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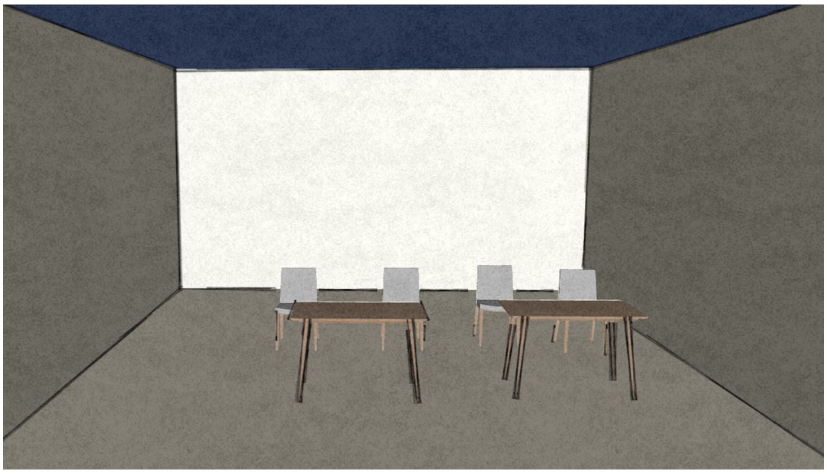

THE EFFECT OF FURNITURE ON ROOM ACOUSTIC PARAMETERS AND ITS DEPENDENCE ON THE SOUND ABSORBING PROPERTIES OF THE CEILING

HUONG NGUYEN

Engineering Acoustics

Master's Dissertation

DEPARTMENT OF CONSTRUCTION SCIENCES
DIVISION OF ENGINEERING ACOUSTICS
ISRN LUTVDG/TVBA--23/5064--SE (1-67) | ISSN 0281-8477
MASTER'S DISSERTATION

THE EFFECT OF FURNITURE ON ROOM ACOUSTIC PARAMETERS AND ITS DEPENDENCE ON THE SOUND ABSORBING PROPERTIES OF THE CEILING

HUONG NGUYEN

Supervisor: Dr **ERLING NILSSON**, Div. of Engineering Acoustics, LTH, Lund.
Examiner: Professor **KENT PERSSON**, Dept. of Construction Sciences, LTH, Lund.

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Printed by V-husets tryckeri LTH, Lund, Sweden, June 2023 *(Pl)*.

For information, address:
Division of Engineering Acoustics,
Faculty of Engineering LTH, Lund University, Box 118, SE-221 00 Lund, Sweden.
Homepage: www.akustik.lth.se

Abstract

In ordinary public rooms such as classrooms and offices, the base line of acoustical treatment is an absorbent suspended ceiling. Due to the non-uniform distribution of the absorptive ceiling material, the scattering as well as the absorption properties of furniture will have a significant effect on room acoustic parameters such as reverberation time, speech clarity and sound strength. In particular, the absorption of the sound scattered energy will depend on the absorbing efficiency of the suspended ceiling. This effect is not accounted for in classical diffuse field models such as Sabine's formula which is the norm for the calculation of reverberation time in existing standards. To evaluate the effect of furniture on room acoustic parameters, measurements were conducted in the reverberant room with varying degrees of furnishing for ceiling configurations ranging from highly reflective to highly absorptive. Using Sabine's formula and the Statistical Energy Analysis model, this dissertation analyzes the scattering and absorptive effects of furniture on reverberation time, speech clarity and sound strength. The absorbing and scattering effects of furniture have been quantified by the parameter equivalent scattering absorption area. How this parameter is affected by the absorptive capacity of the suspended ceiling has also been investigated. It is concluded that both the absorbing and scattering effects of furniture have a significant effect on room acoustic parameters and must be accounted for. Moreover, comparisons of the equivalent scattering absorption area show that the scattering mechanism of furniture dominates at different frequency ranges depending on the ceiling's absorptive efficiency. Therefore, a novel method is needed for quantification of the absorbing and scattering effects of furniture and how it depends on the absorbing efficiency of the suspended ceiling. This master's dissertation gives some guidance towards such a method.

Keywords: Room acoustics, furniture, SEA model, sound absorption, sound scattering

Sammanfattning

I vanliga rum, som till exempel klassrum och kontor, är grunden för akustisk behandling oftast ett ljudabsorberande undertak. På grund av att större delen av ljudabsorptionen är koncentrerad till en yta kommer den ljudspridande och ljudabsorberande effekten av möbleringen att ha en signifikant inverkan på rumsakustiska parametrar såsom efterklangstid, taltydlighet och ljudstyrka. Speciellt så kommer absorptionen av den ljudspridande energin att påverkas av takets absorptionsförmåga. Denna effekt är inte medtagen i den klassiska diffusfältsteorin som Sabines formel bygger på och som refereras till i många standarder vid beräkning av efterklangstid. För att undersöka möblernas effekt på rumsakustiska parametrar har mätningar utförts i ett efterklangsrum med olika möbelkonfigurationer och för olika undertak, från reflekterande till absorberande. Både Sabines formel och en modell som bygger på statistisk energianalys (SEA) har använts för att analysera möblernas effekt på de rumsakustiska parametrarna. Slutsatsen är att både den ljudabsorberande och ljudspridande effekten av möblerna har en signifikant inverkan på de rumsakustiska parametrarna och ska beaktas vid beräkning. Analysen av parametern ekvivalent ljudspridande absorptionsyta visar att den ljudspridande effekten av möblerna dominerar vid olika frekvensområden beroende på takets frekvensberoende absorption. En ny metod behöver utvecklas för kvantifiering av möblernas ljudabsorberande och ljudspridande egenskaper och hur dessa beror av undertakets absorption. Detta examensarbete ger en grund som kan användas för att utveckla en sådan metod.

Nyckelord: Rumsakustik, möbler, SEA modell, ljudabsorption, ljudspridning

Acknowledgements

This thesis concludes my five years of studies at Lund University, Faculty of Engineering (LTH). The work was supported by and conducted at Saint-Gobain Ecophon AB under the supervision of Professor Erling Nilsson. My most sincere thanks to my supervisor Erling for sharing your vast knowledge and providing me with the best guidance I could have hoped for. It has been a formative experience working with you on this project from its conception to its completion.

I would also like to extend my gratitude to my examiner Professor Kent Persson for your valuable input.

Special thanks to Bo Zadig from LTH for helping me with the layout of the thesis.

To my colleagues at WSP, Ecophon and Brekke & Strand, I am grateful for the opportunity to work with and learn from all of you.

To my family and friends, thank you for the inspiration that led me to acoustics and the support that left me with renewed motivation throughout the years.

Lund, June 2023
Huong Nguyen

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1 Introduction

This chapter provides the context of the problem that this thesis addresses, presents the purpose and goals of this thesis project, describes the chosen methodology and outlines the structure of the thesis.

1.1 Background

The significant impacts of room acoustic environment in ordinary public rooms such as classrooms and offices are well documented. Studies have shown how unsatisfactory room acoustics in a classroom environment can negatively affect verbal working memory performances and lead to greater loss of concentration for listeners [1] [2]. The effect is equally detrimental for speakers, as many as 31% of teachers reported high vocal effort in a recent survey of nine Italian case studies [2] and in another study conducted in Sweden, voice problems are listed as one of the most common reasons for sick leave among teachers [3].

To optimize the experience of speech in ordinary rooms and mitigate problems associated with the acoustic environment, suitable parameters should be chosen for evaluation. The acoustic environment in a space is characterized by the reverberation time in international standards such as ISO 3382-1:2009 as it is an easy-to-understand parameter with abundant measurement data [4] [5]. However, studies from 1964 by Lochner and Burger [6] show that reverberation time gives little indication on the intelligibility condition of the room. Instead, it is the early reflection of sound in rooms which can be quantified using speech clarity C_{50}, that determines speech intelligibility. Moreover, the reading speed has shown to have a strong correlation with speech clarity C_{50}, but not with reverberation time T_{20} according to a study of second graders in Italy [7]. In addition to speech clarity C_{50}, another variable of interest when designing rooms for speech is sound strength G which is closely related to the subjective parameter “loudness” [8]. A study by Rantala and Sala from 2015 demonstrates that higher sound strength was connected with higher voice sound pressure level in teachers [9]. By balancing these three parameters, a satisfactory sound environment can be achieved for both speakers and listeners.

The most common room acoustics solution in the design of ordinary rooms is a suspended absorbent ceiling. Once the room is furnished, the scattering as well as the absorption properties of furniture will have a significant influence on room acoustical parameters reverberation time, speech clarity and sound strength due to the non-uniform distribution of the absorptive material. Previous research [10] [11] [12] demonstrates that the effect of sparse furniture on the above-mentioned parameters in a mockup classroom with absorbent ceiling treatment is most prominent in the frequencies between 500-1000 Hz. Furthermore, the addition of furniture contributed to an increase in scattering as the ratio of added absorption to absorbing surface area is negligible.

To arrive at a solution for ordinary rooms, acousticians often rely on calculation which is prone to uncertainties. In rooms with furniture, the absorption of the sound scattered energy will depend on the absorbing efficiency of the suspended ceiling which is not accounted for in classical diffuse field models such as Sabine’s formula. The cause of uncertainties can then be attributed to the lack of a suitable calculation method as well as reliable input data on acoustical properties of furniture. Therefore, the contribution of furniture is of particular interest and shall be studied further to develop a more accurate calculation model and quantifying method for its scattering and absorption properties.

1.2 Characterization of furniture in standards and recommendations

The sound absorbing effect of furniture has been investigated and three different calculation methods for different types of objects are presented in several standards and recommendations namely SS 25268:2023, EN 12354-6:2003 and the handbook on noise protection in residential and public buildings by the Swedish National Board of Housing, Building and Planning (Boverket) [13] [14] [15]. It is important to note that none of these models considers the effect of scattering on room acoustics parameters.

1.2.1 SS 25268:2023

In Swedish Standard 25268:2023 [13], the absorbing effect of furniture is not to be taken into consideration when calculating the reverberation time according to Sabine's formula. This is due to the fact that Sabine's formula assumes a diffuse sound field and consequently overestimates the damping of sound in a room with absorbent ceiling. Including furniture in the calculation using this method will result to even more inaccurate estimation. In other words, the assumption that the sound field is diffused no longer holds true in spaces with a single surface treatment and therefore, the reverberation time might be longer than estimation based on Sabine's formula.

The only exception in which it is acceptable to calculate the effect of furniture is open office landscape of up to 100 m^2 with a predefined interior plan. In such cases, the absorption coefficient of the flooring will be replaced with a standard value for sound absorption coefficient $\alpha = 0.2$ per square meter floor area. This standard value of sound absorption coefficient is not frequency dependent which means that the reverberation time in certain frequencies might be overestimated.

1.2.2 EN 12354-6:2003

Another standard of interest is EN 12354-6:2003 [14] in which an empirical calculation model for the equivalent sound absorption area of objects A_{obj} in enclosed spaces is derived using the volume of the object V_{obj} as followed:

$$A_{obj} = V_{obj}^{2/3} \qquad (1)$$

The reverberation time T is then determined using the total equivalent sound absorption area A which is the sum of the equivalent sound absorption area of surfaces $A_{surface}$ according to Sabine's formulation and A_{obj} from Equation (1) above.

$$T = 0.161\frac{V(1-\Psi)}{\sum A_{surface} + A_{obj}} \quad (2)$$

where Ψ is the object fraction or the ratio of the objects' volume V_{obj} and the volume of the empty room V.

Such empirical calculation model is based on several assumptions:

- the room has regular shaped volumes with no dimension being 5 times more than any other dimension
- the room is diffused with evenly distributed absorption
- the object fraction should be less than 0.2

If any of these assumptions are not met, which often is the case in rooms with only ceiling treatments, the reverberation time can be higher than estimation with Equation (2) above. Another limitation to this calculation model is that it is frequency independent which has the same implication mentioned in 1.2.1.

The standard also provides typical values of the equivalent absorption area A_{obj} for some common objects and sound absorption coefficient α_s for several configurations of objects through measurement in accordance with EN ISO 354 in Annex C [16]. However, the data is limited so any furnishing that differs from the presented options would require the calculation model according to Equation (1).

1.2.3 Boverket's handbook on noise protection in residential and public buildings

The Swedish National Board of Housing, Building and Planning (Boverket) had published a handbook in 2007 on noise protection in residential and public buildings in which the equivalent sound absorption areas for different objects in room were presented in Table 4.13b respective 4.13c [15]. Unlike the models employed in SS 25268:2023 and EN 12354-6:2003 [13] [14], the sound absorption areas of furniture in this recommendation are frequency dependent.

Table 4.13b [15] includes values taken from EN 12354-6:2003, Annex C as well as values derived from the volume-based calculation model in EN 12354-6:2003 with correction in the frequency range 125-500 Hz. The authors are careful to note that the added values derived from the volume-based calculation model shall only be used in rooms with sound absorbing materials.

Table 4.13c [15] presents standard values of the sound absorption areas of a room with and without furniture based on calculation and field measurement values. This empirical model allows for calculation of sparsely furnished rooms and densely furnished rooms.

Although the model in this recommendation is frequency dependent, the absorption area between 250-4000 Hz has the same value and only the absorption area in 125 Hz is somewhat lower. In other words, it does not differ significantly from the suggestion of a standard value for furniture presented in SS 25268:2023. While the standard value of $\alpha = 0.2$ in SS 25268:2023 [13] can only be applied in open office landscapes, the model proposed in the recommendation can be used for all types of premises. In practice, this can also lead to overestimating the absorption effect of furniture in rooms, especially spaces that are sparsely furnished.

1.3 Purpose and goals

An overview of how furniture is treated in standards and recommendation shows that there is a lack of methodology for the scattering effect of furniture in enclosed spaces. Furthermore, the combination of furniture with different types of ceiling treatments is not considered in existing standards. The purpose of this thesis is to investigate the effect of the scattering and absorptive properties of objects in an ordinary room, such as classroom and cellular office with a floor area between 10 - 60 m^2. Furthermore, this study aims to examine how the effect of furniture depends on the type of suspended ceilings. The correlation can be used to further improve the calculation model based on statistical energy analysis (SEA) method presented in [10] [17] and to quantify the scattering and absorptive properties of furniture.

The goal of this project is to investigate the effect of furniture in combination with different types of suspended ceilings. This has been divided into the following sub-goals:

- Evaluate existing methods of estimating the effect of furniture with different types of suspended ceilings
- Examine the effect on room acoustic parameters such as reverberation time, speech clarity and sound strength
- Analyze how the equivalent scattering absorption area is related to the absorbing efficiency of the suspended ceilings

1.4 Methods

The experimental method was chosen for this study in which measurements were conducted and compared with estimated values using both classical diffuse theory model and the SEA model. Measurement values were also used to derive a method for the calculation of the equivalent scattering absorption area A_{sc} in the SEA model. Finally, the numerical method was employed for the estimation of room acoustic parameters using the SEA model.

1.5 Thesis structure

Chapter 2 provides relevant background theory on room acoustic parameters for speech intensive rooms, acoustical phenomena, and the statistical energy analysis (SEA) model used in this thesis. Chapter 3 addresses the methodology employed in this study. Chapter 4 presents the results and analysis of the measurement data. Chapter 5 discusses the findings in this thesis project. Chapter 6 sums up the conclusion of this thesis and suggests possibilities for further investigation on the subject.

2 Theoretical framework

This chapter provides an overview of the room acoustic parameters evaluated in this study, namely reverberation time T_{20}, speech clarity C_{50} and sound strength G. A brief description on the difference between diffusion and scattering in non-diffuse sound field is also lifted in this chapter. Finally, this chapter describes the equivalent scattering absorption area A_{sc} for objects as well as the Statistical Energy Analysis model for the estimation of room acoustic parameters.

2.1 Room acoustic parameters

The most commonly used parameter in the design of room acoustics is reverberation time as it is relatively easy to understand and measure. However, reverberation time as a metric has its limitations and other parameters such as clarity and strength have been evaluated in concert hall design to ensure optimal sound experience for listeners. The latter two parameters should also be considered when designing speech intensive spaces such as classrooms, healthcare facilities and restaurants for reasons stated in 1.1.

2.1.1 Steady state versus Sound decay

In rooms with ceiling acoustic treatments, it is important to distinguish between the two situations, steady state and sound decay, see Figure 2-1 below. The steady state can be created by having a continuously emitting sound source so that the sound level remains constant. During steady state, the sound field is very close to diffuse condition and thus, sound level reduction can be determined using the same method for reverberant room.

Once the sound source is switched off, the room is said to be in the sound decay state in which most of the non-grazing sound waves hitting the ceiling will be absorbed by the surface. The grazing sound waves that propagate almost parallel to the ceiling will remain in the room longer as the walls are acoustically untreated. However, by adding furniture into the room, the grazing sound field can be split up, thus sending some of the sound waves towards the absorbing ceiling surface.

Figure 2-1. Left: Steady state; Right: Sound decay state.
White arrows and yellow arrows depict grazing waves and non-grazing waves respectively (Photo: ecophon.se).

2.1.2 Reverberation time T_{20}

Reverberation time as defined in ISO 3382-1:2009 is the time in seconds required for the sound energy density in an enclosed space to decrease by 60 dB after the source emission has stopped [4]. Reverberation time T can be calculated using Sabine's formula which was derived by the American physicist Wallace Clemence Sabine in the early 1900s [18]. Sabine's formula describes how reverberation time is dependent upon the volume of the room as well as the absorptive properties of the surfaces:

$$T = 0.161\frac{\mathrm{V}}{\mathrm{A}} \tag{3}$$

where V is the volume of the room and A is the equivalent absorptive area.

The equivalent absorptive area A can be defined as the sum of the room surface areas S multiplied by their sound absorption coefficients α:

$$A = \sum_i S_i\alpha_i = S_1\alpha_1 + S_2\alpha_2 + \cdots + S_n\alpha_n \tag{4}$$

The sound absorption coefficient α describes the ratio of the non-reflected sound energy to the incident sound energy and lies between 0 (fully reflected) and 1 (fully absorbed). However, it is important to note that this does not account for the effect of scattering objects in rooms.

According to ISO 3382-1:2009, T can be derived from measurements using the energy decay curve [4]. However, T is evaluated from the time at which the decay curve first reaches 5 dB. This means that the early reflections of the impulse response, which is closely related to speech intelligibility, are not included.

