A critical review on the use of existing formulae for the calculation of the Reverberation Time in auditoria

Lottie Braems, Hannah De Kerpel

Supervisor: Prof. dr. ir. Marcelo Blasco

Master's dissertation submitted in order to obtain the academic degree of
Master of Science in de ingenieurswetenschappen: architectuur

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Foreword

This Master's Dissertation is achieved through the cooperation between two students, Lottie Braems and Hannah De Kerpel, and a promotor Prof. dr. ir. Marcelo Blasco. After 5 years of studying and working together, the cooperation was very fluent. We could always rely on each other.

Without a number of people we might not have come to this result. First of all, we would like to thank our promotor Prof. dr. ir. Marcelo Blasco who made this Master's Dissertation possible. His guidance, help and input was a great motivation and support for the both of us. His great enthusiasm and coaching was undoubtedly an added value.

We would also like to thank our family, friends and boyfriends for the patience, the help and the support they gave us during the process of our Master's Dissertation, and more specific we would like to thank our parents to give us the opportunity to achieve our diploma.

Lottie Braems & Hannah De Kerpel

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Overview

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Keywords

Reverberation Time RT – Prediction models –Acoustic Quality – Speech Intelligibility – Absorption – Auditoria

Abstract

The objective of this study is to examine the existing prediction models for the calculation of the Reverberation Time (RT). The validation of the prediction models is obtained by a thorough analysis. A great deal is being written and said about the RT, before and today. Around 1900, Wallace Clement Sabine [1] determines the first scientific approach to understand the acoustics of performance spaces. Sabine defines the inter-relation between reverberation, volume and absorption. After his theory a lot of researchers follow and determine their own theories. It is generally agreed today that the RT is one of the most important parameters in order to evaluate the quality of a space.

In this study, ten auditoria with different dimensions and properties of the Faculty of Engineering and Architecture in Ghent University are selected carefully. After observing the dimensions and properties of each auditorium, the RT is measured according to ISO/CD 3382-2 [2]. Various prediction models are analyzed and compared with each other (based on the literature study of Neubauer and Kostek [3] [4] [5]). Seven models are selected to predict the RT: the classical models of Sabine, Eyring and Millington and Sette M&S (which assume a uniform distribution of sound absorption) and also the models of Fitzroy, Arau, Kuttruff and the Modification of Fitzroy MOF (which assume a non-uniform distribution of sound absorption). Based on the mean prediction error (the error between the measured RT and the calculated RT) it appears that generally every model overestimates the RT which is safer in comparison with an underestimation of the actual RT because in practice, it is easier to adjust a too high RT in comparison with adjusting a too low RT. A ranking is made which indicates that generally the classical model of Eyring, the Modification of Fitzroy MOF and the model of Kuttruff are the best models to predict the RT accurately in any kind of auditorium. It is not recommended to use the model of Fitzroy because it gives no reliable results in any kind of auditorium which is also pointed out by Neubauer and others. The model of Sabine, which is generally used by designers, turns out to be a mediocre model in general.

The acoustic quality of a space can be estimated in different ways. Besides the measured RT, also other objective acoustic parameters are calculated: the error between the measured RT and the required RT according to the Acoustic Standard for School Buildings NBN S 01-400-2 [6] and important quality numbers (STI, C_{50}-value, SN-ratio). Also some subjective parameters (the Speech Intelligibility SI and the Global Impression GI) are obtained based on a survey. These parameters are compared statistically with each other, which shows that good correlation can be found between the objective parameters mutually. It appears that evaluating the acoustics of a space is justified based on calculating the Speech Transmission Index STI since a high correlation with the nominal RT and with the Acoustic Standard is found. Also the objective parameters and the subjective parameters are compared with each other in order to know if the survey is qualitative enough. It should be taken in mind that the survey is only a first approach towards the right direction since it is quite limited with few questions to a limited amount of students. The Global Impression GI appears to be a better subjective parameter in comparison with the Speech Intelligibility SI as it results in a higher correlation with the objective quality numbers. It also seems that there is a very high correlation between the Global Impression GI and the

STI whereas for the Speech Intelligibility SI the highest correlation is found with the nominal RT. Not linear but polygonal regression is found which may be related to the fact that the response of the ear is not linear as well. Auditorium K and C are two outliers because in auditorium K students were too positive in their judgment while the objective evaluation of the acoustic quality resulted in bad results and in auditorium C students were too negative in their judgment while the objective evaluation of the acoustic quality resulted in very good results. This thorough investigation of the auditoria using different parameters gives the opportunity to evaluate them.

It is remarkable that only four of ten auditoria meet the normal requirement of the Acoustic Standard and only three of them meet the increased requirement of the Acoustic Standard. This is also confirmed with the quality number STI as it yields a 'fair' acoustic evaluation for many auditoria. Since this is a common topic these days, the University of Ghent should investigate this issue more thoroughly. However, the results of the survey are more positive: generally the acoustic quality of the auditoria is considered good by students. This shows that the Acoustic Standard and the quality number STI are more severe in comparison with the subjective parameters. However, when compared to other countries, the Belgian Acoustic Standard does not seem that severe. For a classroom of 200 m^3 in Belgium, the maximum RT may be as high as 1.0 s. This is also the case in the Netherlands and Italy. However other countries such as France and Portugal prescribe a lower maximum RT of 0.8 s and also in the United Kingdom and the United States of America the requirements are becoming much more severe [7].

Based on these several quality parameters the selected auditoria are dived into four categories. Within these categories it appears that there is a good agreement between the different dimensions and characteristics (global absorption coefficient, distribution of the sound absorption, diffusivity) of the corresponding auditoria. The division in categories is as follows: category 1 with an absorptive ceiling and an absorptive rear wall ($\overline{\alpha}$ = 0.20), category 2 with three adjacent absorptive walls ($\overline{\alpha}$ = 0.11), category 3 with no absorption materials ($\overline{\alpha}$ = 0.04) and category 4 with three adjacent absorptive walls and an absorptive ceiling ($\overline{\alpha}$ = 0.19). Dividing the auditoria into categories gives the advantage of a more structured insight in the validation of the prediction models. It gives the designer the opportunity to select a reliable prediction model according to a given category. In order to be able to select a reliable model to predict the RT, a maximum prediction error of 10 % is assumed according to the Acoustic Standard [6], which means that the predicted RT may deviate maximum 10 % from the measured nominal RT. However, out of the literature study it appears that a prediction error of 30 % is also still reliable. Based on the prediction error, it appears that for auditoria of category 2 and 3 (low absorptive spaces with a low diffuse character) a prediction of the RT is not reliable which is in agreement with the literature study: the lower the absorption of the auditorium and the less diffuse, the less accurate the predictions will be as the prediction models make the assumption of a diffuse field. For auditoria belonging to category 2 only the model of Kuttruff yields values with a maximum error of 30 % from the measured nominal RT. The other models are not recommended to predict the RT. For auditoria belonging to category 3 none of the models can be used. In contrary, for auditoria of category 1 and 4 (high absorptive spaces but spaces with a predominantly diffuse character) the classical models of Sabine, Eyring and M&S and the model of Arau can be used to calculate the RT. For auditoria of category 4 even the model of Fitzroy can be used. In these two categories, the models of Kuttruff and the MOF cannot be used as they underestimate the RT which is not safe whereas in auditoria of category 2 and 3 they predict the RT most accurately. This underestimation with the MOF was also pointed out by Neubauer and Kostek [3]. It is very remarkable that for this entire study only the model of Eyring for auditoria of category 1 and the models of Eyring and Arau for auditoria of category 4 meet the requirement of a maximum prediction error of 10 % of the Acoustic Standard. It appears that this is a very severe requirement. The literature study and this study confirm that the classical (and easier to calculate) models yield more reliable results in the case of a live space (low absorptive space and diffuse character). These models calculate an average absorption coefficient for the entire space as they assume a homogeneous distribution of the sound absorption. In this study, the classical models score better for auditoria of category 1 and 4, despite their non-uniform distribution of sound absorption and a high average absorption coefficient. The diffusivity of these spaces is due to other reasons such as geometry, a lowered ceiling, a tribune, furniture, scattering walls, etc. but also because of the low standard deviation between the values of the RT obtained at different locations in the space. For auditoria of category 4 it is remarkable that the model of Kuttruff is the most unreliable to predict the RT and not the models of Fitzroy and Arau which are unreliable prediction models in the other categories. In general, the MOF appears to be a good prediction model whereas for a specific category, it never predicts the RT accurately enough, it always deviates more than 30 %. Based on case studies (another auditorium and an acoustic laboratory with different properties) it appears that the ranking of the different models that is made is accurate and reliable. However, it should be taken in mind that this cannot be 100 % reliable because of the limited set of tested auditoria in this study.

Samenvatting

Het doel van deze studie is om de bestaande modellen voor het voorspellen van de nagalmtijd te onderzoeken. De validatie van de modellen wordt verkregen door een grondige analyse. Er wordt veel geschreven en gezegd over de nagalmtijd, zowel vroeger als vandaag. In 1900 beschrijft Wallace Clement Sabine [1] de eerste wetenschappelijke benadering om de akoestische eigenschappen van concerthallen, theaters, auditoria,… te begrijpen. Sabine definieert de onderlinge relatie tussen nagalm, volume en absorptie. Na zijn theorie volgen vele onderzoekers die hun eigen theorie opstellen. Het is vandaag algemeen gekend dat de nagalmtijd één van de belangrijkste parameters is om de akoestische kwaliteit van een ruimte te evalueren.

In dit onderzoek worden tien auditoria met verschillende afmetingen en eigenschappen van de Faculteit Ingenieurswetenschappen en Architectuur van de Universiteit van Gent geselecteerd. De nagalmtijd wordt gemeten volgens de norm ISO/CD 3382-2 [2] nadat de dimensies en eigenschappen van elk auditorium bestudeerd worden. Verschillende voorspellingsmodellen worden geanalyseerd en vergeleken met elkaar (gebaseerd op de literatuurstudie van Neubauer en Kostek [3] [4] [5]). Vervolgens worden zeven modellen geselecteerd om de nagalmtijd te voorspellen: de klassieke modellen van Sabine, Eyring en Millington en Sette M&S (die een uniforme verdeling van de absorptie veronderstellen) als ook de modellen van Fitzroy, Arau, Kuttruff en de aanpassing van het model van Fitzroy, de MOF (die een niet-uniforme verdeling van de absorptie veronderstellen). Aan de hand van de gemiddelde fout (tussen de gemeten en voorspelde nagalmtijd) blijkt dat in het algemeen alle modellen een overschatting maken van de nagalmtijd. Dit is veiliger dan een onderschatting van de juiste nagalmtijd omdat het in de praktijk eenvoudiger is om een te lange nagalmtijd te corrigeren in plaats van een te korte nagalmtijd. Er is een ordening gemaakt (van meest nauwkeurig tot minst nauwkeurig model) op basis van de fout tussen de gemeten en voorspelde nagalmtijd. Hieruit blijkt dat het klassieke model van Eyring, de aanpassing van de formule van Fitzroy MOF en het model van Kuttruff in het algemeen de beste modellen zijn om de nagalmtijd nauwkeurig te voorspellen. Het is niet aangeraden het model van Fitzroy te gebruiken omdat dit geen betrouwbare resultaten geeft in eender welk auditorium. Neubauer en andere onderzoekers stellen dit ook vast. Het model van Sabine dat vaak gebruikt wordt door ontwerpers blijkt in het algemeen slechts matige voorspellingen te kunnen leveren.

De akoestische kwaliteit van een ruimte kan op verschillende manieren bepaald worden. Naast de gemeten nagalmtijd worden ook een aantal andere objectieve akoestische parameters berekend zoals de fout tussen de gemeten nagalmtijd en de vereiste nagalmtijd volgens de Akoestische Norm voor Schoolgebouwen NBN S 01-400-2 [6] en een aantal belangrijke kwaliteitsnummers (de spraakverstaanbaarheidsindex STI, de C_{50}-waarde en de Signaal-Ruis verhouding SN-ratio). Daarnaast worden ook subjectieve parameters (zoals de Spraakverstaanbaarheid SI en de Globale Impressie GI) verkregen op basis van een enquête. Deze parameters worden statistisch vergeleken met elkaar, waaruit blijkt dat er een goede correlatie gevonden kan worden tussen de objectieve parameters onderling. Het blijkt dat de beoordeling van de akoestiek van een ruimte gerechtvaardigd is op basis van de berekening van de spraakverstaanbaarheidsindex STI, vermits hiervoor een hoge correlatie met de nominale nagalmtijd en met de Akoestische Norm teruggevonden is. Ook de objectieve

en subjectieve parameters worden onderling vergeleken om zo de kwaliteit van de enquête te kunnen beoordelen. Er moet wel rekening gehouden worden met het feit dat de enquête maar een beperkte steekproef is met een beperkt aantal vragen en studenten. Toch vormt het een goede basis voor een uitgebreidere enquête in de toekomst. De Globale Impressie GI blijkt een betere subjectieve parameter te zijn in vergelijking met de Spraakverstaanbaarheid SI, aangezien deze resulteert in een hogere correlatie met de objectieve kwaliteitsnummers. Verder blijkt er een zeer goede correlatie te zijn tussen de Globale Impressie GI en de Spraakverstaanbaarheidsindex STI, terwijl er voor de Spraakverstaanbaarheid SI een betere correlatie is met de nominale nagalmtijd. Er wordt altijd een hogere-graadsvergelijking gevonden in plaats van een lineair verband. Dit kan te wijten zijn aan het feit dat de respons van het oor ook niet-lineair is. Auditorium K en C wijken het meest af van de gevonden trendlijn omdat in auditorium K de studenten te positief waren in hun beoordeling terwijl de objectieve evaluatie van de akoestische kwaliteit slechte resultaten opleverde en in auditorium C waren de studenten te negatief terwijl de objectieve evaluatie van de akoestische kwaliteit zeer goede resultaten opleverde. Dit grondige onderzoek van de auditoria aan de hand van verschillende parameters geeft de mogelijkheid om ze vervolgens te evalueren.

Het is opvallend dat slechts vier van de tien auditoria voldoen aan de normale eis van de Akoestische Norm en slechts drie van de tien auditoria voldoen aan de verhoogde eis van de Akoestische Norm. Dit wordt nog eens bevestigd op basis van het kwaliteitscijfer STI aangezien de akoestische kwaliteit in de meeste auditoria ‘fair’ bevonden is. De Universiteit van Gent zou dit naderbij moeten bekijken. Toch zijn de resultaten van de enquête behoorlijk positief: in het algemeen wordt de akoestische kwaliteit van de auditoria ‘goed’ bevonden. Dit toont dat de Akoestische Norm en het kwaliteitscijfer STI een strengere parameter zijn in vergelijking met de subjectieve parameters. Echter, in vergelijking met andere landen lijkt de Belgische Akoestische Norm niet zo streng. Voor een klaslokaal met een volume van 200 m³ mag de nagalmtijd maximum oplopen tot 1,0 s in België. Hetzelfde geldt voor Nederland en Italië. Andere landen zoals Frankrijk en Portugal schrijven echter een lagere maximale waarde voor de nagalmtijd voor van 0,8 s en ook de eisen in het Verenigd Koninkrijk en de Verenigde Staten van Amerika zijn strenger aan het worden [7].

De geselecteerde auditoria kunnen op basis van de verschillende kwaliteitsparameters onderverdeeld worden in vier categorieën. Binnen deze categorieën blijkt het dat er een goede overeenkomst is tussen de dimensies en eigenschappen (de globale absorptiecoëfficiënt, de distributie van de geluidsabsorptie, de diffusiviteit) van de corresponderende auditoria. De verschillende categorieën zijn opgedeeld als volgt: categorie 1 met een absorberend plafond en een absorberende achterwand ($\overline{\alpha}$ = 0,20), categorie 2 met drie aangrenzende absorberende wanden ($\overline{\alpha}$ = 0,11), categorie 3 met geen absorberende materialen ($\overline{\alpha}$ = 0,04) en categorie 4 met drie aangrenzende absorberende wanden en een absorberend plafond ($\overline{\alpha}$ = 0,19). Het voordeel van de auditoria op te delen in categorieën is een meer gestructureerd inzicht in de validatie van de voorspellingsmodellen. Het geeft de ontwerper de mogelijkheid om een betrouwbaar model te selecteren voor een bepaalde categorie. Om een betrouwbaar model te kunnen selecteren, wordt een maximale fout van 10 % als strengste eis aangenomen (opgelegd door de Belgische Akoestische Norm [6]). Uit de literatuurstudie blijkt echter dat een maximale fout van 30 % ook nog aanvaardbaar is. Op basis van de fout tussen de gemeten en berekende nagalmtijd blijkt dat voor auditoria behorend tot categorie 2 en 3 (lage absorberende ruimtes met een laag diffuus karakter) een voorspelling van de nagalmtijd niet betrouwbaar is. Dit wordt ook afgeleid uit de literatuurstudie: hoe minder absorptie en hoe minder diffuus de ruimte, hoe minder nauwkeurig de voorspellingen zijn aangezien de modellen een diffuus veld veronderstellen. Voor auditoria van categorie 2 resulteert enkel het model van Kuttruff in waarden die maximaal 30 % afwijken van de nominale gemeten nagalmtijd. Andere modellen kunnen niet aangeraden worden om de nagalmtijd te voorspellen. Voor auditoria van categorie 3 levert geen enkel model nauwkeurige voorspellingen. Voor auditoria van categorie 1 en 4 (hoge absorberende ruimtes maar met een overwegend diffuus karakter) kunnen daarentegen de klassieke modellen en het model van Arau gebruikt worden om de nagalmtijd te voorspellen. Zelfs het model van Fitzroy kan gebruikt worden voor auditoria van categorie 4. In deze twee categorieën kunnen het model van Kuttruff en de MOF niet gebruikt worden omdat ze een gevaarlijke onderschatting maken van de nagalmtijd. Deze onderschatting van de nagalmtijd werd ook opgemerkt door Neubauer en Kostek [3]. In auditoria van categorie 2 en 3 daarentegen zijn deze modellen de beste om de nagalmtijd te voorspellen. Het is opvallend dat voor deze gehele studie enkel het model van Eyring voor auditoria van categorie 1 en de modellen van Eyring en Arau voor auditoria van categorie 2 de eis van een maximale afwijking van 10 % voor de voorspelling van de nagalmtijd van de Belgische Akoestische norm niet overschrijden. Dit is dus blijkbaar een zeer strenge eis. De literatuurstudie en deze studie bevestigen dat de klassieke (en eenvoudiger te berekenen) voorspellingsmodellen meer betrouwbare resultaten opleveren voor 'live' ruimtes (weinig absorberende ruimte en een diffuus karakter). Deze modellen berekenen een gemiddelde absorptiecoëfficiënt voor de volledige ruimte aangezien ze een homogene distributie van de geluidsabsorptie veronderstellen. In deze studie scoren de klassieke modellen beter voor auditoria van categorie 1 en 4, ondanks hun niet-uniforme distributie van de geluidsabsorptie en hoge gemiddelde absorptie coëfficiënt. De diffusiviteit van deze ruimtes ontstaat omwille van hun geometrie (verlaagd plafond, tribune, enz.), lage standaardafwijking tussen de verschillende metingen op verschillende meetpunten, meubels, verstrooiing, enz. Het is opmerkelijk dat voor categorie 4 het model van Kuttruff het meest onbetrouwbaar is om de nagalmtijd te voorspellen en niet de modellen van Fitzroy en Arau, die in de andere categorieën het meest onbetrouwbaar zijn. In het algemeen blijkt de MOF een van de beste modellen te zijn om een voorspelling te doen van de nagalmtijd terwijl het voor een specifieke categorie nooit een afwijking kan voorzien lager dan 30 %. Aan de hand van case studies (een ander auditorium en een akoestisch laboratorium met verschillende eigenschappen) blijkt dat de ordening van de voorspellingsmodellen accuraat en betrouwbaar is. Toch moet in acht genomen worden dat deze niet 100 % betrouwbaar kan zijn omwille van de beperkte reeks van geteste auditoria voor deze studie.

Introduction

During our 5-year study of Architecture in the Faculty of Engineering and Architecture in Ghent University we experienced that verbal communication is very important in auditoria. Inadequate acoustic conditions, resulting in poor verbal communication and lower Speech Intelligibility cause two main problems: reduced learning efficiency amongst students and health problems amongst lecturers (fatigue, stress, headaches, sore throats), who are forced to compensate for poor acoustic conditions by raising their voices. Therefore, the acoustic quality of auditoria is an important aspect that needs to be considered thoroughly. Architects use the reverberation time (RT) to estimate a certain quality of a space. One of the advantages of the RT for architects is its ease of calculation in comparison with calculating the absorption coefficient of materials for example, which is much more complex to calculate. Therefore, it is important to have accurate prediction models. In this study, the RT of ten auditoria is measured (actual RT) and is also calculated using prediction models (predicted RT). Comparison of the actual RT and the predicted RT gives the possibility to compare various prediction models. Since the 'classical prediction models' of Sabine and Eyring work with the assumption of a perfectly diffuse field, which does not conform with the true room absorption distribution, it is very important to also analyze other models to predict the RT even for non-uniformly distributed sound absorption in the space. Therefore, the models of Fitzroy, Arau, Kuttruff and the MOF will also be analyzed. Several other parameters can be calculated in order to assess the Speech Intelligibility. It is interesting to see which parameters are accurate to estimate the acoustic quality of an auditorium and which prediction model can be recommended in general and in a specific kind of auditorium.

In chapter 1 – '*Literature study*', a study of important literature is performed in order to fully understand previous research on the acoustic quality of spaces and in specific on the RT. Different models are observed and selected based on their suitability for this study considering auditoria. Chapter 2 – '*Theoretical study',* provides an overview of the basic acoustic principles and concepts needed for this study in order to fully understand what is going on in a space, during the measurements and the calculations. It gives a basic explanation about sound, the fields in which it can be located and its perception. Some basic acoustic variables are explained such as frequency, wave length, amplitude, sound power level, sound pressure level, etc. The concept and definition of the RT and the possibilities to evaluate the acoustic quality of a space (SI, SN-ratio, C_{50}-value, U_{50} , STI and others) are given. Chapter 3 – '*Methodology of the measurements'* lays down the basics about the measuring condition and the measurement procedure. Chapter 4 – '*Measurement results*' gives the results of the measurements in ten auditoria. These results are also represented in the graphical templates, which also show all the basic information about the auditorium, its measured and calculated RT and the acoustic quality. The graphical templates are located in a separate appendix. The quality numbers (SN-ratio, C_{50}-value and STI) and the requirements of the Acoustic Standard for School Buildings are calculated. The results of the surveys are represented as well in this chapter. These subjective and objective quality parameters are compared with each other. At last, an evaluation of each auditorium is performed. Chapter 5 – *'Calculation of the RT using different models and comparison with the measurements*' represents the results of the calculation of the RT with the different predictions models. Based on the different parameters, the auditoria are divided into categories. A thorough investigation about the validation of the prediction models is made. A case study and another selected auditorium are also taken into account to confirm the classification and the observations about the prediction models. Chapter 6 – '*Conclusions*' shows a summary of conclusions that are found in this study. In chapter 7 – '*Future work'* some suggestions for further research are discussed. This Master's Dissertation also contains a chapter 8 – '*Annex'* with additional information, calculation methods and results.

Next to this Master's Dissertation, a separate appendix is made. In this appendix the graphical templates can be found. For each auditorium, the results of the measurements, the calculations and the survey are represented. This makes it possible to have a quick overview of the different auditoria with their specific characteristics and results and can be lied down next to this Master's Dissertation while reading it.

Index

List of abbreviations

Abbreviation	Explanation
Al	Alcons
AUD	Auditorium
BGN	Background noise
C	Ceiling
CF	Ceiling and Floor
F	Floor
GI	Subjective parameter of the Global Impression
M&S	Millington and Sette
MOF	Modification of Fitzroy
mtf	Modulation Transfer Function
RT	Reverberation Time
SFJ-theory	Sabine-Franklin-Jaeger-theory
SI	Subjective parameter of the Speech Intelligibility
SL	The level of speech in dBA
SN-ratio	Signal to Noise - ratio
STI	Speech Transmission Index
T&S	Tohyama and Suzuki
TI	Transmission Index
W	Wall

List of symbols

Symbol	Unit	Physical quantity
A	[m²]	Total area of absorption $A_i = \alpha_i \cdot S_i$
AI	[-]	Articulation Index
B	[Hz]	Filter bandwidth
c	[m/s]	Speed of sound in air = 3,44 m/s
C_{50}	[dB]	Quality number to evaluate the Speech Intelligibility
d_{min}	[m]	Minimum distance required of the microphone position to any source position
E_0	[Watt]	Constant of sound energy in a space
E_{early}	[Watt]	Early energy (arriving before 50 m/s)
$E(f)_m$	[s]	Mean prediction error for n experiments (auditoria) for a frequency f
$E_i(f)$	[s]	Prediction error for experiment (auditorium) I and for frequency f
E_{late}	[Watt]	Late energy (arriving after 50 m/s)
E_m	[s]	Mean prediction error for n experiments and averaged by m frequency bands (from 500 Hz to 1,000 Hz) with m = 2
E_{nom}	[s]	Nominal prediction error for n experiments and averaged by m frequency bands (from 500 Hz to 2,000 Hz) with m = 3
E_t	[s]	Total prediction error for n experiments and averaged by my frequency bands (from 125 Hz to 4,000 Hz) with m = 7
E(t)	[Watt]	Rate of decay of sound energy in a space
f_0	[Hz]	Wave frequency
f_b	[-]	Correction factor used in calculating the sound pressure level with Barron's formula
f	[Hz]	Frequency
f_s	[Hz]	Schroeder frequency $f_s = 2000\sqrt{\frac{T}{V}}\,[\mathrm{Hz}]$
G	[dB]	Strength
G_{dir}	[dB]	Strength of the direct field
G_{diff}	[dB]	Strength of the diffuse field
h	[m]	Height
I	$\left[\frac{\mathrm{Watt}}{\mathrm{m}^2}\right]$	Sound intensity
I_0	$\left[\frac{\mathrm{Watt}}{\mathrm{m}^2}\right]$	Reference intensity $I_0 = 10^{-12}\,\frac{\mathrm{Watt}}{\mathrm{m}^2}$
l	[m]	Length
L	[m]	Total length of the two-dimensional space
L_i	[dB]	Sound intensity level

L_p	[dB]	Sound pressure level
$L_{p,brn}$	[dB]	Custom formula for the sound pressure level of Barron
$L_{p,dir}$	[dB]	Direct sound pressure level
$L_{p,diff}$	[dB]	Diffuse sound pressure level
$L_{p,early}$	[dB]	Early sound pressure level
$L_{p,late}$	[dB]	Late sound pressure level
$L_{p,noise}$	[dB]	Noise pressure level
$L_{p,total}$	[dB]	Total sound pressure level $L_{p,total} = L_{p,dir}"+" L_{p,diff}$
L_w	[dB]	Sound power level
$L_{w,noise}$	[dB]	Noise power level
$L_{w,speech}$	[dB]	The sound power level from speech (replacing L_w which is the sound power level from any source)
L_{xy}	[m]	Circumference $L_{xy} = 2(L_x + L_y)$
$\bar{l}$ = mfp	[m]	Mean free path in a diffuse field $\bar{l} = \frac{4 \cdot V}{S}$
m	[-]	Molecular absorption coefficient of air
m	[-]	Modulation transfer function mtf
n	[-]	Number of decays measured in each position
N	[-]	Number of independent measurement positions
p_0	[Pa]	Reference pressure $p_0 = 2.10^{-5}$ Pascal
P_{atm}	[Pa]	Atmosphere pressure $p_{atm} = 1013$ hPa
p(t)	[Pa]	Acoustic pressure $p(t) = P(t) - P_0$
Q	[-]	Directional coefficient of the source – 2,5 in the axes of the mouth
r	[m]	Distance from the source to the point of measurement
r	[-]	Coefficient of correlation [-1,1]
r_{rev}	[m]	Reverberation radius $r_{rev} = \sqrt{\frac{\alpha \cdot S \cdot Q}{16\,\pi\,(1-\alpha)}}$
RT_{Eyring}	[s]	Reverberation time calculated with the model of Eyring
RT_m	[s]	Mean reverberation time $RT_m = \frac{RT_{500}+RT_{1,000}}{2}$
RT_{nom}	[s]	Nominal reverberation time $RT_{nom} = \frac{RT_{500}+RT_{1,000}+R\,T_{2,000}}{3}$
RT_{60}	[s]	Definition of the Reverberation time: the time needed to decrease energy by 60 dB from its original level after instantaneous termination of the excitation signal
RT_{500}	[s]	Reverberation time at 500 Hz
$RT_{1,000}$	[s]	Reverberation time at 1,000 Hz
$RT_{2,000}$	[s]	Reverberation time at 2,000 Hz
S	[m²]	Total surface of the space $S = S_x + S_y + S_z = 2 \cdot [h \cdot (l + w) + l \cdot w]$
S_{cf}	[m²]	Area of the ceiling and the floor $S_{cf} = 2 \cdot l \cdot w$

S_i	[m²]	Area of the actual surface
S_H	[m²]	The total accessible surface of a corridor, hallway or stairwell, projected perpendicular on a horizontal plane.
S_{ww}	[m²]	Area of the walls $S_{ww} = 2 \cdot l \cdot h + 2 \cdot h \cdot w$
SN-ratio	[dB]	Signal to Noise Ratio, quality number to evaluate the Speech Intelligibility
STI	[-]	Speech Transmission Index, quality number to evaluate the Speech Intelligibility
T	[Kelvin]	Temperature
TI	[-]	Transmission Index
U_{50}	[dB]	Quality number to evaluate the Speech Intelligibility
V	[m³]	Total volume of the space
w	[m]	Width
W	[Watt]	Sound power $W = I \cdot S$
W_0	[Watt]	Reference sound power $W_0 = 10^{-12}$ Watt
W_a	[Watt]	Absorbed power
W_d	[Watt]	Transmitted power
W_i	[Watt]	Incident power
W_r	[Watt]	Reflective power
W(t)	[Watt]	Sound energy at time t
$\overline{\alpha}$	[-]	Global average absorption coefficient $\overline{\alpha} = \frac{A}{S}$
$\overline{\alpha}_{AL-xy}$	[-]	Averaged absorption coefficient in an almost 2 dimensional field $\overline{\alpha}_{AL-xy} = \overline{\alpha}_{xy}(1 - \mu) + \overline{\alpha}_z * \mu$
$\overline{\alpha}^*_{cf}$	[-]	Average effective absorption exponent of the ceiling and the floor
α_i	[-]	Absorption coefficient of the actual surface
α_m	[-]	Mean absorption coefficient
$\overline{\alpha}_{global}$	[-]	Mean global absorption coefficient of the weighted absorption coefficient of all the surfaces in a space: $\overline{\alpha} = \frac{A}{S} = \frac{\sum_i \alpha_i \cdot S_i}{S}$
$\overline{\alpha}^*_{ww}$	[-]	Average effective absorption exponent of the walls
$\overline{\alpha}_x$, $\overline{\alpha}_y$, $\overline{\alpha}_z$	[-]	Area weighted arithmetical mean of the absorption coefficient of the x, y and z walls
$\overline{\alpha}_{xy}$	[-]	Absorption coefficient in the xy-two-dimensional field
λ	[m]	Wavelength
$\overline{\rho}$	[-]	Average reflection coefficient of surface area S_n $\overline{\rho} = 1 - \overline{\alpha}_n$
ρ_n	[-]	Reflection coefficient of surface area S_n
$\frac{\sigma(RT_{30)}}{RT_{30}}$	[-]	The relative standard deviation of the measurement result RT_{30}

1. LITERATURE STUDY

1.1. Room acoustics

Room acoustics is an important field of the more general discipline of acoustics with exciting links to architecture and music. Wallace Clement Sabine [1] creates the first scientific approach to understand the acoustics of performance spaces around 1900. The fundaments for room acoustics, which are still used today, can be found in his ‘collected papers’. Sabine defines the inter-relation between reverberation, volume and absorption. Little later, in the 1930s, Norris [8] and Eyring [9] also present a theory. More and more researchers are interested in ‘the fine structure of reverberation’. Lothar Cremer [10] illustrates the sound reflections by using geometric constructions of rays and image source. This methodology is still among the standard methods in room acoustics. He explains the importance of reflections, their series of arrival, their density and their global late decay. Based on this previous research and the availability of instrumentation for impulse response measurement, the acoustic consulting is put on a scientific basis. There is deeper understanding of sound fields, but the specific subjective effects inside reflectograms are still unknown.

In the 1950s the physical aspects of room acoustics are first studied. Research on the correlation between the subjective impressions and the physical properties of room impulse responses is done. Rolf Thiele [11] (1952) is one of the first researchers who did observations concerning early reflections. He describes the fundaments of the objective descriptors of early-to-late energy integral ratio (the so-called ‘Deutlichkeit’). Today the concept of Early Decay Time is well known. Vilhelm Jordan [12] discovers the relationship between reverberation and subjective reverberance. Numerous publications are the result of the research groups lead by Erwin Meyer (Göttingen), Walter Reichardt (Dresden) and Lothar Cremer (Berlin).

In 1968, Harold Marshall [13] states that spatial impression is created by side wall reflections which are particularly strong in narrow halls. In the early 1970s, Michael Barron [14] in Southampton (1971) and P. Damaske and Y. Ando [15] in Göttingen (1972) explain the importance of lateral reflections. They point out the relevance of early lateral reflections for the spatial impression. It affects the precision of source localization and gives an impression of diffuse sound incidence. Spatial impression still is the most difficult component of multidimensional hearing in rooms.

After the 1970s, acousticians and architects can rely on quite stable and complete knowledge of general principles of the room shape and its effect on early and late reflections. After that time, details are still studied but the general insight into room acoustics is complete.

There are several ways to describe the acoustic quality of a space. The pioneering study of Beranek [16] and other researchers (such as Barron & Marshall [17], Sadowski [18], Souloudre and Bradley [19]) show the importance of some of these ways. However, there is still no consensus on a set of parameters that should be taken into account or not, because of the differences of a given space such as functionality, volume, etc. [20]. This problem can be seen in the so-called optimum RT that differs to a large extent in several sources, which is also pointed out by Straszewics in his paper [21]. It is better to govern other acoustic parameters that influence acoustic quality, rather than trying to achieve the optimum RT for a given space, especially in the case of multifunctional interiors. Niemas, Sadowski and Engel state that there are other quantities than the RT for the evaluation of the acoustic quality, in particular for sacral spaces [22]. A lot of other researchers also review the problems related to designing and estimating acoustic properties of interiors [23] [18] [24] [25]. In addition, there is still a lot of research going on about the relationship between acoustic parameters measured in a space and the acoustic quality assessed subjectively [26] [20]. However, the cognition of reverberation is one of the most relevant parameters and it is still one of the first investigations that are done to predict the acoustics of the space. This is pointed out by Vorländer [25].

The classical definition of RT (in seconds) is '*the time needed to decrease energy by 60 dB from its original level after instantaneous termination of the excitation signal, called* RT_{60}'. This is represented in figure 1.1. However the RT can also be defined as RT_{30} (energy decreased from 35 dB to 5 dB) or RT_{20} (energy decreased from 25 dB to 5 dB), for example. In this study the rate of decay of sound energy in an auditorium will be measured as RT_{30}, which is the time needed to decrease the energy by 30 dB from its original level. The definition of the RT may be fulfilled by linear extrapolation of a shorter evaluation range. The RT is originally introduced by W.G. Sabine (see Chapter 1.2.1 - '*Sabine*'). A sound source is assumed which produces a continuous sound pressure level. In general, the RT depends on the frequency, the volume of the space and the sound absorbing properties of the used materials. The lower the considered frequency, the higher the reverberation time will be, because low frequencies have more energy. For each frequency, a different RT is considered. Since the RT depends on the considered frequency, the RT can be calculated in two ways. The mean RT is the arithmetic mean of the RT in the octave bands of 500 Hz and 1,000 Hz. The nominal RT of a space is defined as the arithmetic mean of the RT in the octave band of 500 Hz, 1,000 Hz and 2,000 Hz which are important frequencies for the SI of a space.

Mean RT: $$RT_m = \frac{RT_{500}+RT_{1,000}}{2}$$

Nominal RT: $$RT_{nom} = \frac{RT_{500}+RT_{1,000}+RT_{2,000}}{3}$$

Reverberation gives an impression of being in a space and an idea of the distance from the source [17]. There are already several models developed for predicting the RT, empirically and theoretically. The paper of Neubauer and Kostek [3] offers an overview of previous research on modelling the RT. For these prediction models two assumptions are made: a homogeneous repartition of sound energy within the space and consequently a uniformly distributed sound absorption. At this point in time, the prediction of the RT for non-uniform distribution is still in research as there is no consensus yet. It is important to realize that acousticians are not satisfied with the existing models on the RT. The use of the European standard prEN 12354-6 [27] concerning this issue is therefore still questionable.

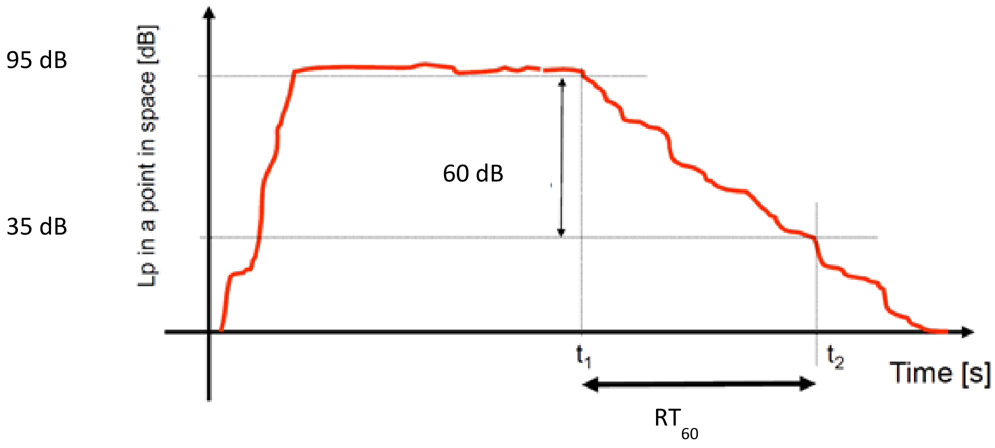


Figure 1.1: Definition of RT [28]

1.2. Modelling the RT

A lot of researchers attempt to describe the sound field in spaces with sound absorption distributed on the space surfaces. It is important to find a model to predict the RT correctly due to ongoing work within the European Standard for rectangular spaces with non-regular distribution of sound absorption as stated in prEN 12354-6 [4].

A general concept (common to all models) is used to derive the RT: it can be derived from the differential equation of the rate of decay of sound (kinetic) energy in a space. This is given as follows:

$$\frac{\Delta E}{\Delta t} \approx \frac{dE}{dt}$$

The difference between the various prediction models is the different assumptions they make for this differential equation. Solving this differential equation gives the RT.

The prediction models are 'global models' to predict the 'global' RT and acoustic quality which is valid in any point. However, this globalization is not realistic, computer simulations come closer to the reality as they calculate the acoustic quality in every point of the space.

The following gives an overview of the best known models for predicting the RT. The average of the absorption coefficient is represented in a graphical icon for each model. The different colors represent the way of averaging (all surfaces the same, walls and ceiling separately, etc.) This overview will lay down the assumptions and limitations of the prediction models in order to select the most applicable models to calculate the RT. The calculation results will be compared with each other and with measurements of the RT in chapter 5 – *'Calculation of the RT using different models and comparison with the measurements'.*

1.2.1. Sabine

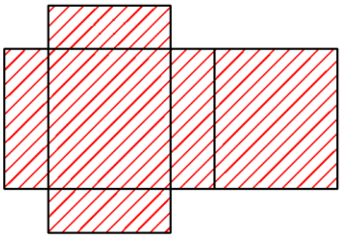


Figure 1.2: Icon of the averaging of the absorption coefficient - Sabine

Around 1900, W.C. Sabine [1] is the first to describe the reverberation characteristics of a space, based on practical results. He invented the RT and is therefore the most known researcher. His equation is based on the assumption that the sound energy is equally diffused throughout the space. That means that the space should be homogeneous and isotropic. The RT is calculated using equation (1.1):

$$RT_{60} = 0.16 \cdot \frac{V}{A} \tag{1.1}$$

where:

RT_{60} – Reverberation Time - The time needed to decrease the energy by 60 dB from its original level [s]

V – Total volume of a space [m^3]

A – Total area of absorption [m^2]

Sabine applies an empirical coefficient of 0.164, depending on propagation conditions (temperature, air pressure). That is the reason why in the literature other values like 0.16, 0.161, 0.162, 0.163 and 0.164 can be found. Using a value of 0.16 is sufficient for comparison purpose; hence this coefficient is taken into account.

An average absorptivity $\bar{\alpha}$ is defined for the entire space, which can be calculated using equation (1.2):

$$\bar{\alpha} = \frac{A}{S} \tag{1.2}$$

where:

A – Total area of absorption [m^2],

S – Total surface area of the space [m^2]

Implementing equation (1.2) in equation (1.1), equation (1.1) becomes:

$$RT_{60} = \frac{0.16 \cdot V}{S \cdot \bar{\alpha}} \tag{1.3}$$

This model depends only on the volume V, the surface of the space S and the average absorption coefficient $\bar{\alpha}$. This average absorption coefficient can be calculated with equation (1.4):

$$\bar{\alpha} = \frac{1}{S}\sum_{i} S_i \cdot \alpha_i \tag{1.4}$$

To complete Sabine's formula, the constant m of the air must also be taken into account. This ensures the attenuation of sound during its free propagation. The final formula is given by equation (1.5):

$$RT_{60} = \frac{0.16 \cdot V}{S \cdot \bar{\alpha} + 4mV} \tag{1.5}$$

where:

RT_{60} – Reverberation Time - The time needed to decrease the energy by 60 dB from its original level [s]

V – Total volume of the space [m^3]

S – Total surface area of the space [m^2]

m – Constant of the air [-]

$\bar{\alpha}$ – Average absorption coefficient [-]

Once the results of Sabine were published, a lot of researchers adopt his model to obtain equations that describe the reverberation characteristics. Among others, the best known researchers who developed theories of reverberation include: Franklin (1903) [29], Jaeger (1911) [30], Fokker (1924) [31], Buckingham (1925) [32], Schuster and Waetzmann (1929) [33]. In 1930, Eyring presented his remarkable paper [34].

1.2.2. Eyring

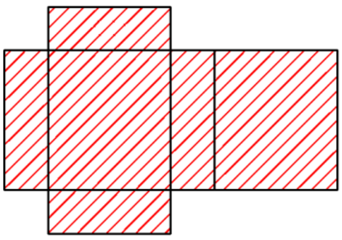


Figure 1.3: Icon of the averaging of the absorption coefficient - Eyring

The model of Eyring (1930) [34] is based on the mean free path between reflections [35] [36]. In a diffuse field the mean free path in a space can be described as follows [37] [38]:

$$\bar{l} = \frac{4 \cdot V}{S} \tag{1.6}$$

where:

$\bar{l}$ – Mean free path [m]

V – Total volume of the space [m^3]

S – Total surface area of the space [m^2]

Eyring discovers that the classical model given by Sabine is not fulfilled when there is considerable space absorption. In his paper [34] he points out that the model of Sabine is essentially a 'live' space model and that the RT is shape-dependent.

The reverberation formula of Eyring is described as follows:

$$RT_{60} = \frac{0.16 \cdot V}{-S \cdot \ln\ (1 - \bar{\alpha})} \tag{1.7}$$

where:

RT_{60} – Reverberation Time - The time needed to decrease energy by 60 dB from its original level [s]

V – Total volume of the space [m³]

S – Total surface area of the space [m²]

$\bar{\alpha}$ – Average absorption coefficient [-]

The model of Eyring is based on the assumption that sound coming from a source in a space is successively reflected by boundaries. When a wave strikes one of the boundaries, a fraction of the energy is absorbed ($\bar{\alpha}$) and a fraction is reflected ($1 - \bar{\alpha}$). The amount of reflections per second can be calculated. This is equal to the distance that sound will travel in one second divided by the average distance between reflections.

Equation (1.7) shows that Eyring makes the assumption that:

$(1 - \bar{\alpha}_{Eyring})^n$ per second is equal to the energy attenuation where:

$$\bar{\alpha}_{Eyring} = \frac{A}{S_{bound}} \tag{1.8}$$

where:

$\bar{\alpha}_{Eyring}$ - Average absorption coefficient [-]

S_{bound} – Total area of the bounding surfaces [m²]

A – Total absorption surface [m²]

1.2.3. Millington and Sette: M&S

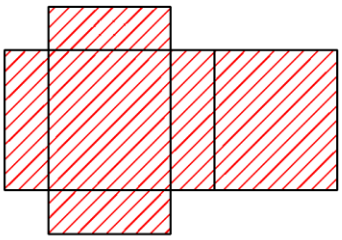


Figure 1.4: Icon of the averaging of the absorption coefficient – Millington and Sette

Shortly after Eyring, Millington and Sette (1932) [39] make the same assumptions as Eyring. The difference is the way in which the absorption coefficients of the various portions of a wall are averaged. Millington and Sette's formula is as follows:

$$RT_{60} = \frac{0.16 \cdot V}{-\sum_i S_i \cdot \ln\ (1 - \alpha_i)} \tag{1.9}$$

which reduces to the model of Sabine when all α_i <<1

where:

RT_{60} – Reverberation Time - The time needed to decrease energy by 60 dB from its original level [s]

S_i – Surface area of each surface [m²]

α_i – Absorption coefficient of each surface [-]

V – Total volume of the space [m³]

1.2.4. Fitzroy

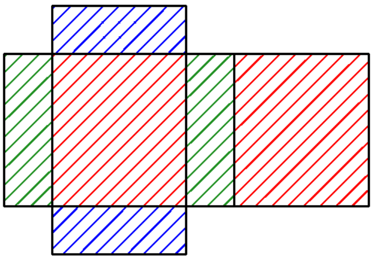


Figure 1.5: Icon of the averaging of the absorption coefficient – Fitzroy

Another 25 years later, Dariel Fitzroy (1959) [40] points out that it is possible to also take geometrical aspects of a sound field in a space into account, and not only physical considerations. This is something completely new. A sound field may tend to settle into a pattern of simultaneous oscillations along a rectangular space with three major axes (vertical, transverse and longitudinal). Choosing three axes makes that there is a relationship within the three possible basic decay rates along these axes, each being influenced by the different average absorptivity's normal to these axes. There are three sets of parallel boundaries in a rectangular space. The average absorption in each pair will control sound waves travelling between that specific pair during the sound decay period when energy oscillates simultaneously between each pair of boundaries.

The classical models assume that sound absorption is equal in all directions. The model of Fitzroy takes three-dimensional geometry in the case of rectangular spaces into account. That means that Fitzroy empirically derives an equation in which non-uniform distribution of absorption is assumed:

$$RT_{60} = 0.16 \cdot \frac{V}{S^2}\left[\frac{-S_x}{\ln(1-\bar{\alpha}_x)} + \frac{-S_y}{\ln(1-\bar{\alpha}_y)} + \frac{-S_z}{\ln(1-\bar{\alpha}_z)}\right] \quad (1.10)$$

where:

RT_{60} – Reverberation Time - The time needed to decrease energy by 60 dB from its original level [s]

$\bar{\alpha}_x, \bar{\alpha}_y, \bar{\alpha}_z$ – Average absorption coefficient of two opposite walls [-]

S_x, S_y, S_z – Total areas of two opposite parallel walls [m²]

S – Total surface area of the space [m²]

V – Total volume of the space [m³]

However, the empirical solution for RT prediction in non-uniform rooms of Fitzroy goes almost unrecognized and is rather negatively perceived. In the last 30 years, Schroeder (1965) [41], Kosten (1965) [42], Cremer and Muller (1978) [43], Kuttruff (1975) [44], Nilsson (1992) [45], Tohyama et al. (1995) [46] added some new issues to his theory.

1.2.5. Tohyama and Suzuki: T&S

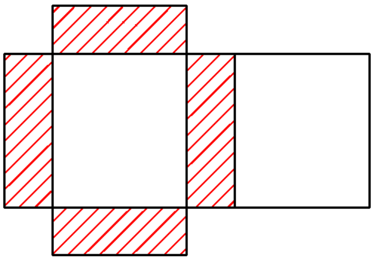


Figure 1.6: Icon of the averaging of the absorption coefficient – Tohyama and Suzuki

In their paper [46], Tohyama and Suzuki T&S present the 'almost-two-dimensional' diffuse field theory in 1995. The physical space inside boundaries is three-dimensional but in some cases the two-dimensional field is better suited to estimate the reverberation. The formula for the RT in a two-dimensional diffuse field determined by 'the later part of the energy decay', and assuming that sound velocity equals 340m/s, becomes:

$$RT_{60} = \frac{0.128 \cdot S}{-L \cdot \ln(1 - \bar{\alpha}_{xy})} \quad (1.11)$$

where:

RT_{60} – Reverberation Time - The time needed to decrease energy by 60 dB from its original level [s]

S – Total surface area of the space [m²]

L – Total length of the two-dimensional space [m]

$\bar{\alpha}_{xy}$ – Absorption coefficient in the xy-two-dimensional field [-]

In the case of a two-dimensional field, reflections at the z-walls are neglected. However, for small-sized spaces characterized by an almost two-dimensional diffuse field, z-walls reflections are taken into account. This field is assumed to be composed of tangential, oblique and 'almost-tangential' waves. By replacing $\bar{\alpha}_{xy}$ with the averaged absorption coefficient $\bar{\alpha}_{AL-xy}$ characterizing the almost two-dimensional diffuse field, equation (1.11) becomes:

$$RT_{AL-xy} = \frac{0.128 \cdot S_{xy}}{-L_{xy} \cdot \ln(1 - \bar{\alpha}_{AL-xy})} \quad (1.12)$$

where:

RT_{AL-xy} – Reverberation Time in an almost xy-two-dimensional field [s]

$\bar{\alpha}_{AL-xy} = \bar{\alpha}_{xy}(1-\mu) + \bar{\alpha}_z * \mu$ – Averaged absorption coefficient in almost xy-two-dimensional field [-]

$\bar{\alpha}_z$ – Averaged absorption of the z wall [-]

$\bar{\alpha}_{xy}$ – Averaged absorption in the xy-two-dimensional field [-]

$L_{xy} = 2(L_x + L_y)$ – Circumference [m]

$$\mu = \frac{m \cdot c}{L^2{}_z \cdot 4 \cdot f_0} \tag{1.13}$$

$$m = \frac{\pi \cdot S_{xy}}{L_{xy}} \tag{1.14}$$

where:

m – Mean free path [m]

L_z – Length of the z-surface [m]

c – Speed of sound in air [m/s]

f_0– Constant wave frequency [Hz]

S_{xy} – Surface area of the space in the xy-two-dimensional field [m²]

1.2.6. Arau

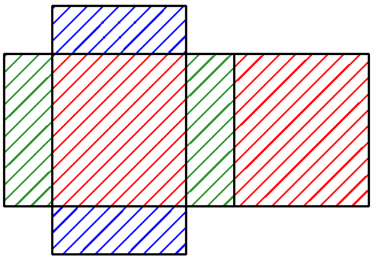


Figure 1.7: Icon of the averaging of the absorption coefficient – Arau

In 1988, Arau introduces a model for calculating the RT for the case of non-uniform distribution of sound absorption in his paper [47]. He makes the assumption that the reverberation decay is a hyperbolic process, consisting of three contributions: the initial decay, the first and second linear portion of the decay, and the third linear portion. The model of Arau considers the RT of a space to be equal to the area-weighted geometrical mean of the reverberation periods in each of the rectangular directions. The absorption coefficients used in his model are the average absorptivities of each pair of opposite walls.

$$RT_{60} = \left[\frac{0.16V}{-S \cdot \ln(1-\bar{\alpha}_x) + 4mV}\right]^{\frac{S_x}{S}} \cdot \left[\frac{0.16V}{-S \cdot \ln\left(1-\bar{\alpha}_y\right) + 4mV}\right]^{\frac{S_y}{S}} \cdot \left[\frac{0.16V}{-S \cdot \ln(1-\bar{\alpha}_z) + 4mV}\right]^{\frac{S_z}{S}} \tag{1.15}$$

where:

RT_{60} – Reverberation Time - The time needed to decrease energy by 60 dB from its original level [s]

$\overline{\alpha_x}$ – Area-weighted arithmetical mean of the energetic absorption coefficients of the floor S_{x1} and ceiling S_{x2} surfaces [-]

$S_x = S_{x1} + S_{x2}$ – Surface area of the floor and ceiling [m²]

$\overline{\alpha_x}$ and $\overline{\alpha_z}$ – Area-weighted arithmetical mean of energetic absorption coefficients of the side-walls and front- and end-walls, respectively [-]

$S = S_x + S_y + S_z$ – Total surface area of the space surfaces [m²]

m – Molecular absorption coefficient of air [-]

V – Total volume of the space [m³]

1.2.7. Nilsson

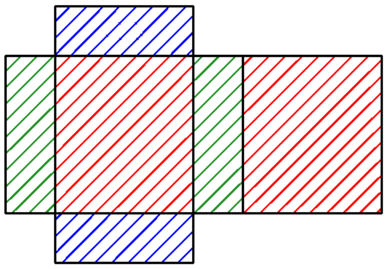


Figure 1.8: Icon of the averaging of the absorption coefficient – Nilsson

Classical RT models rarely solve the problem in the case of an essentially rectangular space with non-uniform distribution of absorption, or when a space consists of irregular shapes or is filled in, to a large extent, with e.g. equipment, decorative elements, etc. The Nilsson model (1992) [45] provides a model to calculate the RT in these cases. This may improve predictions of the RT for the non–uniform distribution of absorption. Nilsson proposes to divide the sound field into the most characteristic part, i.e. tangential to the considered surface, and remaining parts of space surfaces. The different effect of absorbing materials for these different sound fields and the effect of diffusing elements of mixing the sound fields is taken into account by considering the balance of power between the sound fields. A practical approach based on that model but making use of absorption data measured according to standard methods, is presented in the European Standard prEN 12354-6 [27].

1.2.8. Kuttruff

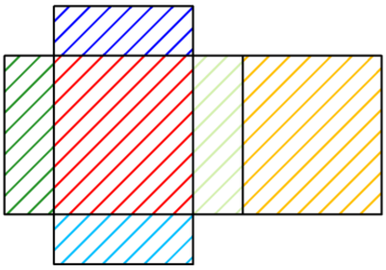


Figure 1.9: Icon of the averaging of the absorption coefficient – Kuttruff

Kuttruff (1975) [44] considers the case of the partially diffuse field within the space and introduces the concept of the reflection coefficient $\rho = 1 - \alpha$. He assumes that the absorption coefficient α and hence the reflection coefficient ρ are independent of the angles and introduces Lambert's law of diffuse reflection. By focusing on the overall RT and neglecting details of the decay process and additionally under the assumption of an exponential law for the time dependence of the irradiation strength over the whole surface of reflecting walls, he defines an absorption exponent α*. This assumption of an exponential law is reasonable since, at least in rectangular spaces, the decay process of the sound energy will decrease exponentially.

Kuttruff introduces a correction to the model of Eyring. He shows that the absorption coefficient α* would assume it is Eyring's value if the irradiation strength was constant [44]:

$$\alpha_{Eyring} = -\ln \bar{\rho} = -\ln(1 - \bar{\alpha}) \tag{1.16}$$

This is true if ρ and hence α have the same value everywhere. In general, the effective absorption exponent will be smaller or bigger than *(-ln* $\bar{\rho}$*)*, depending on the space shape and the distribution of the wall absorption. The absorption coefficient α* is calculated using equation (1.17):

$$\alpha^* = \ln\left(\frac{1}{\bar{\rho}}\right) + \ln\left(1 + \frac{\sum_n \rho_n(\rho_n - \bar{\rho})S_n^2}{(\bar{\rho}S)^2 - \sum \rho_n^2 S_n^2}\right) \tag{1.17}$$

where:

$\bar{\rho} = 1 - \bar{\alpha}_n$ – Average reflection coefficient of surface area S_n [-]

S – Total surface area of the space [m²]

$\bar{\alpha}_n$ – Average absorption coefficient of surface area S_n [-]

In most cases the second term in equation (1.17) in the denominator is much smaller than the first and can be neglected. Expanding the second logarithm into a power series and neglecting all terms higher than first order gives:

$$\alpha^* = \alpha_{Eyring} + \frac{\sum_n \rho_n(\rho_n - \bar{\rho})\, S_n^2}{(\bar{\rho}\, S)^2} \tag{1.18}$$

Inserting Kuttruff's correction (equation (1.18)) into the model of Eyring (equation (1.7)) and completing this formula by taking the attenuation constant *m* of air into account, leads to equation (1.19):

$$RT_{60} = \frac{0.16 \cdot V}{S \cdot [-\ln(1-\alpha^{*})] + \Delta + 4mV} \tag{1.19}$$

where:

RT_{60} – Reverberation Time - The time needed to decrease energy by 60 dB from its original level [s]

V - Total volume of the space [m³]

m – Constant of air [-]

S – Total surface area of the space [m²]

α* - Correction of Kuttruff to the average absorption coefficient, equation (1.18) [-]

Δ - See equation (1.20) [-]

$$\Delta = \frac{\sum_i \rho_i(\rho_i - \bar{\rho})S_i^2}{(\bar{\rho}S)^2 - \sum_i \rho_i^2 \cdot S_i^2} \tag{1.20}$$

The correction that Kuttruff introduces to the model of Eyring could easily be applied where *n-1* surfaces have nearly the same reflection coefficient and one surface, the *n*th surface, is characterized by a different absorption coefficient. This gives good conformity with computer simulated results. In the case of a space with asymmetric absorption, Eyring's modified model is considerably incorrect.

1.2.9. Modification of Fitzroy's equation: MOF

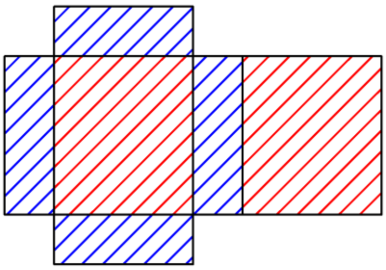


Figure 1.10: Icon of the averaging of the absorption coefficient – Modification of Fitzroy MOF

In order to approximate the calculated RT values closer to the measured ones, Neubauer suggests a modification of Fitzroy's model (equation (1.10)) [5]. This model is based on the Eyring correction derived by Kuttruff (equation (1.18)) [44] (see chapter 1.2.8 – '*Kuttruff*'). Since Kuttruff introduces a correction to Eyring's model, and since Fitzroy's equation [40] is based on Eyring's concept, it seems possible to introduce a similar correction to Fitzroy's equation, which results in the Fitzroy-Kuttruff equation. In cases where the main absorbing surface is the floor and the ceiling, this can be done to achieve more accurate approximation of the reverberation. This modification gives a Fitzroy's modified equation which considers also non-uniform distribution of sound absorption in rectangular spaces. The modification of Fitzroy's equation MOF is also called the New Formula in literature studies.

The RT according to the MOF is useful in cases where the sound absorption on opposite sides is substantially higher than on the remaining space surfaces. For practical use one may modify Fitzroy's equation by splitting Kuttruff's correction into two parts, namely the part of the ceiling-floor $\bar{\alpha}_{cf}^{*}$ and the part of the remaining walls $\bar{\alpha}_{ww}^{*}$.

Fitzroy uses examples in his paper conform to the three-term formula. When compared to calculated RT results, this method shows no advantages to the more simple equation of Sabine or Eyring. In particular, there are higher values for the results of simulations for a space different from those given as examples in Fitzroy's papers than these based on models of Sabine or Eyring. When either the ceiling and/or the floor are/is highly absorptive, it results in the almost two-dimensional field. When the absorbing capacity of the ceiling and floor exceeds that of the remaining walls, Fitzroy's equation may be rewritten using an appropriate modification.

By dividing the space surfaces into the floor and ceiling areas and the remaining wall areas, one obtains the following expressions:

S_{cf} – Surface area of the ceiling and the floor [m²]:

$$S_{cf} = 2 \cdot l \cdot w \tag{1.21a}$$

S_{ww} – Surface area of the walls [m²]:

$$S_{ww} = 2 \cdot l \cdot h + 2 \cdot h \cdot w \tag{1.21b}$$

S_{total} – Total surface area of the space [m²]:

$$S_{total} = 2 \cdot [h \cdot (l + w) + l \cdot w] \tag{1.21c}$$

where:

h, l, w – Space dimensions (height, length, width) [m]

Introducing equation (1.21a) to (1.21c) allows rewriting Fitzroy's equation and using Kuttruff's correction from equation (1.20) to form a New Formula (the MOF):

$$RT_{60} = \left(\frac{0.32 \cdot V}{S^2}\right) \cdot \left(\frac{h(l + w)}{\bar{\alpha}_{ww}^{*}} + \frac{l \cdot w}{\bar{\alpha}_{cf}^{*}}\right) \tag{1.22}$$

where:

RT_{60} – Reverberation Time - The time needed to decrease energy by 60 dB from its original level [s]

V – Total volume of the space [m³]

S – Total surface area of the space [m²]

h, l, w – Space dimensions (height, length, width) [m]

$\bar{\alpha}_{ww}^{*}$ - Average effective absorption exponent of the walls [-]:

$$\bar{\alpha}_{ww}^{*} = \ln\left(\frac{1}{\bar{\rho}}\right) + \left[\frac{\rho_{w1}(\rho_{w1} - \bar{\rho}_{ww})S_{w1}^{2} + \rho_{w2}(\rho_{w2} - \bar{\rho}_{ww})S_{w2}^{2} + \rho_{w3}(\rho_{w3} - \bar{\rho}_{ww})S_{w3}^{2} + \cdots}{[\bar{\rho}_{ww}(S_{w1} + S_{w2} + S_{w3} + S_{w4})]^{2}}\right] \tag{1.23a}$$

$\bar{\alpha}_{cf}^{*}$ - Average effective absorption exponent of the ceiling and the floor [-]:

$$\bar{\alpha}_{cf}^{*} = \ln\left(\frac{1}{\bar{\rho}}\right) + \left[\frac{\rho_{c} \cdot (\rho_{c} - \bar{\rho}_{cf}) \cdot S_{c}^{2} + \rho_{f} \cdot (\rho_{f} - \bar{\rho}_{cf}) \cdot_{f}^{2}}{[\bar{\rho}_{cf} \cdot (S_{f} + S_{c})]^{2}}\right] \tag{1.23b}$$

where:

$\bar{\alpha}$ – Arithmetic mean of the surface averaged absorption coefficient

$\bar{\rho} = 1 - \bar{\alpha}_{n}$ – Average reflection coefficient

Empirical investigation shows that the Fitzroy equation can also be modified differently if the space is a cube and the average geometrical mean absorption coefficient is $\bar{\alpha}_{geo} \geq 0{,}2$ or if a flat (i.e. l/h > 3 ∧ w/h < 3) or long space (i.e. l/h > 3 ∧ w/h < 3 ∧ l/w > 6) is investigated.

The modified Fitzroy equation in case of a cube space (i.e. l = w = h) and $\bar{\alpha}_{geo} \geq 0{,}2$ is:

$$RT_{60} = \left[\frac{0{,}126 \cdot S_{x}}{-L_{x}\ln(1 - \alpha_{x})} + \frac{0{,}126 \cdot S_{y}}{-L_{y}\ln(1 - \alpha_{y})} + \frac{0{,}126 \cdot S_{z}}{-L_{z}\ln(1 - \alpha_{z})}\right]^{1/3} \tag{1.24}$$

The modified Fitzroy equation in case of a flat and a long space is:

$$RT_{60} = \left[\frac{0{,}126 \cdot S_{x}}{-L_{x}\ln(1 - \alpha_{x})} + \frac{0{,}126 \cdot S_{y}}{-L_{y}\ln(1 - \alpha_{y})} + \frac{0{,}126 \cdot S_{z}}{-L_{z}\ln(1 - \alpha_{z})}\right]^{1/2} \tag{1.25}$$

where:

$$\bar{\alpha}_{x} = \frac{S_{x1}\alpha_{x1} + S_{x2}\alpha_{x2}}{S_{x1} + S_{x2}} \tag{1.26}$$

$$L_{x} = 4(w + h) \tag{1.27}$$

$$S_{x} = 2wh \tag{1.28}$$

The same applies for the y and z index.

1.3. Overview of the characteristics of the models

In this chapter an overview of the characteristics of the different prediction models is provided. The overview is based on the kind of sound field, the assumptions and the limitations of the model, the used absorption coefficient, some specifications, the shape of the room and the distribution of absorption material.

