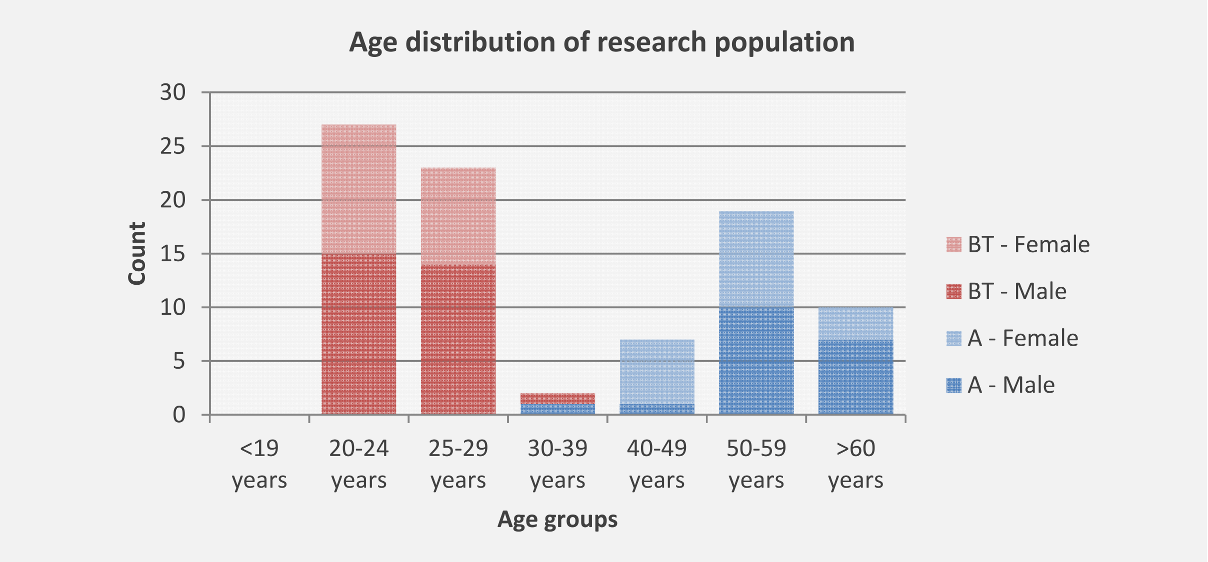
30. If you have any further remarks regarding your experience with noise this room, please write them here.
Heeft u nog verdere opmerkingen over uw ervaring met geluid in deze studio?

…

Appendix B FULL RESULTS OF QUESTIONNAIRES

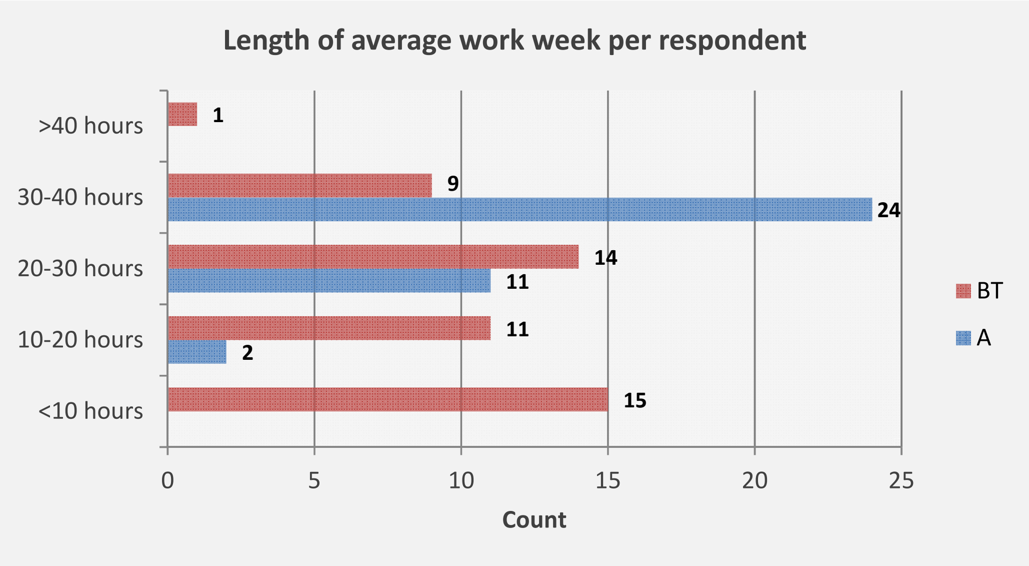
All of the results from the questionnaires discussed in *chapter 0* of the main report have been gathered and are shown in the following series of graphs. The first series, starting below, summarizes comparable questions for both cases. From *page 115* onwards, questions are distinguished by case study.

Answers summarized for both cases

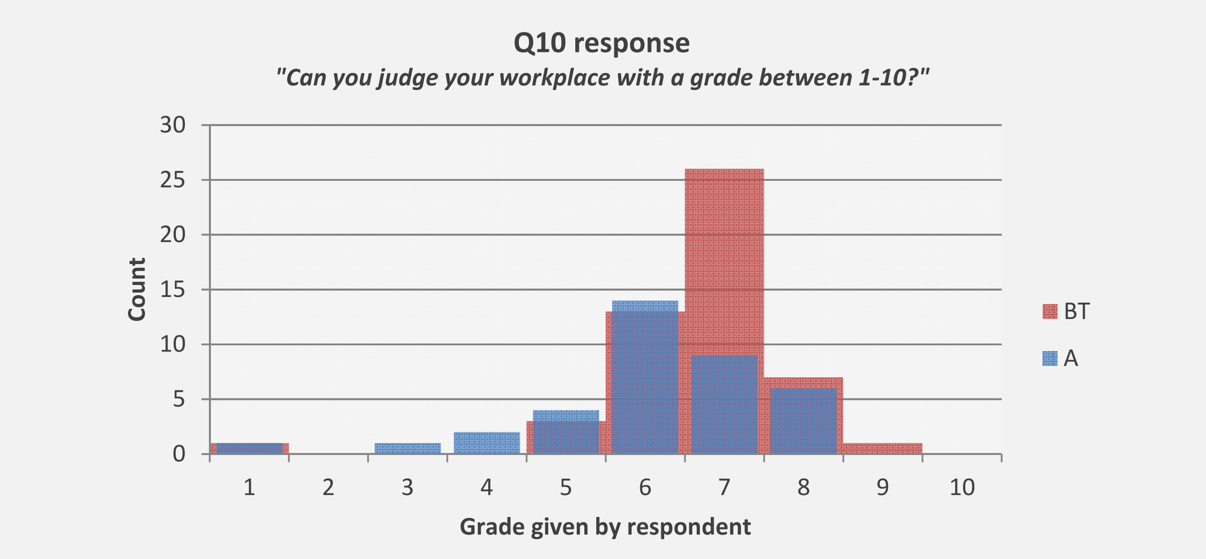


Gender	Age <19	20-24	25-29	30-39	40-49	50-59	>60	Total
A - Female	-	-	-	-	6	9	3	18
A - Male	-	-	-	1	1	10	7	19
BT - Female	-	12	9	-	-	-	-	21
BT - Male	-	15	14	1	-	-	-	30
Total	0	27	23	2	7	19	10	88

Graph 27. Questionnaire research population

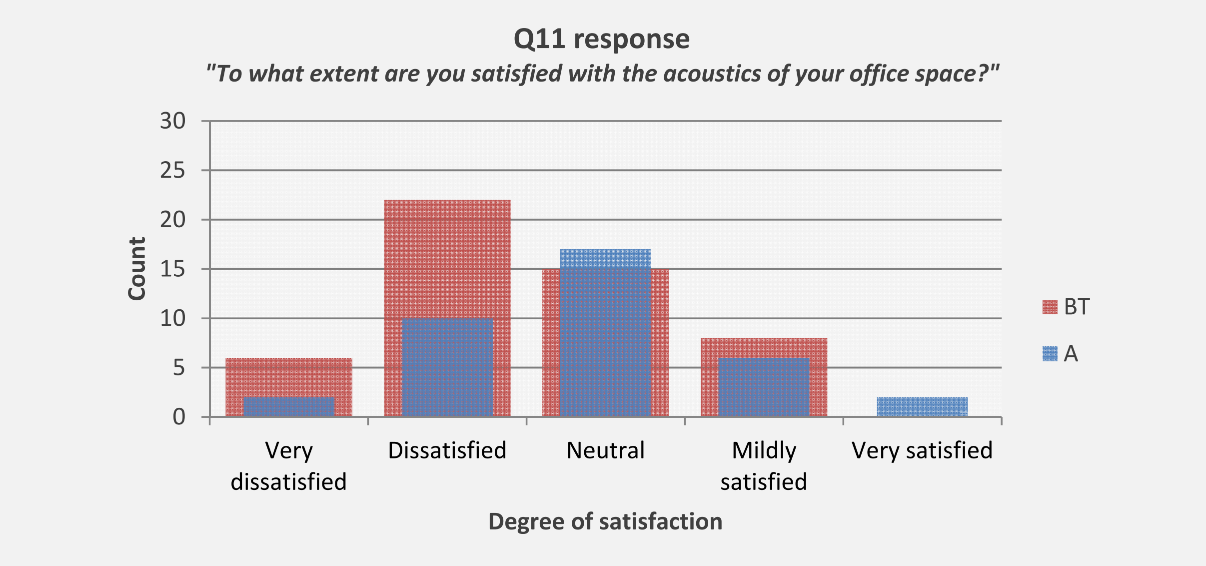


Graph 28. Amount of time per each respondent spends in the investigated rooms



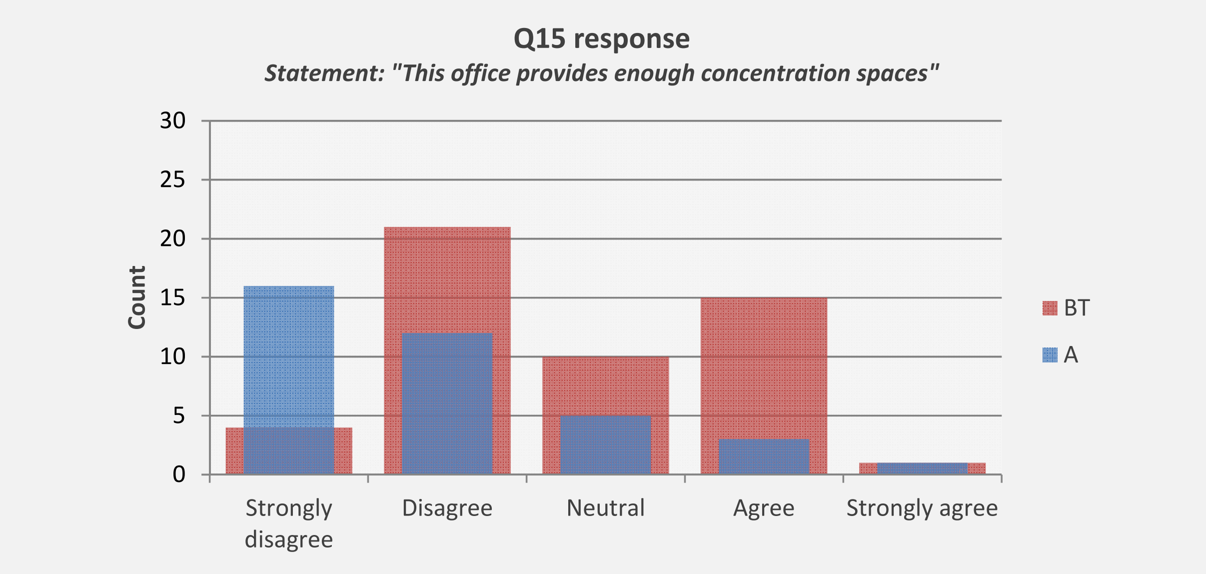
	Grade										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Mean**	**St.dev.**
BT	1	-	-	-	3	13	26	7	1	-	6,69	1,157
A	1	-	1	2	4	14	9	6	-	1	6,14	1,475