Moreover, Sabine's formula assumes that the sound field in the room is completely diffused [19],which means the amount of sound energy is equal in all places in the room. Such is the case in rooms with very little to no absorption area where the sound absorbing surfaces are evenly distributed. Therefore, the equation is no longer suitable for rooms with treatments only on one surface of the room such as the ceiling. In such rooms, sound energy traveling upwards is absorbed by the ceiling treatment while the sound energy moving between untreated walls remains in the room for a longer duration. Another practical consideration when evaluating reverberation time using Sabine's formula, especially in small rooms, is that it is less accurate for all frequencies below the Schroeder's limiting frequency f_s. The Schroeder's limiting frequency f_s defines the division between low and high frequency responses of the room and is dependent on the reverberation time and volume of the room. The sound field below this cut-off frequency is characterized by low modal density which means single room modes can be recognized [19] [18]. Thus, a different model than the Sabine's formula should be used to evaluate spaces with a single sound absorbing surface such as the ceiling [10] [20] [21].

2.1.3 Speech clarity C_{50}

Speech clarity C_{50}, in decibel, refers to the ratio between the sound energy received by the listener in the first 50 *ms* and the remaining sound energy. Speech clarity C_{50} is defined as followed [4]:

$$C_{50} = 10log\left(\frac{\int_0^{0.05} p^2(t)dt}{\int_0^{\infty} p^2(t)dt}\right) \quad (5)$$

where p is the instantaneous sound pressure of the impulse response measured at the measurement point.

Unlike reverberation time which depends solely on the geometry of the room, speech clarity C_{50} is dependent on the reflection path from the sound source to the receiver. The relationship between clarity and speech intelligibility has been investigated both in design of performance space as well as of rooms used for speech [22] [23]. Suitable room acoustics for speech in ordinary rooms requires a balance between early and late reflections. In this respect, the location and amount of the absorbent and sound reflecting surfaces is crucial. By adding a significant amount of absorption to the room might reduce early reflection levels which would negatively affect speech intelligibility [23].

2.1.4 Sound Strength G

Sound strength, G, refers to the ratio of the sound pressure measured in the room and the sound pressure of the same source in a free field. The magnitude of sound strength is inversely dependent on the total amount of absorption in the room [8]. For an omnidirectional sound source with known sound power level, the sound strength G, in decibel, can be derived using the equation below [4]:

$$\mathrm{G} = \mathrm{L_P} - \mathrm{L_W} + 31 \quad (6)$$

where L_P is the sound pressure level at the measurement point and L_W is the sound power level of the sound source.

In rooms with sound absorbing ceiling treatment, there is a difference in the characteristics of the sound field at steady-state and the latter part of the decay. As sound strength is measured during the steady state, the parameter provides information on how early reflections contribute to the sound pressure level and thus, is of interest when designing room acoustics in spaces for speech.

2.2 Diffusion and scattering

In geometrical room acoustic models, sound is often treated as rays which means that sound energy is reflected off the surface like light. Sound reflections in rooms can be categorized as followed [21]:

- Specular reflections in which the angle of reflection is equal to the angle of incidence
- Diffuse reflections in which the angle of reflection is independent of the angle of incidence
- A combination of specular reflections and diffuse reflections

To describe these different sound reflections, two frequency-dependent coefficients, namely the scattering coefficient and the diffusion coefficient, were derived and presented in ISO 17497 part 1 and 2 respectively [24] [25]. The two terms are often used interchangeably but there is significant difference in what they entail. An object might have a high scattering coefficient which has to do with ratio of energy but low diffusion coefficient which is related to uneven spread of sound energy. Both phenomena are most prominent in the frequencies between 500-2000 Hz which is due to the corresponding wavelength of that range and thus, a brief description of the relationship between frequency and wavelength will be discussed.

2.2.1 Wavelength

The speed of sound is defined as the distance travelled during one period times the number of periods per second or frequency. The distance sound wave travelled during one period is called wavelength and can be expressed as:

$$\lambda = \frac{c}{f} \tag{7}$$

where λ is the wavelength, *c* is the speed of sound and *f* is the frequency.

For indoor air with a temperature of approximately 20°C, the speed of sound is 343 *m/s* which means for frequency band 100 Hz, the wavelength can be estimated to be:

$$\lambda = \frac{343}{100} \approx 3.43\ m$$

Wavelength λ is directly related to both absorption and scattering. Absorption is proportional to the particle velocity and the maximum particle velocity is achieved at a distance of ¼ λ from the surface [19]. The phenomenon scattering occurs when the dimensions of the objects or surfaces hit by a sound wave are equal or less than the wavelength [26]. In other words, for objects such as furniture, scattering takes place at the frequency range 500-2000 Hz.

2.2.2 Scattering coefficient

Scattering mainly concerns with the diffuse reflections in rooms and the scattering coefficient *s* is the ratio of the non-specularly reflected acoustic energy to the total reflected energy in a diffuse sound field [24]. In rooms with acoustic ceiling treatments, the sound field is instead made up of a grazing field and a non-grazing field. In such cases, scattering helps split up the grazing sound field and as the result, some of the horizontal sound energy is transmitted upwards and absorbed by the ceiling treatment (see 2.3).

2.2.3 Diffusion coefficient

Unlike scattering, diffusion has to do with how even the distribution of reflected sound in all directions is. In other words, the diffusion coefficient *d* determines the uniformity of the energy reflected from the surface [25]. A value closer to zero means that sound is reflected almost in one direction whereas a higher diffusion coefficient indicates an even spread of sound energy around the object's surface.

2.3 The Statistical Energy Analysis model

In rooms with highly absorptive ceiling treatment, it is known that the Sabine's formula is significantly less accurate and thus a non-diffuse model is employed in this study to evaluate the room acoustical parameters reverberation time T_{20}, speech clarity C_{50} and sound strength G. This chapter provides a general description of this non-diffuse model which is based on the statistical energy analysis (SEA) approach.

2.3.1 Overview of the SEA model

A room with absorptive ceiling treatment can be modelled as an SEA system with two subsystems, namely a grazing system (g) and a non-grazing system (ng) as illustrated in Figure 2-2 below. E_g and E_{ng} denote the total energy in respective subsystems. Input power for each subsystem are expressed as Π_g and Π_{ng} while dissipated power are $\Pi_{g,d}$ and $\Pi_{ng,d}$. This model applies to porous ceiling absorbers with mean absorption coefficient greater than 0.7 in the frequency range 250-4000 Hz [10] [11].

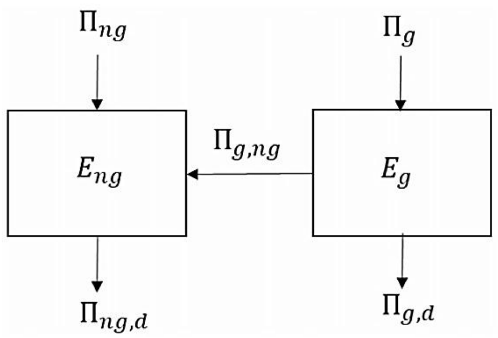


Figure 2-2. The SEA model for rooms with highly absorptive ceiling treatment.

The grazing system consists of waves that move almost parallel with the absorbent ceiling (white arrows in Figure 2-1, chapter 2.1.1) as the term grazing refers to the angle of incidence of waves propagating towards the ceiling absorber. The grazing waves are disrupted due to objects such as furniture in the room, causing energy to transfer from the grazing system to the non-grazing system. This can be interpreted as the coupling loss factor from the grazing system to the non-grazing subsystem $\eta_{ng,g}$ which is assumed to be less than the internal losses in both subsystems [10] [17] [20]. Power transfer from the non-grazing system to the grazing system $\Pi_{ng,g}$ is neglected in this model as this is often much smaller than $\Pi_{g,ng}$ [17]. The total energy decay in a room with absorbent ceiling is the sum of the energy in the grazing and non-grazing sound fields as seen in Figure 2-3.

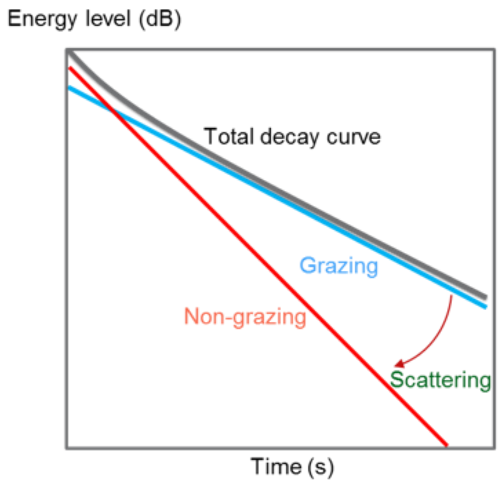


Figure 2-3. The total decay curve in a room with absorbent ceiling

The non-grazing modes dominate the early part of the decay while the grazing modes are predominant in the latter part. The energy transfer mechanism from the grazing to non-grazing sound field is depicted as scattering [11]. This means that the reverberation time is mainly determined by the grazing modes. Once the reverberation time and number of modes for respective subsystems are determined, the total decay curve can be calculated and from this, reverberation time T_{20}, speech clarity C_{50} and sound strength G of the room can also be estimated [10].

2.3.2 Practical versus angle dependent absorption coefficient

As mentioned in 2.1.2, the sound absorption coefficient α is an important parameter in Sabine's formula. The absorption coefficient α can be obtained through several different methods such as measurement from the reverberant room and measurement in impedance tube [16] [21] [27]. This study mainly discusses practical absorption coefficient $\alpha_{p,}$ which is the most common data provided by manufacturers and angle-dependent absorption coefficient which is used in the SEA model.

The practical absorption coefficient α_p for a test specimen can be obtained through measurement in a reverberant chamber and is based on the Sabine's absorption coefficient [28]. The specimen is often mounted and measured at a specific distance from the room's boundary, often referred to as the overall depth of the system (o.d.s). The difference in the measured reverberation time for a room without and with the test specimen at a defined o.d.s can then be used to calculate the Sabine's absorption coefficient α_{Sab} in one-third octave bands between 100-5000 Hz as followed [16]:

$$\alpha_{\mathrm{Sab}} = \frac{55.3\mathrm{V}}{\mathrm{S}}\left(\frac{1}{\mathrm{c_2 T_2}} - \frac{1}{\mathrm{c_1 T_1}}\right) \tag{8}$$

where

V is the volume of the room
S is the area of the test specimen
c_1 is the speed of sound and T_1 is the reverberation time in the room without test specimen
c_2 is the speed of sound and T_2 is the reverberation time in the room with test specimen

From these values, the practical absorption coefficient α_p is arithmetically averaged in the octave bands and approximated in steps of 0.05 [29]. This method of calculating absorption coefficient from measurement data in the reverberant chamber is based on the assumption that sound propagates from a multitude of incident angles at once under diffuse field condition. The quantified absorption coefficient α_p can be said to be the average value over all angles of incidence.

There are several drawbacks with the usage of the practical absorption coefficient α_p in calculation and simulation. Firstly, measurement data is often available for a few overall depth of the system (o.d.s) which means that estimation using this input data will be less accurate. Secondly, measurement data can deviate significantly depending on conditions of the testing facilities and measurement methods [28]. In reality, the sound absorption coefficient α is dependent on the angles of incidence. This is illustrated in Figure 2-4 below for example of absorption capacity as a function of incidence angles for two porous materials with different values of air flow resistivity. Absorption capacity is higher at an incidence angle perpendicular to the surface than if it is parallel.

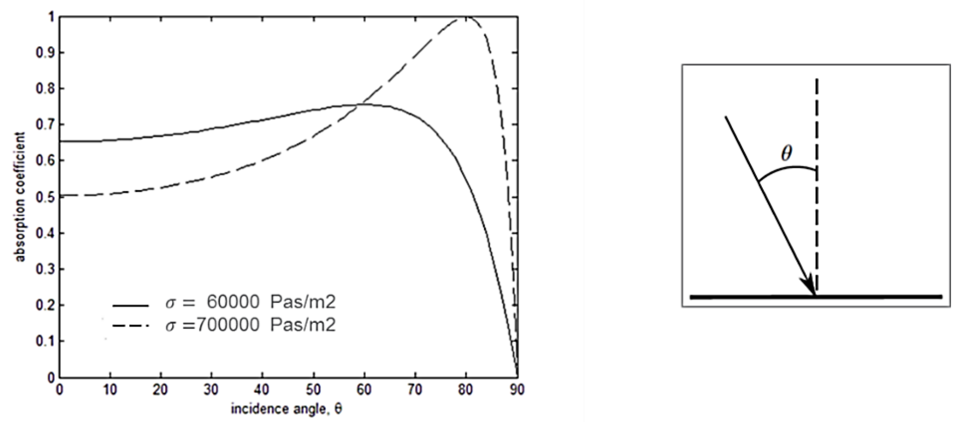


Figure 2-4. Absorption coefficient as a function of incidence angle for two porous materials with different flow resistivity.

The sound absorption coefficient α can then be described as following [18] (see also 2.1.2):

$$\alpha(\theta) = 1 - |\mathrm{R}(\theta)|^2 \qquad (9)$$

where R denotes the reflection factor and is related to surface impedance Z which gives information about changes in magnitude and phase of reflection. The relationship between the reflection factor and the surface impedance is given by [18]:

$$R(\theta) = \frac{\mathrm{Z}(\theta)\cos(\theta) - \rho_0 \mathrm{c}_0}{\mathrm{Z}(\theta)\cos(\theta) - \rho_0 \mathrm{c}_0} \qquad (10)$$

The sound absorption coefficient α at incidence angle θ can be determined from Equation (9) and (10) as:

$$\alpha(\theta) = 1 - \left|\frac{\mathrm{Z}(\theta)\cos(\theta) - \rho_0 \mathrm{c}_0}{\mathrm{Z}(\theta)\cos(\theta) - \rho_0 \mathrm{c}_0}\right|^2 \qquad (11)$$

where ρ_0 is the density of air and c_0 is the speed of sound in air.

In this SEA model developed for porous materials, the surface impedance Z is obtained using the air flow resistivity σ assuming extended reaction [10]. A material is considered to be extendedly reacting if the surface impedance is dependent on the incidence angle which is typical behavior for fibrous materials [21].

In the SEA model [10] a grazing and non-grazing sector are defined by corresponding angles of incidence according to Figure 2-5. Derivation of θ_g and θ_{ng} as well as the sound absorption coefficients α_g and α_{ng} for respective sectors are described in detail in [10].

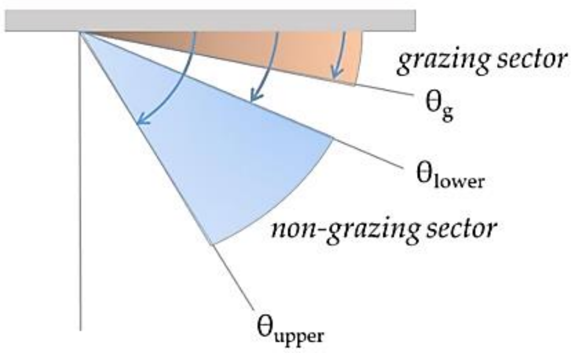


Figure 2-5. Incidence angle and the grazing and non-grazing sectors.

2.3.3 Equivalent scattering absorption area A_{sc}

In rooms with ceiling treatment, the coupling loss factor from the grazing subsystem to the non-grazing subsystem $\eta_{g,ng}$ is attributed to the effect of objects in the room and can be expressed as [17]:

$$\eta_{g,ng} = \frac{c}{\pi \omega V} A_{sc} \tag{12}$$

where

V is the volume of the room
c is the speed of sound and ω is the angular frequency
A_{sc} is the equivalent scattering absorption coefficient

Assuming that the SEA model is valid for the sound field in the room both with and without scattering objects such as furniture, the coupling loss factor $\eta_{g,ng}$ can then be expressed as [10]:

$$\eta_{g,ng} = \eta_{g,with\ obj} - \eta_{g,without\ obj} \tag{13}$$

where

$\eta_{g,with\ obj}$ is the coupling loss factor in the grazing subsystem with objects in the room
$\eta_{g,without\ obj}$ is the coupling loss factor in the grazing subsystem without objects in the room

The coupling loss factor can also be expressed in terms of reverberation time as followed [10]:

$$\eta = \frac{6 ln 10}{\omega T} \tag{14}$$

Combining Equation (12), (13) and (14), the equivalent scattering absorption area A_{sc} can be determined from measurement data in rooms with and without furniture as [10]:

$$A_{sc} = 0.127V \left(\frac{1}{T_{20,with}} - \frac{1}{T_{20,without}} \right) \tag{15}$$

where

A_{sc} is the equivalent scattering absorption area of the furniture
$T_{20,with}$ is the measured reverberation time in room with ceiling treatment and with objects
$T_{20,without}$ is the measured reverberation time in room with ceiling treatment and without objects

By employing the method described in 2.3.2, the ceiling absorption area in the non-grazing subsystem and grazing subsystem can be estimated. This means that the reverberation time can be calculated separately for each subsystem. In the non-grazing subsystem, the formula for reverberation time is similar to Sabine's formula in which [10]:

$$\mathrm{T_{ng}} = \frac{0.161V}{A_{ng,ceiling} + A_{surface} + A_{furniture} + 4mV} \tag{16}$$

where

V is the volume of the room
$A_{ng,ceiling}$ is the ceiling absorption area in the non-grazing subsystem
$A_{surface}$ is the equivalent absorption area of the floor and walls
$A_{furniture}$ is the equivalent absorption area of the furniture according to Sabine's model
4mV is the air absorption with *m* being the energy attenuation constant in air

In the two-dimensional sound field that is characteristic for the grazing subsystem, the formula for the reverberation time is given by [10]:

$$\mathrm{T_g} = \frac{0.127\mathrm{V}}{\mathrm{A_{g,ceiling}} + \mathrm{A_{surface}} + \mathrm{A_{sc}} + \pi\mathrm{mV}} \tag{17}$$

where

$A_{g,ceiling}$ is the ceiling absorption area in the grazing subsystem
$A_{surface}$ is the equivalent absorption area of the floor and walls
A_{sc} is the equivalent scattering absorption area of the furniture
πmV is the air absorption in the two-dimensional sound field with *m* being the energy attenuation constant in air

3 Methodology

The purpose of this chapter is to provide an overview of the research method used in this thesis. Section 3.1 describes the experimental design. Section 3.2 details the measurement method. Section 3.3 explains the techniques used to evaluate the repeatability of the measurement method.

3.1 Experimental design

To evaluate the effect of furniture for different types of suspended ceilings, the experimental method is chosen in which a series of measurements were conducted with varying degrees of furnishing. The measurements were performed in a reverberant room with dimensions 3.99 m × 3.57 m × 4.00 m as seen in Figure 3-1 below.