SABINE	
Field	*- Diffuse*
Assumption/based on	*- The sound energy is equally diffused throughout the room which means that the room should be homogeneous and isotropic*
Limitation	*- Model is not fulfilled when there is considerable space absorption* *- Model is not fulfilled in the case of non-uniform distribution of sound absorption* *- It is a live-room model*
Absorption coefficient	*- $\bar{\alpha}$ is a general coefficient for the entire space*
Specifications	*- Takes also the constant m of the air into account* *- The RT is shape-dependent*
Shape of room	*- Regular spaces*
Distribution of absorption material	*- 3D*
EYRING	
Field	*- Diffuse*
Assumption/based on	*- The mean free path between reflections* *- Sound coming from a source in a room is successively reflected by boundaries*
Limitation	*- Model is not fulfilled in the case of non-uniform distribution of sound absorption*
Absorption coefficient	*- $\bar{\alpha}$ is a general coefficient for the entire space*
Shape of room	*- Regular spaces*
Distribution of absorption material	*- 3D*
MILLINGTON AND SETTE	
Field	*- Diffuse*
Assumption/based on	*- Based on Eyring* *- The difference is in the way in which absorption coefficients of the various portions of a wall are averaged*
Limitation	*- Reduces to Sabine's model with $\alpha_i = \alpha_{Eyring}$ (in the limit of all α_i <<1)* *- Model is not fulfilled in the case non-uniform distribution of sound absorption*
Absorption coefficient	*- $\bar{\alpha}$ is a general absorption coefficient for the entire space*
Shape of room	*- Regular spaces*
Distribution of absorption material	*- 3D*

FITZROY	
Field	*- Diffuse*
Assumption/based on	*- Non-uniform distribution of absorption* *- Three axes*
Absorption coefficient	- $\bar{\alpha}_x$ - $\bar{\alpha}_y$ - $\bar{\alpha}_z$: average absorptivity's of each pair of opposite walls
Specifications	*- Takes also (three-dimensional) geometrical aspects of a sound field in a space into account and not only physical considerations*
Shape of room	*- Rectangular spaces*
Distribution of absorption material	*- 3D*
TOHYAMA AND SUZUKI	
Field	*- Almost two-dimensional diffuse field, composed of tangential, oblique and 'almost-tangential' waves*
Assumption/based on	*- The physical space inside boundaries is three-dimensional but in some cases the two-dimensional field is better suited to estimate the RT*
Limitation	*- z-wall reflections are neglected for big spaces*
Absorption coefficient	*-* $\bar{\alpha}_{xy}$ *of a two-dimensional field;* $\bar{\alpha}_{AL-xy}$ *of an almost two-dimensional field*
Specifications	*- Non-uniform distribution of absorption*
Shape of room	*- Regular spaces*
Distribution of absorption material	*- 2D*
ARAU	
Field	*-Diffuse*
Assumption/based on	*- Non-uniform distribution of absorption*
Limitation	*- Not for irregular shapes*
Absorption coefficient	*-* $\bar{\alpha}_x$ *-* $\bar{\alpha}_y$ *-* $\bar{\alpha}_z$*: average absorptivity's of each pair of opposite walls*
Specifications	*- The reverberation decay is a hyperbolic process* *- The RT of a space is equal to the area-weighted geometrical mean of the reverberation periods in each of the rectangular directions*
Shape of room	*- Rectangular spaces*
Distribution of absorption material	*- 3D*
NILSSON	
Field	*- Non-diffuse sound field*
Assumption/based on	*- Rectangular spaces with non-uniform distribution of absorption, spaces consisting of irregular shapes, spaces filled with a lot of equipment, decorative elements, etc.*
Limitation	*- Complex – uses the European Standard prEN 12354-6*
Absorption coefficient	*-* $\bar{\alpha}_x$ *-* $\bar{\alpha}_y$ *-* $\bar{\alpha}_z$*-* $\bar{\alpha}_d$*: average absorptivity's of each pair of opposite walls and the diffuse field*

Specifications	*- By dividing the sound field into the most characteristic part, i.e. tangential to the considered surface, and remaining parts of space surfaces, the different effect of absorbing materials can be taken into account*
Shape of room	*- Regular and irregular spaces*
Distribution of absorption material	*- 3D*
KUTTRUFF	
Field	*- Partially diffuse field*
Assumption/based on	*- Correction to Eyring if (n-1) surfaces have approximately the same reflection coefficient (non-uniform distribution of sound absorption)* *- Absorption coefficient α and hence ρ are independent of the angles* *- Lambert's exponential law of diffuse reflection*
Limitation	*- For rectangular spaces because only in this case the decay process of the sound energy will decrease exponentially* *- In the case of a room with asymmetric absorption, the model is considerably incorrect*
Absorption coefficient	*- Reflection coefficient $\rho_i = 1 - \alpha_i$*
Specifications	*- Takes also m of air into account*
Shape of room	*- Rectangular spaces*
Distribution of absorption material	*- 3D*
MOF	
Field	*- Diffuse*
Assumption/based on	*- Modification of Fitzroy's model* *- Based on the Eyring correction derived by Kuttruff* *- Considers also non-uniform distribution of sound absorption in rectangular rooms*
Limitation	*- In the case of a room with asymmetric absorption, the model is considerably incorrect*
Absorption coefficient	*- α 3 directions*
Specifications	*- Useful in cases where the sound absorption on opposite sides is substantially higher than on the remaining room surfaces* *- The advantage of using the MOF is especially important in cases of irregularly distributed absorption*
Shape of room	*- Irregular spaces*
Distribution of absorption material	*- 3D*

Table 1.1: Summary of the different models

With this information a table can be made up which gives a summary of the prediction models, according to the observations of Neubauer and Kostek. Except for the model of Nillsson, none of the models can predict the RT for the case of a non-diffuse space. The only solution is with Ray-tracing programs which is very difficult and takes a lot of time.

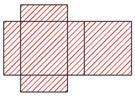
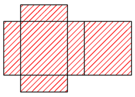
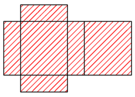
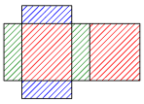
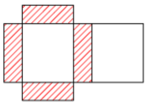
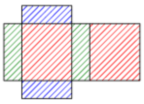
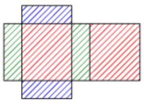
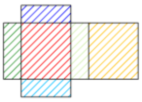
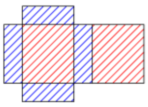
Model	α [-]	Distribution of absorption material			Field			Shape of room	
		Icon of the averaging of α	Uniform	Non-uniform	Diffuse	Non-diffuse	Partially diffuse	Regular	Irregular
Sabine	$\overline{\alpha}$		X		X			X	
Eyring	$\overline{\alpha}$		X		X			X	
M&S	$\overline{\alpha}$		X		X			X	
Fitzroy	$\overline{\alpha}_x$ - $\overline{\alpha}_y$ - $\overline{\alpha}_z$			X	X			X	
T&S	$\overline{\alpha}_{xy}$ - $\overline{\alpha}_{AL-xy}$			X	X			X	
Arau	$\overline{\alpha}_x$ - $\overline{\alpha}_y$ - $\overline{\alpha}_z$			X	X			X	
Nilsson	$\overline{\alpha}_x$ - $\overline{\alpha}_y$ - $\overline{\alpha}_z$			X		X			X
Kuttruff	$\rho = 1 - \alpha$			X			X	X	
MOF	$\overline{\alpha}^*_{ww}$ - $\overline{\alpha}^*_{cf}$			X	X				X

Table 1.2: Summary of the different prediction models for RT

1.4. Mutual comparison of various prediction models

In their paper, Neubauer and Kostek [3] compare calculated results using different models. The simulations presented in the next chapters are performed for the case of a rectangular space of dimension l, w, h (consecutively: length, width and height). The rectangular shape of the space is chosen because of its systematically treatable dimensions. However, Neubauer and Kostek state that there is no need to reduce the findings to rectangular rooms only, as long as no elliptical or circular rooms are being considered. The European Standard prEN 12354-6 [27] makes no distinction between rectangular and irregular shaped spaces. The investigated space volumes are from 50 m³ to 8,000 m³, which are arbitrarily chosen. However, it should be taken into account that for very large rooms, especially if the ceiling is low, the prediction of the RT is no longer justified. Since the 'classical models' of Sabine and Eyring make the assumption of a perfectly diffuse field which does not conform with the true room absorption distribution in reality, it is very important to develop a proper prediction model to calculate the RT even for non-uniformly distributed sound absorption in the room. The conclusions of Neubauer and Kostek will be evaluated (confirmed or rejected) with the conclusions of this study in chapter 5 – *'Calculation of the RT using different models and comparison with the measurements'*.

1.4.1. <u>*Low absorption on all surfaces*</u>

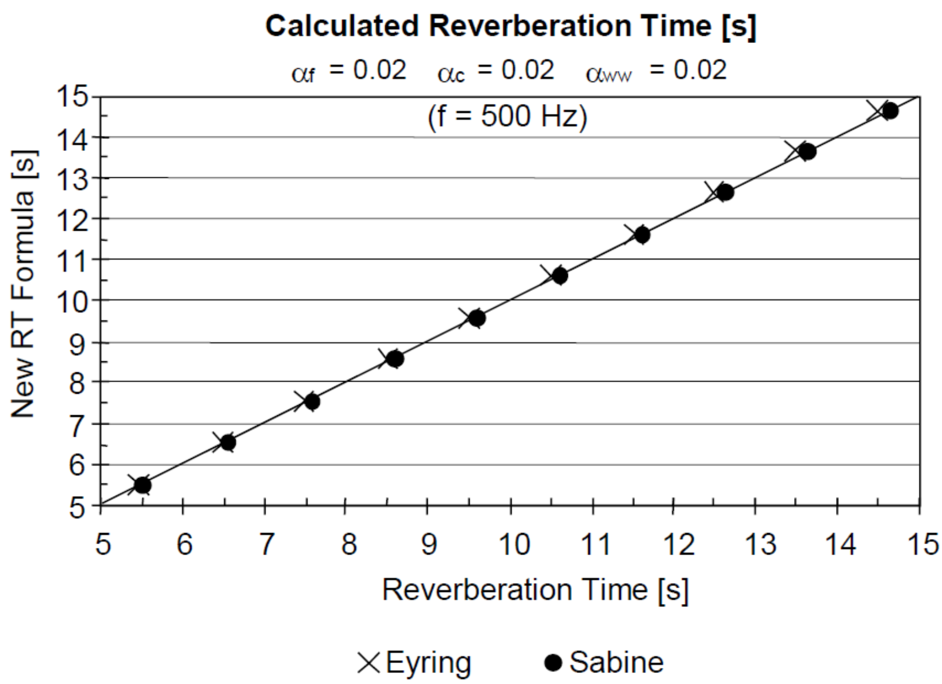


Figure 1.11: Calculated RT for low absorption [3]

Figure 1.11 represents the situation where all surfaces have low absorption (absorption coefficient of 0.02 for the walls, ceiling and floor).

where:

α_f – Absorption coefficient of the floor [-]

α_c – Absorption coefficient of the ceiling [-]

α_{ww} – Average absorption coefficient of the four walls [-]

The y-axis contains the RT calculated with the MOF. The MOF is represented by a full line in the graph. The x-axis represents the RT calculated with the model of Eyring (cross) and with the model of Sabine (dot). Good conformity can be noted between the models of Sabine, Eyring and the MOF for the case where all surfaces have low absorption (absorption coefficient of 0.02 for all surfaces). However, the model of Eyring reveals about 1 % smaller values for the calculated RT compared with the MOF.

1.4.2. *High absorption on the floor and low absorption of remaining surfaces*

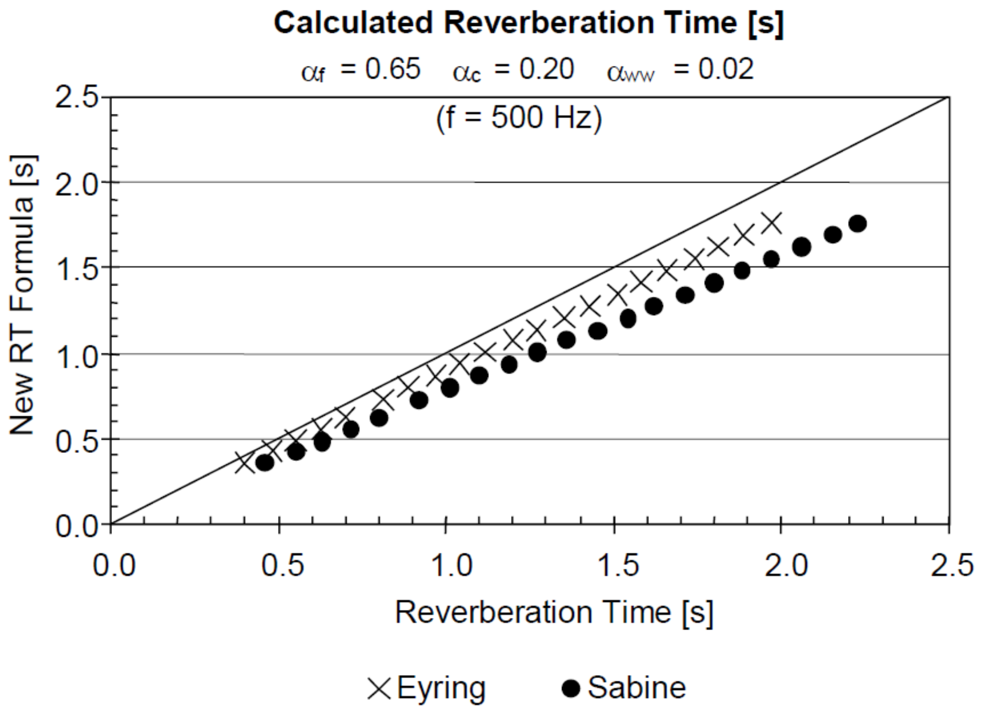


Figure 1.12: Calculated RT for high absorption on the floor and low absorption on the remaining surfaces [3]

Figure 1.12 represents the calculation of the RT where the floor is characterized by high absorption (absorption coefficient of 0.65) and the remaining surfaces have low absorption (absorption coefficient of 0.2 for the ceiling and absorption coefficient of 0.02 for the other surfaces). There is an uneven distribution of the sound absorption in the room. This is the reason why both the models of Sabine and Eyring give 25 % to 35 % higher values for the calculated RT in comparison with the MOF. The differences are not negligible but very logic: Sabine and Eyring make the assumption of a perfectly diffuse field and the sound absorption should be regularly distributed throughout the room. This graph shows the advantage of using the MOF when there is a non-uniform distribution of the sound absorption.

1.4.3. Uniform distribution of sound absorption

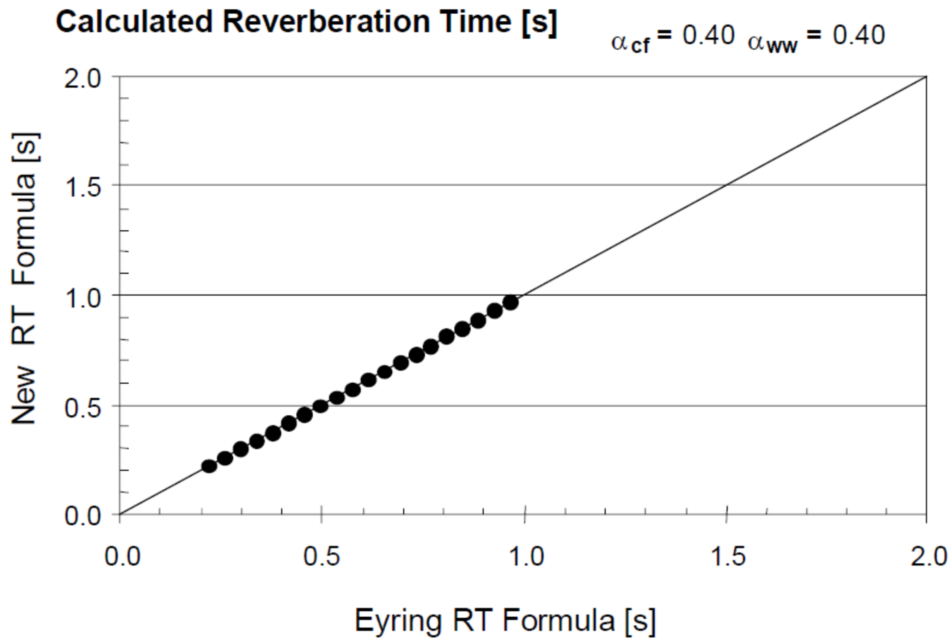


Figure 1.13: Calculated RT for regularly distributed sound absorption [3]

Figure 1.13 represents the case of high (absorption coefficient of 0.40 for the walls, ceiling and floor), but evenly distributed absorption. The results are nearly the same using both Eyring's model (dots) and the MOF (full line). However, the results of the model of Eyring still reveal a deviation of about 0.16 % smaller values. This shows that the MOF is better applicable than the model of Eyring both in the case of uniform and non-uniform distribution of sound absorption.

The graphs in the following chapters give the effect of computing the RT using various prediction models.

1.4.4. Live-room condition

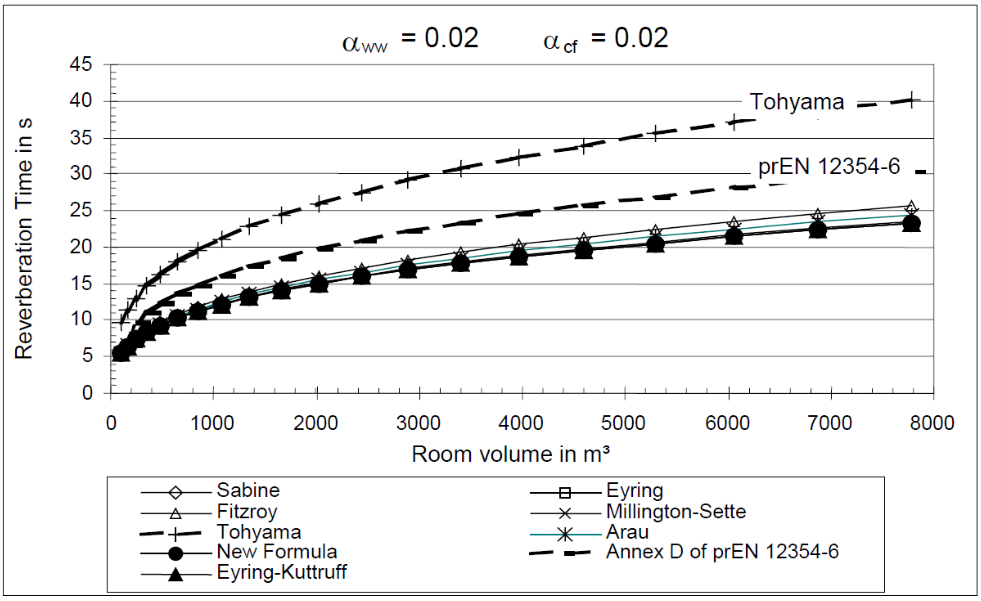


Figure 1.14: Calculated RT for low absorption of all room surfaces [3]

Figure 1.14 represents the predicted RT-values for a live room calculated with different prediction models. A live room is a room with little absorption and diffuse conditions. All room surfaces have an absorption coefficient of 0.02. This room condition gives a good diffusion of the room. Only the models of Tohyama and Nilsson give meaningful differences for the calculated RT values compared with the other models. It seems that the room volume (x-axis) has no influence on the validation of the models to predict the RT.

1.4.5. Dead-room condition

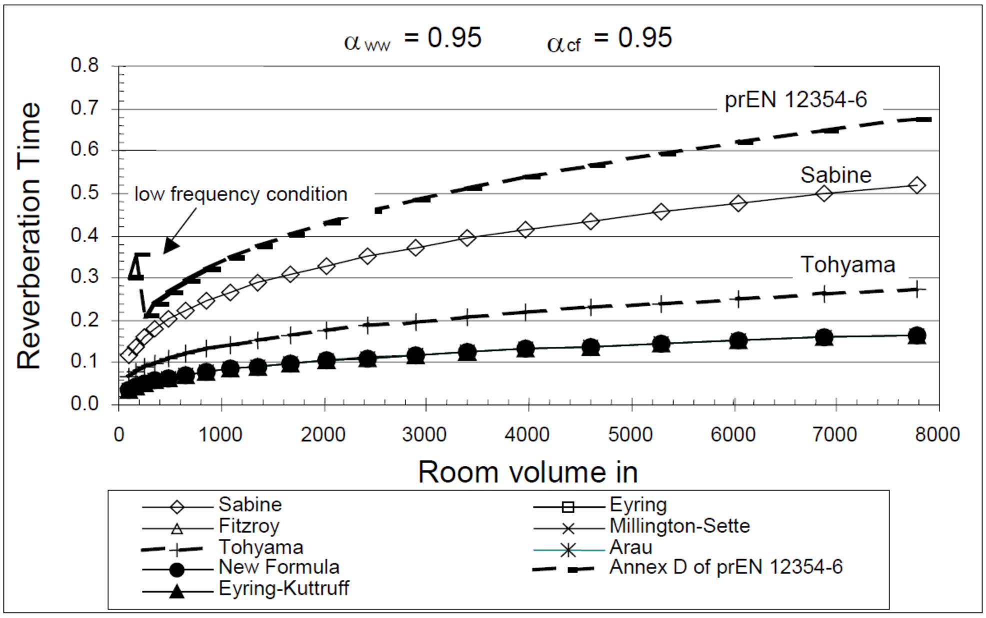


Figure 1.15: Calculated RT for high absorption of all room surfaces [3]

Figure 1.15 represents the predicted RT-values for a dead room calculated with different prediction models. A dead room is a room where all surfaces have a high absorption. All room surfaces have an absorption coefficient of 0.95. Only the RT calculated with the models of Nilsson, Sabine and Tohyama are discrepant compared with the other models which yield more or less the same calculated RT. Again the room volume (x-axis) has no influence on the validation of the different models.

1.4.6. One surface highly absorptive and all others low absorptive

It is interesting to compare results when only one surface is highly absorptive and all others are characterized by low absorption, for example when the floor is covered with seats but the walls are bare, which is often the case in auditoria. Figure 1.16 gives results in the case of an average absorption coefficient of 0.43 for the ceiling and the floor and 0.02 for the walls. The model of Fitzroy results in the highest values of the RT, followed by the model of Arau. The models of Tohyama and Sabine give close results followed by the model of Eyring. The model of Millington & Sette gives the lowest values.

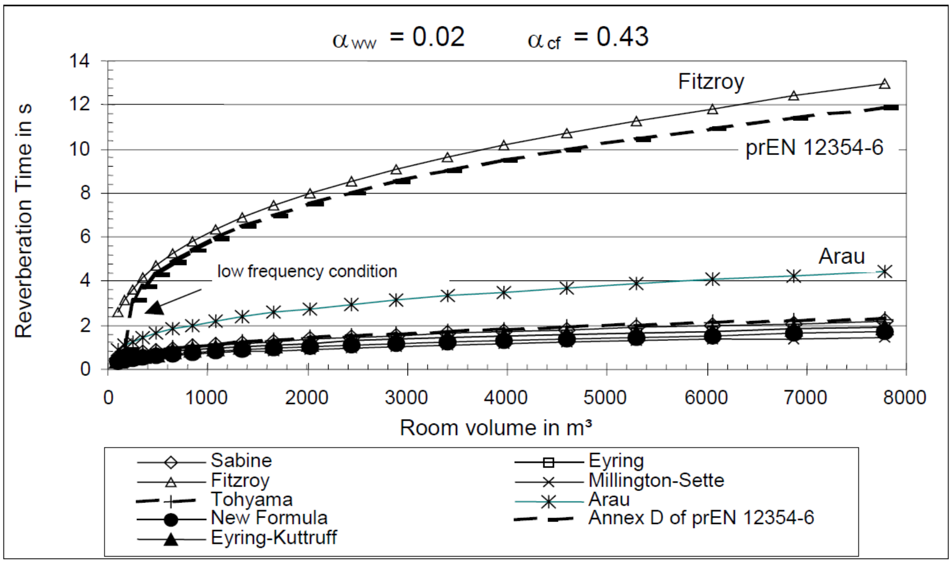


Figure 1.16: Calculated RT using various calculation models for high absorption of the floor and low absorption of other surfaces [3]

1.5. Comparison of measured RT and calculated RT

In chapter 5 – *'Calculation of the RT using different models and comparison with the measurements',* it is the aim to compare the calculated RT based on various models (see chapter 1 – '*Literature study'*) with the measured RT in situ (see chapter 3 – '*Methodology of the measurements'* and chapter 4 – *'Measurement results'*). This gives the ability to evaluate the validation and quality of the models. In what is next, an overview of the study that is already done about this comparison by Neubauer and Kostek [3] is briefly discussed.

1.5.1. <u>Prediction of the sound absorption coefficient values</u>

The measurement procedures and assumptions are given in chapter 3 – '*Methodology of the measurements'*. To compare measured with calculated RT-values Neubauer and Kostek point out that it is interesting to estimate the individual sound absorption coefficients as these are rarely known in places that are already built. Two assumptions are made:

1. In engineering applications there is often 10 % accuracy adopted for RT predictions.
2. Any absorption coefficients enable prediction of RT of a bare room within this 10 % range accuracy, as shown by Bistafa and Bradley [48] and other researchers.

From these two assumptions follows that the adequate values of the unknown sound absorption of the room surfaces can be predicted from measurements using either Sabine's or Eyring's classical model. Such an assumption can also be found in standards (e.g. DIN 52212, DIN EN 20354, ISO 354). In the experimental study of Neubauer and Kostek [3] the model of Sabine is used: calculated RT using the model of Sabine and comparing the obtained results with the measured RT are 'calibrated' which gives the respective sound absorption coefficients. To calculate the RT the respective individual sound absorption coefficients are used. Such a method is often used for engineering applications and has proven to be satisfactory [48]. The accuracy that is obtained when comparing the approximated RT (with the model of Sabine) and the measured RT is given in the graph of figure 1.17. There is a good conformity between the two values. Bistafa and Bradley [48] also use this way of reasoning. They prove that the method is effective in cases of unknown absorption coefficients of a room in which the RT was measured. The obtained sound absorption coefficients can then be used to compare calculated RT-values using various prediction models with measured RT-values.

However, for this study, standard values of the absorption coefficient for different materials (given by the European standard prEN 12354-6, Annex B and C [27]) are used to calculate the RT with various prediction models. These values are obtained with the model of Sabine. There are no predictions of the sound absorption coefficient performed.

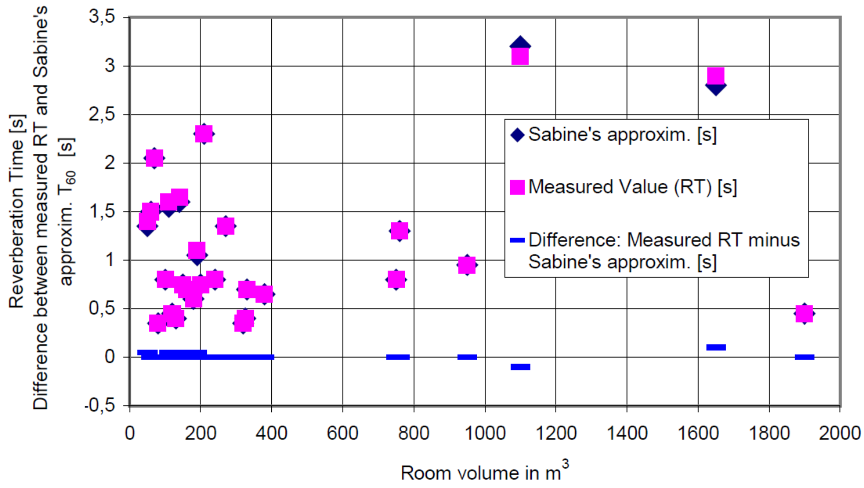


Figure 1.17: Differences between predicted and measured RT [3]

1.5.2. *Comparison of measured and calculated values for RT*

Neubauer and Kostek make a comparison of the measured RT-values with the calculated RT-values using various prediction models [3]. The calculations have to be performed for all frequency bands. The obtained results of Neubauer and Kostek are represented in figures 1.18 and 1.19. The comparison of measured and predicted RT-values is done for respectively a room with a volume range from 50 m³ to 200 m³ and from 200 m³ to 1,000 m³, but only for a mid-frequency range of 500 Hz. Spaces with different distributions of the sound absorption are analyzed. In general, it can be seen that results obtained with the MOF conform best to the measured RT-values, followed by the model of Eyring. The MOF provides values within a range of approximately ±28 % and is always within the same range as the measured RT. There is no proper approximation to the measured RT using the models of Fitzroy, Nilsson, Arau and Tohyama-Suzuki.

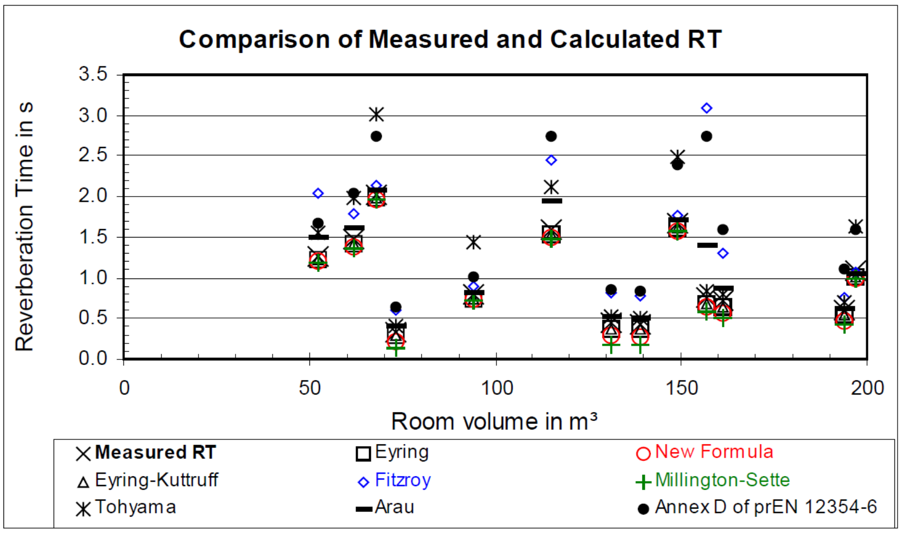


Figure 1.18: Comparison of measured and predicted RT for a room with a volume range of from 50 to 200 m³ [3]

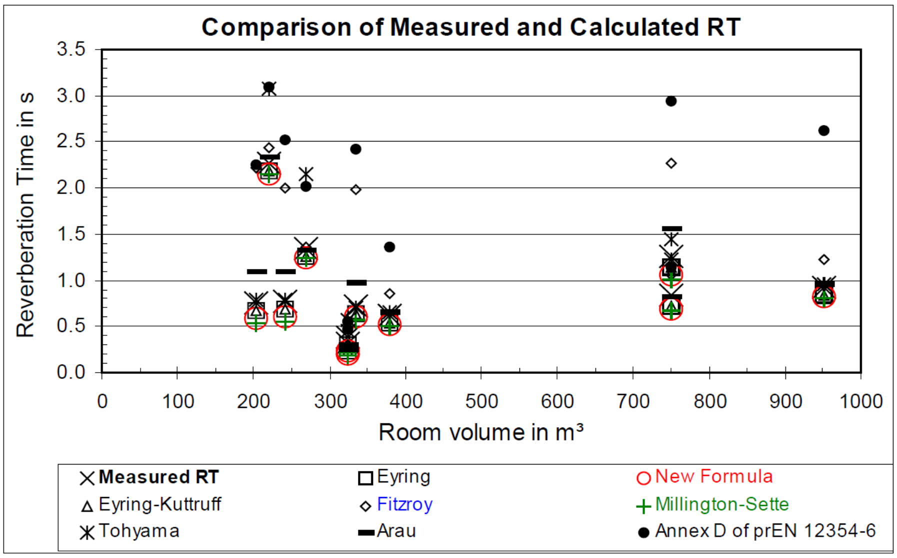


Figure 1.19: Comparison of measured and predicted RT for a room with a volume range of from 200 to 1,000 m³ [3]

1.6. Conclusions of the RT models according to Neubauer and Kostek

In the paper of Neubauer and Kostek [3] it is concluded that for any kind of situation (for a mid-frequency range of 500 Hz) the results obtained with the MOF conform best to the measured RT values, followed by the model of Eyring. Also, various room volumes have no impact on the MOF. The models of Nilsson, T&S, Fitzroy and Arau do not correspond well with the measured RT values. The paper also states that the results obtained with the MOF generally conform better to the measured RT-values in comparison with the classical models. As the model of Eyring is also a classical model, Neubauer contradicts himself by stating that it conforms well to the measured RT-values. This will be studied in chapter 5 – *'Calculation of the RT using different models and comparison with the measurements'*.

Neubauer and Kostek also notice that the predicted RT obtained with the MOF gives a shorter RT than the measured RT, especially in the higher octave band frequencies. This means that the best results are observed below or equal to the octave center frequency of 1,000 Hz. This is very important to get adequate reverberation characteristics.

In another paper of Neubauer [4] he compares the predicted RT-values with computer simulated RT-values for different room sizes. In recent years, the geometrical acoustics methods of ray tracing and image sources calculations have been very successful implemented using computers. Such a way of calculating the RT is very accurate as it calculates the RT in every point of the space. It is important to note that calculating the RT with a prediction model gives only an approximation of the global RT for the entire space. The used computer programs are CATT-Acoustics [49] and CAESAR [50]. Also in this second paper of Neubauer it is shown that in general the MOF yields reliable results in cases where classical models predict too short RT, especially in cases of non-uniformly distributed sound absorption.

Moreover, the investigation reveals little differences between predicted RT-values mutually if sound absorption in rooms is little (live space, diffuse condition). Only the models of T&S and Nilsson differ. However, if low absorption is applied, the values of every calculated RT differ considerably with the measured RT. This is also pointed out in Neubauer's first paper. The greater the absorption coefficient becomes (e.g. if the global absorption coefficient is about 0.2 or higher) the more the MOF gives the best results in comparison with the other models.

In the case of high and evenly distributed absorption (e.g. if the global absorption coefficient is about 0.40 or higher), which makes the space more diffuse, there also is a good agreement between the classical models and the MOF but the model of Eyring still reveals a little deviation compared to the MOF. In the case of high absorption (dead space) and unevenly distributed sound absorption, there is a considerable difference between various calculation models. The models of Nilsson, Sabine and T&S differ considerably in comparison with the other prediction models. But in general, for high absorptive spaces, the models give a better prediction of the RT in comparison with low absorptive spaces. This will also be analyzed in chapter 5 - *'Calculation of the RT using different models and comparison with the measurements'.*

Neubauer and Kostek [3] discover that if the sound absorption at opposite sides is substantially higher than on the other room surfaces, the RT according to the MOF is useful. This is typically for offices (flat rooms) where the assumption of diffuse field conditions for applying Sabine's theory are not in agreement with the existing absorber distribution. In this case, equation (1.25) can successfully be applied to estimate the RT. This can also be observed in the case of a long room, e.g. a hall with absorbing ceiling.

1.7. Selection of the RT models for this study

For this study not every model that is discussed in chapter 1.2 – *'Modelling the RT'* will be used to calculate the RT. The models of Sabine, Eyring and M&S are simple, classical models that can be used in the case of a perfectly diffuse field. Because of their simplicity they are easy to use by designers and can therefore not lack in this study. These models are the most reliable in live-room conditions (low absorption and diffuse character). This is an interesting statement of Neubauer and Kostek [3] that will be confirmed or rejected in chapter 5 - '*Calculation of the RT using different models and comparison with the measurements'.*

The models of Fitzroy and Kuttruff will be used to compare with the classical models of Sabine and Eyring because they emanate from the same assumptions and coefficients. The model of Fitzroy will be used because the literature study shows that this model does not always score very well. This statement will be investigated to see if this is also the case for any kind of auditorium in this study. It is interesting that the model of Kuttruff is based on a partially diffuse field. The literature study does not say that much about this model, which gives the possibility to this study to get more clarity about it. Besides the model of Fitzroy, the model of Arau generally also gets a bad evaluation in the literature study of Neubauer and Kostek [3]. It will be interesting to analyze whether or not this is true.

The MOF will be useful because generally it conforms better to the measured RT-values than the classical models according to Neubauer [3]. Various room volumes have no impact on it. In the literature study, it always appears to be one of the better models to predict the RT. If the sound absorption at opposite sides is substantially higher than on the other room surfaces, it is shown that the RT according to the MOF is very useful. In this case, the assumption of diffuse field conditions for applying Sabine's theory is not in agreement with the existing absorber distribution.

The Nilsson model will not be considered because it is used for spaces filled with a lot of equipment, decorative elements, etc. and it does not make a distinction between regular or irregular spaces. The auditoria are regular spaces and don't have a lot of equipment. Therefore, this model won't give representative results. The formulae to obtain the RT are also very complex and the model is therefore not user-friendly for designers which is also the case for Tohyama and Suzuki's model T&S.

This results in seven models that will be used to calculate the RT in the 5th chapter of this study – '*Calculation of the RT using different models and comparison with the measurements'.*

2. THEORETICAL STUDY

This chapter gives an overview of the principles and concepts which are needed for the further part of this study. In order to fully understand what is going on during the measurements and calculations it is important to know the basic principles of acoustics. Studying these concepts will provide a better insight. First of all it is important to know what sound exactly is and in which field it can be located. How can sound be expressed? How to evaluate a space for speech activities such as auditoria? This chapter is based on the course of Prof. dr. ir. M. Blasco (Inleiding tot de Bouwakoestiek UGent) [28] and the course of the TU Delft (Acoustic measures for Speech Intelligibility) [51].

2.1. Perception and propagation of sound waves

Sound is a quick variation of under and over (air) pressures as compared to the atmospheric pressure which is represented in figure 2.1. The vibration causes movement of our eardrum. The propagation of sound can only exist in an elastic medium like air, a liquid or a solid medium. Therefore, there is no sound in the vacuum. In other words, sound is the vibration of air particles around an equilibrium state (at rest). The kinetic energy of the particles is spread through the medium by means of 'collisions'. This elaborate balance of movement and energy distribution gives rise to 'sound waves', which propagate with a speed called the 'celerity' (in the air there is approximately c = 344 m/s). The sound can be named 'noise' when it is generally experienced as unpleasant.

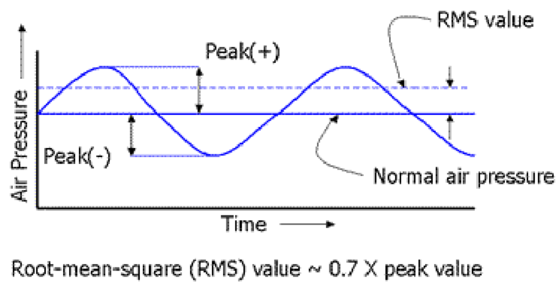


Figure 2.1: Acoustic pressure $p(t) = P(t) - P_0$ [28]

The propagation of sound is longitudinal, which means that the (air) particles move in the same direction as the displacement of the wave, which results in a longitudinal wave. Propagation of sound in a solid medium can be longitudinal and transversal.

The sound volume is a physical measure expressed in dB. The perception of the sound volume is the 'loudness'. Thus, there is a difference between the physical sound volume and our subjective perception of sound. The relationship between those concepts can be found in the curves of Fletcher and Munson [52]. In this study the subjective opinion of students will be compared with the objective calculated and measured values and with objective acoustic quality numbers (STI, C_{50}-value, SN-ratio, etc.).

2.2. Basic acoustic variables

2.2.1. Frequency f, wavelength λ and amplitude A

The **frequency** is the amount of vibrations (around an equilibrium state) per second of the air particles. A high frequency gives a high tone. The unit of frequency is 'Hertz': 1 Hz = $\frac{1}{s}$. The **wavelength** is the distance between two points of a sound wave with a same phase: the air particles will have the same 'moving distance' and 'direction' around an equilibrium. The **amplitude** is a measure of the energy that a wave contains and the displacement of the air particle in comparison with the equilibrium. The bigger the wavelength, the smaller the frequency, the higher the amplitude (more energy) and the more difficult it is to counter the sound.
The celerity of the sound c can be written as:

$$c \approx 20{,}1 \cdot T = \lambda \cdot \mathrm{f} \;\; [\mathrm{m}/s]$$

where:
T – Temperature [Kelvin]
At 20°C (293 K) there is a sound velocity of 342 m/s in air. In water, the velocity is 1,435 m/s, in steel it is 5,000 m/s and glass gives a velocity of 5,200 m/s.

The human hearing is sensitive to frequencies between 20 Hz and 20,000 Hz. It does not have the same reaction for equal (linear) increments of frequencies, but it does with ratios of frequencies. For example, an increase from 200 Hz to 300 Hz is not the same an increase from 1,000 Hz tot 1,100 Hz, but a doubling from 200 Hz to 400 Hz is the same as a doubling from 1,000 Hz to 2,000 Hz. Traditionally, building acoustics generally investigates the frequencies between 100 Hz and 5,000 Hz. All frequencies can be grouped into one-third octave bands or octave bands as represented in figure 2.2. The bands can be found by multiplying and dividing by:

- For one-third octave bands: $2^{1/3}$ (0.23 · f_m)
- For octave bands: 2 (0.71 · f_m)

The limit of each band is the average of two successive intermediate mid frequencies.

In this study, the RT is measured in octave bands from 125 Hz to 4,000 Hz.

1/3 octave bands [Hz]	1/1 octave bands [Hz]
20,000	
16,000	16,000
12,500	
10,000	
8,000	8,000
6,300	
5,000	
4,000	4,000
3,150	
2,500	
2,000	2,000
1,600	
1,250	
1,000	1,000
800	
630	
500	500
400	
315	
250	250
200	
160	
125	125
100	
80	
63	63
50	
40	
31.5	31.5
25	

Figure 2.2: One-third octave bands and octave bands (frequencies) [28]

2.2.2. Sound absorption

To characterize the sound absorption of a material, the quantity **sound absorption coefficient** can be used. This quantity can be determined for each material according to the reverberating space method (NBN EN ISO 354). A sound wave loses an amount (portion) of its energy at each reflection against a material. This energy is represented by the sound absorption. For flat surfaces, the amount of the sound absorption coefficient is between 0 and 1, where 0 is total reflection and 1 is total absorption. In practice, it varies between 0.02 (e.g. glass or special painted concrete) and 0.80 (e.g. Glass- and Rockwool). The sound absorption has no unit as it is a proportion between the absorbing sound wave and the incident sound wave.

It is important to make a distinction between acoustic isolation and acoustic absorption as represented in figure 2.3. Acoustic isolation is part of the acoustic study between two spaces. This can be written as [53]:

$$R_{\theta,f} = 10\log\frac{W_i}{W_d}$$

where:

W - The power is the energy emitted by a source per second [J/s, Watt]

W_i – Incident power [Watt]

W_d – Transmitted power [Watt]

W_a – Absorbed power [Watt]

W_r – Reflective power [Watt]

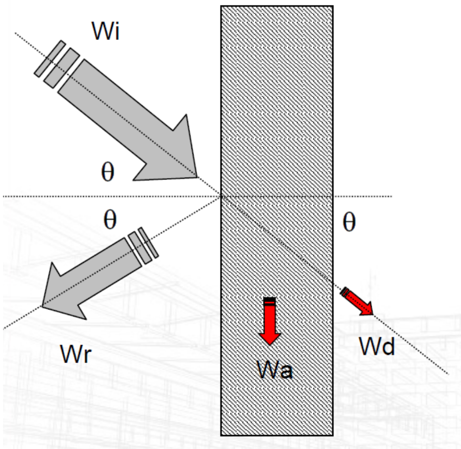


Figure 2.3: Acoustic isolation and absorption [53]

Absorption is the study of canceling resonances and reverberation in a cavity or space by using absorbing materials, mineral wool, perforated panels, etc. Room acoustics is the discipline that is applied for this study. The sound absorption coefficient can be written as [53]:

$$\alpha_{\theta,f} = \frac{W_d + W_a}{W_i}$$

To characterize the total absorption of a space, not only the sound absorption coefficient α is important, but also the surface of the absorbing material A (in m^2). The total sound absorption area A in a space can be written as:

$$A = S_1\alpha_1 + S_2\alpha_2 + \cdots + S_n\alpha_n = \sum S_i\alpha_i$$

where:

A – Total area of absorption of the space [m^2 – Sabine]

S_i – Surface area of the actual surface [m^2]

α_i – Absorption coefficient of the actual surface [-]

It is clear that a lot of absorbing surface is necessary to obtain enough sound absorption. That's why ceiling absorption is very popular and efficient. The unit of the sound absorption is Sabine, named after the American acoustician Wallace Clement Sabine (1868-1919).

The global average absorption coefficient for the space can be expressed as:

$$\bar{\alpha} = \sum \frac{A_{tot}}{S_{tot}}$$

where:

$\bar{\alpha}$ – Global average absorption coefficient [-]

A – Total area of absorption [m^2 – Sabine]

S – Total surface area of the space [m^2]

The sound absorption coefficient depends on the frequency as reverberation depends on the frequency. Some materials absorb better or worse with certain frequencies. When the amount of reflections increases, the sound pressure level in a point of measurement will be more important. Thus when the total area of absorption is smaller, the total sound pressure level decreases by applying extra absorbing materials. When reducing the RT to half the time (by using absorbing materials) the original sound pressure level decreases with 3dB.

Table 2.1 shows an overview of absorption coefficients that are used for this study. They are based on annex B of prEN 12354-6 [27], measured in accordance with EN ISO 354. These values can be considered as typical minimum values. They are derived from the RT calculated with the model of Sabine. It should be taken in mind that there are always some deviations on these values which are not taken into account for this study. The RT will be calculated with these absorption coefficients using different predication models.

Material	Frequency [Hz]					
	125	250	500	1,000	2,000	4,000
Window	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)	0.05	0.04	0.03	0.02	0.02	0.02
Plastered brick	0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood	0.38	0.24	0.17	0.10	0.08	0.05
PUR	0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminum	0.01	0.02	0.03	0.03	0.04	0.04
Curtains (<0.2 kg/m²)	0.05	0.04	0.03	0.02	0.02	0.02
Door wood	0.14	0.10	0.08	0.08	0.08	0.08
Door aluminum	0.01	0.02	0.03	0.03	0.04	0.04
Acoustic element	0.10	0.30	0.70	0.80	0.85	0.90
Carpet	0.01	0.02	0.06	0.15	0.25	0.45
Chalkboard	0.15	0.15	0.11	0.03	0.05	0.03
White projection board	0.20	0.20	0.20	0.20	0.25	0.25
Linoleum	0.02	0.03	0.03	0.03	0.03	0.02
Wood	0.02	0.03	0.04	0.05	0.05	0.06
Desk laminated wood	0.02	0.02	0.03	0.04	0.04	0.04
Seats and backs	0.02	0.02	0.03	0.04	0.04	0.04
Acoustic ceiling	0.20	0.35	0.70	0.65	0.60	0.55

Table 2.1: Absorption coefficients of the different materials for the different octave bands [27]

It is important to know that the concepts of absorption and isolation are often confused. For example rock wool (5 cm- 60 kg/m^3) gives an isolation of 5 dB, while the absorption is 0.8 – 1. On the other hand, the isolation of plywood (17 mm – 722 kg/m^3) is 29 dB, while the absorption is 0.2. Absorption is the limitation of reverberation in a space or cavity. A study of absorption takes into account the spatial distribution of the sound, calculations of the RT in a space and the parameters to change this (absorption panels, panel- and Helmholtz resonators, etc.). Room acoustics is the discipline that, next to all these concepts, also takes the impact of the shape of the space into account, with the aim of acoustic comfort and the improvement of Speech Intelligibility.

To improve the acoustic comfort, both isolation and absorption have to be considered. Isolation is the difference (measured) of the sound pressure level between two spaces. It is called 'airborne sound isolation'. It is a term that indicates whether a material or construction sound stops. It is important to make a distinction between airborne sound (when air particles are excited, for example 'speaking') and contact sound (when particles of the material are excited, for example 'steps on a floor'). The isolation depends on the amount of sound that can pass through from one space to another.
Absorption is the second concept that has to be considered to improve the acoustic comfort in a space. Absorption is converting the energy of sound waves into heat by friction in an open-celled absorbent material. The higher the absorption in a space, the smaller the reverberation will be. There is no link with

isolation as it depends on one space only. Still, a higher absorption of a cavity of a doubled construction gives indirectly an isolation of sound.

The reflection coefficient is the complement of the absorption coefficient and can be written as:

$$\rho = 1 - \alpha$$

2.3. Sound power level and sound pressure level

2.3.1. *Power versus intensity of sound waves*

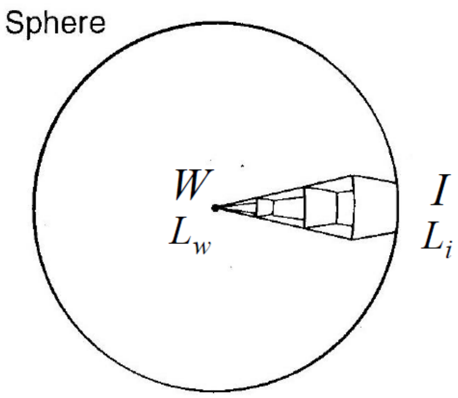


Figure 2.4: Power versus intensity of sound waves [28]

The power W of sound is the energy emitted by a source per second (J/s, Watt). The next formula shows the relationship between sound power level and sound power and is also represented in figure 2.4:

$$L_w = 10 \log \left(\frac{W}{\mathrm{W}_0}\right) [dB]$$

where:
$\mathrm{W}_0 = 10^{-12}\, Watt = \text{Reference power}$

The sound intensity I is the power received in one point per m² of surface (W/m²). It depends on the environment. The sound power W can also be written as:

$$\mathrm{W} = I \cdot S$$

The relationship between sound intensity level and sound intensity is as follows:

$$L_i = 10 \log \left(\frac{I}{\mathrm{I}_0}\right) [dB]$$

where:

$I_0 = 10^{-12}\ Watt/m^2 =$ Reference intensity

2.3.2. Sound pressure p and sound pressure level L_p

The sound pressure level L_p is a measure for the displacement of the air particle around the equilibrium. The greater the distance is, the more energy hence the level of sound. L_p is used to describe the greatness of sound. The sound pressure level is measured by measuring the sound pressure p.

Acoustic pressure is given in the next formula:

$$p(t) = P(t) - P_0\ [Pa]$$

The relationship between the two concepts is represented in figure 2.5 and is also given in the next formula:

$$L_p = 10\ log\frac{p^2}{p_0^2}\ [dB]$$

where:

$p_0 = 2\ \cdot 10^{-5}\ Pascal =$ Reference pressure
$p_{atm} = 1013\ hPa$

The sound pressure level is dimensionless. The unit dB is used to refer to the logarithm in its calculation. 'Decibel' is used because of the factor 10.

$$\log x = B\ (Bel)$$
$$10 \log x = dB\ (deciBel)$$

The reference pressure p_0 is the lowest pressure needed to create sound. If $p = p_0$, the sound pressure level $L_p = 0$ dB. Figure 2.5 shows the relationship between sound pressure and sound pressure level. The weakest audible sound a human can hear has a sound pressure of 0.00002 Pa. The maximum is about 20 Pa which is perceived as painful to our ears. There are some rules of thumb for human hearing:

- Increase of 3 dB: the smallest difference a human can perceive, when recording the two sound pressure levels in quick succession.
- Increase of 10 dB: gives a perception of a doubling of loudness.

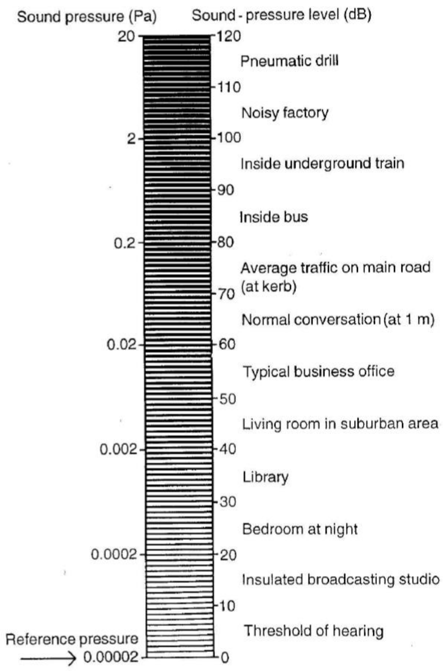


Figure 2.5: Relationship between sound pressure and sound pressure level [28]

2.4. The acoustic sound field

2.4.1. Direct sound field

The distribution of sound pressure level in a space is often very irregular. This is due to the direction of the source, the domination of the direct sound close to the source and the different objects in the space which prevent the direct sound and reflect the sound. The absorbing and diffusing properties of the walls, ceiling and floor differ as well and give a certain distribution of sound pressure level in a space. If $L_{p,dir} > L_{p,diff}$, it is called a direct sound field. If $L_{p,dir} < L_{p,diff}$, it is called a diffuse sound field.

The direct field is the first important one. This field is directional. There are no reflections in the environment. It is called a reactive field when the sound is close to the source (a near field). In contrast, it is called an active field when the sound is far away from the source (a far field). The direct sound field is approximated by an open field (a free field). There are four important principles to consider about the direct field:

1. $\vec{I} \neq \vec{0}$
2. $I = \frac{p^2}{\rho \, . \, c}$
3. $L_p \downarrow 6 \, dB \; for \; each \; r \; 2x \uparrow$
4. $L_{p,dir} \sim L_w$

First of all, the intensity vector is not equal to zero. This means that the direct field is directional. In this area the intensity I (W/m²) is the ratio of the sound pressure quadrant and the product of the mass density ρ and speed of air c. It can be inferred that the sound pressure level L_p decreases with 6 dB (for a point source) and with 3 dB (for a linear source) when increasing the distance away from the source r two times. It depends on the type of sound source: point source (e.g. sound speaker), linear source (e.g. train) or surface source (e.g. public). For example in a corner, the energy increases 8 times which means an increase of 9 dB (10log 8 = 9). At last, the sound pressure level is proportional to the sound power level L_w. These concepts are represented in figure 2.6 and figure 2.7.

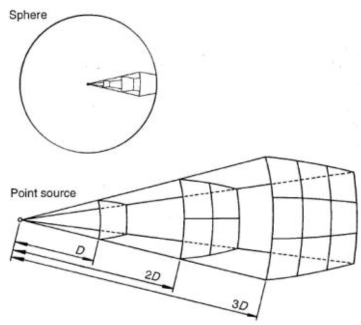


Figure 2.6: Point source in direct field [28]

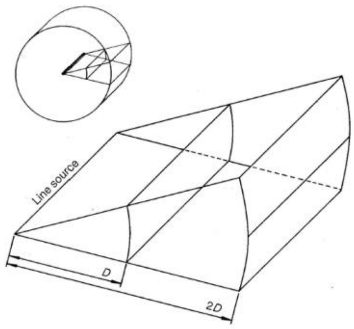


Figure 2.7: Linear source in direct field [28]

2.4.2. *Diffuse sound field*

The second field is the diffuse field. This field is non-directional and has a random phase. In contrast with the direct field, this field is a sound reflecting environment. The direct and diffuse field is represented in a scheme in figure 2.8. The diffuse field is approximated by a reverberant field. There are also four important principles to know about the diffuse field.

1. $\vec{I}_m = \vec{0}$
2. $I = \frac{p^2}{4\ .\ \rho\ .\ c}$
3. $L_p = constant$
4. $L_{p,diff} \sim L_w$

The mean intensity vector is equal to zero. This means that, in contrast with the direct field, the field is non-directional which means that the place of measurement is not important, neither the place of absorption in the space. The intensity I (W/m²) in a diffuse field is four times smaller than the intensity in a direct field, which means that the sound pressure level remains constant with distance. It depends on the acoustic properties of the reflecting environment (e.g. decrease of 3 - 4 dB for reflecting surfaces as concrete, decrease of 6dB for absorbing surfaces). In this study (and studies done before) the assumption is made that the measured space is a perfectly diffuse (homogeneous) field. This gives the possibility to calculate the RT with the different models because these are based on the assumption that the field is a diffuse field. This static field is applied to the mid and high frequencies (> 200 Hz).

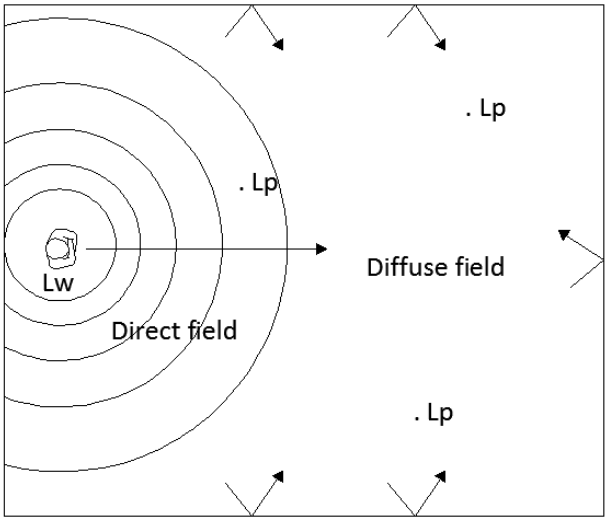


Figure 2.8: Scheme of acoustic field [28]

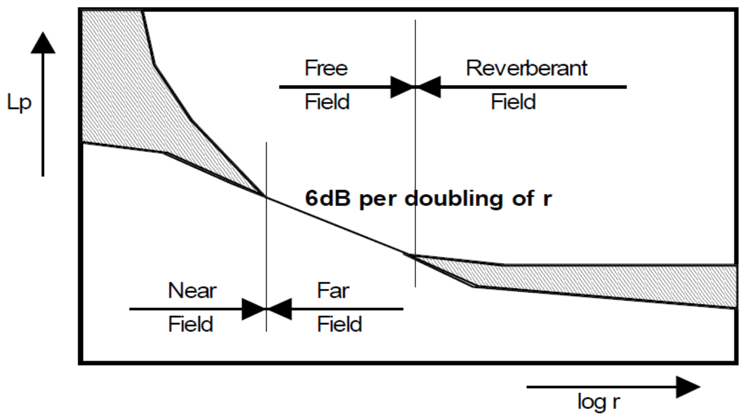


Figure 2.9: Direct and diffuse sound fields [28]

Figure 2.10 shows the characterization of a space which depends on its acoustic field (high reverberant, half high reverberant and anechoic room). The greater the distance to the source r (in m), the more the sound pressure level decreases until it becomes a constant.

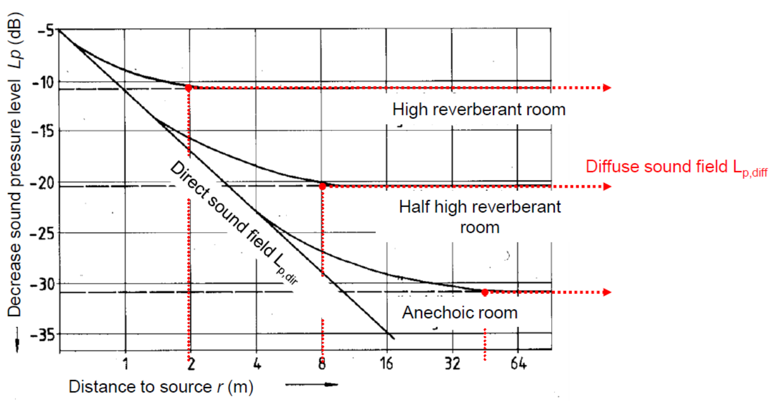


Figure 2.10: Characterization of a space [28]

2.4.3. *Total sound field*

The sound pressure level L_p can eventually be derived from the Sabine Franklin Jaeger Theory as follows [51] [54]:

$$L_{p,total} = L_{p,dir} "+" L_{p,diff}$$

$$L_p = L_w + 10 \log \left(\underbrace{\frac{Q}{4\pi r^2}}_{\text{direct}} + \underbrace{\frac{4\,(1-\bar{\alpha})}{A}}_{\text{diffuse}} \right)$$

where:

$L_{p,\ total}$ – Total sound pressure level [dB]

$L_{p,dir}$ – Direct sound pressure level [dB]

$L_{p,dif}$ – Diffuse sound pressure level [dB]

L_p – Sound pressure level [dB]

L_w – Sound power level [dB]

Q – Directional coefficient of the source

r – Distance from the source to the point of measurement [m]

A – Total area of absorption of the space [m²]

$\bar{\alpha}$ – Average absorption coefficient

The first term between the brackets represents the direct sound. The direct sound is independent of the absorption in the room but it depends on the distance and the direction characteristic Q of the source. In the axes of the mouth, the value of Q is 2.5. More away from the mouth Q it is equal to 1. On the back of the head of a person the value of Q will be much lower than 1. From this equation it can be confirmed that the further away from the source, the more diffuse the field is, the bigger the second term becomes. The sound pressure level decreases until it becomes a constant. At one distance, the reverberation radius r_G, the two terms of the equation are equal:

$$L_{p,diff} = L_{p,dir}$$

The reverberation radius r_{rev} can be described as:

$$r_{rev} = \sqrt{\frac{A \cdot Q}{16\,\pi\,(1-\bar{\alpha})}}$$

where:

r_{rev} – Reverberation radius [m]

S – Total surface area [m²]

Q – Directional coefficient of the source

α – Absorption coefficient

Increasing α gives an increase of the reverberation radius. Even for a well-designed classroom, the reverberation radius is limited to 2 m. This means that in the back row of an auditorium the direct sound is almost inaudible. The Speech Intelligibility results from a good ratio between the early and late sound. The early sound must sufficiently exceed the noise. For bigger spaces such as auditoria, the ratio is most of the time more unfavorable.

The second term between the brackets in the equation of the sound pressure level represents the diffuse sound. It only depends on the absorbing properties of the space, and is independent of the distance. This is contrary with our daily experience. That is why there is a custom formula of Barron [55] which also depends on the distance r.

$$L_{p,brn} = L_w + 10 \log \left(\frac{Q}{4\pi r^2} + \frac{4}{\alpha \cdot S} \exp\left(\frac{-0.04\, r}{RT}\right) \right)$$

where:

$L_{p,brn}$ – Sound pressure level according to Barron [dB]

L_w – Sound power level [dB]

Q – Directional coefficient of the source

r – Distance from the source to the point of measurement [m]

A – Total area of absorption of the space [m²]

α – Absorption coefficient

Using Eyring's formula for the RT (equation (1.7)) gives an interesting transition:

$$RT_{Eyring} = \frac{-0.16 \cdot V}{S \cdot \ln(1-\alpha)} = \frac{0.04\, mfp}{\ln(1-\alpha)}$$

where:

V – Total volume of the space [m³]

S – Total surface area of the space [m²]

α – Absorption coefficient

mfp – Mean free path between reflections

$$mfp = \frac{4V}{S}$$

Implementing this in Eyring's formula gives:

$$L_{p,brn} = L_w + 10 \log \left(\frac{Q}{4\pi r^2} + \frac{4(1-\alpha)^{r/mfp}}{\alpha \cdot S} \right)$$

If r = mfp, the two equations are equal. This formula gives higher predictions for smaller distances. At greater distances, there is a downward trend. Ray-tracing-models show the accuracy of the Barron's formula. However, it does not take scattering by furniture into account. Therefore there is a custom formula that makes a correction by multiplying the distance r with a factor fb. For offices and classrooms fb = 2 [56] [57] [58].

$$L_{p,brn} = L_w + 10 \log \left(\frac{Q}{4\pi r^2} + \frac{4(1-\alpha)^{r \cdot fb / mfp}}{\alpha \cdot S} \right)$$

2.4.4. Other acoustic fields

There are two other fields: the *modal field* (< 200 Hz) and the so called *transition field* (around a frequency of 100 Hz). The *modal field* is deterministic: there are few modes so this means that measurements can be done with significant measuring differences. The *transition field* makes the transition between the modal and the diffuse field. It corresponds with the Schroeder cut-off frequency [41]:

$$f_s = 2{,}000 \sqrt{\frac{RT}{V}} \, [Hz]$$

To calculate the parameters that describe the characteristics of an acoustic space, the assumption is made that it is usually sufficient to consider only the propagation of sound energy and not sound pressure or particle velocity. This means that all phase effects can be neglected. The basis of this assumption is that the dimensions of a space should be large enough in comparison with the acoustic wavelengths. Dr. Manfred Schroeder notes this and formulates the so-called Schroeder cut-off frequency [41]. He refers to it as the frequency at which a space goes from being a resonator to being a reflector/diffusor, the 'crossover frequency'. It defines the boundary between the diffuse field and the modal field.

Beneath this Schroeder cut-off frequency, the previous assumption is not justified. This means that f_s can be considered as the lower limit of frequencies at which a statistical treatment of superimposed normal modes in a room is permissible. In contrast, it is not possible to statistically analyze the resonance peaks of the sound field below the Schroeder cut-off frequency because they are insufficiently dense.

2.5. Reverberation

In chapter 3 – '*Methodology of the measurements'*, the RT will be measured. In the case of spaces for speech activities (such as auditoria) the RT is measured to evaluate the acoustic quality of a space. The RT is the most important quantity to make an evaluation. It is usually assumed that a short RT leads to better Speech Intelligibility.

There are two advantages to applying the RT for measurements. First, it can be measured with quite simple equipment and second, it appears quite constant trough a room [59]. However, there are some reasons to be cautious with the use of the RT [59]:

- The desired RT is dependent on the volume of the space. This will be explained in chapter 4.2.3 - 'Acoustic *Standard for School Buildings NBN S 01-400-2'* [6].
- The RT can also be too short. In situations with very high absorption the Speech Intelligibility is perfect for one listener at a limited distance. However, in the case of a whole auditorium, there are big differences of Speech Intelligibility, because the lack of reflections. Students on the last row will not hear or understand everything.
- The RT was invented to express musical quality. However, since acoustic quality depends mainly on noise levels, the RT may not be the best variable.
- Eventually, an architect wants his/her information about acoustic quality expressed in room shape plus the material properties of the room.

Measuring the RT is useful for regular shaped spaces and uniform distribution of absorption. The European standard prEN 12354-6 [27] offers calculation models (Annex D) for other situations, such as irregularly shaped spaces and irregular absorption distribution. The performance in irregular shaped spaces, such as stairwells or spaces filled with machinery, can be better characterized by the sound pressure level and hence absorption than by RT.

2.5.1. Defining Reverberation Time

The classical definition of the RT (in seconds) is '*the time needed to decrease energy by 60 dB from its original level after instantaneous termination of the excitation signal, called RT_{60}*'. This is represented in figure 2.11. This definition of the RT may be fulfilled by linear extrapolation of a shorter evaluation range. The parameter is originally introduced by W. G. Sabine. A sound source is assumed which produces a continuous sound pressure level. In general, the RT depends on the frequency, the volume of the space and the sound absorbing properties of the used materials. The lower the considered frequency, the higher the reverberation because low frequencies have more energy.

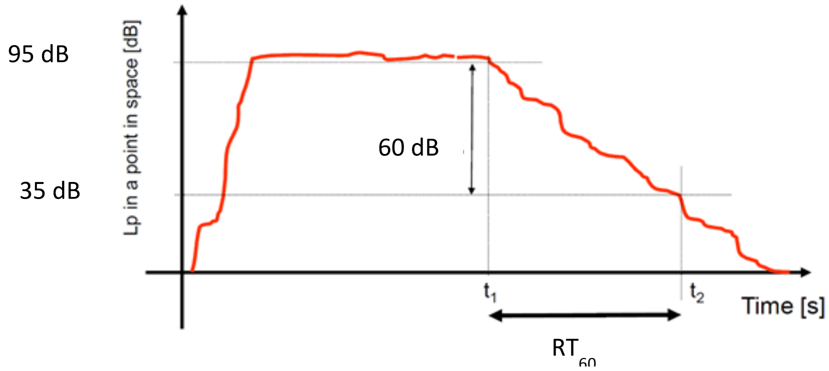


Figure 2.11: Definition of RT [28]

For each frequency there is a different RT considered. Since the RT depends on the considered frequency, the RT can be written in 2 ways. The mean RT is the arithmetic mean of the RT in the octave bands of 500 Hz and 1,000 Hz. The nominal RT of a space is defined as the arithmetic mean of the RT in the octave band of 500 Hz, 1,000 Hz and 2,000 Hz.