Graph 29. General grades given to the investigated rooms by respondents



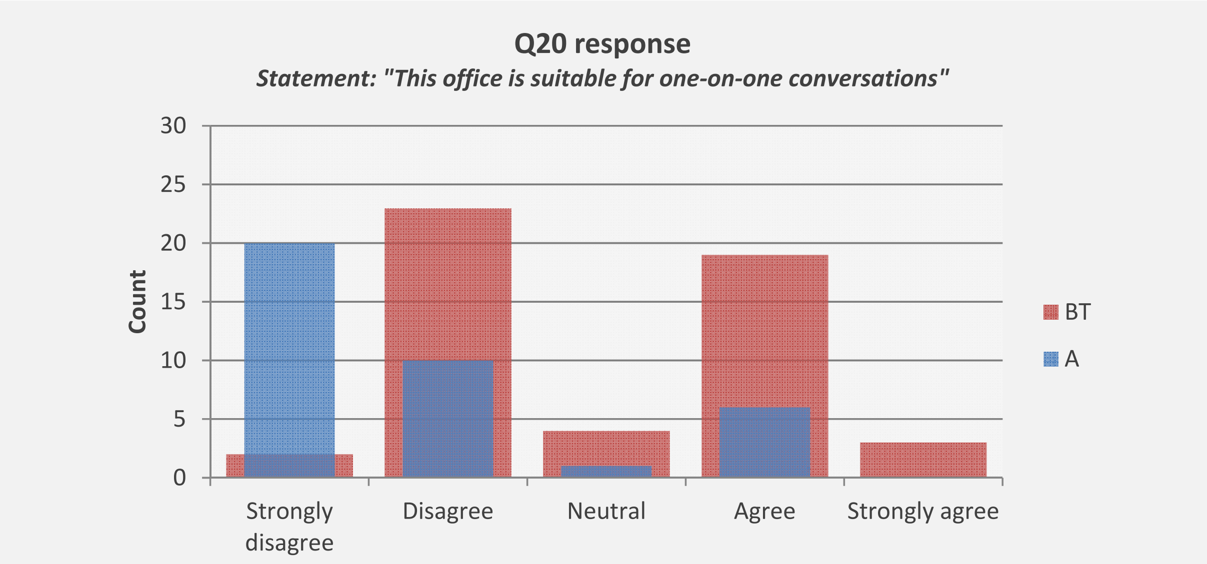
	Very dissatisfied	Dissatisfied	Neutral	Mildly satisfied	Very satisfied	Mean	St.dev.
BT	6	22	15	8	-	-0,059	0,903
A	2	10	17	6	2	-0,11	0,936

Graph 30. General satisfaction of respondents with regards to general room acoustics



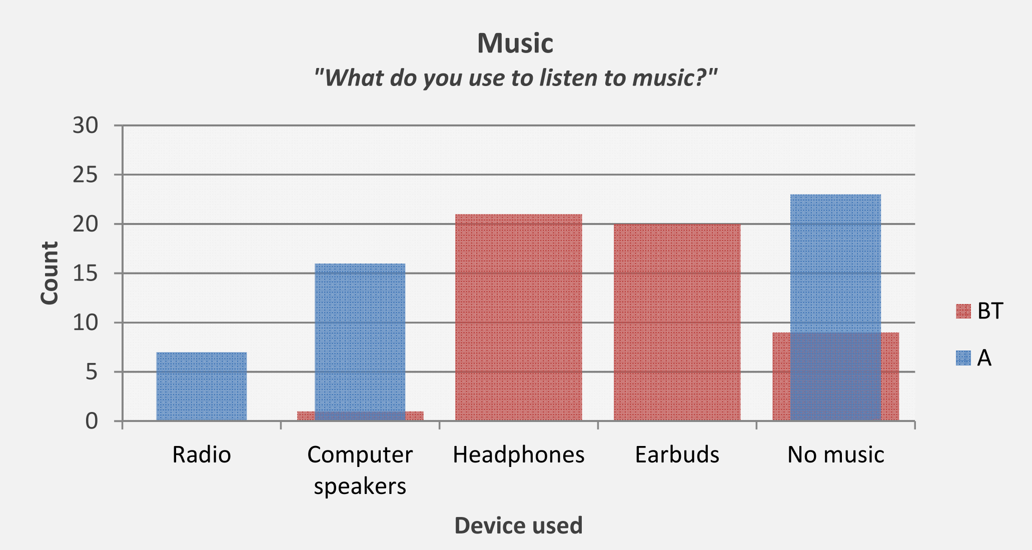
	Strongly disagree	Dissatisfied	Neutral	Agree	Strongly agree	Mean	St.dev.
BT	4	21	10	15	1	-0,24	1,031
A	16	12	5	3	1	-1,05	1,079

Graph 31. Respondents' opinion on whether enough spaces are provided to perform tasks requiring concentration



	Strongly disagree	Dissatisfied	Neutral	Agree	Strongly agree	Mean	St.dev.
BT	2	23	4	19	3	-0,04	1,113
A	20	10	1	6	-	-1,19	1,101

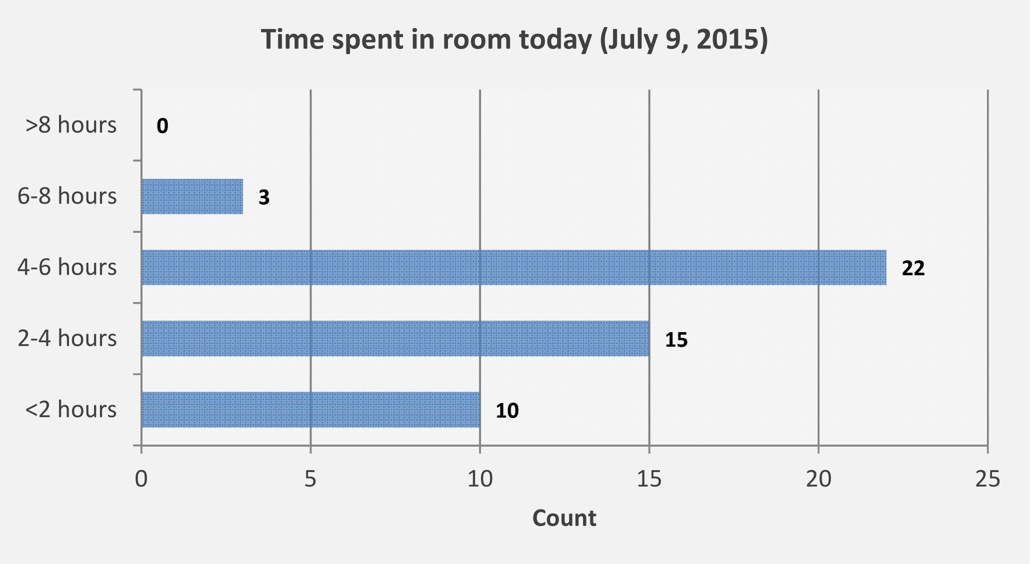
Graph 32. Respondents' opinion on whether confidential conversations can be held in the investigated rooms



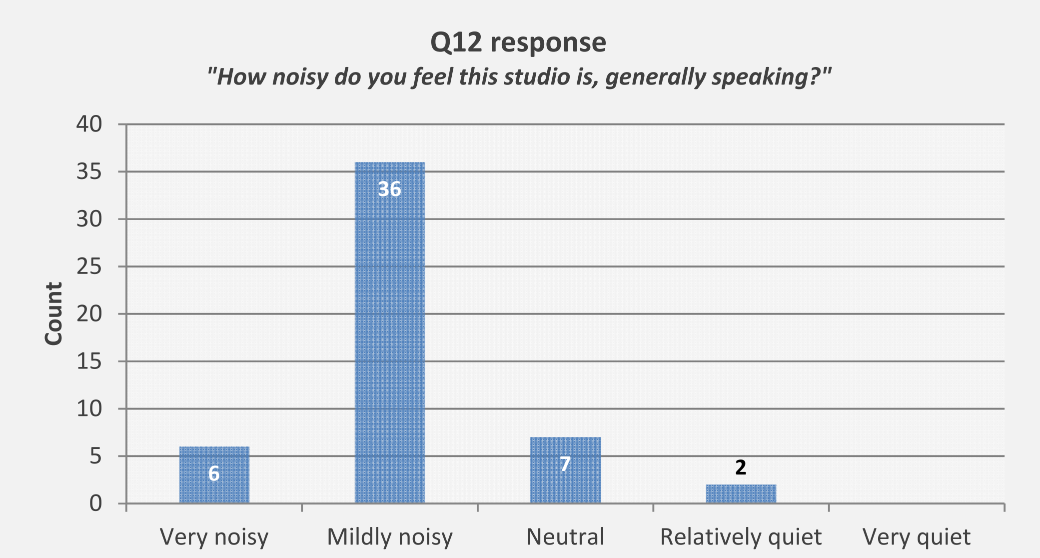
	Radio	Speakers	Headphones	Earbuds	No music
BT	-	1	21	20	9
A	7	16	-	-	23

Graph 33. Devices used by respondents to listen to music while working in the investigated rooms

Specifics for BT Studio

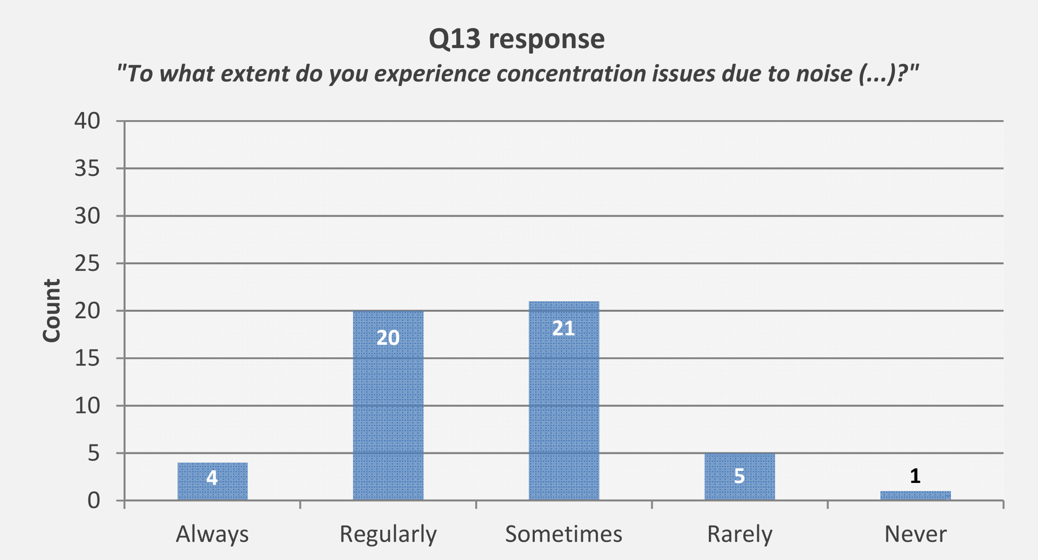


Graph 34. Amount of time students already spent in the BT Studio when given the questionnaire