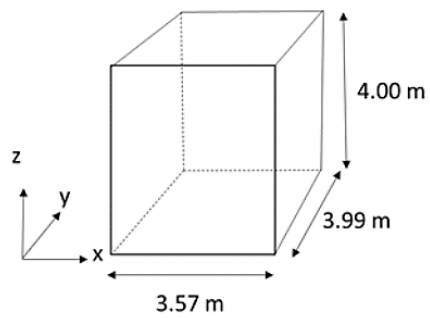


Figure 3-1. Dimensions of the reverberant room

The types of ceiling tiles and the furniture used in this study are described in 3.1.1 and 3.1.2. Furthermore, diffusers were added to the room to generate scattering effects and description of the diffusers is detailed in 3.1.3.

Another set of previous measurements carried out in a mock-up classroom will be used to evaluate whether it is suitable to quantify the equivalent scattering absorption area of furniture beforehand using the method in the reverberant chamber. The mock-up classroom has the following dimensions 7.32 m × 7.57 m × 3.50 m, see Figure 3-2.

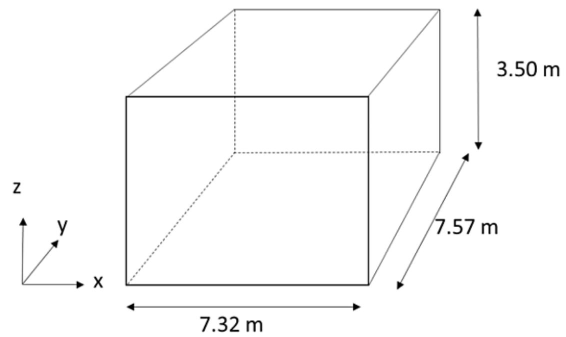


Figure 3-2. Dimensions of the mock-up classroom

3.1.1 Ceiling configurations

In this study, 4 ceiling materials were mounted in 7 different configurations in the reverberant chamber. The thickness of each material as well as their acoustical absorption coefficients between 125-4000 Hz for an overall depth of system of 200 mm are presented in Table 1 below. The materials' practical absorption data are provided by respective manufacturers with the exception of Gyptone Base 31 in which no standard measurement results were available. The absorption coefficients for Gyptone Base 31 were calculated from measurement data at an overall depth of the system of 120 cm using Sabine's formula in Equation (3). The absorption coefficients for the mixed ceiling configurations were calculated by averaging the absorption coefficients for the two included absorber panels as stated in Table 1 below.

Table 1. Absorption coefficients of the tested ceiling tiles.

Type of ceiling	Frequency [Hz]					
	125	250	500	1000	2000	4000
Gedina A (15 mm)[1]	0.45	0.90	1.0	0.85	0.95	0.95
Master A (40 mm)[1]	0.60	0.95	1.0	1.0	1.0	1.0
Gyptone Base 31 (10 mm)[2]	0.07	0.07	0.07	0.12	0.13	0.12
Gyptone Quattro 20 (10 mm)[3]	0.40	0.70	0.80	0.70	0.70	0.60
Gyptone Base 31 + Gyptone Quattro 20	0.24	0.39	0.44	0.41	0.42	0.36
Gyptone Base 31 + Master A	0.34	0.51	0.54	0.56	0.57	0.56
Gyptone Quattro 20 + Master A	0.50	0.83	0.90	0.85	0.85	0.80

[1] Master A and Gedina A are classified as porous absorbers.

[2] Gyptone Base 31 is a plasterboard.

[3] Gyptone Quattro 20 is a perforated plasterboard with sound absorption tissue backing and can be classified as resonant absorber.

A total of 8 ceiling configurations were tested, of which 1 is untreated and the other 7 treated with panels mounted onto a suspended grid system 120 cm from the ceiling in the reverberant room (see Figure 3-3). For configurations 6-8, the tiles are mounted in a chess pattern to reduce the risk of non-uniform absorption in the ceiling surface. The 8 configurations are presented in Table 2. In the first configuration where the ceiling is untreated, the soffit height of the room is 4 meters. The soffit height of the reverberant room for configuration 2-8 is measured from the floor up to the ceiling tiles which gives 2.8 meters.

Table 2. Measured ceiling configurations in reverberant room.

Number	Description
1	Untreated ceiling
2	Gyptone Base 31 (10 mm)
3	Gyptone Quattro 20 (10 mm)
4	Gedina A (15 mm)
5	Master A (40 mm)
6	Gyptone Base 31 (10 mm) and Gyptone Quattro 20 (10 mm) in chess pattern
7	Master A (40 mm) and Gyptone Base 31 (10 mm) in chess pattern
8	Master A (40 mm) and Gyptone Quattro 20 (10 mm) in chess pattern

For the mock-up classroom, the soffit height without and with ceiling tiles is 3.5 meters and 2.8 meters respectively. Three ceiling types with the same practical absorption coefficient and thickness as stated in Table 1 above were tested:

Table 3. Measured ceiling configurations in mock-up classroom.

Number	Description
1	Untreated ceiling
2	Gyptone Quattro 20 (10 mm)
3	Gedina A (15 mm)
4	Master A (40 mm)

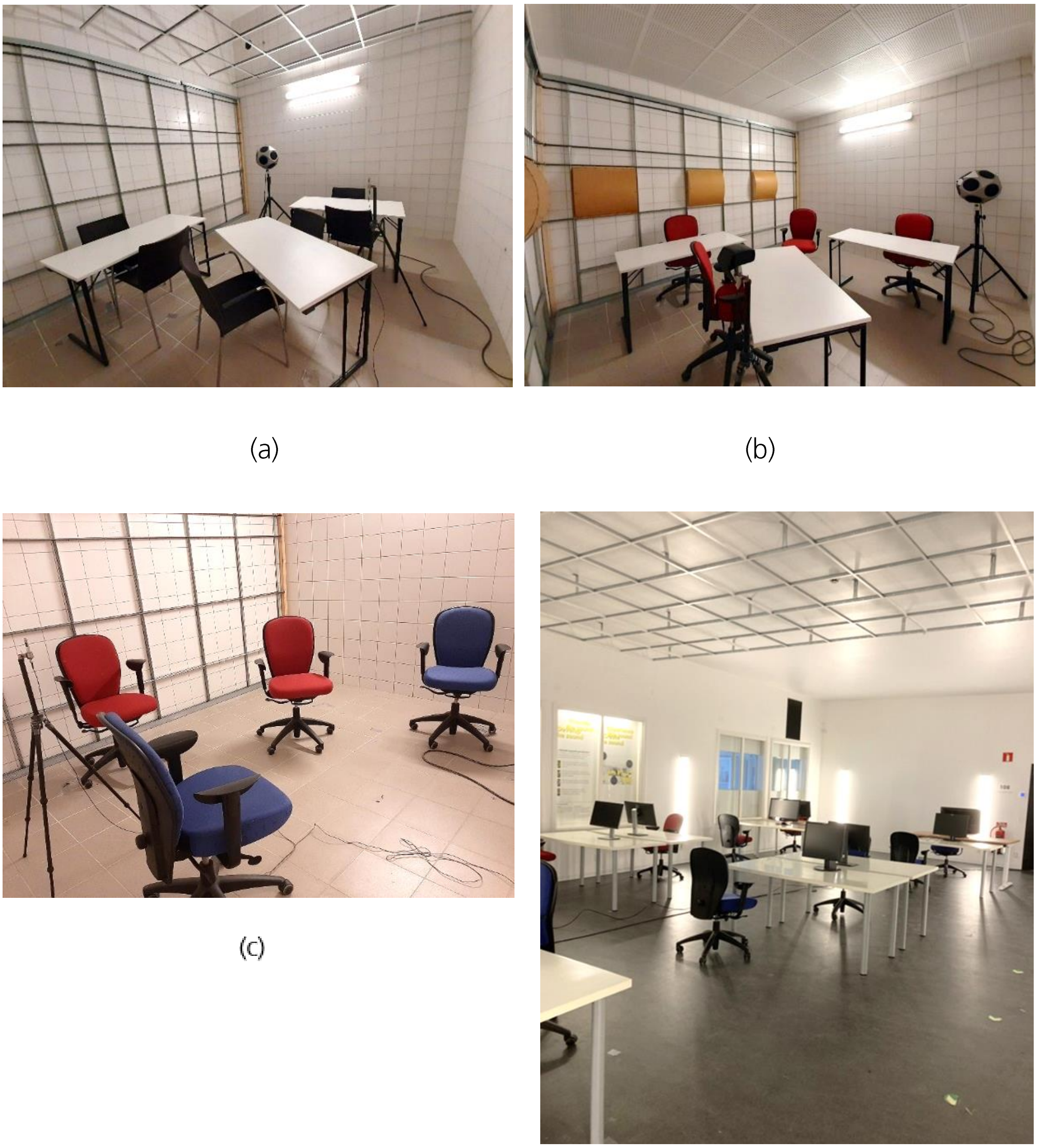
3.1.2 Furniture configurations

The following configurations of furniture consisting of 3 tables, 6 chairs, 4 upholstered chairs as well as 6 diffusers were measured for every type of suspended ceilings in the reverberant chamber (see also Figure 3-3 (a) and (b)):

Table 4. Measured furniture configurations in reverberant room.

Configuration	Description
a	Unfurnished
b	3 tables
c	3 tables and 6 chairs
d	3 tables, 6 chairs and 6 diffusors
e	3 tables and 4 upholstered chairs
f	3 tables, 4 upholstered chairs and 6 diffusors

To evaluate the possibility of estimating with data of few objects in larger scale according to EN 12354-6:2003 [14], measurements were performed for 6 chairs, 4 upholstered chairs and 6 diffusers separately, see Figure 3-3 (c) for measurement setting of 4 upholstered chairs. Hereafter, the combinations of ceiling and furniture in the reverberant room will be addressed as 1a-1f, 2a-2f and so forth. For the mock-up classroom, only one furniture configuration with 12 tables, 12 computer screens and 12 upholstered chairs was measured, see Figure 3-3 (d).



(a) (b) (c) (d)

Figure 3-3. Measurement set-up: (a) Furniture configuration 3 tables and 6 chairs; (b) Furniture configuration with 3 tables and 4 upholstered chairs; (c) Measurement set-up to obtain the equivalent absorption area of furniture objects in the reverberant room; (d) Furniture arrangement in the mock-up classroom (Photo: Erling Nilsson).

3.1.3 Diffusers

Diffusers can be defined as the surface or element that contributes to the spatial and temporal dispersion of reflected sound [21]. Six diffusers of the same geometry and dimensions 600 mm × 600 mm with a maximum depth of 100 mm, see Figure 3-4, were installed on two adjacent walls in the reverberant room. These diffusers were made of a curved hardboard attached to a wooden frame. The diffusers are open in the back to allow air gaps between the wall surface which gives them a Helmholtz resonance between 125-250 Hz. The diffusion characteristics of these diffusers were measured and presented in a previous study [12].

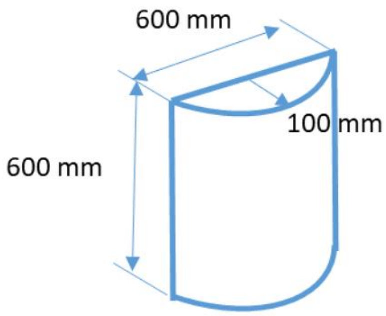


Figure 3-4. Dimensions of the diffusers used in this study.

The diffusers can be mounted either horizontally or vertically (see Figure 3-5) which has an implication for the direction in which the sound waves are reflected. When mounted vertically, most sound waves are reflected in the vertical direction while horizontally oriented diffusers help reflect the sound waves in a horizontal direction [11].

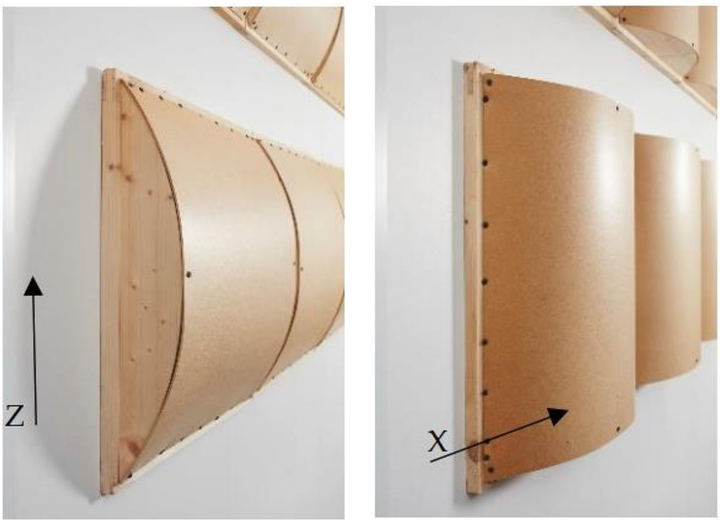


Figure 3-5. Left: Vertically mounted diffusers; Right: Horizontally mounted diffusers (Photo: Emma Arvidsson).

Previous measurements of these diffusers demonstrate that directional scattering effect is dependent on the mounting orientation and most evident at mid and high frequencies

[11]. By evaluating the equivalent scattering absorption area A_{sc}, the effect of mounting orientation can be quantified, and a larger effect can be seen in the case of vertically oriented diffusers. This is because sound waves are vertically redirected towards the absorbent ceiling surface whereas with horizontal diffusers, reflected sound waves are dispersed mainly in the horizontal plane and remain in the same plane without being absorbed.

The effect of mounting patterns has also been studied [11] and greater effect is seen in both orientations when the diffusers were mounted with space in between compared to the connected pattern as seen in Figure 3-6. However, when furniture is added to the room, the mounting patterns did not exhibit any significant differences.

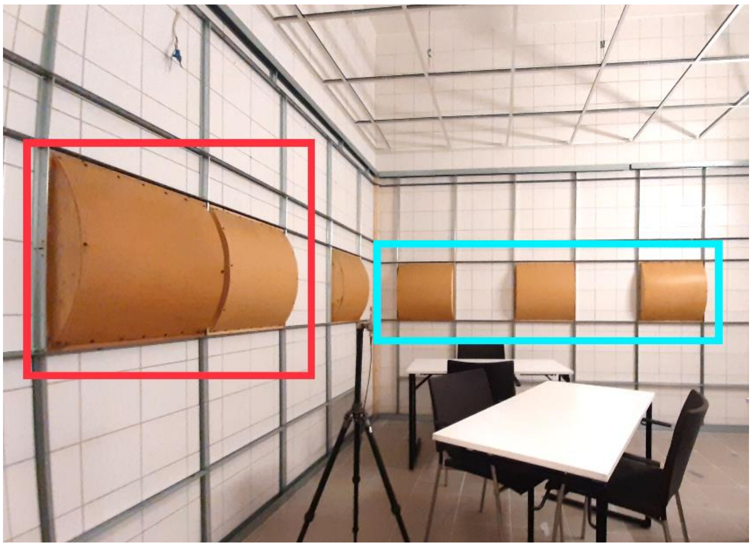


Figure 3-6. Red marker: connected mounting pattern; Blue marker: separate mounting pattern.

From the results mentioned above, the diffusers in this study were mounted vertically as this orientation redirects sound waves towards the ceiling and thus, can give a more noticeable indication for the effect of different suspended ceilings. In ceiling configuration 5, Master A, the diffusers were installed both vertically and horizontally to evaluate the effect of directional scattering when comparing with existing standards. As the mounting patterns do not show considerable effect on the equivalent scattering absorption area A_{sc}, the diffusers in this study were installed both with and without space in between (see Figure 3-6).

3.2 Measurement method

3.2.1 Measurement conditions

According to SS EN ISO 354 [16], temperature and relative humidity can have significant effect on the measured reverberation time, especially at high frequencies and at low relative humidities. Measurements were performed in the reverberant room under temperature conditions between 18.3 and 18.8°C and relative humidity ranging from 21% to 38%. Measurements in the mock-up classroom were conducted in similar conditions. In other words, the conditions were stable which means that the adjustments due to air absorption do not differ significantly.

3.2.2 Measurement equipment and techniques

3.2.2.1 Reverberant room

For the measurements of reverberation time and speech clarity, an exponential sweep signal was sent to an omnidirectional loudspeaker and the room’s impulse response was recorded by a free-field microphone from Brüel & Kjær (model 4188-A-021). A total of six measurements were carried out with two source positions and three receiver positions for each source. Two different models of loudspeakers (Brüel & Kjær 4292 and Nor276) and their respective amplifiers (Brüel & Kjær 2716 and Nor280) were used in this study. The same set of loudspeaker and amplifier was used to perform furniture configurations a-f for each ceiling configuration to ensure that the results are repeatable. The loudspeaker and the microphone were mounted on tripod so that the distance from the floor to the center of the loudspeaker is approximately 130 cm and the microphone is 120 cm from the floor, see Figure 3-7.

Figure 3-7. Left: Microphone and loudspeaker set up in the reverberant room. Right: Reference sound source for measurement of sound strength G.

For the measurements of sound strength, a calibrated sound source with known sound power from Norsonic (model Nor278, Figure 3-7) was used to produce a steady state in the room. The room’s impulse response was then recorded with the same free-field microphone as above, mounted on a tripod 120 cm from the floor. The placements of the sound source and the microphone were the same as in the measurements of reverberation time and speech clarity above. The measurements were saved and analyzed using the Dirac system type 7841, v.6.0.

3.2.2.2 Mock-up classroom

The equipment and methods used for measuring reverberation time, speech clarity and sound strength in the mock-up classroom are identical to those in the reverberant room. Due to the difference in dimensions, the measurement procedure in the mock-up classroom is adjusted with three source positions and five microphone positions per source.

3.3 Repeatability of measurement method

To test the repeatability of the measurement method, impulse response measurements using the omnidirectional speaker Nor276 and the reference sound source Nor278 were performed three times respectively for the untreated and unfurnished reverberant room. The repeatability test was conducted on the same day to ensure the same temperature and humidity conditions.

The untreated and unfurnished reverberant room was chosen as this configuration is the most sensitive to placements of the microphone. For each of the three tests, a total of six measurements were performed using two sound source positions and three microphone positions for each sound source position.

For each of the three tests, the results from the six measurements were averaged. These averaged values from the three tests are compared in pairs and the standard deviation for each pair was calculated. Results of the repeatability test and the averaged standard deviation for the three test σ_{avr} are shown in Appendix A. Assuming normal distribution, the uncertainty limit corresponding to a 95% confidence internal for the measurement procedure performed in the reverberant room is presented in Table 5 below.