Mean RT:

$$RT_m = \frac{RT_{500} + RT_{1,000}}{2}$$

Nominal RT:

$$RT_{nom} = \frac{RT_{500} + RT_{1,000} + RT_{2,000}}{3}$$

2.5.2. Classical formula for the RT

In general, there are three important assumptions:

- The space is a perfectly diffuse field
- Absorption is uniformly distributed over all surfaces
- For smaller volumes: air conditions have no impact

Sabine introduces the RT to record the reverberation in a physical greatness. In chapter 3 – *'Methodology of the measurements'* the rate of decay of sound energy in an auditorium will be measured. The rate of decay sound energy in a space (assumption: totally diffuse field) can be written as:

$$\frac{\Delta E}{\Delta t} \approx \frac{dE}{dt} = \frac{-\alpha \cdot c}{d} \cdot E$$

where:

d – Mean free path: $mfp = \frac{4V}{S}$ [m]

c – Celerity of sound [m/s]

α – Absorption coefficient [-]

Solving the differential equation gives:

$$E(t) = E_0 \cdot e^{\frac{-\alpha \cdot c}{d} t}$$

Using the definition of RT_{60}, this equation can also be written as:

$$10^{-6} E_0 = E_0 \cdot e^{\frac{-\alpha \cdot c}{d} RT60}$$

$$RT_{60} = \frac{-d}{\alpha \cdot c} \ln(10^{-6})$$

$$RT_{60} = 0.16 \cdot \frac{V}{A}$$

This results in the classical formula of Sabine for the calculation of the RT in function of the frequency.

where:

V – Total volume of the space [m³]

A – Total area of absorption of the space [m²]

The classical formula of Sabine shows that the RT depends on the volume of the space V and the area of absorption A. It is important to note that in auditoria, the audience is also an important factor. The additional sound absorption caused the audience introduces an important reduction of the RT.

2.5.3. Correction of the RT

Figure 2.12 explains the method to modify the RT in a space.

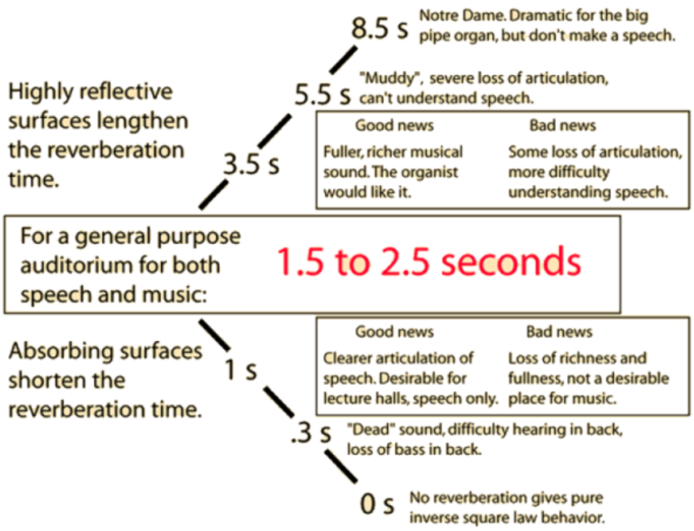


Figure 2.12: Correction of the RT [28]

The RT for an auditorium for both speech and music should be between 1.5 and 2.5 seconds. In most of the auditoria, we find acoustic elements such as carpet on the walls, acoustic boards, acoustic ceilings, etc.

These are absorbing surfaces that shorten the RT, resulting in clearer articulation. This is desirable for lecture halls. However, this also results in the loss of richness and fullness of the sound which is not desirable for music halls. This means that a space or auditorium with absorbing surfaces has 'good' conditions for speech and 'bad' conditions for music.

Most auditoria also have hard, reflecting surfaces such as furniture, plastered walls, etc. These are reflective surfaces that lengthen the RT, resulting in loss of articulation and difficulty understanding speech. However, this also results in fuller and richer musical sound. This means that a space or auditorium with reflective surfaces has 'good' conditions for music and 'bad' conditions for speech. The combination of both absorbing and reflecting surfaces results in an auditoria with good acoustic characteristics.

Persons who are present in a space will also absorb a part of the sound. There are some rules of thumb: to obtain a higher RT (for instance in a concert hall a higher RT gives a beautiful 'coloring' of the sound), 12 m^3 volume per person will be taken into account. To obtain a lower RT (for instance in an auditorium) 3 - 8 m^3 per person will be taken into account. If the volume is very big (in a modern cinema), then there will be extra sound absorbing surfaces to reduce the RT. There needs to be a good balance: the RT in the other frequency bands may not deviate too much of the mean RT: 20 % is the maximum deviation [28]. If there is a high RT required, it is always better to start with a high RT that can be reduced later in time with absorbing materials. Vice-versa is more difficult: starting with a low RT is more difficult to adapt later in time. It is possible to reduce the RT by placing an absorbing material against one of two parallel walls. This avoids a 'pingpong effect' of reverberation between two parallel walls. Another rule of thumb is that for common spaces 1/8 of the volume in m^2 absorbing material has to be taken into account.

There are three types of absorption to correct the RT which are represented in figures 2.13 and 2.14 and table 2.2.

Type A materials are uncovered porous materials. High frequent absorbing materials have a higher absorption coefficient α for high frequencies ($\geq$ 1,400 Hz). These materials are often characterized by soft panels with open cell structure or porous structure. There also exist other perforated foils depending if their use having enhanced absorbing properties. Using such materials result in the dissipation of the sound energy. In this case it is because of friction in the structure of the pores: mechanical energy is converted into warmth-energy.

Type B materials are resonators. Low frequent absorbing materials have a high absorption coefficient α for low frequencies (< 300 Hz). These materials are often characterized by panel absorption (for instance resonator panels). The panels (for instance of wood) form a cavity. When the panel bends, the energy of low frequent waves dissipate (low frequencies have more energy). An empty cavity gives a strong dissipation around a certain frequency. The peak frequency depends on the surface mass of the panel and the depth of the cavity: the deeper and/or the heavier the panel is, the lower the absorption frequency. A

Helmholtz resonator is a resonator panel with an opening in the panel. The same principles of absorption continue to apply.

Type C materials are a combination of a porous material and a panel. The peak frequency of a cavity filled with high frequent absorbing material is lower, still a wider range of frequency absorption. Drilled or sewed tiles of fiberboard (soft board) can be attached to a lath or tiles of mineral wool that are pressed can be applied to a lath. In this case, there is an absorption efficiency is in low frequencies, as well as in high frequencies. Practically, such an acoustic absorbing ceiling is one of the most used solutions and is often seen in auditoria.

Figure 2.13: Types of absorption materials [28]

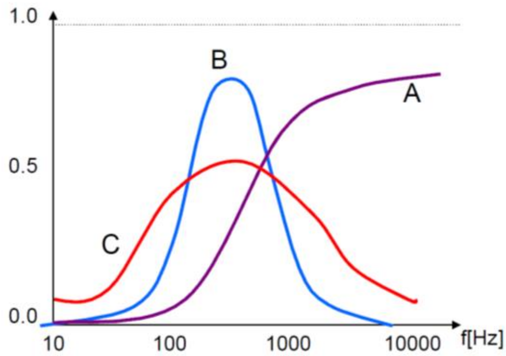


Figure 2.14: absorption materials and their frequencies [28]

A	Porous absorption	Uncovered	High frequency absorption	> 1,400 Hz
B	Helmholtz Resonance	Panel with empty cavity	Low frequency absorption	< 300 Hz
C	Combination	Panel with filled cavity	Wide range of frequency absorption with lower absorption peak	

Table 2.2: Types of absorption materials [28]

2.6. Evaluating acoustic quality of a space

As already mentioned in the introduction of this master's dissertation, the major acoustic concern in spaces with speech activities is verbal communication as represented in figure 2.15. The quality of verbal communication can be quantified by the Speech Intelligibility. It is recommended that, in case of normal-hearing adults working in their first language, the Speech Intelligibility should exceed 97 % [60] [61].

Calculating or measuring the RT is not always useful to determine the acoustic quality of a space. However, depending on room shape and dimensions, architectural function and acoustic use, other acoustic numbers may be more adequate. In practice, there is a variety of rooms and functions on one side and a set of available acoustic quality numbers on the other [59]. In this study the Speech Intelligibility of ten auditoria is evaluated to determine the quality of these auditoria. The quality of the Speech Intelligibility depends on the ratio of the direct sound pressure level (this is the direct signal from the source to which we listen) and the noise sound pressure level coming from background noise produced by hearers, background installations and reflections of the space. The signal to noise ratio gives the quality of a space [62]:

$$Quality = \frac{Signal}{Noise}$$

The more signal, the better the acoustic quality of a space is. The more noise, the worse the acoustic quality is. This can be expressed in several ways. One way to quantify the Speech Intelligibility in a space is with the Speech Transmission Index (STI). However, there are several other methods to evaluate the Speech Intelligibility. In what comes next, several methods will be discussed.

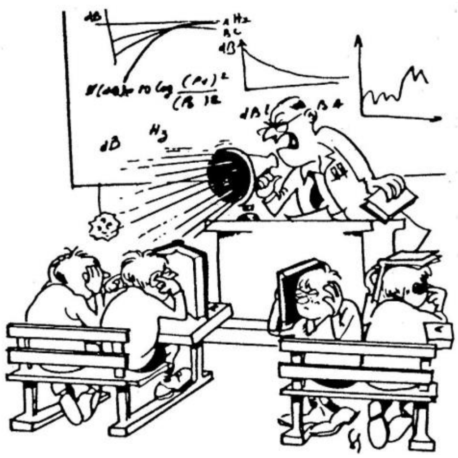


Figure 2.15. : Noise in a classroom [53]

2.6.1. <u>Influence of parameters on the Speech Intelligibility</u>

a. Early and late sound energy

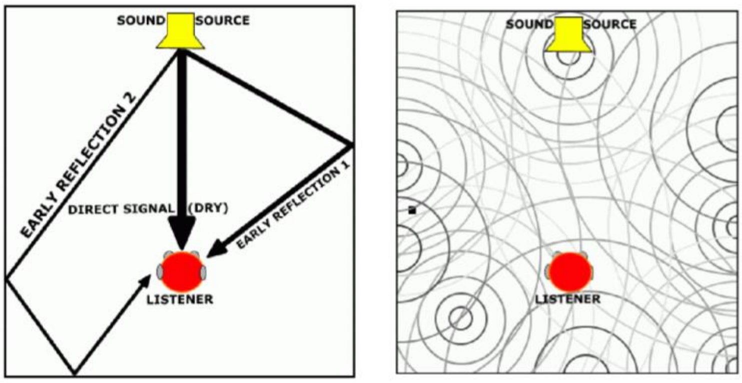


Figure 2.16: Direct and indirect sound [28]

In general, a speaker can talk in a space of 3,000m³ - 6,000m³. The bigger the volume, the more difficult it is for a speaker to be understood well. To overcome this, electro-acoustic resources can be used. This is represented in figures 2.16, 2.17 and 2.18. Figure 2.16 represents three possible sound paths in a space. However, the possibilities are infinite. There is a combination of the direct sound, early reflections and late reflections in the space. The early reflections can be useful for the Speech Intelligibility. The late reflections however are negative for the Speech Intelligibility. This will be explained using figures 2.17 and 2.18. Figure 2.17 represents the theoretical microphone signal when it gives a 'pulse' (a clap in your hands, a gunshot, a record, etc.). First of all the direct sound (shortest path, red line) arrives followed by the successive, reflective sound pulses (green lines). The amplitude of the pulses is getting smaller because of the increase of the distance and because of the absorption when reflecting against a wall. Reflecting sound needs more time to reach the listener: some reflecting pulses of a spoken vowel take so long to arrive that it coincides with the direct sound of a following vowel. This gives a longer RT and disturbs the Speech Intelligibility. Our hearing cannot capture the pulses separately. Neighboring pulses are energetic summed together which gives a pulse with reverberation. This summation is useful for the Speech Intelligibility. 'Early' pulses are combined with the direct sound and they increase the power and are considered as useful energy because it amplifies the sound pressure level and makes a speaker more intelligible. 'Later' pulses disturb the Speech Intelligibility: the speaker starts with a new sound when the previous sound still reverberates. This can be seen in figure 2.18. In acoustic practice, it is assumed that the upper limit for Speech Intelligibility is ca. 2,000 Hz and 1/20st of a second or 50 ms (millisecond). This leads to a dilemma: on the one hand, the RT should be lowered in order to limit the disturbing reverberation, on the other hand a too short RT causes a sound pressure level that is too low. It is the aim of the designer to find a good balance between those two. This means that the geometry (shape) of the space and the amount of absorption are important. The difference in path length between the direct sound wave and the reflected sound wave is very important. To avoid echo's, this difference should be lower than 17 m, corresponding to an elapsed difference in time of 50 ms. Exceeding this value gives our brain the interpretation of hearing an echo. For instance, musical events demand a maximum path length of 27 m: there is a need for a light echo which is important for the capacity of the music and for beautifying the music. A path length of 27 m corresponds with a difference in time of 80 ms. Reflections from the ceiling and walls are useful for the spatial effect of a space [51] [63] [64] [65].

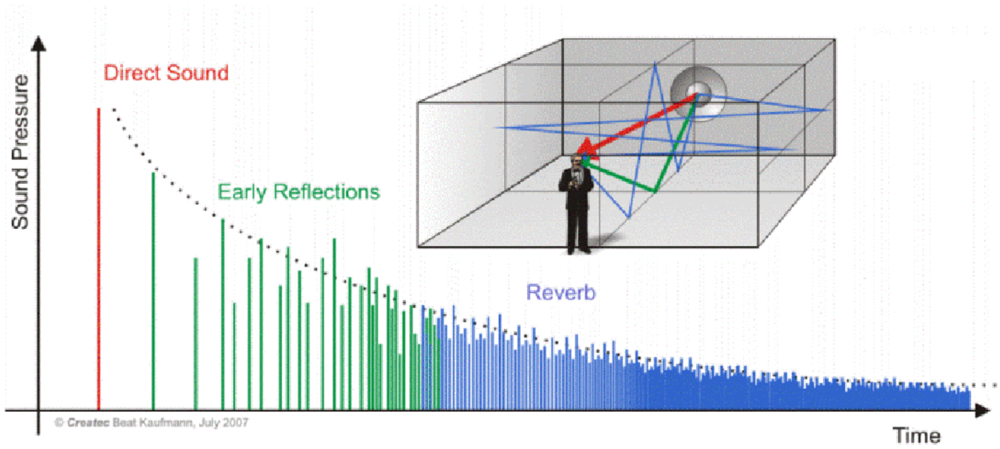


Figure 2.17: Direct sound, early reflection and reverberation [28]

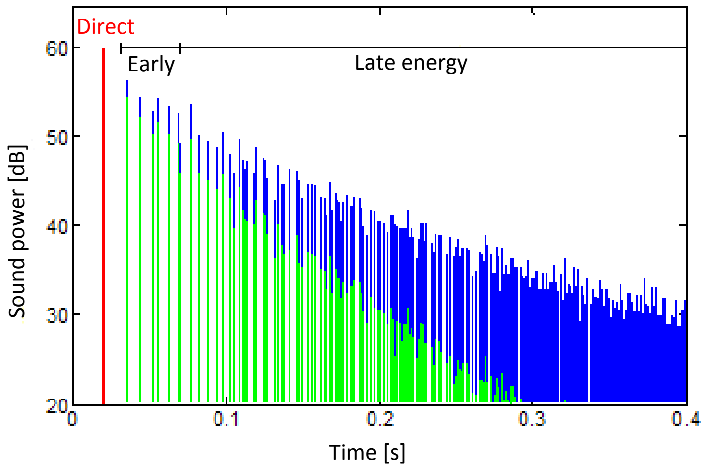


Figure 2.18: Influence of absorbing materials on the RT [51]

Using absorbing materials has an influence on the pulses. Several effects can be seen:

- The direct sound is independent of the absorption of a space. The loudness of a speaker can change, which will be indicated with direct power D of speech.
- The early power V, which arrives within 50 ms. Adding absorption gives a decrease of the value (and decrease of reverberation).
- The late power L which also decreases when adding absorption. The ratio between V and L gives the speech intelligiblity. Adding absorption materials gives an increase of the Speech Intelligibility.
- The total power T is the sum of V and L

Replacing the source and/or microphone changes the course of the pulse response. The value of D changes with its distance. The course of the pulses changes but the values of V, L and T stay the same, according to the Sabine-Franklin-Jaeger-theory [54]. They do change when there is change in absorption.

The ratio of the early power V (arrives before 50 ms) and late power L (arrives after 50 ms) gives an indication of the SI. It can be estimated from the RT by using the SFJ-theory (Sabine-Franklin-Jaeger-theory [54]). The theories of Sabine and Eyring predict a straight decay curve. For the sound energy this is an exponential attenuation as a function of time t as a reaction to a pulse on t = 0.

$$W(t) = W(t=0) \cdot \exp(\frac{-13{,}8 \ \cdot t}{RT})$$

Integrating this formula from 0 to 50 ms gives the early energy. Integrating from 50 ms to infinite gives the late energy:

$$E_{early} = E_0(1 - \exp\left(\frac{-0{,}69}{RT}\right))$$

$$E_{late} = E_0(\exp\left(\frac{-0{,}69}{RT}\right))$$

where:

E_0 – Constant which doesn't matter because it will disappear in the next models.

The general formula for sound pressure level was given as:

$$L_{p,brn} = L_w + 10 \ \log\left(\frac{Q}{4\pi r^2} + \frac{4(1-\alpha)^{r/_{mfp}}}{\alpha \cdot S}\right)$$

Where L_w is the sound pressere level from any source. To evaluate SI, it is uselful to use $L_{w,speech}$. The formula becomes:

$$L_{p,early} = L_{w,speech} + 10 \ \log\left(\frac{Q}{4\pi r^2} + \frac{4(1-\alpha)^{fb \cdot r/_{mfp}}}{\alpha \cdot S}(1 - \exp\left(\frac{-0.69}{RT}\right))\right)$$

$$L_{p,late} = L_{w,speech} + 10 \ \log\left(\frac{4(1-\alpha)^{fb \cdot r/_{mfp}}}{\alpha \cdot S}\exp(\frac{-0.69}{RT})\right)$$

b. SN-ratio

A first quantity that will be calculated for the auditoria in this study is the signal to noise ratio or SN-ratio. With this quantity the Speech Intelligibility of a space can be evaluated. This is equal to the speech level SL in dBA minus the background noise level BGN in dBA, both at the listener's position. The speech level depends on the speaker's voice level, the distance between the speaker and the listener and on the acoustic conditions in the classroom. The background noise level results from noise, coming from the ventilation system, projectors, in-class student activity, sources outside the classroom and reverberation. However, for this study, only the reverberation will be considered as background noise. Therefore, the acoustic quality will be measured on a Saturday (not much traffic, no students) because it is the aim to evaluate only the quality of the auditoria and not the entire room acoustic quality. The levels depend on the acoustic conditions in the classroom. A disadvantage of the formula for the sound pressure level $L_{p,brn}$ is that the sound power level L_w has to be known. In order to filter this out of the formula, the signal is compared with the sound pressure level in the free field at a distance of 10 m from the source with Q = 1. This gives a sound pressure level of L_w = 31 dB. The difference is called the strength G and can be written as:

$$G = 31 + 10\ \log\left(\frac{Q}{4\pi r^2} + \frac{4(1-\bar{\alpha})}{S_{tot}}\right)$$

The sound power level and the strength are used to define the sound pressure level produced by a source in a space. They are more suited to predict noise levels in spaces than RT. This is also why G-RT-diagrams are a very powerful tool for the comparison between measured and calculated RT. The correlation for G is higher than for RT which is as expected since the ray-tracing models used for predicting the RT are based on sound energy propagation [59].

The equation for the strength G was developed by Barron [55] as:

$$G = 31 + 10\ \log\left(\frac{Q}{4\pi r^2} + \frac{\exp(\frac{-0.04 \cdot r}{RT})}{S_{tot}}\right)$$

It depends on the directivity of the source is Q, the source receiver distance r and the RT. This equation is useful when one specific distance is reached, the mean free path: $r = \frac{4 \cdot S}{V}$. The equation can then be converted into:

$$G = 31 + 10\ \log\left(\frac{4(1-\bar{\alpha})}{S_{tot}}\right)$$

This equation can be used backwards to calculate α from measurements of G. The same can be done with Sabine's formula for the RT.

To describe the Speech Intelligibility in an auditorium, the equation for G will be separated into the direct field and the diffuse field. This gives:

$$G_{dir} = 31 + 10\ \log\left(\frac{Q}{4\pi r^2}\right)$$

$$G_{diff} = 31 + 10\ \log\left(\frac{4(1-\bar{\alpha})}{S_{tot}}\right)$$

Eventually, the signal-noise ratio can be written as the difference between those two:

$$\frac{S}{N} = G_{dir} - G_{diff}$$

$$\frac{S}{N} = 10 \log\left(\frac{Q}{4\pi r^2}\right) - 10 \log\left(\frac{4(1-\bar{\alpha})}{S_{tot}}\right)$$

$$\frac{S}{N} = 10 \log\left(\frac{\frac{Q}{4\pi r^2}}{\frac{4(1-\bar{\alpha})}{S_{tot}}}\right)$$

where:

Q – Directional coefficient of the source = 2.5

r – Distance from the source to the point of measurement [m]

S_{tot} – Total surface area of the space [m²]

$\bar{\alpha}$ – Average absorption coefficient [-]

Research has shown that to obtain a Speech Intelligibility of 100 % for normal-hearing people the RT must not exceed 0.7 s. With this RT, the signal-noise ratio must exceed 15 dB. Given typical speech levels, this implies that the background noise level must not exceed about 35 dBA [66]. The results of the calculation of the SN-ratio will be given in chapter 4 - '*Measurement results*'.

Using the results of the SN-ratio the space has a certain normative quality [51] which is given in table 2.3.

Bad	Poor	Good	Excellent
SN < -6 dB	-6 dB < SN < 0 dB	0 dB < SN < 6 dB	SN > 6 dB

Table 2.3: Qualification based on the SN-ratio [51]

c. C_{50}-value

The quality number C_{50} is another method to evalute the SI of a space and therefore will also be used for this study. It gives the difference between 'direct + early' sound and 'late' sound pressure level. It has been derived from an older German quantity D_{50} which stands for 'Deutlichkeit'. D_{50} provides the ratio between the total early power of direct + early and the total power of direct + diffuse which gives directly a number between 0 and 1. The C_{50}-value works logarithmic as D_{50} does not. Therefore, the C_{50}-value is more convenient and is more used in practice. Loudness has no impact on the value of C_{50} or D_{50}. This is in conflict with our daily experience: talking more softly results in lower SI. The reason is that there is always some noise in the space at low sound pressure levels. The lower the sound, the more the sound level under the limit goes. This is also a type of a source of noise. If it is possible to have a very low backgroundlevel, the C_{50}–value is indeed constant. The quantity C_{50} gives the SI where only the reveberation of the speaker itself disturbs [7].

The C_{50}-value can be calculated as:

$$C_{50} = L_{p,early} - L_{p,late}$$

$$C_{50} = 10 \log \left(\frac{Q}{4\pi r^2} + \frac{4(1-\alpha)^{fb \cdot r / mfp}}{\alpha \cdot S} (1 - \exp\left(\frac{-0,69}{RT}\right)) \right) - 10 \log \left(\frac{4(1-\alpha)^{fb \cdot r / mfp}}{\alpha \cdot S} \exp\left(\frac{-0,69}{RT}\right) \right)$$

This equation will be used to calculate the C_{50}-value for the auditoria at different distances away from the source. For great distances (not for the case of auditoria) the first term drops out of the formula. If only the diffuse field is considered, the C_{50}-value can also be written as:

$$C_{50} = 10 \log \left(1 - \exp\left(\frac{-0.69}{RT}\right) \right) - 10 \log \left(\exp\left(\frac{-0.69}{RT}\right) \right)$$

$$C_{50} = 10 \log \left(\frac{1 - \exp\left(\frac{-0.69}{RT}\right)}{\exp\left(\frac{-0.69}{RT}\right)} \right)$$

This last formula to calculate the C_{50}-value is useful when there is no noise and when the distance of the source is quite big so that the diffuse sound has no influence. Closer to the source, the value is not longer correct because the direct sound makes the value of C_{50} rising. If the RT = 1 s, the C_{50}-value becomes equal to 0 dB. It is interesting to see that raising the voice of the speaker has no impact on the value because the sound power level is filtered out of the formula.

However, it is possible to determine a ‘minimum requirement’. If a C_{50}-value of 6 dB can be realized (which is a good value for a classroom), the RT cannot exceed 0.43 s. In the front of the classroom, the C_{50}-value is higher because of the direct sound but in the back of the classroom, the C_{50}-value and thus the SI is lower because of the noise that is present. An RT of 0.43 s can thus be seen as a ‘minimum requirement’. The results of the calculation of the C_{50}-value will be shown in chapter 4 - ‘*Measurement results*’.

Using the results of the C_{50} the space has a certain normative quality [51] which is given in table 2.4.

Bad	Poor	Fair	Good	Excellent
C_{50} < -8.5 dB	-8.5 dB < C_{50} < -3.5 dB	-3.5 dB < C_{50} < 1.5 dB	1.5 dB < C_{50} < 6.5 dB	6.5 dB < C_{50} < 11.5 dB

Table 2.4: Qualification based on the U_{50}-value [51]

d. U_{50}

Not only the reverberation of the speaker itself but also noise has an influence on SI. There are several kinds of noise such as ventilation, background noise of a highway or an airplane. When there is noise it is convenient to use U_{50} instead of the C_{50}-value. The power of the noise is surmised with the power of the late sound of the speaker. U_{50} is always lower in comparison with the C_{50}-value. For the C_{50}-value, the absolute sound level of speech does not matter because it is about the ratio between the powers. For the U_{50}, the loudness of the speech and noise are independent. When there is a lot of noise, one can speak louder to increase U_{50}.

To calculate U_{50}, the position of the source of the noise is not always exactly known (for example ventilation, several speakers, etc.). The noise can be considered as a uniform distribution when the distance between source of noise and observer is relative big because it contains the diffuse field.

The noise pressure level can be described as:

$$L_{p,noise} = L_{w,noise} + 10 \log\left(\frac{4}{\alpha \cdot S}\right)$$

The late sound and noise must be added to each other, which gives:

$$L_{p,late+noise} = L_{w,speech} + 10 \log\left(\frac{4(1-\alpha)^{fb \cdot r/_{mfp}}}{\alpha \cdot S} \exp(\frac{-0.69}{RT})\right) + \frac{4 \cdot 10^{\frac{-SN}{10}}}{\alpha \cdot S}$$

where:

$SN = L_{w,speech} - L_{w,noise}$

SN is called the signal-noise ratio as already mentioned. It is important to know that in literature they commonly use the sound pressure level instead of the sound power level. Using sound power level is more accurate. Using absorption gives a decrease of the sound pressure level but the sound power level remains equal. That is why several absorption coefficients for a space have to be used.

The difference between $L_{p,early}$ and $L_{p,late+noise}$ gives the U_{50}-value:

$$U_{50} = L_{p,early} - L_{p,late+noise}$$

$$U_{50} = 10 \log\left(\frac{Q}{4\pi r^2} + \frac{4(1-\alpha)^{fb \cdot r/_{mfp}}}{\alpha \cdot S}(1 - \exp\left(\frac{-0.69}{RT}\right))\right) - 10 \log\left(\frac{4(1-\alpha)^{fb \cdot r/_{mfp}}}{\alpha \cdot S} \exp(\frac{-0,69}{RT})\right) + \frac{4 \cdot 10^{\frac{-SN}{10}}}{\alpha \cdot S}$$

In contrast with the C_{50}-value, raising the voice of the speaker has impact on the value of U_{50}. The speaker tries to exceed the ambient noise.

Using the results of the U_{50} the space has a certain normative quality [51] which is given in table 2.5.

Bad	Poor	Fair	Good	Excellent
$U_{50} < -8.5$	$-8.5 < U_{50} < -3.5$	$-3.5 < U_{50} < 1.5$	$1.5 < U_{50} < 6.5$	$6.5 < U_{50} < 11.5$

Table 2.5: Qualification based on the U_{50}-value [51]

However, for this study the U_{50}-value will not be calculated as there is no noise taken into account.

e. STI

It can be surmised that spectral effects and specific reflections also have to be taken into account. In the seventies, the concept of STI is developed by Houtgast and Steeneken [67]. They believe that the Speech Intelligibility is essentially a matter of modulation transfer: the variations in strength associated with speech are transferred in a sufficient manner. Indeed, in the presence of strong reverberation or background noise the amplitude variation is suppressed. [7]

The speech transmission index STI is the quantity that is mostly used to evaluate Speech Intelligibility and takes this into account. It is an objective measure, based on the contribution of a number of frequency bands within the frequency range of speech signals. The contribution is determined by the effective SN-ratio (it is called effective because it may be determined by several factors, the most obvious one being background noise) [67]. Nowadays it is also possible to predict the STI with complex ray-tracing models when designing a room. Nevertheless the STI is more useful for measurements that have been done in a space than for calculations in the designing-phase.

For the different frequencies of speech and for the different modulation rhythms, the modulation transfer function mtf has to be determined. The measurement and/or the calculation of the transfer occurs in octave bands. The transfer in one octave band is called transmission index (TI). Out of a curve a value of m can be deducted: the modulation transfer function. Next a logarithmic value SNR has to be chosen which can be described as:

$$SNR = 10\log\left(\frac{m}{1-m}\right)$$

where:

m – Modulation transfer function [-]

When m = 0.5; SNR = 0 dB and when m =1 there is an ideal transfer, so that SNR is infinite. A value of 0 for m (when there is no transfer) gives a value of minus infinite for SNR. In practice, SNR = 15 dB indicates that noise or reverberation is inaudible when there is somebody speaking. When SNR = -15 dB it indicates that the speaker is not audible anymore because of noise or reverberation. This is the reason why the STI-method only uses the range of -15 dB and 15 dB to evaluate the SI. STI gives a value between 0 and 1 respectively at SNR -15 dB and 15 dB. The conversion factor is linear:

$$TI = \frac{SNR + 15}{30}$$

Out of these 7 values for TI, one number can be calculated using weight factors: the STI. These weight factors are determined by the importance of the corresponding frequency band. For SI, 2,000 Hz and 4,000 Hz are the most important ones. Table 2.6 represents the weight factor for the frequency bands between 125 - 8,000 Hz and between 125 - 4,000 Hz.

Octave band [Hz]	125	250	500	1,000	2,000	4,000	8,000
Weight factor [125 – 8,000 Hz]	0.13	0.14	0.11	0.12	0.19	0.17	0.14
Weight factor [125 – 4,000 Hz]	0.15	0.16	0.13	0.14	0.22	0.20	/

Table 2.6: Weight factors

However, for this study, a simplification will be made to calculate the STI. A correlation will be used between the C_{50}-value and TI. To calculate the C_{50}-value, the nominal RT is taken into account. The C_{50}-value is calculated with the formula which is already given in the discussion of the C_{50}-value. Using this correlation the STI can be calculated at different distances away from the source. These results will be presented in chapter 4 - '*Measurement results*'.

$$TI = 0.030 \cdot C_{50} + 0.555$$

STI has a value between 0 and 1. STI = 0.3 forms the threshold to understand sentences. Using the results of the STI, a space has a certain normative quality [67] [51] which is given in table 2.7.

Bad	Poor	Fair	Good	Excellent
STI < 0.30	0.30 < STI < 0.45	0.45 < STI < 0.60	0.60 < STI < 0.75	STI > 0.75

Table 2.7: Qualification based on the STI-value [67] [51]

f. Other quantities to evaluate Speech Intelligibility

In 1971 Peutz and Klein [68] introduced a method of calculating the **Alcons** (Articulation Loss of Consonants) [69]. Consonants are more important in SI than vowels. The intention of the method is to make calculations in the designing-phase. It is quite the same method as the C_{50}-value but the numbers are calculated in a different way. A value of 0 - 3 % means that there is hardly any loss of consonants which leads to an excellent Speech Intelligibility. In practice it is often used, but more in America than in Europe. It is often used when there has to be an amplifier installation.

The **AI** (Articulation Index) is developed in America [70]. It only takes the signal-noise ratio into account and not the influence of the reverberation. However, in America it is often used in restaurants, offices, etc. because in such spaces the signal-noise ratio is normative.

SP (Speech privacy) is the ability to have a confidential discussion. There is no separate quantity; mostly STI or AI is used. A low value of STI results in a low Speech Intelligibility but a high speech privacy.

2.6.2. Comparison U_{50}, C_{50}, STI and SN-ratio to evaluate Speech Intelligibility

The STI can be measured with an instrument but it can also be calculated if the pulse reaction is known. This is possible with a ray-tracing-model, which has the advantage that it can be calculated in the designing-phase. However, for a restaurant for instance, a simple scheme is missing. But there are formulas that take the impact of reverberation into account; the RT is then considered as a low-pass filter [66] [71] [72]. A distribution between direct and early sound is often difficult. That is the reason why U_{50} may be eligible [51].

However, the quantities U_{50} and STI can be used interchangeable without any problems because their correlation is very big. Bradely shows these correlations with several correlation methods [66] [71] [72].

As already mentioned, the correlation between TI (value for each frequency band) and the C_{50}-value (minimal noise) is given by:

$$TI = 0.030 \cdot C_{50} + 0.555$$

$$C_{50} = 33.33 \cdot TI - 18.5$$

An increase of 0.15 in TI corresponds with an increase of 5dB in the C_{50}-value.

If either STI or U_{50} is possible it is best to use the parameter STI. U_{50} has a limit of 50 ms: a reflection against a ceiling after 51 ms gives a totally different value when there is a reflection after 49 ms. This weakness can be solved by using a flow transition. However, this problem does not affect STI. The U_{50}-value will not be calculated in this study.

There is also a correlation between the SN-ratio and the STI. A SN = -6 dB corresponds with the lower limit of the STI = 0.3. A SN = 0 dB corresponds with a good SI (STI = 0.6). SN = +6 dB is called ‘excellent’. Note that if SN = 0 dB, direct and diffuse are even strong. The distance where the SN-ratio becomes equal to 0 is the so called reverberation radius.

3. METHODOLOGY OF THE MEASUREMENTS

3.1. Scope

In the experimental part of this study the RT will be measured in ten auditoria of the Faculty of Engineering and Architecture at Ghent University. The decay curve is a curve indicating the decay of the sound pressure level as a function of time in one point in space after the sound source has been interrupted and for one particular frequency. This decay has to be measured after the actual cut-off of a continuous sound source in the space (interrupted noise method) or it can be derived from the reverse-time integrated squared impulse response of the space (integrated impulse response method). In this study, it is measured after the actual cut-off of a continuous sound source, so the interrupted noise method is used. This is a method of obtaining decay curves by direct recording of the decay of sound pressure level after exciting a space with broadband or band limited noise and turning it off. It is not recommended to obtain the decay directly after non-continuous excitation of a space (e.g. by recording a gunshot with a level recorder). It gives no accurate evaluation of the RT. The method is only useful for survey purposes.

The decay curve is not monotonic. This implies that the range that has to be evaluated is defined by the times at which the decay curve first reaches 35 dB and 65 dB below the initial level. It is also allowed to use a value for the RT based on the decay rate over a dynamic range of 20 dB and further interpolating the results. In this study, the range which is used is 30 dB. Measuring the decay between 35 dB and 65 dB is labelled RT_{30}. This is represented in figure 3.1.

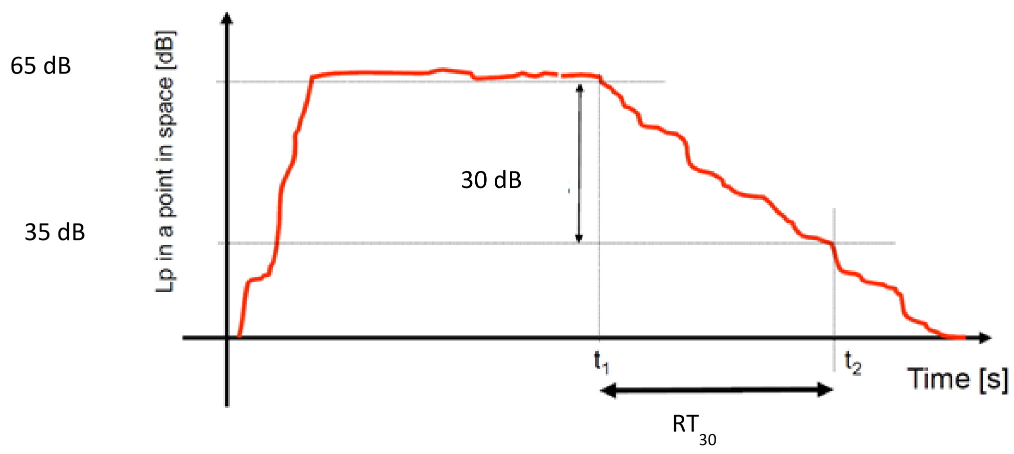


Figure 3.1: Decay curve RT_{30} [28]

The scope of this study is to compare the measured values of this experiment with the results which are calculated with the seven selected models, given in the literature study chapter 1.7 – '*Selection of the RT models for this study*'. The measurements will also be compared with acoustic quality numbers, the Acoustic Standard for School Buildings NBN S 01-400-2 [6] and a survey in chapter 4 - '*Measurement results*'. The current chapter provides an overview of the method that is used for measuring. The measurements are performed according to the International Standard ISO/CD 3382-2 [2]. The next table shows some general information of each auditorium where measurements are performed.

AUD	Dimensions					Absorption	
	Volume [m³]	Length [m]	Width [m]	Height [m]	Compactness [m]	α global [-]	Location*
A	2118	22.00	19.25	5.00	1.37	0.20	C/W
C	333	10.35	7.27	4.43	1.50	0.21	C/W
D	1121	19.62	12.12	4.80	1.21	0.16	C/W
E	542	13.40	8.37	4.83	0.96	0.06	3W
G	576	10.30	10.00	5.59	1.20	0.08	3W
H	284	9.00	6.30	5.00	0.95	0.03	/
I	439	14.00	6.27	5.00	0.83	0.10	3W
J	319	10.00	6.50	4.90	0.99	0.10	3W
K	519	9.90	9.95	5.27	1.11	0.04	/
N	996	22.00	9.43	6.92	1.15	0.19	C/3W
*C/W: absorption on the ceiling and on the rear wall – 3W: absorption on three walls – C/2W: absorption on the ceiling and on two opposite walls – /: no absorption							

Table 3.1: Data of ten auditoria

3.2. Measurement Conditions

3.2.1. General

The RT measurements are performed in unoccupied rooms. The acoustic impact of the presence of people will be higher in small spaces than in big spaces. However, it is allowed to represent the space as 'unoccupied' with up to two persons present in the space, unless something else is demanded by the requirements. It is important to have the same occupancy when the measuring result of the RT is used for correction of a measured sound pressure level. During the measurements for this experimental study, only two persons were present in the auditoria.

The temperature and relative humidity of the air in the space must be measured for more accurate measurements: at high frequencies in large spaces, the attenuation by the air may contribute significantly to the sound absorption. If the RT is shorter than 1.5 s at 2,000 Hz and shorter than 0.8 s at 4,000 Hz the contribution from air absorption is of minor importance. It is not necessary to measure the temperature and relative humidity if one of the conditions is satisfied. In this experimental study, the relative humidity is taken at 50 % to 70 %, and the mean temperature at 20 °C.

3.2.2. <u>Equipment</u>

Figure 3.2: Sound source and amplifier (Mackie SRM 450 v2)

The sound source should be as close to an omni-directional as possible. This gives more accurate measurements. To validate this, the loudspeaker is placed in a corner of the space, facing the corner walls at a distance of approximately 1.5 m. The sound source should also produce a sound pressure level that is sufficient to provide decay curves with the required minimum dynamic range. There is no disturbance from background noises. The measurements take place in time periods avoiding noise from students, traffic, ventilation, etc. The used sound source is a full-range, portable, powered loudspeaker system providing high-output, ultra-wide dispersion and low-distortion performance. More specifications can be found in the product data in annex 8.7 – '*Product data'*.

The noise used by the amplifier is white noise, a random signal with a constant power spectral density. An infinite-bandwidth white noise signal is a theoretical construction. The bandwidth of white noise is limited in practice by the mechanism of noise generation, by the transmission medium and by finite observation capabilities. Thus, a random signal is considered 'white noise' if it has a flat spectrum over the range of frequencies that is relevant to the context. For an audio signal, for example, the relevant range is the band of audible sound frequencies, between 20 to 20,000 Hz. Such a signal is heard as a hissing sound (resembling the /sh/ sound in 'ash'). In music and acoustics, the term 'white noise' may be used for any signal that has a similar hissing sound.

Figure 3.3: Sonometer and earmuff

To measure the RT a sonometer is used. The sonometer (sound level meter) records and displays everything for later analysis. It is also needed for creating, displaying and/or evaluating the decay record.

The microphone should preferably have a maximum diaphragm diameter of 14 mm. It should be as small as possible. If the microphone is based on the pressure response type or on the free field response type with a random incidence corrector, then a maximum diameter of 27 mm is allowed. The filters (octave or one-third octave) should be conform to IEC 1260. In this study, the sonometer is a ‘hand-held Analyser Type 2250’ (Bruël and Kjaer) and has a free-field ½” microphone type 4189. More specifications are given in annex 8.7 – ‘*Product data’*.

The device uses any of the following options for displaying the decay curves:

- Exponential averaging, with continuous curve as output
- Exponential averaging, with successive discrete sample points from the continuous average as output. The time interval between points on the record should be less than 1.5 times the averaging time of the device.
- Linear averaging, with successive discrete linear averages as output (in some cases with small pauses between performances of averages)

The averaging time is the time constant of an exponential averaging device. This should not be higher than RT_{30}, but as close as possible to this value. It is equal to 4.34 divided by the decay rate in decibels per second of the device. Commercial level recorders, in which sound pressure level is recorded graphically as a function of time, are usually equivalent to exponential averaging devices. There is little advantage in setting the averaging time very much less than $\frac{RT}{30}$. In some sequential measuring procedures it is feasible to reset the averaging time appropriately for each frequency band. In other procedures this is not feasible, and an averaging time or interval chosen as above with reference to the shortest RT in any band has to serve for measurements in all bands. In this study the last method is used. The averaging time of a linear averaging device should be less than $\frac{RT}{12}$ with RT being the measured RT.

A distribution of sound for the sound source can be found in annex 8.7 – ‘*Product data’*. It can be noticed that the distribution is not always omni-directional.

3.2.3. *Position of the measurements*

Several measurement positions have to be taken into account to achieve an appropriate coverage in the space. The number of measurement positions is given in table 3.2 and represents a minimum.

	Survey	Engineering *	Precision
Source-microphone combinations	2	6	12
Source positions	≥ 1	≥ 2	≥ 2
Microphone positions	≥ 2	≥ 2	≥ 3
Number of decays in each position (interrupted noise method)	1	2	3
* When the result is used for a correction term to other engineering-level measurements, only one source position and three microphone positions are required.			

Table. 3.2: Minimum requirements for the measurements [2]

The more complex the space, the more measurement positions should be used. A distribution of microphone-positions has to be chosen, taking the major influences into account to cause differences in the RT throughout the space.

There are two possibilities to obtain the total number of decays. It can be obtained by a number of repeated decays in each position or it can be obtained by taking a new position for each decay, provided that the total number of decays is as prescribed. For this experimental study the engineering method is used: in each position two decays are obtained and dependent of the size of the space 9, 12 or 18 positions are taken into account.

The source position is chosen as the normal position according to the use of the space. In auditoria the normal positions are known (in contrast to domestic spaces where no normal positions exist). The microphone position should be at least half a wavelength apart. For the usual frequency range, this is a minimum distance of around 2 m. They cannot be too close together otherwise the number of independent positions is less than the actual number of measurement positions. The microphone should also be at least a quarter of a wavelength away from the nearest reflecting surface, including the floor. This is normally around 1 m. Symmetric positions are not preferable. The microphone position cannot be too close to any source position, as the direct sound would have a too strong influence. The minimum distance d_{min} can be calculated as:

$$d_{min} = 2\sqrt{\frac{V}{cRT}}$$

where:

V – Total volume of the space[m^3]

c – Speed of sound [m/s]

RT – Estimate of the expected RT [s]

For example for auditorium A (V = 2,117.5 m³, $RT_{nom, Sabine}$= 0.79 s) a minimum distance of 5.58 m is taken into account.

Table 3.2 distinguishes three methods of measuring the RT. The survey method will be used when there is information needed about the amount of the space absorption for noise control purposes and about the sound isolation. These survey measurements are made in octave bands only. For octave bands, the nominal accuracy should be better than 10 %. Measurements for at least one source-position and at least two microphone-positions have to be made (see table 3.2).

The engineering method is used for verification of building performance which is also the aim of this study. The results can be compared with specifications of RT or space absorption. This method should be used for measurements in ISO 140 Parts 4, 5 and 8. The nominal accuracy should be better than 5 % in octave band and better than 10 % in one-third octave bands. For this method, measurements for at least one source-position and at least three microphone-positions have to be made (see table 3.2).

The precision method is used when high measurement accuracy is required. The nominal accuracy should be better than 2.5 % in octave bands and better than 5 % in one-third octave bands. Measurements have to be made for at least two source-positions. There are at least 12 independent source-microphone-positions required. This means that a minimum of 36 decays is required for the interrupted noise method (three decays in each position or 1 decay in each of 36 positions). One decay in each 36 positions gives a more accurate measurement.

As already mentioned above, the engineering method is used for this experimental study.

3.3. Measurement Procedures

3.3.1. <u>General</u>

As previously mentioned, there are two methods for measuring the RT (according to ISO/CD3382-2): the interrupted noise method and the integrated impulse response method. In this study the interrupted noise method is used. There is no difference in the expectation value. Depending on the purpose of the measurements, another frequency range can be chosen. For the survey method, the frequency range should cover at least 250 Hz to 2,000 Hz. For the engineering and precision method the frequency range should cover at least 125 Hz to 4,000 Hz in octave bands, or 100 Hz to 5,000 Hz in one-third octave bands. In this study a frequency range from 125 Hz to 4,000 Hz in octave bands is used.

3.3.2. Interrupted noise method

a. Excitation of the room

The signal from the loudspeaker source should be derived from broadband random electrical noise or broadband pseudo-random electrical noise. A pseudo-random noise is randomly ceased not using a repeated sequence. The loudspeaker source has to produce a peak sound pressure level sufficient to ensure a decay curve starting at least 35 dB above the background noise in the corresponding frequency band. There is at least 45 dB above the background level needed to measure RT_{30}. When measuring in octave bands, the bandwidth of the signal should be bigger than one octave. Measuring in one-third octave bands, the bandwidth should be bigger than one-third octave. The spectrum should be reasonably flat within the actual octave band to be measured. Another way is shaping the broadband noise spectrum to provide a pink spectrum of steady-state reverberant sound in the space from 88 Hz to 5,657 Hz. Thus the frequency range covers the one-third octave bands with mid-frequencies from 100 Hz to 5,000 Hz or octave bands from 125 Hz to 4,000 Hz. For this study, the octave bands from 125 Hz to 4,000 Hz will be used.

The duration of excitation of the space should be sufficient for the sound field to have achieved a steady state before the source is switched off. This is for the engineering and precision methods. The noise should be radiated for a minimum period of $\frac{RT}{2}$ seconds. For large volumes, the duration of excitation should be at least a few seconds.

An alternative to the interrupted noise signal is a short excitation or an impulse signal. This is less accurate and can only be used for the survey method. That is why it is not used in this study.

b. Averaging of measurements

The measured results (with different microphone positions which depend on the required accuracy) can be combined either for separate identified areas or for the space as a whole. In this study a mean RT has to be calculated to evaluate an entire auditorium. To achieve an acceptable measurement uncertainty, it is necessary to average over a number of measurements at each position because of the randomness inherent in the source signal. Making the spatial averaging can be done in two different ways:

1. Arithmetic averaging of the RT: taking the mean of the individual RT for all the relevant source and microphone positions. A standard deviation has to be determined to provide a measure of accuracy.
2. Find the RT of the decay curve that is a result of an ensemble average of the squared sound pressure decays. The individual decays have to be superposed with their beginnings synchronized. For each time interval increment of the decays the discrete squared sound pressure sample values are summed. The sequence of these sums is used as a single overall ensemble decay from which RT

is then evaluated. It is important that the sound power emitted by the source is kept the same for all measurements.

For this study the first method is used: an arithmetic average of the individual RT is calculated.

3.3.3. Integrated impulse response method

The integrated impulse response method gives a well-defined quantity of the impulse response from a source position to a receiver position in a space. This quantity can be measured in different ways. For example: using pistol shots, spark gap impulses, noise bursts, chirps or m-sequences as signal, etc. This method will not be used in this study since the results are less accurate.

Using an impulse source such as a pistol shot or any other source which is not reverberant itself, the impulse response can be measured, as long as its spectrum is broad enough to meet the requirements. Special sound signals may be used which yield the impulse response only after special processing of the recorded microphone signal, see ISO 18233. This can provide an improved signal-to-noise ratio. It is necessary to verify that the averaging process does not alter the measured impulse response if time averaging is used. The frequency filtering is often inherent in the signal analysis and it is sufficient that the excitation signal covers the frequency bands to be measured.

The decay curve has to be generated for each octave band or one-third octave band by a backward integration of the squared impulse response.

3.4. Evaluation of decay curves

To determine RT_{30} the evaluated range for the decay curves is from 65 dB to 35 dB. Within the evaluation range a least-squares fit line has to be computed for the curve. When the decay curves are plotted directly by the sonometer, a straight line has to be fitted manually as closely as possible to the decay curve (see figure 3.4). The rate of decay (in decibels per second) is given by the slope of this straight line. It is essential that the decay curves follow approximately a straight line in order to specify a RT. A wavy or bending curve indicates a mixture of modes with different RT and the result will be unreliable [2].

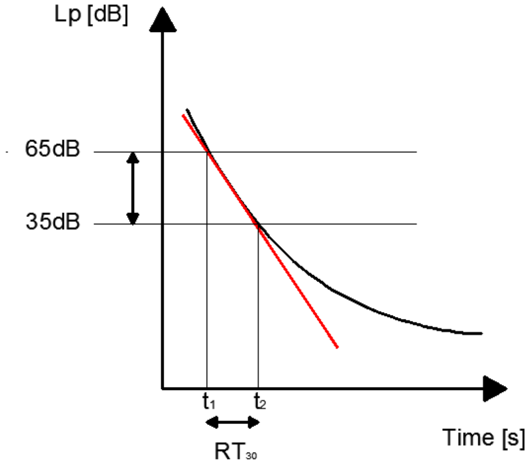


Figure 3.4: Straight line fitted close to the decay curve to find the rate of decay

3.5. Measurement uncertainty for the interrupted noise method

There are two methods to calculate the measurement uncertainty. In chapter 4 – *'Measurement results'*, the results of these two methods will be compared with each other.

3.5.1. Method 1 – Depending on the conditions of the experiment

The first method takes the measurement conditions into account. The excitation signal depends on the random nature. That is why the number of averages performed has a strong influence on the measurement uncertainty of the interrupted noise method. The relative standard deviation of the measurement result RT_{30} can be estimated from:

$$\frac{\sigma(RT_{30})}{RT_{30}} = 55 \cdot \sqrt{\frac{1 + \frac{1.52}{n}}{N \cdot B \cdot RT_{30}}}\ \%$$

where:

n – The number of decays measured in each position (in this study n = 1)

N – The number of independent measurement positions (combinations of source and receiver positions)

B – The bandwidth [Hz] (in this study B = 0.71 f_c)

RT_{30} – The RT at the corresponding frequency [s]

For an octave filter B = 0.71 f_c and for one-third octave filter B = 0.23 $f_{c,}$ where f_c is the mid-band frequency of the filter in Hz. A better accuracy is obtained using octave measurements instead of one third octave measurements with the same number of measurement positions.

3.5.2. *Method 2 – Mathematical*

Another way to calculate the standard deviation σ is arithmetic. The different positions are considered as N independent observations $RT_{30,pos.1}$, $RT_{30,pos.2}$, …, $RT_{30,pos.n}$ of a normal distributed variable RT ~ N(μ, σ^2). A confidence interval of 95 % (coverage factor k = 1.96) can be calculated. This means that based on these observations it can be assumed that the mean RT is located in an interval with a certainty of 95 %. This can be written as:

$$P\left[-1.96 \le \frac{RT_m - \mu}{\sigma/\sqrt{N}} \le 1.96\right] = 95\ \%$$

This interval can be calculated as:

$$\left[RT_m - 1.96\,\frac{\sigma}{\sqrt{N}}\,, RT_m + 1.96\,\frac{\sigma}{\sqrt{N}}\right]$$

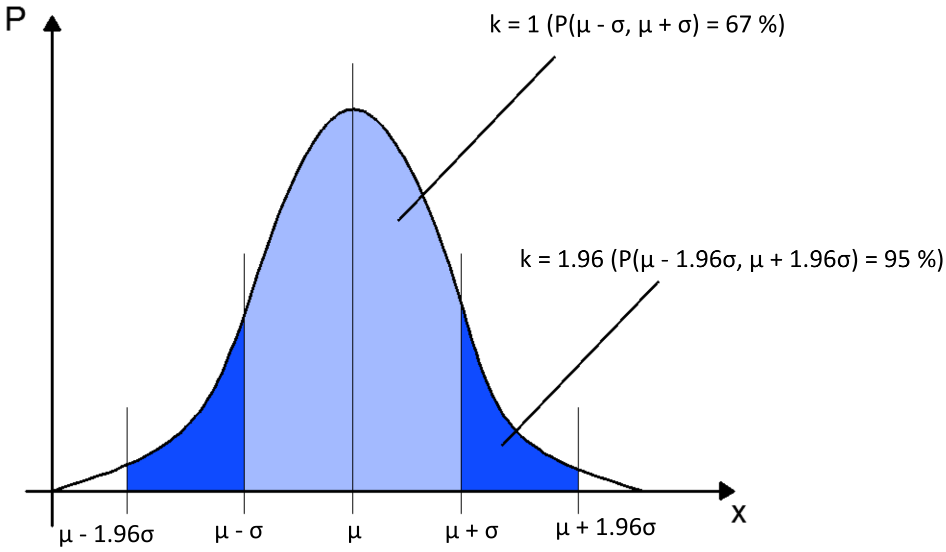


Figure 3.5: Gauss-curve, shows the confidence interval of 67 % and 95 %

4. MEASUREMENT RESULTS

4.1. Goal of the measurements

In this chapter the results of the experimental part of this study are given. The measurements are performed twice on different days and times in order to obtain more confidence in the results of the measurements and to avoid possible false results. The results of the measured RT and the standard deviation are given and are compared with the Acoustic Standard for School Buildings NBN S 01-400-2 [6]. These results will also be compared with the calculations of some important quality numbers in order to know which parameter is reliable to use: the SN-ratio, the C_{50}-value and the STI. There is also a survey handed out to the students in order to compare these previous objective parameters with subjective parameters such as the Speech Intelligibility and the Global Impression GI. It is important to know if the survey is qualitative enough. Finally, based on all these parameters an evaluation of the acoustic quality of the ten auditoria will be made. This method is represented in figure 4.1. In the last part of this chapter a summary is given and a classification of the auditoria into four categories based on the previous parameters is made. Within these categories, the validation of the different prediction models can be analyzed in chapter 5 – *'Calculation of the RT using different models and comparison with the measurements'.*

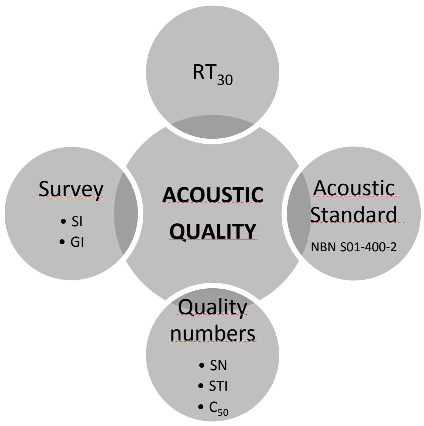


Figure 4.1: Scheme of evaluating the acoustic quality

4.2. Results of the measurements

4.2.1. Graphical templates

The International Standard ISO/CD 3382-2 [2] provides recommendations of how to make a test report. For this study the test reports are called 'graphical templates'. More information can be found in annex 8.2 - '*Statement of the results*'. The graphical templates of the ten auditoria are located in the separate appendix.

4.2.2. Measured RT

Table 4.1a shows the measured RT for auditorium A for each frequency as well as the mean RT over the different frequencies and the nominal RT over the different positions (in accordance with the International Standard ISO/CD 3382-2 [2]). The measurements of the other auditoria are given in annex 8.3 – '*Results of the measured RT*'. Table 4.1b gives the standard deviation and the confidence interval of the different measurements. The standard deviation is calculated with the first method (circumstances of the experiment taken into account) and the second method (arithmetic) as explained in chapter 3.5 – *'Measurement uncertainty for the interrupted noise method'*. Based on the standard deviation a 95 % confidence interval can be calculated (coverage factor k = 1.96). There is a chance of 95 % that the mean RT is located between this interval.

AUD A	**Measured RT [s]**						**RT_{nom} [s]**
	125 Hz	**250 Hz**	**500 Hz**	**1,000 Hz**	**2,000 Hz**	**4,000 Hz**	
1	1.47	0.89	0.82	0.76	0.96	1.07	**0.85**
2	1.24	0.94	0.83	0.84	1.03	1.05	**0.90**
3	1.33	0.96	0.84	0.80	1.00	1.04	**0.88**
4	1.24	0.88	0.82	0.76	1.03	1.10	**0.87**
5	1.23	0.84	0.77	0.76	1.07	1.08	**0.87**
6	1.14	0.89	0.84	0.78	1.01	1.06	**0.88**
7	1.10	0.91	0.76	0.79	1.00	1.04	**0.85**
8	1.21	0.85	0.80	0.75	0.99	1.07	**0.85**
9	1.12	0.83	0.78	0.74	1.00	1.08	**0.84**
10	1.31	0.92	0.84	0.81	1.02	1.10	**0.89**
11	1.29	0.77	0.83	0.80	1.02	1.07	**0.88**
12	1.19	0.86	0.83	0.77	1.01	1.07	**0.87**
13	1.34	0.86	0.76	0.78	1.01	1.09	**0.85**
14	1.28	0.96	0.85	0.77	1.02	1.06	**0.88**
15	1.56	0.93	0.79	0.79	1.00	1.06	**0.86**
16	1.71	0.81	0.81	0.78	1.03	1.08	**0.87**
17	1.26	0.97	0.74	0.81	1.01	1.06	**0.85**
18	1.22	1.02	0.80	0.84	0.99	1.09	**0.88**
RT_m [s]	**1.29**	**0.89**	**0.81**	**0.79**	**1.01**	**1.07**	**0.87**

Table 4.1a: Results of the measured RT - auditorium A

AUD A	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	Nominal
St Dev method 1 σ [s]	0.25	0.15	0.10	0.07	0.05	0.04	**0.07**
95% Confidence interval [s]	[1.18-1.41]	[0.83-0.96]	[0.76-0.85]	[0.75-0.82]	[0.99-1.04]	[1.05-1.09]	**[0.83-0.90]**
St Dev method 2 σ [s]	0.15	0.06	0.03	0.03	0.02	0.02	**0.05**
95% Confidence interval [s]	[1.22-1.36]	[0.86-0.92]	[0.79-0.82]	[0.77-0.80]	[1.00-1.02]	[1.06-1.08]	**[0.95-1.00]**

Table 4.1b: Calculation of the standard deviation σ and 95% confidence interval - auditorium A

Figures 4.2a to 4.2j show the measured RT (the mean of the different positions) for each frequency band for the ten auditoria. The standard deviation for each frequency is indicated on the curve (dashed lines). The graphs show some differences. Most of the curves of the measured RT decline towards the higher frequencies. Also the standard deviation becomes smaller towards the higher frequencies. The materials absorb the sound mostly in the high frequencies. This will generally tend to a longer RT in the low frequencies whereby possible high low-frequent background levels could arise which masks speech signals. In the low frequencies a modal field with standing waves can be assumed. This gives much higher RT. However, for auditoria A and H, the curve does not always decline but it shows lower values for the mid-frequencies and again higher values for the higher frequencies. For example figure 4.1a shows that auditorium A has a higher RT (1.29 s – 0.89 s) for the low frequencies (125 to 250 Hz), a lower RT (0.81 s – 0.79 s) in the mid frequencies (500 to 1,000 Hz) and again a higher RT (1.01 s – 1.07 s) for the high frequencies (2,000 to 4,000 Hz). The reverberation is the smallest in the mid-frequencies which means that there is the most absorption in the mid-frequencies. This can be the result of the presence of Helmholtz resonance which absorbs the reverberation in the mid-frequencies or the absence of porous absorption or the combination of both. Since the speech range is located in the mid-frequency range from 500 to 2,000 Hz, only these values are important for the Speech Intelligibility.