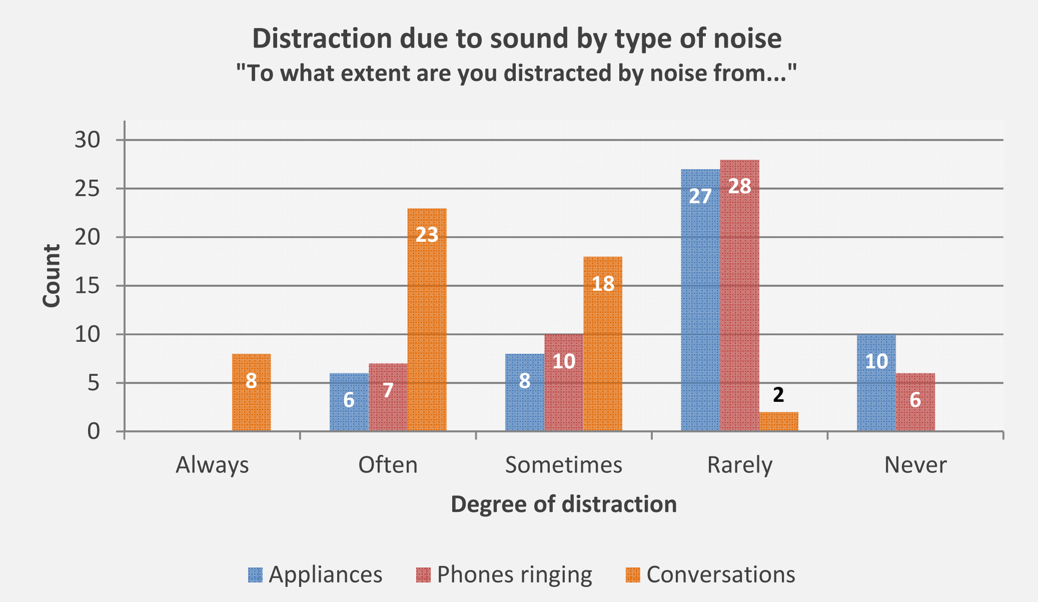
Mean	St.dev.	Range
-0,92	0,627	-2 to 2

Graph 35. Students' general perception of noise in the BT Studio



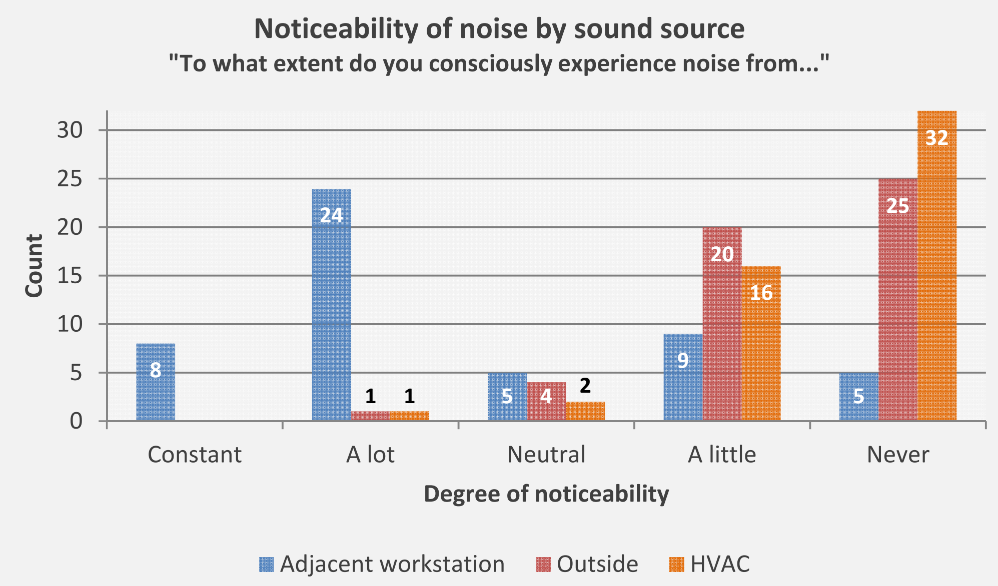
Mean	St.dev.	Range
-0,41	0,853	-2 to 2

Graph 36. Problems concentrating as a result of noise in the workplace, BT Studio students' perception



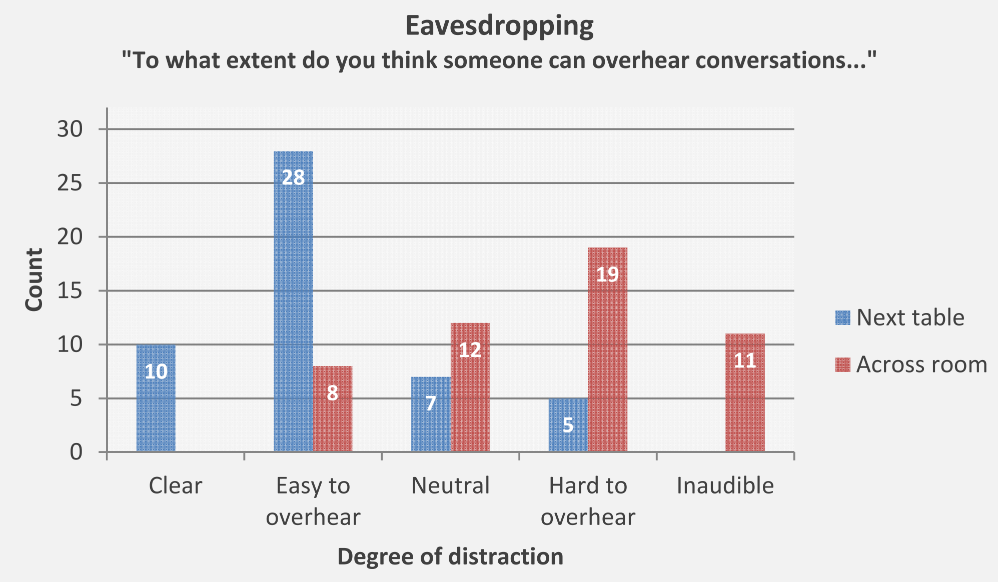
	Mean	St.dev.	Range
Appliances	-0,80	0,895	-2 to 2
Phones ringing	0,65	0,868	-2 to 2
Conversations	-0,73	0,777	-2 to 2

Graph 37. Problems concentrating as a result of noise in the workplace, BT Studio students' perception



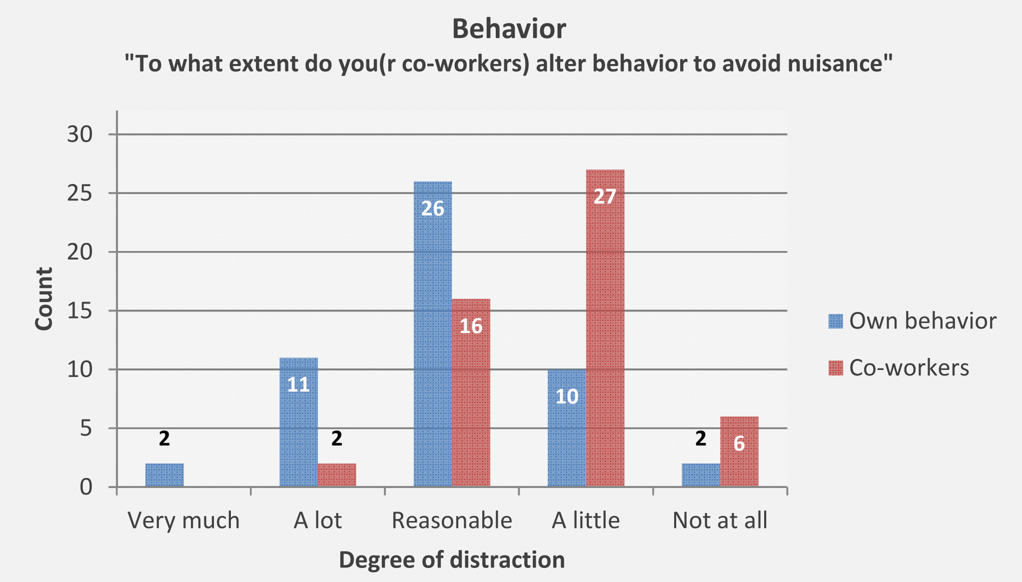
	Mean	St.dev.	Range
Adjacent workstation	-0,41	1,236	-2 to 2
Outside	1,38	0,725	-2 to 2
HVAC	1,55	0,673	-2 to 2

Graph 38. Students' rating of the degree at which each noise type causes distraction, BT Studio



	Mean	St.dev.	Range
At the next table	-0,86	0,857	-2 to 2
From across the room	0,66	1,002	-2 to 2

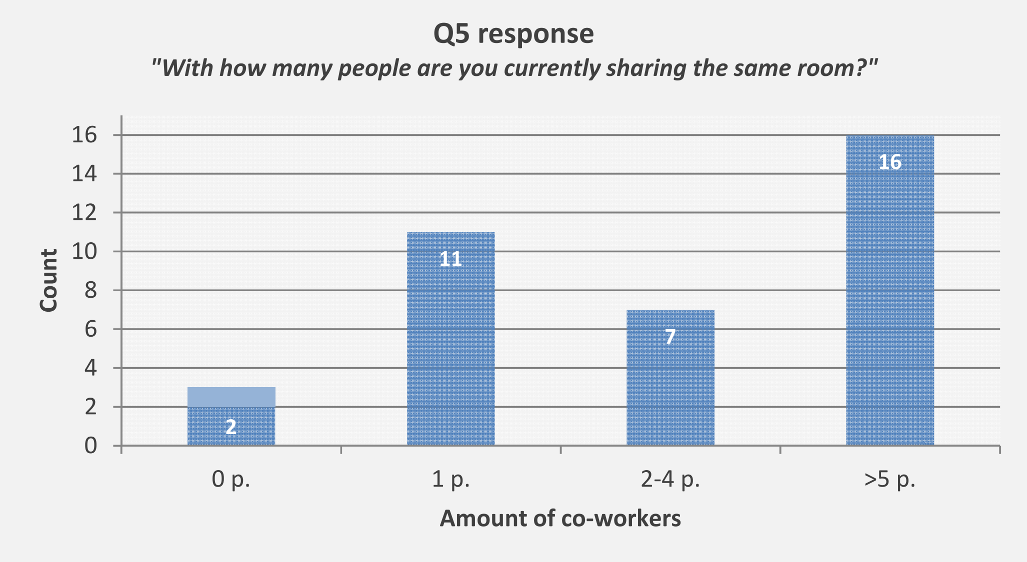
Graph 39. The extent at which students think their conversations can be overheard by others in the room