Table 5. Approximate uncertainty limit corresponding to a 95% confidence interval for the measurement procedure in the reverberant room.

Frequency	T_{20} (s)	C_{50} (dB)	G (dB)
125 Hz	± 0.126	± 0.16	± 0.29
250 Hz	± 0.066	± 0.57	± 0.23
500 Hz	± 0.018	± 0.76	± 0.35
1000 Hz	± 0.015	± 0.64	± 0.12
2000 Hz	± 0.019	± 0.19	± 0.35
4000 Hz	± 0.033	± 0.77	± 0.23

The result of the repeatability test shows the variation of the average reverberation time T_{20}, speech clarity C_{50}, and sound strength G over six measurement positions. This variation can give an indication of the influence of the measurement procedure when comparing configurations of different ceiling treatments and levels of furnishing. Table 5 shows that the variations in the repeated measurements are less than just noticeable difference (JND) of rel. 5% for T_{20}, 1 dB for C_{50} as well as G [4].

4 Results and Analysis

4.1 Characterization of ceilings using Sabine's formula

According to SS 25268:2023 and EN 12354-6:2003 [13] [14], the reverberation time can be calculated using Sabine's formula. As mentioned in 2.3.2, most widely available absorption data provided by manufacturers is the practical absorption coefficient and it is expected to deviate from data obtained from measurement performed in another room as it depends on the diffuse condition of the room, measurement techniques and the room geometry. To illustrate this, the absorption coefficients from measurements for ceiling configuration 3a, 4a and 5a are estimated with Sabine's formula and plotted together with practical absorption data in Figure 4-1. The absorption coefficient from measurements is hereby denoted as apparent absorption coefficient to distinguish between data from manufacturers and measurements.

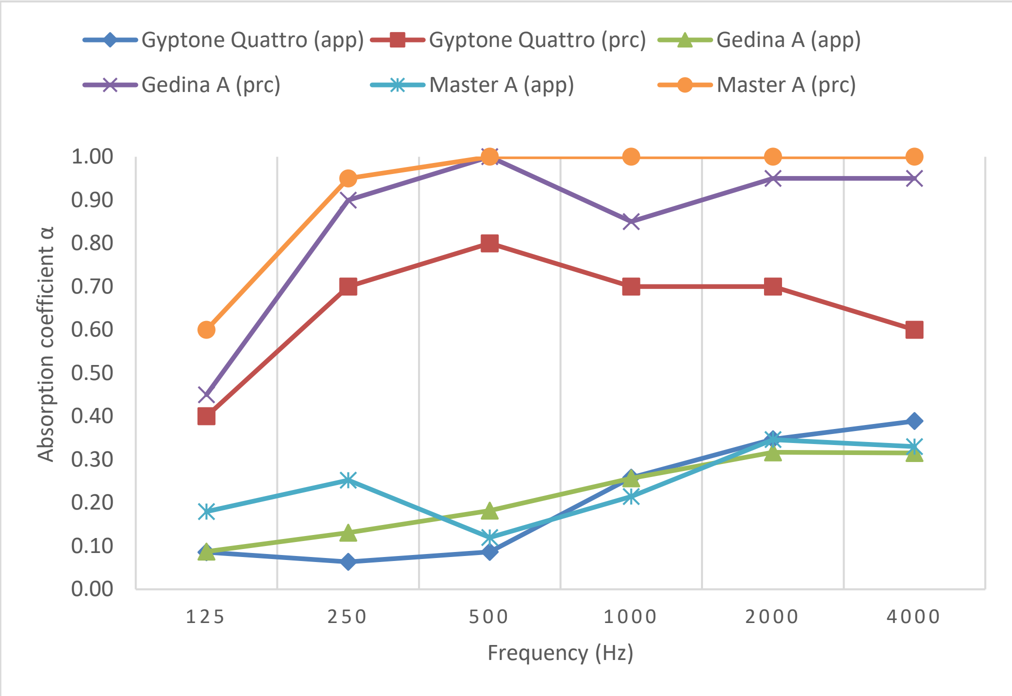


Figure 4-1. Comparison of practical absorption coefficient (prc) and apparent absorption coefficient (app) for three ceiling types: Gyptone Quattro, Gedina A and Master A.

It is evident from the apparent absorption coefficients in Figure 4-1 that the absorptive properties of these three ceilings are similar between 500-4000 Hz. The practical absorption coefficients, however, demonstrate that Gyptone Quattro has less absorptive capacity than the other two ceiling types for the same frequency range. This is because the apparent absorption coefficient was calculated using reverberation time T_{20}, which is a parameter that describes the later part of the energy decay curve. If the measurement values for sound strength G is instead evaluated, the results are presented in Figure 4-2 below.

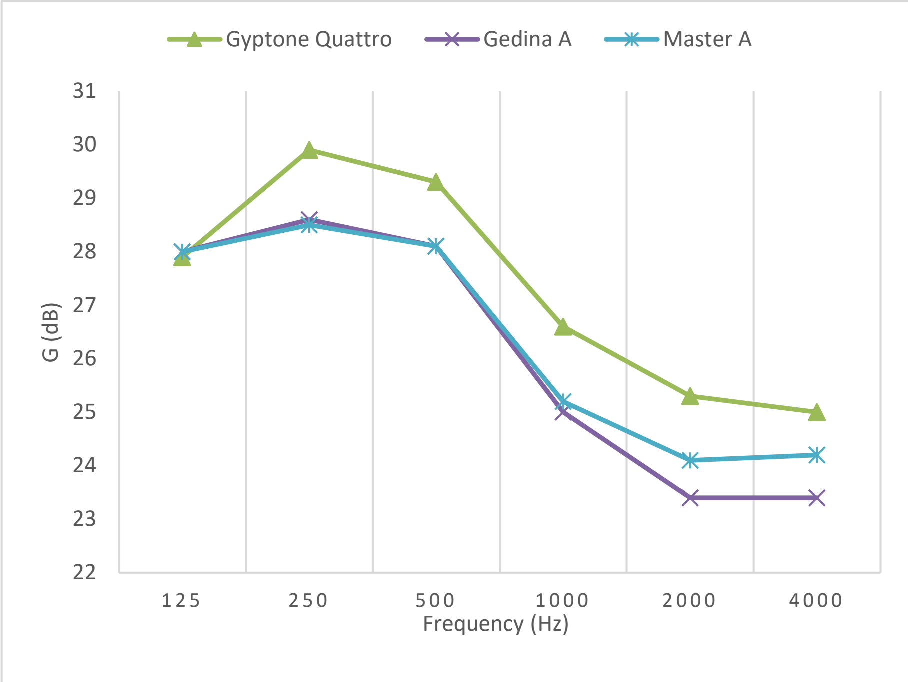
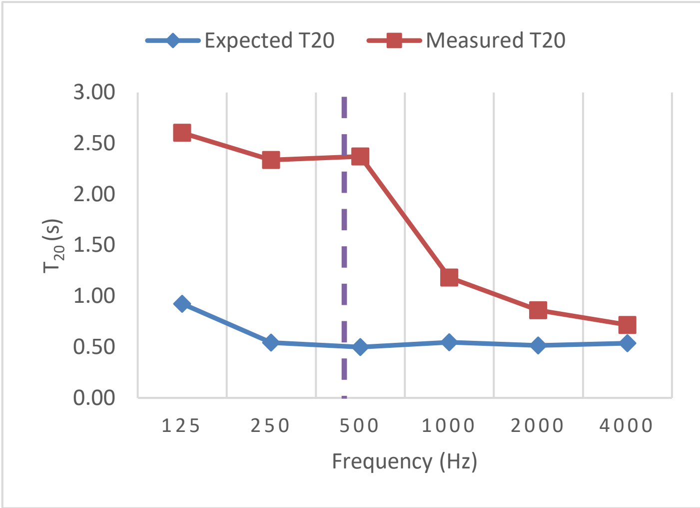


Figure 4-2. Comparison of measurement values of sound strength G for three ceiling configurations.

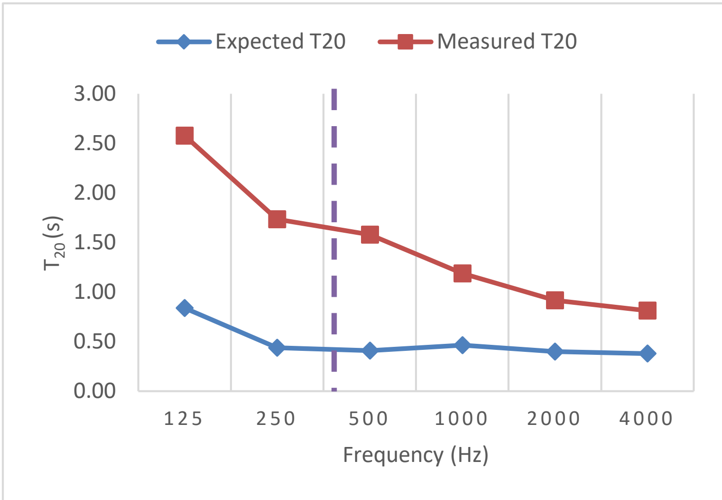
The reduction in sound strength G between 500-4000 Hz can be seen when Gyptone Quattro is replaced with Gedina A or Master A. This corresponds with the difference in practical absorption coefficients for the three ceiling types with Gyptone Quattro being less absorptive compared with the other two configurations. This is because the measurement for sound strength G is conducted in a steady state which implies a diffuse condition and thus, it can be concluded that the practical absorption coefficient is accurate when this sound field condition is fulfilled.

With uncertainties stemming from input data, the calculation model for reverberation time prescribed in SS 25268:2023 and EN 12354-6:2003 [13] [14] is assessed together with collected data in the unfurnished reverberant room for ceiling configurations 3a, 4a, and 5a. The expected reverberation time using practical absorption coefficient and the measured reverberation time are plotted in Figure 4-3.

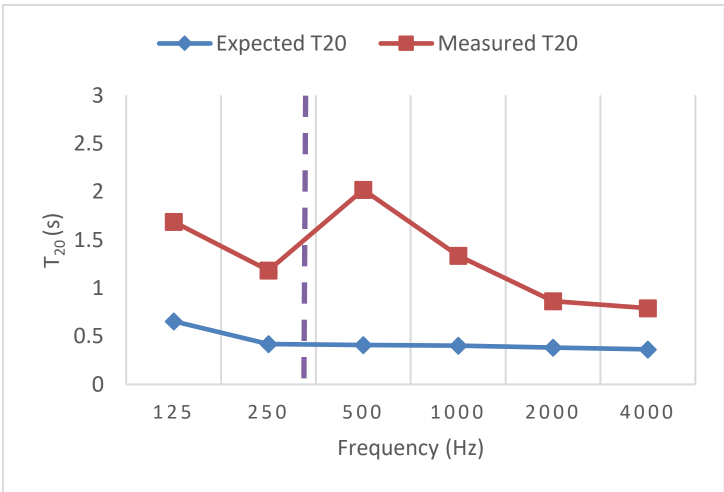
In all three ceilings, the reverberation time calculated with manufacturer's data in Table 1 is lower than that from the measurements. Statistical behaviour of the sound field is assumed to be valid above the Schroeder's limiting frequency in a reverberant rooms [18]. However, a significant deviation is still noticeable for the high frequencies above the cut-off frequency marked with the vertical dashed line.



(a)



(b)



(c)

Figure 4-3. Estimated and measured reverberation time for (a) Gyptone Quattro, (b) Gedina A, (c) Master A.

Several factors can be linked to the discrepancies shown in Figure 4-1 and Figure 4-3. First, the absorption data provided by manufacturers is specifically for an overall depth of the system (o.d.s) of 200 mm which equates to an approximate air gap between 160-190 mm depending on the thickness of the acoustic product. However, the grid system for tile installation is suspended at a height of 120 cm from the ceiling making the overall depth of the system 1200 mm. As absorption mechanism is directly related to wavelength (see 2.2.1), a change in the distance between the ceiling tiles and the rigid surface can alter the absorption efficiency for some of the frequencies.

Another issue with input data α_p is that it was measured with the assumption that the sound field is diffused and that soundwaves hit the surface from all possible angles. However, as absorption coefficient is angle dependent (see 2.3.2), this practical absorption coefficient α_p is not useful in predicting reverberation time since the actual absorption capacity is much lower.

Finally, studies have shown that Sabine's formula becomes less accurate for highly absorbent materials due to the non-diffuse nature of the sound field. All three measured ceiling types, two porous absorbers and a resonant absorber, are highly absorptive with a mean absorption coefficient equal to or greater than 0.7 in frequency range 250-4000 Hz. As discussed in 2.3.1, a two-dimensional grazing sector will exist for rooms with ceiling treatments as in Figure 4-3 which consequently leads to a longer reverberation time in this sector.

4.2 Characterization of furniture using Sabine equation

The calculation method described in EN 12354-6:2003 [14] is valid under the assumption that the room is diffused with uniformly distributed absorption. In rooms with only ceiling treatment, the assumption can hold true for ceilings with low practical absorption coefficient. Four ceiling configurations with mean absorption coefficients ranging between 0.4 and 0.99 are compared. The absorption coefficient for these four ceiling configurations is shown in Figure 4-4.

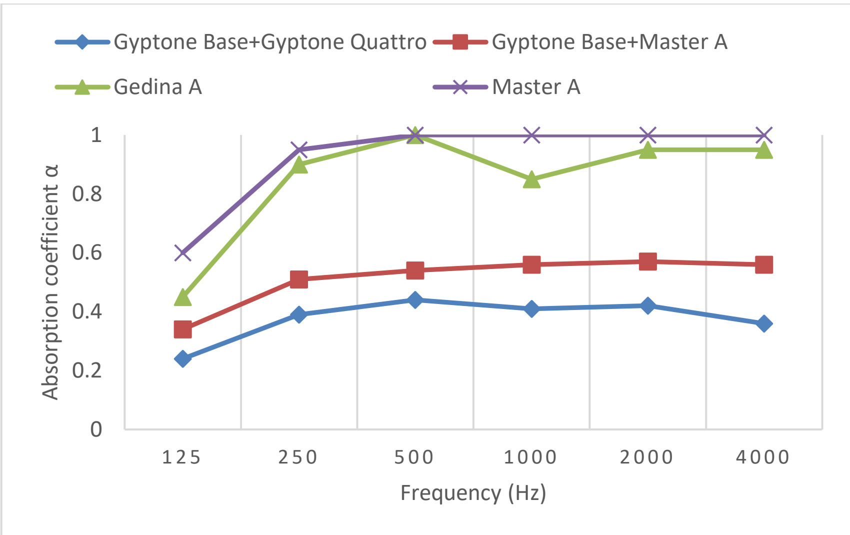


Figure 4-4. Absorption coefficient for four ceiling configurations.

The expected and measured reverberation time T_{20} for the four ceiling configurations are presented in Figure 4-5 below. The dashed vertical line denotes the Schroeder's limiting frequency.

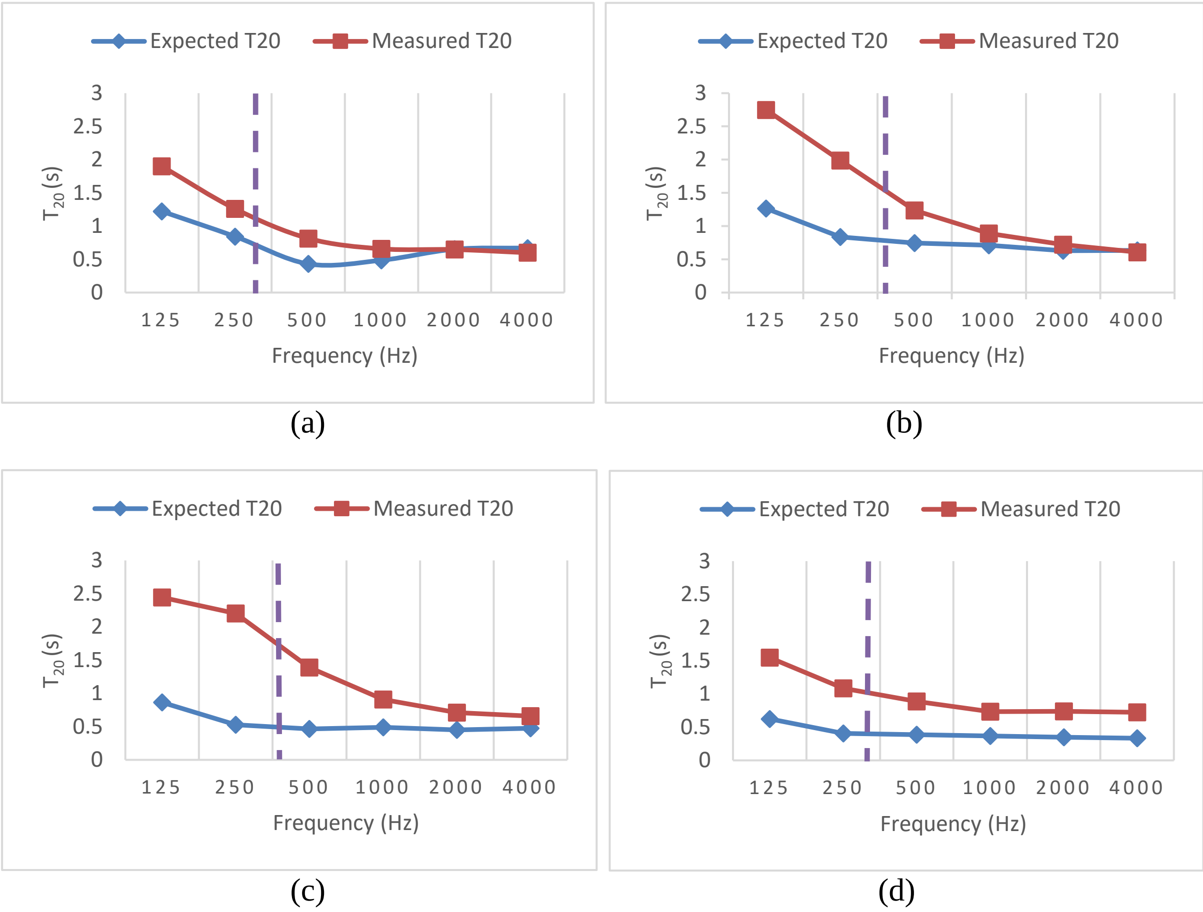


Figure 4-5. Furniture configuration with 3 tables and 6 chairs for ceiling configurations: (a) Gyptone Base & Master A; (b) Gyptone Base & Gyptone Quattro; (c) Gyptone Quattro; (d) Master A.