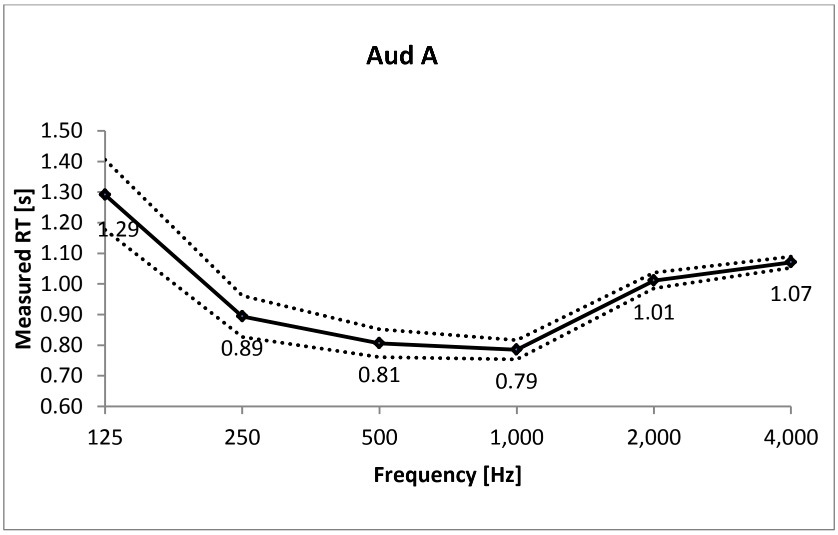


Figure 4.2a: Results of the measured RT and standard deviation σ (method 1) - Auditorium A

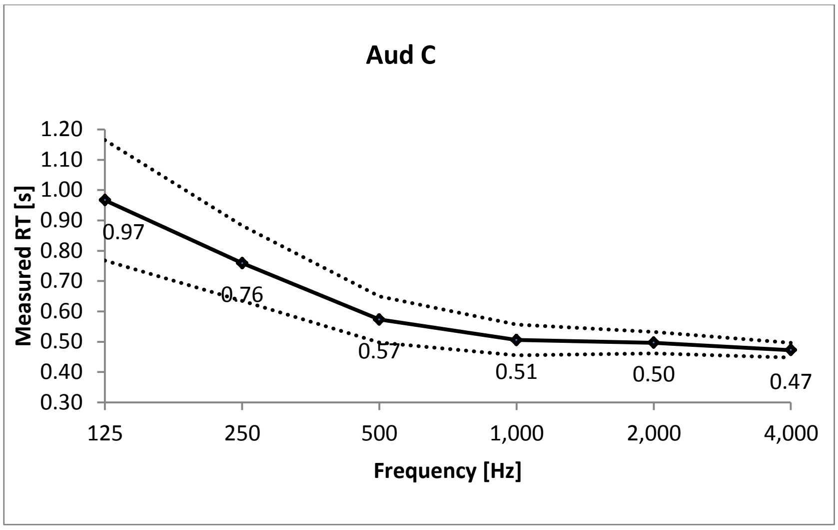


Figure 4.2b: Results of the measured RT and standard deviation σ (method 1) - Auditorium C

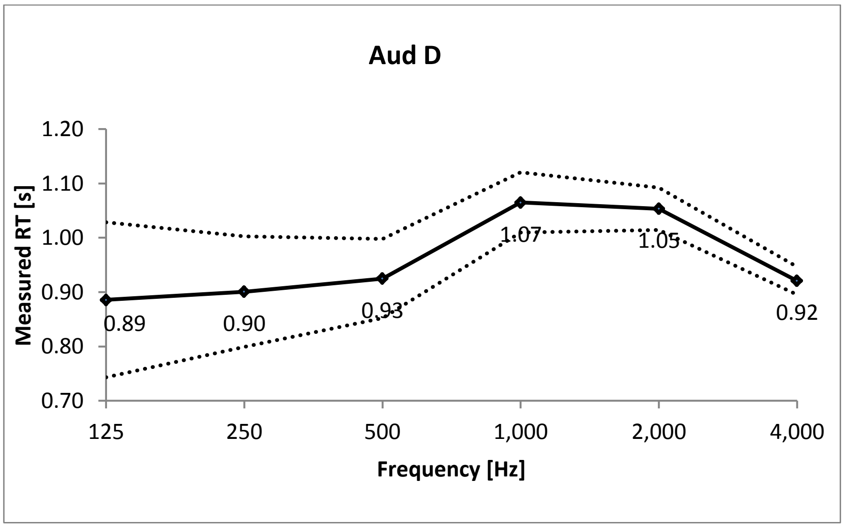


Figure 4.2c: Results of the measured RT and standard deviation σ (method 1) - Auditorium D

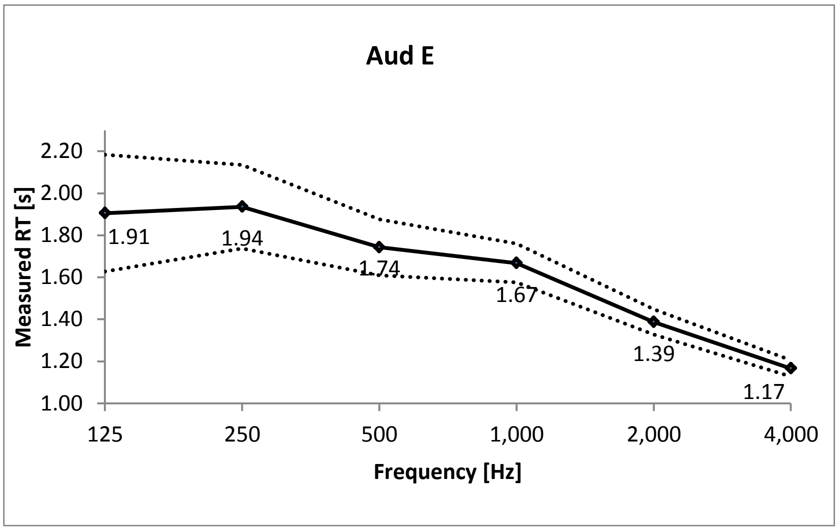


Figure 4.2d: Results of the measured RT and standard deviation σ (method 1) - Auditorium E

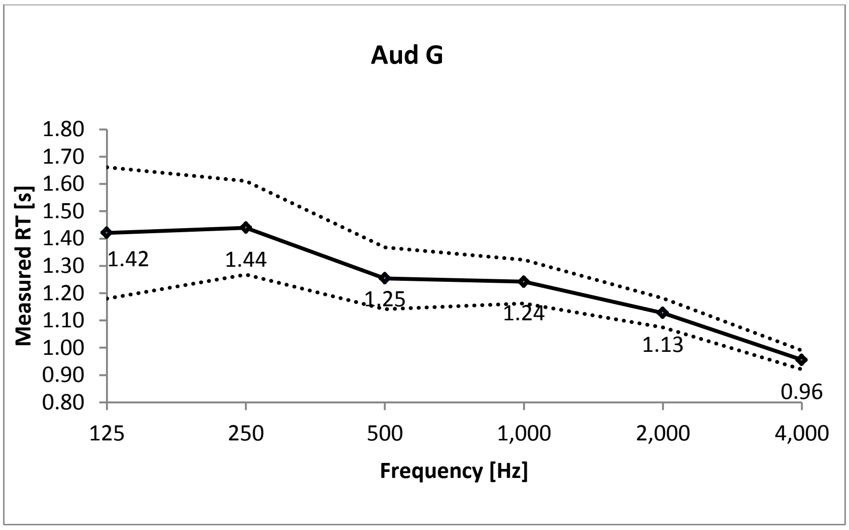


Figure 4.2e: Results of the measured RT and standard deviation σ (method 1) - Auditorium G

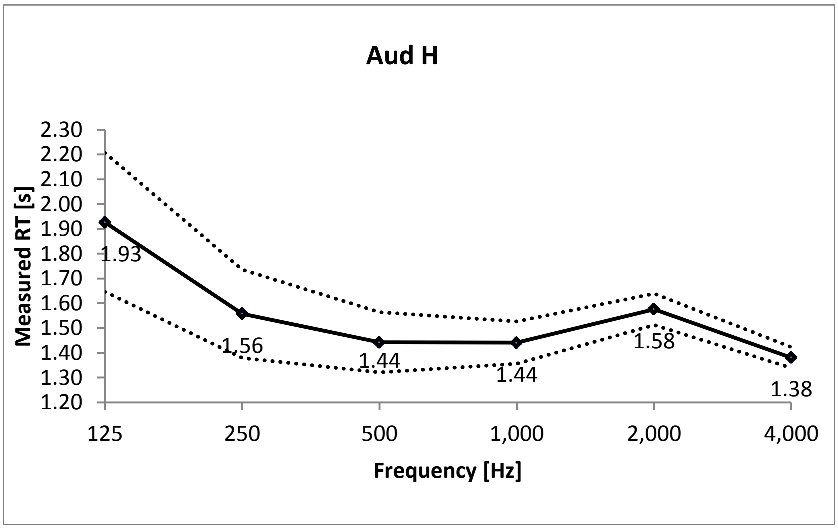


Figure 4.2f: Results of the measured RT and standard deviation σ (method 1) - Auditorium H

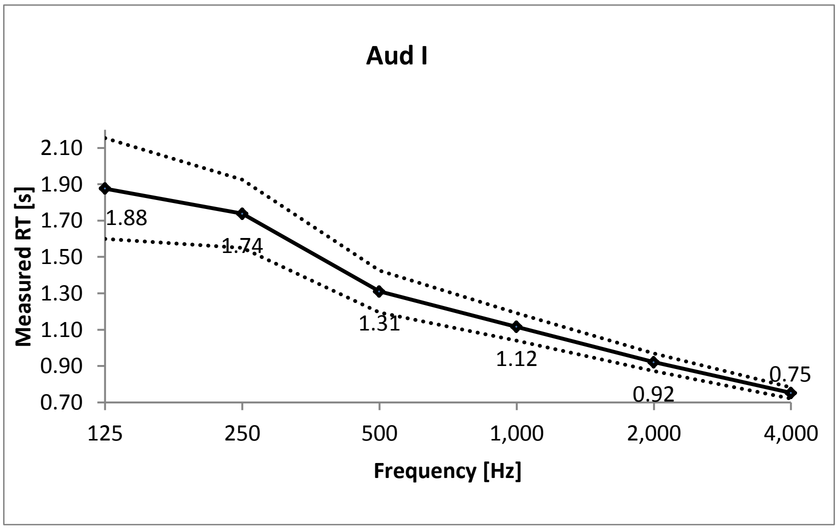


Figure 4.2g: Results of the measured RT and standard deviation σ (method 1) - Auditorium I

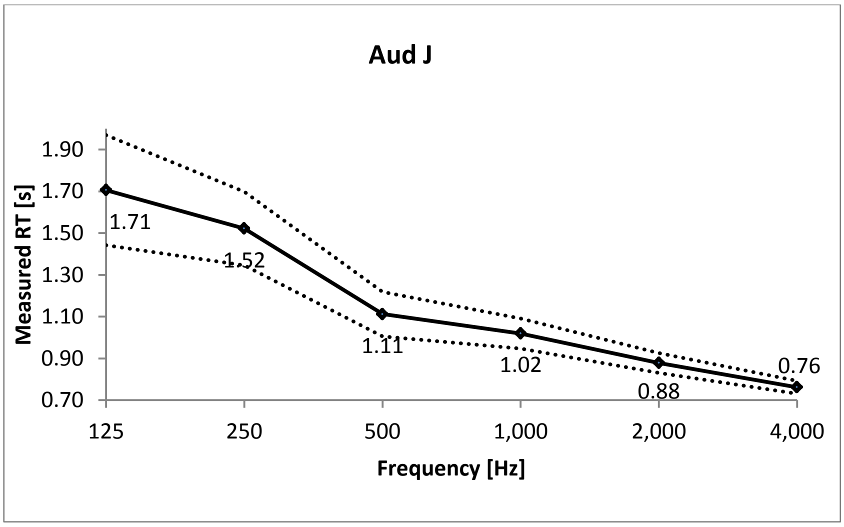


Figure 4.2h: Results of the measured RT and standard deviation σ (method 1) - Auditorium J

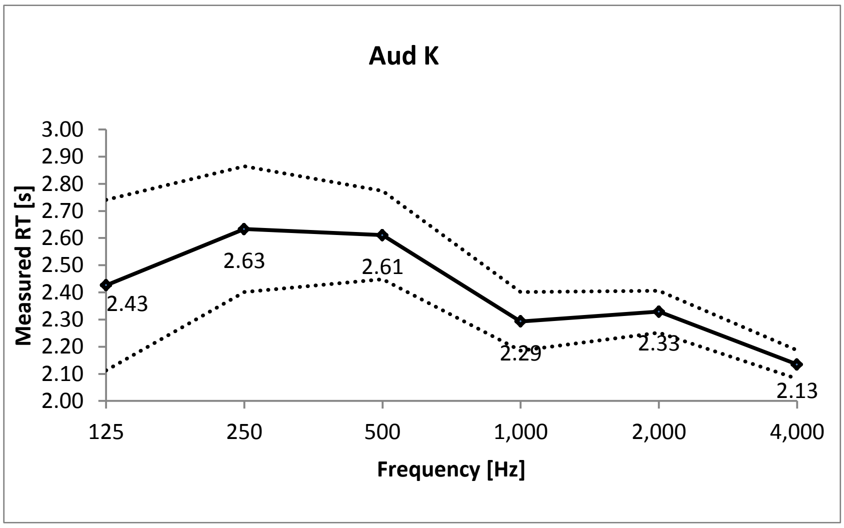


Figure 4.2i: Results of the measured RT and standard deviation σ (method 1) - Auditorium K

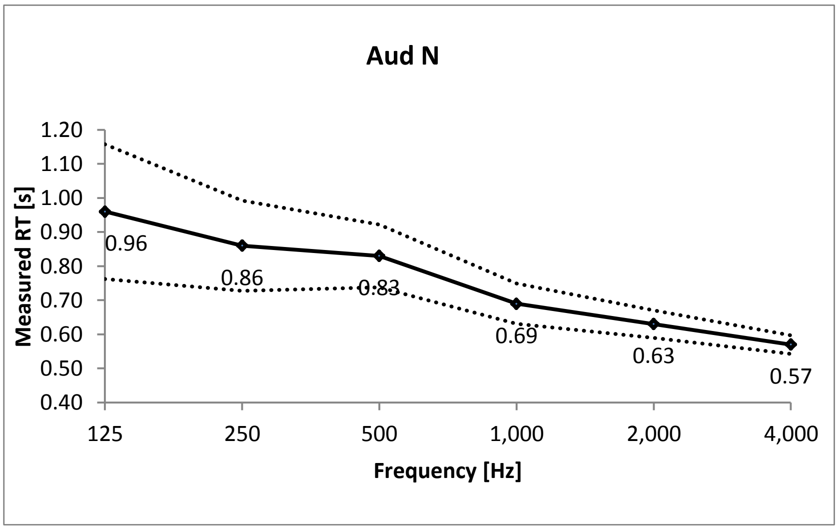


Figure 4.2j: Results of the measured RT and standard deviation σ (method 1) - Auditorium N

Table 4.2 shows the measured RT, the (nominal) standard deviation and the confidence interval for each auditorium. The standard deviation is calculated with the two methods that are explained in chapter 3.5 - *'Measurement uncertainty for the interrupted noise method'*. The highest value will be used to compare the auditoria with each other.

AUD	Measured RT [s]		Standard deviation σ [s]		95% Confidence interval [s]	
	RT_{nom} [s]	RT_m [s]	Method 1	Method 2	Method 1	Method 2
A	0.87	0.80	0.07	0.03	[0.83-0.90]	[0.85-0.88]
C	0.53	0.54	0.08	0.03	[0.47-0.58]	[0.51-0.54]
D	1.01	1.00	0.10	0.04	[0.96-1.07]	[0.99-1.04]
E	1.60	1.71	0.15	0.04	[1.50-1.69]	[1.57-1.63]
G	1.21	1.25	0.13	0.03	[1.13-1.29]	[1.19-1.23]
H	1.49	1.44	0.14	0.04	[1.40-1.58]	[1.46-1.51]
I	1.12	1.21	0.12	0.04	[1.04-1.20]	[1.09-1.14]
J	1.00	1.07	0.12	0.03	[0.93-1.08]	[0.99-1.02]
K	2.41	2.45	0.18	0.05	[2.30-2.53]	[2.38-2.44]
N	0.72	0.76	0.10	0.03	[0.65-0.78]	[0.70-0.74]

Table 4.2: Summary of the measured RT and standard deviation for ten auditoria

As already mentioned, measuring the RT is a good way to evaluate the acoustic quality of a space. A first evaluation can be made, based on the results of the measured RT as given in table 4.2. The values of RT_{nom} and RT_m show that auditoria A, C, D and N have a better acoustic quality with an RT_m equal or below 1 second which is the maximum recommended RT in Belgium for auditoria [7]. The other auditoria have higher values for the measured RT, especially auditoria E, H and K. In chapter 4.2.3 – 'Acoustic *Standard for School Buildings NBN S 01-400-2'* the evaluation based on the values of RT_{nom} will be investigated more in detail. But these results already give a first impression of the quality of the auditoria.

Table 4.2 also represents the results for the standard deviation calculated with the two methods. A low standard deviation indicates that the data points tend to be very close to the mean. A small confidence interval shows that there is a bigger chance that the actual value will be the same as the measured value. The acoustic quality will not depend on the location in the auditorium which results in a more diffuse field. A high standard deviation indicates that the data points are spread out over a large range of values. The confidence interval is bigger which means that there is a bigger spread of the results of the measured RT. The acoustic quality will vary depending on the location in the auditorium which results in a more direct field. The values for the standard deviation calculated with the first method show that auditorium A has the lowest standard deviation (0.07 s), followed by auditorium C (0.08 s), D (0.10 s) and N (0.10 s). For these auditoria the acoustic quality will be quite the same at every location and therefore these auditoria can be assumed as diffuse. The other auditoria show higher values and are less diffuse. Auditorium K has the highest standard deviation (0.18 s): the acoustic quality will not be the same at every point of the auditorium. This will later on be confirmed by calculating the acoustic quality numbers. The standard deviation calculated with the second method (mathematical) gives lower values and more or less the same conclusions can be derived from the calculation of the standard deviation with the first method. Auditoria A, C, N, J, and G show the lowest standard deviation (0.03 s). Auditoria E, H and I have a standard deviation of 0.04 s and for auditorium K the standard deviation is again the highest one (0.05 s). The confidence interval is calculated based on the standard deviation. It shows that there is a chance of 95 % that the mean RT is located between this interval. Again the first method gives a wider confidence interval in comparison with the second method. The values show that auditoria A, C, D and N have the smallest interval. Auditoria E, G, H, I, J and K have a bigger interval.

This leads to the conclusion that some auditoria give similar results as represented in table 4.3:

AUD	Min. and max. of RT_{nom} [s]	Average Standard deviation σ [s]
A – C – D – N	0.53 – 1.01	0.09
G – I – J	1.00 – 1.21	0.12
E – H – K	1.49 – 2.41	0.15

Table 4.3: Minimum and maximum value of the nominal RT and the average standard deviation

- Auditoria A, C, D and N: the lowest values for the measured RT (RT_{nom} between 0.53 s and 1.01 s) and an average standard deviation of 0.09 s (method 1).
- Auditoria G, I, J: the mediocre values for the measured RT (RT_{nom} between 1.00 s and 1.21 s) and an average standard deviation of 0.12 s (method 1).
- Auditoria E, H and K: the highest values for the measured RT (RT_{nom} between 1.49 s and 2.41 s) and an average standard deviation of 0.15 s (method 1)

4.2.3. Acoustic Standard for School Buildings: NBN S 01-400-2

Using the Acoustic Standard for School Buildings (NBN S 01-400-2) [6] it is possible to compare the measured results with the acoustic requirements. The Acoustic Standard gives requirements for two stages in the building process: the designing phase and the finished phase. For each requirement there is a normal and an increased requirement. The increased requirement is used when the Speech Intelligibility needs extra attention in situations like spaces for children or students with auditory and communicative limitations.

a. The design phase of the building

The design of a space is sufficient for compliance with the requirements for a minimum mean absorption coefficient $\bar{\alpha}$ or for a minimum mean equivalent sound absorption area *A*. Note that the surfaces with a mean absorption coefficient $\alpha_i \leq 0.5$ cannot be included in the calculation of *A*.

For the normal requirement: $\bar{\alpha} \geq 0.20$

$A \geq 0.4 \cdot S_H$

For the increased requirement: $\bar{\alpha} \geq 0.25$

$A \geq 0.5 \cdot S_H$

where:

$\bar{\alpha}$ – Global average absorption coefficient [-]: $\bar{\alpha} = \frac{A}{S} = \frac{\sum_i \alpha_i \cdot S_i}{S}$

A – Mean equivalent sound absorption area: $A = \sum_i A_i = \sum_i \alpha_i \cdot S_i$

S – The total accessible surface, projected perpendicular on a horizontal plane [m²]

b. The finished phase of the building

Since the measurements are done in auditoria which are already finished (according to NBN EN ISO 2282-2, engineering method, [2]), the following requirements are followed. The nominal RT (RT_{nom}) cannot exceed the maximum values for compliance with the requirements. First the reference RT (RT_0) needs to be calculated as follows:

$$RT_0 = 0.35 \cdot \lg(1.25 \cdot V)$$

where:

RT_0 – Reference RT [s] for spaces with $V \geq 30\ m^3$

$RT_0 = 0.3\ s$ for spaces where $V \leq 20\ m^3$ and $RT_0 = 0.02 \cdot V - 0.1\ s$ for spaces with $20 < V \leq 30\ m^3$

V – Total volume of the space [m³]

It can be seen that the desired RT depends of the volume of a space. The higher the volume, the greater the limit of maximum RT. The Acoustic Standard specifies the following requirements for auditoria:

For the normal requirement: $RT_{nom} \leq RT_0$

For the increased requirement: $RT_{nom} \leq 0.8 \cdot RT_0$

When the measured RT_{nom} meets the requirements, the requirements for the design phase can be neglected. However when the requirements for the RT_{nom} are not met two things need to be checked:

- Are the requirements for the design phase met?
- Was the workmanship good enough to ensure the sound absorbing performance of the surfaces?

If the answer to these two questions is 'yes', the space is executed conform the Acoustic Standard but it is strongly advised to provide more or better sound absorbing surfaces or to provide furniture with the same result as absorbing surfaces.

It is also important to note that for spaces where the SI is important (such as auditoria) it is highly recommended to limit the RT in the octave bands of 125 Hz and 250 Hz. The Acoustic Standard for School Buildings gives the next recommendations:

$$RT_{250} < 1.2\ RT_{nom}$$

$$RT_{125} < 1.4\ RT_{nom}$$

Furthermore, the requirement for the RT_{nom} may never be lower than 0.4 s. In finished school buildings (as in this study) the measured RT_{nom} is still acceptable if it only deviates 10% of the reference RT_0. This margin refers to the uncertainty on the prediction and to the limitations on the accuracy of the measuring techniques, which means:

The Acoustic Standard also specifies that the measurements need to be done in a finished space without lose furniture. However when the measurements take place in a furnished space with a lot of lose furniture, the maximum values of the RT_{nom} should be decreased with 10 % to compensate the effect of additional sound absorption by furniture. In the auditoria, no lose furniture is present.

c. Results

Tables 4.4a and 4.4b and figure 4.3 show the results of the calculations of the normal and increased requirement compared with the measured RT_{nom} of ten auditoria. The normal and increased requirement are indicated with RT_0. Tables 4.4a and 4.4b also give the error between the required RT and the measured RT_{nom}.

$$Error = Measured\ RT_{nom} - Required\ RT\ according\ to\ the\ Acoustic\ standard$$

$$= RT_{nom} - RT_0$$

A negative value (or a value of zero) of the error between the measured RT_{nom} and the requirement RT_0 indicates that the measured RT_{nom} has a lower value of the requirement and therefore the corresponding auditorium meets the requirement. For that case the value of RT_{nom} is colored green which means it is in agreement with the Acoustic Standard for School Buildings.

AUD	Normal requirement	Measured RT	Error [s]
	RT_0 [s]	RT_{nom} [s]	
A	1.20	0.87	-0.33
C	0.98	0.53	-0.46
D	1.10	1.01	-0.09
E	0.98	1.60	0.62
G	1.00	1.21	0.21
H	0.89	1.49	0.59
I	0.91	1.12	0.21
J	0.91	1.00	0.09
K	0.98	2.41	1.44
N	1.08	0.72	-0.37

Table 4.4a: Results for the normal requirement compared with measured RT_{nom}

Negative value = colored green = corresponding auditorium meets the requirement

AUD	Increased requirement	Measured RT	Error [s]
	RT_0 [s]	RT_{nom} [s]	
A	0.96	0.87	-0.09
C	0.78	0.53	-0.26
D	0.88	1.01	0.13
E	0.79	1.60	0.81
G	0.80	1.21	0.41
H	0.71	1.49	0.77
I	0.73	1.12	0.39
J	0.73	1.00	0.28
K	0.78	2.41	1.63
N	0.87	0.70	-0.15

Table 4.4b: Results for the increased requirement compared with measured RT_{nom}

Negative value = colored green = corresponding auditorium meets the requirement

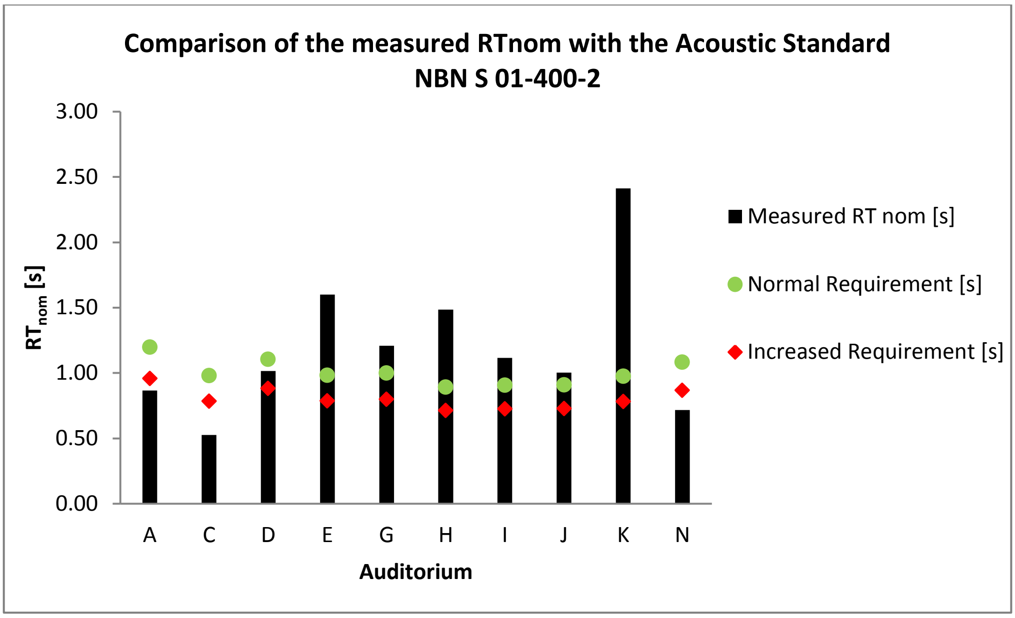


Figure 4.3: Results for the normal and increased requirement compared with the measured RT_{nom}

For the normal requirement it can be observed from tables 4.4a and 4.4b and figure 4.3 that the values of the measured RT_{nom} do not exceed the requirement for auditoria A, C, D, and N (colored green, negative values for the error). Auditorium C gives the lowest error in comparison with the Acoustic Standard. However, auditorium J only deviates 10% from the maximum reference RT_0 which means it is still acceptable. For auditoria E, G, H, I and K the requirements for the design phase need to be calculated because they do not meet the requirement for the finished phase. Auditorium K has clearly the highest error (1.44 s) in comparison with the normal requirement, followed by auditorium E (0.62 s) and H (0.59 s). In the case of the increased requirement only auditorium A, C and N are according to the Acoustic Standard (colored green, negative values for the error). This means that for auditoria D, E, G, H, I, J and K the requirements for the design phase need to be calculated. For example auditorium K has an error of 1.63 s in comparison with the increased requirement. Many auditoria do not meet the requirements of the Acoustic Standard for School Buildings. The fact that only four auditoria meet the normal requirement and only three auditoria meet the increased requirement means that the University of Ghent should think about it more thoroughly or maybe is the Acoustic Standard too severe? For the design phase, the requirements are as follows:

- Normal requirement: $\bar{\alpha} \geq 0.20$
- Increased requirement: $\bar{\alpha} \geq 0.25$

AUD	$\bar{\alpha}$ [-]
A	0.20
C	0.21
D	0.16
E	0.06
G	0.08
H	0.03
I	0.10
J	0.10
K	0.04
N	0.19

Table 4.5: Results for $\bar{\alpha}$ – green = corresponding auditorium meets the normal requirement

Table 4.5 shows that only auditoria A and C meet the normal requirement. The other auditoria do not meet the normal or increased requirement for the design phase. This shows that they are not designed according to the Acoustic Standard for School Buildings and need adjustments to improve their acoustic quality.

Table 4.6 represents the results of the recommendations of the Acoustic Standard for School Buildings for the RT for the frequency of 125 Hz and 250 Hz. The requirements are:

$$RT_{250} < 1.2\ RT_{nom}$$

$$RT_{125} < 1.4\ RT_{nom}$$

AUD	Requierd RT [s]			
	RT_{125}	$1.4*RT_{nom}$	RT_{250}	$1.2*RT_{nom}$
A	1.29	1.21	0.89	1.04
C	0.97	0.74	0.76	0.63
D	0.89	1.42	0.90	1.22
E	1.91	2.24	1.94	1.92
G	1.42	1.69	1.44	1.45
H	1.93	2.08	1.56	1.78
I	1.88	1.56	1.74	1.34
J	1.71	1.41	1.52	1.20
K	2.43	3.38	2.63	2.89
N	0.92	0.98	0.83	0.84

Table 4.6: Results for low frequency requirements of the Acoustic Standard for School Buildings

green = corresponding auditorium meets the requirement

For the frequency band 125 Hz auditoria D, E, G, H and N meet the requirement (colored green). For the frequency band 250 Hz auditoria A, D, G, H, K and N (colored green) are according to the requirement. For auditoria D, G, H and N it can be concluded that the RT is low enough for a good SI in the low frequencies.

4.2.4. Quality numbers

Another way to evaluate the acoustic quality of the auditoria and the SI is by calculating the quality numbers as discussed in the theoretical study in chapter 2.6 – *'Evaluating acoustic quality of a space'*. These results will be compared with the measured RT, the Acoustic Standard for School Buildings NBN S 01-400-2 and with the subjective opinion of students using a survey. The results of these quality numbers can also be found on the graphical templates of each auditorium, given in the separate appendix. It gives a quick overview of the distribution of the acoustic quality in the auditoria.

In annex 8.4 – '*Quality numbers*' the calculations of the SN-ratio, C_{50}-value and the STI are calculated for every 20 centimeters. It can be observed that the closer to the source the higher the **SN-ratio**. This corresponds to what is explained in chapter 2.6.1 - '*Influence of parameters on the Speech Intelligibility*', paragraph e. When SN = 15 dB the noise or reverberation is inaudible when someone is speaking. When SN = -15 dB the speaker is not audible because of noise or reverberation taking the upper hand. The higher the SN-ratio (more signal, less noise) the better the acoustic quality of the auditorium. A SN = -6 dB corresponds with the lower limit of the STI = 0.3. A SN = 0 dB corresponds with a good SI (STI = 0.6). SN = +6 dB is called 'excellent'.

The STI is calculated based on the linear relationship with the **C_{50}-value**.

$$STI = 0.030 \cdot C_{50} + 0.555$$

The results of the **STI** are related to a certain quality as given in table 4.7. Each quality has its own corresponding color that will also be used further on in this study to represent the acoustic quality of the auditoria.

Bad	Poor	Fair	Good	Excellent
STI < 0.30	0.30 < STI < 0.45	0.45 < STI < 0.60	0.60 < STI < 0.75	STI > 0.75

Table 4.7: Qualification based on the STI-value [67] [51]

STI = 0.60 is often used as a limit for the Speech Intelligibility. However, a 'sentence intelligibility' of 100 % can only be reached with a STI = 0.75. In that case the intelligibility of meaningful words is 98 %. The intelligibility of 'nonsense words' is 81 %. Apparently a listener takes as much information from the context as possible, so that a STI of 0.60 is also justified. However for auditoria a STI of 0.60 is too low and a STI of 0.70 is more desirable [7]. Using the values of STI and the ranges to evaluate the quality of the auditorium, again it can be observed that the further away from the source, the lower the value of the STI is which is in agreement with the theoretical part of this study.

Based on the margin values for the STI, the boundaries between the different zones with a different quality can be found. These are colored in the table of annex 8.4 –'*Quality numbers*' and also represented in the graphical templates of each auditorium which can be found in the separate appendix. Table 4.8 gives the boundaries of the different zones for each auditorium with the representative quality numbers and the corresponding color of the acoustic quality based on the STI.

AUD	Zone	Distance [m]	SN [dB]	C_{50} [dB]	STI	Quality [STI]
A	1	0 – 2.60	19.48	12.54	0.93	Excellent
	2	2.60 – 14.20	2.41	2.37	0.63	Good
	3	14.20 – 22	-5.12	1.21	0.59	Fair
C	1	0 – 2.40	13.44	10.92	0.88	Excellent
	2	2.40 – 7.27	-2.23	4.86	0.70	Good
	3	-	-	-	-	-
D	1	0 – 1.60	20.90	12.36	0.93	Excellent
	2	1.60 – 4.60	8.35	2.98	0.64	Good
	3	4.60 – 19.62	-3.60	0.31	0.56	Fair
E	1	0 – 0.80	23.34	10.15	0.86	Excellent
	2	0.80 – 1.40	14.67	2.74	0.64	Good
	3	1.40 – 13.40	-1.58	-2.18	0.49	Fair
G	1	0 – 1.00	21.50	9.40	0.84	Excellent
	2	1.00 – 1.80	12.28	2.34	0.63	Good
	3	1.80 – 10.00	-0.33	-0.69	0.53	Fair
H	1	0 – 0.60	22.85	9.39	0.84	Excellent
	2	0.60 – 1.00	15.07	2.89	0.64	Good
	3	1.00 – 9.00	-0.97	-1.81	0.50	Fair
I	1	0 – 0.60	24.18	11.95	0.91	Excellent
	2	0.60 – 1.60	13.58	3.50	0.66	Good
	3	1.60 – 14.00	-3.44	-0.40	0.54	Fair
J	1	0 – 0.80	21.29	10.20	0.86	Excellent
	2	0.80 – 2.00	10.54	2.63	0.63	Good
	3	2.00 – 10.00	-2.36	0.22	0.56	Fair
K	1	0 – 0.80	22.37	8.77	0.82	Excellent
	2	0.80 – 1.00	15.52	2.55	0.63	Good
	3	1.00 – 3.20	8.04	-1.99	0.50	Fair
	4	3.20 – 9.90	-2.44	-4.41	0.42	Poor
N	1	0 – 2.40	17.42	12.35	0.93	Excellent
	2	2.40 – 22.00	-3.20	2.87	0.64	Good
	3	-	-	-	-	-

Table 4.8: Boundaries of the zones with different acoustic qualities [67] [51]

Table 4.8 shows that zones with an excellent and good quality have a good **SN-ratio** (positive value, most desirable higher than 6 dB). A negative value of the SN-ratio can be found in the zones with a fair to poor acoustic quality. This is the case for all the auditoria except auditoria C and N where the negative value of the SN-ratio can be found in the zone with a good acoustic quality. The SN-ratio can be improved by adding more absorption material because it will decrease the speech and the noise level. However, theoretically the noise level will decrease more than the speech level because speech is also determined by the direct sound [7]. Too much absorption will lead to a good intelligibility in the front but a bad intelligibility in the back of the space due to a low SN-ratio [7]. This means that the amount of absorption in a space is very important.

Table 4.8 also shows the **C_{50}-value** for the different quality zones in each auditorium. The higher the value of C_{50}, the better the acoustic quality of the auditorium and the more absorption in a space, the higher the value of C_{50} will be. The amount of absorption needs to be related to the volume of the space. Auditoria A, D and N show the highest values of the C_{50} (above 12 dB) in the zone with an excellent acoustic quality (according to the STI). For the zone with a good acoustic quality (according to the STI), all auditoria have more or less the same C_{50}-value (2 – 3 dB) except for auditorium C which has a C_{50}-value of 4.86 dB. Negative values of the C_{50} can be found for auditoria E, G, H, I and K for the zones with a fair to poor acoustic quality (according to the STI).

The **STI** (with the corresponding boundaries of each zone) is also represented in table 4.8. In auditoria A, C, D and N the acoustic quality is excellent in the zone of 1 – 2 m from the front of the space. The remaining space has a good acoustic quality. For the other auditoria there is only a small area (less than 1 m) where the acoustic quality is excellent. The biggest part of auditoria E, G, I, J, H and K have a fair acoustic quality. Auditoria H and K only have a very small area with a good acoustic quality. In auditorium K there is even a rather big zone with a poor acoustic quality. The different zones give an indication of interesting places with a good acoustic quality to sit in the auditoria for the students.

Table 4.9 gives an overview of the mean STI calculated over the different zones for each auditorium. The number gives an indication of the 'global' acoustic quality of the entire space. This is calculated using the following formula:

$$STI_{mean} = \frac{\sum \Delta r_n \cdot STI_n}{r_{tot}}$$

where:

Δr_n – The length of a zone with a specific quality [m]

STI_n – The corresponding STI of the n^{th} – zone [0-1]

r_{tot} – The total length of the auditorium [m]

AUD	STI [0-1]	Quality
A	0.65	Good
C	0.76	Excellent
D	0.61	Good
E	0.52	Fair
G	0.57	Fair
H	0.53	Fair
I	0.57	Fair
J	0.59	Fair/Good
K	0.47	Fair/Poor
N	0.67	Good

Table 4.9: Mean of the STI for each auditorium

Table 4.9 shows that (according to the STI) auditorium C is the only one with an excellent acoustic quality (mean STI of 0.76) for the entire auditorium. Auditoria A, D and N have a good acoustic quality (mean STI of 0.65, 0.61 and 0.67) for the entire auditorium whereas auditoria E, G, H, I and J have a fair acoustic quality (mean STI around 0.50). Auditorium K has an STI of 0.47 for the entire auditorium which represents a fair acoustic quality but is close to the margin of a poor acoustic quality. It has the worst acoustic quality in comparison with the other auditoria. It is notable that the acoustic quality of many auditoria is fair (according to the STI) which is not desirable. These results were expected as also auditorium A, C, D and N meet the increased requirement of the Acoustic Standard for School Buildings. Especially auditorium K showed the biggest error between the measured nominal RT and the required RT. This is confirmed with the quality number STI. To look for correlations between the STI and the C_{50}-value, a fixed distance (center of the auditorium) is chosen. There is a known correlation between the STI and the C_{50}-value. When STI = 0.60, the C_{50}-value should be 1 – 2 dB. When STI = 0.70, the C_{50}-value should be 5 – 6 dB. This means that when STI increases with about 0.05 then the C_{50}-value increases with about 2 dB [51]. This correlation is represented in table 4.10.

AUD	Distance [m]	C_{50} [dB]	STI [0-1]
A	11.00	1.54	0.60
C	3.65	5.26	0.71
D	9.81	0.31	0.56
E	6.70	-2.44	0.48
G	5.00	-0.79	0.53
H	4.50	-2.05	0.49
I	7.00	-0.54	0.54
J	5.00	0.18	0.56
K	4.95	-4.29	0.43
N	11.00	2.58	0.63

Table 4.10: Quality numbers at the center of the auditorium

Based on the values of table 4.10 a comparison of the STI and the C_{50}-value is made in figure 4.4. The known correlation between the STI and the C_{50}-value can be retrieved. There is a positive coefficient of correlation of 1 which means that the STI and the C_{50}-value correlate 100 %.

$$STI = 0.030 \cdot C_{50} + 0.555$$

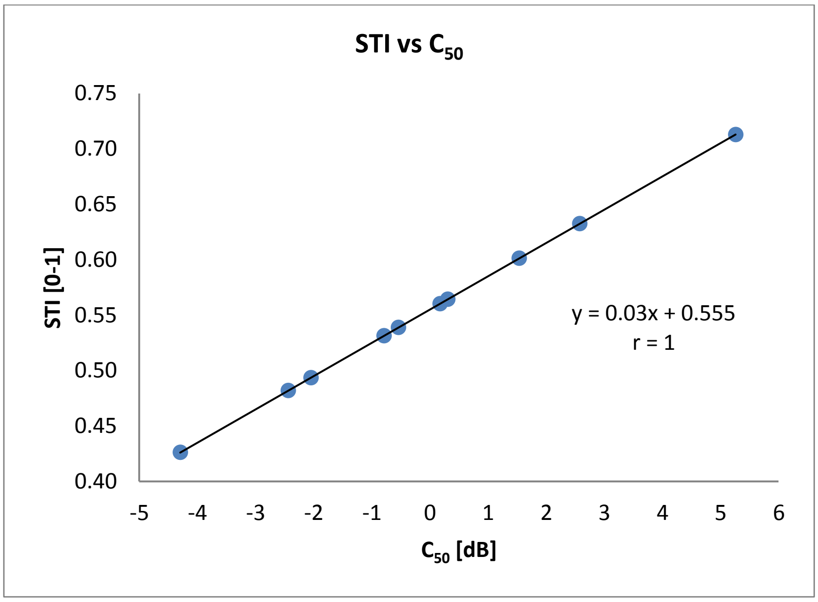


Figure 4.4: STI vs C_{50}

4.2.5. *Survey*

The relationship between acoustic parameters measured in a room and the experienced acoustic quality is still under a lot of research [26] [20]. However, one of the most relevant sensations of the sound field in rooms is still the cognition of reverberation as pointed out by Vorländer [25]. Reverberation is responsible for the impression of being in a room as well as providing an awareness of distance to the source, whereas for example spatial impression due to lateral reflections appears to be more a source-specific effect involving the feeling to be close to the listener [17]. It will be interesting if a correlation between the survey and the previous objective parameters can be found.

For this survey, questionnaires are handed out before the start of a course and are collected at the end of the course. This gives the students time to consider the questions carefully. The survey results can be found in annex 8.5 –*'Survey'* and in the separate appendix. The questionnaire asks the students where they are located in the room. This is important for the reliability of the survey: with a bigger spread of the students the results of the survey will be more accurate. Not only the spread of the students is important but also the amount of students participating in the survey. Students with hearing problems are also taken into account. The questionnaire asks the students whether or not the professor gave the course using a microphone. Depending on this question, the students are asked what they think about the Speech Intelligibility (SI) of the professor and what their Global Impression (GI) is of the auditorium. These questions are linked to the STI by using the same rating system (5 = excellent, 4 = good, 3 = fair, 2 = poor, 1 = bad).

For example, the results of the survey in auditorium A are given in table 4.11. The results of the other auditoria can be found in annex 8.5 – '*Survey*' and on the graphical templates in the separate appendix.

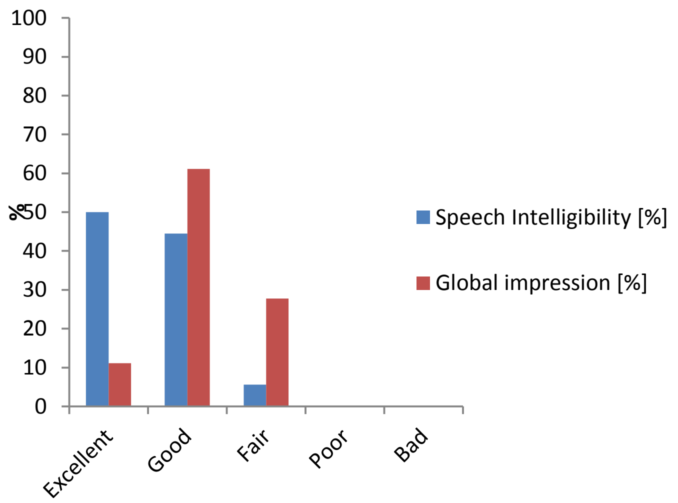
<table>
<tr><th colspan="5">Auditorium A – 18 opinions</th></tr>
<tr><th colspan="4">Speech Intelligibility SI <u>with</u> micro</th><th>Graph</th></tr>
<tr><th>STI</th><th>Rate</th><th># students</th><th>%</th><td rowspan="13">
</td></tr>
<tr><th>Excellent</th><td>5</td><td>9</td><td>50</td></tr>
<tr><th>Good</th><td>4</td><td>8</td><td>44</td></tr>
<tr><th>Fair</th><td>3</td><td>1</td><td>6</td></tr>
<tr><th>Poor</th><td>2</td><td>0</td><td>0</td></tr>
<tr><th>Bad</th><td>1</td><td>0</td><td>0</td></tr>
<tr><th colspan="4">Global Impression GI</th></tr>
<tr><th>STI</th><th>Rate</th><th># students</th><th>%</th></tr>
<tr><th>Excellent</th><td>5</td><td>2</td><td>11</td></tr>
<tr><th>Good</th><td>4</td><td>11</td><td>61</td></tr>
<tr><th>Fair</th><td>3</td><td>5</td><td>28</td></tr>
<tr><th>Poor</th><td>2</td><td>0</td><td>0</td></tr>
<tr><th>Bad</th><td>1</td><td>0</td><td>0</td></tr>
<tr><th colspan="4">Mean Speech Intelligibility SI</th><td>4,44 – Good/Excellent</td></tr>
<tr><th colspan="4">Mean Global Impression GI</th><td>3,83 – Fair/Good</td></tr>
<tr><th colspan="4">Seat positions + opinion on the SI</th><td>
</td></tr>
</table>

Table 4.11: Summary of the results of the survey (SI and GI) – Auditorium A

The graph in table 4.11 shows that for auditorium A, the Speech Intelligibility SI is found excellent by most of the students and the Global Impression GI is found good by most of the students. The mean opinion of the students for the mean Speech Intelligibility is good to excellent (4.44) and the mean Global Impression is fair to good (3.83).

Table 4.12 gives a summary of the results of the survey in ten auditoria. In every auditorium there were some background noises from students, traffic, etc. and therefore it is not indicated in this table. Other important factors are included in the table. For the students, the SI is good in auditoria A, D, G and N and fair in auditoria C, E, H, I, J and K. The GI is good in auditoria A, C, I and N and fair in auditoria D, G, H, J and K. According to the students' opinion, auditorium E gives a poor Global Impression.

AUD	Survey						
	Number of opinions	Number of persons with hearing problems	Micro	Mean SI [1-5]		Mean GI [1-5]	
A	18	1	1	4.44	Good/Excellent	3.83	Good
C	17	0	0	3.44	Fair/Good	4.22	Good/Excellent
D	32	1	0	3.91	Good	3.56	Fair/Good
E	25	2	0	3.32	Fair/Good	2.76	Poor/Fair
G	28	0	0	3.86	Good	3.54	Fair/Good
H	15	0	0	3.47	Fair/Good	3.20	Fair/Good
I	28	1	0	3.61	Fair/Good	4.00	Good
J	10	0	0	3.60	Fair/Good	3.60	Fair/Good
K	23	3	0	3.35	Fair/Good	3.30	Fair/Good
N	39	2	1	4.41	Good/Excellent	4.00	Good

Table 4.12: Results of the survey (SI = Speech Intelligibility, GI = Global Impression)

The results for the Speech Intelligibility (SI) and the Global Impression (GI) are represented in figures 4.5 and 4.6 for each auditorium separately. Figure 4.7 represents the mean of the different judgments in the ten auditoria. According to the results for the SI, it can be observed that the quality perception 'poor' and 'bad' are seldom used. Only for auditorium E, G and K there are some students who evaluate the global acoustics bad. For the Speech Intelligibility auditoria A and N show the best result compared with the other auditoria. This can be explained because a microphone was used in these auditoria because of the higher volume of these spaces. For the Global Impression again auditoria A and N but especially C show the best result compared with the other auditoria. This was expected as these auditoria also get a good or excellent objective evaluation based on the measured RT, the Acoustic Standard for School Buildings and the quality numbers. Based on figure 4.7, it can be said that in general the auditoria are considered to be 'good' by the students for both the Speech Intelligibility and the Global Impression. This is a little bit too positive as it came out that many auditoria don't meet the Acoustic Standard for School Buildings.

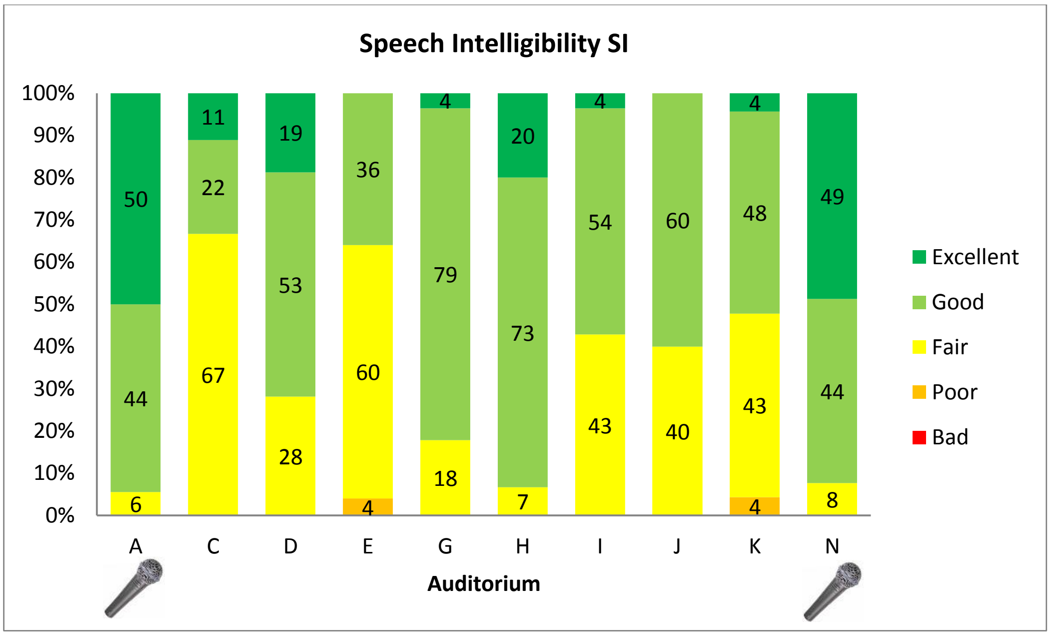


Figure 4.5: Results of the survey for ten auditoria for the Speech Intelligibility SI

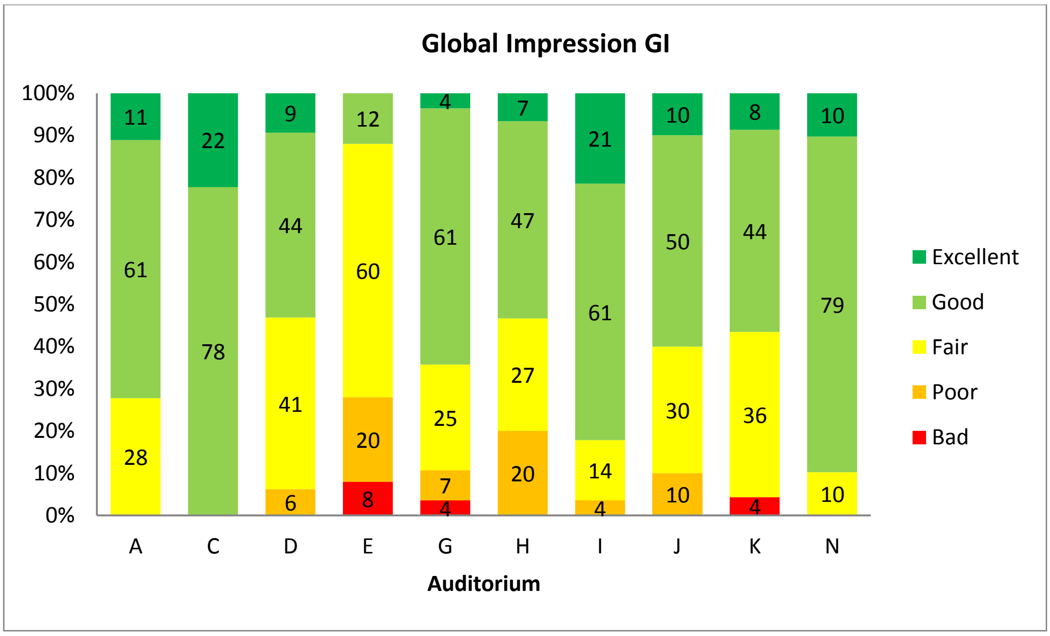


Figure 4.6: Results of the survey for ten auditoria for the Global Impression GI

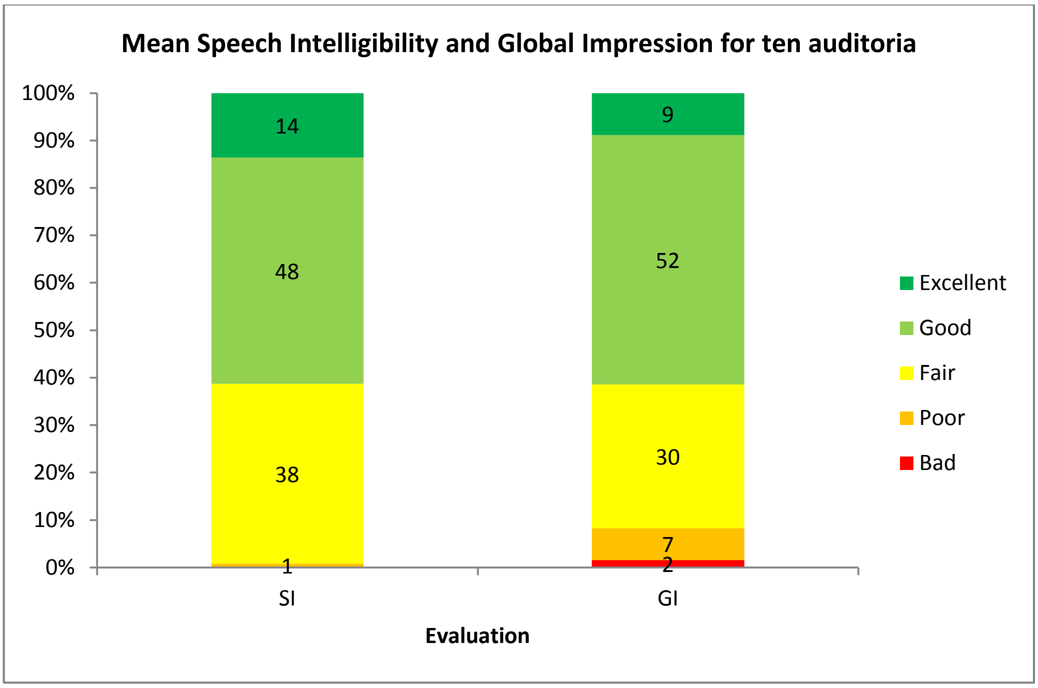


Figure 4.7: Results of the survey (mean of ten auditoria) for the SI and GI

4.3. Discussion and first approach towards a classification

In this chapter a comparison will be made based on different parameters: the measured RT, the standard deviation of the measured RT, the Acoustic Standard for School Buildings, the calculated quality number STI and the questions of the survey. Table 4.13 gives a summary of these results in order to compare them with each other. Calculating the coefficient of correlation will give a clear view of the correlations between the parameters. Eventually it is the aim of this study to make a first classification based on these parameters. It will appear that there are also some other parameters to take into account such as location of absorption, dimensions, etc.

4.3.1. Comparison of the parameters: RT, Acoustic Standard, quality number STI and survey

Table 4.13 shows a summary of the measured RT_{nom} and its standard deviation (according to method 1), the error between the normal and increased requirement of the Acoustic Standard for School Buildings and the measured RT_{nom}, the calculated mean quality number STI and the results of the survey (SI= Speech Intelligibility and GI= Global Impression) for each auditorium. The numbers in the columns of the Acoustic Standard show how many seconds the RT_{nom} deviates from the normal and increased requirement. A negative number means it is lower than the required RT and therefore meets the requirement. The colors represent the acoustic quality corresponding to the STI (see table 4.4).

AUD	Measured Reverberation [s]		NBN S 01-400-2: Error [s]		Quality number	Survey	
	RT_{nom}	Standard deviation σ	Normal	Increased	STI [0-1]	Mean SI [1-5]	Mean GI [1-5]
A	0.80	0.07	**-0.33**	**-0.09**	0,65	4.44	3.83
C	0.54	0.08	**-0.46**	**-0.26**	0,76	3.44	4.22
D	1.00	0.10	**-0.09**	0.13	0,61	3.91	3.56
E	1.71	0.15	0.62	0.81	0,52	3.32	2.76
G	1.25	0.13	0.21	0.41	0,57	3.86	3.54
H	1.44	0.14	0.59	0.77	0,53	3.47	3.20
I	1.21	0.12	0.21	0.39	0,57	3.61	4.00
J	1.07	0.12	0.09	0.28	0,59	3.60	3.60
K	2.45	0.18	1.44	1.63	0,47	3.35	3.30
N	0.74	0.10	**-0.37**	**-0.15**	0,67	4.41	4.00

Table 4.13: Comparison of the objective and subjective parameters

A reasonable agreement between the STI and survey results can be concluded from table 4.13. A more thorough observation will be made in the next chapters using correlation factors. For clarity, only the measured RT_{nom}, the error between the normal requirement of the Acoustic Standard for School Buildings and the measured RT_{nom}, the STI and the evaluations of the SI and GI of the survey are considered.

a. Comparison of objective and subjective parameters

It is important to know if the survey is qualitative enough. Therefore correlations will be analyzed between objective and subjective parameters. The coefficient of correlation r represents the degree of approximation obtained in the calculation of the regression. It should be noted that it is always:

$$r \in [-1, 1]$$

The coefficient of correlation represents a number between -1 and 1, which shows how well the regression line approximates the input data. With the coefficient of correlation, the following can be assumed:

- r = 0 : no correlation
- r = + 1 : a perfectly positive correlation
- r = - 1: a perfectly negative correlation

The further away the coefficient of correlation is located from 0, the stronger the correlation and the more accurate the value of the one parameter can be predicted on the basis of the value of the other parameter [73]. Based on the results of table 4.13, table 4.14 gives the results of the coefficient of correlation between the objective parameters and the subjective judgment.

Coefficient of correlation - r		Objective parameters		
		Measured RT_{nom}	NBN S 01-400-2: Error*	STI
Subjective parameters	SI	- 0.61	- 0.68	0.46
	GI	- 0.75	- 0.74	0.86

Table 4.14: Comparison of the objective parameters (measured RT, *error between the normal requirement of the Acoustic Standard NBN S01-400-2 and the measured RT_{nom}, STI) with the subjective parameters (SI = Speech Intelligibility, GI = Global Impression) based on the coefficient of correlation r

A quick look at tables 4.13, 4.14 and figures 4.8a to 4.8f demonstrates that some objective parameters and some subjective survey questions (SI and GI) happen to correlate more easily than others. In general, it can be seen that the GI corresponds better with the objective parameters in comparison with the SI.

Figures 4.8a to 4.8c represent the polygonal line regression between the objective parameters and the subjective parameter SI. Figures 4.8d to 4.8f represent the polygonal line regression between the objective parameters and the subjective parameter GI.

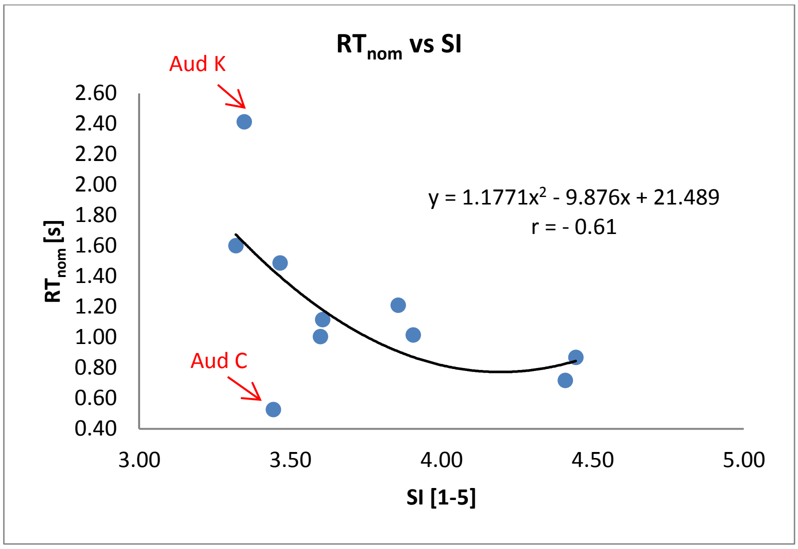


Figure 4.8a: Polygonal line regression between the measured RT_{nom} (objective) and the Speech Intelligibility SI (subjective)

Figure 4.8a shows a declining polygonal line regression. First a linear regression was considered, but it seemed that a polygonal line resulted in a higher correlation. This means that the lower the SI, the higher the measured RT_{nom}, which is logical. There are two outliers due to the SI of auditoria C and K. Earlier observations of this study show that auditorium C is a very good auditorium according to the STI value but also because it meets the requirement of the Acoustic Standard for school buildings and because the measured RT_{nom} is below 1 second. In contrary, the observations of this study show that auditorium K is the worst auditorium according to the STI value but also because it does not meet the requirement of the Acoustic Standard for School Buildings and the measured RT_{nom} is very high. However, the judgment of the students is for these two (completely different) auditoria quite the same which results in these two outliers in figure 4.8a. It appears that students in auditorium K were very positive in their opinion about the SI whereas in auditorium C they were too negative. This can be explained because in auditorium K the professor adjusts his way of teaching by talking slower and by articulating more because he knows that the acoustics of the auditorium are poor and there is a lot of reverberation. The bad evaluation of the students in auditorium C can be explained because auditorium C is located adjacent to a road with some times a lot of traffic. Maybe there was too much background noise during the course when the survey was handed out.

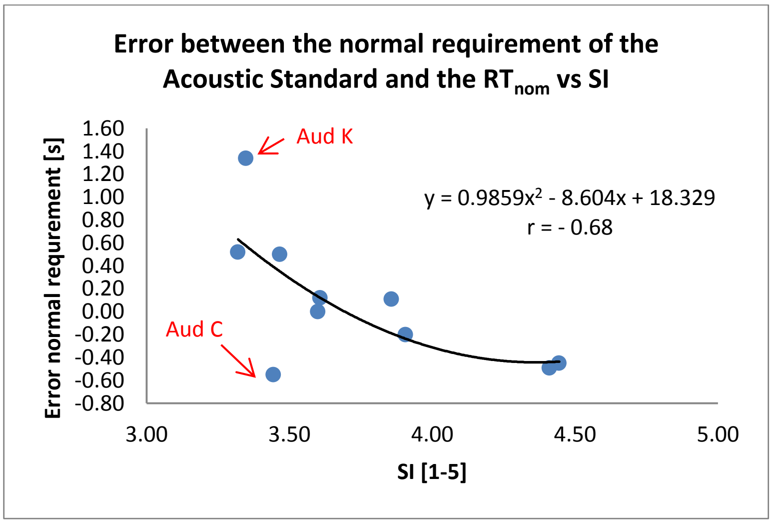


Figure 4.8b: Polygonal line regression between the error (between the normal requirement of the Acoustic Standard and the RT_{nom}) (objective) and the Speech Intelligibility SI (subjective)

Figure 4.8b shows again a declining polygonal regression with a stronger correlation in comparison with the previous one. The lower the judgment of the SI, the higher the error between the measured nominal RT and the normal requirement. Again the same two outliers can be found: auditoria C and K for the same reasons as already explained.

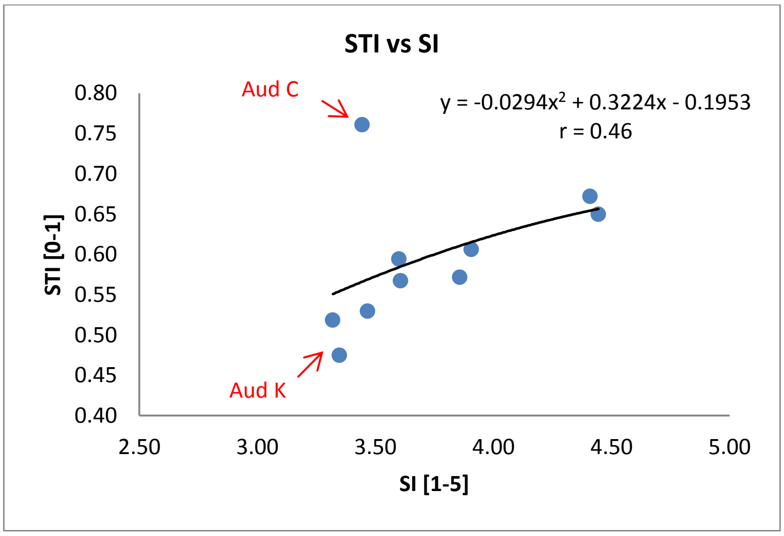


Figure 4.8c: Polygonal line regression between the STI (objective) and the Speech Intelligibility SI (subjective)

Figure 4.8c represents an increasing polygonal line regression. A positive coefficient of correlation can be found: the higher the SI, the higher the STI. Comparing the STI with the SI results in a lower coefficient of correlation in comparison with the two previous figures. A question for the students about the SI seems not such a good question if it is the aim of a designer to obtain results of the STI. One outlier is observed: auditorium C but also again auditorium K deviates more in comparison with the other auditoria.

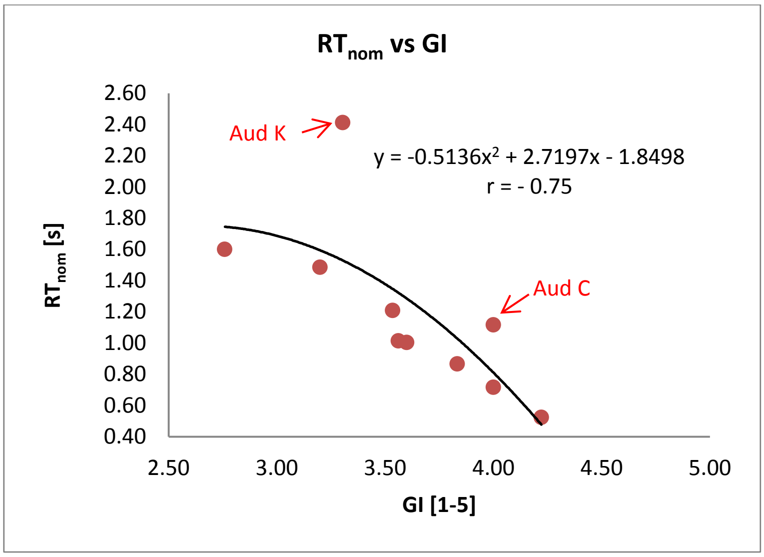


Figure 4.8d: Polygonal line regression between the measured RT_{nom} (objective) and the Global Impression GI (subjective)

Figure 4.8d represents a declining polygonal line regression. As already mentioned, the question about the GI appears to correlate more with the objective parameters in comparison with the question about the SI. Now it is only auditorium K that is clearly an outlier but also auditorium C deviates a little bit. It seems that students in auditoria C and K were too positive now in their judgment of the global acoustics.

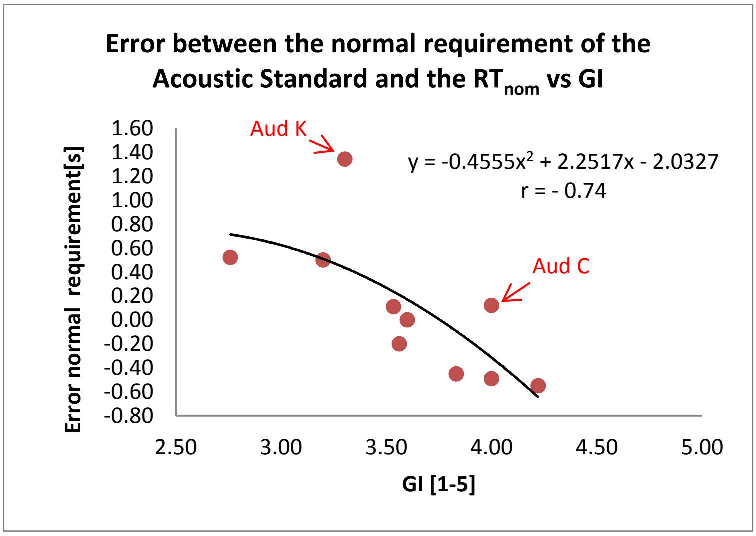


Figure 4.8e: Polygonal line regression between the error (between the normal requirement of the Acoustic Standard and the RT_{nom}) (objective) and the Global Impression GI (subjective)

Figure 4.8e also represents a declining polygonal line regression. The same observations can be made as the previous figure.

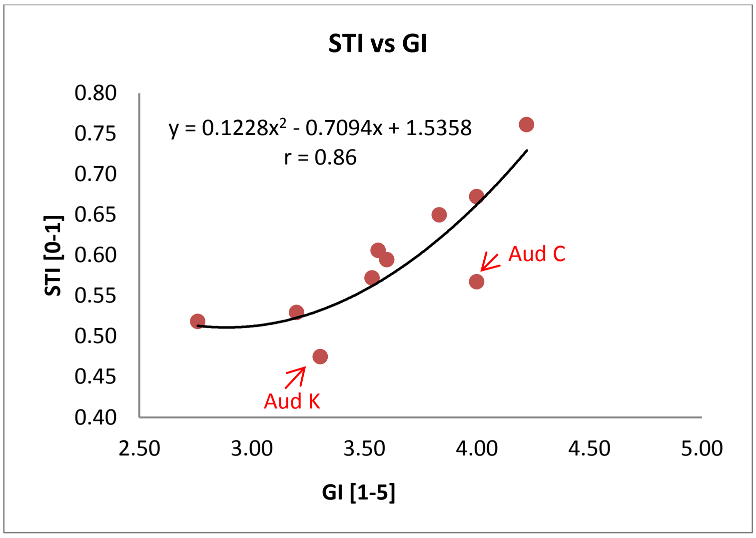


Figure 4.8f: Polygonal line regression between the STI (objective) and the GI (subjective)

At last, figure 4.8f represents an increasing polygonal regression line. The correlation is higher in comparison with the two previous figures. This means that a question about the GI is more in agreement with the STI than with the measured RT_{nom} or the Acoustic Standard.