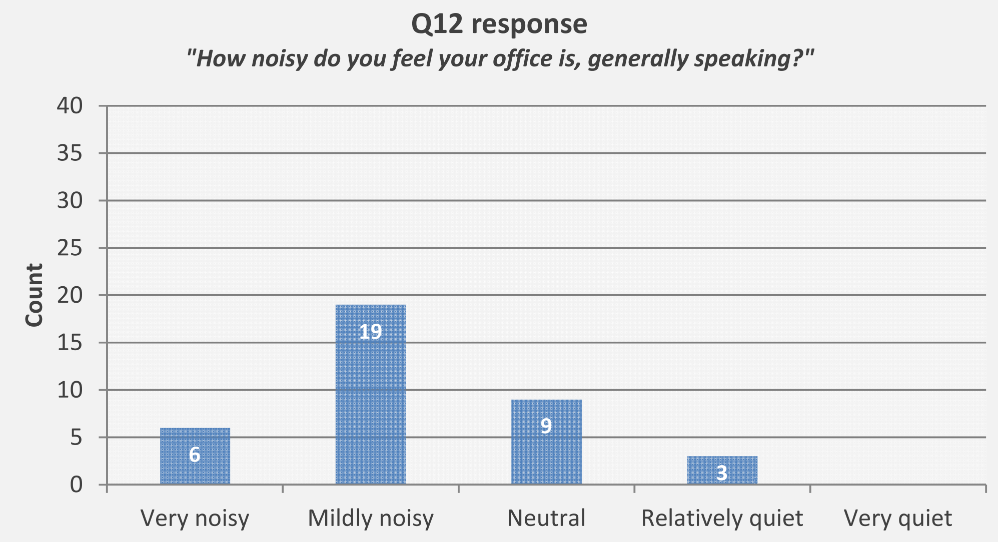
	Mean	St.dev.	Range
Own behavior	-0,02	0,860	-2 to 2
Behavior of co-workers	0,73	0,723	-2 to 2

Graph 40. Students' perceived adaptation of behavior when working in the BT Studio

Specifics for office A

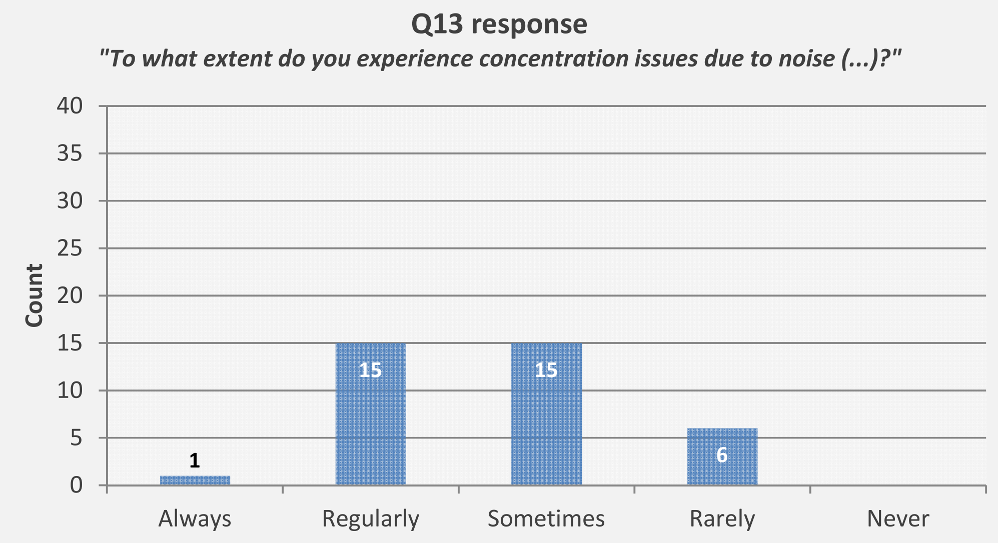


Graph 41. Amount of co-workers respondents share a room with while filling in their questionnaire



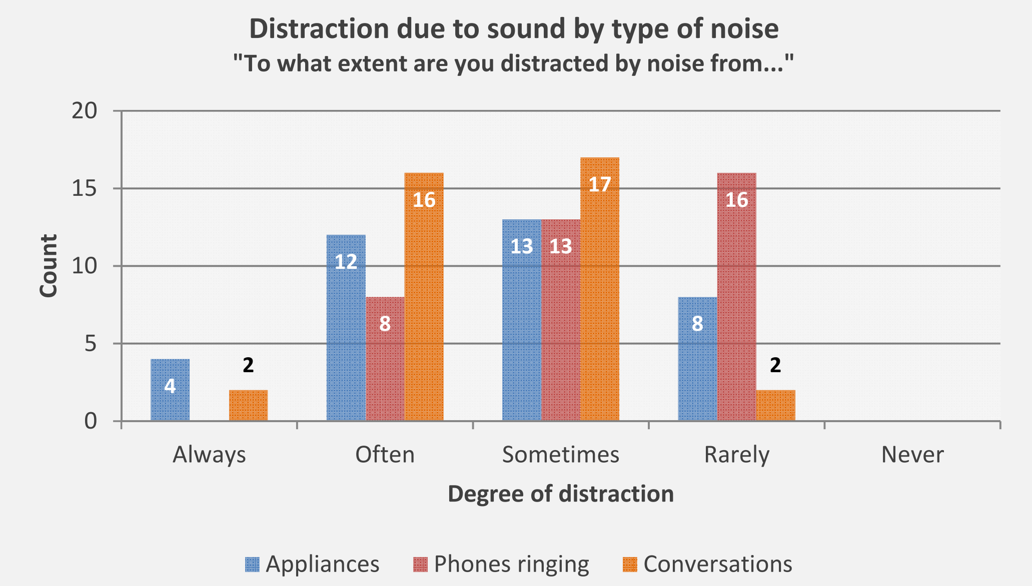
Mean	St.dev.	Range
-0,76	0,830	-2 to 2

Graph 42. Employees' general perception of noise in office A



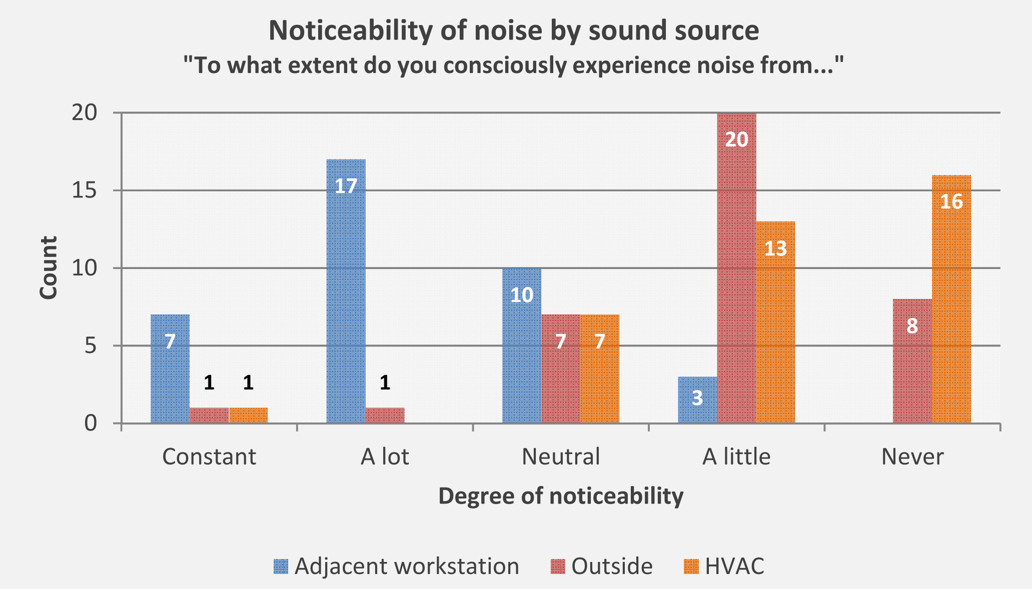
Mean	St.dev.	Range
-0,30	0,777	-2 to 2

Graph 43. Problems concentrating as a result of noise in the workplace, office A employees' perception



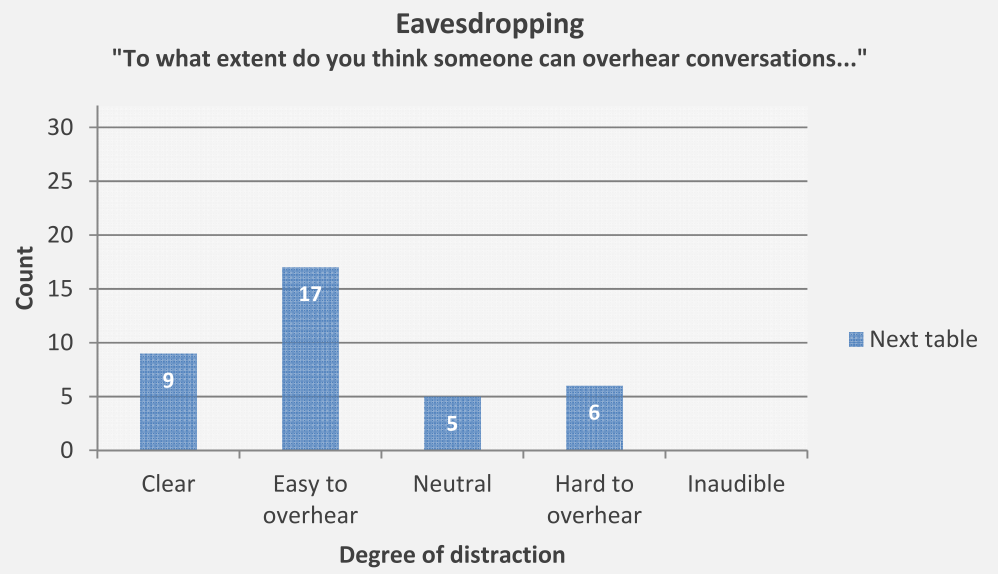
	Mean	St.dev.	Range
Appliances	-0,32	0,944	-2 to 2
Phones ringing	0,22	0,787	-2 to 2
Conversations	-0,49	0,692	-2 to 2

Graph 44. Employees' rating of the degree at which each noise type causes distraction, office A