Figure 4-5 illustrates that the difference between measurement and calculation is most prominent for ceiling configuration (3) Gyptone Quattro and (5) Master A which have a mean absorption coefficient equal to or greater than 0.7. This finding is consistent with the results in unfurnished room in section 4.1 above. Estimation using Sabine's formula is closer to actual measurement values above Schroeder's limiting frequency (dashed vertical line) for ceiling configuration (6) Gyptone Base & Gyptone Quattro and (7) Gyptone Base & Master A. These two ceiling configurations have a mean absorption coefficient of 0.4 and 0.5 for frequency range 250-4000 Hz respectively. Thus, the diffuse field assumption holds better for those cases.

To assess the calculation method described in EN 12354-6:2003 for highly absorptive ceilings, the expected reverberation time T_{20} of the room with and without furniture for two ceiling configurations, Gyptone Quattro and Master A, is estimated using Sabine's formula. The furniture configuration consists of 3 tables and 6 chairs, and the equivalent absorption area of the furniture is obtained from measurement data. The expected reverberation time T_{20} is presented together with measurement data for each ceiling configuration in Figure 4-6 and Figure 4-7.

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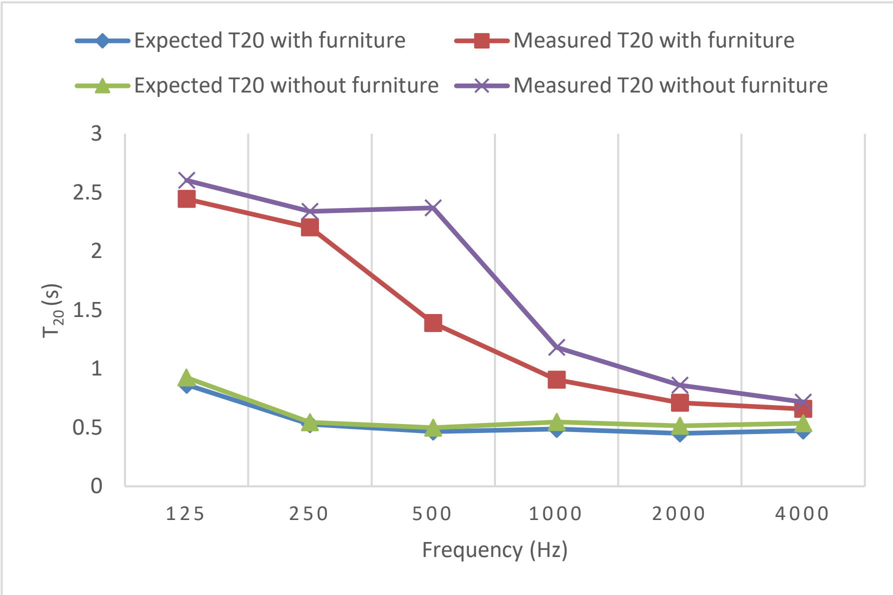


Figure 4-6. Expected and measured reverberation time T_{20} for a room with Gyptone Quattro.

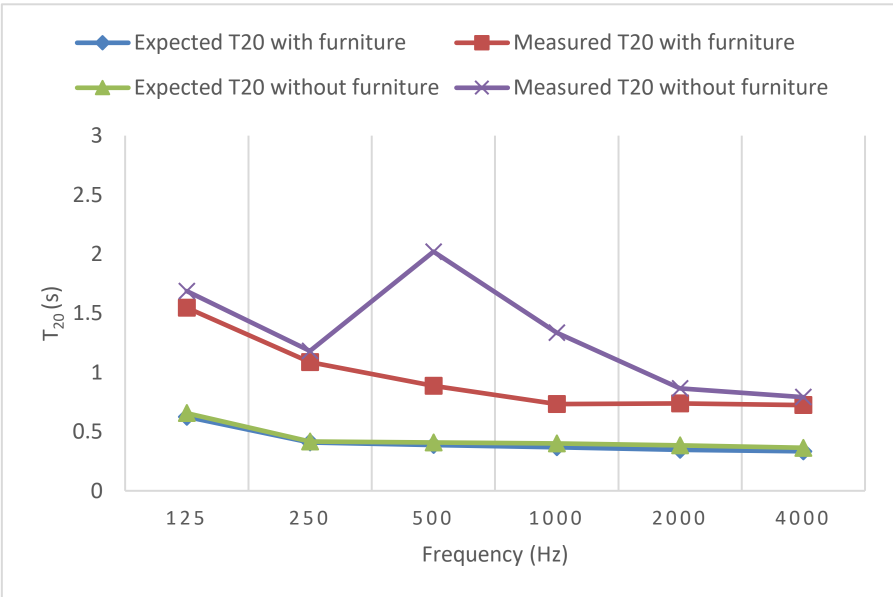


Figure 4-7. Expected and measured reverberation time T_{20} for a room with Master A.

The discrepancy between the expected and the measured reverberation time T_{20} can be seen for both furnished and unfurnished cases. For rooms with absorbent ceiling treatment, it is the grazing sound field that dominates due to the non-diffuse condition of the room. Consequently, the reverberation time T_{20} is primarily determined by the two-dimensional sound field (see also Figure 2-3). This lateral sound field is, however, not accounted for in Sabine's model which explains significant deviation between estimation and measurement values.

Furthermore, the difference between the estimated reverberation time T_{20} for a room with and without furniture using Sabine's formula is negligible as illustrated in Figure 4-6 and Figure 4-7. This is because the equivalent absorption area of the furniture estimated with Sabine's formula is significantly less than that of the absorptive ceiling. However, measurement data demonstrates that the effect of furniture is most prominent between 500-1000 Hz with a reduction of 0.9 seconds and 1.1 seconds at 500 Hz for Gyptone Quattro and Master A respectively. The contribution of furniture can be said to be both absorption and scattering, of which scattering refers to the splitting up of grazing waves travelling almost parallel to the ceiling surface.

If the reverberation time T_{20} in the unfurnished room with ceiling treatment is known through measurement, the total equivalent absorption area for the room surfaces $A_{surface}$ can be derived using Sabine's formula. By combining $A_{surface}$ with the equivalent absorption area of furniture $A_{furniture}$ obtained from measurement, the expected reverberation time T_{20} when the room is furnished with 3 tables and 6 chairs can be calculated. Comparisons between measured and expected reverberation time T_{20} for ceiling configurations Gyptone Quattro and Master A are presented in Figure 4-8 and Figure 4-9.

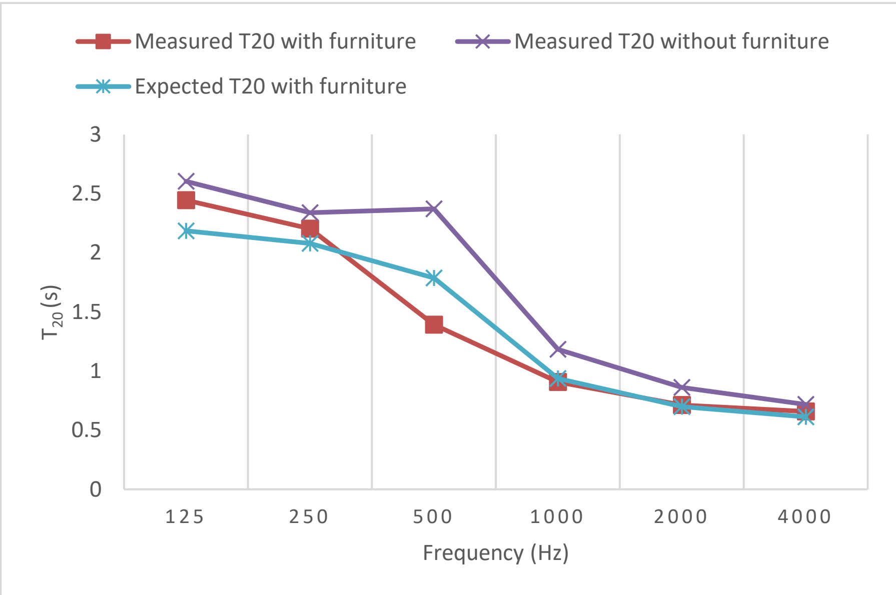


Figure 4-8. Comparison of expected T_{20} and measured T_{20} for a room with Gyptone Quattro.

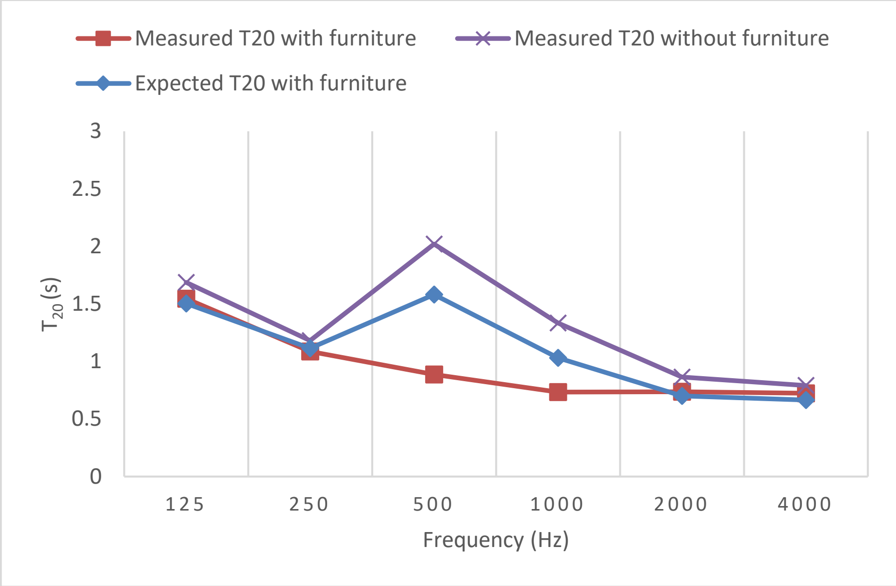
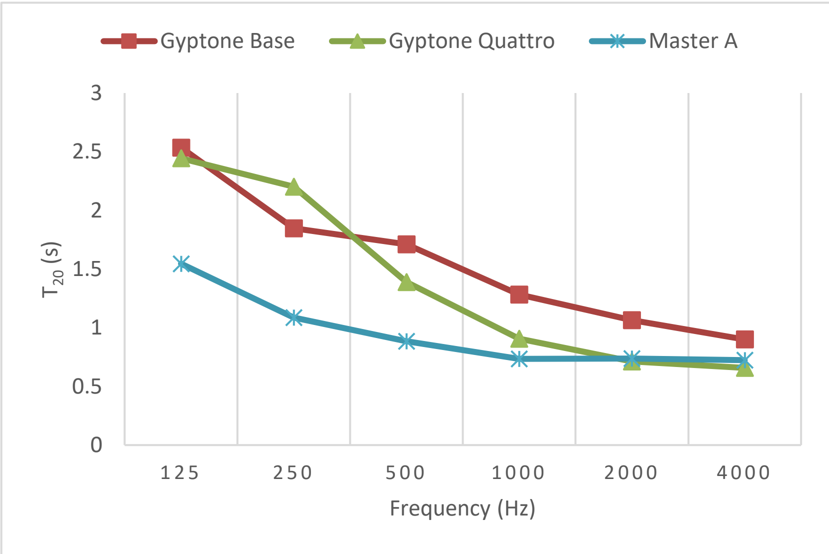


Figure 4-9. Comparison of expected T_{20} and measured T_{20} for a room with Master A.

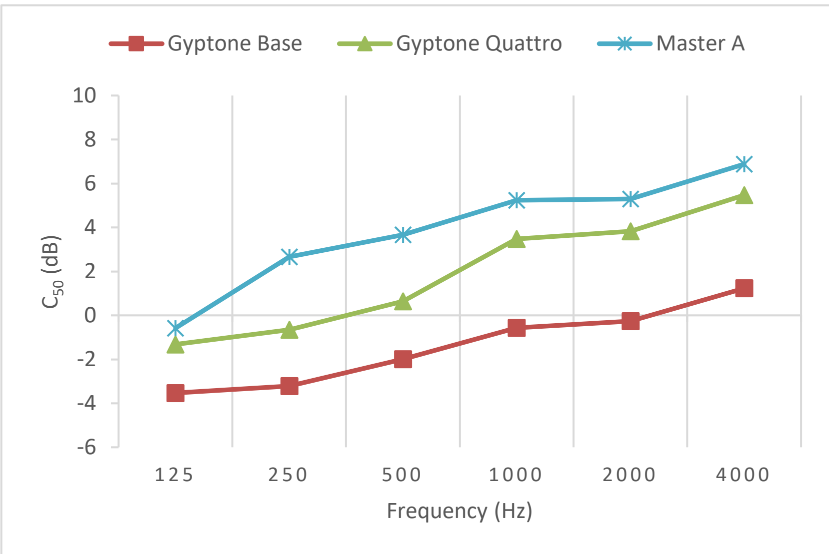
The estimated reverberation time T_{20} is approximately 0.4 seconds longer than measurement data at 500 Hz with Gyptone Quattro and 0.7 seconds longer with Master A for the same frequency band. The disparity is due to the diffuse model employed in calculating the equivalent absorption area of furniture $A_{furniture}$ which does not encompass the scattering effect mentioned above. Moreover, it is evident that the scattering effect of furniture depends on the absorptive properties of the ceiling treatment.

4.3 Effect of furniture on room acoustics parameters in combination with different suspended ceilings

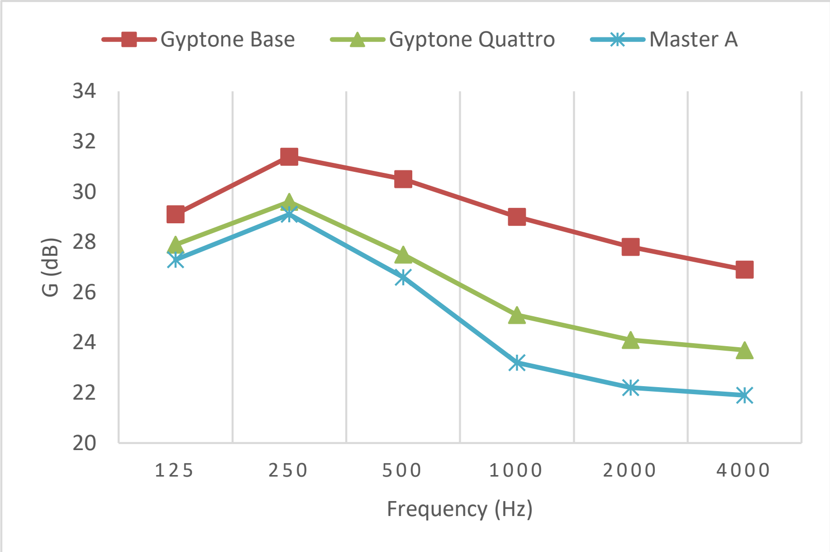
To further evaluate the effect of furniture on room acoustical parameters, the measured reverberation time T_{20}, speech clarity C_{50} and sound strength G of the room furnished with 3 tables and 6 chairs for ceiling configurations Gyptone Base, Gyptone Quattro and Master A are presented in Figure 4-10.



(a)



(b)



(c)

Figure 4-10. Measured values of (a) reverberation time T_{20}, (b) speech clarity C_{50} and (c) sound strength G in a room with 3 tables and 6 chairs for ceiling types Gyptone Base, Gyptone Quattro and Master A.

The effect of furniture on reverberation time T_{20}, speech clarity C_{50} and sound strength G is most significant between 500-2000 Hz for all ceiling configurations with the addition of chairs or upholstered chairs to the unfurnished room. This is consistent with findings from previous research [12].

For reverberation time T_{20}, the just noticeable difference is a change of 5%. A significant reduction in reverberation time can be seen in Figure 4-10 (a) for more absorptive ceiling configurations compared with a highly reflective ceiling solution. A decrease of approximately 0.3 seconds and 0.8 seconds from 1.7 seconds at 500 Hz is seen when the highly reflective ceiling Gyptone Base is replaced with resonant absorber Gyptone Quattro and porous absorber Master A respectively. The difference is less prominent between 1000-4000 Hz, although still a noticeable difference at 1000 Hz when comparing two highly absorptive ceilings Gyptone Quattro and Master A.

For speech clarity C_{50} and sound strength G, 1 dB difference is considered to be just noticeable difference according to ISO 3382-1:2009 [4]. Figure 4-10 (b) illustrates a noticeable increase in speech clarity C_{50} with an increase in practical absorption coefficient for all frequency ranges. At 500 Hz, an approximate increase of 2.5 dB in speech clarity is achieved by replacing Gyptone Base with Gyptone Quattro. A further increase of 3dB is seen when the ceiling is treated with Master A instead of Gyptone Quattro. In other words, ceilings with higher absorption property can take up more grazing sound waves split up by the furniture and thus, reduce more of the later reflex energy.

A considerable reduction of 3 dB and 3.9 dB at 500 Hz in sound strength G is seen for more absorptive ceiling treatments Gyptone Quattro and Master A compared with a highly reflective ceiling Gyptone Base as shown in Figure 4-10 (c). Comparison of Gyptone Quattro and Master A shows that a JND can be achieved for frequency range 1000-4000 Hz. However, this is due to an increase in the total absorption in the room rather than the scattering effect of the furniture as sound strength G is a steady state measurement and mainly related to the absorption capacity.

4.4 Quantification of A_{sc} for furniture in combination with different suspended ceilings

Assuming diffuse condition in the reverberant chamber when untreated, the equivalent absorption areas for configurations 1b-1f are calculated using Sabine's formula and presented in Figure 4-11 below.