It can be concluded that the question about the GI is in general a better question in order to obtain reliable results about the acoustic quality of an auditorium. A question about the SI corresponds better with the nominal RT and the Acoustic Standard, whereas a question about the GI corresponds better with the STI.

b. Comparison of the objective parameters mutually

In the next paragraph the correlation between the objective parameters will be compared mutually: the mean of the calculated quality number STI and the measured RT_{nom} and the error (between the normal requirement of the Acoustic Standard for School Buildings and the measured RT_{nom}) will be examined.

Based on the results of table 4.13, the coefficient of correlation between these parameters can again be calculated. This is represented in table 4.15 and in figures 4.9a and 4.9b.

Coefficient of Correlation – r	Measured RT_{nom}	NBN S 01-400-2: Error*
STI	- 0.98	- 0.99

Table 4.15: Comparison of the STI with the measured RT_{nom} and the Acoustic Standard NBN S 01-400-2, based on the coefficient of correlation r

*error between the normal requirement of the Acoustic Standard NBN S01-400-2 and the measured RT_{nom}

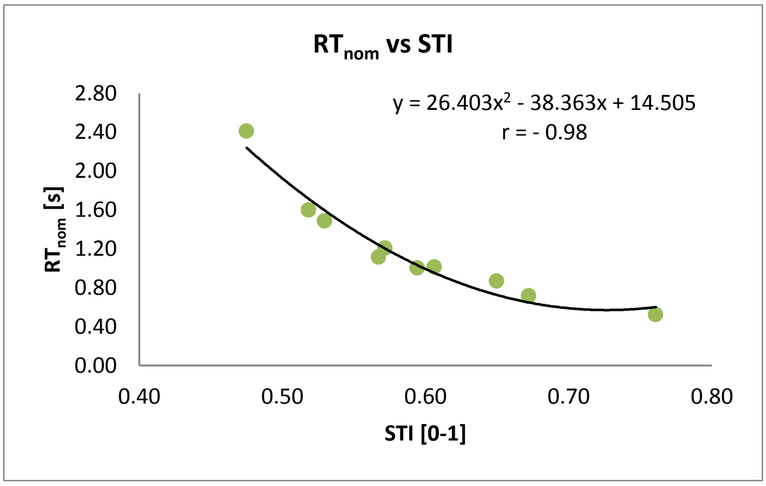


Figure 4.9a: Linear regression between measured RT_{nom} and the mean STI

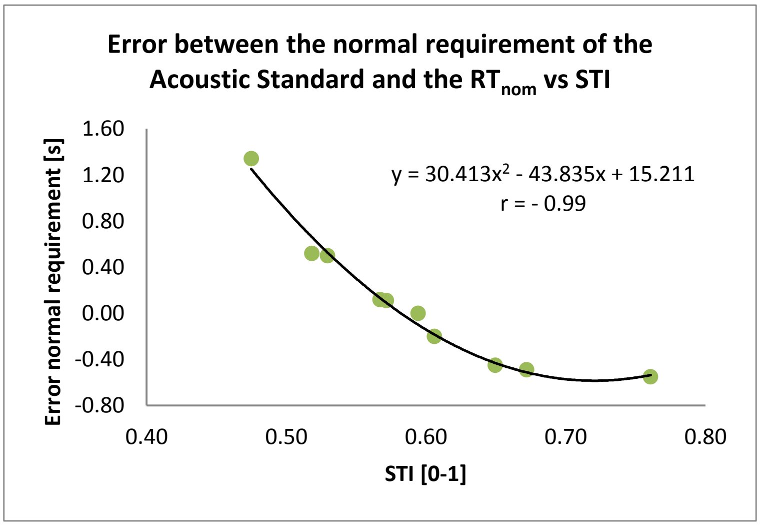


Figure 4.9b: Linear regression between the error (between the normal requirement of the Acoustic Standard and the RT_{nom}) and the mean STI

It can be concluded that there is a very high coefficient of correlation. The linear regression is also studied but it seems that again the polygonal line regression results in a higher correlation coefficient. There is a good correlation between the STI and the measured RT_{nom} and between the STI and the error between the normal requirement of the Acoustic Standard for School Buildings and the measured RT_{nom}. This means that calculating the quality number STI to evaluate the acoustic quality of an auditorium is therefore a reliable method.

4.3.2. First approach towards a classification

Based on the results of table 4.13 it appears that few auditoria meet the requirements of the Acoustic Standard for School Buildings. Auditoria A, C, D and N are according to the normal requirement but only A, C and N are according to the increased requirement. These three auditoria have a low measured RT (beneath 1 s) and a low standard deviation of the measured RT (between 1.09 s and 1.40 s). They also have good quality numbers and have positive opinions of the students. The other auditoria are found fair/good according to students but do not meet the Acoustic Standard and have fair/poor quality numbers. This means that the Acoustic Standard and the quality number can be found more severe than the opinion of the students. Auditorium E, H and K are different from the other auditoria. In these auditoria a high RT is measured and there is a high standard deviation. The measured RT of these auditoria differs a lot from the Acoustic Requirements for School Buildings and the quality numbers are low. This is also reflected in the opinion of students.

The conclusions of the different parameters (measured RT_{nom}, the standard deviation, the quality number STI, the error between the measured RT_{nom} and the Acoustic Standard, but also the results of the survey) indicate some first possible categories, as given in table 4.16.

Based on the results of table 4.13 another table can be made that gives a score from 1 (= worst auditorium) to 10 (= best auditorium) for each auditorium and for each parameter which is represented in table 4.17. The red color indicates the ‘worst’ auditoria, orange indicates the ‘mediocre’ auditoria and green indicates the ‘good’ auditoria.

Parameters		**‘Best’ auditorium**	⟵							⟶	**‘Worst’ auditorium**
Measured Reverberation	**RT_{nom} [s]**	C	N	A	J	D	I	G	H	E	K
	St. dev. σ method 1	A	C	D- N		I-J		G	H	E	K
	St. dev. σ method 2	A-C-G-J-N	D-E-H-I								K
	Confidence interval	A-C-G-J-N	D-E-H-I								K
Error of NBN S01-400-2	**Normal requirement**	C	N	A	D	J	I	G	H	E	K
	Increased requirement	C	N	A	D	J	I	G	H	E	K
Quality number	**STI**	C	N	A	D	J	G – I		H	E	K
Survey	**SI**	A	N	D	G	I	J	H	C	K	E
	GI	C	N	I	A	J	D	G	K	H	E

Table 4.16: Comparison of ten auditoria for the standard deviation, the confidence interval, the variance, the quality numbers and the survey

Score [.../10]	Measurements		Acoustic Standard		Quality number	Survey	
	RT_{nom}	Standard deviation	Normal	Increased	STI [0-1]	Mean SI [1-5]	Mean GI [1-5]
1	K	K	K	K	K	E	E
2	E	E	E	E	E	K	H
3	H	H	H	H	H	C	K
4	G	G	I	G	I	H	G
5	I	J	G	I	G	J	D
6	D	I	J	J	J	I	J
7	J	N	D	D	D	G	A
8	A	D	A	A	A	D	I
9	N	C	N	N	N	N	N
10	C	A	C	C	C	A	C

Table 4.17: Score (from 1 – 10) for the auditoria based on the results of the measured RT_{nom}, the error between the measured RT_{nom} and the requirements of the Acoustic Standard, the quality number (STI) and the survey (SI = Speech Intelligibility, GI = Global Impression)

With table 4.17 a general – weighted – score (in %) can be calculated for each auditorium which is given in table 4.18 in descending order. It is also important to look at the dimensions of each auditorium and the amount and location of absorption.

AUD	Score	Dimensions					Absorption	
	[%]	Volume [m³]	Length [m]	Width [m]	Height [m]	Compactness [m]	$\bar{\alpha}$ [-]	Location*
C	90.00	333	10.35	7.27	4.43	1.50	0.21	C/W
A	84.44	2118	22.00	19.25	5.00	1.37	0.20	C/W
N	84.44	996	22.00	9.43	6.92	1.15	0.19	C/3W
D	71.11	1121	19.62	12.12	4.80	1.21	0.16	C/W
J	56.67	319	10.00	6.50	4.90	0.99	0.10	3W
G	53.33	576	10.30	10.00	5.59	1.20	0.08	3W
I	48.89	439	14.00	6.27	5.00	0.83	0.10	3W
H	27.78	284	9.00	6.30	5.00	0.95	0.03	/
E	15.56	542	13.40	8.37	4.83	0.96	0.06	3W
K	14.44	519	9.90	9.95	5.27	1.11	0.04	/

*C/W (absorption on the ceiling and on the rear wall) – 3W (Absorption only on three walls) – C/2W (absorption on the ceiling and on two opposite walls) – / (no absorption)

Table 4.18: Score in % (based on the measured RT, the standard deviation (method 1), the Acoustic Standard for school buildings, the quality number STI and the survey for each auditorium)

It can be concluded that according to table 4.13 and tables 4.16 to 4.18 auditoria A, C, D and N always score best for every criteria. Also the same auditoria keep scoring worst: auditoria H, E and K. The other auditoria (J, G and I) always score mediocre: not good but also not too bad. These observations are a first approach towards a classification. Auditorium A, C and D have a high compactness. Auditorium N also scores well but has a lower compactness (in comparison with auditorium A, C and D). Auditorium E, G, I and J have similar results in table 4.13, 4.16-4.18. They have a compactness around 1 m. Auditorium H and K show always more or less the same results. When the location and amount of absorption are taken into account, an approach towards a classification can be made:

- The auditoria with absorption material located on the rear wall and the ceiling: A, C and D
- The auditoria with absorption material located on three adjacent walls that are not the front wall (indicated with the chalkboard): E, G, I and J
- The auditoria with no absorption material: H and K
- The auditoria with absorption material located on three adjacent walls that are not the front wall (indicated with the chalkboard) and the ceiling: N

This results into four categories which will be further discussed in chapter 5 – *'Calculation of the RT using different models and comparison with the measurements'*. Dividing into categories gives the advantage of a more structured insight in the validation of the models.

5. CALCULATION OF THE RT USING DIFFERENT MODELS AND COMPARISON WITH THE MEASUREMENTS

5.1. Approach

As discussed in chapter 1 – *'Literature study'*, the RT will be calculated using seven different prediction models: the models of Sabine, Eyring, Millington and Sette M&S, Fitzroy, Arau, Kuttruff and the Modification of Fitzroy MOF.

In this chapter the calculated RT, predicted with the seven selected models (see chapter 1 – *'Literature study'*) will be compared with the measured RT (see chapter 4 – *'Measurement results'*) in order to analyze the validation of each model, which is also done by Neubauer and Kostek [3] [4]. Modelling the RT is done by using a spreadsheet program. The results of the calculated RT are given in tables 5.2a to 5.2j and also in the graphical templates which can be found in the separate appendix. Calculations are performed for the total frequency band (250 Hz to 4,000 Hz), however for comparison purposes the presented values are only for the nominal RT (500 Hz to 2,000 Hz) and the mean RT (500 Hz to 1,000 Hz). Table 2.1 gives an overview of the absorption coefficients that are used to calculate the RT with the different prediction models. These absorption coefficients can also be found in annex B of prEN 12354-6 [27] and are measured in accordance with EN ISO 354. It is important to note that Sabine's formula is used to determine these absorption coefficients. The values can be considered as typical minimum values. It is important to mention that there are always some deviations on the absorption coefficients of different materials. However these are not taken into account in the calculation error.

For comparison purposes the prediction error and the standard deviation are calculated which are also represented in the graphs of table 5.2a to 5.2j. The prediction error for the total frequency range from 125 to 4,000 Hz is given next to the name of the model in the legend of the graphs. The prediction error is represented for the total frequency range (from 125 to 4,000 Hz) but also for the mean frequency range (from 500 to 1,000 Hz) and the nominal frequency range (from 500 to 2,000 Hz). A corresponding graph is given next to the values of the prediction errors.

The prediction error E_i for experiment (auditorium) i can be calculated as follows:

$$E_i(f) = RT_{i,predicted} - RT_{i,measured} \quad [s]$$

A negative value of the prediction error is not desirable for auditoria. An overestimation of the RT (and thus a positive value of the prediction error) is safer because it is easier to decrease the RT by adding more absorption materials for example.

The mean prediction error $\mathbf{E(f)_m}$ for a certain frequency band for n experiments (auditoria) can be calculated as follows (with n = 10 auditoria):

$$E(f)_m = \frac{1}{n}\sum_{i=1}^{n} E_n(f) \quad [s]$$

The prediction error $\mathbf{E_t}$ for the total RT for n experiments and averaged by m frequency bands (from 125 Hz to 4,000 Hz) can be described as follows (with m = 6):

$$E_t = \frac{1}{n}\sum_{i=1}^{n} E_n(f) = \frac{1}{m}\sum_{f=125\,Hz}^{f=4{,}000\,Hz} E(f) \quad [s]$$

The prediction error $\mathbf{E_m}$ for the mean RT_m, for n experiments and averaged by m frequency bands (from 500 Hz to 1,000 Hz) can be described as follows (with m = 2):

$$E_m = \frac{1}{m}\sum_{f=500\,Hz}^{f=1{,}000\,Hz} E(f) \quad [s]$$

At last the prediction error $\mathbf{E_{nom}}$ for the measured RT_{nom}, for n experiments and averaged by m frequency bands (from 500 Hz to 2,000 Hz) can be described as follows (with m = 3):

$$E_{nom} = \frac{1}{m}\sum_{f=500\,Hz}^{f=2{,}000\,Hz} E(f) \quad [s]$$

These prediction errors need to be calculated for each prediction model. For auditoria, the prediction error for the nominal RT is the most important for the Speech Intelligibility because the range from 500 Hz to 2,000 Hz is the range where the speech is located.

A maximum prediction error of 10 %, which means a maximum deviation of 10 % from the measured nominal RT, is assumed as the most severe requirement prescribed by the Belgian Acoustic Standard [6]. This is always indicated with a dashed black line on the graphs of the prediction error in tables 5.2a to 5.2j. However, in the literature study, Neubauer and Kostek state that the MOF, the model that is recommend as the best model in general, always provides values within a range of approximately 28 % [3]. Therefore, also an error of 30 % will be taken into account which is less severe. This second threshold will be indicated with a full black line on the graphs of the prediction error in tables 5.2a to 5.2j. It is important to note that the measured RT also deviates from itself between a certain range as shown in the tables of the measured RT (see chapter 4.2.2. – *'Measured RT'* and figures 4.2a to 4.2f). This is not taken into account in the calculation of the prediction error.

It is the aim of this study to look which model is reliable to predict the RT in any kind of auditorium, but also which model can be recommended for a certain kind of auditorium, thus for a certain category which are made based on the different quality parameters.

To end the chapter, two case studies are analyzed in order to confirm the conclusions about the validation of the prediction models. Measured and calculated RT are compared and a ranking is made. The first case study consists of three different situations of an acoustic laboratory in the Netherlands. The second case study is a different auditorium (auditorium B) of the Faculty of Engineering and Architecture in Ghent University. This second case study can be found in annex 8.1 –'*Case study of another auditorium'.*

5.2. Calculation of the RT

5.2.1. The use of a spreadsheet program

To calculate the RT with seven different prediction models, a template is made in a spreadsheet program. This template can be used for each auditorium. It consists of two parts. Figure 5.1 represents the coordinate system that is used for the calculations. Each surface has a name to prevent the calculator from mistakes or confusions. This is given in table 5.1.

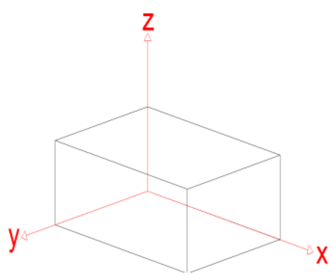


Figure 5.1: Coordinate system

Surface	Element of the space
x_1	Wall
x_2	Wall
y_1	Wall
y_2	Wall
z_1	Floor
z_2	Ceiling

Table 5.1: Defining the surfaces

The first part of the template consists of the input data, using a table with the different surfaces of the auditorium – ceiling, floor, walls with their dimensions (length, width and surface) – and the possible materials of these surfaces. Each material has its own absorption coefficient for each frequency. For this study, the absorption coefficients (see table 2.1 in chapter 2 – '*Theoretical study*') that are given by the European Standard prEn 12354-6, Annex B and Annex C [27] are used. The general dimensions of the auditoria are also calculated using the following formulae:

S – Total surface area [m²]

$$S_{total} = S_{x1} + S_{x2} + S_{y1} + S_{y2} + S_{z1} + S_{z2}$$

V – Total volume of the space [m³]

$$V = l \cdot h \cdot w$$

where:

l – Length of the space [m]

h – Height of the space [m]

w – Width of the space [m]

C – Compactness [m]

$$C = \frac{V}{S}$$

The materials used for each surface are highlighted in yellow in the tables to get a quick overview of the materials present in the auditorium.

The second part of the template is the calculation of the RT with the seven prediction models for each frequency band, using the input data of the first part of the template. The first part with the input data is essential for the second to get results. Eventually, with these results, the prediction error for each frequency can be calculated. The mean prediction error for the frequency range from 125 Hz to 4,000 Hz, from 500 Hz to 1,000 Hz and from 500 Hz to 2,000 Hz (nominal) is calculated. This information will be useful later on to link the categories to the corresponding 'best' model to predict the RT. There can also be deducted how well a model can be used to calculate the RT in an unknown space.

The templates with the data of each auditorium are represented in annex 8.6 – '*Template of the auditoria: data and calculation'*. The results of the calculations, the graphs and the prediction errors of each auditorium can be found in tables 5.2a to 5.2j and on the graphical templates in the separate appendix.

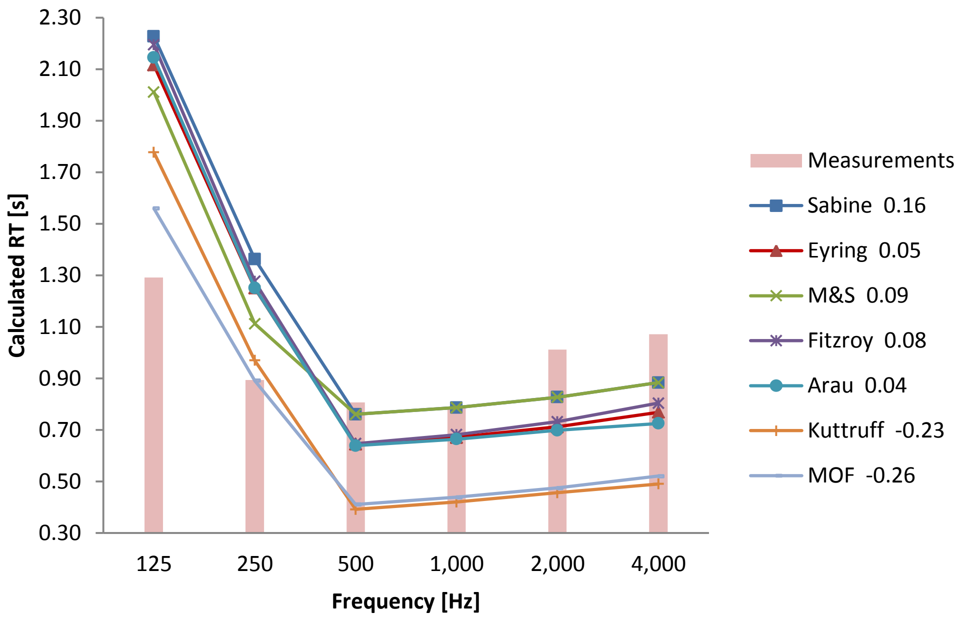
5.2.2. Results of the calculated RT

Tables 5.2a to 5.2j show the calculated RT and the measured RT for each auditorium with the corresponding graph. A calculation error is calculated based on the prediction errors. There is also a deviation of the absorption coefficients of the different materials but this is not taken into account. In this study, the absorption coefficients used to calculate the RT are derived from the model of Sabine. These are given in table 2.1 in chapter 2 – *'Theoretical study'*.

Table 5.2a shows that every model yields a negative prediction error for the nominal RT (500 to 2,000 Hz). This means that an underestimation of the RT is made, which is less safe in comparison with an overestimation. The models of Sabine and M&S give the lowest negative prediction error for the nominal RT and therefore the closest RT to the measured RT, followed by the models of Fitzroy, Eyring, Arau, the MOF and Kuttruff. The model of Kuttruff gives the highest negative prediction error for the nominal RT and therefore the results differ the most from the measured RT compared with the other models. The 10 % error (± 0.09 s) and 30 % error (± 0.26 s) are indicated on the graph. These values lead to the conclusion that only the error of the models of M&S and Sabine is located beneath the range of 10% which means that only these two models deviate 10 % or less from the measured RT_{nom}. The models of Eyring, Fitzroy and Arau deviate within a range of 30 %. The other models all deviate more than 30 % from the measured RT_{nom} and therefore are not reliable to use to predict the RT in auditorium A.

AUD A	Calculated RT [s]					
Frequency [Hz]	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**
Measurements	1.29	0.89	0.81	0.79	1.01	1.07
Sabine	2.23	1.36	0.76	0.79	0.83	0.88
Eyring	2.12	1.25	0.64	0.67	0.71	0.77
M&S	2.01	1.11	0.76	0.79	0.83	0.88
Fitzroy	2.19	1.28	0.65	0.68	0.73	0.80
Arau	2.14	1.25	0.64	0.66	0.70	0.72
Kuttruff	1.78	0.97	0.39	0.42	0.46	0.49
MOF	1.56	0.89	0.41	0.44	0.47	0.52

Graph



	Prediction error [s]		
Frequency [Hz]	**125-4,000**	**500-1,000**	**500-2,000**
Sabine	0.16	-0.02	-0.08
Eyring	0.05	-0.14	-0.19
M&S	0.09	-0.02	-0.08
Fitzroy	0.08	-0.13	-0.18
Arau	0.04	-0.14	-0.20
Kuttruff	-0.23	-0.39	-0.44
MOF	-0.26	-0.37	-0.43
MEAN	**-0.01**	**-0.17**	**-0.23**

Graph

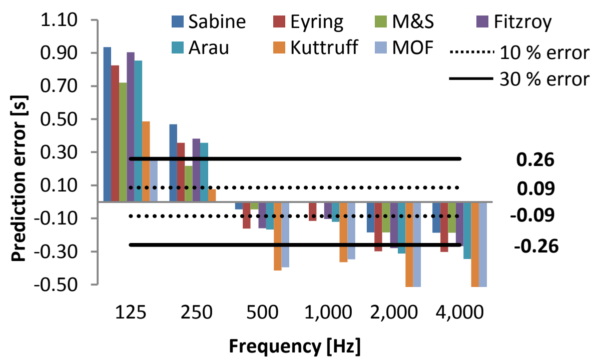
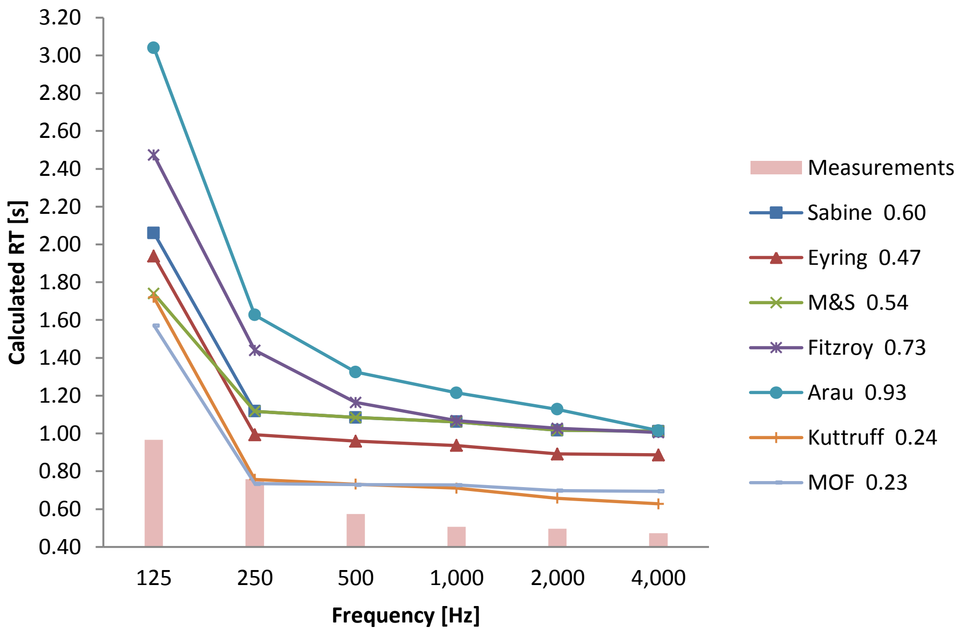


Table 5.2a: Calculated RT – auditorium A

Table 5.2b shows that every model yields a positive prediction error for the nominal RT (500 to 2,000 Hz). This means that an overestimation of the RT is made. The model of Kuttruff gives the lowest prediction error for the nominal RT and therefore the closest RT to the measured RT, followed by the MOF and the models of Eyring, Sabine, M&S, Fitzroy and Arau. The model of Arau yields the highest prediction error for the nominal RT and therefore the results differ the most from the measured RT compared with the other models. The 10 % error (± 0.05 s) and 30 % error (± 0.16 s) are indicated on the graph. However, all the models deviate more than 30 % from the measured RT_{nom} which means that none of the models is reliable to predict the RT in auditorium C.

AUD C	Calculated RT [s]					
Frequency [Hz]	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**
Measurements	0.97	0.76	0.57	0.51	0.50	0.47
Sabine	2.06	1.12	1.08	1.06	1.02	1.01
Eyring	1.94	0.99	0.96	0.94	0.89	0.89
M&S	1.74	1.12	1.08	1.06	1.02	1.01
Fitzroy	2.47	1.44	1.16	1.07	1.03	1.00
Arau	3.04	1.63	1.32	1.21	1.13	1.01
Kuttruff	1.72	0.76	0.73	0.71	0.66	0.63
MOF	1.57	0.73	0.73	0.73	0.70	0.69

Graph



	Prediction error [s]		
Frequency [Hz]	**125-4,000**	**500-1,000**	**500-2,000**
Sabine	0.60	0.53	0.53
Eyring	0.47	0.41	0.40
M&S	0.54	0.53	0.53
Fitzroy	0.73	0.58	0.56
Arau	0.93	0.73	0.70
Kuttruff	0.24	0.18	0.17
MOF	0.23	0.19	0.19
MEAN	**0.53**	**0.45**	**0.44**

Graph

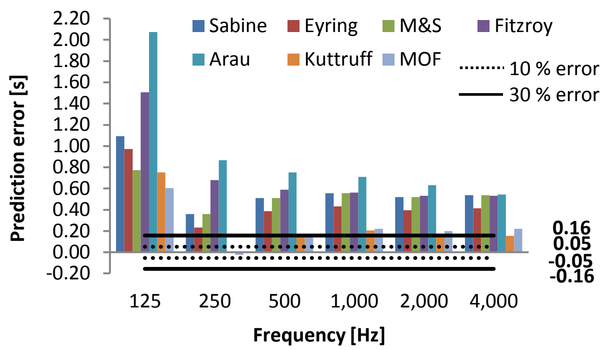
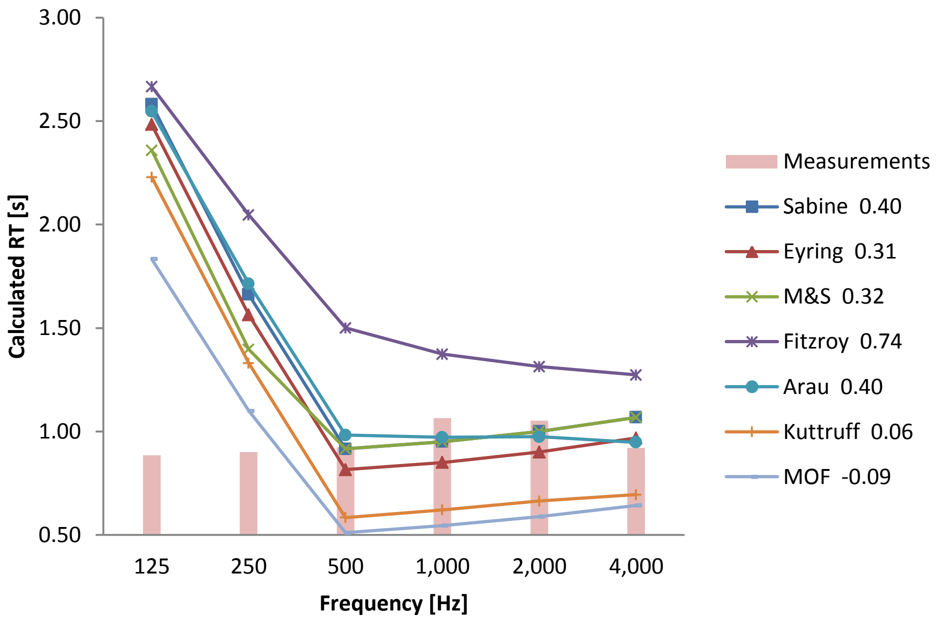


Table 5.2b: Calculated RT – auditorium C

Table 5.2c shows that only the model of Fitzroy yields a positive prediction error for the nominal RT (500 to 2,000 Hz) while the other models yield a negative value. This means that only the model of Fitzroy makes an overestimation of the RT while the other models make an underestimation. However, the model of Fitzroy deviates more than 30 % (±0.30 s) from the measured RT_{nom}. Therefore, first a look at the models that deviate maximum 10 % or 30 % of the measured RT is taken. The model of Arau gives the closest RT to the measured RT, followed by the models of Sabine, M&S, Eyring, Fitzroy, Kutruff and the MOF. The MOF gives the highest negative prediction error for the nominal RT and therefore the results differ the most from the measured RT compared with the other models. The 10 % error (± 0.10 s) and 30 % error (± 0.30 s) are indicated on the graph. Only the models of Arau, Sabine and M&S deviate less than 10 % from the measured RT_{nom} but the errors are negative which means they give an underestimation of the RT which is not desirable. The models of Fitzroy, Kuttruff and the MOF deviate more than 30 % and are not reliable to use in auditorium D.

AUD D	Calculated RT [s]					
Frequency [Hz]	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**
Measurements	0.89	0.90	0.93	1.07	1.05	0.92
Sabine	2.58	1.66	0.92	0.95	1.00	1.07
Eyring	2.48	1.56	0.82	0.85	0.90	0.97
M&S	2.36	1.40	0.92	0.95	1.00	1.07
Fitzroy	2.67	2.05	1.50	1.37	1.31	1.27
Arau	2.55	1.71	0.98	0.97	0.97	0.95
Kuttruff	2.23	1.33	0.58	0.62	0.66	0.70
MOF	1.83	1.10	0.51	0.55	0.59	0.64
Graph						

	Prediction error [s]		
Frequency [Hz]	**125-4,000**	**500-1,000**	**500-2,000**
Sabine	0.40	-0.06	-0.06
Eyring	0.31	-0.16	-0.16
M&S	0.32	-0.06	-0.06
Fitzroy	0.74	0.44	0.38
Arau	0.40	-0.02	-0.04
Kuttruff	0.06	-0.39	-0.39
MOF	-0.09	-0.47	-0.47
MEAN	**0.31**	**-0.10**	**-0.11**

Graph

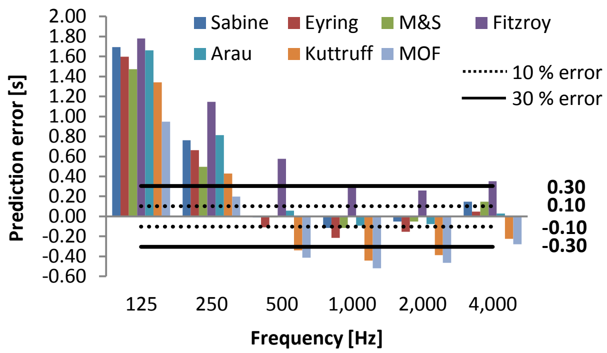
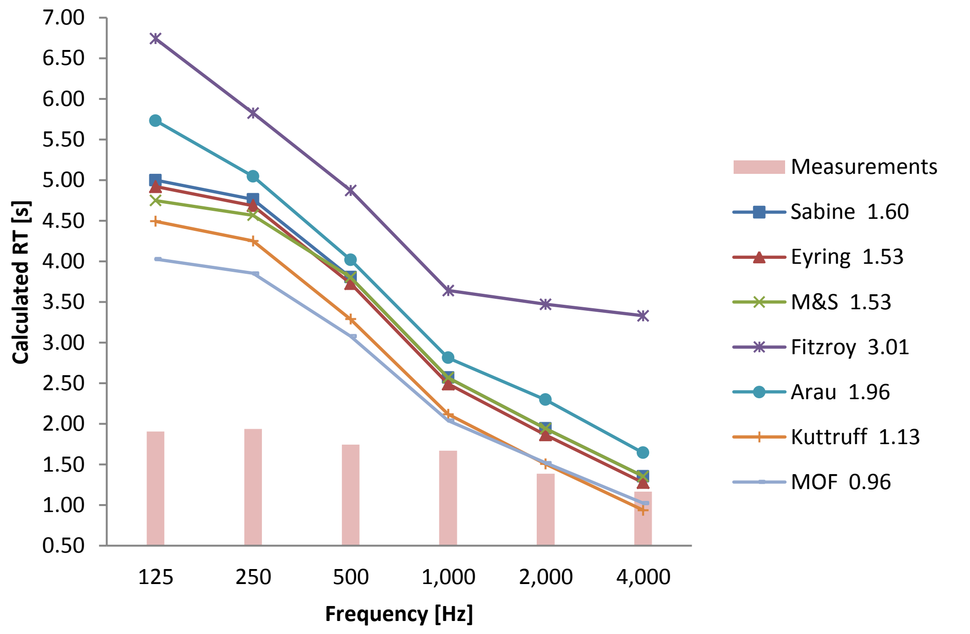


Table 5.2c: Calculated RT – auditorium D

Table 5.2d shows that every model yields a positive prediction error for the nominal RT (500 to 2,000 Hz). This means that an overestimation of the RT is made which is safer. The MOF gives the lowest prediction error for the nominal RT and therefore the closest RT to the measured RT, followed by the models of Kuttruff, Eyring, Sabine, M&S, Arau and Fitzroy. The model of Fitzroy gives the highest prediction error for the nominal RT and therefore the results differ the most from the measured RT compared with the other models. The 10 % error (± 0.16 s) and 30 % error (± 0.48 s) are indicated on the graph. However, all the models deviate more than 30 % from the measured RT_{nom} which means that none of the models is recommended to predict the RT in auditorium E.

AUD E	Calculated RT [s]					
Frequency [Hz]	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**
Measurements	1.91	1.94	1.74	1.67	1.39	1.17
Sabine	5.00	4.76	3.80	2.57	1.94	1.35
Eyring	4.92	4.68	3.73	2.49	1.86	1.28
M&S	4.75	4.57	3.80	2.57	1.94	1.35
Fitzroy	6.74	5.83	4.87	3.64	3.47	3.33
Arau	5.73	5.04	4.02	2.81	2.30	1.64
Kuttruff	4.49	4.25	3.29	2.12	1.51	0.94
MOF	4.03	3.85	3.08	2.04	1.52	1.02

Graph



	Prediction error [s]		
Frequency [Hz]	**125-4,000**	**500-1,000**	**500-2,000**
Sabine	1.60	1.48	1.17
Eyring	1.53	1.40	1.09
M&S	1.53	1.48	1.17
Fitzroy	3.01	2.55	2.39
Arau	1.96	1.71	1.44
Kuttruff	1.13	1.00	0.70
MOF	0.96	0.85	0.61
MEAN	**1.67**	**1.50**	**1.23**

Graph

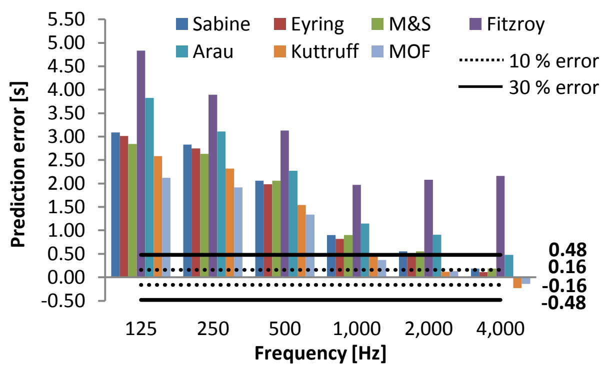
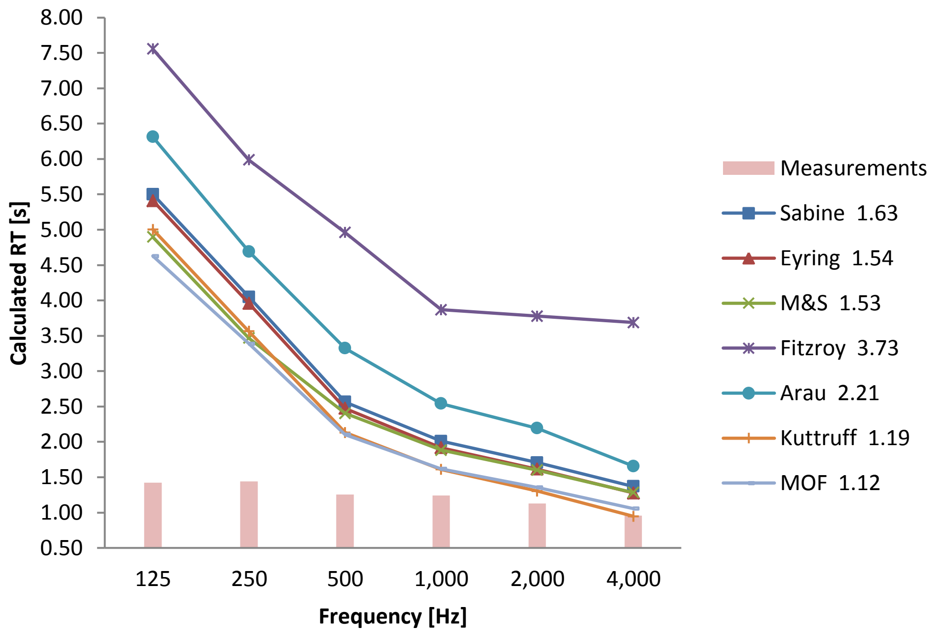


Table 5.2d: Calculated RT – auditorium E

Table 5.2e shows that again every model yields a positive prediction error for the nominal RT (500 to 2,000 Hz). This means that an overestimation of the RT is made which is safer. The model of Kuttruff gives the lowest prediction error for the nominal RT and therefore the closest RT to the measured RT, followed by the MOF and the models of M&S, Eyring, Sabine, Arau and Fitzroy. The model of Fitzroy gives the highest prediction error for the nominal RT and therefore the results differ the most from the measured RT compared with the other models. The 10 % error (± 0.12 s) and 30 % error (± 0.36 s) are indicated on the graph. However, all the models deviate more than 30 % from the measured RT_{nom} which means that none of the models is recommended to predict the RT in auditorium G.

AUD G	Calculated RT [s]					
Frequency [Hz]	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**
Measurements	1.42	1.44	1.25	1.24	1.13	0.96
Sabine	5.50	4.05	2.56	2.01	1.71	1.37
Eyring	5.41	3.96	2.47	1.92	1.62	1.28
M&S	4.90	3.47	2.40	1.88	1.60	1.28
Fitzroy	7.56	5.99	4.96	3.87	3.78	3.69
Arau	6.31	4.69	3.32	2.54	2.19	1.66
Kuttruff	5.00	3.56	2.13	1.61	1.30	0.95
MOF	4.63	3.39	2.10	1.62	1.36	1.06

Graph



	Prediction error [s]		
Frequency [Hz]	**125-4,000**	**500-1,000**	**500-2,000**
Sabine	1.63	1.04	0.89
Eyring	1.54	0.95	0.79
M&S	1.35	0.90	0.75
Fitzroy	3.73	3.17	2.99
Arau	2.21	1.68	1.48
Kuttruff	1.19	0.62	0.47
MOF	1.12	0.61	0.48
MEAN	**1.82**	**1.28**	**1.12**

Graph

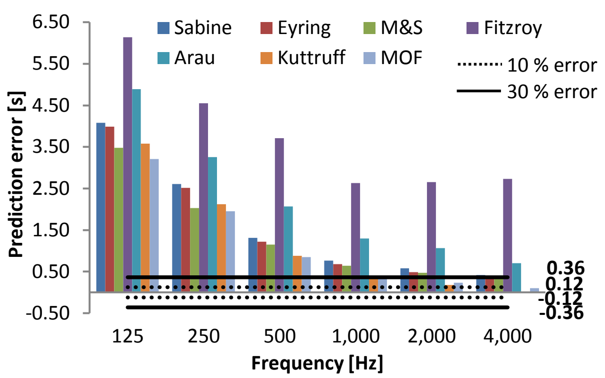
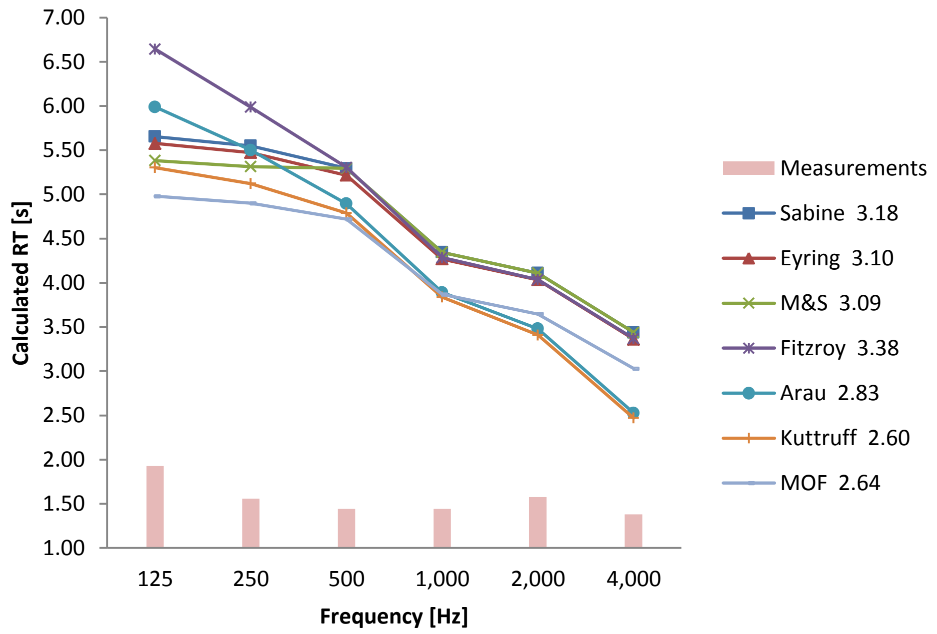


Table 5.2e: Calculated RT – auditorium G

Table 5.2f shows also that every model yields a positive prediction error for the nominal RT (500 to 2,000 Hz). This means again that an overestimation of the RT is made. The model of Kuttruff gives the lowest prediction error for the nominal RT and therefore the closest RT to the measured RT, followed by the MOF and the models Arau, Eyring, Fitzroy, Sabine and M&S. The models of Sabine and M&S give the highest prediction error for the nominal RT and therefore the results differ the most from the measured RT compared with the other models. The 10 % error (± 0.15 s) and 30 % error (± 0.45 s) are indicated on the graph. However, all the models deviate more than 30 % from the measured RT_{nom} which means again that none of the models is reliable to predict the RT in auditorium H.

AUD H	Calculated RT [s]					
Frequency [Hz]	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**
Measurements	1.93	1.56	1.44	1.44	1.58	1.38
Sabine	5.65	5.55	5.29	4.34	4.11	3.44
Eyring	5.58	5.47	5.22	4.27	4.03	3.36
M&S	5.38	5.31	5.29	4.34	4.11	3.44
Fitzroy	6.64	5.99	5.30	4.29	4.04	3.37
Arau	5.99	5.50	4.90	3.89	3.48	2.53
Kuttruff	5.30	5.12	4.79	3.84	3.41	2.47
MOF	4.98	4.90	4.72	3.87	3.65	3.03

Graph



	Prediction error [s]		
Frequency [Hz]	**125-4,000**	**500-1,000**	**500-2,000**
Sabine	3.18	3.38	3.10
Eyring	3.10	3.30	3.02
M&S	3.09	3.38	3.10
Fitzroy	3.38	3.35	3.06
Arau	2.83	2.95	2.60
Kuttruff	2.60	2.87	2.53
MOF	2.64	2.85	2.59
MEAN	**2.97**	**3.15**	**2.86**

Graph

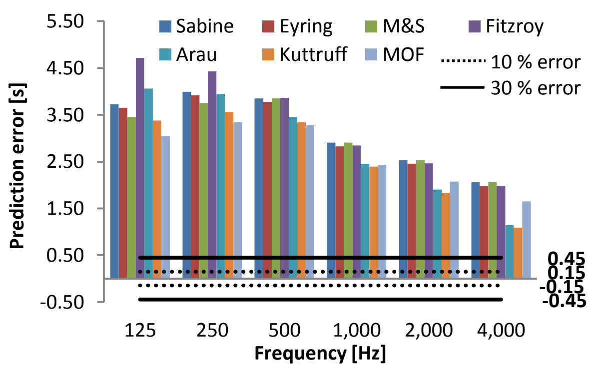
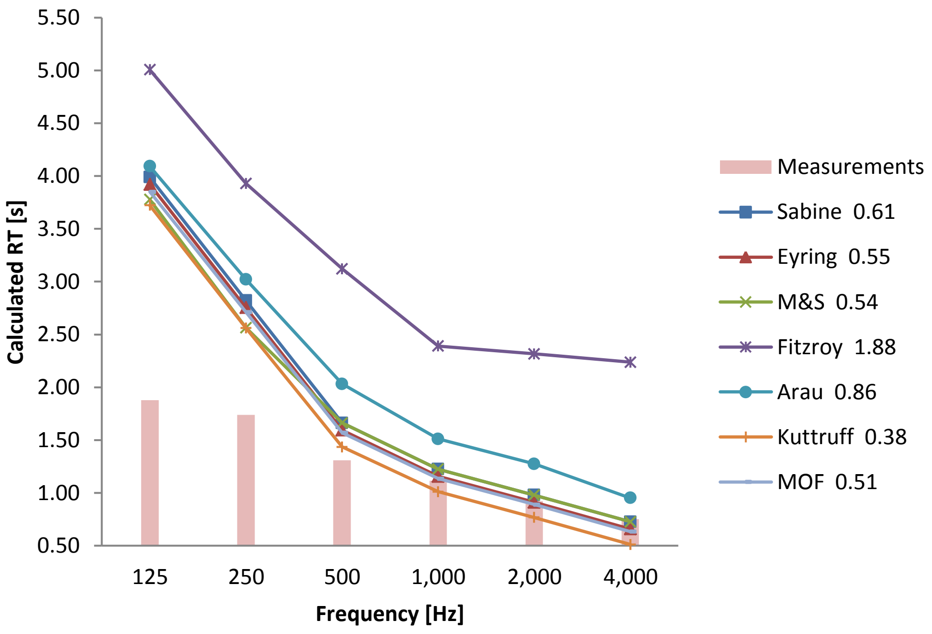


Table 5.2f: Calculated RT – auditorium H

Table 5.2g shows that only the model of Kuttruff yields a negative prediction error for the nominal RT (500 to 2,000 Hz) while the other models yield a positive value. This means that only the model of Kuttruff makes an underestimation of the RT while the other models make an overestimation. After the model of Kuttruff, the MOF yields the closest calculated RT to the measured RT, followed by the models of Eyring, Sabine, M&S, Arau and Fitzroy. The model of Fitzroy gives the highest prediction error for the nominal RT and therefore the results differ the most from the measured RT compared with the other models. The 10 % error (± 0.11 s) and 30 % error (± 0.33 s) are indicated on the graph. Only the models of Eyring, Kuttruff and the MOF deviate less than 10 % from the measured RT_{nom}. The models of Sabine and M&S deviate less than 30 %. The models of Fitzroy and Arau deviate more than 30 % and are therefore not reliable to predict the RT in auditorium I.

AUD I	Calculated RT [s]					
Frequency [Hz]	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**
Measurements	1.88	1.74	1.31	1.12	0.92	0.75
Sabine	3.99	2.82	1.66	1.22	0.98	0.73
Eyring	3.92	2.75	1.59	1.16	0.91	0.66
M&S	3.78	2.56	1.66	1.22	0.98	0.73
Fitzroy	5.01	3.93	3.12	2.39	2.32	2.24
Arau	4.09	3.02	2.03	1.51	1.28	0.95
Kuttruff	3.72	2.56	1.43	1.01	0.77	0.51
MOF	3.85	2.71	1.57	1.14	0.89	0.63

Graph



	Prediction error [s]		
Frequency [Hz]	**125-4,000**	**500-1,000**	**500-2,000**
Sabine	0.61	0.23	0.17
Eyring	0.55	0.16	0.11
M&S	0.54	0.23	0.17
Fitzroy	1.88	1.54	1.49
Arau	0.86	0.56	0.49
Kuttruff	0.38	0.01	-0.04
MOF	0.51	0.14	0.08
MEAN	**0.76**	**0.41**	**0.35**

Graph

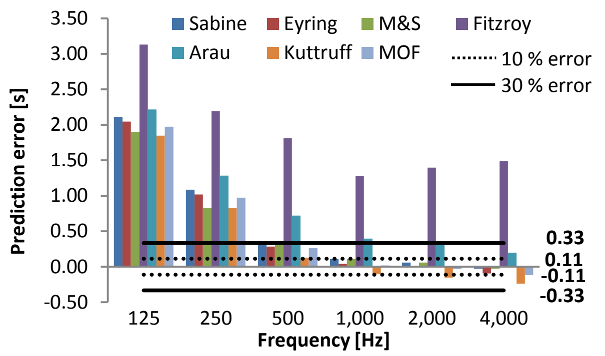
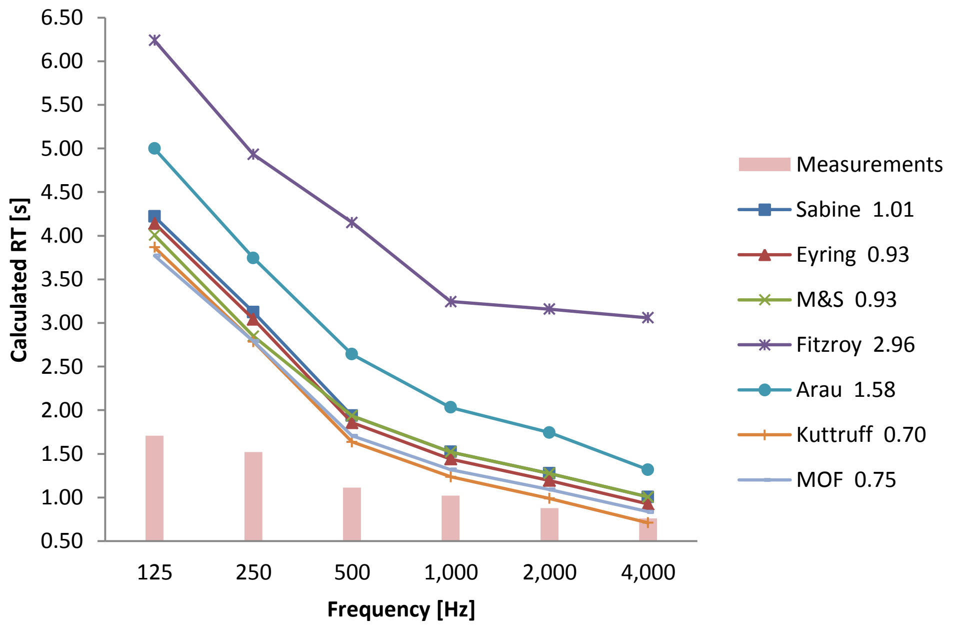


Table 5.2g: Calculated RT – auditorium I

Table 5.2h shows that every model yields a positive prediction error for the nominal RT (500 to 2,000 Hz). This means that an overestimation of the RT is made. The model of Kuttruff gives the lowest prediction error for the nominal RT and therefore the closest RT to the measured RT, followed by the MOF and the models of Eyring, Sabine, M&S, Arau and Fitzroy. The model of Fitzroy yields the highest prediction error for the nominal RT and therefore the results differ the most from the measured RT compared with the other models. The 10 % error (± 0.10 s) and 30 % error (± 0.30 s) are indicated on the graph. None of the models deviates less than 10 % from the measured RT_{nom}. Only the model of Kuttruff deviates less than 30 % which means that this model is still acceptable to predict the RT. The other models deviate more than 30 % and are not recommended to predict the RT in auditorium J.

AUD J	Calculated RT [s]					
Frequency [Hz]	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**
Measurements	1.71	1.52	1.11	1.02	0.88	0.76
Sabine	4.22	3.12	1.94	1.52	1.28	1.01
Eyring	4.14	3.04	1.86	1.44	1.20	0.93
M&S	4.01	2.85	1.94	1.52	1.28	1.01
Fitzroy	6.24	4.93	4.15	3.25	3.16	3.06
Arau	5.00	3.74	2.64	2.03	1.74	1.32
Kuttruff	3.87	2.79	1.64	1.24	0.99	0.71
MOF	3.77	2.79	1.71	1.32	1.09	0.84

Graph



	Prediction error [s]		
Frequency [Hz]	**125-4,000**	**500-1,000**	**500-2,000**
Sabine	1.01	0.66	0.57
Eyring	0.93	0.58	0.49
M&S	0.93	0.66	0.57
Fitzroy	2.96	2.63	2.51
Arau	1.58	1.27	1.14
Kuttruff	0.70	0.37	0.28
MOF	0.75	0.45	0.37
MEAN	**1.27**	**0.95**	**0.85**

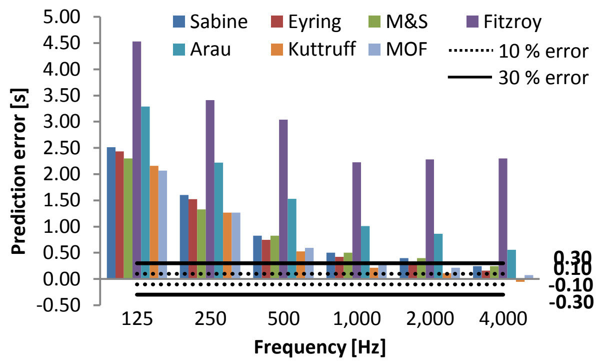
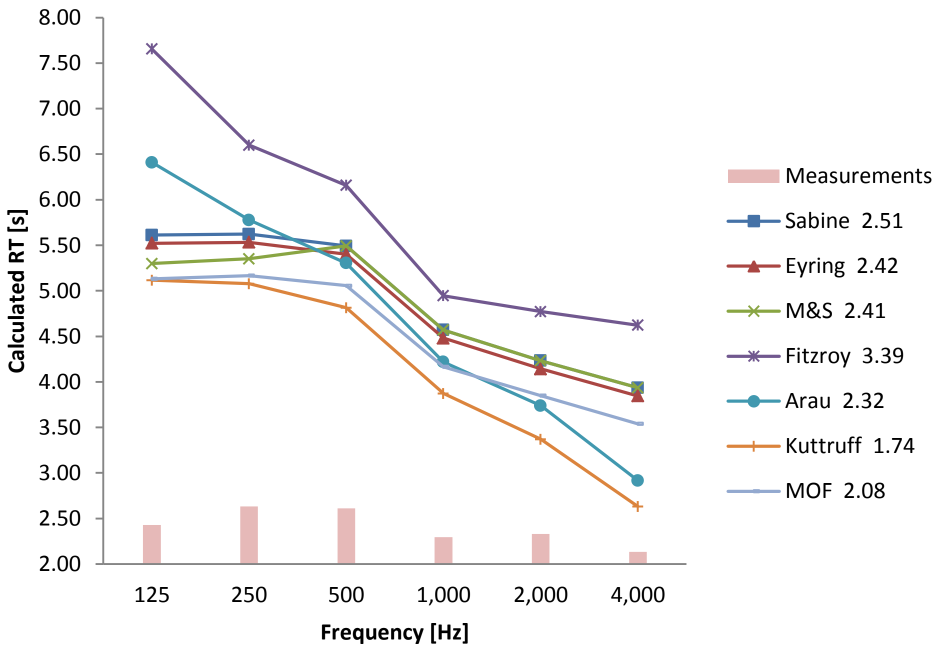


Table 5.2h: Calculated RT – auditorium J

Table 5.2h shows that every model yields a positive prediction error for the nominal RT (500 to 2,000 Hz). This means that an overestimation of the RT is made. The model of Kuttruff gives the lowest prediction error for the nominal RT and therefore the closest RT to the measured RT, followed by the MOF and the models of Arau, Eyring, Sabine, M&S and Fitzroy. The model of Fitzroy gives the highest prediction error for the nominal RT and therefore the results differ the most from the measured RT compared with the other models. The 10 % error (± 0.24 s) and 30 % error (± 0.72 s) are indicated on the graph. However, all the models deviate more than 30 % from the measured RT_{nom} which means that none of the models is reliable to predict the RT in auditorium K.

AUD K	Calculated RT [s]					
Frequency [Hz]	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**
Measurements	2.43	2.63	2.61	2.29	2.33	2.13
Sabine	5.61	5.62	5.49	4.57	4.23	3.93
Eyring	5.52	5.53	5.40	4.48	4.14	3.85
M&S	5.30	5.35	5.49	4.57	4.23	3.93
Fitzroy	7.65	6.60	6.16	4.95	4.77	4.62
Arau	6.41	5.78	5.30	4.22	3.74	2.92
Kuttruff	5.12	5.08	4.81	3.87	3.37	2.63
MOF	5.13	5.17	5.06	4.17	3.85	3.54

Graph



	Prediction error [s]		
Frequency [Hz]	**125-4,000**	**500-1,000**	**500-2,000**
Sabine	2.51	2.58	2.35
Eyring	2.42	2.49	2.26
M&S	2.41	2.58	2.35
Fitzroy	3.39	3.10	2.88
Arau	2.32	2.31	2.01
Kuttruff	1.74	1.89	1.61
MOF	2.08	2.16	1.95
MEAN	**2.41**	**2.44**	**2.20**

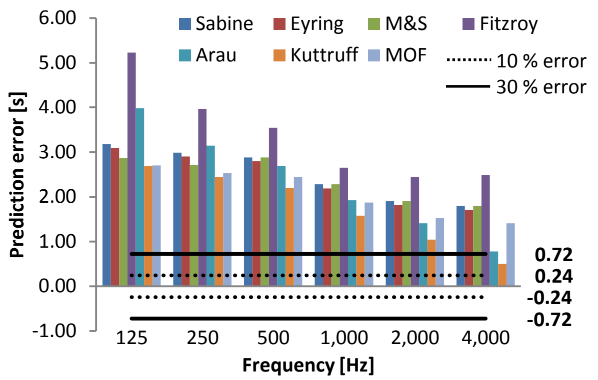
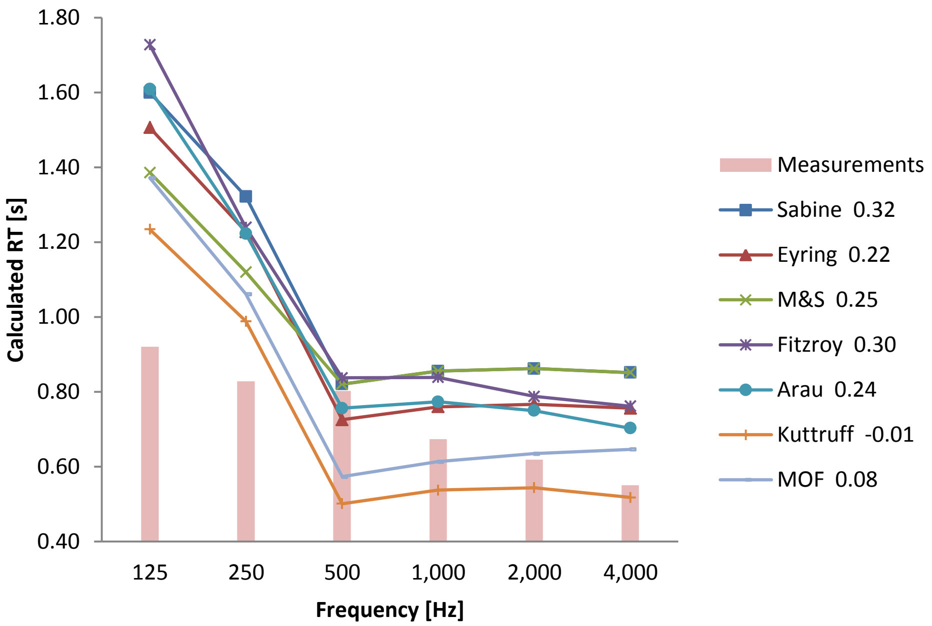


Table 5.2i: Calculated RT – auditorium K

Table 5.2j shows that only the model of Kuttruff and the MOF yield a negative prediction error for the nominal RT (500 to 2,000 Hz) while the other models yield a positive value. This means that only the model of Kuttruff and the MOF make an underestimation of the RT (which is not safe) while the other models make an overestimation (which is safer). The model of Eyring gives the closest RT to the measured RT, followed by the models of Arau, Fitzroy, Sabine, M&S, the MOF and the model of Kuttruff. The model of Kuttruff gives the highest prediction error for the nominal RT and therefore the results differ the most from the measured RT compared with the other models. The 10 % error (± 0.07 s) and 30 % error (± 0.21 s) are indicated on the graph. Only the models of Eyring and Arau deviate less than 10 % from the measured RT_{nom}. The other models deviate less than 30 %. This means that all of the models deviate maximum 30 % from the measured RT_{nom} and can all be used to predict the RT in auditorium N.

AUD N	Calculated RT [s]					
Frequency [Hz]	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**
Measurements	0.92	0.83	0.80	0.67	0.62	0.55
Sabine	1.60	1.32	0.82	0.86	0.86	0.85
Eyring	1.51	1.23	0.73	0.76	0.77	0.76
M&S	1.39	1.12	0.82	0.86	0.86	0.85
Fitzroy	1.73	1.24	0.84	0.84	0.79	0.76
Arau	1.61	1.22	0.76	0.77	0.75	0.70
Kuttruff	1.23	0.99	0.50	0.54	0.54	0.52
MOF	1.37	1.06	0.57	0.61	0.63	0.65

Graph



	Prediction error [s]		
Frequency [Hz]	**125-4,000**	**500-1,000**	**500-2,000**
Sabine	0.32	0.10	0.15
Eyring	0.22	0.00	0.05
M&S	0.25	0.10	0.15
Fitzroy	0.30	0.10	0.12
Arau	0.24	0.03	0.06
Kuttruff	-0.01	-0.22	-0.17
MOF	0.08	-0.14	-0.09
MEAN	**0.20**	**0.00**	**0.04**

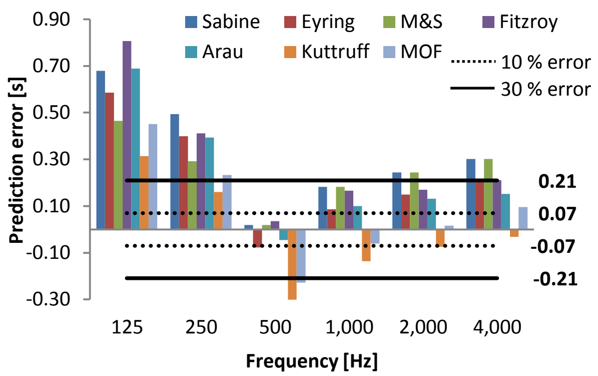


Table 5.2j: Calculated RT – auditorium N

Tables 5.3a and 5.3b give a summary of the calculated and measured RT for the ten auditoria for the mean RT (frequency range from 125 to 4,000 Hz) and the nominal RT (frequency range from 500 to 2,000 Hz).

AUD	Measured and calculated RT_m [s]							
	Measured	**Sabine**	**Eyring**	**M&S**	**Fitzroy**	**Arau**	**Kuttruff**	**MOF**
A	0.80	0.77	0.66	0.77	0.66	0.65	0.41	0.42
C	0.54	1.07	0.95	1.07	1.12	1.27	0.72	0.73
D	1.00	0.93	0.83	0.93	1.44	0.98	0.60	0.53
E	1.71	3.19	3.11	3.19	4.26	3.41	2.70	2.56
G	1.25	2.29	2.20	2.14	4.41	2.93	1.87	1.86
H	1.44	4.82	4.74	4.82	4.79	4.39	4.31	4.29
I	1.21	1.44	1.38	1.44	2.76	1.77	1.22	1.35
J	1.07	1.73	1.65	1.73	3.70	2.34	1.44	1.51
K	2.45	5.03	4.94	5.03	5.55	4.76	4.34	4.61
N	0.74	0.84	0.74	0.84	0.84	0.76	0.52	0.59
GRAPH								

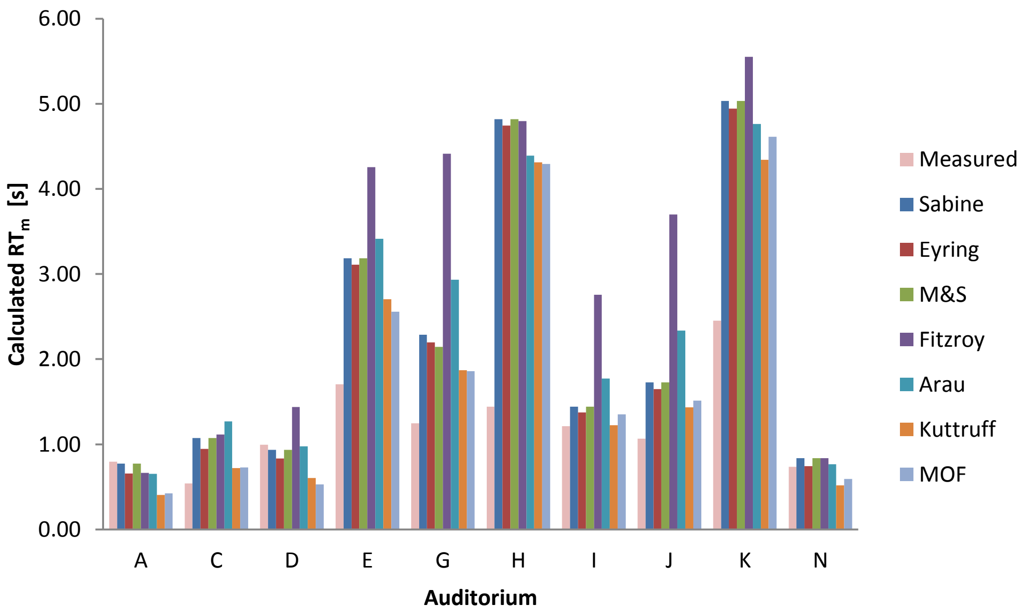


Table 5.3a: Measured and calculated mean RT for ten auditoria

The graph represented in table 5.3a gives a quick view of which models give a higher (safer) or lower (not desirable) calculated RT in comparison with the measured RT (pink bar). It can again be observed that for auditorium A the calculated RT (with any model) yield lower values in comparison with the measured RT. For auditorium D only the calculation using Fitzroy's model gives a higher result than the measured RT. For auditorium N only the calculations with the models of Kuttruff and the MOF yield an underestimation. In the other auditoria the results of all the models give a higher result in comparison with the measured RT. The graph represented in table 5.3b shows the same observations as in table 5.3a.