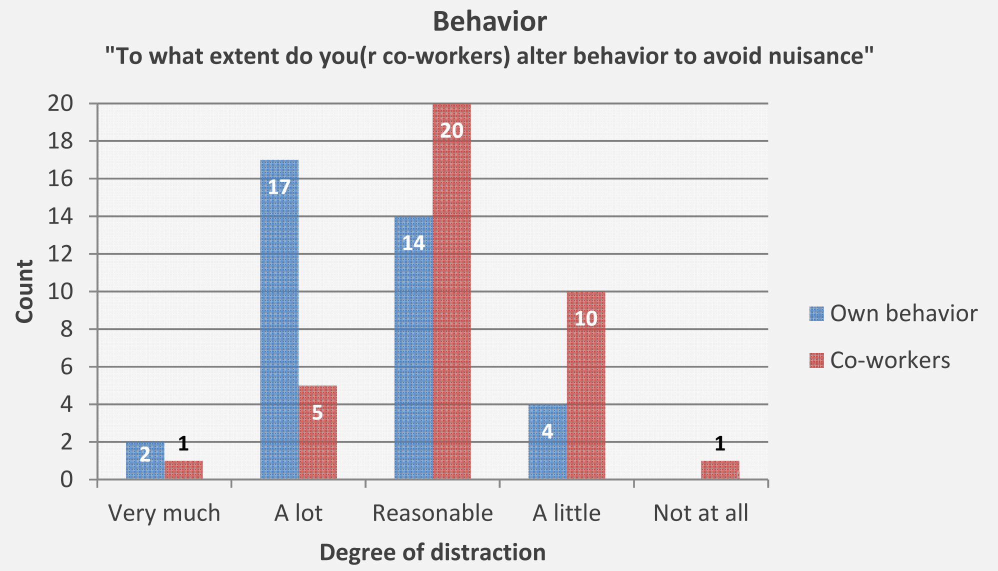
	Mean	St.dev.	Range
Adjacent workstation	-0,76	0,863	-2 to 2
Outside	0,89	0,875	-2 to 2
HVAC	1,16	0,928	-2 to 2

Graph 45. Employees' rating of the degree at which each noise type causes distraction, office A



Mean	St.dev.	Range
-0,78	1,002	-2 to 2

Graph 46. The extent at which employees think their conversations can be overheard by others in the room

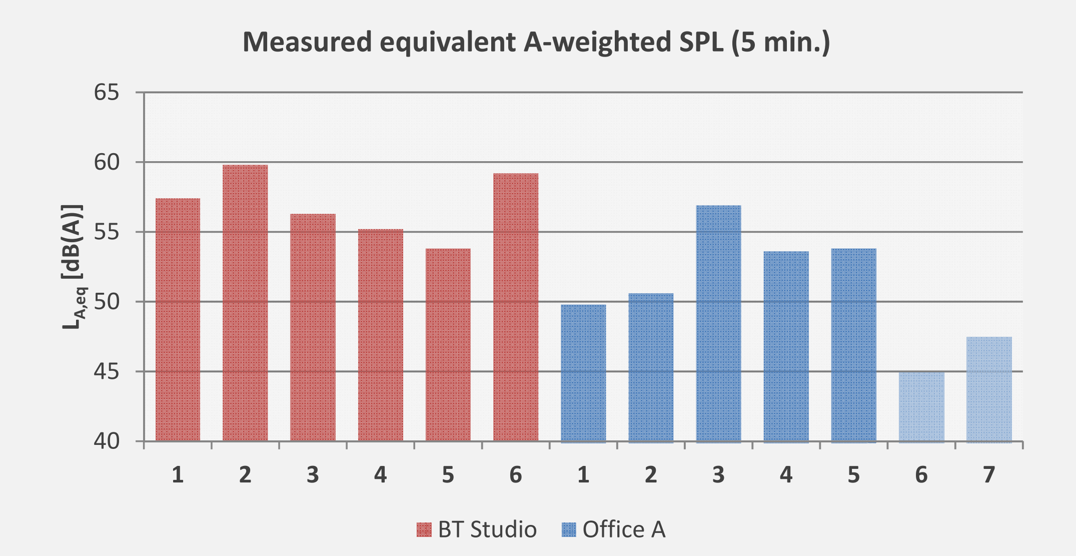


	Mean	St.dev.	Range
Own behavior	-0,46	0,767	-2 to 2
Behavior of co-workers	0,14	0,787	-2 to 2

Graph 47. Employees' perceived adaptation of behavior when working in office A

Appendix C FULL RESULTS OF ACOUSTIC MEASUREMENTS

The results for the acoustic measurements of both case studies, as referred in to *chapter 8* of the main report, are shown in this appendix for purpose of comparison. More detailed maps indicating measurement locations are also included, once for each case.



BT Studio

	1	2	3	4	5	6
Time	14:56 h	15:03 h	15:09 h	15:17 h	15:25 h	15:44 h
$L_{A,eq}$ [dB(A)]	57,4	59,8	56,3	55,2	53,8	59,2

Office A

	1	2	3	4	5	6	7
Time	12:34 h	12:44 h	12:52 h	13:01 h	13:18 h	13:30 h	13:42 h
$L_{A,eq}$ [dB(A)]	49,8	50,6	56,9	53,6	53,8	44,9	47,5

Graph 48. Results of all noise level measurements

BT Studio

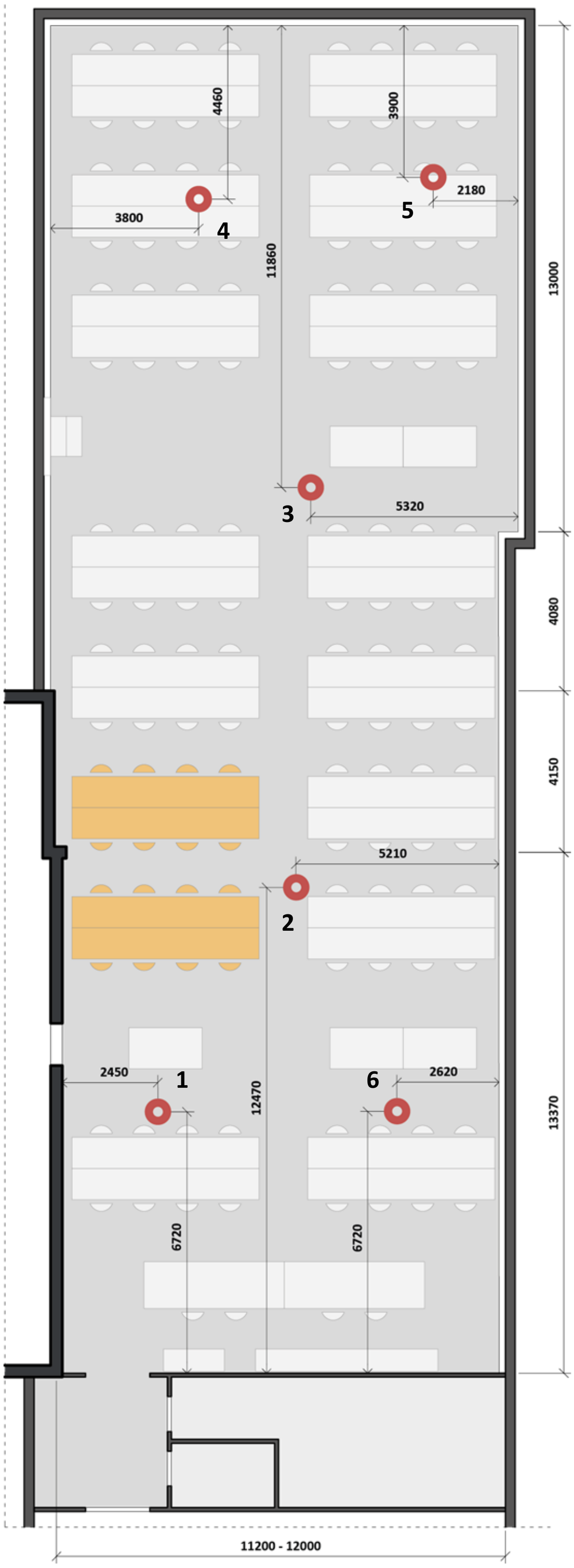
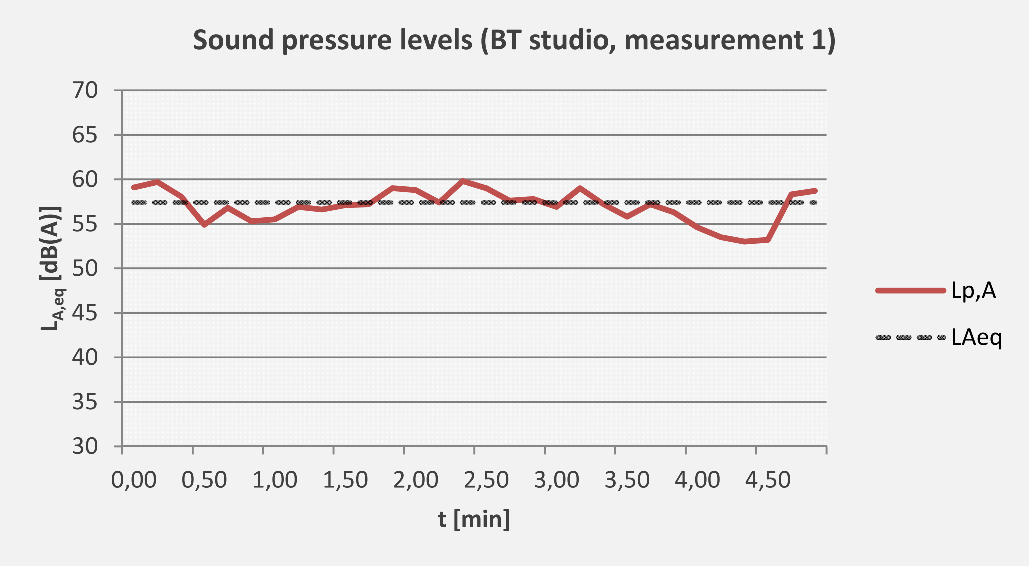
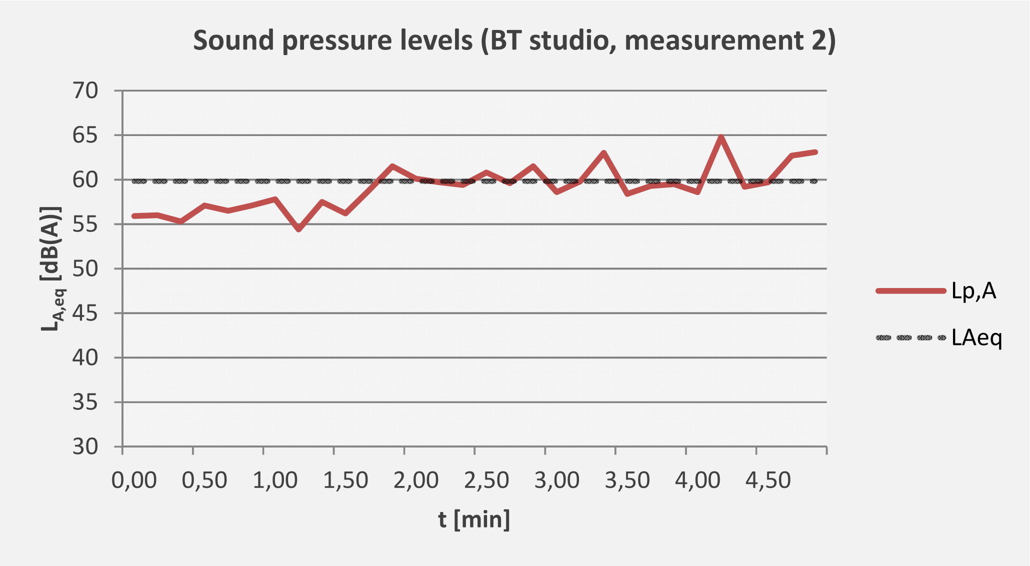