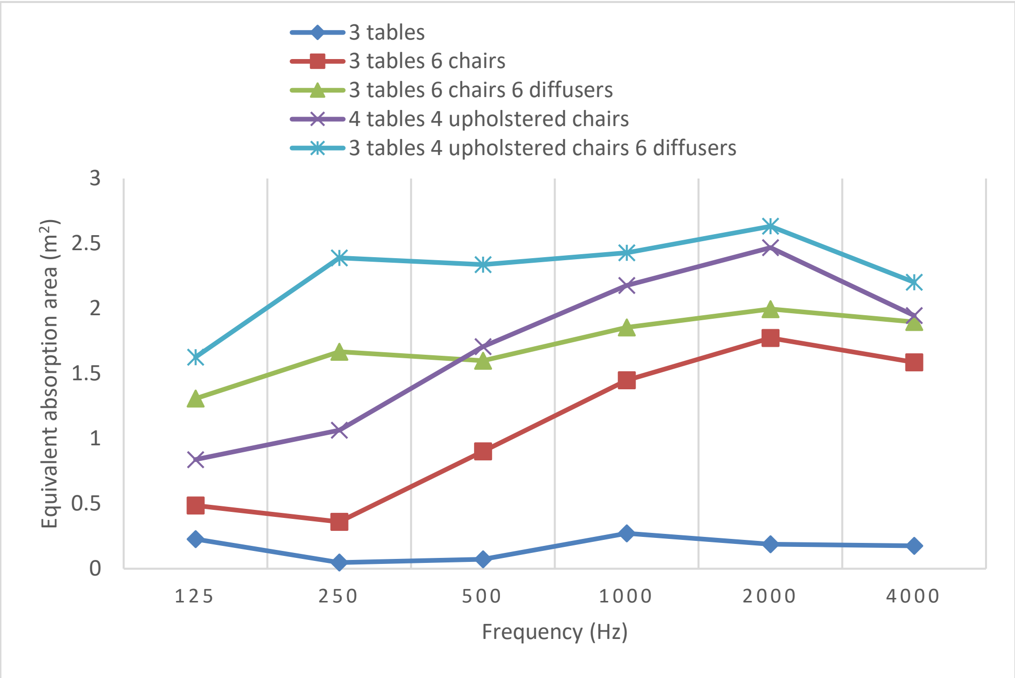


Figure 4-11. The equivalent absorption area of the 5 furniture configurations derived using Sabine's formula.

The results are consistent with previous studies [11] in which diffusers provided added absorption between 125-500 Hz and scattering effects between 1000-4000 Hz when combined with furniture. By adding furniture covered with textile such as chairs and upholstered chairs, an increase in equivalent absorption area can be seen between 500-4000 Hz.

The absorption properties of the furniture are evaluated using measurement data in the reverberant room without ceiling treatment according to Sabine's formula under the assumption that the sound field is diffuse. Once the ceiling tiles are mounted, the equivalent scattering absorption area A_{sc} for each ceiling configuration can be estimated using Equation (15) from the SEA model. The equivalent absorption area A and the equivalent scattering absorption area A_{sc} for furniture configuration consisting of 3 tables and 6 chairs are presented in Figure 4-12.

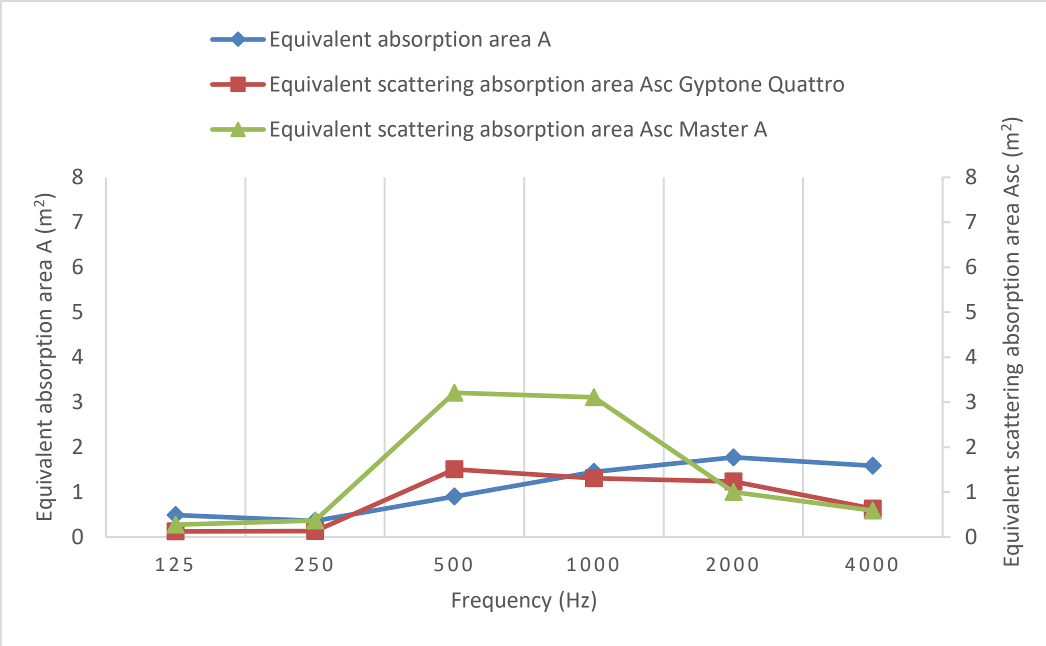


Figure 4-12. The equivalent absorption area of 3 tables and 6 chairs in an untreated room and the equivalent scattering absorption area A_{sc} from the same furniture configuration in a room treated with Gyptone Quattro and Master A respectively.

A correlation between A_{sc} and the room acoustic parameters T_{20} and C_{50} can be seen in Figure 4-10 and Figure 4-12 where T_{20} decreased and C_{50} increased for higher value of A_{sc}. This accords with earlier observations in [11]. It is also apparent from Figure 4-12 that the scattering and absorption effects of furniture depend on the ceiling's absorptive capacity. In a room mounted with resonance absorber Gyptone Quattro, the scattering effect of furniture is most effective around 500 Hz while the furniture's absorption property dominates from approximately 1000 Hz to 4000 Hz. For porous absorber Master A, the scattering effect of furniture spans between 500-1000 Hz and absorption effect becomes prominent from 2000 Hz to 4000 Hz.

Previous investigation shows that by combining furniture and diffusers, an additional effect on A_{sc} can be achieved. The equivalent absorption area A and the equivalent scattering absorption area A_{sc} for furniture configuration consisting of 3 tables, 6 chairs and 6 vertically mounted diffusers are presented in Figure 4-13.

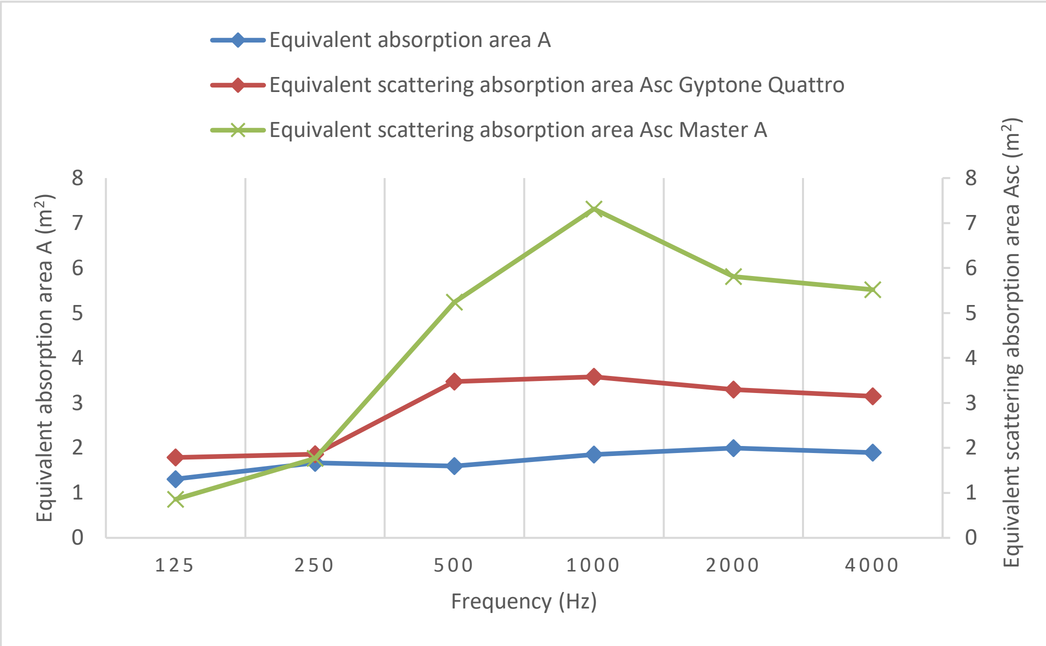


Figure 4-13. The equivalent absorption area of 3 tables, 6 chairs and 6 diffusers in an untreated room and the equivalent scattering absorption area A_{sc} from the same furniture configuration in a room treated with Gyptone Quattro and Master A respectively.

Comparison between Figure 4-12 and Figure 4-13 reveals an increase in both equivalent absorption area A and the equivalent scattering absorption area A_{sc} at 125-250 Hz due to the diffusers' resonance absorption properties. The interesting aspect of this combination is the dramatic increase in scattering effect between 500-4000 Hz. Furthermore, it is the scattering effect instead of absorption that dominates the frequency range 2000-4000 Hz for both ceiling configurations. This additional contribution, consequently, also influenced the room acoustic parameters T_{20} and C_{50}.

Moreover, it can be assumed from these two figures that the equivalent scattering absorption area A_{sc} is the sum of the equivalent absorption area in the three-dimensional diffuse field and the equivalent scattering area in the two-dimensional diffuse field. Previous findings [30] demonstrate that the difference between the three-dimensional absorption coefficient and the two-dimensional one is small so the assumption above is acceptable.

To achieve a reliable estimation using the SEA model, a method should be developed to accurately approximate the equivalent scattering absorption area A_{sc} of furniture for ceilings with different absorptive efficiency. One possibility is to investigate the correlation between the scattering effect of the furniture and the practical absorption coefficient of the ceiling.

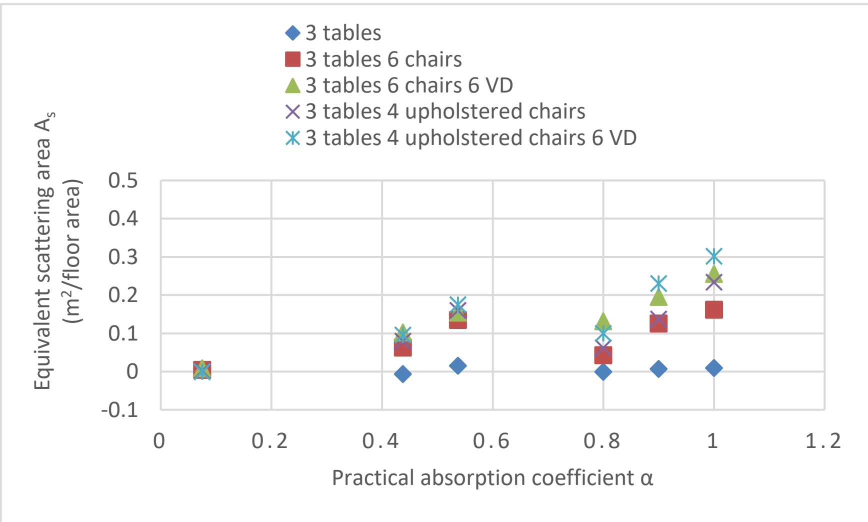
4.5 Correction factor for scattering effect of furniture

4.5.1 Approximation of the equivalent scattering area A_s

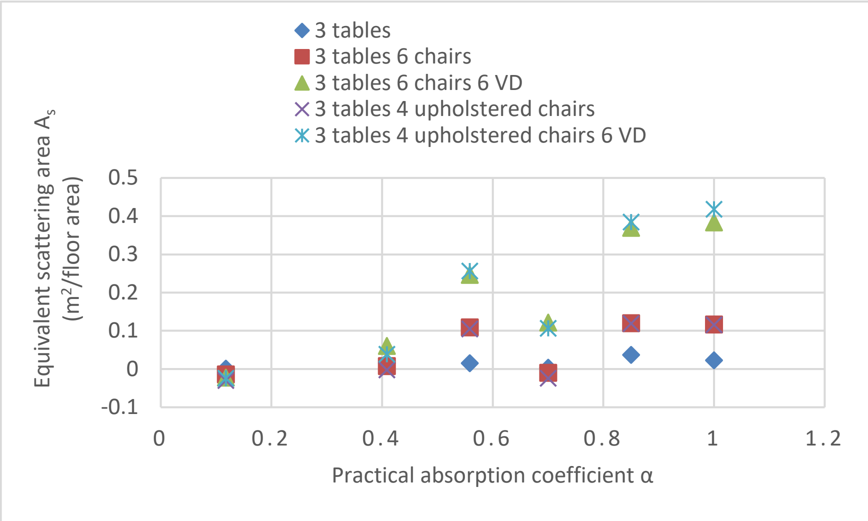
Based on the results presented in 4.2 and 4.4, the equivalent scattering absorption area A_{sc} can be written as the sum of the equivalent absorption area A derived using Sabine's formula and the equivalent scattering area, henceforth denoted as A_s:

$$A_{sc} = A + A_s \tag{18}$$

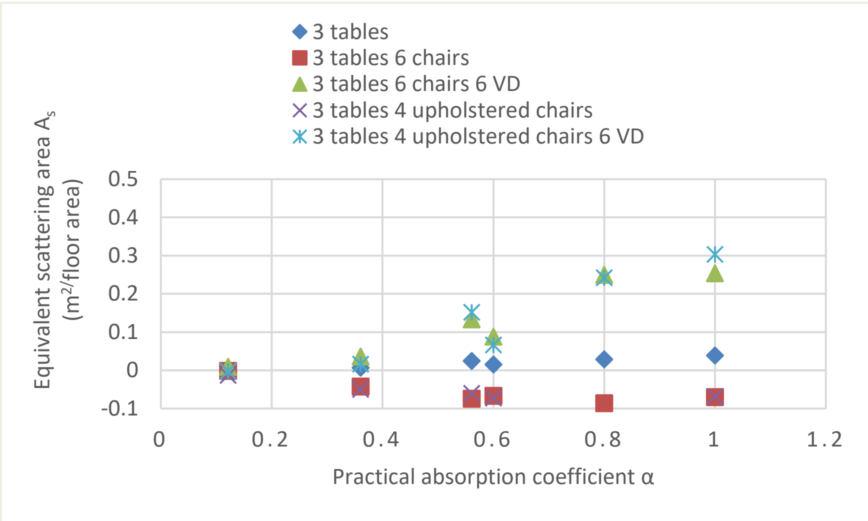
Since limited data on absorption properties of furniture is available [14] [15], the equivalent scattering absorption area A_{sc} for objects in an ordinary room can be estimated once the equivalent scattering area A_s is known. Using measurement data in the reverberant room, the equivalent scattering area A_s per floor square meter can be calculated from Equation (18) for every furniture configuration and ceiling type. The equivalent scattering area A_s for all furniture configurations can then be plotted as a function of the ceilings' practical absorption coefficient α for frequency band 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz, see Figure 4-14. This is due to the effect of furniture being most prominent between 500-2000 Hz according to results from 4.4. The linear regression line shall be fitted for each furniture combination and evaluated for three different degrees of furnishing: sparse, normal, and dense. This relation can be used to approximate the equivalent scattering area A_s for different ceiling treatments provided that the practical absorption coefficient α for the ceiling is given.



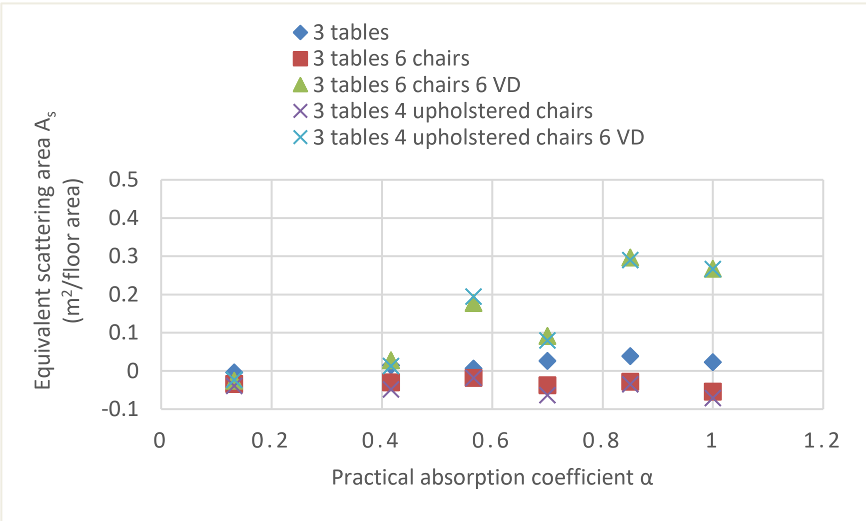
(a)



(b)



(c)



(d)

Figure 4-14. The equivalent scattering area As as the function of the practical absorption coefficient α at: (a) 500 Hz, (b) 1000 Hz, (c) 2000 Hz, and (d) 4000 Hz.

4.5.2 Estimation using the scattering correction factor in the mock-up classroom

Using available measurement data for the sparse furnishing in the mock-up classroom (see Figure 3-3 (d)), an evaluation has been done to best fit the sparse furnishing for ceiling configurations Gyptone Quattro, Gedina A and Master A. The equivalent scattering area A_s over the total floor area for frequency range 500-4000 Hz in the mock-up classroom is approximated using the regression line for 3 tables as the correction factor fitted with this configuration yields the closest approximation to measurement data. The scattering absorption area A_{sc} can then be determined as the sum of the equivalent scattering area A_s and the equivalent absorption area A of the furniture obtained from measurement data. In cases which measurement data is not available, the absorption area of the furniture can be obtained from data for example, Annex C in EN 12354-6:2003 [14]. Finally, by inputting A_{sc} into the SEA model in 2.3.3, room acoustic parameters T_{20}, C_{50} and G can be estimated. The script used to evaluate C_{50} and G was programmed for rooms of smaller dimensions in which the distance to the source is taken into account in a simplified manner. Therefore, adjustment must be made in the script to obtain more accurate approximation for C_{50} and G in larger rooms as the distance to the source has a significant impact on these two parameters.

To assess the plausibility of this scattering correction method, the estimated reverberation time T_{20} employing SEA model for Gyptone Quattro and Master A respectively (see also Figure 4-1 for the absorptive properties of the respective ceilings) are plotted with the estimated reverberation time T_{20} using Sabine's formula for Gyptone Quattro and the measured reverberation time T_{20} for Gyptone Quattro in Figure 4-15 below. The scattering correction factor is applied for frequency range 500-4000 Hz for both ceilings. Figure 4-15 demonstrates that the approximation with the scattering correction factor for Gyptone Quattro is more aligned with measurement data than approximation with correction for the absorptive properties of Master A. This corroborates the need for a scattering correction factor to reflect the influence of the ceiling on the effect of the furniture.