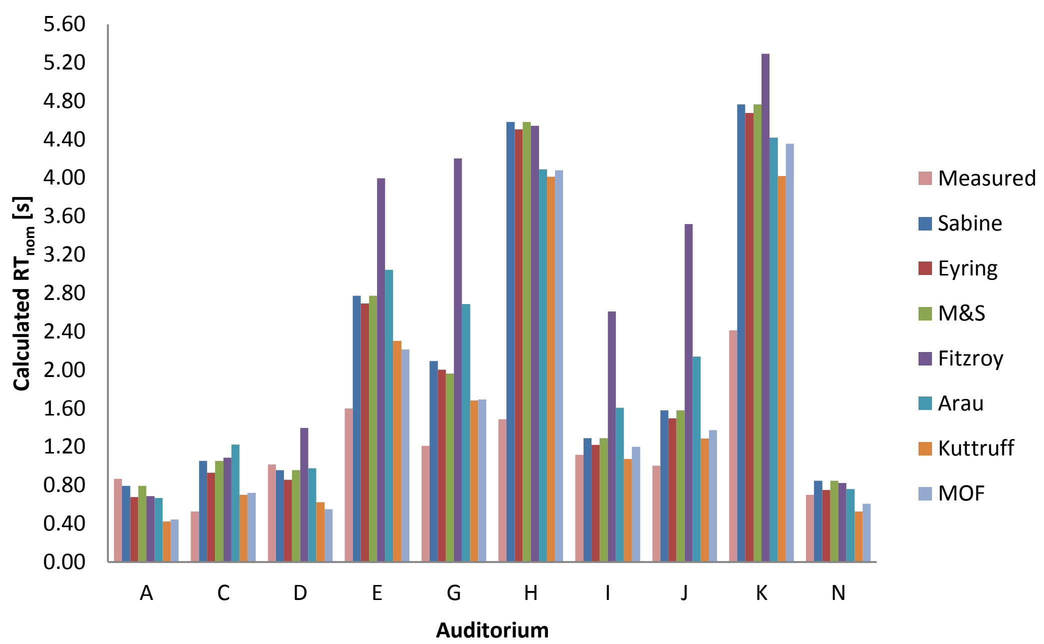
AUD	Measured and calculated RT_{nom} [s]						
	Measured	**Sabine**	**Eyring**	**M&S**	**Fitzroy**	**Arau**	**Kuttruff**	**MOF**
A	0.87	0.79	0.68	0.79	0.69	0.67	0.42	0.44
C	0.53	1.05	0.93	1.05	1.09	1.22	0.70	0.72
D	1.01	0.96	0.86	0.96	1.40	0.98	0.62	0.55
E	1.60	2.77	2.69	2.77	3.99	3.04	2.30	2.21
G	1.21	2.09	2.00	1.96	4.20	2.69	1.68	1.69
H	1.49	4.58	4.51	4.58	4.54	4.09	4.01	4.08
I	1.12	1.29	1.22	1.29	2.61	1.61	1.07	1.20
J	1.00	1.58	1.50	1.58	3.52	2.14	1.29	1.37
K	2.41	4.77	4.68	4.77	5.29	4.42	4.02	4.36
N	0.70	0.85	0.75	0.85	0.82	0.76	0.53	0.61
Graph								

Table 5.3b: Measured and calculated nominal RT for ten auditoria

Table 5.4a gives an overview of the prediction error for the measured RT_{nom} for the frequency range from 500 to 2,000 Hz for each auditorium and each model. Again, the 10 % (black dashed line) en 30 % (black full line) maximum deviation are indicated on the graph. The results and the graph show again that for auditorium A every model yields an underestimation (as every prediction error has a negative value). This is less safe in comparison with an overestimation of the RT. In auditorium A, only the error of the models of M&S and Sabine is located beneath the range of 10% which means that only these two models deviate 10 % or less from the measured RT_{nom}. The models of Eyring, Fitzroy and Arau deviate within a range of 30 %. The other models all deviate more than 30 % from the measured RT_{nom} and therefore are not reliable to use in this auditorium. As already mentioned, for auditorium D only the model of Fitzroy yields an overestimation of the RT (positive prediction error). Only the models of Arau, Sabine and M&S deviate less than 10 % from the measured RT_{nom} but the error is negative which means these models underestimate the RT and this is not desirable. The models of Fitzroy, Kuttruff and the MOF deviate more than 30 % and are also not reliable to use in auditorium D. For auditorium N only the model of Kuttruff and the MOF yield an underestimation of the RT. Only the models of Eyring and Arau deviate less than 10 % from the measured RT_{nom}. The other models deviate less than 30 %. This means that all of the models deviate maxium 30 % from the measured RT_{nom} and can be used in auditorium N.

The values of the prediction error for the measured RT_{nom} are the highest for auditoria H and K. In auditorium E, G, I and J it is very clear that the model of Fitzroy is not a good model to predict the RT because of its very high prediction error for the measured RT_{nom} in comparison with the other models. The observations of each model separately will be discussed more thoroughly in a later part of this chapter after the definitive classification. This classification gives the advantage of a more structured overview of the prediction models.

AUD	Prediction error for the measured nominal RT (from 500 to 2,000 Hz)						
	Sabine	**Eyring**	**M&S**	**Fitzroy**	**Arau**	**Kuttruff**	**MOF**
A	-0.08	-0.19	-0.08	-0.18	-0.20	-0.44	-0.43
C	0.53	0.40	0.53	0.56	0.70	0.17	0.19
D	-0.06	-0.16	-0.06	0.38	-0.04	-0.39	-0.47
E	1.17	1.09	1.17	2.39	1.44	0.70	0.61
G	0.89	0.79	0.75	2.99	1.48	0.47	0.48
H	3.10	3.02	3.10	3.06	2.60	2.53	2.59
I	0.17	0.11	0.17	1.49	0.49	-0.04	0.08
J	0.57	0.49	0.57	2.51	1.14	0.28	0.37
K	2.35	2.26	2.35	2.88	2.01	1.61	1.95
N	0.15	0.05	0.15	0.12	0.06	-0.17	-0.09

Graph

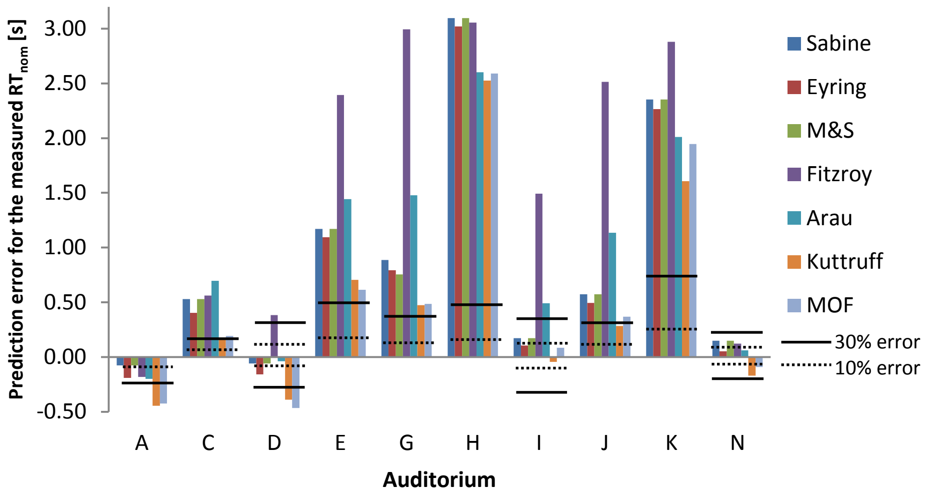


Table 5.4a: Prediction error for the measured nominal RT (from 500 to 2,000 Hz) for ten auditoria

Table 5.4b represents an overview of the prediction error for the mean RTm for the frequency range 500 to 1,000 Hz for each auditorium and each model. The same observations can be found as in table 5.4a.

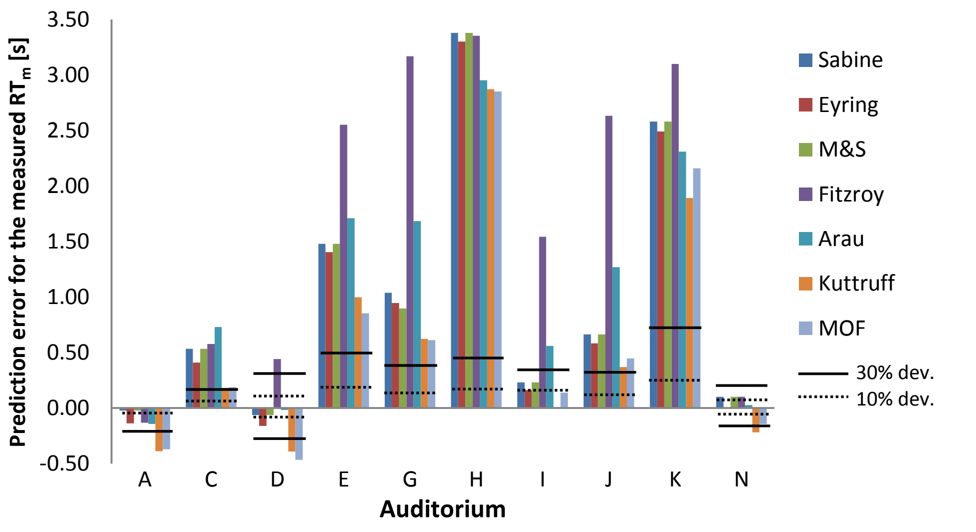
AUD	Prediction error for the measured mean RT (from 500 to 1,000 Hz)						
	Sabine	Eyring	M&S	Fitzroy	Arau	Kuttruff	MOF
A	-0.02	-0.14	-0.02	-0.13	-0.14	-0.39	-0.37
C	0.53	0.41	0.53	0.58	0.73	0.18	0.19
D	-0.06	-0.16	-0.06	0.44	-0.02	-0.39	-0.47
E	1.48	1.40	1.48	2.55	1.71	1.00	0.85
G	1.04	0.95	0.90	3.17	1.68	0.62	0.61
H	3.38	3.30	3.38	3.35	2.95	2.87	2.85
I	0.23	0.16	0.23	1.54	0.56	0.01	0.14
J	0.66	0.58	0.66	2.63	1.27	0.37	0.45
K	2.58	2.49	2.58	3.10	2.31	1.89	2.16
N	0.10	0.00	0.10	0.10	0.03	-0.22	-0.14
Graph							

Table 5.4b: Prediction error for the measured mean RT (from 500 to 1,000 Hz) for ten auditoria

5.3. Validation of the models

5.3.1. Classification

A first approach towards a classification is made based on different parameters in the previous chapter 4 - ‘*Measurement results*’.

- The measured RT
- The quality numbers: SN-ratio, C_{50}-value and STI
- The survey: SI and GI
- The Acoustic Standard for School Buildings NBN S 01-400-2

However, also the dimensions and properties (distribution, amount of absorption and diffusivity) should be taken into account. The global absorption coefficient is calculated for each surface (x_1, x_2, y_1, y_2, z_1, z_2) and for each category in order to find how absorptive the auditoria of each category are. This is represented in table 5.5. The considered surface is colored pink. High values of the global absorption coefficient for the corresponding surface are colored pink. Every category has its own icon on which the acoustic surfaces (pink) are located and the ‘front’ of the auditorium (chalk board) can be seen. This gives a quick view of the distribution of sound absorption as this is important for the validation of the models.

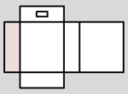
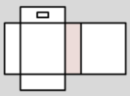
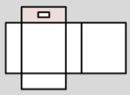
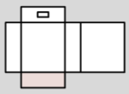
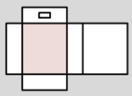
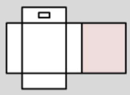
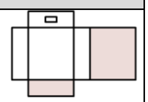
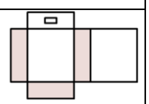
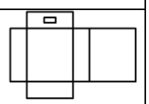
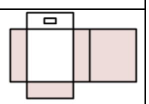
Cat.	**Absorption coefficient α [-]**						$\overline{\alpha}$	**Icon**
								
	x_1	**x_2**	**y_1**	**y_2**	**z_1**	**z_2**		
1	0.15	0.15	0.07	0.30	0.03	0.53	**0.20**	
2	0.18	0.18	0.06	0.19	0.03	0.02	**0.11**	
3	0.04	0.05	0.07	0.03	0.03	0.02	**0.04**	
4	0.16	0.16	0.14	0.25	0.03	0.51	**0.19**	

Table 5.5: Absorption coefficient for each surface and the global absorption coefficient for each category

The observations of these parameters and results lead to a classification of ten auditoria in four different categories which is given in table 5.6. The corresponding mean values of the different parameters on which this classification is based are given. Each category has its own icon which will be used in the further part of this study.

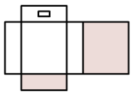
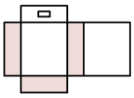
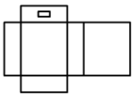
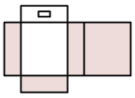
CATEGORY		AUD	Measured Reverberation [s]		NBN S 01-400-2: error [s]		Quality number	Survey	
			RT_{nom}	Standard deviation	Normal	Increased	STI [0-1]	Mean SI [1-5]	Mean GI [1-5]
1		A - C - D	0.80	0.09	-0.29	-0.07	0.67	3.93	3.87
2		E - G - I - J	1.23	1.26	0.28	0.47	0.56	3.60	3.47
3		H - K	1.95	1.44	1.01	1.20	0.50	3.94	3.25
4		N	0.70	0.10	-0.37	-0.15	0.67	4.41	4.00

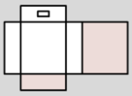
Table 5.6: Mean results for the measured RT, the Acoustic Standard for School Buildings, the quality number and the survey for the four categories

Table 5.6 shows that category 1 and 4 have a lower measured nominal RT_{nom} (lower than 1 s) in comparison with category 2 and 3 (higher than 1 s). The standard deviation of category 1 and 4 is low. Since the lower the standard deviation, the more chance of a diffuse character, this is a first indication that category 1 and 4 are more diffuse in comparison with category 2 and 3 who have a higher standard deviation. The error between the normal (and increased) requirement and the measured nominal RT result in a negative value for category 1 and 4 which means that they meet the requirements of the Acoustic Standard for School Buildings. Category 2 and 3 do not meet the requirements which is indicated by the positive values of the error. A high weighted mean STI (0.67) can be found for category 1 and 4 which corresponds with a 'good' acoustic quality (green color). For auditoria belonging to category 2 or 3 the STI is 0.56 and 0.50 which corresponds with a 'fair' acoustic quality (yellow color). Also the survey shows better appreciations of the SI and GI for category 1 and 4. Category 2 scores mediocre for every parameter and category 3 always scores the worst.

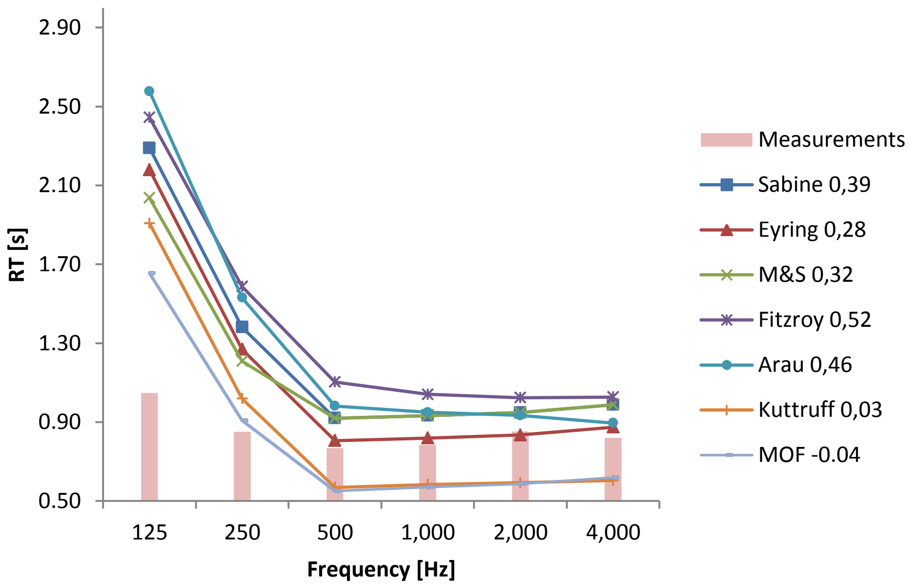
The diffusivity of a space is not only determined by the standard deviation of the measured RT but also by the amount and the distribution of sound absorption. Table 5.5 shows that auditoria of category 1 and 4 have a higher global absorption coefficient ($\overline{\alpha}$ = 0.20 and $\overline{\alpha}$ =0.19) in comparison with category 2 and 3 ($\overline{\alpha}$ = 0.11 and $\overline{\alpha}$ =0.04). Therefore it can be said that auditoria of category 1 and 4 are more dead spaces. The higher the amount of absorption, the less chance of a diffuse character. This would mean that auditoria of category 1 and 4 are less diffuse. The statement that the higher the absorption, the less chance of a diffuse character does not immediately mean that auditoria of category 1 and 4 have a less diffuse character. If the global absorption coefficient of these spaces is not too high, the diffusivity of these auditoria can also be obtained by the geometry of the auditoria, for example non-parallel walls, a lowered ceiling, a tribune, etc. but also by furniture, reflectors, etc.

The distribution of the sound absorption in a space also determines the diffusivity of a space. The more uniform the distribution of sound absorption, the more chance of a diffuse space: sound scatters in three dimensions, so if one of two parallel walls is not absorbent, then the intensity vector in that direction will be much larger and cannot be compensated by the intensity vector in the other direction to obtain an intensity vector of zero (as assumed by a diffuse field). Auditoria of category 1 and 4 have a non-uniform distribution of the sound absorption. Again, this would mean that these categories have a less diffuse character. However, the previous findings indicate that these categories have a more diffuse character in comparison with category 2 and 3 due to geometry, a tribune, a lowered ceiling, furniture, lower standard deviation etc. as already mentioned.

Tables 5.7a to 5.7d represent the measured and calculated RT for each frequency. The mean is calculated for the different auditoria belonging to the corresponding category. The total prediction error (for a frequency range from 125 Hz to 4,000 Hz) is given next to the name of the model in the legend of the graph. The prediction error is also represented for the mean frequency range (500 Hz to 1,000 Hz) and the nominal frequency range (500 Hz to 2,000 Hz). A corresponding graph is given next to the values of the prediction error. Note that these errors are absolute values. A summary is given in the following tables.

Category 1 	Calculated RT [s]					
Frequency [Hz]	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**
Measurements	1.05	0.85	0.77	0.79	0.85	0.82
Sabine	2.29	1.38	0.92	0.93	0.95	0.99
Eyring	2.18	1.27	0.81	0.82	0.83	0.87
M&S	2.04	1.21	0.92	0.93	0.95	0.99
Fitzroy	2.44	1.59	1.10	1.04	1.02	1.03
Arau	2.58	1.53	0.98	0.95	0.93	0.90
Kuttruff	1.91	1.02	0.57	0.58	0.59	0.60
MOF	1.66	0.91	0.55	0.57	0.59	0.62

Graph



	Prediction error [s]		
Frequency [Hz]	**125-4,000**	**500-1,000**	**500-2,000**
Sabine	0.39	0.15	0.13
Eyring	0.28	0.04	0.02
M&S	0.32	0.15	0.13
Fitzroy	0.52	0.30	0.25
Arau	0.46	0.19	0.15
Kuttruff	0.03	-0.20	-0.22
MOF	-0.04	-0.22	-0.23
MEAN	**0.28**	**0.06**	**0.03**

Graph

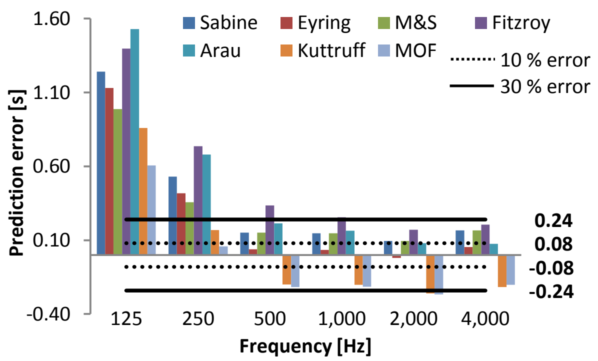
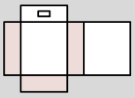
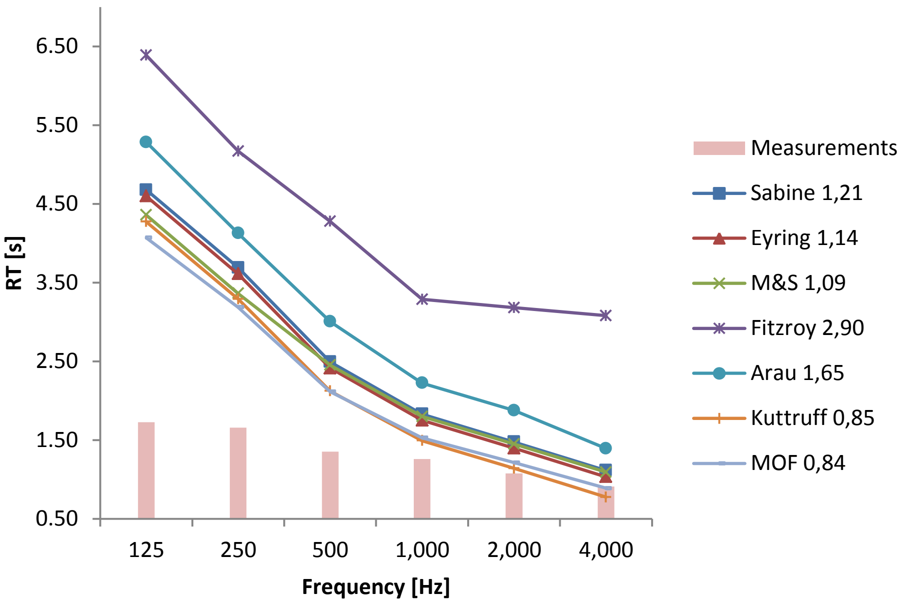


Table 5.7a: Calculated RT – Category 1

Category 2	Calculated RT [s]					
						
Frequency [Hz]	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**
Measurements	1.73	1.66	1.36	1.26	1.08	0.91
Sabine	4.68	3.69	2.49	1.83	1.48	1.11
Eyring	4.60	3.61	2.41	1.75	1.40	1.03
M&S	4.36	3.36	2.45	1.80	1.45	1.09
Fitzroy	6.39	5.17	4.28	3.29	3.18	3.08
Arau	5.28	4.13	3.00	2.22	1.88	1.39
Kuttruff	4.27	3.29	2.12	1.49	1.14	0.78
MOF	4.07	3.19	2.11	1.53	1.21	0.89

Graph



	Prediction error [s]		
Frequency [Hz]	**125-4,000**	**500-1,000**	**500-2,000**
Sabine	1.21	0.85	0.70
Eyring	1.14	0.77	0.62
M&S	1.09	0.82	0.67
Fitzroy	2.90	2.47	2.35
Arau	1.65	1.31	1.14
Kuttruff	0.90	0.50	0.35
MOF	0.84	0.51	0.39
MEAN	**1.39**	**1.03**	**0.89**

Graph

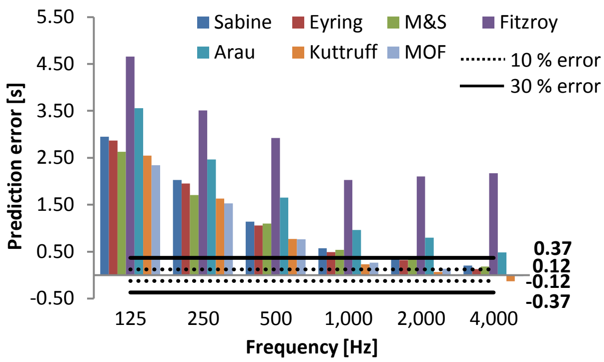
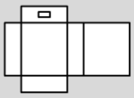
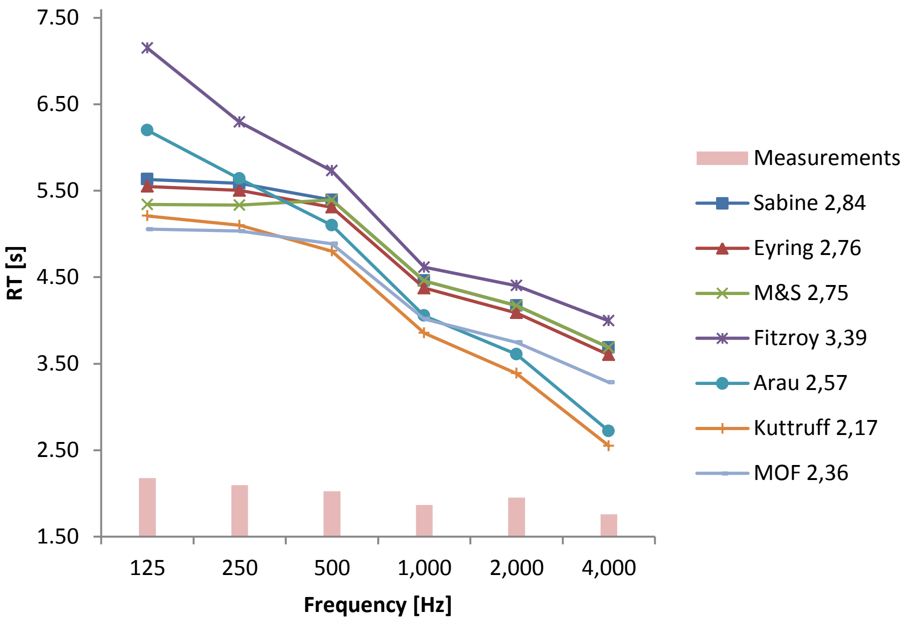


Table 5.7b: Calculated RT – Category 2

Category 3 	Calculated RT [s]					
Frequency [Hz]	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**
Measurements	2.18	2.10	2.03	1.87	1.95	1.76
Sabine	5.63	5.59	5.39	4.46	4.17	3.69
Eyring	5.55	5.50	5.31	4.37	4.09	3.60
M&S	5.34	5.33	5.39	4.46	4.17	3.69
Fitzroy	7.15	6.29	5.73	4.62	4.40	4.00
Arau	6.20	5.64	5.10	4.05	3.61	2.72
Kuttruff	5.21	5.10	4.80	3.85	3.39	2.55
MOF	5.06	5.03	4.89	4.02	3.75	3.28
Graph						

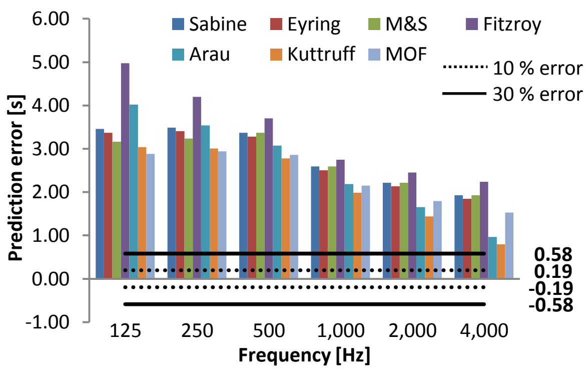
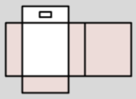
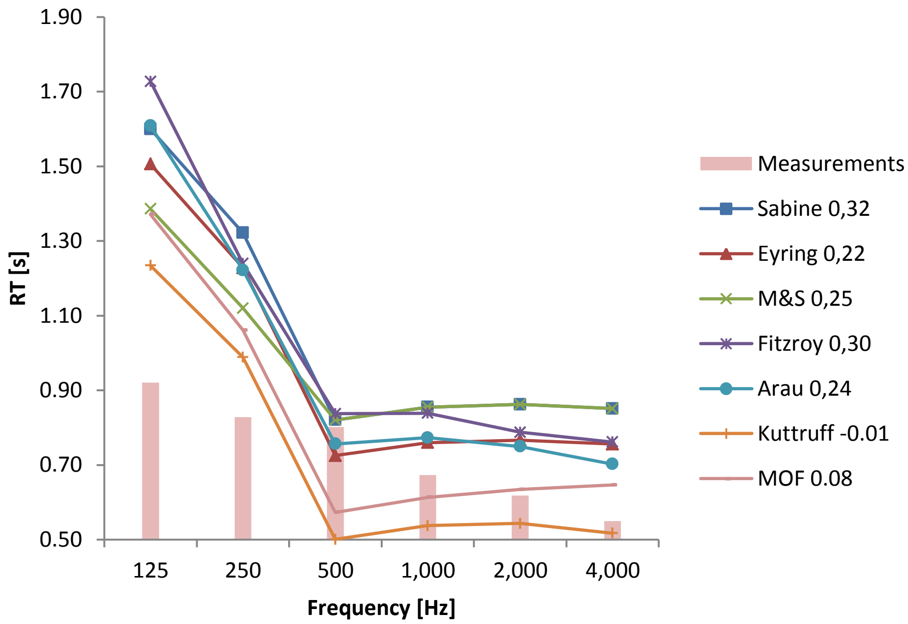
	Prediction error [s]			Graph
Frequency [Hz]	**125-4,000**	**500-1,000**	**500-2,000**	
Sabine	2.84	2.98	2.73	
Eyring	2.76	2.90	2.64	
M&S	2.75	2.98	2.73	
Fitzroy	3.39	3.23	2.97	
Arau	2.57	2.63	2.31	
Kuttruff	2.17	2.38	2.07	
MOF	2.36	2.51	2.27	
MEAN	**2.69**	**2.80**	**2.53**	

Table 5.7c: Calculated RT – Category 3

Category 4 	**Calculated RT [s]**					
Frequency [Hz]	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**
Measurements	0.92	0.83	0.80	0.67	0.62	0.55
Sabine	1.60	1.32	0.82	0.86	0.86	0.85
Eyring	1.51	1.23	0.73	0.76	0.77	0.76
M&S	1.39	1.12	0.82	0.86	0.86	0.85
Fitzroy	1.73	1.24	0.84	0.84	0.79	0.76
Arau	1.61	1.22	0.76	0.77	0.75	0.70
Kuttruff	1.23	0.99	0.50	0.54	0.54	0.52
MOF	1.37	1.06	0.57	0.61	0.63	0.65

Graph



	Prediction error [s]		
Frequency [Hz]	**125-4,000**	**500-1,000**	**500-2,000**
Sabine	0.32	0.10	0.15
Eyring	0.22	0.00	0.05
M&S	0.25	0.10	0.15
Fitzroy	0.30	0.10	0.12
Arau	0.24	0.03	0.06
Kuttruff	-0.01	-0.22	-0.17
MOF	0.08	-0.14	-0.09
MEAN	**0.20**	**0.00**	**0.04**

Graph

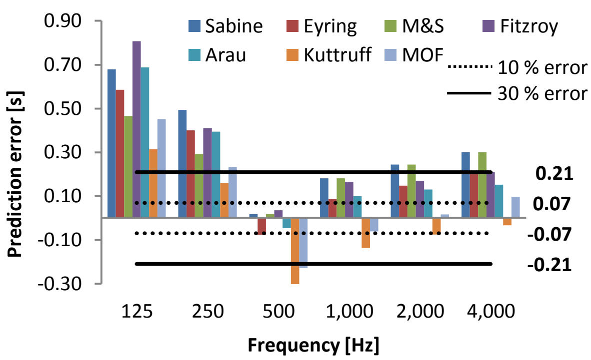


Table 5.7d: Calculated RT – Category 4

Tables 5.7a to 5.7d show that the mean prediction error for the nominal RT is very low for category 1 and 4 (0.03 s and 0.04 s). Previous findings indicate that these categories have a more diffuse character in comparison with category 2 and 3. The low prediction error is due to the fact that the calculation of the RT with the different models is based on the assumption of a diffuse field and therefore good conformity is observed (low prediction error). In contrary, the mean prediction error for the nominal RT of category 2 and 3 is higher (0.89 s and 2.53 s), especially for category 3. Therefore it can again be said that these categories have a less diffuse character in comparison with category 1 and 4. The graph of the prediction error in table 5.7a to 5.7d indicates the maximum error of 10 % or 30 %. It is important to mention that in category 1 and 4 an underestimation can be seen by the models of Kuttruff and the MOF. In these kind of auditoria a prediction with these models will not be reliable as they deviate more than 10 %. For category 1 this corresponds with a maximum error of ± 0.08 s and for category 4: ± 0.07 s. A more detailed research of each model (for each category) is given in the next chapter 5.3.2 – *'Analysis and discussion of the models'.*

Tables 5.8a and 5.8b give a summary of the calculated and measured RT for four categories for the mean RT_m and the nominal RT_{nom}. The graph represented in table 5.8a shows which models give higher calculated RT in comparison with the measured RT (pink). It is clear that for every category the model of Fitzroy results in the highest RT. Again, it can be observed that in category 1 and 4 the models of Kuttruff and the MOF give lower results in comparison with the measured RT. Therefore, these two models are less reliable as it is safer to obtain a higher RT than a lower RT. For category 2 and 3 all the models give higher results in comparison with the measured RT. Here, the models of Kuttruff and the MOF yield the lowest predictions. The same observations can be found in table 5.8b. For more detailed comparison purpose the prediction errors will be calculated in the next chapter 5.3.2 – *'Analysis and discussion of the models'.*

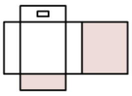
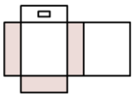
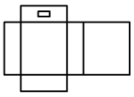
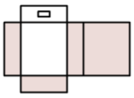
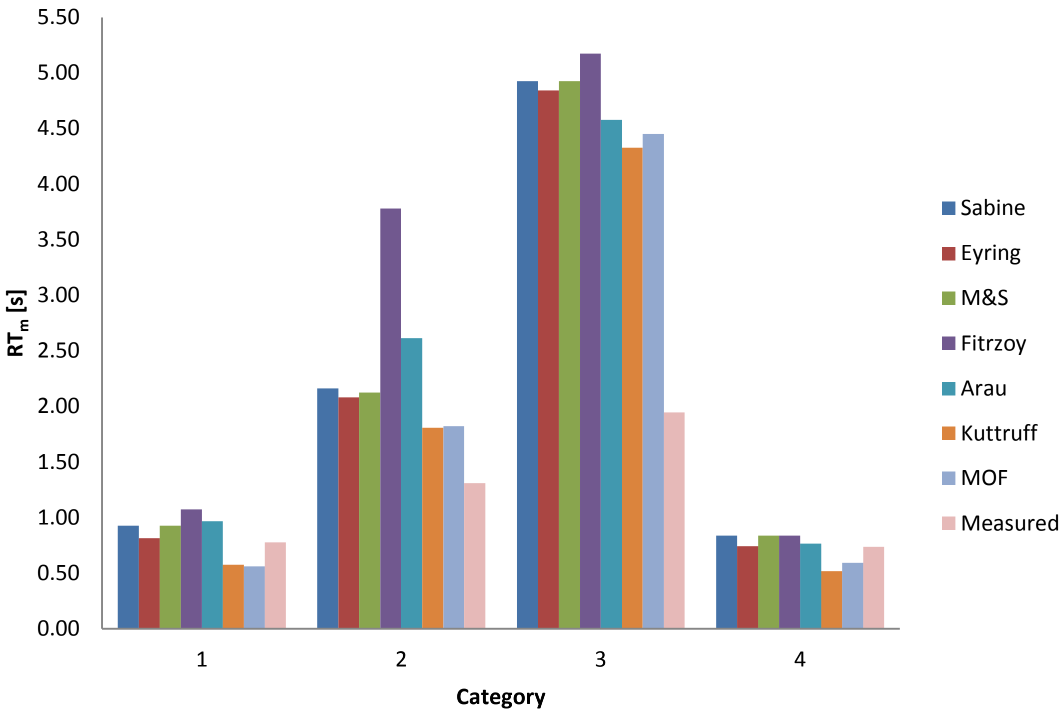
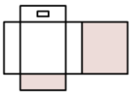
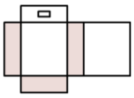
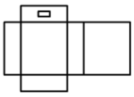
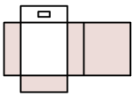
<table>
<tr><th colspan="11">Measured and calculated RT_m [s]</th></tr>
<tr><th colspan="2">Category</th><th>AUD</th><th>Measured</th><th>Sabine</th><th>Eyring</th><th>M&S</th><th>Fitzroy</th><th>Arau</th><th>Kuttruff</th><th>MOF</th></tr>
<tr><td>1</td><td></td><td>A-C-D</td><td>0.78</td><td>0.93</td><td>0.81</td><td>0.93</td><td>1.07</td><td>0.97</td><td>0.58</td><td>0.56</td></tr>
<tr><td>2</td><td></td><td>E-G-I-J</td><td>1.31</td><td>2.16</td><td>2.08</td><td>2.13</td><td>3.78</td><td>2.61</td><td>1.81</td><td>1.82</td></tr>
<tr><td>3</td><td></td><td>H-K</td><td>1.95</td><td>4.93</td><td>4.84</td><td>4.93</td><td>5.17</td><td>4.58</td><td>4.33</td><td>4.45</td></tr>
<tr><td>4</td><td></td><td>N</td><td>0.74</td><td>0.84</td><td>0.74</td><td>0.84</td><td>0.84</td><td>0.76</td><td>0.52</td><td>0.59</td></tr>
<tr><td>Graph</td><td colspan="10">
</td></tr>
</table>

Table 5.8a: Measured and calculated mean RT (for 500 Hz to 1,000 Hz) for four categories

Measured and calculated RT_{nom} [s]										
Category		**AUD**	**Measured**	**Sabine**	**Eyring**	**M&S**	**Fitzroy**	**Arau**	**Kuttruff**	**MOF**
1		A-C-D	0.80	0.93	0.82	0.93	1.06	0.96	0.58	0.57
2		E-G-I-J	1.23	1.93	1.85	1.90	3.58	2.37	1.59	1.62
3		H-K	1.95	4.67	4.59	4.67	4.92	4.25	4.02	4.22
4		N	0.70	0.85	0.75	0.85	0.82	0.76	0.53	0.61

Graph

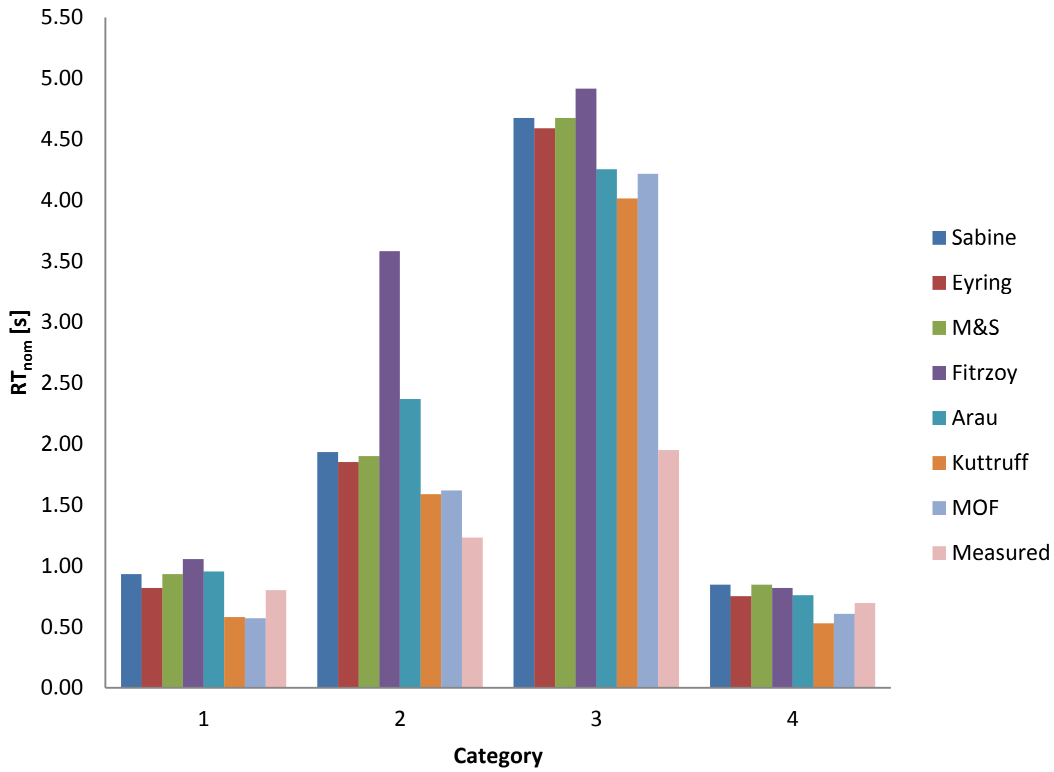


Table 5.8b: Measured and calculated nominal RT (for 500 Hz to 2,000 Hz) for four categories

5.3.2. Analysis and discussion of the models

The aim of this study is to look which model has the lowest prediction error for the RT in any kind of auditorium which is given in paragraph a – *'validation of the models'* or for a specific kind of auditorium (category) which is represented in paragraph b – '*Validation of the models according to the category of the auditorium'*. Observations about the prediction models made by Neubauer and others (see chapter 1 - *'Literature study'*) will be confirmed or rejected in this part of the study.

a. Validation of the models

The validation of each model will be checked in no matter what kind of auditorium (category). This can be done based on the prediction error. As already mentioned, it shows which model correlates most with the measured (actual) results of the RT.

First of all, the prediction error is calculated for each frequency (mean of the four categories). This is represented in table 5.9. The dashed line represents a 10 % error from the RT_{nom} and the full line represents a 30 % error from the RT_{nom}. As already mentioned, the higher the frequency, the lower the prediction error and the more accurate the prediction of the actual RT will be.

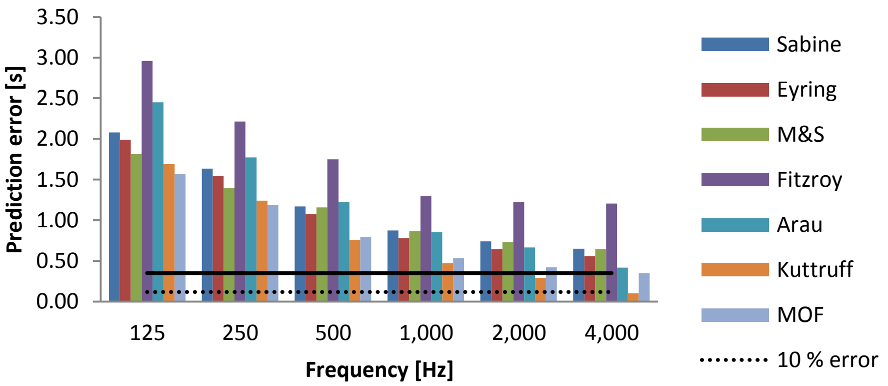
Prediction error for four categories [s]						
Model	**Frequency [Hz]**					
	125	**250**	**500**	**1,000**	**2,000**	**4,000**
Sabine	2.08	1.64	1.17	0.87	0.74	0.65
Eyring	1.99	1.54	1.08	0.78	0.65	0.56
M&S	1.81	1.40	1.16	0.86	0.73	0.65
Fitzroy	2.96	2.21	1.75	1.30	1.22	1.21
Arau	2.45	1.77	1.22	0.85	0.67	0.42
Kuttruff	1.69	1.24	0.76	0.47	0.29	0.10
MOF	1.57	1.19	0.79	0.54	0.42	0.35
Graph						

Table 5.9: Prediction error (125 to 4,000 Hz) for the four categories

Table 5.9 shows that for each frequency band the model of Fitzroy has the highest prediction error and is the worst model to predict the RT, in general. For the lower frequencies (from 125 Hz to 500 Hz) the model of Fitzroy is followed by the model of Arau. In the paper of Neubauer and Kostek these two models are also considered as the two worst models to predict the RT in general. Neubauer and Kostek observe that, for non-uniform distribution of the sound absorption, the models of Arau and Fitzroy are the worst models to predict the RT [3]. After these two outliers, the models of Sabine, M&S and Eyring follow. In general, the models of Kuttruff and the MOF are the best models to predict the RT in these frequencies. In the higher frequencies (from 1,000 Hz to 4,000 Hz) only the model of Fitzroy yields an excessive prediction error. Again the model of Kuttruff and the MOF are the better models to predict the RT but also the models of Arau and Eyring reveal lower prediction errors.

With the results of table 5.9 the prediction error for the frequency range from 125 Hz to 4,000 Hz, the prediction error for the frequency range from 500 Hz to 1,000 Hz and the prediction error for the frequency range from 500 Hz to 2,000 Hz can be calculated. This is represented in table 5.10.

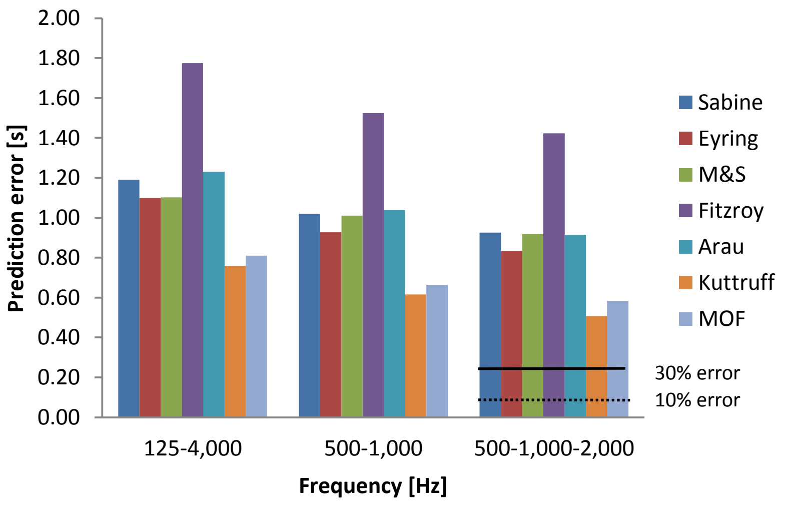
Prediction errors [s]			
Model	**Frequency range[Hz]**		
	125 – 4,000	**500 – 1,000**	**500 – 1,000 – 2,000**
Sabine	1.19	1.02	0.93
Eyring	1.10	0.93	0.83
M&S	1.10	1.01	0.92
Fitzroy	1.77	1.52	1.42
Arau	1.23	1.04	0.91
Kuttruff	0.76	0.62	0.51
MOF	0.81	0.66	0.58
Graph			

Table 5.10: Mean prediction errors for the four categories

Table 5.10 reveals that every prediction error is positive which means that the models make an overestimation of the RT, in general. This is safer than obtaining a negative prediction error and thus a lower predicted RT in comparison with the measured RT. Based on the prediction error (mean of the four categories) for the nominal RT the best model for no matter what kind of auditorium is in descending order: Kuttruff, MOF, Eyring, M&S, Sabine, Arau and Fitzroy. This is the case for the total frequency range as well as for the mean and nominal frequency range However, for auditoria where the SI is important, the prediction error for the nominal RT is the most important. Therefore only this range will be considered in the following chapters. A general ranking from 1 to 7 (with 1 the best model to predict RT) based on the prediction error (mean of four categories) for the nominal RT is given in table 5.11. As already mentioned, this general ranking is in agreement with the observations of Neubauer.

Rank [1 - 7]	Model	Prediction error for RT_{nom}	
		[s]	[%]
1	Kuttruff	0.51	43
2	MOF	0.58	50
3	Eyring	0.83	71
4	Arau	0.91	78
5	M&S	0.92	78
6	Sabine	0.93	79
7	Fitzroy	1.42	122

Table 5.11: Ranking of the models based on the prediction error for the measured nominal RT of table 5.10

In general, it can be observed that for none of the models the prediction error is lower than the limit of 10 % or 30 % whereas Neubauer points out that the MOF yields a maximum error of 28% in general. Actually this means that in general none of the models can be used to calculate the RT accurately. This can be explained because the models assume a diffuse field which is not always the case in reality. However, the models of Kuttruff and the MOF have the lowest prediction errors for the measured RT_{nom} and thus yield the most reliable results for the prediction of the RT and the global acoustics. These models are based on a non-uniform distribution of the sound absorption which is more in agreement with the reality. These observations are in agreement with the literature study and with the observations of Neubauer and Kostek [3]. Neubauer points out that in his study, for a mid-frequency range of 500 Hz, the MOF generally conforms better to the measured RT-values than the classical models and that various room volumes have no impact on it. However he contradicts himself by saying that the classical model of Eyring is also a good model to predict the RT. Indeed, the model of Eyring also has a lower prediction error in comparison with the other classical models, but only in the high frequencies. It is remarkable that the model of Sabine, which is often used by designers, only gets a ranking of 6 out of 7.

Later on, this score will be calculated in another – more accurate – way. The models will be analyzed in a specific kind of auditorium (category) based on the prediction error for the nominal RT. With this error a ranking can be given to each model, in each category. With this ranking, again another general ranking and a weighted general score can be given to each model (table 5.16).

b. Validation of the models according to the category of the auditorium

A summary of the prediction error for the nominal RT for the different categories is given in table 5.12. Also the mean of the prediction error (for the seven prediction models) is calculated for every category. Another way to represent the same results of the prediction error for the nominal RT in a specific category for a specific model is given in table 5.13. This gives the possibility to get insight in the results in different ways. First table 5.12 will be discussed in order to analyze the four categories.

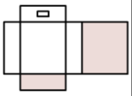
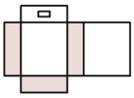
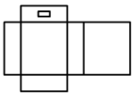
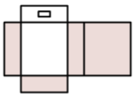
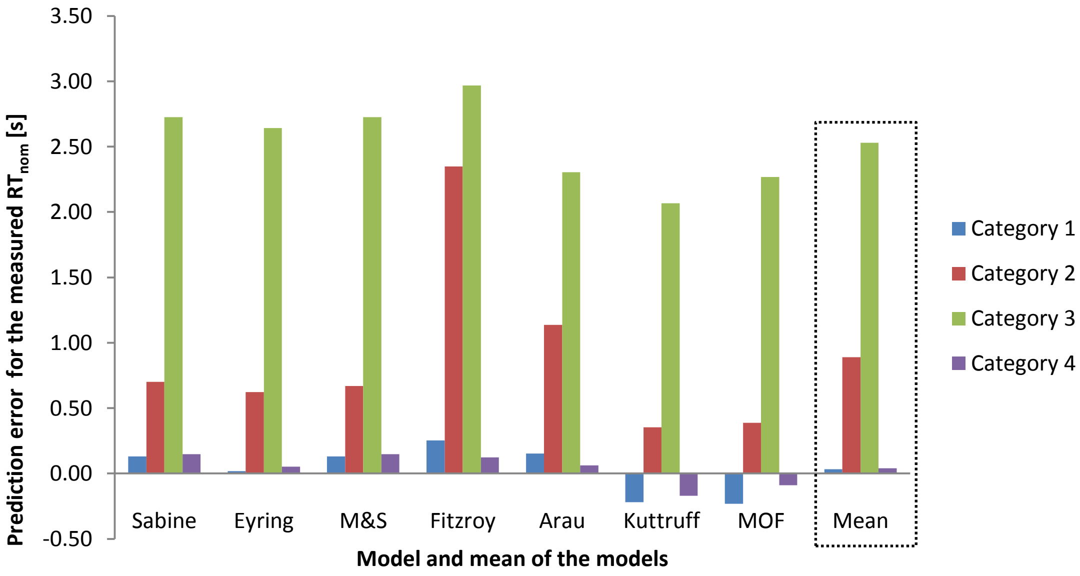
Prediction error for the measured RT_{nom} [s]												
Category		**AUD**	**Sabine**	**Eyring**	**M&S**	**Fitzroy**	**Arau**	**Kuttruff**	**MOF**	**Mean**	**Mean [%]**	**St. Dev [s]**
1		A-C-D	0.13	0.02	0.13	0.25	0.15	-0.22	-0.23	**0.03**	4	0.19
2		E-G-I-J	0.70	0.62	0.67	2.35	1.14	0.35	0.39	**0.89**	72	0.69
3		H-K	2.73	2.64	2.73	2.97	2.31	2.07	2.27	**2.53**	130	0.32
4		N	0.15	0.05	0.15	0.12	0.06	-0.17	-0.09	**0.04**	6	0.12
Graph												

Table 5.12: Prediction error for the measured nominal RT for the four categories

Based on the prediction error for the nominal RT of each category (see table 5.12 and 5.13) it can be seen that auditoria of category 3 (no absorption materials, $\overline{\alpha}$ = 0.04, less diffuse) have an excessive prediction error for every model (mean prediction error of 2.53 s or 130 %) in comparison with the other categories, as already analyzed. In this category a prediction of the RT is not reliable. This is due to the fact that there is no absorption at all in the auditoria of category 3 (global absorption coefficient of the walls and the ceiling is between 0.02 and 0.07). It is proven that the higher the global absorption coefficient of a space, the more accurate the prediction will be. Moreover, auditoria of category 3 have a less diffuse character. As the models are based on a diffuse field, the high prediction errors can be explained, as already mentioned.

For auditoria of category 2 (three adjacent absorptive walls, $\overline{\alpha}$ = 0.11, less diffuse) there are also high prediction errors (mean prediction error of 0.89 s or 72 %) in comparison with category 1 (an absorptive ceiling and absorptive rear wall, $\overline{\alpha}$ = 0.20, prediction error of 0.03 s or 4 %) and category 4 (three adjacent absorptive walls and an absorptive ceiling, $\overline{\alpha}$ = 0.19, 0.04 s or 6 %). This is due to the fact that in auditoria of category 1 and 4 a higher global absorption coefficient and a more diffuse character are observed. Therefore a prediction in a space of category 1 or 4 will give very good correlation with the measurements. These findings are in agreement with the literature study. As already mentioned, Neubauer [3] states that if low absorption is applied, the RT-values obtained with any prediction model differ considerably with the measured RT. He also states that the higher the absorption coefficient, the better the predicted RT-values conform to the measured RT-values. It can also be seen that the models of Kuttruff and the MOF yield a negative prediction error for auditoria of category 1 and 4. This means that these models underestimate the RT which is not desirable. Neubauer also states that the MOF can yield a prediction that is too short, especially in the high frequencies.

To study if any model can be used in a specific situation and if there is a meaningful difference between various prediction models, the standard deviation (between the different prediction models) of the prediction error is calculated for each category in table 5.12. A high standard deviation indicates that not any model can be used to calculate the RT and thus some models give better conformity in comparison with other models. For an auditorium of category 2 or 3 not any model can be used (standard deviation of 0.69 s and 0.32 s). Especially for category 2 a prediction of the RT is not always justified with any model. In category 1 and 4 (higher absorptive categories but with a more diffuse character) a lower standard deviation (0.19 s and 0.12 s) is observed. In these categories it is less important which model will be used to calculate the RT. Again, this is in agreement with the papers of Neubauer and Kostek. They state that in the case of a live space (good diffuse condition) there are little differences between the prediction models mutually.

Table 5.12 gives a summary of the prediction error for the nominal RT. The same results are represented in a different way in table 5.13: the prediction error for the nominal RT in a specific category for a specific prediction model is represented. This gives the possibility to make further conclusions.

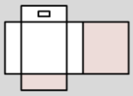
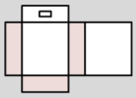
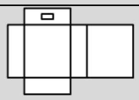
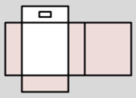
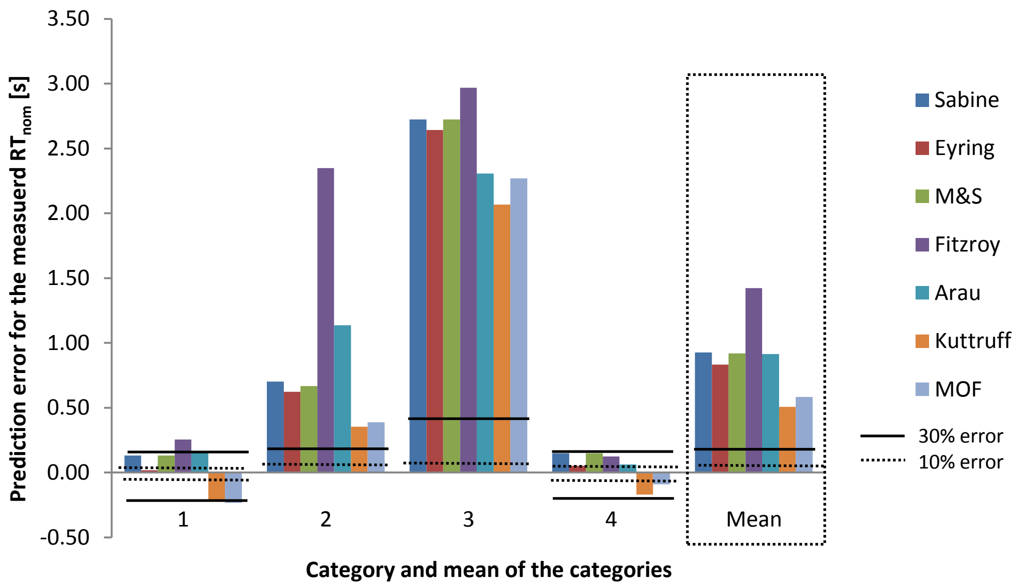
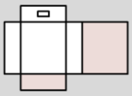
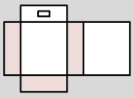
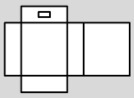
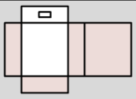
Prediction error for the nominal RT_{nom} [s]							
Category					**Mean**	**Mean**	**St. Dev**
	1	**2**	**3**	**4**	**[s]**	**[%]**	**[s]**
Sabine	0.131	0.701	2.725	0.148	**0.93**	79	1.23
Eyring	0.018	0.622	2.642	0.053	**0.83**	71	1.24
M&S	0.131	0.668	2.725	0.148	**0.92**	78	1.23
Fitzroy	0.254	2.349	2.968	0.123	**1.42**	121	1.45
Arau	0.153	1.136	2.305	0.062	**0.91**	78	1.05
Kuttruff	-0.220	0.354	2.066	-0.171	**0.51**	43	1.07
MOF	-0.233	0.388	2.269	-0.091	**0.58**	50	1.15
Graph							

Table 5.13: Prediction error for the measured nominal RT for the four categories and mean of the four categories

The graph in table 5.13 shows the same general conclusions as table 5.12: the prediction of the RT is most reliable in auditoria of category 1 and 4 and is less justified in auditoria of category 2 and 3. In auditoria of category 2 and 3 every model exceeds the maximum error of 30 % (black full line). Based on the mean of the four categories it can again be observed that the best model in no matter what kind of auditorium is in descending order: the models of Kuttruff, the MOF, Eyring, M&S, Sabine, Arau and Fitzroy. As already mentioned, in general, the predictions are overestimated which is safer. The models of Kuttruff and the MOF correlate most with the measured RT for any kind of auditoria. Kutrruff provides values of the prediction error within a range of approximately 43 %. The results calculated with the MOF have a range of 50 %. The models of Sabine, Eyring, M&S and Arau score normal within a range of 70-80 %. The values of the model of Fitzroy are located in a range of ±121.68 %. Again, it can be concluded that the best model to calculate the RT in any kind of auditorium is the model of Kuttruff (lowest mean prediction error for the measured RT_{nom} of 0.51 s), but also the MOF (mean prediction error for the measured RT_{nom} of 0.58 s) can be used to predict the RT. The model of Fitzroy gives the worst conformity (highest mean prediction error for the measured RT_{nom} of 1.42 s). As already mentioned, this is in agreement with the observations of Neubauer and Kostek [3].

Another way to confirm the validation of the prediction models is by calculating the standard deviation. This gives the reproducibility of a certain model. The model of Fitzroy has a high standard deviation (1.45 s) which means that it cannot be used in any kind of auditorium. The model of Arau has the lowest standard deviation (1.05 s) and thus it can be used for any specific situation, followed by the model of Kuttruff. The other models (Sabine, Eyring, M&S and the MOF) are located in between.

Using tables 5.12 and 5.13 each model can be analyzed separately for a specific kind of auditorium. Eventually, it is the aim of this study to link the best model to a specific category. Based on the results of table 5.13, a ranking of each model is given for each category and the prediction error for the nominal RT is calculated in percentage. The ranking goes from 1 (= the best model with the lowest mean prediction error) to seven (= the worst model with the highest mean prediction error) as there are seven prediction models. The results are represented in table 5.14. This gives the designer the possibility to select the most accurate model to predict the RT (and thus the global acoustics) for a specific kind of auditorium. As already mentioned, a maximum error of 10 % is assumed, prescribed by the Acoustic Standard (colored green). However, the literature study shows that a maximum error of 30 % is also acceptable (colored orange). A negative value of the prediction error indicates that there is an underestimation of the RT which is not desirable in auditoria. Negative values and an error that exceeds the limit of 30 % are colored red.

Rank [1 – 7]	Category							
	1		2		3		4	
								
	Model	**Error [%]**	**Model**	**Error [%]**	**Model**	**Error [%]**	**Model**	**Error [%]**
1	Eyring	2	Kuttruff	29	Kuttruff	106	Eyring	8
2	Sabine	16	MOF	31	MOF	116	Arau	9
3	M&S	16	Eyring	50	Arau	118	Fitzroy	18
4	Arau	19	M&S	54	Eyring	136	Sabine	21
5	Kuttruff	-27	Sabine	57	Sabine	140	M&S	21
6	MOF	-29	Arau	92	M&S	140	MOF	-13
7	Fitzroy	32	Fitzroy	191	Fitzroy	152	Kuttruff	-24

Graph

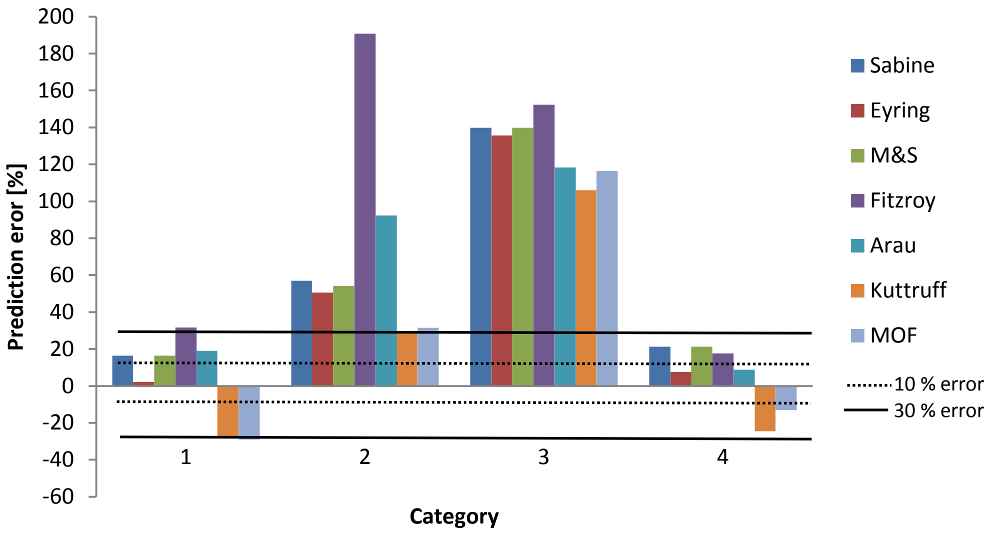


Table 5.14: Ranking (1 – 7) and error between measured RT_{nom} and calculated RT_{nom} [%] for each model and for each category

Based on table 5.14 it is observed that for an auditorium belonging to category 1 (with an absorptive ceiling and absorptive rear wall, $\overline{\alpha}$ = 0.20, high diffuse character) it is recommended to calculate the RT with the classical models, especially with the model of Eyring which has an error of only 2% from the measured RT_{nom}. It is the only model that does not exceed the limit of 10 % and therefore it is very reliable to predict the RT with this model in this specific category. The models of Kuttruff and the MOF yield negative prediction errors which is not desirable. The model of Fitzroy is ranked as last because it yield an error that is higher than 30 %. However, as already mentioned, any prediction model will yield quite reliable results as the calculated RT_{nom} maximum deviates 32% (with the model of Fitzroy) from the measured RT_{nom} for category 1.

In contrary, for an auditorium belonging to category 2 (with three adjacent absorptive walls, $\overline{\alpha}$ = 0.11, less diffuse character) and category 3 (no absorption materials, $\overline{\alpha}$ = 0.04, less diffuse character) not the classical models, but the model of Kuttruff yields the best results. For an auditorium belonging to category 2 reliable results of the predicted RT can be obtained with the model of Kuttruff as it yields values within a range of 29 % which is under the limit of 30 %. For auditoria of category 3 none of the models are reliable to predict the RT since they all deviate much more than 30 %. The classical models score mediocre in category 3. It should be taken in mind that in these categories the 'best' model still scores worse in comparison with the 'worst' model of auditoria belonging to category 1 or 4. But also this is in agreement with the literature study as Neubauer states that for spaces with low absorption, the prediction models in general all deviate considerably from the measured RT.