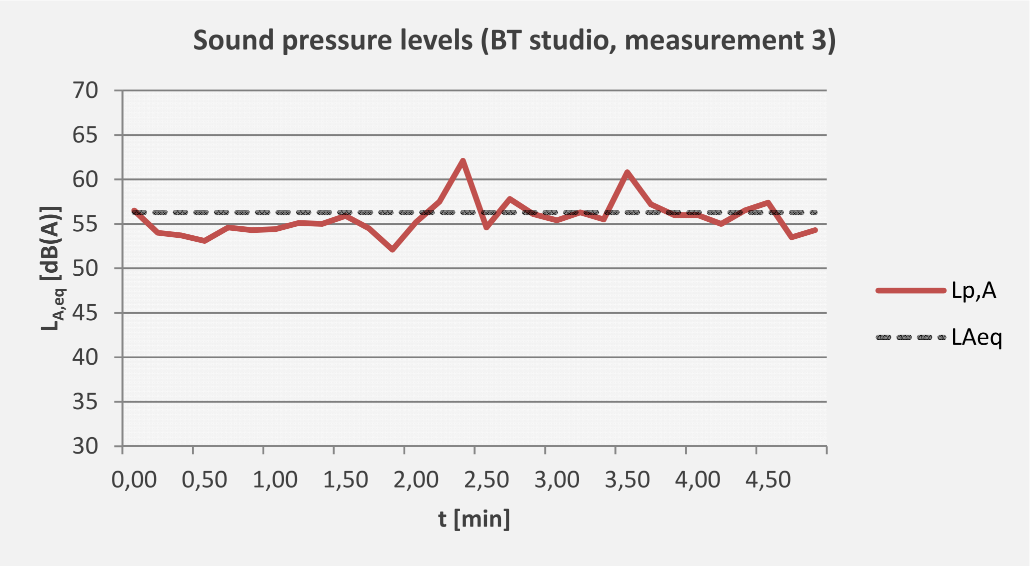
Figure 51. Measuring positions BT Studio



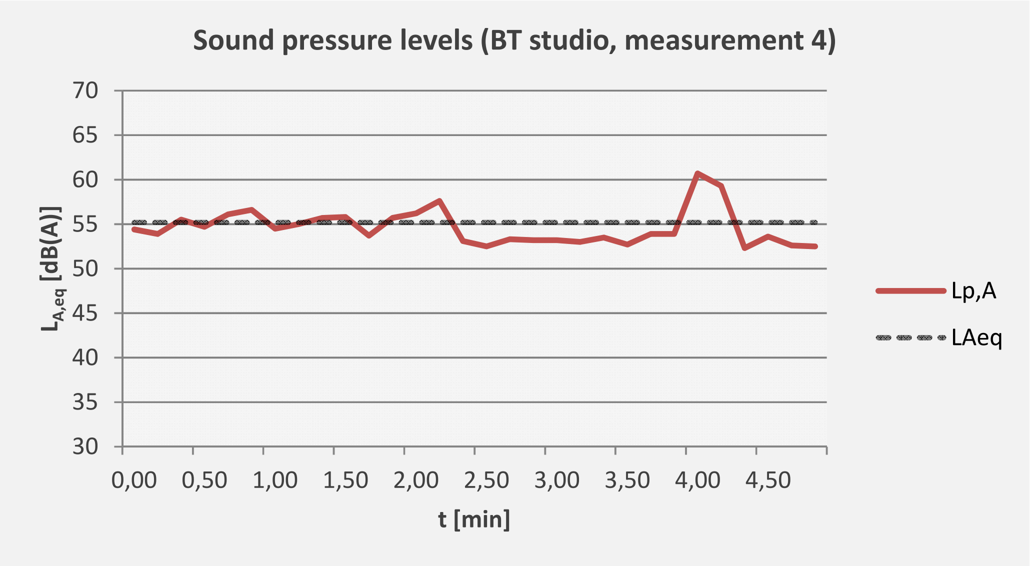
Graph 49. Equivalent A-weighted SPL measured over all frequency bands, position 1 (t = 0 at 14:57 h.)



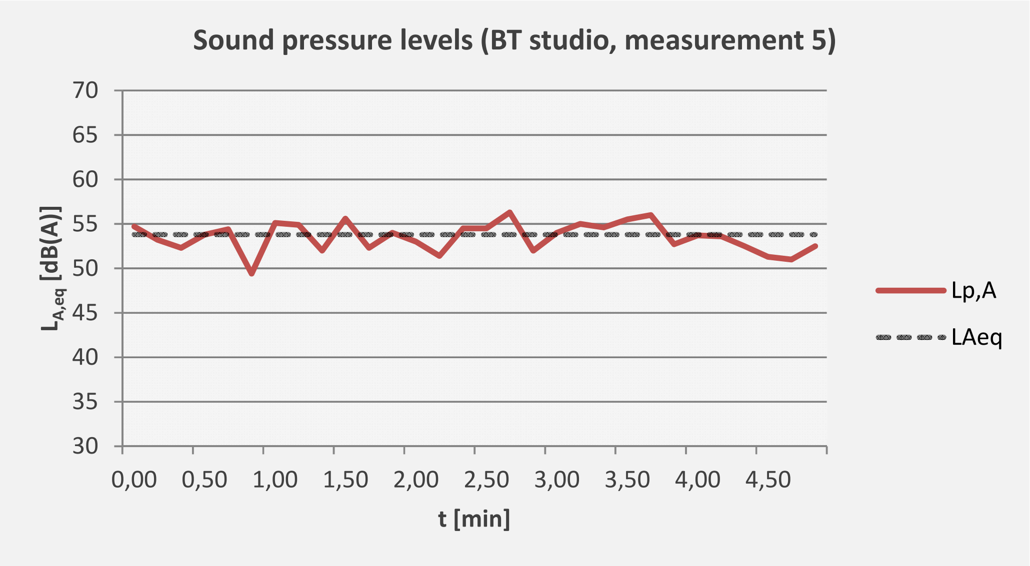
Graph 50. Equivalent A-weighted SPL measured over all frequency bands, position 2 (t = 0 at 15:03 h.)



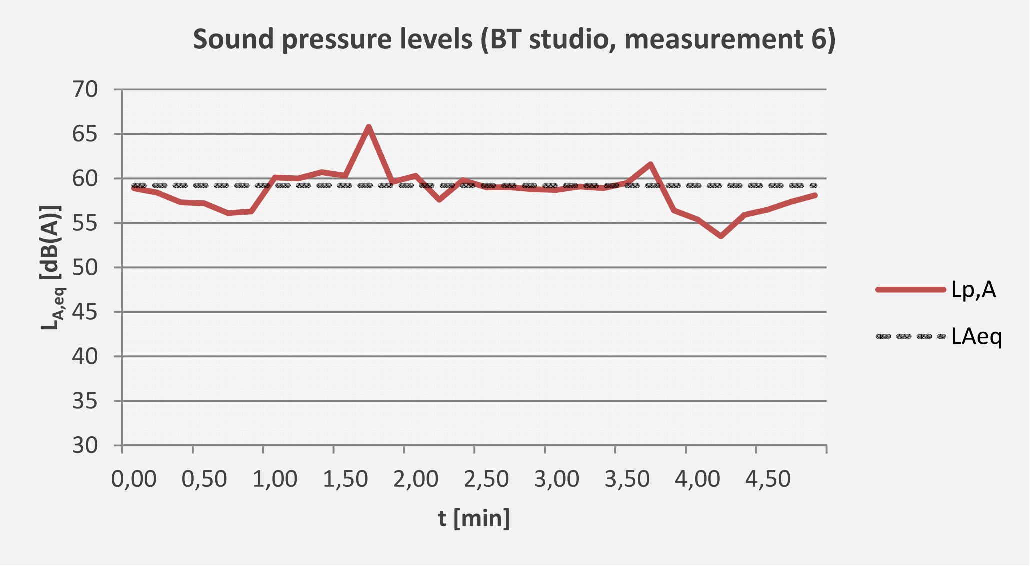
Graph 51. Equivalent A-weighted SPL measured over all frequency bands, position 3 (t = 0 at 15:10 h.)



Graph 52. Equivalent A-weighted SPL measured over all frequency bands, position 4 (t = 0 at 15:17 h.)



Graph 53. Equivalent A-weighted SPL measured over all frequency bands, position 5 (t = 0 at 15:26 h.)



Graph 54. Equivalent A-weighted SPL measured over all frequency bands, position 6 (t = 0 at 15:45 h.)