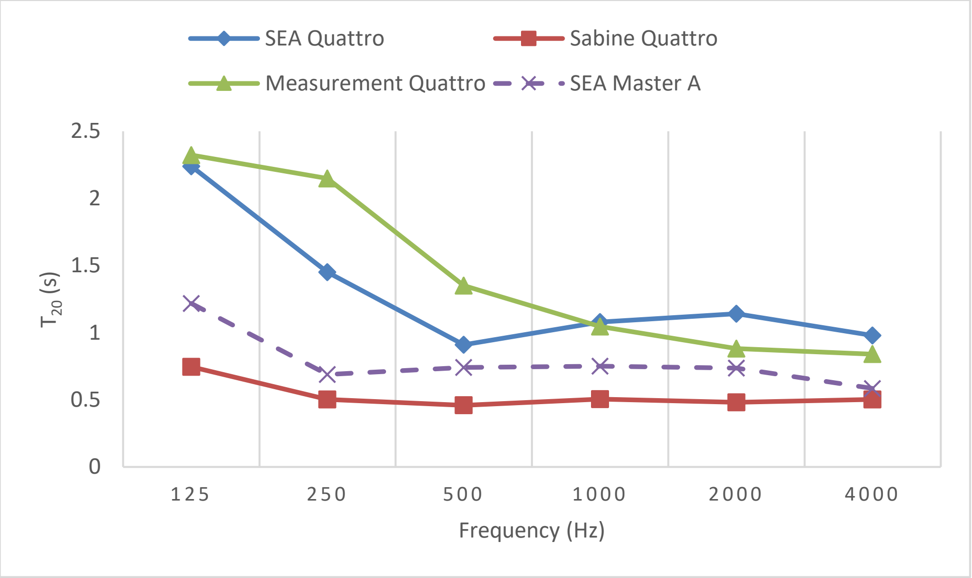
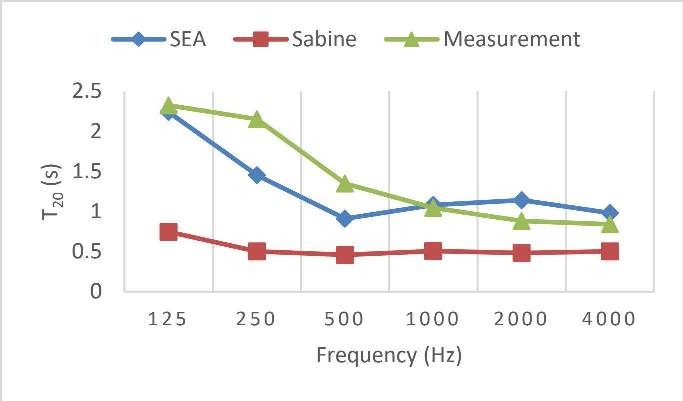
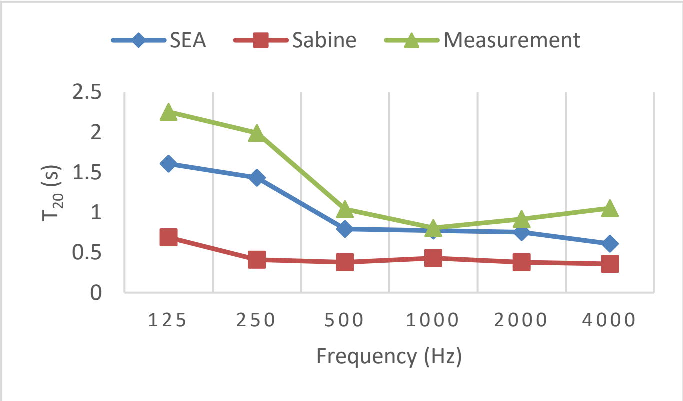


Figure 4-15. Comparison of estimated reverberation time T_{20} with SEA model for Gyptone Quattro (blue), Sabine's formula for Gyptone Quattro (red), estimated reverberation time T_{20} with SEA model for Master A (dashed purple) and measured reverberation time T_{20} for Gyptone Quattro (green) in a mock-up classroom with sparse furnishing.

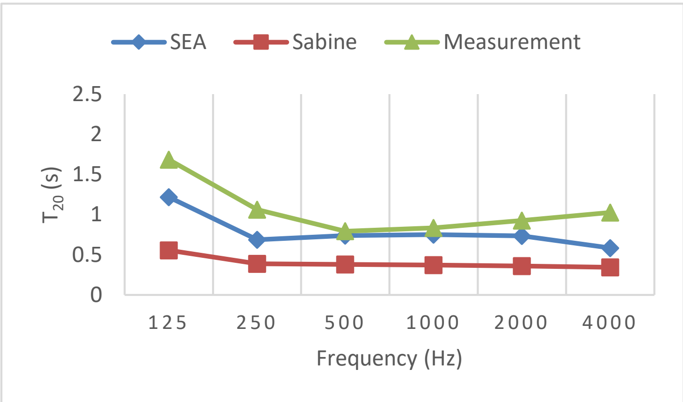
Furthermore, the purpose of this thesis is to evaluate existing methods which employ Sabine's formula so the main interest is to assess whether a correction factor for the scattering effect in the SEA model can yield a more accurate estimation. The estimated reverberation time T_{20} using the scattering correction factor for frequency range 500-4000 Hz in the mock-up classroom for Gyptone Quattro, Gedina A, and Master A are presented together with the estimated reverberation time T_{20} using Sabine's formula and reverberation time T_{20} from measurement data in Figure 4-16.



(a)



(b)



(c)

Figure 4-16. Comparison of estimated reverberation time T_{20} with SEA model (blue), Sabine's formula (red) and measured reverberation time T_{20} (green) for ceiling configuration (a) Gyptone Quattro, (b) Gedina A, and (c) Master A in a mock-up classroom with sparse furnishing.

For all three ceiling configurations with sparse furnishing, the estimated reverberation time T_{20} employing SEA model with a correction factor for scattering effect agrees better with measurement data than calculation with Sabine's formula.

Comparison of speech clarity C_{50} using Sabine's formula and the SEA model with scattering correction factor for frequency range 500-4000 Hz in the mock-up classroom for Gyptone Quattro, Gedina A, Master A are presented in Figure 4-17.

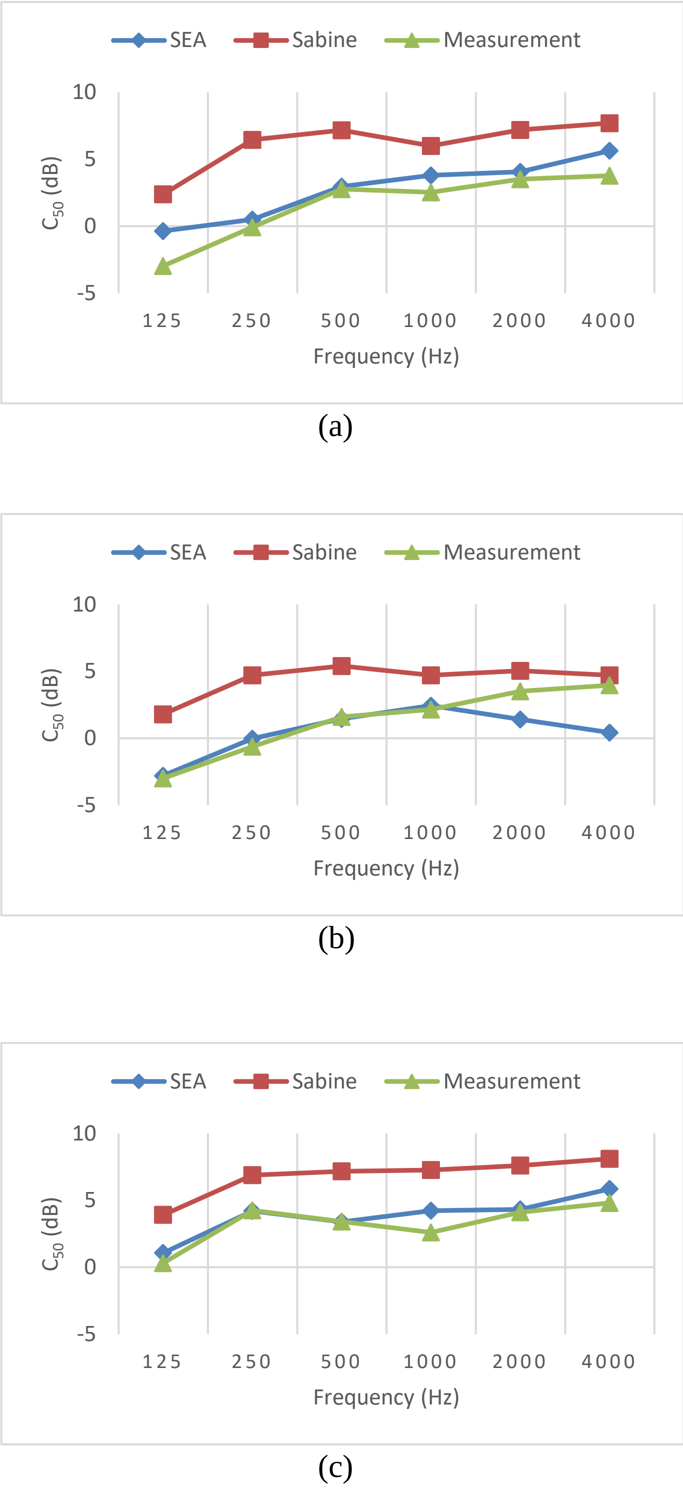


Figure 4-17. Comparison of estimated speech clarity C_{50} with SEA model (blue), Sabine's formula (red) and measured speech clarity C_{50} (green) for ceiling configuration (a) Gyptone Quattro, (b) Gedina A, and (c) Master A in a mock-up classroom with sparse furnishing.

The SEA calculation model also yields more accurate estimation of speech clarity C_{50} overall when compared with Sabine's formula. For resonant absorber Gyptone Quattro, the result of speech clarity C_{50} between 2000-4000 Hz does deviate significantly from measurement value. This could be attributed to uncertainty in input data for air flow resistivity of the tissue backing in the SEA model.

5 Discussion

5.1 Characterization of furniture in existing standards

In current standards such as EN 12354-6:2003, the reverberation time of a room with objects is estimated using Sabine's formula assuming the sound field in the room is diffuse. Swedish Standard SS25268:2023 recommends excluding the effect of furniture in Sabine's formula. Comparison of estimated reverberation time using Sabine's formula and measurement data in the reverberant room with furniture shows that for ceiling treatments with mean absorption coefficient value lower than 0.6 between 500-4000 Hz, the calculated results are acceptable for high frequencies above Schroeder's limiting frequency. However, for more absorptive ceilings, the estimation using Sabine's formula is no longer accurate. This is because in a room with unevenly distributed absorption, two sound fields are present: a grazing and a non-grazing field. The energy lost from the grazing sound field to the non-grazing one is due to the scattering effect of objects in the room such as furniture. This means that furniture has both an absorption effect and also a scattering effect on room acoustic parameters. Moreover, these effects are frequency dependent with scattering dominating in the middle frequency range for more absorptive materials. These two factors are not accounted for in Sabine's formula. Thus, this supports the reccomendation in SS 25268:2023 to not include furniture in the Sabine's formula.

5.2 On the importance of including relevant room acoustic parameters

Experiment results from this study demonstrate that the sound fields in a room with absorptive ceiling are complex, however, the reverberation time only delivers information on the later part of the energy decay curve. Information during steady state and the reflection path is of equal interest for design of rooms used for speech as mentioned in chapter 2.1. Ceiling treatments with varying degree of absorptive properties can yield similar results in reverberation time but the difference in speech clarity and sound strength between two materials can be noticeable. Therefore, additional parameters such as speech clarity and sound strength are needed in the design process for speech intensive spaces to achieve a satisfactory sound environment for both speakers and listeners. It is illustrated in this study that the effects of furniture on room acoustic parameters depend considerably on the absorptive properties of the ceiling and thus, a suitable calculation model should be used to arrive at reasonable estimations.

5.3 Application of the SEA model and the correction factor for scattering

For highly absorptive ceilings with an average absorption coefficient greater than 0.7 for octave bands 250-4000 Hz, a calculation model based on the SEA approach can be employed to account for the scattering effect of objects in the room. The model also takes into consideration the actual mounting height of the ceiling treatment which otherwise is not reflected in classical diffuse theory model. Room acoustic parameters reverberation time, speech clarity and sound strength can be determined if the equivalent scattering absorption area A_{sc} of objects is known. However, this study shows that the effect of furniture is dependent on the ceiling's absorptive properties. This means that the equivalent scattering absorption area A_{sc} of the same object will vary for different ceiling treatments. It can be assumed that the equivalent scattering absorption area A_{sc} is the sum of the equivalent absorption area and the equivalent scattering area. This study suggests a correction factor for the estimation of the equivalent scattering area if the ceiling's absorption coefficient is given. The method can be used to estimate A_{sc} for any ceiling configuration.

The method has been tested and compared with measurement data in the mock-up classroom. The results of reverberation time T_{20} and speech clarity C_{50} for sparse furnishing illustrate a better fit with measurement data than Sabine's formula. While the result of sound strength G using SEA model is closer to actual measurement values than estimation with Sabine's formula, it is not reasonably accurate enough with the existing script. As sound strength G is dependent on the distance from the sound source to the receiver, a different approach is needed to accurately compute this parameter. For normal and dense furnishing, further measurements should be conducted in the mock-up classroom to find a reasonable correlation for these furnishing configurations.

The SEA model was first developed to compute room acoustic parameters in rooms with porous absorbers. In this study, the model was further improved to calculate for resonant absorbers. The ambition is to utilize this model in combination with existing absorption data of furniture to estimate reverberation time T_{20}, speech clarity C_{50} and sound strength G for any absorptive ceilings. By employing this SEA calculation model, acousticians should be able to obtain direct and reasonably accurate results if the furniture configuration and the absorption coefficient of the ceiling are given.

6 Conclusions and Future work

6.1 Conclusions

The purpose of this thesis is to investigate the scattering and absorptive effects of objects in an ordinary room and its dependence on the absorptive properties of the suspended ceiling.

It is concluded that objects, such as furniture, have a scattering as well as an absorptive effect that influence room acoustic parameters namely reverberation time T_{20}, speech clarity C_{50} and sound strength G.

The scattering effect depends on the absorbing efficiency of the ceiling and it is more pronounced in rooms with a highly absorptive ceiling. The scattering and absorptive effects of furniture can be quantified in the parameter equivalent scattering absorption area A_{sc}. A correction method is presented to account for the influence of the ceiling absorption efficiency on the equivalent scattering absorption area A_{sc}.

It is further concluded that in rooms with absorbent ceiling treatment, Sabine's formula generally estimates too short reverberation times compared to measurements. For high frequencies above Schroeder's limiting frequency and a mean absorption coefficient for the ceiling below 0.6, the agreement to measurements improves.

The effect of furniture should be excluded if Sabine's formula is used as per recommendation described in SS 25268:2023.

6.2 Future work

The SEA model employed in this study provides estimations closer to measurement data but is so far validated for porous materials. To achieve more accurate results for resonant absorbers and for ceilings with the average absorption coefficients below 0.7, the model should be improved further.

The method for quantifying A_{sc} accommodates only sparse furnishing as measurement data for normal and dense furnishing is not readily available. Measurements of these two furnishing configurations in a mock-up classroom should be conducted to determine the appropriate correction factors for scattering in normal and dense furnishing.

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Appendix A. Measurement results

Table A1. Results of the repeatability test in the reverberant room

Reverberation time T_{20} (s)				
Frequency	Test 1	Test 2	Test 3	σ_{avr}
125 Hz	4.35	4.25	4.24	0.051
250 Hz	2.97	2.94	2.91	0.026
500 Hz	3.78	3.77	3.78	0.007
1000 Hz	3.21	3.19	3.19	0.006
2000 Hz	2.28	2.29	2.30	0.008
4000 Hz	1.68	1.71	1.69	0.013
Speech Clarity C_{50} (dB)				
Frequency	Test 1	Test 2	Test 3	σ_{avr}
125 Hz	-7.2	-7.1	-7.1	0.07
250 Hz	-4.7	-4.5	-4.3	0.23
500 Hz	-7.0	-6.4	-6.4	0.31
1000 Hz	-4.9	-5.4	-5.4	0.26
2000 Hz	-4.8	-4.6	-4.7	0.08
4000 Hz	-2.5	-2.4	-3.1	0.31
Sound Strength G (dB)				
Frequency	Test 1	Test 2	Test 3	σ_{avr}
125 Hz	32.1	31.6	31.7	0.24
250 Hz	32.9	32.9	33.1	0.09
500 Hz	33.4	33.4	33.7	0.14
1000 Hz	31.9	32.0	32.0	0.05
2000 Hz	30.3	30.1	30.0	0.14
4000 Hz	29.0	28.8	28.9	0.09

Table A2. Measurement results of ceiling configuration 1 (reverberant room)

Reverberation time T_{20} (s)						
Frequency	1a	1b	1c	1d	1e	1f
125 Hz	4.491	4.04	3.626	2.738	3.183	2.5
250 Hz	3.038	2.991	2.714	1.957	2.246	1.696
500 Hz	3.802	3.692	2.767	2.287	2.226	1.931
1000 Hz	3.197	2.92	2.124	1.942	1.817	1.731
2000 Hz	2.236	2.138	1.561	1.504	1.396	1.362
4000 Hz	1.639	1.589	1.277	1.224	1.216	1.176
Speech clarity C_{50} (dB)						
Frequency	1a	1b	1c	1d	1e	1f
125 Hz	-7.24	-7.09	-7.26	-4.7	-6.32	-4.12
250 Hz	-4.75	-4.22	-4.45	-3.31	-3.75	-2.81
500 Hz	-6.21	-6.19	-6.47	-4.9	-5.26	-3.82
1000 Hz	-5.72	-5.28	-3.22	-2.92	-3.68	-2.66
2000 Hz	-5.03	-4.47	-2.35	-2.3	-2.04	-1.82
4000 Hz	-2.46	-2.18	-0.77	-0.75	-1.16	-0.8
Sound strength G (dB)						
Frequency	1a	1b	1c	1d	1e	1f
125 Hz	31.7	31.9	32	29.7	31.3	29.6
250 Hz	32.5	32.9	31.6	30.9	31.3	30.3
500 Hz	33.1	33.2	31	30.6	30.3	29.4
1000 Hz	31.5	31.8	29.6	29.6	29	28.8
2000 Hz	29.8	29.6	28.1	27.8	27.4	27.2
4000 Hz	28.5	28.3	26.9	26.6	26.4	26.2
Equivalent absorption area A of furniture (m^2)						
Frequency	1a	1b	1c	1d	1e	1f
125 Hz	0.0	0.228	0.487	1.308	0.839	1.627
250 Hz	0.0	0.047	0.360	1.668	1.065	2.389
500 Hz	0.0	0.072	0.902	1.598	1.708	2.338
1000 Hz	0.0	0.272	1.450	1.854	2.179	2.430
2000 Hz	0.0	0.188	1.774	1.997	2.469	2.633
4000 Hz	0.0	0.176	1.587	1.898	1.947	2.204