For an auditorium belonging to category 4 (with three adjacent absorptive walls and an absorptive ceiling, $\overline{\alpha}$ = 0.19, more diffuse character) something remarkable can be observed. The worst model to predict the RT is now the model of Kuttruff. The models of Eyring and Arau yield less than 10 % from the measured RT. This means that these two models are very reliable to use in auditoria of category 4. However it is very remarkable that the model of Arau is the second best model to predict the RT as Neubauer and Kostek state that this is one of the worst models to use, together with the model of Fitzroy. However, the model of Fitzroy only deviates 18 % and it is therefore also justified to predict the RT with this model. The previous findings in this study and the findings of Neubauer [3] about the models of Fitzroy and Arau always being the worst models to predict the RT can be partially rejected, since for an auditorium of category 4 the models of Fitzroy and Arau do not give the worst results. The models of Fitzroy, Sabine and M&S yield an error lower than 30 % from the measured RT_{nom} which means that these models are also acceptable to use. Only the MOF and the model of Kuttruff are not reliable as these models yield an underestimation of the RT with a deviation of more than 30 % which is not desirable.

It can be concluded that a good correlation can be found between the measured RT and the classical models for category 1 and 4. In these categories the MOF and the model of Kuttruff yield an underestimation of the RT whereas for auditoria of category 2 and 3 the MOF and the model of Kuttruff yield the most accurate results. Eyring points out that the model of Sabine is a live space formula. This is confirmed by table 5.14. A live space means that the sound comes from every direction, thus the space is more diffuse and there is a good scattering. For auditoria belonging to category 1 and 4 the assumption of a diffuse field is indeed made. But the classical models assume a homogeneous distribution of sound absorption: they calculate an average absorption coefficient without taking the distribution of the sound absorption into account, which is not the case for auditoria of category 1 and 4 where the distribution of the sound is non-uniform. Even more, the literature study showed that in the case of too high absorption the classical models will not give accurate results of the RT. This is already explained by the more absorption, the smaller the chance of a diffuse space. Still, for these categories good correlation can be found with the measured RT. As already mentioned, this can be explained because the diffusivity can also be obtained for instance by the geometry, a tribune, non-parallel walls, furniture, a lowered ceiling, scattering walls, etc. which is often the case in these auditoria.

c. General score and ranking of the models

Already one general ranking of the prediction models is obtained and is again represented in table 5.15 for comparison purposes.

Rank [1 - 7]	Model	Prediction error for RT_{nom} [s]	Mean error [%]
1	Kuttruff	0.51	43
2	MOF	0.58	50
3	Eyring	0.83	71
4	Arau	0.91	78
5	M&S	0.92	78
6	Sabine	0.93	79
7	Fitzroy	1.42	122

Table 5.15: Ranking of the prediction models based on the mean prediction error (for RT_{nom}) of table 5.10

A second general ranking of the models is obtained with a more accurate weighted calculation method. Based on table 5.14 a general rank from 1 to 7 (with 1 the best model to predict the RT) is given to the different models. The weighted score is given by weighting the prediction models based on their ranking of table 5.14. The results of this score (%) is given in table 5.15

$$Score\ (model) = \frac{\#\ rank1 \cdot 7 + \#\ rank2 \cdot 6 + \cdots + \#rank7 \cdot 1}{28} \cdot 100\%$$

where:

rank 1 – Number of times a specific model gets a rank of 1

Rank [1 - 7]	Model	Score [0 % - 100 %]
1	Eyring	82
2	MOF	71
3	Kuttruff	64
4/5	Sabine/Arau	61
6	M&S	50
7	Fitzroy	29

Table 5.16: Ranking of the prediction models based on the weighted prediction error for the nominal RT

Using this weighted calculation method, a different ranking is obtained in comparison with table 5.15. Comparing table 5.15 and 5.16, it can be seen that the model of Eyring is now better than the MOF and the model of Kuttruff. It can be concluded that for any category (any kind of auditorium) the model of Eyring is the best model to predict the RT (82 %). This is not completely in agreement with the findings of Neubauer as he states that in any kind of situation, the MOF is the best model to predict the RT, followed by the model of Eyring. For this study, the model of Eyring is the best model to predict the RT in any kind of situation, followed by the MOF.

5.4. Case study

A case study is analyzed in order to compare the measured RT with the calculated RT. Three different situations which belong to a specific category (1, 2, 3 or 4) will be analyzed. The analysis of the case study should confirm the earlier made conclusions about the models and the categories of auditoria. The dimensions of the space are the same for each situation. In the first situation a bare space with walls of poured concrete is observed in order to have a reverberation as high as possible (reverberation space). In the other two situations there is an extra 11.52 m² Rockwool on the floor taken into account. In these two situations other absorption coefficients for the Rockwool are considered. The measured value of the RT is known for these three situations as they are real existing spaces of a EN ISO 17025 BELAC-accredited acoustic laboratory LARGE (Laboratory for Acoustic Research on Glass and Large Envelopes) located in Middelburg, The Netherlands. It is important to note that the walls of this laboratory are smooth. However, the models used to calculate the RT assume a diffuse field with scattering walls (live spaces). Therefore the prediction will always deviate a little bit. The actual values of the RT and the global absorption coefficient of the space are given in table 5.17. Table 5.18 represents the absorption coefficients that are used to calculate the RT with the different models. Tables 5.19a to 5.19c represent the template where the data is inserted for the three different situations.

Space	Materials	Measured RT [s]						Measured RT_{nom} [s]	Global absorption coefficient $\bar{\alpha}$ [-]
		125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	500 – 2,000 Hz	
1	Poured concrete	9.99	6.18	4.89	4.17	3.49	2.15	4.18	0.03
2	All surfaces: Concrete Floor: Partially Rockwool 1	5.84	2.75	2.01	1.86	1.74	1.33	1.87	0.07
3	All surfaces: Concrete Floor: Partially Rockwool 2	5.84	2.75	2.01	1.86	1.74	1.33	1.87	0.06

Table 5.17: Three spaces with the corresponding actual RT for the different octave bands and the nominal RT

Absorption coefficient α [-]							
Space		125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz
1	**Poured concrete**	0.02	0.02	0.02	0.03	0.04	0.04
2	**Rockwool 1 [60mm]**	0.25	0.68	1.05	1.09	1.05	1.07
3	**Rockwool 2 [60mm]**	0.20	0.60	0.90	0.90	0.90	1.00

Table 5.18: Absorption coefficient of the three spaces for the different octave bands

		Compactness	**C [m]**	0.85						
		Total surface area	**S [m²]**	253.04						
		Total volume	**V [m³]**	214.09						
Surface	**Length**	**Width**	**Surface**	**Surface**	**Absorption coefficient**					
	L [m]	**W [m]**	**S_i [m²]**	**S_i [m²]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**
Surfacel x1	11.50	4.30	49.45		**125Hz**	**250Hz**	**500Hz**	**1,000Hz**	**2,000Hz**	**4,000Hz**
Concrete				49.45	0.02	0.02	0.02	0.03	0.04	0.04
Surface x2	10.10	4.30	43.43							
Concrete				43.43	0.02	0.02	0.02	0.03	0.04	0.04
Surface y1	7.00	4.30	30.10							
Concrete				30.10	0.02	0.02	0.02	0.03	0.04	0.04
Surface y2	7.09	4.30	30.49							
Concrete				30.49	0.02	0.02	0.02	0.03	0.04	0.04
Surface z1	10.80	4.61	49.79							
Concrete				49.79	0.02	0.02	0.02	0.03	0.04	0.04
Surface z2	10.80	4.61	49.79							
Concrete				49.79	0.02	0.02	0.02	0.03	0.04	0.04

Table 5.19a: Template to calculate the RT with the different models – Situation 1 (poured concrete)

		Compactness	**C [m]**	0.85						
		Total surface area	**S [m²]**	253.04						
		Total volume	**V [m³]**	214.09						
Surface	**Length**	**Width**	**Surface**	**Surface**	**Absorption coefficient**					
	L [m]	**W [m]**	**S_i [m²]**	**S_i [m²]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**
Surfacel x1	11.50	4.30	49.45		**125Hz**	**250Hz**	**500Hz**	**1,000Hz**	**2,000Hz**	**4,000Hz**
Concrete				49.45	0.02	0.02	0.02	0.03	0.04	0.04
Surface x2	10.10	4.30	43.43							
Concrete				43.43	0.02	0.02	0.02	0.03	0.04	0.04
Surface y1	7.00	4.30	30.10							
Concrete				30.10	0.02	0.02	0.02	0.03	0.04	0.04
Surface y2	7.09	4.30	30.49							
Concrete				30.49	0.02	0.02	0.02	0.03	0.04	0.04
Surface z1	10.80	4.61	49.79							
Concrete				38.27	0.02	0.02	0.02	0.03	0.04	0.04
Rockwool				11.52	0.25	0.68	1.05	1.09	1.05	1.07
Surface z2	10.80	4.61	49.79							
Concrete				49.79	0.02	0.02	0.02	0.03	0.04	0.04

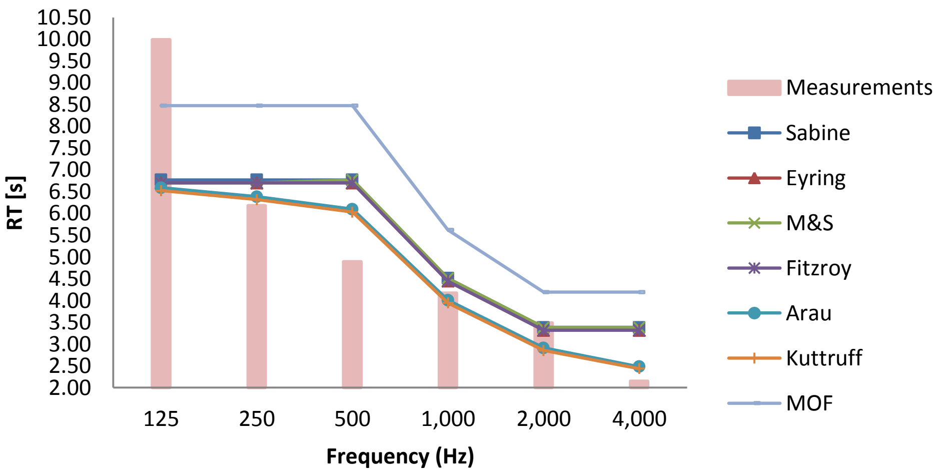
Table 5.19b: Template to calculate the RT with the different models – Situation 2 (poured concrete + Rockwool 1)

		Compactness	**C [m]**	0.85						
		Total surface area	**S [m²]**	253.04						
		Total volume	**V [m³]**	214.09						
Surface	**Length**	**Width**	**Surface**	**Surface**	**Absorption coefficient**					
	L [m]	**W [m]**	**S_i [m²]**	**S_i [m²]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**
Surfacel x1	11.50	4.30	49.45		**125Hz**	**250Hz**	**500Hz**	**1,000Hz**	**2,000Hz**	**4,000Hz**
Concrete				49.45	0.02	0.02	0.02	0.03	0.04	0.04
Surface x2	10.10	4.30	43.43							
Concrete				43.43	0.02	0.02	0.02	0.03	0.04	0.04
Surface y1	7.00	4.30	30.10							
Concrete				30.10	0.02	0.02	0.02	0.03	0.04	0.04
Surface y2	7.09	4.30	30.49							
Concrete				30.49	0.02	0.02	0.02	0.03	0.04	0.04
Surface z1	10.80	4.61	49.79							
Concrete				38.27	0.02	0.02	0.02	0.03	0.04	0.04
Rockwool				11.52	0.20	0.60	0.90	0.90	0.90	1.00
Surface z2	10.80	4.61	49.79							
Concrete				49.79	0.02	0.02	0.02	0.03	0.04	0.04

Table 5.19c: Template to calculate the RT with the different models – Situation 3 (poured concrete + Rockwool 2)

5.4.1. Sitation 1: poured concrete

Table 5.20 shows that there is a high prediction error for the measured RT_{nom} for every model for the first situation (bare space, global absorption coefficient of 0.03). Predicting the RT is not accurate in the case of a bare space (mean prediction error for the nominal RT of 0.69 s). However, the best predictions of the RT can be obtained with the models of Kuttruff and Arau, followed by the models of Eyring, Fitzroy, Sabine and M&S. Predicting the RT with the MOF gives results which do not correspond well with the actual RT. For the nominal frequency range, each model yields a positive prediction error which means that every model makes an overestimation of the RT. It is important to note that for the frequency of 125 Hz every model predict a RT lower than the measured RT which can also be seen in the negative prediction errors of this frequency band. The 10 % error (± 0.42 s) and 30 % error (± 1.26 s) are indicated on the graph. Only the models of of Kuttruff and Arau deviate less than 10 % from the measured RT_{nom} and therefore these models are reliable to predict the RT. The other models deviate less than 30 %, except for the MOF. This means that only the MOF is not recommended to predict the RT in this situation.

Situation 1	Calculated RT [s]					
Frequency [Hz]	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**
Measurements	9.99	6.18	4.89	4.17	3.49	2.15
Sabine	6.77	6.77	6.77	4.51	3.38	3.38
Eyring	6.70	6.70	6.70	4.44	3.32	3.32
M&S	6.70	6.70	6.77	4.51	3.38	3.38
Fitzroy	6.70	6.70	6.70	4.44	3.32	3.32
Arau	6.59	6.39	6.10	4.01	2.91	2.48
Kuttruff	6.52	6.32	6.03	3.94	2.85	2.44
MOF	8.48	8.48	8.48	5.62	4.19	4.19
Graph						

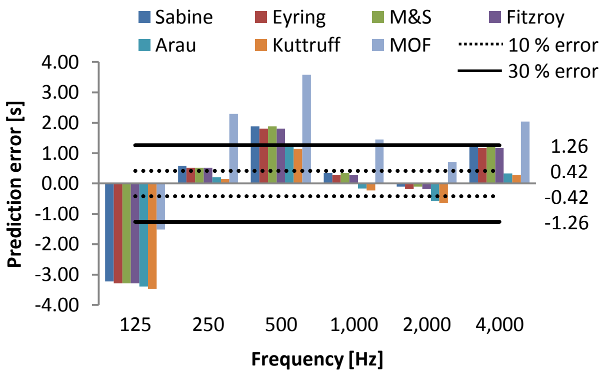
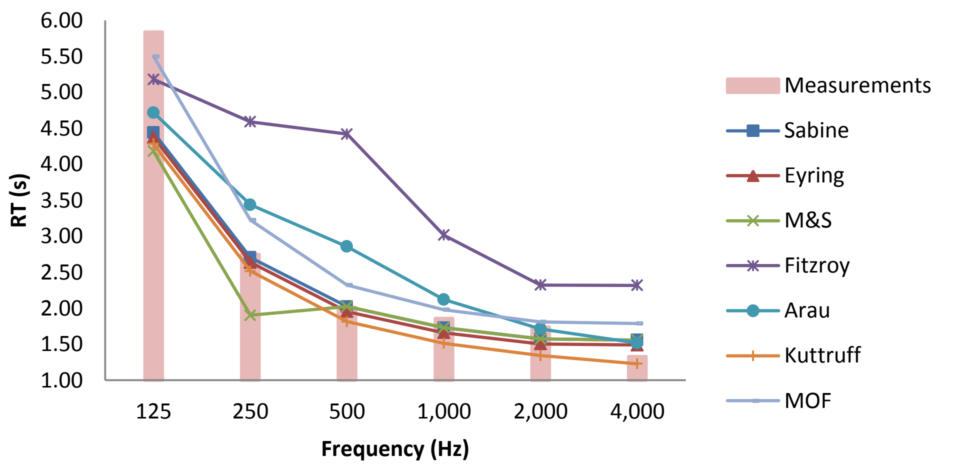
	Prediction error [s]			Graph
Frequency [Hz]	**125-4,000**	**500-1,000**	**500-2,000**	
Sabine	0.12	1.11	0.70	
Eyring	0.05	1.04	0.64	
M&S	0.10	1.11	0.70	
Fitzroy	0.05	1.04	0.64	
Arau	-0.40	0.52	0.16	
Kuttruff	-0.46	0.46	0.09	
MOF	1.43	2.52	1.91	
MEAN	**0.13**	**1.12**	**0.69**	

Table 5.20: Calculated RT – Situation 1 (poured concrete)

5.4.2. Situation 2: poured concrete + Rockwool 1

Table 5.21 shows that the prediction errors are much lower for the second situation (global absorption coefficient of 0.07) in comparison with the first situation (bare space). Predicting the RT is more justified in the case of more absorbing spaces (mean prediction error for the nominal RT of 0.18 s) which is in agreement with what Neubauer and Kostek state [3]. For this situation the MOF does not give poor results but the model of Fitzroy does. However, it can be seen in the nominal frequency range that the models of Sabine, Eyring, M&S and Kuttruff yield an underestimation of the actual RT which is not desirable. The 10 % error (± 0.19 s) and 30 % error (± 0.56 s) are indicated on the graph. Only the MOF deviates less than 10 % from the measured RT_{nom} and therefore it is a reliable model to predict the RT. The model of Arau deviates less than 30 % and is also still acceptable to predict the RT.

Situation 2	**Calculated RT [s]**					
Frequency [Hz]	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**
Measurements	5.84	2.75	2.01	1.86	1.74	1.33
Sabine	4.44	2.70	2.02	1.73	1.57	1.56
Eyring	4.37	2.64	1.96	1.66	1.51	1.49
M&S	4.18	1.90	2.02	1.73	1.57	1.56
Fitzroy	5.18	4.59	4.42	3.02	2.32	2.32
Arau	4.72	3.44	2.86	2.12	1.71	1.52
Kuttruff	4.28	2.52	1.81	1.51	1.34	1.23
MOF	5.50	3.23	2.32	1.98	1.81	1.79
Graph						

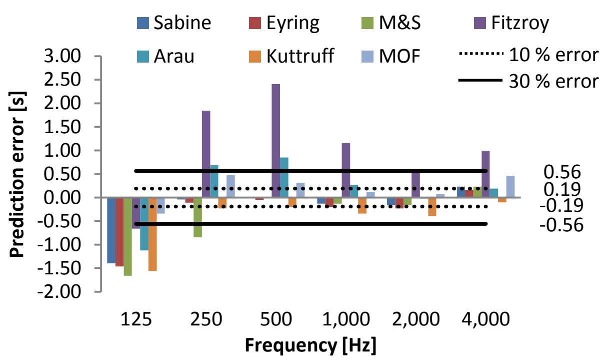
	Prediction error [s]			**Graph**
Frequency [Hz]	**125-4,000**	**500-1,000**	**500-2,000**	
Sabine	-0.25	-0.06	-0.09	
Eyring	-0.32	-0.13	-0.16	
M&S	-0.43	-0.06	-0.09	
Fitzroy	1.05	1.78	1.38	
Arau	0.14	0.55	0.36	
Kuttruff	-0.47	-0.27	-0.31	
MOF	0.18	0.22	0.17	
MEAN	**-0.01**	**0.29**	**0.18**	

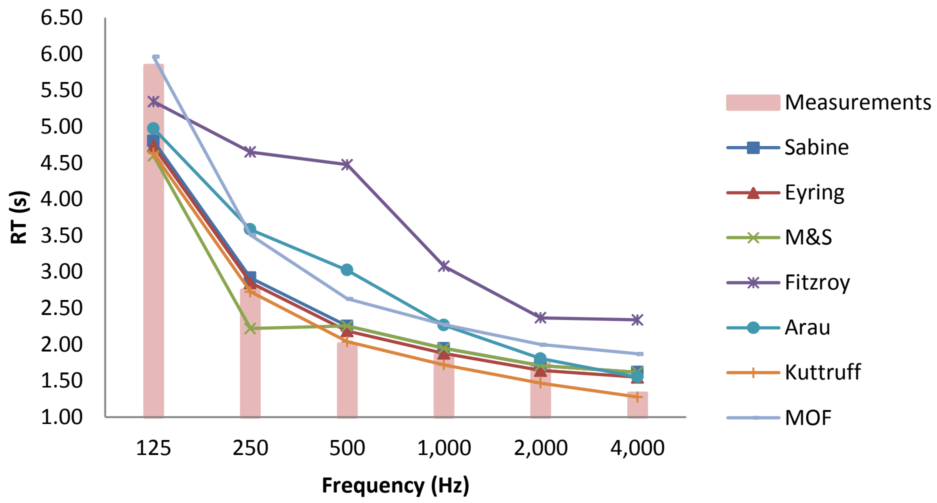
Table 5.21: Calculated RT – Situation 2 (poured concrete + Rockwool 1)

5.4.3. *Situation 3: poured concrete + Rockwool 2*

Table 5.22 shows that it is again more justified to predict the RT for the third situation (global absorption coefficient of 0.06) in comparison with the first situation (bare space) but also in comparison with the second situation (with a higher global absorption coefficient). There is a lower mean prediction error for the measured RT_{nom} of 0.35 s in comparison with 0.69 s (for the first situation with bare space) and a higher mean prediction error in comparison with 0.18 s (for the second situation with a space with higher absorption coefficients of the Rockwool.) For the nominal frequency range, it can be seen that for this situation only the model of Kuttruff yields an underestimation of the actual RT which is not desirable. The 10 % error (± 0.19 s) and 30 % error (± 0.56 s) are indicated on the graph. The classical models of Eyring, Sabine and M&S deviate less than 10 % from the measured RT_{nom} and therefore it is a reliable model to predict the RT. The MOF and the model of Arau are still acceptable as these models deviate less than 30 %. The model of Fitzroy is not recommended to predict the RT because it deviates more than 30 % from the measured RT_{nom}.

Situation 3	Calculated RT [s]					
Frequency [Hz]	**125**	**250**	**500**	**He 1,000**	**2,000**	**4,000**
Measurements	5.84	2.75	2.01	1.86	1.74	1.33
Sabine	4.80	2.92	2.25	1.94	1.71	1.62
Eyring	4.73	2.85	2.19	1.88	1.64	1.55
M&S	4.60	2.22	2.25	1.94	1.71	1.62
Fitzroy	5.34	4.65	4.47	3.08	2.37	2.34
Arau	4.97	3.58	3.02	2.27	1.80	1.55
Kuttruff	4.63	2.73	2.04	1.72	1.47	1.28
MOF	5.96	3.51	2.63	2.27	2.00	1.87

Graph



	Prediction error [s]		
Frequency [Hz]	**125-4,000**	**500-1,000**	**500-2,000**
Sabine	-0.05	0.16	0.10
Eyring	-0.12	0.10	0.03
M&S	-0.20	0.16	0.10
Fitzroy	1.12	1.84	1.44
Arau	0.28	0.71	0.49
Kuttruff	-0.28	-0.06	-0.13
MOF	0.45	0.52	0.43
MEAN	**0.17**	**0.49**	**0.35**

Graph

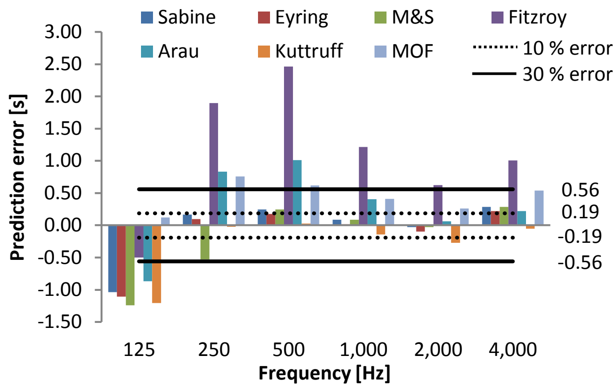


Table 5.22: Calculated RT – Situation 3 (poured concrete + Rockwool 2)

5.4.4. Discussion

Rank [1-7]	Poured concrete	Category 3
1	Kuttruff	Kuttruff
2	Arau	MOF
3	Fitzroy	Arau
4	Eyring	Eyring
5	Sabine	Sabine
6	M&S	M&S
7	MOF	Fitzroy

Table 5.23: Ranking of the different models: poured concrete vs category 3

The same conclusion as for the study of the categories (auditoria) and also as Neubauer and Kostek [3] can be made: the more absorption, the more reliable the results of the calculated RT will be in general. Table 5.23 gives a ranking (from 1 to 7 with 1 the best model to predict the RT) of the different models, based on the prediction error for the nominal RT. This ranking is given for the situation of poured concrete and for auditoria of category 3 because the laboratory can be seen as a kind of space like the auditoria in category 3. More or less the same ranking can be found between the situation with poured concrete and category 3. The similarities are colored green. It is interesting to see that the MOF is not a good model to predict the RT in the case of a bare space. This observation differs from the earlier observations in this study where the MOF was a good model to predict the RT in spaces with little absorption (category 2 and 3). Also the model of Fitzroy is in this case more on top of the ranking. The models of Kuttruff and Arau yield reliable results whereas the models of Sabine and M&S yield less reliable results for both. Again, it can be confirmed that classical models are not interesting to use in the case of a bare space.

Rank [1-7]	All surfaces: Concrete Floor: 11.52 m² Rockwool 1	All surfaces: Concrete Floor: 11.52 m² Rockwool 2	Category 1
1	MOF	Eyring	Eyring
2	Arau	Sabine	Sabine
3	Sabine	M&S	M&S
4	M&S	MOF	Arau
5	Eyring	Arau	Kuttruff
6	Kuttruff	Kuttruff	MOF
7	Fitzroy	Fitzroy	Fitzroy

Table 5.24: Ranking of the different models: additional absorption vs category 1

Table 5.24 represents a ranking for the other two situations (from 1 to 7 with 1 the best model to predict the RT) of the different models, based on the prediction error for the nominal RT. This ranking is given for the two situations with additional absorption material and for auditoria of category 1 (higher absorptive spaces). The similarities are again colored green. It can be confirmed (according to Neubauer and Kostek [3]) that the more absorption, the better the results with the MOF are: the model of MOF gets no longer the worst rank out of 7 (which is the case in the first situation). However, this is not the case in the study of the auditoria. Adding absorption material results in a ranking with the classical models more on top. This is also in agreement with the study of auditoria as for auditoria of category 1 and 4 (higher absorptive spaces) the classical models are also on top of the ranking. This is due to the more diffuse character (more live space).

For the second situation (Rockwool 1) the ranking is not completely the same. It is remarkable that the model of Eyring is still not a good model to predict the RT accurate. However, in the third situation (Rockwool 2) Eyring is on top of the ranking which is more in agreement with the study of the auditoria. The model of Fitzroy seems to yield the most unreliable predictions of the RT in every kind of situation.

6. CONCLUSIONS

6.1. Acoustic quality of the auditoria

6.1.1. *Parameters to estimate the global acoustic quality of the auditoria*

Chapters 4.2 – *'Results of the measurements'* and 4.3 – '*Discussion and first approach towards a classification*' give an extensive observation, calculation and discussion of the different parameters to estimate the global acoustic quality of the auditoria. It is more accurate to estimate the acoustic quality of a space by using more than one parameter. A combination of objective and subjective parameters and indicators gives a more thorough and reliable observation of the acoustic quality of a space. For this study, the objective parameters are the measured RT (and derived from the measured RT: the standard deviation and the confidence interval), the quality numbers (the STI, the C_{50}-value and the SN-ratio) and the Acoustic Standard for School Buildings NBN S 01-400-2 (the error between the measured RT_{nom} and the required RT_{nom} of the auditoria). The subjective parameters derived from the survey are the Speech Intelligibility SI and the Global Impression GI of the space.

The results of these objective and subjective parameters and indicators of the acoustic quality of a space are compared with each other based on statistical analysis and using a coefficient of correlation r to find correlations [63]. This leads to several observations. There is a very good correlation between the objective parameters mutually. The quality number STI correlates good with the measured RT_{nom} (r = - 0.98) and with the Acoustic Standard for School Buildings (r = - 0.99). Therefore, it is justified to calculate the acoustic quality with the quality number STI. The subjective parameter GI corresponds better with the objective parameters (r = - 0.75 for the measured RT_{nom}, r = - 0.74 for the error with the requirement for school buildings and r = + 0.46 for the STI) in comparison with the subjective parameter SI (r = - 0.61 for the measured RT_{nom}, r = - 0.68 for the error with the requirement for school buildings and r = 0.46 for the STI). Therefore, a question about the global acoustics results in more accurate information about the acoustic quality of a space. The parameter SI seems to correlate most with the measured RT_{nom} whereas the parameter GI seems to correlate most with the STI. Non-linearity was found between the subjective and objective parameters which can be explained because the response of the ear is also not-linear. In the comparison between the subjective parameters and the objective parameters it appears that auditorium C and K are two outliers. Auditorium K and C are two outliers because in auditorium K students were too positive in their judgment while the objective evaluation of the acoustic quality resulted in bad results and in auditorium C students were too negative in their judgment while the objective evaluation of the acoustic quality resulted in very good results. In auditorium C this can be explained by the possible presence of background noise due to traffic during the course as this auditorium is located next to an important street.

In auditorium K this can be explained by the way the professor adjusted his way of teaching and articulation because he knows that the auditorium reverberates a lot.

Calculating the requirements for the Acoustic Standard for School Buildings leads to the observation that only three of ten auditoria meet the increased requirement and only four of ten auditoria meet the normal requirement. The quality number STI confirms this. However, the subjective parameters (the SI and the GI) are more positive. It can be concluded that the Acoustic Standard and the quality number STI can be found more severe than the subjective parameters. However, when compared to other countries, the Belgian Acoustic Standard does not seem that severe. For a classroom of 200 m³ in Belgium, the maximum RT may be as high as 1.0 s. This is also the case in the Netherlands and Italy. However other countries such as France and Portugal prescribe a lower maximum RT of 0.8 s and also in the United Kingdom and the United States the requirements are becoming much more severe [7].

6.1.2. Evaluation of the acoustic quality of auditoria

The determination of the auditorium with the best acoustic quality for teaching purposes is based on the objective and subjective parameters discussed in chapters 4.2 – '*Results of the measurements'*. Considering the parameters, a global score on a scale of 0 to 100 % can be given to ten auditoria which can be found in table 6.1.

Aud	Score [%]
C	90
A	84
N	84
D	71
J	57
G	53
I	59
H	28
E	16
K	14

Table 6.1: Global score of the acoustic quality of ten auditoria

Auditorium C, a small auditorium with absorption material against the rear wall and on the ceiling and a lowered ceiling, scores best with 90 % and auditorium K, a small, completely bare auditorium, scores worst with 14 %. This is the logical result of the dimensions, materials, amount and location of absorption material and acoustic quality of the space which are explained extensively in the chapters 4.2 – '*Results of the measurements*', 4.3 – '*Discussion and first approach towards a classification'* and 5.2 – '*Calculation of the RT*'.

The acoustic quality of the auditoria based on the objective and subjective quality parameters and the score of the auditoria together with the dimensions of the auditoria, the amount and location of absorption led to a division into four categories. The extended division can be found in chapters 4.3 - '*Discussion and first approach towards a classification'* and 5.3.1 – *'Classification'*. The categories are divided as follows: **Category 1** are the auditoria with absorption material located on the rear wall and the ceiling: auditoria A, C and D. They score very well in general (70 – 90 %). **Category 2** are the auditoria with absorption material located on three adjacent walls that are not the front wall (indicated with the chalkboard): auditoria E, G, I and J. These auditoria score mediocre. Auditoria G (53 %) and J (56 %) score above 50 %, auditorium I (48 %) scores just below 50 % but auditorium E scores very bad with 15 %. **Category 3** are the auditoria with no absorption material: auditoria H and K. In general they score very badly but auditorium H scores a little bit higher (27 %) than auditorium K (14 %). **Category 4** are the auditoria with absorption material located on three adjacent walls that are not the front wall (indicated with the chalkboard) and the ceiling: auditorium N. It has a general score of 84 % which is very good. It does not belong in category 1 because the location of the absorption material is different.

Category 1 and 4 are obviously the 'best' categories consisting of auditoria with good to excellent acoustic qualities which is confirmed by the high values for the STI. They have a lower measured RT_{nom} in comparison with category 2 and 3. They meet the requirements of the Acoustic Standard for School Buildings while category 2 and 3 do not meet these requirements. The survey also shows better appreciations of the SI and GI in comparison with category 2 and 3. Category 2 are the mediocre auditoria with a fair acoustic quality which is confirmed by the mediocre values for the STI. They have higher values for the RT_{nom}. Improvements of the acoustic situation in these auditoria is recommended. Category 3 is the 'worst' and contains auditoria with poor acoustic qualities. This is confirmed by the high RT_{nom} and the very low STI. Again, improvements of the acoustic situation in these auditoria is recommended.

Figure 6.1 represents a general cross-section of an auditorium which illustrates possible improvements that can be applied in order to realize a better acoustic quality and a better Speech Intelligibility. One of the most common ways to improve the acoustic quality is an acoustic ceiling. This is also proven as auditoria of category 1 and 4 (auditoria with an absorbing ceiling) get the best evaluation. To reduce the RT, additional absorbing elements can be placed on at least one of two parallel walls. Different absorption panels are already discussed in chapter 2.5.3 – '*Correction of the RT'*. Bare parallel walls without any absorbing material should be avoided because a 'ping-pong effect' of reverberation will occur between two bare parallel walls. More specific, the Acoustic Standard for School Buildings NBN S 01-400-2 [6] notes that big parallel opposite sound reflecting surfaces with a distance of more than 8.5 m between them need to be avoided, especially when the sound absorbing in the space is concentrated on one boundary surface (for instance the ceiling). Absorbing materials can also be placed against the rear wall of the auditorium. Figure 6.1 also suggests to place reflectors above the stage of the auditorium which will result in a better Speech Intelligibility.

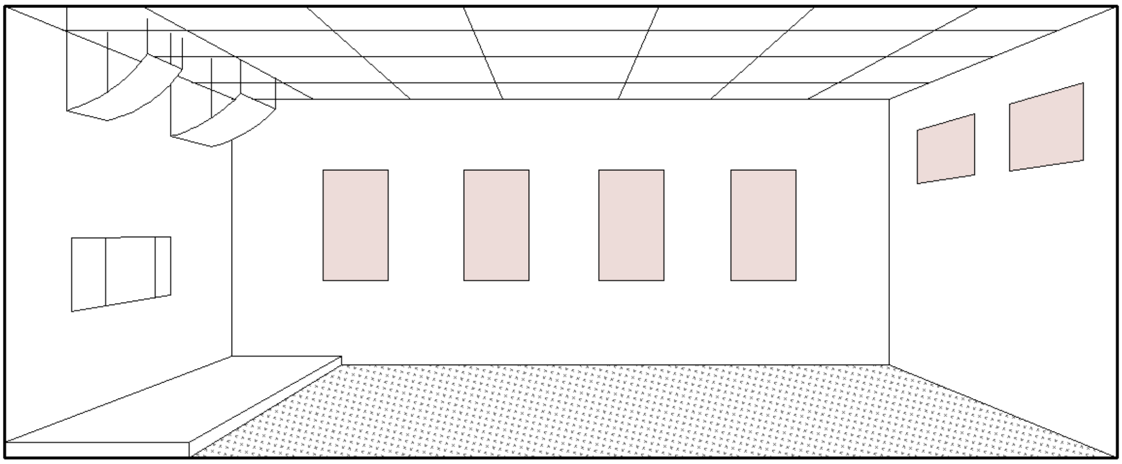


Figure 6.1: Possible improvements in auditoria

6.2. Evaluation of the prediction models

Based on chapter 1 – '*Literature study',* seven models are chosen for this study. The RT for each auditorium is calculated using these models. In chapter 1 – '*Literature study'*, a thorough observation of the models is given. Each model has its assumptions and limitations. It is important to know whether the calculated RT is valid for the entire space or not. With computer simulations (such as ray tracing, etc.) the quality of the space can be analyzed more in detail in every point of the space. This is more accurate as the RT depends on the location in the space. However, in this study the RT calculated with the different models is one global value for the entire space. It is interesting to see in which category a specific model can be used to calculate the RT and yield reliable results.

A general ranking from 1 to 7 (with 1 the best model to predict the RT) of the different models is calculated in chapter 5 – '*Calculation of the RT using different models and comparison with the measurements'* in two different ways. The second method using the weighted mean is more accurate in comparison with the method using the arithmetic mean. With this ranking a designer knows which model is most reliable to use if he does not know what kind of auditorium he is dealing with. The ranking is given in table 6.2. However, it should be noted that in general, none of the models yield a prediction error (for the nominal RT) lower than the limit of 10 % (according to the Belgian Acoustic Standard) or 30 % (according to the literature study) which means that in general none of the models can be used to calculate the RT accurately. This can be explained because the models assume a diffuse field which is not always the case in reality.

Rank [1-7]	Model
1	Eyring
2	MOF
3	Kuttruff
4/5	Sabine/Arau
6	M&S
7	Fitzroy

Table 6.2: Ranking of the prediction models based on the weighted prediction error for the nominal RT

It can be concluded that the model of Fitzroy is not recommended to predict the RT in any situation, which is in agreement with the observation of Neubauer and others. Although, Neubauer also discourages the model of Arau, while it seems that this model is not always that bad in this study. Since the MOF and Kuttruff are based on a non-uniform distribution of the sound absorption, which is more in agreement with the reality, these models are indeed more recommended to use in comparison with the classical models. However, the classical model of Eyring is in general better than the MOF and the models of Kuttruff and Arau. The same observations as Neubauer are made as he also recommends the MOF and the model of Eyring in his paper to predict the RT in any situation. Different is the fact that Neubauer recommends the MOF as the best model whereas in this study it is found that the model of Eyring is the best model. Even more, for a designer the RT is much easier to calculate with the model of Eyring. It is remarkable that in general the model of Sabine, which is often used by designers, is ranked 6th out of 7. It can also be concluded that in general the prediction models make an overestimation of the RT which is safer in comparison with an underestimation.

Eventually also a ranking from 1 to 7 (with 1 the best model to predict the RT) of the different models according to a specific category is made. This gives the designer the possibility to use the most accurate prediction model if he knows to which category the auditorium belongs. An overview is given in table 6.3. In order to get adequate results of the RT a maximum prediction error of 10 % from the measured RT_{nom} is assumed according to the Belgian Acoustic Standard [6]. However, out of the literature study it seems that a prediction error of 30 % is still reasonable. In table 6.3 the models that yield values within a range of 10 % are colored green, those that yield values within a range of 30 % are colored orange and those which deviate more than 30 % are colored red. The models that yield an underestimation of the RT are also colored red because it is not desirable to obtain a RT that is lower than the actual RT. An overestimation is safer. It is recommended to only use the green-colored prediction models in a specific category, however the orange-colored prediction models are also acceptable.

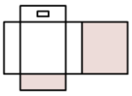
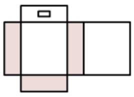
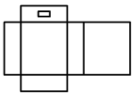
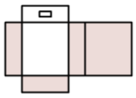
Rank [1-7]	Category			
	1	2	3	4
				
1	Eyring	Kuttruff	Kuttruff	Eyring
2	Sabine	MOF	MOF	Arau
3	M&S	Eyring	Arau	Fitzroy
4	Arau	M&S	Eyring	Sabine
5	Kuttruff	Sabine	Sabine	M&S
6	MOF	Arau	M&S	MOF
7	Fitzroy	Fitzroy	Fitzroy	Kuttruff

Table 6.3: Ranking of the prediction models according to a specific category

For auditoria belonging to **category 1** (with an absorptive ceiling and rear wall, $\bar{\alpha}$ = 0.20 and more diffuse character) the classical models (Sabine, M&S and Eyring) and the model of Arau are recommended to use. The models of Kuttruff, the MOF and Fitzroy are not recommended. This is due to the more diffuse character of the space even though there is a high global absorption coefficient. The diffusivity is probably obtained by other reasons such as a geometry (lowered ceiling, tribune, etc.), low standard deviation between the RT values of the different measurement positions, furniture, scattering walls, etc., as already explained in chapter 5.3.1 – *'Classification'*. As the prediction models are based on a diffuse field, the low prediction errors can be explained in category 1. This is also in agreement with the literature study as Neubauer states that in the case of high absorption good predictions can be made with any model. It is very remarkable that only the model of Eyring meets the requirement of a maximum prediction error of 10 % for auditoria of category 1. For auditoria belonging to **category 4** (with three adjacent absorptive walls and an absorptive ceiling, $\bar{\alpha}$ = 0.19 and also a more diffuse character) only the models of Eyring and Arau provide values within the range of 10 %. However, the models of Fitzroy, Sabine and M&S are also acceptable. The models of Kuttruff and the MOF cannot be used as they underestimate the RT which is not safe. Also Neubauer discovered that the MOF can yield a prediction that is too short, especially in the high frequencies. In auditoria of category 1 and 4, calculating the RT with the classical models is more reliable in comparison with category 2 and 3 because of the more diffuse character of category 1 and 4 which is in agreement with the literature study. It is also interesting to see that the literature study shows that in general the models of Fitzroy and Arau are not reliable to predict the RT. However for category 4, the model of Kuttruff is the worst model to predict the RT and not the model of Fitzroy or Arau. Even more, the model of Arau is the second best model to predict the RT in category 4. For auditoria belonging to **category 3** (no absorption materials, $\bar{\alpha}$ = 0.04 and a less diffuse character) none of the models can be used to predict the RT which is proven by the high prediction errors. This is in agreement with the literature study as Neubauer points out that there are bigger differences between measured an calculated RT in the case of low absorption. Also because of the lower diffuse character, predictions are less justified. For auditoria belonging to **category 2** (with three adjacent absorptive walls, $\overline{\alpha}$ = 0.11 and also a less diffuse character) only the model of Kuttruff can be used to predict the RT as the prediction error for the nominal RT is lower than 30%. Other models cannot be used to get accurate results. The same conclusions can be made as for category 3.

In order to prove the accuracy of the ranking of table 6.3 a case study (auditorium B) is analyzed in the same way as the other ten auditoria. This is represented in annex 8.1. Based on the same acoustic quality parameters it is proven that the auditorium belongs to category 2. It appears that the same ranking is made for auditorium B and for category 2. Also a second case study (a laboratory) is taken into account of which the measured values were already known. Same but also other conclusions are made in general in comparison with the study of the auditoria. The results differ as it was said (by Neubauer and the study of the ten auditoria) that the MOF yields reliable results in the case of low absorption whereas for the case of a completely bare space it seems that the MOF is not a reliable model.

To finish this chapter of conclusions, an overview is given of the applicability of the models in table 6.4a (with 10 % accuracy assumed) and table 6.4b (with 30 % accuracy assumed). This gives a designer a quick idea of which model he can use to calculate the RT in a specific category. Taking the Belgian Acoustic Standard into account (with an accuracy of 10 % assumed) it is very notable that only the model of Eyring can be used for category 1 and only the models of Eyring and Arau for category 4. For the other categories none of the models are reliable. Maybe this requirement is too severe since only two models meet it. Taking the lower requirement into account (accuracy of 30 %), for an auditorium of category 1, a designer can use the models of Sabine, Eyring, M&S and Arau to calculate the RT. For an auditorium of category 2 a designer can use the model of Kuttruff and for category 4 a designer can use the models of Sabine, Eyring, M&S, Fitzroy and Arau. It can be concluded that the MOF is in general (if a designer does not know which kind of auditorium he is handling with) a good model to predict the RT whereas for a specific category, it always yields results that deviate more than 30 % which is not accurate.

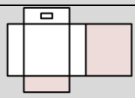
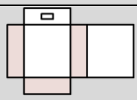
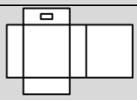
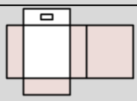
Category		**Model**						
		Sabine	**Eyring**	**M&S**	**Fitzroy**	**Arau**	**Kuttruff**	**MOF**
1			x					
2								
3								
4			x			x		

Table 6.4a: Applicability of the models – maximum error of 10 %

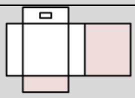
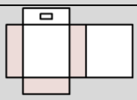
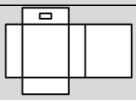
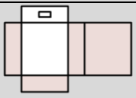
Category		Model						
		Sabine	Eyring	M&S	Fitzroy	Arau	Kuttruff	MOF
1		x	x	x		x		
2							x	
3								
4		x	x	x	x	x		

Table 6.4b: Applicability of the models – maximum error of 30 %

7. FUTURE WORK

7.1. Describing the acoustic quality of a space

There is still no consensus on a set of parameters that should be taken into account while describing the acoustic quality of a space [20]. This is due to differences in functionality of a given space, volume of spaces, distribution of absorption, etc. For example a so-called optimum RT can be calculated to evaluate the acoustic quality. However, in many literature sources the optimum values of this acoustic quantity differ a lot. For this study the Acoustic Standard for School Buildings NBN S 01-400-2 is used. In this respect, the following is pointed out by Straszewicz [21]: "there are a lot of different opinions which makes it doubtful whether or not it is possible to obtain an optimum RT related to the volume of a space or to the kind and level of sound produced only" [21]. This is also observed with the results of the survey that took place for this study as they are often not in agreement with the objective parameters such as the measured RT, the Acoustic Standard for School Buildings and the quality numbers. There are a lot of research studies that show that it is better to govern other acoustic parameters that influence acoustic quality instead of trying to achieve the optimum RT, especially in the case of the multifunction interiors. Further research should be done on parameters to describe the acoustic quality of a space and on more detailed studies. Is it generally justified to use the RT as the main criterion? For instance a more detailed survey (with different versions, manipulations, languages, more scientific, etc.) could be handed out to the students. A. Farina, for example, did a thorough investigation of the questions of the survey in order to find those acoustic parameters, which strongly relate to the subjective judgment of the 'acoustic comfort' in opera houses employed for symphonic music [73].

7.2. Vocal effort of the speaker

An important assumption needs to be held into account. A professor will automatically adjust his/her sound level to the acoustic environment. Few research has been done on the feedback of the acoustic environment on the power of speech in a teaching space. It is important to not only realize a good Speech Intelligibility in the entire space but also to ensure a constant quality in the entire space and this with a minimum vocal effort for the professor [7]. For this study, the minimum vocal effort was not taken into account. It can be interesting to analyze this too. For instance in auditorium K the evaluation of the acoustic quality was very poor. However, students do not notice this fully because the professor adjust his way of teaching by raising his voice and a better articulation.

In order to be able to realize a constant quality in the entire space, it would be interesting to use computer simulation programs as used in the study of Neubauer [3]: they calculate the RT in every point of the space instead of calculating a global RT that is valid for the entire space. This will lead to more accurate results of the RT.

7.3. Further research on existing models

Based on the conclusions of this study, some future research on the existing models can be recommended. Based on the mean prediction errors for the measured RT_{nom} (of the four categories) it is observed that none of the models yield a prediction with an error lower than 10 % (prescribed by the Belgian Acoustic Standard) or 30 % (according to the literature study). This is due to the fact that every model assumes a perfectly diffuse field which is not the case in reality. Besides the complex model of Nillsson, the only solution is calculating the RT with complex Ray-tracing programs. A 3D simulation has to be made of the auditorium and this takes a lot of time but it would be interesting to analyze this possibility.

For any kind of auditorium, the model of Fitzroy is often not very reliable. For this models in specific, possible improvements should be considered in order to get more accurate results. For instance for auditoria of category 4 it is observed that the model of Fitzroy does not score that bad at all. More in specific, it appears that in auditoria of category 2 (three adjacent absorptive walls, $\bar{\alpha}$ = 0.11) and 3 (no absorption materials, $\bar{\alpha}$ = 0.04) there are not a lot of models that give accurate results: the calculated RT differs a lot from the measured RT. In spaces with low absorption such as category 2 and 3, it is very difficult to predict the RT. The models should be redefined to result in accurate predictions of the RT for spaces with little to no absorption as well. It also appears that for auditoria of category 1 (absorptive ceiling and rear wall, $\bar{\alpha}$ = 0.20) and 4 (three adjacent absorptive walls and an absorptive ceiling, $\bar{\alpha}$ = 0.19) the model of Kuttruff and the MOF yield an underestimation of the RT which is not desirable and dangerous. These models can be redefined in order to yield more accurate results for spaces with high absorption.

Using classical models is the easiest way to calculate the RT. Therefore, it should be interesting if these models also give reliable results in the case of non-uniform distribution of sound absorption and when there is not a perfectly diffuse field. For auditoria of category 2 and 3 the predictions with the classical models are less accurate in comparison with the predictions for category 1 and 4. Searching for compromises between the more complex models and the more easy classical models could result in improvements of the models or could result in new models which give more reliable results.

7.4. Future research on different spaces

It will be interesting to expand the set of tested auditoria with more different characteristics in order to define other categories besides the four categories which are found in this study. For example, ten categories will give a more detailed and thorough insight in the accuracy of the models. With more results it will be more justified to develop a system of ‘correction factors’ in order to find the actual RT of the space. However, to develop these ‘correction factors’ much more parameters need to be measured and calculated. In the future, it would be interesting for the designer to get an overview of a ranking of the prediction models for different type of spaces and not only for auditoria. Also sacral spaces, concert halls, sport facilities, restaurants, etc. need to be evaluated and therefore the RT has to be predicted. According to their function, other rankings will be obtained with the different prediction models.

8. ANNEX

8.1. Case study of another auditorium

In order to confirm the observations and conclusions about the validation of the models for a specific category, another auditorium in the Faculty of Engineering and Architecture in Ghent University (auditorium B) is chosen to measure the RT and discuss the results. The dimensions, absorbing materials and kind of category are analyzed. Tables 8.1a and 8.1b give the results of the measurements.

AUD B	Measured RT [s]						RT_{nom} [s]
	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	
1	1.69	1.61	1.34	1.27	0.98	0.85	**1.20**
2	2.06	1.73	1.34	1.21	1.01	0.82	**1.19**
3	2.34	1.67	1.29	1.23	1.02	0.85	**1.18**
4	2.03	1.69	1.31	1.21	1.02	0.83	**1.18**
5	2.14	1.60	1.35	1.15	1.01	0.85	**1.17**
6	2.09	1.64	1.32	1.14	0.97	0.87	**1.14**
7	1.85	1.64	1.33	1.18	1.02	0.86	**1.18**
8	1.82	1.79	1.33	1.27	1.15	0.86	**1.25**
9	1.85	1.70	1.29	1.52	1.00	0.82	**1.27**
RT_m	**1.99**	**1.67**	**1.32**	**1.24**	**1.02**	**0.85**	**1.19**

Table 8.1a: Results of the measured RT – Auditorium B

AUD B	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	Mean
St Dev σ method 1 [s]	0.44	0.28	0.18	0.12	0.08	0.05	**0.13**
Confidence interval [s]	[1.70-2.27]	[1.49-1.86]	[1.21-1.44]	[1.16-1.32]	[0.97-1.07]	[0.81-0.88]	**[1.11-1.28]**
St Dev σ method 2 [s]	0.20	0.06	0.02	0.11	0.05	0.02	**0.06**
Confidence interval [s]	[1.86-2.12]	[1.63-1.71]	[1.31-1.34]	[1.17-1.32]	[0.99-1.05]	[0.83-0.86]	**[1.15-1.24]**

Table 8.1b: Calculation of the standard deviation σ and 95% confidence interval (k=1.96) – Auditorium B

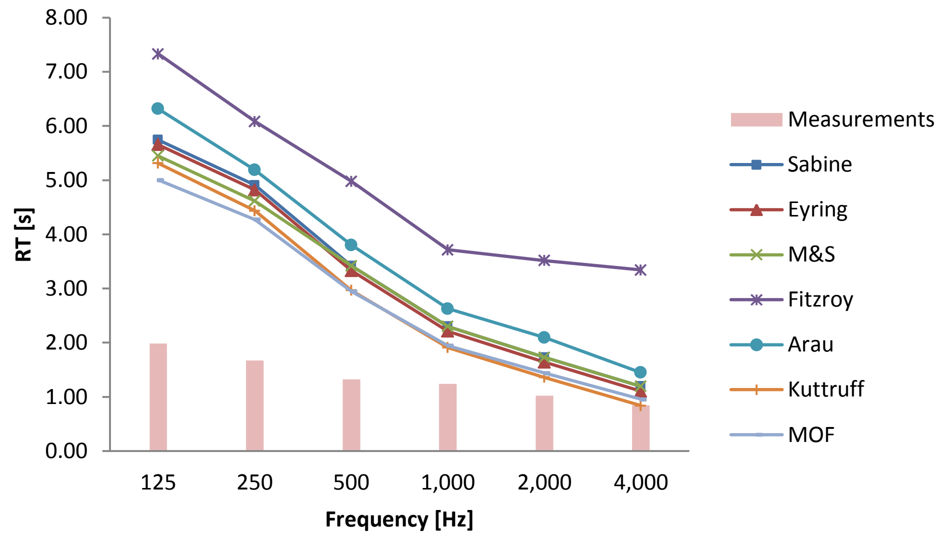
Table 8.2 represents the results of the measurements of the acoustic quality of auditorium B. The results of the other auditoria which also belong to category 2 are also given. This shows that the values for auditorium B lie in the same range of the other auditoria of category 2. Taking these results into consideration, it can be concluded that auditorium B belongs to category 2.

AUD	Measured Reverberation [s]		NBN S01-400-2: Error [s]		Quality numbers
	RT_{nom}	Standard deviation σ	Normal	Increased	STI [0-1]
B	1.28	0.13	0.23	0.42	0.55
E	1.60	0.15	0.62	0.81	0.52
G	1.21	0.13	0.21	0.41	0.57
I	1.12	0.12	0.21	0.39	0.57
J	1.00	0.12	0.09	0.28	0.59

Table 8.2: Comparison of the measured RT, the standard and the quality numbers

The results of the calculations with the prediction models can be found in table 8.3. The same conclusions need to be made as for the auditoria in category 2. For auditorium B, all the models have a positive prediction error for the nominal RT. This means that every model makes an overestimation of the RT. The models of Kuttruff and the MOF give the lowest prediction error for the nominal RT which means these are the best models to predict the RT. It is less justified to predict the RT with the classical models of Eyring, Sabine and M&S because of their higher prediction error for the nominal RT. The models of Arau and Fitzroy give the highest prediction errors for the nominal RT and therefore predicting the RT with these models will give results that are not accurate at all. The 10 % error (± 0.12 s) and 30 % error (± 0.36 s) are indicated on the graph. However, all the models deviate more than 30 % from the measured RT_{nom} which means that none of the models is reliable to predict the RT in auditorium B. The same observations are made for the auditoria belonging to category 2.

AUD B	Calculated RT [s]					
Frequency [Hz]	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**
Measurements	1.99	1.67	1.32	1.24	1.02	0.85
Sabine	5.74	4.91	3.42	2.30	1.73	1.19
Eyring	5.65	4.82	3.33	2.21	1.64	1.10
M&S	5.45	4.62	3.42	2.30	1.73	1.19
Fitzroy	7.33	6.08	4.98	3.71	3.52	3.34
Arau	6.32	5.19	3.80	2.63	2.10	1.45
Kuttruff	5.31	4.44	2.97	1.91	1.36	0.84
MOF	5.00	4.27	2.95	1.94	1.44	0.96
Graph						



	Prediction error [s]			Graph
Frequency [Hz]	**125-4,000**	**500-1,000**	**500-2,000**	
Sabine	1.87	1.58	1.29	
Eyring	1.78	1.49	1.20	
M&S	1.77	1.58	1.29	
Fitzroy	3.48	3.06	2.87	
Arau	2.23	1.93	1.65	
Kuttruff	1.46	1.16	0.88	
MOF	1.41	1.16	0.91	
MEAN	**2.00**	**1.71**	**1.44**	

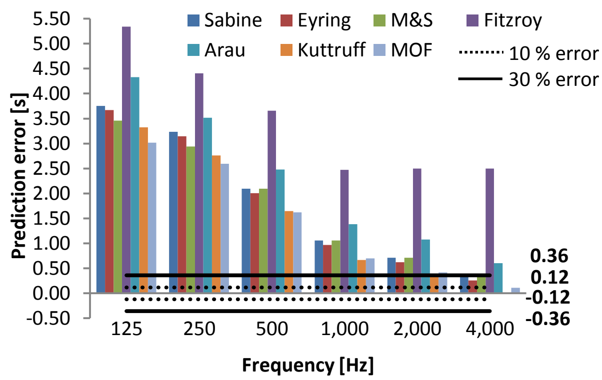


Table 8.3: Calculated RT – auditorium B

The ranking from 1 to 7 (with 1 the best model to predict the RT) of the prediction models for auditoria belonging to category 2 is given in table 8.4. In this same table 8.4 the ranking of the models for auditorium B are represented in order to compare them.

Rank [1-7]	**Aud B**	**Category 2**
1	Kuttruff	Kuttruff
2	MOF	MOF
3	Eyring	Eyring
4	M&S	M&S
5	Sabine	Sabine
6	Arau	Arau
7	Fitzroy	Fitzroy

Table 8.4: Rank of the models for auditorium B and category 2

Based on the prediction error for the nominal RT for the different models the same ranking can be given to each model. It is observed that the models of Kuttruff and the MOF give the lowest prediction error thus the RT calculated with these models give values closest to the measured RT. In contrary, Fitzroy gives the highest prediction error and gets the lowest score. It appears that the classification is justified.

8.2. Statement of the results

8.2.1. Test report according to the Standard ISO/CD 3382-2

The measured RT for each frequency is stated in a test report. The result is also plotted in the form of a graph. The norm ISO/CD 3382-2 [2] advises a graph of either straight lines connecting the points or a bar graph. The abscissa presents frequency on a logarithmic scale, whilst the ordinate uses a linear time scale with an origin of zero.

ISO/CD 3382-2 describes the layout of a test report. The test report has to state that the measurements were made in conformity with this International Standard ISO/CD 3382-2. It has to include:

- The name and place of the room tested
- A sketch plan of the room, with an indication of the scale
- The volume of the room
- The condition of the room (furniture, number of persons present, etc.)
- The type of sound source
- A description of the sound signal sound
- The degree of precision (survey, engineering or precision) including details of the source and microphone positions, preferably shown on a plan together with an indication of the heights of the positions
- The description of measuring apparatus and the microphones
- The method used for evaluation of the decay curves, either computed least squares best fit or a visual best fit
- The method used for averaging the result in each position
- The method used for averaging the result over the positions
- A table with the measuring results
- The date of measurement and name of the measuring organization

8.2.2. Test report for this study

The test report for this study is a graphical template and consists of four parts. The graphical templates of the ten auditoria can be found in the separate appendix.

a. General information

This shows the location of the ten auditoria on plans of the building of the Faculty of Engineering and Architecture in Ghent University. It also gives information about the time and place of the measurements and the measuring procedure.

b. Measurements

The results of the measurements of the RT are represented in the graphical template. It consists of different parts:

- General information of the auditorium
- A list of the materials that are located in the ten auditoria with a corresponding index that can be found on the plan of each auditorium. The surface area of each material is given to get an idea of the materials present in the auditorium.
- The numerical results of the measured RT
- A graph that presents the RT, the required RT (normal and increased requirement) and the nominal RT
- The acoustic quality of the auditorium and the quality numbers for three zones. The auditoria are divided into three zones (based on the STI fair, good and excellent). These are also represented on the plan.
- A plan of the auditorium showing the index of the materials, the absorbing surfaces (pink), the measuring and the loudspeaker positions and the zones of the STI. This makes it possible to choose where one wants to be seated to understand the speaker best.
- Panoramic photos that give an idea of how the auditorium looks like

c. Calculations

The results of the calculation of the RT with the seven models is represented in the graphical template. It consist of the following parts:

- The numerical results of the calculated RT for each model and for each frequency and also the results of the measurements for each frequency.
- A graph of the calculated RT for each model and the measured RT. The graph gives an immediate overview of which formula conforms best and which conforms worst to the measured RT.
- The numerical results of the prediction error for each model and for each frequency.
- A graph of the prediction error. A low prediction error means that it is justified to use the corresponding model to predict the RT. The higher the prediction error, the less accurate results the model will give.

d. Survey

The results of the survey are represented in the graphical template. It consist of the following parts:

- The number of opinions
- Whether or not a microphone is used

- The results for the Speech Intelligibility and the results for the Global Impression GI of the acoustics in percentage. These values give an indication of the students' judgment of the acoustic quality of the auditorium.
- The mean Speech Intelligibility and the mean Global Impression GI of the acoustics on a scale from 1 to 5. This scale was chosen in order to be able to compare these results with the STI which also works with a scale of 1 to 5.
- A graph of the results of the Speech Intelligibility SI and the Global Impression GI in percentage. This gives a clear overview of the students' judgment.
- A plan of where the students are seated in the auditorium and what their judgment is.