Office A

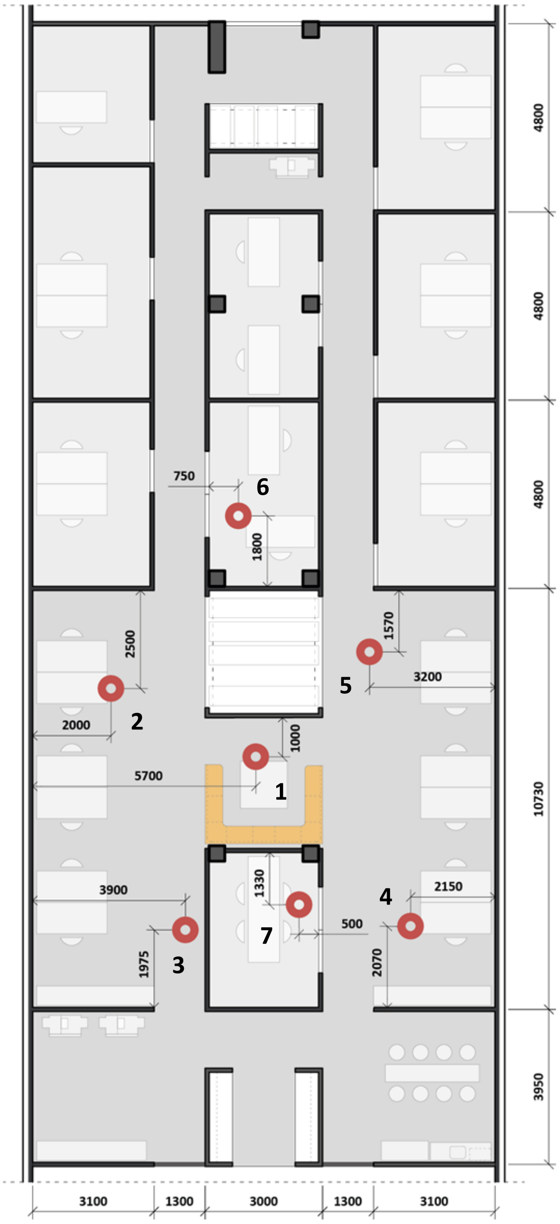
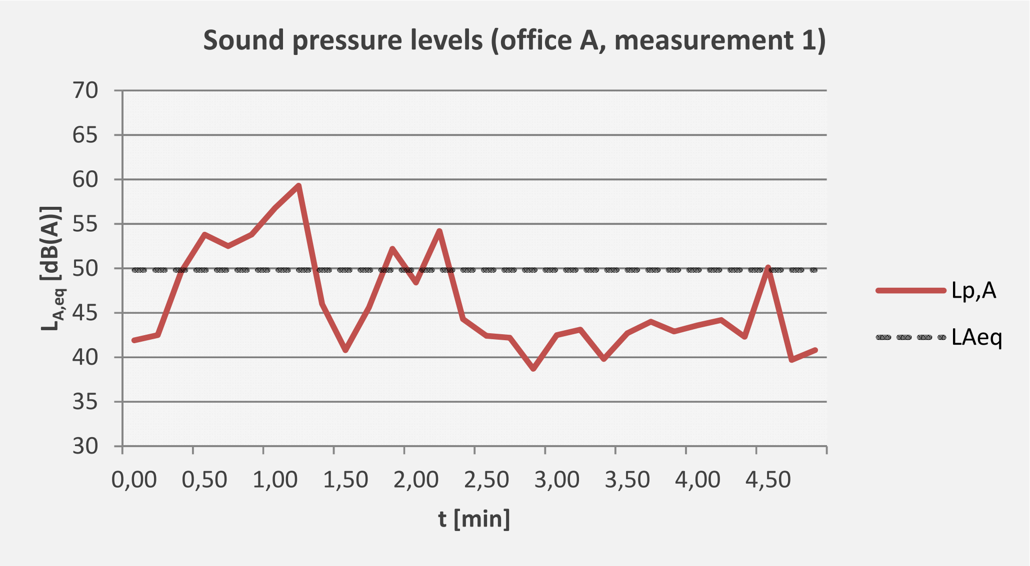
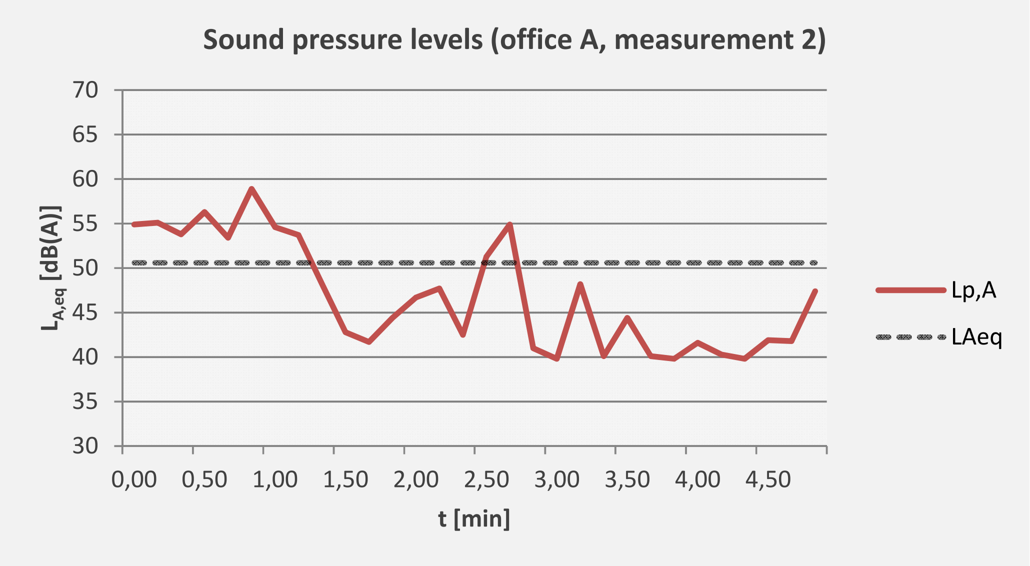


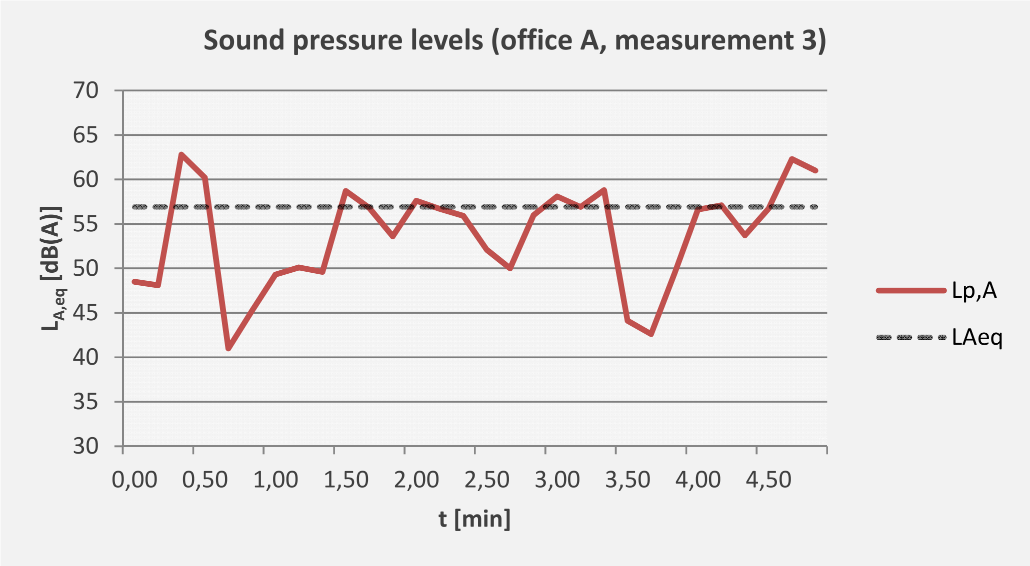
Figure 52. Measuring positions office A



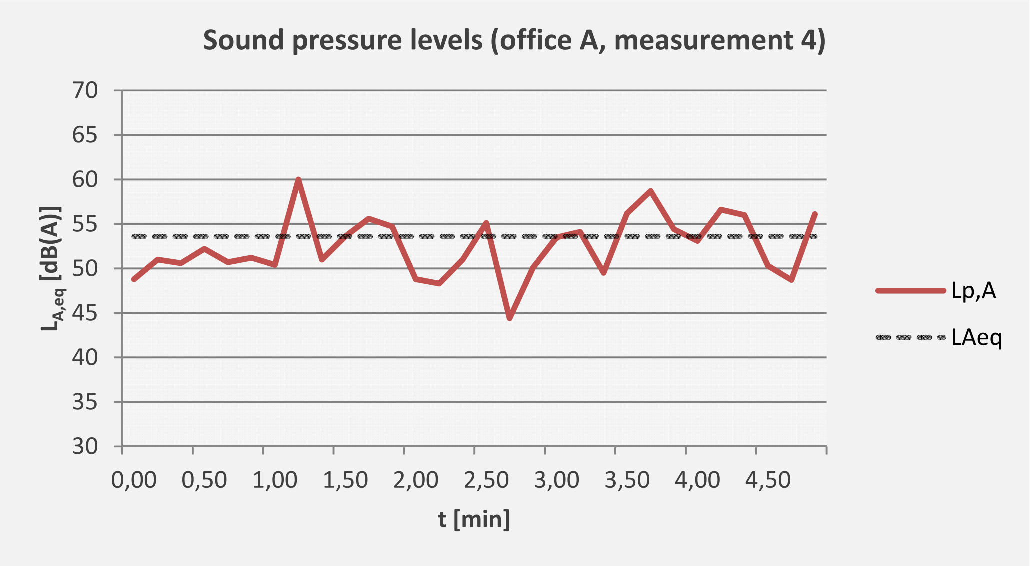
Graph 55. Equivalent A-weighted SPL measured over all frequency bands, position 1 (t = 0 at 12:34 h.)



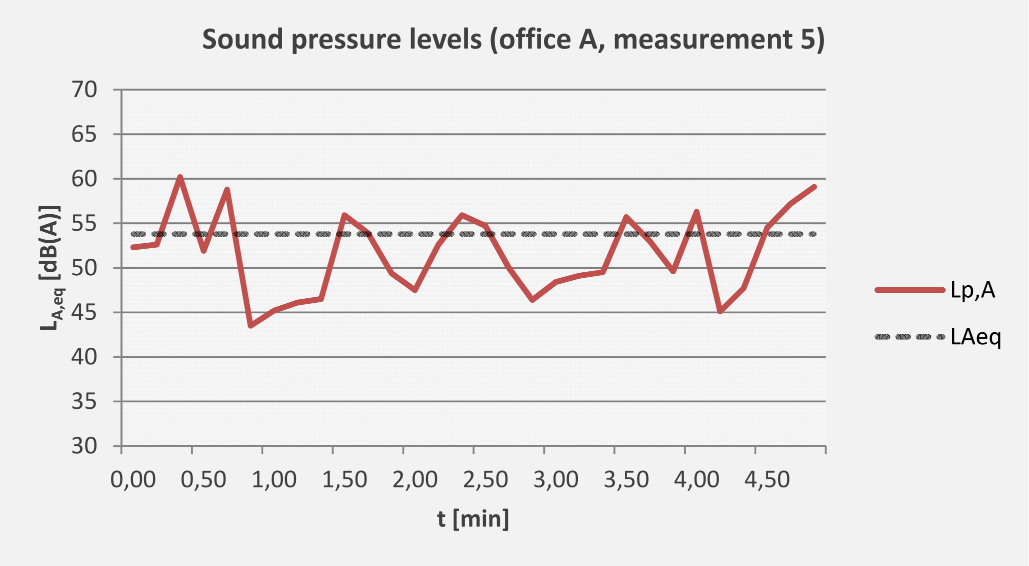
Graph 56. Equivalent A-weighted SPL measured over all frequency bands, position 2 (t = 0 at 12:44 h.)



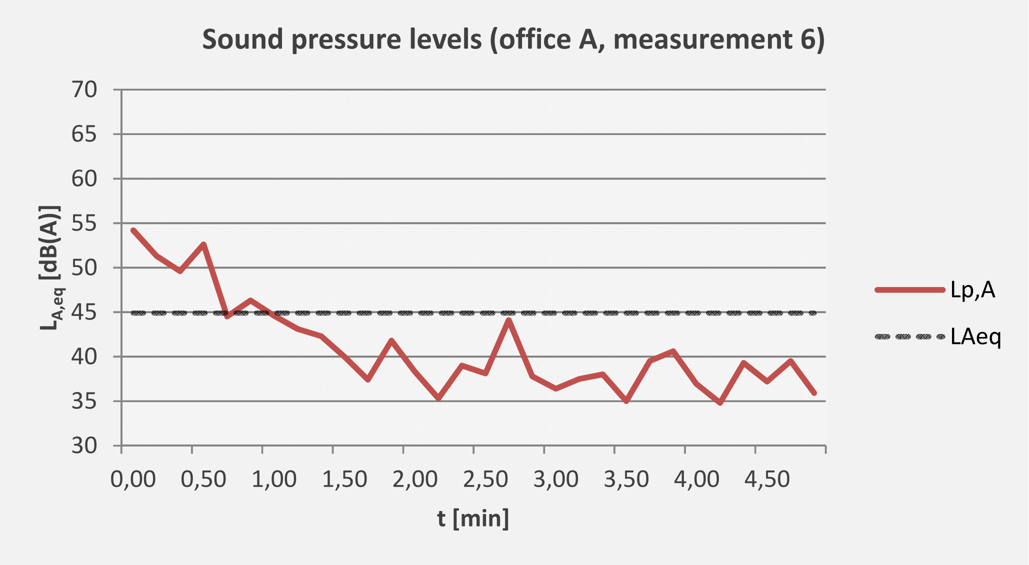
Graph 57. Equivalent A-weighted SPL measured over all frequency bands, position 3 (t = 0 at 12:52 h.)