Table A3. Measurement results of ceiling configuration 2 (reverberant room)

Reverberation time T_{20} (s)						
Frequency	2a	2b	2c	2d	2e	2f
125 Hz	2.87	2.662	2.536	1.685	2.306	1.525
250 Hz	2.28	2.303	1.848	1.393	1.554	1.242
500 Hz	2.531	2.334	1.711	1.362	1.357	1.169
1000 Hz	1.874	1.7	1.284	1.196	1.138	1.058
2000 Hz	1.463	1.41	1.065	0.994	0.943	0.879
4000 Hz	1.247	1.198	0.9	0.832	0.87	0.812
Speech clarity C_{50} (dB)						
Frequency	2a	2b	2c	2d	2e	2f
125 Hz	-3.76	-3.23	-3.53	-0.39	-3.21	-0.07
250 Hz	-3.71	-3.27	-3.21	-1.93	-2.1	-1.16
500 Hz	-3.79	-3.73	-1.99	-0.93	-0.79	0.6
1000 Hz	-2.44	-2.34	-0.56	-0.45	0.09	0.75
2000 Hz	-2.06	-2.24	-0.26	0.31	0.16	0.76
4000 Hz	-1.27	-0.64	1.23	1.76	1.02	1.54
Sound strength G (dB)						
Frequency	2a	2b	2c	2d	2e	2f
125 Hz	29.6	29	29.1	27.3	29.4	26.8
250 Hz	31.5	31.9	31.4	30.5	30.6	30.1
500 Hz	31.2	31.7	30.5	29.4	29	28.6
1000 Hz	30.1	30.5	29	28.7	27.9	28
2000 Hz	29	29.2	27.8	27.6	27.1	27.1
4000 Hz	27.5	28.4	26.9	26.8	26.7	26.5
Equivalent scattering absorption area A_{sc} of furniture (m^2)						
Frequency	2a	2b	2c	2d	2e	2f
125 Hz	0.0	0.138	0.232	1.241	0.432	1.557
250 Hz	0.0	-0.022	0.519	1.415	1.038	1.857
500 Hz	0.0	0.169	0.959	1.718	1.731	2.332
1000 Hz	0.0	0.277	1.242	1.532	1.748	2.085
2000 Hz	0.0	0.130	1.294	1.634	1.909	2.300
4000 Hz	0.0	0.166	1.566	2.026	1.760	2.176

Table A4. Measurement results of ceiling configuration 3 (reverberant room)

Reverberation time T_{20} (s)						
Frequency	3a	3b	3c	3d	3e	3f
125 Hz	2.603	2.412	2.444	1.357	2.422	1.495
250 Hz	2.338	2.521	2.202	1.259	2.132	1.241
500 Hz	2.37	2.301	1.39	0.903	1.07	0.86
1000 Hz	1.182	1.1	0.906	0.644	0.828	0.616
2000 Hz	0.862	0.786	0.712	0.552	0.68	0.525
4000 Hz	0.717	0.679	0.658	0.496	0.635	0.496
Speech clarity C_{50} (dB)						
Frequency	3a	3b	3c	3d	3e	3f
125 Hz	-2.19	-2.18	-1.32	1.49	-1.01	1.9
250 Hz	-1.74	-1.25	-0.66	1.01	-0.5	1.56
500 Hz	-1.97	-1.25	0.64	2.15	1.97	2.97
1000 Hz	2.02	2.77	3.47	4.86	3.87	5.01
2000 Hz	2.76	2.79	3.82	5.73	4	6.01
4000 Hz	4.46	4.39	5.47	6.42	5.74	6.28
Sound strength G (dB)						
Frequency	3a	3b	3c	3d	3e	3f
125 Hz	27.9	28.6	27.9	26.9	28	26.6
250 Hz	29.9	30.1	29.6	28.7	29	28.4
500 Hz	29.3	28.7	27.5	26.4	26.6	25.7
1000 Hz	26.6	26.1	25.1	24.5	24.1	23.9
2000 Hz	25.3	24.9	24.1	23.9	23.4	23.4
4000 Hz	25	24.6	23.7	23.6	23.3	23.2
Equivalent scattering absorption area A_{sc} of furniture (m^2)						
Frequency	3a	3b	3c	3d	3e	3f
125 Hz	0.0	0.154	0.127	1.787	0.145	1.442
250 Hz	0.0	-0.157	0.134	1.857	0.209	1.915
500 Hz	0.0	0.064	1.507	3.472	2.597	3.753
1000 Hz	0.0	0.319	1.305	3.580	1.832	3.938
2000 Hz	0.0	0.568	1.238	3.300	1.573	3.772
4000 Hz	0.0	0.395	0.633	3.148	0.912	3.148

Table A5. Measurement results of ceiling configuration 4 (reverberant room)

Reverberation time T_{20} (s)						
Frequency	4a	4b	4c	4d	4e	4f
125 Hz	2.578	2.433	2.358	1.314	2.188	1.378
250 Hz	1.733	1.869	1.706	1.147	1.529	1.058
500 Hz	1.58	1.6	1.132	0.834	0.894	0.718
1000 Hz	1.188	1.095	0.811	0.555	0.75	0.516
2000 Hz	0.915	0.827	0.745	0.449	0.694	0.439
4000 Hz	0.812	0.737	0.78	0.422	0.763	0.43
Speech clarity C_{50} (dB)						
Frequency	4a	4b	4c	4d	4e	4f
125 Hz	-1.8	-1.18	-1.26	1.75	-1.51	1.91
250 Hz	0.64	0.77	0.48	0.7	1.24	1.84
500 Hz	0.13	0.77	1.79	2.77	2.71	3.51
1000 Hz	3.89	3.93	4.87	6.75	4.99	6.75
2000 Hz	4.08	3.71	5.39	7.92	5.98	8.46
4000 Hz	5.07	5.62	6.36	8.95	6.76	9.52
Sound strength G (dB)						
Frequency	4a	4b	4c	4d	4e	4f
125 Hz	28	27.9	27.6	26.3	27.9	26.7
250 Hz	28.6	28.4	28.7	27.6	28.5	27.5
500 Hz	28.1	27.7	26.5	25.2	25.9	25
1000 Hz	25	24.6	23.7	22.9	23.2	22.8
2000 Hz	23.4	23.1	22.2	22.1	21.7	21.6
4000 Hz	23.4	23	21.8	21.8	21.5	21.3
Equivalent scattering absorption area A_{sc} of furniture (m^2)						
Frequency	4a	4b	4c	4d	4e	4f
125 Hz	0.0	0.117	0.183	1.890	0.350	1.711
250 Hz	0.0	-0.213	0.046	1.493	0.390	1.865
500 Hz	0.0	-0.040	1.269	2.868	2.460	3.849
1000 Hz	0.0	0.362	1.982	4.863	2.490	5.553
2000 Hz	0.0	0.589	1.263	5.745	1.763	6.002
4000 Hz	0.0	0.635	0.256	5.765	0.401	5.542

Table A6. Measurement results of ceiling configuration 5 (reverberant room)

Reverberation time T_{20} (s)						
Frequency	5a	5b	5c	5d	5e	5f
125 Hz	1.688	1.573	1.546	1.313	1.368	1.29
250 Hz	1.181	1.169	1.087	0.836	1.04	0.728
500 Hz	2.02	1.871	0.886	0.654	0.671	0.554
1000 Hz	1.335	1.154	0.734	0.456	0.665	0.416
2000 Hz	0.864	0.794	0.738	0.434	0.692	0.412
4000 Hz	0.791	0.71	0.724	0.425	0.687	0.392
Speech clarity C_{50} (dB)						
Frequency	5a	5b	5c	5d	5e	5f
125 Hz	-0.3	0.2	-0.58	3.31	1.17	3.66
250 Hz	1.61	2.68	2.66	3.49	3.44	4.62
500 Hz	-0.04	0.75	3.67	4.85	5.23	6.05
1000 Hz	4.56	4.72	5.24	8.77	5.91	9.26
2000 Hz	3.33	4.23	5.3	8.77	6.61	9.27
4000 Hz	5.47	5.86	6.88	9.92	7.87	10.09
Sound strength G (dB)						
Frequency	5a	5b	5c	5d	5e	5f
125 Hz	28	27.1	27.3	26.1	28.6	26.2
250 Hz	28.5	29.2	29.1	28	27.5	27.8
500 Hz	28.1	28.2	26.6	25.6	25.6	25
1000 Hz	25.2	24.7	23.2	22.9	23.3	23
2000 Hz	24.1	23.5	22.2	22.7	22.8	22.5
4000 Hz	24.2	23.5	21.9	22.4	22.6	22.5
Equivalent scattering absorption area A_{sc} of furniture (m^2)						
Frequency	5a	5b	5c	5d	5e	5f
125 Hz	0.0	0.219	0.276	0.857	0.702	0.926
250 Hz	0.0	0.044	0.371	1.770	0.581	2.669
500 Hz	0.0	0.200	3.209	5.238	5.041	6.636
1000 Hz	0.0	0.595	3.107	7.314	3.823	8.382
2000 Hz	0.0	0.517	1.001	5.809	1.457	6.432
4000 Hz	0.0	0.731	0.593	5.515	0.969	6.518

Table A7. Measurement results of ceiling configuration 6 (reverberant room)

Reverberation time T_{20} (s)						
Frequency	6a	6b	6c	6d	6e	6f
125 Hz	3.07	2.875	2.749	1.562	2.469	1.458
250 Hz	2.343	2.412	1.988	1.248	1.679	1.172
500 Hz	2.208	2.233	1.237	0.948	0.986	0.846
1000 Hz	1.222	1.094	0.888	0.739	0.806	0.711
2000 Hz	0.894	0.836	0.722	0.628	0.68	0.597
4000 Hz	0.689	0.664	0.608	0.519	0.59	0.518
Speech clarity C_{50} (dB)						
Frequency	6a	6b	6c	6d	6e	6f
125 Hz	-2.18	-1.4	-1.42	1.39	-1.56	1.76
250 Hz	-2.24	-1.23	-0.47	-0.2	-0.09	0.83
500 Hz	-1.55	-0.58	0.82	1.45	2.32	2.26
1000 Hz	1.14	2.13	3.15	3.58	3.77	3.7
2000 Hz	1.38	1.91	3.51	3.8	3.89	4.33
4000 Hz	3.56	3.67	4.65	5.65	4.51	5.3
Sound strength G (dB)						
Frequency	6a	6b	6c	6d	6e	6f
125 Hz	28.6	28	28.1	27.1	27.7	26.6
250 Hz	29.8	29.6	29.4	29.2	29.3	28.5
500 Hz	29	28.8	27.4	27.3	27.5	26.2
1000 Hz	27.3	27.1	25.9	25.8	25.7	25.3
2000 Hz	26.4	25.9	25.1	24.9	24.7	24.7
4000 Hz	25.6	25.2	24.3	24.2	24.2	24.1
Equivalent scattering absorption area A_{sc} of furniture (m^2)						
Frequency	6a	6b	6c	6d	6e	6f
125 Hz	0.0	0.112	0.193	1.593	0.402	1.824
250 Hz	0.0	-0.062	0.386	1.897	0.855	2.160
500 Hz	0.0	-0.026	1.801	3.049	2.843	3.693
1000 Hz	0.0	0.485	1.559	2.709	2.139	2.979
2000 Hz	0.0	0.393	1.350	2.400	1.783	2.819
4000 Hz	0.0	0.277	0.979	2.408	1.234	2.427

Table A8. Measurement results of ceiling configuration 7 (reverberant room)

Reverberation time T_{20} (s)						
Frequency	7a	7b	7c	7d	7e	7f
125 Hz	1.82	1.846	1.899	1.165	1.756	1.146
250 Hz	1.247	1.269	1.26	0.94	1.164	0.863
500 Hz	1.491	1.374	0.815	0.704	0.686	0.616
1000 Hz	1.079	0.978	0.658	0.504	0.606	0.47
2000 Hz	0.802	0.769	0.647	0.467	0.594	0.432
4000 Hz	0.639	0.599	0.599	0.432	0.562	0.412
Speech clarity C_{50} (dB)						
Frequency	7a	7b	7c	7d	7e	7f
125 Hz	-0.83	-0.99	-0.79	2.54	-0.45	2.43
250 Hz	-0.42	0.84	0.86	1.21	1.92	1.89
500 Hz	0.39	1.67	2.89	4.29	4.33	4.84
1000 Hz	3.72	3.92	5.99	5.81	5.71	6.74
2000 Hz	3.16	3.54	5.01	6.26	5.02	6.43
4000 Hz	4.33	4.55	6.37	7.24	6.12	7.29
Sound strength G (dB)						
Frequency	7a	7b	7c	7d	7e	7f
125 Hz	27.5	27.4	27.6	26.4	27.4	26.1
250 Hz	29.5	29	29.1	28.2	28.7	28
500 Hz	28.5	28.1	26.9	25.6	26.4	25.4
1000 Hz	26	25.9	25	24.2	24.4	24.1
2000 Hz	25	24.8	23.9	24	23.7	23.5
4000 Hz	24.7	24.5	23.4	23.4	23.3	23.2
Equivalent scattering absorption area A_{sc} of furniture (m^2)						
Frequency	7a	7b	7c	7d	7e	7f
125 Hz	0.0	-0.039	-0.116	1.565	0.101	1.637
250 Hz	0.0	-0.070	-0.042	1.327	0.290	1.807
500 Hz	0.0	0.289	2.818	3.798	3.987	4.826
1000 Hz	0.0	0.485	3.004	5.356	3.664	6.083
2000 Hz	0.0	0.271	1.513	4.531	2.212	5.409
4000 Hz	0.0	0.529	0.529	3.798	1.086	4.367

Table A9. Measurement results of ceiling configuration 8 (reverberant room)

Reverberation time T_{20} (s)						
Frequency	8a	8b	8c	8d	8e	8f
125 Hz	2.14	2.081	2.113	1.286	2.006	1.212
250 Hz	1.32	1.339	1.363	0.968	1.281	0.889
500 Hz	1.523	1.452	0.842	0.658	0.725	0.566
1000 Hz	1.253	1.047	0.704	0.454	0.64	0.424
2000 Hz	0.92	0.811	0.736	0.432	0.677	0.413
4000 Hz	0.812	0.742	0.767	0.433	0.75	0.426
Speech clarity C_{50} (dB)						
Frequency	8a	8b	8c	8d	8e	8f
125 Hz	-0.4	0.27	0.15	2.78	0.15	3.09
250 Hz	1.21	1.78	2.11	2.67	2.26	3.34
500 Hz	1.34	2.06	3.78	4.87	4.16	5.58
1000 Hz	4.42	5.49	6.75	8.17	5.84	8.82
2000 Hz	3.38	3.93	5.61	8.01	6.28	8.74
4000 Hz	4.68	5.31	6.35	8.69	6.4	8.26
Sound strength G (dB)						
Frequency	8a	8b	8c	8d	8e	8f
125 Hz	27	26.9	26.8	25.9	27.4	25.7
250 Hz	28.5	28.7	28.6	28.1	28.7	27.9
500 Hz	28.3	27.9	26.4	25.6	26.4	25.3
1000 Hz	25	25	23.8	23.5	23.2	22.7
2000 Hz	23.9	23.9	22.9	22.9	22.3	22.4
4000 Hz	24.1	23.7	22.7	22.6	22.3	22.2
Equivalent scattering absorption area A_{sc} of furniture (m^2)						
Frequency	8a	8b	8c	8d	8e	8f
125 Hz	0.0	0.067	0.030	1.572	0.158	1.812
250 Hz	0.0	-0.054	-0.121	1.395	0.117	1.860
500 Hz	0.0	0.163	2.690	4.372	3.661	5.623
1000 Hz	0.0	0.795	3.152	7.114	3.872	7.904
2000 Hz	0.0	0.740	1.376	6.219	1.976	6.759
4000 Hz	0.0	0.588	0.366	5.460	0.516	5.652

Table A10. Measurement results in mock-up classroom

Reverberation time T_{20} (s)					
Frequency	Empty room	Empty room + furniture	Gyptone Quattro + furniture	Gedina A + furniture	Master A + furniture
125 Hz	3.569	2.80	2.714	2.253	1.685
250 Hz	4.104	2.941	2.644	1.99	1.063
500 Hz	4.775	2.806	2.18	1.039	0.793
1000 Hz	4.444	2.49	1.738	0.807	0.833
2000 Hz	3.506	2.041	1.513	0.918	0.926
4000 Hz	2.895	1.781	1.184	1.053	1.026
Speech clarity C_{50} (dB)					
Frequency	Empty room	Empty room + furniture	Gyptone Quattro + furniture	Gedina A + furniture	Master A + furniture
125 Hz	-7.99	-5.15	-4.57	-2.97	0.31
250 Hz	-7.47	-4.65	-3.34	-0.07	4.25
500 Hz	-7.5	-4.19	-0.88	2.77	3.4
1000 Hz	-7.16	-4.81	0.08	2.54	2.59
2000 Hz	-5.89	-3.67	2.06	3.51	4.1
4000 Hz	-5.23	-2.92	3.31	3.77	4.8
Sound strength G (dB)					
Frequency	Empty room	Empty room + furniture	Gyptone Quattro + furniture	Gedina A + furniture	Master A + furniture
125 Hz	22.9	21.6	19.1	18	15.2
250 Hz	25.7	25	20.4	18.5	16.2
500 Hz	27.1	22.8	18.3	15.6	14.4
1000 Hz	26.1	21.5	17.6	13.7	12.5
2000 Hz	24.5	21.2	17.4	13.1	13.1
4000 Hz	23.5	20.3	16.4	12.3	12.4

Table A10. Measurement results in mock-up classroom (cont.)

Frequency	Equivalent absorption area A (m^2)	Equivalent scattering absorption area A_{sc} (m^2)		
	Empty room + furniture	Gyptone Quattro + furniture	Gedina A + furniture	Master A + furniture
125 Hz	2.403	1.178	0.803	-0.239
250 Hz	3.009	1.655	1.625	0.895
500 Hz	4.589	5.359	6.681	13.214
1000 Hz	5.514	7.233	12.498	12.087
2000 Hz	6.393	8.985	8.976	9.011
4000 Hz	6.746	6.572	5.706	5.550