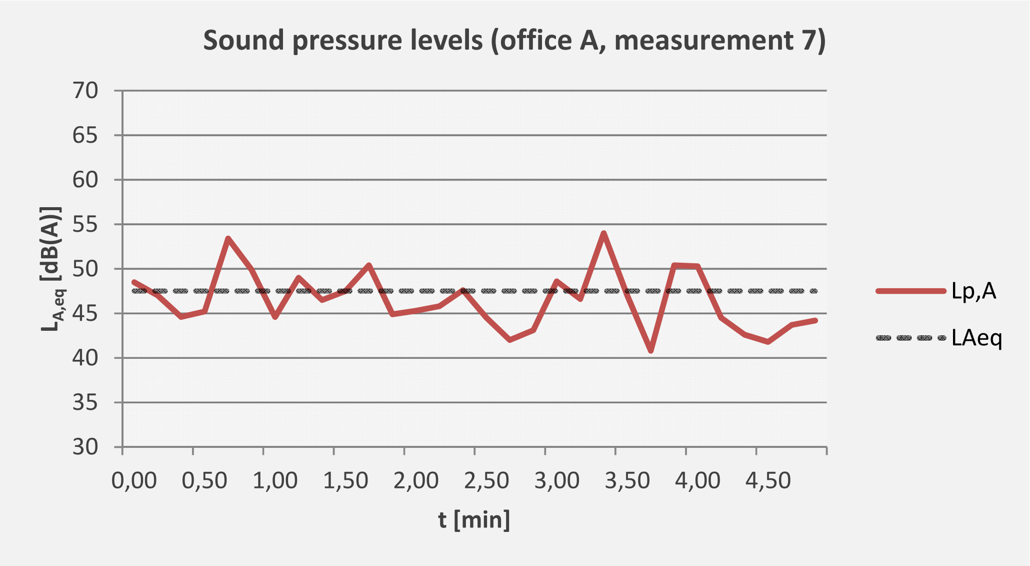
Graph 58. Equivalent A-weighted SPL measured over all frequency bands, position 4 (t = 0 at 13:01 h.)



Graph 59. Equivalent A-weighted SPL measured over all frequency bands, position 5 (t = 0 at 13:18 h.)



Graph 60. Equivalent A-weighted SPL measured over all frequency bands, position 6 (t = 0 at 13:30 h.)



Graph 61. Equivalent A-weighted SPL measured over all frequency bands, position 1 (t = 0 at 13:42 h.)

Appendix D END USER FEEDBACK QUESTIONS

The questions and test procedures of the feedback sessions conducted on 27 November 2015 with employees at office A, are explained in detail in order. For a summary of the results and findings, see *paragraph 12.1 End users*.

Benchmarking questions

1.	How proficient are you in understanding and interpreting spoken English? *Hoe vaardig bent u in het verstaan en interpreteren van Engelse spraak?*
☐	Bilingual proficiency *Vloeiend twee- of meertalig*
☐	Professional proficiency *Gevorderd / professioneel vaardig*
☐	Working proficiency *Redelijk vaardig*
☐	Limited proficiency *Zeer gelimiteerd*
☐	Not proficient *Niet vaardig*

Respondents listened to two auralized recordings. The first recording was a single line of female speech at 1 m distance from the source. The second file consisted of several fragments of normal speech (both male and female) recorded at five different receivers, placed in a single line, with the distance from the source increasing for each fragment. The distance between the source and final receiver is 11 m.

2.	How loud do you think fragment A is compared to what you perceive as a normal speech level? *Hoe luid ervaart u fragment A ten opzichte van u als gangbaar geluidsniveau beschouwt voor een regulier gesprek zonder stemverheffing?*
☐	Very loud *Zeer luid*
☐	Relatively loud *Redelijk luid*
☐	Neutral *Normaal niveau*
☐	Relatively quiet *Redelijk rustig*
☐	Very quiet *Zeer rustig*

3.	Can you estimate the distance from the source at which the final fragment of sound clip B was recorded? *Kunt u een schatting maken van de afstand waarop de microfoon stond bij de allerlaatste opname in fragment B?*
…	

A/B-testing

Respondents were given two recordings to compare. One of them was made in an auralization on a model resembling the current situation. The other record is produced the same way, using the same source and receiver positions, but with changes (improvements) made to the model. Respondents are asked to identify and quantify the difference in sound level they perceive upon listening to both sound files.

Auralization performed using receiver 03.

4.	To what extent do you notice a difference in sound level between the two voice clips? *In welke mate kunt u het verschil horen in geluidsniveaus tussen de twee fragmenten?*
☐	B is clearly louder than A *B is overduidelijk luider dan A*
☐	B is slightly louder than A *Met enige inspanning kan ik horen dat B luider is dan A*
☐	I don't hear a difference *Ik hoor geen verschil*
☐	B is slightly less loud than A *Met enige inspanning kan ik horen dat B minder is dan A*
☐	B is clearly less loud than A *B is overduidelijk minder luid dan A*

Auralization performed using receiver 15.

5.	To what extent do you notice a difference in sound level between the two voice clips? *In welke mate kunt u het verschil horen in geluidsniveaus tussen de twee fragmenten?*
☐	B is clearly louder than A *B is overduidelijk luider dan A*
☐	B is slightly louder than A *Met enige inspanning kan ik horen dat B luider is dan A*
☐	I don't hear a difference *Ik hoor geen verschil*
☐	B is slightly less loud than A *Met enige inspanning kan ik horen dat B minder is dan A*
☐	B is clearly less loud than A *B is overduidelijk minder luid dan A*

Auralization performed using receiver 22.

6.	To what extent do you notice a difference in sound level between the two voice clips? *In welke mate kunt u het verschil horen in geluidsniveaus tussen de twee fragmenten?*
☐	B is clearly louder than A *B is overduidelijk luider dan A*
☐	B is slightly louder than A *Met enige inspanning kan ik horen dat B luider is dan A*
☐	I don't hear a difference *Ik hoor geen verschil*
☐	B is slightly less loud than A *Met enige inspanning kan ik horen dat B minder is dan A*
☐	B is clearly less loud than A *B is overduidelijk minder luid dan A*

Respondents listened to two recordings, each consisting of two sets of three normal speech fragments mixed together. One set of three belonged to source A, with the other set being produced by source B. Respondents are asked to judge the intelligibility of one set over the other. Receiver 01 is used for the recording.

7.	Between the two recordings, in which mix did you find it easier to distinguish the main conversation from the conversation in the background? *Tussen de twee door elkaar lopende geluidsopnamen, bij welk fragment kon u het luidere hoofdgesprek beter onderscheiden van het gesprek op de achtergrond?*
☐	The conversations were far harder to distinguish in B than in A *In fragment B waren de gesprekken overduidelijk slechter te onderscheiden dan bij A*
☐	The conversations were slightly harder to distinguish in B than in A *In fragment B waren de gesprekken een beetje slechter te onderscheiden dan bij A*
☐	Little to no difference, in both cases conversations are hard to distinguish *Geen tot weinig verschil, in beide gevallen slecht te onderscheiden*
☐	Little to no difference, in both cases conversations are easily distinguishable *Geen tot weinig verschil, in beide gevallen goed te onderscheiden*
☐	The conversations were slightly easier to distinguish in B than in A *In fragment B waren de gesprekken een beetje beter te onderscheiden dan bij A*
☐	The conversations were far easier to distinguish in B than in A *In fragment B waren de gesprekken overduidelijk beter te onderscheiden dan bij A*

Personal stance on architectural implications

8.	What is your general stance on open plan offices? *Wat vindt u in het algemeen van open kantoren?*
☐	They ought to be banned from the face of the earth (extremely negative) *Ze zouden verboden moeten worden (zeer negatief)*
☐	Do not like it; consider them a necessary evil (moderately negative) *Vind ze niet leuk; een nodig kwaad (gematigd negatief)*
☐	No opinion (neutral) *Geen mening (neutraal)*
☐	Okay under the right conditions (moderately positive) *Aardig bij de juiste condities (gematigd positief)*
☐	Best invention since sliced bread (extremely positive) *Beste uitvinding sinds het gesneden brood (extreem positief)*

Respondents are shown an interior impression of the room (rendered images) before and after changes are made.

9.	Do you think the illustrated design alternative would be an acceptable solution for acoustic treatment in terms of visual appeal and practicality? *Acht u de voorgestelde aanpassing ter verbetering van de akoestiek aanvaardbaar vanuit visueel en praktisch oogpunt?*
☐	Absolutely not (extremely negative) *Absoluut niet (zeer negatief)*
☐	Probably not; defeats the purpose of the space (slightly negative) *Waarschijnlijk niet (gematigd negatief)*
☐	Makes no difference to me (neutral) *Neutraal (neutraal)*
☐	Possibly (slightly positive) *Misschien (gematigd positief)*
☐	Absolutely, I really like it (extremely positive) *Tuurlijk (extreem positief)*

Appendix E PROFESSIONAL CONSULTANT INTERVIEW QUESTIONS

Below the questions are presented that served as framework for the interviews conducted with several acoustics and building physics consultants. An account for the events of these consultations is given in *paragraph 12.2*.

Professional background

1. What is your job title?
Wat is uw werktitel?

…

2. Can you give a general description on your usual activities and role within a design team?
Kunt u een algemene omschrijving geven van uw activiteiten en uw rol in een ontwerpteam?

…

3. To what extent do you take acoustics into account in the decision-making process (with regard to altering design or providing consultation)?
In welke mate is akoestiek van belang in uw besluitvorming in relatie tot het maken van ontwerpveranderingen of het uitbrengen van professioneel advies?

…

Stance on office design

4. Would you qualify you own workplace as an open plan office?
Zou u uw eigen werkplek als open kantoor omschrijven?

…

5. …and how is that working out for you?
…en bevordert deze ruimte uw productiviteit?

…

6. What is your general stance on open plan offices?
Wat vindt u in het algemeen van open kantoren?

☐ They ought to be banned from the face of the earth (extremely negative)
Ze zouden verboden moeten worden (zeer negatief)

☐ Do not like it; consider them a necessary evil (moderately negative)
Vind ze niet leuk; een nodig kwaad (gematigd negatief)

☐ No opinion (neutral)
Geen mening (neutraal)

☐ Okay under the right conditions (moderately positive)
Aardig bij de juiste condities (gematigd positief)

☐ Best invention since sliced bread (extremely positive)
Beste uitvinding sinds het gesneden brood (extreem positief)

☐ They make a great torture device (tremendously evil)
Ik zie ze als ideaal martelwerktuig (ongelooflijk kwaadaardig)

…

Parametric modelling

7.	To what extent does parametric modelling play a role in your current practice? *In welke mate speelt de toepassing van parametrische modellen een rol in uw hedendaagse praktijk?*
…	

8.	What aspect of a parametric model do you think is most worthwhile to develop further? *Welk aspect van een parametrisch model lijkt u het belangrijkst om door te ontwikkelen?*
☐	Support for different / wider range of software *Ondersteuning voor andere programma's*
☐	Speed *Snelheid*
☐	Ease of use *Gebruiksgemak*
☐	Accuracy *Precisie*
☐	Visualization features *Visualisatiemogelijkheden*
☐	Acoustic parameters *Akoestische parameters*
…	

9.	What are your thoughts specifically, on the ray tracing script developed in this research? *Wat vindt u specifiek van het script dat is ontwikkeld in dit onderzoek?*
…	