8.3. Results of the measured RT

8.3.1. *Auditorium A*

AUD A	Measured RT [s]						RT_{nom} [s]
	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	
1	1.47	0.89	0.82	0.76	0.96	1.07	**0.85**
2	1.24	0.94	0.83	0.84	1.03	1.05	**0.90**
3	1.33	0.96	0.84	0.80	1.00	1.04	**0.88**
4	1.24	0.88	0.82	0.76	1.03	1.10	**0.87**
5	1.23	0.84	0.77	0.76	1.07	1.08	**0.87**
6	1.14	0.89	0.84	0.78	1.01	1.06	**0.88**
7	1.10	0.91	0.76	0.79	1.00	1.04	**0.85**
8	1.21	0.85	0.80	0.75	0.99	1.07	**0.85**
9	1.12	0.83	0.78	0.74	1.00	1.08	**0.84**
10	1.31	0.92	0.84	0.81	1.02	1.10	**0.89**
11	1.29	0.77	0.83	0.80	1.02	1.07	**0.88**
12	1.19	0.86	0.83	0.77	1.01	1.07	**0.87**
13	1.34	0.86	0.76	0.78	1.01	1.09	**0.85**
14	1.28	0.96	0.85	0.77	1.02	1.06	**0.88**
15	1.56	0.93	0.79	0.79	1.00	1.06	**0.86**
16	1.71	0.81	0.81	0.78	1.03	1.08	**0.87**
17	1.26	0.97	0.74	0.81	1.01	1.06	**0.85**
18	1.22	1.02	0.80	0.84	0.99	1.09	**0.88**
RT_m [s]	**1.29**	**0.89**	**0.81**	**0.79**	**1.01**	**1.07**	0.87

Table 8.5a: Results of the measured RT - Auditorium A

AUD A	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	Mean
St Dev method 1 σ [s]	0.25	0.15	0.10	0.07	0.05	0.04	**0.07**
Confidence interval [s]	[1.18-1.41]	[0.83-0.96]	[0.76-0.85]	[0.75-0.82]	[0.99-1.04]	[1.05-1.09]	**[0.83-0.90]**
St Dev method 2 σ [s]	0.15	0.06	0.03	0.03	0.02	0.02	**0.03**
Confidence interval [s]	[1.22-1.36]	[0.86-0.92]	[0.79-0.82]	[0.77-0.80]	[1.00-1.02]	[1.06-1.08]	**[0.85-0.88]**

Table 8.5b: Calculation of the standard deviation σ and 95% confidence interval (k=1.96) - Auditorium A

8.3.2. Auditorium C

AUD C	Measured RT [s]						RT_{nom} [s]
	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	
1	0.88	0.73	0.64	0.48	0.47	0.47	**0.53**
2	1.06	0.74	0.54	0.48	0.52	0.48	**0.51**
3	0.88	0.79	0.56	0.49	0.51	0.48	**0.52**
4	0.90	0.77	0.59	0.50	0.48	0.44	**0.52**
5	1.03	0.75	0.58	0.58	0.50	0.50	**0.55**
6	1.08	0.62	0.53	0.50	0.51	0.47	**0.51**
7	1.07	0.78	0.55	0.51	0.50	0.47	**0.52**
8	0.84	0.75	0.59	0.51	0.50	0.47	**0.53**
9	0.96	0.90	0.58	0.50	0.48	0.47	**0.52**
RT_m [s]	**0.97**	**0.76**	**0.57**	**0.51**	**0.50**	**0.47**	**0.53**

Table 8.6a: Results of the measured RT - Auditorium C

AUD C	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	Nominal
St Dev method 1 σ [s]	0.30	0.19	0.12	0.08	0.05	0.04	**0.08**
Confidence interval [s]	[0.77-1.17]	[0.63-0.88]	[0.50-0.65]	[0.45-0.56]	[0.46-0.53]	[0.45-0.50]	**[0.47-0.58]**
St Dev method 2 σ [s]	0.09	0.07	0.03	0.03	0.02	0.02	**0.03**
Confidence interval [s]	[0.90-1.03]	[0.71-0.81]	[0.55-0.60]	[0.49-0.53]	[0.49-0.51]	[0.46-0.48]	**[0.51-0.54]**

Table 8.6b: Calculation of the standard deviation σ and 95% confidence interval (k=1.96) - Auditorium C

8.3.3. Auditorium D

AUD D	Measured RT [s]						RT_{nom} [s]
	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	
1	1.07	0.81	0.87	1.03	1.05	0.93	**0.98**
2	0.94	0.77	0.88	1.04	1.08	0.94	**1.00**
3	0.87	0.82	0.97	1.08	1.06	0.95	**1.04**
4	0.84	0.84	0.90	1.07	1.13	0.96	**1.03**
5	0.98	0.90	0.89	1.07	1.10	0.98	**1.02**
6	0.82	0.93	0.98	1.10	1.07	0.97	**1.05**
7	0.79	0.99	0.91	1.14	1.05	0.92	**1.03**
8	0.82	0.89	0.94	1.04	1.00	0.87	**0.99**
9	0.82	1.04	0.97	1.02	1.05	0.94	**1.01**
10	0.98	0.87	0.92	1.03	1.02	0.83	**0.99**
11	0.79	1.01	0.93	1.09	1.07	0.95	**1.03**
12	0.91	0.94	0.94	1.07	0.96	0.81	**0.99**
RT_m [s]	**0.89**	**0.90**	**0.93**	**1.07**	**1.05**	**0.92**	**1.01**

Table 8.7a: Results of the measured RT - Auditorium D

AUD D	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	Nominal
St Dev method 1 σ [s]	0.25	0.18	0.13	0.10	0.07	0.05	**0.10**
Confidence interval [s]	[0.74-1.03]	[0.80-1.00]	[0.85-1.00]	[1.01-1.12]	[1.01-1.09]	[0.90-0.95]	**[0.96-1.07]**
St Dev method 2 σ [s]	0.09	0.08	0.04	0.04	0.04	0.05	0.04
Confidence interval [s]	[0.83-0.94]	[0.85-0.95]	[0.90-0.95]	[1.05-1.08]	[1.03-1.08]	[0.89-0.95]	**[0.99-1.04]**

Table 8.7b: Calculation of the standard deviation σ and 95% confidence interval (k=1.96) - Auditorium D

8.3.4. <u>Auditorium E</u>

AUD E	Measured RT [s]						RT_{nom} [s]
	125 Hz	**250 Hz**	**500 Hz**	**1,000 Hz**	**2,000 Hz**	**4,000 Hz**	
1	1.76	1.99	1.70	1.65	1.39	1.16	**1.58**
2	1.89	1.93	1.66	1.68	1.38	1.16	**1.57**
3	1.87	1.86	1.65	1.63	1.38	1.16	**1.55**
4	1.90	1.93	1.77	1.71	1.34	1.19	**1.61**
5	1.60	1.94	1.83	1.66	1.41	1.17	**1.63**
6	2.04	1.83	1.72	1.69	1.38	1.18	**1.60**
7	1.96	1.86	1.72	1.62	1.39	1.16	**1.58**
8	2.01	2.14	1.80	1.65	1.37	1.15	**1.61**
9	2.12	1.94	1.84	1.72	1.45	1.17	**1.67**
RT_m [s]	**1.91**	**1.94**	**1.74**	**1.67**	**1.39**	**1.17**	**1.60**

Table 8.8a: Results of the measured RT - Auditorium E

AUD E	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	Nominal
St Dev method 1 σ [s]	0.43	0.30	0.20	0.14	0.09	0.06	**0.15**
Confidence interval [s]	[1.63-2.18]	[1.74-2.13]	[1.61-1.88]	[1.58-1.76]	[1.33-1.45]	[1.13-1.21]	**[1.50-1.69]**
St Dev method 2 σ [s]	0.16	0.09	0.07	0.03	0.03	0.01	**0.04**
Confidence interval [s]	[1.80-2.01]	[1.88-2.00]	[1.70-1.79]	[1.65-1.69]	[1.37-1.41]	[1.16-1.17]	**[1.57-1.63]**

Table 8.8b: Calculation of the standard deviation σ and 95% confidence interval (k=1.96) - Auditorium E

8.3.5. *Auditorium G*

AUD G	Measured RT [s]						RT_{nom} [s]
	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	
1	1.57	1.46	1.26	1.27	1.12	0.89	**1.22**
2	1.60	1.52	1.28	1.23	1.12	0.93	**1.21**
3	1.37	1.50	1.28	1.28	1.13	0.97	**1.23**
4	1.31	1.51	1.31	1.25	1.12	0.96	**1.23**
5	1.37	1.58	1.20	1.24	1.11	0.98	**1.18**
6	1.32	1.48	1.22	1.24	1.12	0.97	**1.19**
7	1.49	1.35	1.26	1.25	1.20	0.97	**1.24**
8	1.46	1.44	1.26	1.22	1.13	0.95	**1.20**
9	1.30	1.12	1.22	1.20	1.10	0.98	**1.17**
RT_m [s]	**1.42**	**1.44**	**1.25**	**1.24**	**1.13**	**0.96**	**1.21**

Table 8.9a: Results of the measured RT - Auditorium G

AUD G	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	Nominal
St Dev method 1 σ [s]	0.37	0.26	0.17	0.12	0.08	0.05	**0.13**
Confidence interval [s]	[1.18-1.66]	[1.27-1.61]	[1.14-1.37]	[1.16-1.32]	[1.07-1.18]	[0.92-0.99]	**[1.13-1.29]**
St Dev method 2 σ [s]	0.11	0.14	0.04	0.02	0.03	0.03	**0.03**
Confidence interval [s]	[1.35-1.50]	[1.35-1.53]	[1.23-1.28]	[1.23-1.26]	[1.11-1.15]	[0.94-0.97]	**[1.19-1.23]**

Table 8.9b: Calculation of the standard deviation σ and 95% confidence interval (k=1.96) - Auditorium G

8.3.6. *Auditorium H*

AUD H	Measured RT [s]						RT_{nom} [s]
	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	
1	1.96	1.55	1.37	1.48	1.54	1.36	**1.46**
2	1.88	1.59	1.42	1.46	1.57	1.37	**1.48**
3	2.02	1.39	1.50	1.44	1.60	1.40	**1.51**
4	1.85	1.52	1.40	1.46	1.60	1.40	**1.49**
5	1.78	1.67	1.50	1.40	1.56	1.37	**1.49**
6	1.98	1.56	1.45	1.42	1.61	1.39	**1.49**
7	1.93	1.54	1.44	1.45	1.53	1.37	**1.47**
8	1.92	1.58	1.43	1.41	1.63	1.40	**1.49**
9	2.02	1.62	1.47	1.45	1.54	1.37	**1.49**
RT_m [s]	**1.93**	**1.56**	**1.44**	**1.44**	**1.58**	**1.38**	**1.49**

Table 8.10a: Results of the measured RT - Auditorium H

AUD H	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	Nominal
St Dev method 1 σ [s]	0.43	0.27	0.19	0.13	0.10	0.06	**0.14**
Confidence interval [s]	[1.65-2.21]	[1.38-1.74]	[1.32-1.56]	[1.36-1.53]	[1.51-1.64]	[1.34-1.42]	**[1.40-1.58]**
St Dev method 2 σ [s]	0.08	0.08	0.04	0.03	0.04	0.02	**0.04**
Confidence interval [s]	[1.87-1.98]	[1.51-1.61]	[1.41-1.47]	[1.42-1.46]	[1.55-1.60]	[1.37-1.39]	**[1.46-1.51]**

Table 8.10b: Calculation of the standard deviation σ and 95% confidence interval (k=1.96) - Auditorium H

8.3.7. Auditorium I

AUD I	Measured RT [s]						RT_{nom} [s]
	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	
1	2.01	1.73	1.37	1.19	0.96	0.79	**1.17**
2	1.88	1.73	1.34	1.13	0.92	0.77	**1.13**
3	1.69	1.73	1.27	1.06	0.95	0.78	**1.09**
4	1.77	1.62	1.26	1.16	0.90	0.73	**1.11**
5	1.78	1.76	1.31	1.12	0.92	0.73	**1.12**
6	1.75	1.81	1.35	1.09	0.90	0.74	**1.11**
7	1.92	1.76	1.28	1.06	0.89	0.74	**1.08**
8	2.20	1.74	1.29	1.10	0.91	0.72	**1.10**
9	1.89	1.76	1.32	1.13	0.94	0.77	**1.13**
RT_m [s]	**1.88**	**1.74**	**1.31**	**1.12**	**0.92**	**0.75**	**1.12**

Table 8.11a: Results of the measured RT - Auditorium I

AUD I	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	Nominal
St Dev method 1 σ [s]	0.42	0.29	0.18	0.12	0.07	0.05	**0.12**
Confidence interval [s]	[1.60-2.15]	[1.55-1.93]	[1.19-1.43]	[1.04-1.19]	[0.87-0.97]	[0.72-0.78]	**[1.04-1.20]**
St Dev method 2 σ [s]	0.16	0.05	0.04	0.04	0.02	0.03	**0.04**
Confidence interval [s]	[1.77-1.98]	[1.70-1.77]	[1.29-1.33]	[1.09-1.14]	[0.91-0.94]	[0.74-0.77]	**[1.09-1.14]**

Table 8.11b: Calculation of the standard deviation σ and 95% confidence interval (k=1.96) - Auditorium I

8.3.8. Auditorium J

AUD J	Measured RT [s]						RT_{nom} [s]
	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	
1	1.65	1.45	1.14	0.99	0.88	0.77	**1.00**
2	1.65	1.51	1.07	0.99	0.88	0.70	**0.98**
3	1.63	1.67	1.19	1.06	0.89	0.77	**1.05**
4	1.80	1.47	1.06	1.01	0.87	0.78	**0.98**
5	1.87	1.52	1.12	1.00	0.87	0.75	**1.00**
6	1.75	1.54	1.12	0.99	0.88	0.76	**1.00**
7	1.74	1.54	1.10	1.05	0.89	0.78	**1.01**
8	1.78	1.42	1.12	1.08	0.89	0.78	**1.03**
9	1.49	1.58	1.09	1.01	0.86	0.77	**0.99**
RT_m [s]	**1.71**	**1.52**	**1.11**	**1.02**	**0.88**	**0.76**	**1.00**

Table 8.12a: Results of the measured RT - Auditorium J

AUD J	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	Nominal
St Dev method 1 σ [s]	0.40	0.27	0.16	0.11	0.07	0.05	**0.12**
Confidence interval [s]	[1.44-1.97]	[1.35-1.70]	[1.01-1.22]	[0.95-1.09]	[0.83-0.93]	[0.73-0.79]	**[0.93-1.08]**
St Dev method 2 σ [s]	0.11	0.07	0.04	0.03	0.01	0.03	**0.03**
Confidence interval [s]	[1.63-1.78]	[1.47-1.57]	[1.09-1.14]	[1.00-1.04]	[0.87-0.89]	[0.75-0.78]	**[0.99-1.02]**

Table 8.12b: Calculation of the standard deviation σ and 95% confidence interval (k=1.96) - Auditorium J

8.3.9. Auditorium K

AUD K	Measured RT [s]						RT_{nom} [s]
	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	
1	2.42	2.73	2.64	2.25	2.32	1.98	**2.40**
2	2.33	2.76	2.59	2.23	2.32	2.03	**2.38**
3	2.57	2.60	2.64	2.30	2.36	3.01	**2.43**
4	2.25	2.59	2.61	2.36	2.33	2.04	**2.43**
5	2.17	2.68	2.78	2.35	2.30	2.03	**2.48**
6	2.49	2.54	2.52	2.26	2.32	2.02	**2.37**
7	2.53	2.67	2.62	2.35	2.33	2.03	**2.43**
8	2.37	2.62	2.58	2.29	2.35	2.03	**2.41**
9	2.71	2.51	2.52	2.25	2.33	2.04	**2.37**
RT_m [s]	**2.43**	**2.63**	**2.61**	**2.29**	**2.33**	**2.13**	**2.41**

Table 8.13a: Results of the measured RT - Auditorium K

AUD K	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	Nominal
St Dev method 1 σ [s]	0.48	0.35	0.25	0.17	0.12	0.08	**0.18**
Confidence interval [s]	[2.11-2.74]	[2.40-2.86]	[2.45-2.77]	[2.19-2.40]	[2.25-2.41]	[2.08-2.19]	**[2.30-2.53]**
St Dev method 2 σ [s]	0.17	0.08	0.08	0.05	0.02	0.33	**0.05**
Confidence interval [s]	[2.32-2.54]	[2.58-2.69]	[2.56-2.66]	[2.26-2.33]	[2.32-2.34]	[1.92-2.35]	**[2.38-2.44]**

Table 8.13: Calculation of the standard deviation σ and 95% confidence interval (k=1.96) - Auditorium K

8.3.10. Auditorium N

AUD N	Measured RT [s]						RT_{nom} [s]
	125 Hz	**250 Hz**	**500 Hz**	**1,000 Hz**	**2,000 Hz**	**4,000 Hz**	
1	0.88	0.94	0.81	0.70	0.66	0.62	**0.72**
2	1.03	0.97	0.78	0.70	0.63	0.60	**0.70**
3	0.99	0.99	0.75	0.68	0.64	0.61	**0.69**
4	0.92	1.09	0.84	0.76	0.64	0.56	**0.75**
5	0.94	0.98	0.83	0.75	0.61	0.54	**0.73**
6	0.97	1.00	0.85	0.71	0.63	0.55	**0.73**
7	0.96	0.99	0.82	0.71	0.62	0.54	**0.72**
8	0.98	0.92	0.88	0.72	0.64	0.56	**0.75**
9	0.83	1.02	0.76	0.73	0.60	0.56	**0.70**
RT_m [s]	**0.96**	**0.86**	**0.83**	**0.69**	**0.63**	**0.57**	**0.72**

Table 8.14a: Results of the measured RT - Auditorium N

AUD N	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	Nominal
St Dev method 1 σ [s]	0.30	0.20	0.14	0.09	0.06	0.04	**0.10**
Confidence interval [s]	[0.76-1.16]	[0.73-0.99]	[0.74-0.92]	[0.63-0.75]	[0.59-0.67]	[0.54-0.60]	**[0.65-0.78]**
St Dev method 2 σ [s]	0.06	0.05	0.04	0.03	0.02	0.03	**0.03**
Confidence interval [s]	[0.92-1.00]	[0.83-0.89]	[0.80-0.86]	[0.67-0.71]	[0.62-0.64]	[0.55-0.59]	**[0.70-0.74]**

Table 8.14b: Calculation of the standard deviation σ and 95% confidence interval (k=1.96) - Auditorium N

8.4. Quality numbers

8.4.1. Auditorium A, C, D, E and G

R	A			C			D			E			G		
[m]	SN [dB]	C_{50} [dB]	STI [1-5]	SN [dB]	C_{50} [dB]	STI [1-5]	SN [dB]	C_{50} [dB]	STI [1-5]	SN [dB]	C_{50} [dB]	STI [1-5]	SN [dB]	C_{50} [dB]	STI [1-5]
0.20	33.94	26.27	1.34	27.26	22.69	1.24	31.48	22.45	1.23	28.53	15.08	1.01	28.41	15.77	1.03
0.40	27.92	20.32	1.16	21.24	16.89	1.06	25.46	16.53	1.05	22.51	9.28	0.83	22.38	10.02	0.86
0.60	24.40	16.89	1.06	17.72	13.69	0.97	21.94	13.15	0.95	18.99	6.11	0.74	18.86	6.90	0.76
0.80	21.90	14.50	0.99	15.22	11.60	0.90	19.44	10.83	0.88	16.49	4.04	0.68	16.36	4.92	0.70
1.00	19.96	12.70	0.94	13.28	10.12	0.86	17.50	9.11	0.83	14.55	2.61	0.63	14.43	3.55	0.66
1.20	18.38	11.27	0.89	11.70	9.04	0.83	15.92	7.77	0.79	12.97	1.56	0.60	12.84	2.58	0.63
1.40	17.04	10.10	0.86	10.36	8.23	0.80	14.58	6.70	0.76	11.63	0.78	0.58	11.50	1.87	0.61
1.60	15.88	9.12	0.83	9.20	7.60	0.78	13.42	5.83	0.73	10.47	0.19	0.56	10.34	1.34	0.60
1.80	14.86	8.29	0.80	8.18	7.11	0.77	12.40	5.11	0.71	9.44	-0.27	0.55	9.32	0.93	0.58
2.00	13.94	7.59	0.78	7.26	6.71	0.76	11.48	4.51	0.69	8.53	-0.63	0.54	8.41	0.61	0.57
2.20	13.12	6.97	0.76	6.43	6.40	0.75	10.65	4.01	0.68	7.70	-0.92	0.53	7.58	0.35	0.57
2.40	12.36	6.44	0.75	5.68	6.14	0.74	9.90	3.57	0.66	6.95	-1.15	0.52	6.82	0.15	0.56
2.60	11.66	5.97	0.73	4.98	5.93	0.73	9.20	3.21	0.65	6.25	-1.34	0.51	6.13	-0.01	0.55
2.80	11.02	5.55	0.72	4.34	5.75	0.73	8.56	2.89	0.64	5.61	-1.50	0.51	5.48	-0.15	0.55
3.00	10.42	5.19	0.71	3.74	5.60	0.72	7.96	2.61	0.63	5.01	-1.63	0.51	4.88	-0.26	0.55
3.20	9.86	4.86	0.70	3.18	5.48	0.72	7.40	2.37	0.63	4.45	-1.74	0.50	4.32	-0.36	0.54
3.40	9.33	4.57	0.69	2.65	5.37	0.72	6.87	2.16	0.62	3.92	-1.84	0.50	3.80	-0.44	0.54
3.60	8.84	4.31	0.68	2.15	5.28	0.71	6.38	1.98	0.61	3.42	-1.92	0.50	3.30	-0.50	0.54
3.80	8.37	4.07	0.68	1.68	5.20	0.71	5.91	1.81	0.61	2.95	-1.99	0.50	2.83	-0.56	0.54
4.00	7.92	3.86	0.67	1.24	5.13	0.71	5.46	1.67	0.61	2.51	-2.05	0.49	2.38	-0.61	0.54
4.20	7.50	3.67	0.67	0.82	5.07	0.71	5.04	1.54	0.60	2.08	-2.10	0.49	1.96	-0.66	0.54
4.40	7.10	3.50	0.66	0.41	5.01	0.71	4.63	1.42	0.60	1.68	-2.15	0.49	1.56	-0.70	0.53
4.60	6.71	3.34	0.66	0.03	4.96	0.70	4.25	1.32	0.59	1.29	-2.19	0.49	1.17	-0.73	0.53
4.80	6.34	3.20	0.65	-0.34	4.92	0.70	3.88	1.23	0.59	0.92	-2.23	0.49	0.80	-0.76	0.53
5.00	5.98	3.07	0.65	-0.70	4.88	0.70	3.52	1.14	0.59	0.57	-2.26	0.49	0.45	-0.79	0.53
5.20	5.64	2.94	0.64	-1.04	4.85	0.70	3.18	1.07	0.59	0.23	-2.29	0.49	0.11	-0.81	0.53
5.40	5.32	2.83	0.64	-1.37	4.82	0.70	2.85	1.00	0.58	-0.10	-2.32	0.49	-0.22	-0.84	0.53
5.60	5.00	2.73	0.64	-1.68	4.79	0.70	2.54	0.93	0.58	-0.41	-2.34	0.48	-0.54	-0.85	0.53
5.80	4.70	2.64	0.63	-1.99	4.76	0.70	2.23	0.87	0.58	-0.72	-2.36	0.48	-0.84	-0.87	0.53
6.00	4.40	2.55	0.63	-2.28	4.74	0.70	1.94	0.82	0.58	-1.01	-2.38	0.48	-1.14	-0.89	0.53
6.20	4.12	2.47	0.63	-2.57	4.72	0.70	1.65	0.77	0.58	-1.30	-2.40	0.48	-1.42	-0.90	0.53
6.40	3.84	2.40	0.63	-2.84	4.70	0.70	1.38	0.73	0.58	-1.57	-2.41	0.48	-1.70	-0.92	0.53
6.60	3.57	2.33	0.62	-3.11	4.68	0.70	1.11	0.69	0.58	-1.84	-2.43	0.48	-1.97	-0.93	0.53
6.80	3.31	2.26	0.62	-3.37	4.67	0.69	0.85	0.65	0.57	-2.10	-2.44	0.48	-2.22	-0.94	0.53
7.00	3.06	2.20	0.62	-3.62	4.65	0.69	0.60	0.61	0.57	-2.35	-2.46	0.48	-2.48	-0.95	0.53
7.20	2.82	2.15	0.62	-3.87	4.64	0.69	0.36	0.58	0.57	-2.60	-2.47	0.48	-2.72	-0.96	0.53
7.40	2.58	2.10	0.62	-4.10	4.62	0.69	0.12	0.55	0.57	-2.84	-2.48	0.48	-2.96	-0.97	0.53
7.60	2.35	2.05	0.62	-4.34	4.61	0.69	-0.11	0.52	0.57	-3.07	-2.49	0.48	-3.19	-0.98	0.53
7.80	2.12	2.00	0.62	-4.56	4.60	0.69	-0.34	0.50	0.57	-3.29	-2.50	0.48	-3.42	-0.98	0.53
8.00	1.90	1.96	0.61	-4.78	4.59	0.69	-0.56	0.47	0.57	-3.51	-2.50	0.48	-3.64	-0.99	0.53
8.20	1.69	1.92	0.61	-5.00	4.58	0.69	-0.77	0.45	0.57	-3.73	-2.51	0.48	-3.85	-1.00	0.53
8.40	1.48	1.88	0.61	-5.21	4.57	0.69	-0.98	0.43	0.57	-3.94	-2.52	0.48	-4.06	-1.00	0.52
8.60	1.27	1.84	0.61	-5.41	4.56	0.69	-1.19	0.41	0.57	-4.14	-2.53	0.48	-4.26	-1.01	0.52

8.60	1.27	1.84	0.61	-5.41	4.56	0.69	-1.19	0.41	0.57	-4.14	-2.53	0.48	-4.26	-1.01	0.52
8.80	1.07	1.81	0.61	-5.61	4.56	0.69	-1.39	0.39	0.57	-4.34	-2.53	0.48	-4.46	-1.01	0.52
9.00	0.88	1.78	0.61	-5.80	4.55	0.69	-1.58	0.37	0.57	-4.54	-2.54	0.48	-4.66	-1.02	0.52
9.20	0.69	1.75	0.61	-6.00	4.54	0.69	-1.77	0.35	0.57	-4.73	-2.54	0.48	-4.85	-1.02	0.52
9.40	0.50	1.72	0.61	-6.18	4.54	0.69	-1.96	0.34	0.57	-4.91	-2.55	0.48	-5.04	-1.03	0.52
9.60	0.32	1.69	0.61	-6.36	4.53	0.69	-2.14	0.32	0.56	-5.10	-2.55	0.48	-5.22	-1.03	0.52
9.80	0.14	1.67	0.61	-6.54	4.52	0.69	-2.32	0.31	0.56	-5.28	-2.56	0.48	-5.40	-1.03	0.52
10.00	-0.04	1.64	0.60	-6.72	4.52	0.69	-2.50	0.29	0.56	-5.45	-2.56	0.48	-5.57	-1.04	0.52
10.20	-0.21	1.62	0.60	-6.89	4.51	0.69	-2.67	0.28	0.56	-5.62	-2.57	0.48	-5.75	-1.04	0.52
10.40	-0.38	1.60	0.60	-7.06	4.51	0.69	-2.84	0.27	0.56	-5.79	-2.57	0.48			
10.60	-0.54	1.58	0.60				-3.00	0.26	0.56	-5.96	-2.58	0.48			
10.80	-0.70	1.56	0.60				-3.17	0.25	0.56	-6.12	-2.58	0.48			
11.00	-0.86	1.54	0.60				-3.33	0.24	0.56	-6.28	-2.58	0.48			
11.20	-1.02	1.52	0.60				-3.48	0.23	0.56	-6.43	-2.59	0.48			
11.40	-1.17	1.50	0.60				-3.64	0.22	0.56	-6.59	-2.59	0.48			
11.60	-1.32	1.49	0.60				-3.79	0.21	0.56	-6.74	-2.59	0.48			
11.80	-1.47	1.47	0.60				-3.94	0.20	0.56	-6.89	-2.59	0.48			
12.00	-1.62	1.46	0.60				-4.08	0.19	0.56	-7.03	-2.60	0.48			
12.20	-1.76	1.44	0.60				-4.23	0.18	0.56	-7.18	-2.60	0.48			
12.40	-1.90	1.43	0.60				-4.37	0.18	0.56	-7.32	-2.60	0.48			
12.60	-2.04	1.42	0.60				-4.51	0.17	0.56	-7.46	-2.60	0.48			
12.80	-2.18	1.40	0.60				-4.64	0.16	0.56	-7.59	-2.61	0.48			
13.00	-2.31	1.39	0.60				-4.78	0.16	0.56	-7.73	-2.61	0.48			
13.20	-2.45	1.38	0.60				-4.91	0.15	0.56	-7.86	-2.61	0.48			
13.40	-2.58	1.37	0.60				-5.04	0.14	0.56	-7.99	-2.61	0.48			
13.60	-2.71	1.36	0.60				-5.17	0.14	0.56						
13.80	-2.83	1.35	0.60				-5.30	0.13	0.56						
14.00	-2.96	1.34	0.60				-5.42	0.13	0.56						
14.20	-3.08	1.33	0.59				-5.54	0.12	0.56						
14.40	-3.20	1.32	0.59				-5.67	0.12	0.56						
14.6	-3.32	1.31	0.59				-5.79	0.11	0.56						
14.8	-3.44	1.30	0.59				-5.90	0.11	0.56						
15	-3.56	1.29	0.59				-6.02	0.10	0.56						
15.2	-3.67	1.29	0.59				-6.14	0.10	0.56						
15.4	-3.79	1.28	0.59				-6.25	0.10	0.56						
15.6	-3.90	1.27	0.59				-6.36	0.09	0.56						
15.8	-4.01	1.26	0.59				-6.47	0.09	0.56						
16	-4.12	1.26	0.59				-6.58	0.08	0.56						
16.2	-4.23	1.25	0.59				-6.69	0.08	0.56						
16.4	-4.33	1.24	0.59				-6.80	0.08	0.56						
16.6	-4.44	1.24	0.59				-6.90	0.07	0.56						
16.8	-4.54	1.23	0.59				-7.00	0.07	0.56						
17	-4.64	1.22	0.59				-7.11	0.07	0.56						
17.2	-4.75	1.22	0.59				-7.21	0.07	0.56						
17.4	-4.85	1.21	0.59				-7.31	0.06	0.56						
17.6	-4.95	1.21	0.59				-7.41	0.06	0.56						
17.8	-5.04	1.20	0.59				-7.51	0.06	0.56						
18	-5.14	1.20	0.59				-7.60	0.05	0.56						
18.2	-5.24	1.19	0.59				-7.70	0.05	0.56						
18.4	-5.33	1.19	0.59				-7.79	0.05	0.56						
18.6	-5.43	1.18	0.59				-7.89	0.05	0.56						
18.8	-5.52	1.18	0.59				-7.98	0.04	0.56						

19	-5.61	1.18	0.59				-8.07	0.04	0.56						
19.2	-5.70	1.17	0.59				-8.16	0.04	0.56						
19.4	-5.79	1.17	0.59				-8.25	0.04	0.56						
19.6	-5.88	1.16	0.59				-8.34	0.04	0.56						
19.8	-5.97	1.16	0.59				-8.43	0.03	0.56						
20	-6.06	1.16	0.59				-8.52	0.03	0.56						
20.2	-6.14	1.15	0.59												
20.4	-6.23	1.15	0.59												
20.6	-6.31	1.14	0.59												
20.8	-6.40	1.14	0.59												
21	-6.48	1.14	0.59												
21.2	-6.56	1.13	0.59												
21.4	-6.64	1.13	0.59												
21.6	-6.72	1.13	0.59												
21.8	-6.80	1.13	0.59												
22	-6.88	1.12	0.59												

Table 8.15a: Calculation of quality numbers SN-ratio, C_{50}-value and the STI - Auditorium A, C, D, E and G

8.4.2. *Auditorium H, I, J, K and N*

R	H			I			J			K			N		
[m]	SN [dB]	C_{50} [dB]	STI [1-5]	SN [dB]	C_{50} [dB]	STI [1-5]	SN [dB]	C_{50} [dB]	STI [1-5]	SN [dB]	C_{50} [dB]	STI [1-5]	SN [dB]	C_{50} [dB]	STI [1-5]
0.20	25.86	12.18	0.92	27.19	14.77	1.00	26.48	14.91	1.00	27.56	13.73	0.97	31.24	25.18	1.31
0.40	19.84	6.61	0.75	21.16	9.12	0.83	20.46	9.30	0.83	21.54	7.90	0.79	25.22	19.27	1.13
0.60	16.32	3.75	0.67	17.64	6.15	0.74	16.94	6.38	0.75	18.02	4.67	0.70	21.70	15.89	1.03
0.80	13.82	2.03	0.62	15.14	4.31	0.68	14.44	4.60	0.69	15.52	2.55	0.63	19.20	13.57	0.96
1.00	11.88	0.92	0.58	13.21	3.10	0.65	12.50	3.44	0.66	13.58	1.05	0.59	17.26	11.85	0.91
1.20	10.30	0.17	0.56	11.62	2.26	0.62	10.92	2.64	0.63	12.00	-0.06	0.55	15.68	10.50	0.87
1.40	8.96	-0.36	0.54	10.28	1.66	0.60	9.58	2.08	0.62	10.66	-0.89	0.53	14.34	9.42	0.84
1.60	7.80	-0.73	0.53	9.12	1.22	0.59	8.42	1.67	0.61	9.50	-1.53	0.51	13.18	8.53	0.81
1.80	6.77	-1.01	0.52	8.10	0.89	0.58	7.39	1.37	0.60	8.48	-2.04	0.49	12.16	7.80	0.79
2.00	5.86	-1.23	0.52	7.19	0.64	0.57	6.48	1.14	0.59	7.56	-2.44	0.48	11.24	7.18	0.77
2.20	5.03	-1.39	0.51	6.36	0.44	0.57	5.65	0.96	0.58	6.73	-2.76	0.47	10.42	6.66	0.75
2.40	4.27	-1.52	0.51	5.60	0.29	0.56	4.89	0.81	0.58	5.98	-3.03	0.46	9.66	6.21	0.74
2.60	3.58	-1.62	0.51	4.91	0.16	0.56	4.20	0.70	0.58	5.28	-3.24	0.46	8.97	5.82	0.73
2.80	2.94	-1.71	0.50	4.26	0.06	0.56	3.56	0.60	0.57	4.64	-3.42	0.45	8.32	5.49	0.72
3.00	2.34	-1.78	0.50	3.66	-0.03	0.55	2.96	0.53	0.57	4.04	-3.58	0.45	7.72	5.20	0.71
3.20	1.78	-1.83	0.50	3.10	-0.10	0.55	2.40	0.46	0.57	3.48	-3.70	0.44	7.16	4.94	0.70
3.40	1.25	-1.88	0.50	2.58	-0.16	0.55	1.87	0.41	0.57	2.95	-3.81	0.44	6.64	4.72	0.70
3.60	0.75	-1.92	0.50	2.08	-0.21	0.55	1.37	0.36	0.57	2.46	-3.91	0.44	6.14	4.52	0.69
3.80	0.28	-1.96	0.50	1.61	-0.25	0.55	0.90	0.32	0.56	1.99	-3.99	0.44	5.67	4.34	0.69
4.00	-0.16	-1.99	0.50	1.16	-0.29	0.55	0.46	0.29	0.56	1.54	-4.06	0.43	5.22	4.19	0.68
4.20	-0.59	-2.01	0.49	0.74	-0.33	0.55	0.03	0.26	0.56	1.12	-4.12	0.43	4.80	4.05	0.68
4.40	-0.99	-2.04	0.49	0.34	-0.35	0.54	-0.37	0.24	0.56	0.71	-4.17	0.43	4.40	3.92	0.67
4.60	-1.38	-2.06	0.49	-0.05	-0.38	0.54	-0.76	0.21	0.56	0.33	-4.22	0.43	4.01	3.81	0.67
4.80	-1.75	-2.07	0.49	-0.42	-0.40	0.54	-1.13	0.19	0.56	-0.04	-4.27	0.43	3.64	3.70	0.67

5.00	-2.10	-2.09	0.49	-0.77	-0.42	0.54	-1.48	0.18	0.56	-0.40	-4.30	0.43	3.29	3.61	0.66
5.20	-2.44	-2.10	0.49	-1.11	-0.44	0.54	-1.82	0.16	0.56	-0.74	-4.34	0.42	2.94	3.52	0.66
5.40	-2.77	-2.12	0.49	-1.44	-0.45	0.54	-2.15	0.15	0.56	-1.07	-4.37	0.42	2.62	3.45	0.66
5.60	-3.08	-2.13	0.49	-1.76	-0.47	0.54	-2.46	0.13	0.56	-1.38	-4.40	0.42	2.30	3.38	0.66
5.80	-3.39	-2.14	0.49	-2.06	-0.48	0.54	-2.77	0.12	0.56	-1.69	-4.42	0.42	2.00	3.31	0.65
6.00	-3.68	-2.15	0.49	-2.36	-0.49	0.54	-3.06	0.11	0.56	-1.98	-4.44	0.42	1.70	3.25	0.65
6.20	-3.97	-2.15	0.49	-2.64	-0.50	0.54	-3.35	0.10	0.56	-2.27	-4.46	0.42	1.42	3.20	0.65
6.40	-4.24	-2.16	0.49	-2.92	-0.51	0.54	-3.62	0.09	0.56	-2.54	-4.48	0.42	1.14	3.15	0.65
6.60	-4.51	-2.17	0.49	-3.18	-0.52	0.54	-3.89	0.09	0.56	-2.81	-4.50	0.42	0.87	3.10	0.65
6.80	-4.77	-2.18	0.49	-3.44	-0.53	0.54	-4.15	0.08	0.56	-3.07	-4.52	0.42	0.61	3.06	0.65
7.00	-5.02	-2.18	0.49	-3.70	-0.54	0.54	-4.40	0.07	0.56	-3.32	-4.53	0.42	0.36	3.02	0.65
7.20	-5.27	-2.19	0.49	-3.94	-0.54	0.54	-4.65	0.07	0.56	-3.56	-4.54	0.42	0.12	2.98	0.64
7.40	-5.51	-2.19	0.49	-4.18	-0.55	0.54	-4.89	0.06	0.56	-3.80	-4.56	0.42	-0.12	2.94	0.64
7.60	-5.74	-2.20	0.49	-4.41	-0.56	0.54	-5.12	0.05	0.56	-4.03	-4.57	0.42	-0.35	2.91	0.64
7.80	-5.96	-2.20	0.49	-4.64	-0.56	0.54	-5.34	0.05	0.56	-4.26	-4.58	0.42	-0.58	2.88	0.64
8.00	-6.18	-2.20	0.49	-4.86	-0.57	0.54	-5.56	0.05	0.56	-4.48	-4.59	0.42	-0.80	2.85	0.64
8.20	-6.40	-2.21	0.49	-5.07	-0.57	0.54	-5.78	0.04	0.56	-4.69	-4.60	0.42	-1.01	2.83	0.64
8.40	-6.61	-2.21	0.49	-5.28	-0.58	0.54	-5.99	0.04	0.56	-4.90	-4.61	0.42	-1.22	2.80	0.64
8.60	-6.81	-2.21	0.49	-5.48	-0.58	0.54	-6.19	0.03	0.56	-5.11	-4.62	0.42	-1.43	2.78	0.64
8.60	-6.81	-2.21	0.49	-5.48	-0.58	0.54	-6.19	0.03	0.56	-5.11	-4.62	0.42	-1.43	2.78	0.64
8.80	-7.01	-2.22	0.49	-5.68	-0.58	0.54	-6.39	0.03	0.56	-5.31	-4.62	0.42	-1.63	2.76	0.64
9.00	-7.21	-2.22	0.49	-5.88	-0.59	0.54	-6.59	0.03	0.56	-5.50	-4.63	0.42	-1.82	2.74	0.64
9.20				-6.07	-0.59	0.54	-6.78	0.02	0.56	-5.69	-4.64	0.42	-2.01	2.72	0.64
9.40				-6.26	-0.59	0.54	-6.96	0.02	0.56	-5.88	-4.64	0.42	-2.20	2.70	0.64
9.60				-6.44	-0.60	0.54	-7.15	0.02	0.56	-6.06	-4.65	0.42	-2.38	2.68	0.64
9.80				-6.62	-0.60	0.54	-7.33	0.02	0.56	-6.24	-4.65	0.42	-2.56	2.66	0.63
10.00				-6.79	-0.60	0.54	-7.50	0.01	0.56	-6.42	-4.66	0.42	-2.74	2.65	0.63
10.20				-6.97	-0.61	0.54							-2.91	2.63	0.63
10.40				-7.13	-0.61	0.54							-3.08	2.62	0.63
10.60				-7.30	-0.61	0.54							-3.24	2.60	0.63
10.80				-7.46	-0.61	0.54							-3.40	2.59	0.63
11.00				-7.62	-0.61	0.54							-3.56	2.58	0.63
11.20				-7.78	-0.62	0.54							-3.72	2.57	0.63
11.40				-7.93	-0.62	0.54							-3.87	2.56	0.63
11.60				-8.08	-0.62	0.54							-4.02	2.55	0.63
11.80				-8.23	-0.62	0.54							-4.17	2.54	0.63
12.00				-8.38	-0.62	0.54							-4.32	2.53	0.63
12.20				-8.52	-0.62	0.54							-4.46	2.52	0.63
12.40				-8.66	-0.63	0.54							-4.60	2.51	0.63
12.60				-8.80	-0.63	0.54							-4.74	2.50	0.63
12.80				-8.94	-0.63	0.54							-4.88	2.49	0.63
13.00				-9.07	-0.63	0.54							-5.01	2.48	0.63
13.20				-9.21	-0.63	0.54							-5.15	2.48	0.63
13.40				-9.34	-0.63	0.54							-5.28	2.47	0.63

13.60				-9.46	-0.63	0.54							-5.41	2.46	0.63
13.80				-9.59	-0.63	0.54							-5.53	2.46	0.63
14.00				-9.72	-0.63	0.54							-5.66	2.45	0.63
14.20													-5.78	2.44	0.63
14.40													-5.90	2.44	0.63
14.60													-6.02	2.43	0.63
14.80													-6.14	2.43	0.63
15.00													-6.26	2.42	0.63
15.20													-6.37	2.42	0.63
15.40													-6.49	2.41	0.63
15.60													-6.60	2.41	0.63
15.80													-6.71	2.40	0.63
16.00													-6.82	2.40	0.63
16.20													-6.93	2.40	0.63
16.40													-7.03	2.39	0.63
16.60													-7.14	2.39	0.63
16.80													-7.24	2.38	0.63
17.00													-7.34	2.38	0.63
17.20													-7.45	2.38	0.63
17.40													-7.55	2.37	0.63
17.60													-7.65	2.37	0.63
17.80													-7.74	2.37	0.63
18.00													-7.84	2.36	0.63
18.20													-7.94	2.36	0.63
18.40													-8.03	2.36	0.63
18.60													-8.13	2.35	0.63
18.80													-8.22	2.35	0.63
19.00													-8.31	2.35	0.63
19.20													-8.40	2.35	0.63
19.40													-8.49	2.34	0.63
19.60													-8.58	2.34	0.63
19.80													-8.67	2.34	0.63
20.00													-8.76	2.34	0.63
20.20													-8.84	2.33	0.63
20.40													-8.93	2.33	0.62
20.60													-9.01	2.33	0.62
20.80													-9.10	2.33	0.62
21.00													-9.18	2.33	0.62
21.20													-9.26	2.32	0.62
21.40													-9.34	2.32	0.62
21.60													-9.42	2.32	0.62
21.80													-9.50	2.32	0.62
22.00													-9.58	2.32	0.62

Table 8.15b: Calculation of quality numbers SN-ratio, C_{50}-value and the STI - Auditorium H, I, J, K and N

8.5. Survey

8.5.1. Survey-sheet

Dear Respondent,

As a part of our Master's Dissertation about acoustic absorption in auditoria, we would like to ask some questions. The questions are about the Speech Intelligibility of the professor, depending on the auditorium where you are located.

Thank you for your attention and time.

Lottie Braems & Hannah De Kerpel

SURVEY

1. In which auditorium are you located?

……

2. Where did you sit down?

Row (counted from the front):…………………………………………………………………………………………………

Left / Middle / Right in the row

3. Do you have a hearing problem?

Yes / No

4. Was the professor speaking with a microphone? If no, proceed to question 6.

Yes / No

5. What was the Speech Intelligibility of the professor? (1 = unintelligible, 5 = perfectly intelligible)

Unintelligible	1	2	3	4	5	Perfectly intelligible

6. If the professor did not speak with a microphone, how loud did the professor speak? (1 = very quiet, 5 = very loud)

Very quiet	1	2	3	4	5	Very loud

7. What do you think about the global acoustics in the auditorium during the lesson? (1 = very bad, 5 = very good)

Very bad	1	2	3	4	5	Very good

8. Was the intelligibility of the professor prevented by background noise?

Yes / No

9. If yes, which?

……

8.5.2. *Results of the survey*

Auditorium C – 18 opinions

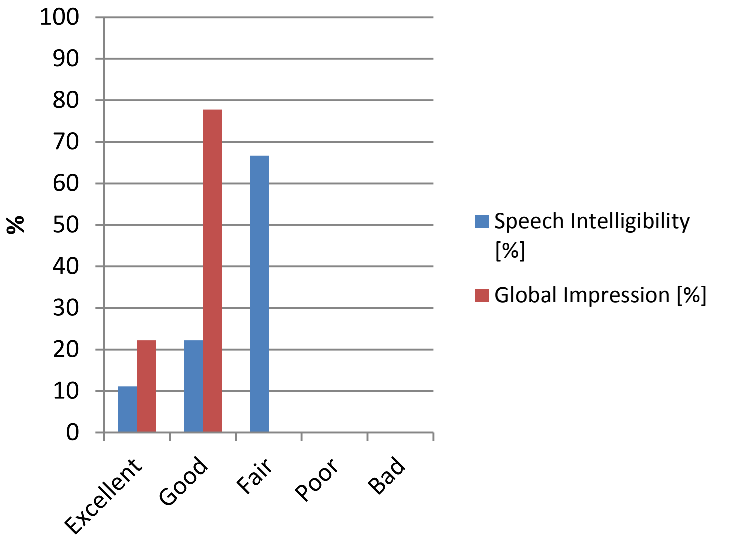
Speech Intelligibility without micro

STI	Rate	# students	%
Excellent	5	2	11
Good	4	4	22
Fair	3	12	67
Poor	2	0	0
Bad	1	0	0

Global Impression

STI	Rate	# students	%
Excellent	5	4	22
Good	4	14	78
Fair	3	0	0
Poor	2	0	0
Bad	1	0	0

Graph



Mean Speech Intelligibility	4.44
Mean Global Impression	3.83

Positions + opinion on SI

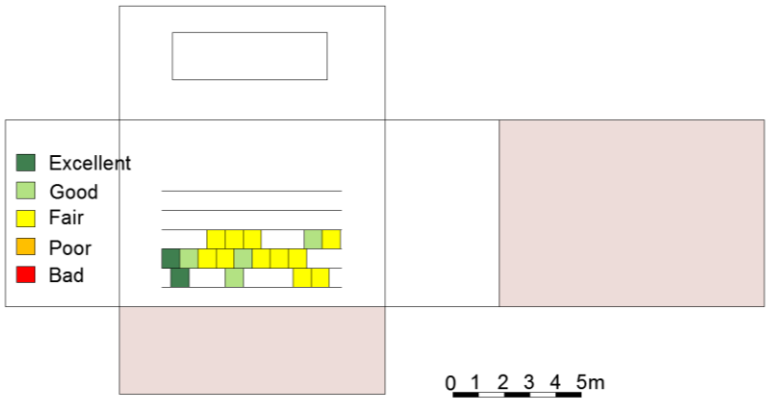


Table 8.16a: Results of the survey – Auditorium C

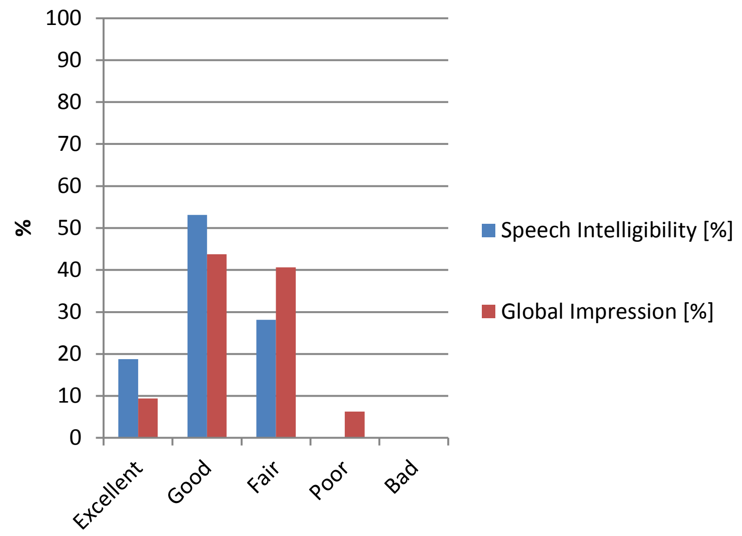
Auditorium D – 32 opinions				
Speech Intelligibility without micro				**Graph**
STI	**Rate**	**# students**	**%**	
Excellent	5	6	19	
Good	4	17	53	
Fair	3	9	28	
Poor	2	0	0	
Bad	1	0	0	
Global Impression				
STI	**Rate**	**# students**	**%**	
Excellent	5	3	9	
Good	4	14	44	
Fair	3	13	41	
Poor	2	2	6	
Bad	1	0	0	
Mean Speech Intelligibility				3.91
Mean Global Impression				3.56
Positions + opinion on SI				

Table 8.16b: Results of the survey – Auditorium D

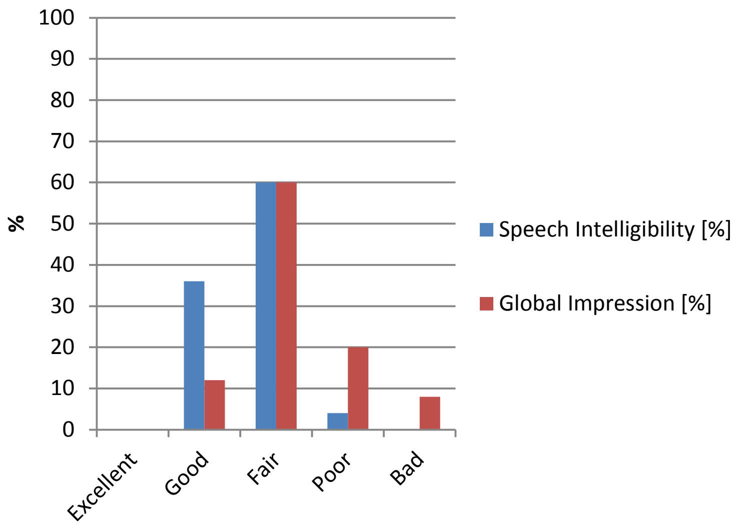
Auditorium E – 25 opinions				
Speech Intelligibility without micro				**Graph**
STI	**Rate**	**# students**	**%**	
Excellent	5	0	0	
Good	4	9	36	
Fair	3	15	60	
Poor	2	1	4	
Bad	1	0	0	
Global Impression				
STI	**Rate**	**# students**	**%**	
Excellent	5	0	0	
Good	4	3	12	
Fair	3	15	60	
Poor	2	5	20	
Bad	1	2	8	
Mean Speech Intelligibility				3.32
Mean Global Impression				2.76
Positions + opinion on SI				

Table 8.16c: Results of the survey – Auditorium E

Auditorium G – 28 opinions

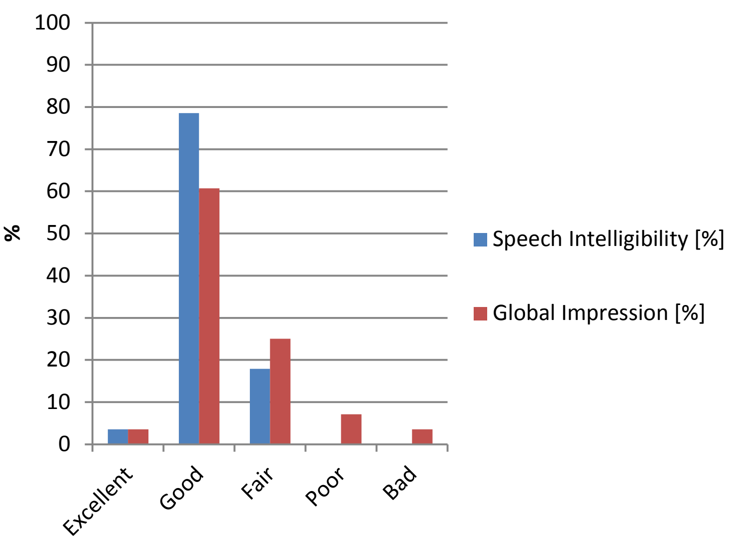
Speech Intelligibility without micro

STI	Rate	# students	%
Excellent	5	1	4
Good	4	22	79
Fair	3	5	18
Poor	2	0	0
Bad	1	0	0

Global Impression

STI	Rate	# students	%
Excellent	5	1	4
Good	4	17	61
Fair	3	7	25
Poor	2	2	7
Bad	1	1	4

Graph



Mean Speech Intelligibility	3.86
Mean Global Impression	3.54

Positions + opinion on SI

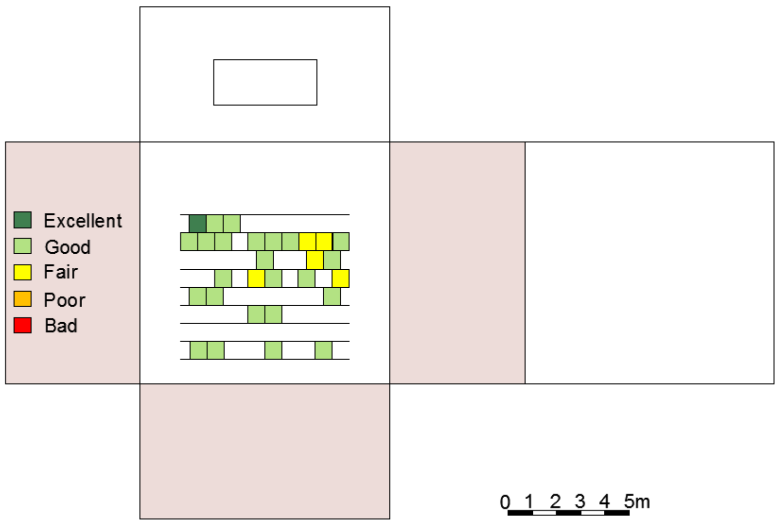


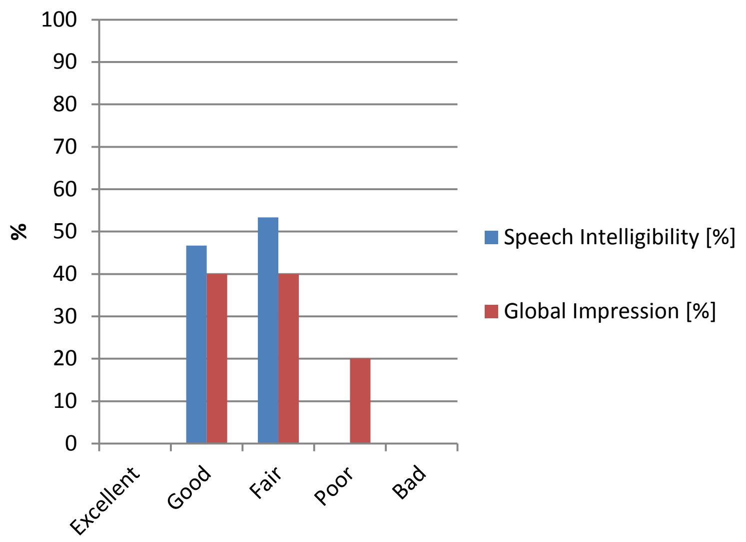
Table 8.16d: Results of the survey – Auditorium G

Auditorium H – 15 opinions

Speech Intelligibility <u>without</u> micro			
STI	**Rate**	**# students**	**%**
Excellent	5	0	0
Good	4	7	47
Fair	3	8	53
Poor	2	0	0
Bad	1	0	0

Global Impression			
STI	**Rate**	**# students**	**%**
Excellent	5	0	0
Good	4	6	40
Fair	3	6	40
Poor	2	3	20
Bad	1	0	0

Graph



Mean Speech Intelligibility	3.47
Mean Global Impression	3.20

Positions + opinion on SI

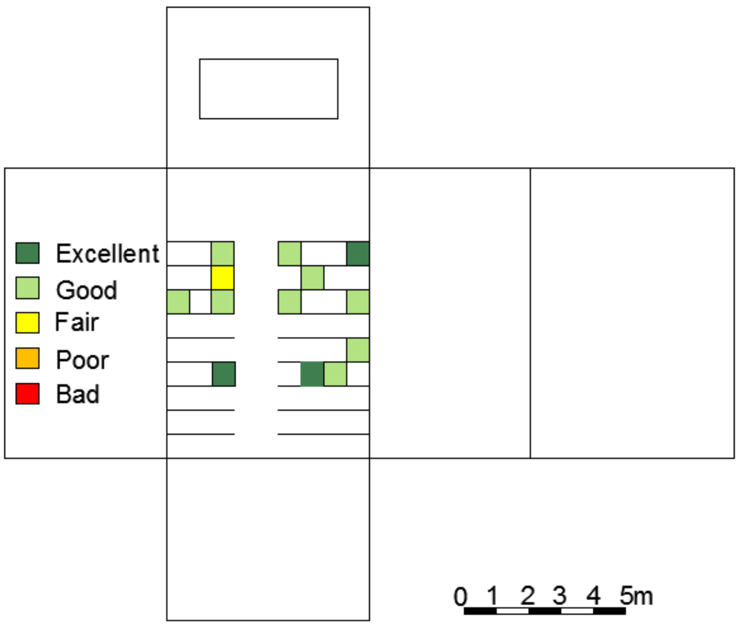


Table 8.16e: Results of the survey – Auditorium H

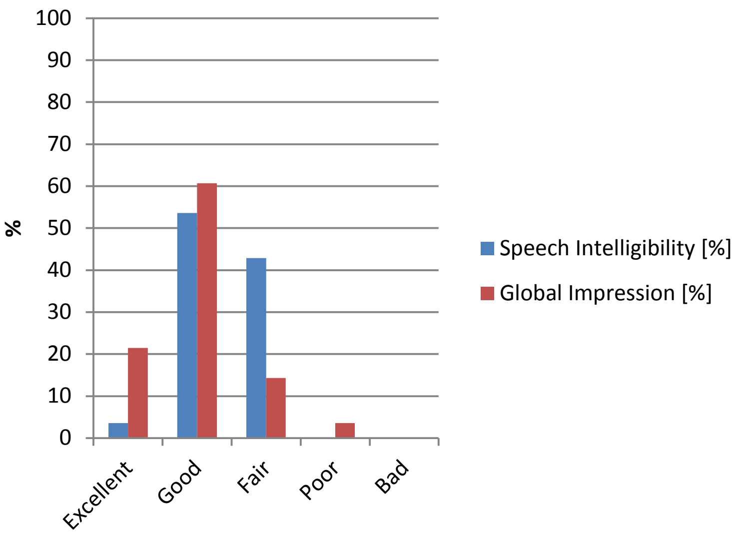
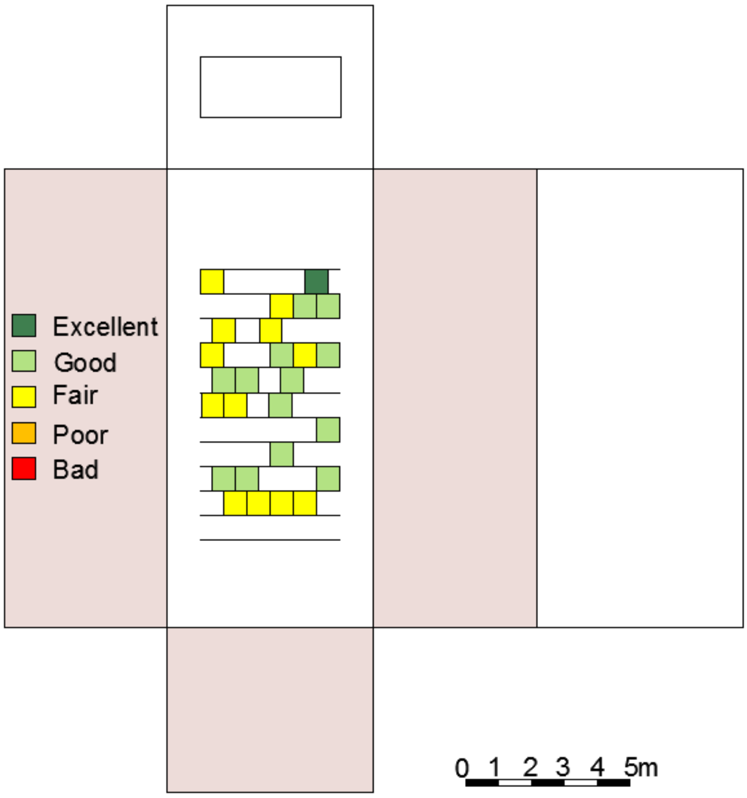
Auditorium I – 28 opinions				
Speech Intelligibility without micro				**Graph**
STI	**Rate**	**# students**	**%**	
Excellent	5	1	4	
Good	4	15	54	
Fair	3	12	43	
Poor	2	0	0	
Bad	1	0	0	
Global Impression				
STI	**Rate**	**# students**	**%**	
Excellent	5	6	21	
Good	4	17	61	
Fair	3	4	14	
Poor	2	1	4	
Bad	1	0	0	
Mean Speech Intelligibility				3.61
Mean Global Impression				4.00
Positions + opinion on SI				

Table 8.16f: Results of the survey – Auditorium I

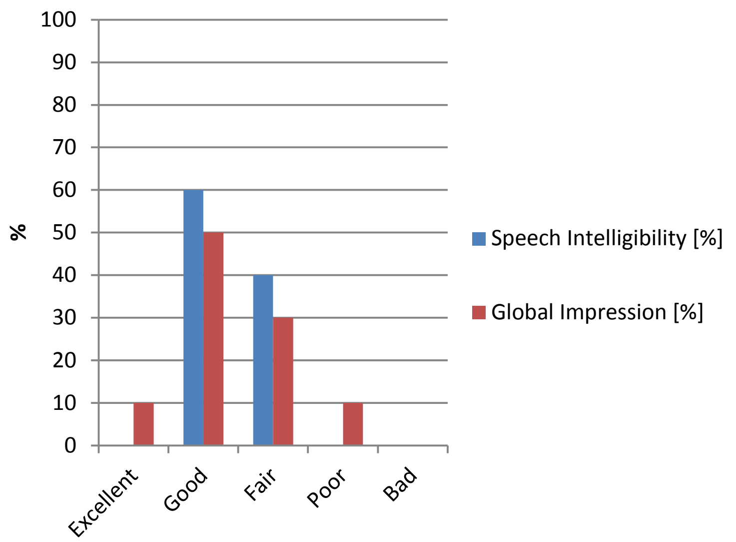
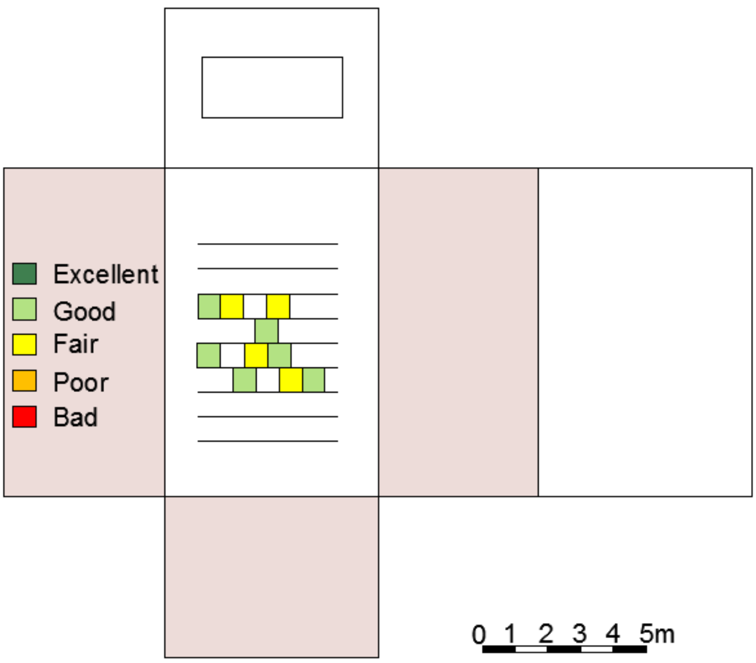
Auditorium J – 10 opinions				
Speech Intelligibility without micro				**Graph**
STI	**Rate**	**# students**	**%**	
Excellent	5	0	0	
Good	4	6	60	
Fair	3	4	40	
Poor	2	0	0	
Bad	1	0	0	
Global Impression				
STI	**Rate**	**# students**	**%**	
Excellent	5	1	10	
Good	4	5	50	
Fair	3	3	30	
Poor	2	1	10	
Bad	1	0	0	
Mean Speech Intelligibility				3.60
Mean Global Impression				3.60
Positions + opinion on SI				

Table 8.16g: Results of the survey – Auditorium J

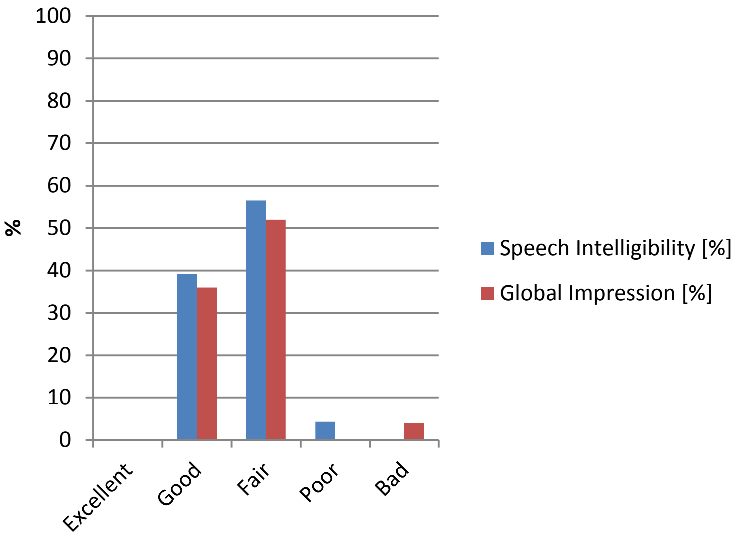
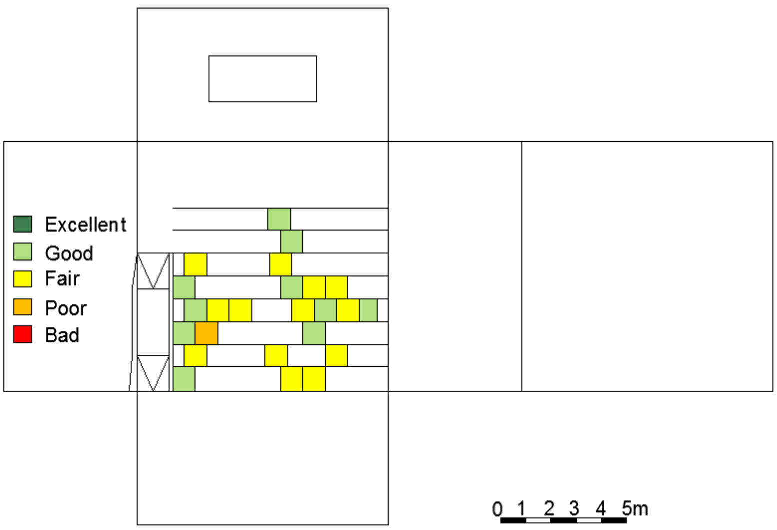
Auditorium K – 23 opinions				
Speech Intelligibility <u>without</u> micro				**Graph**
STI	**Rate**	**# students**	**%**	
Excellent	5	0	0	
Good	4	9	39	
Fair	3	13	57	
Poor	2	1	4	
Bad	1	0	0	
Global Impression				
STI	**Rate**	**# students**	**%**	
Excellent	5	0	0	
Good	4	9	36	
Fair	3	13	52	
Poor	2	0	0	
Bad	1	1	4	
Mean Speech Intelligibility				3.35
Mean Global Impression				3.30
Positions + opinion on SI				

Table 8.16h: Results of the survey – Auditorium K

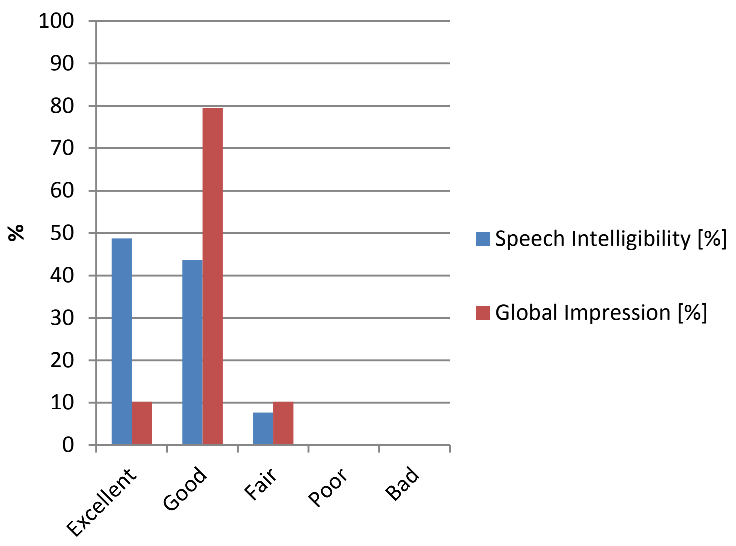
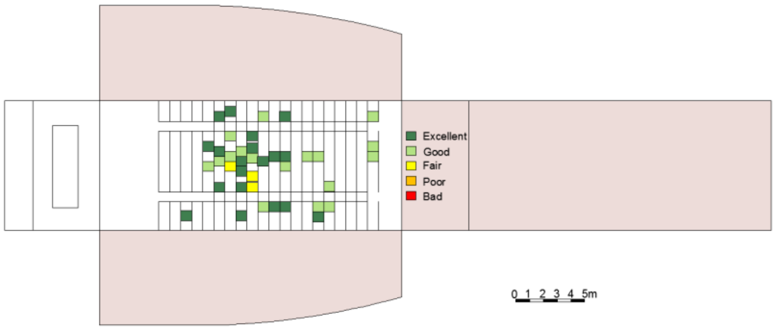
Auditorium N – 39 opinions				
Speech Intelligibility with micro				**Graph**
STI	**Rate**	**# students**	**%**	
Excellent	5	19	49	
Good	4	17	44	
Fair	3	3	8	
Poor	2	0	0	
Bad	1	0	0	
Global Impression				
STI	**Rate**	**# students**	**%**	
Excellent	5	4	10	
Good	4	31	79	
Fair	3	4	10	
Poor	2	0	0	
Bad	1	0	0	
Mean Speech Intelligibility				4.41
Mean Global Impression				4.00
Positions + opinion on SI				

Table 8.16i: Results of the survey – Auditorium N

8.6. Template of the auditoria: data + calculation

8.6.1. Auditorium A

Compactness	**C [m]**	**1.37**
Total surface area	**S [m²]**	**1545.50**
Total volume	**V [m³]**	**2117.50**

Surface	**Length**	**Width**	**Surface**	**Surface**	**Absorption coefficient**					
	L [m]	**W [m]**	**S_i [m²]**	**S_i [m²]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**
Surfacel x_1	**22.00**	**5.00**	**110.00**		**125Hz**	**250Hz**	**500Hz**	**1,000Hz**	**2,000Hz**	**4,000Hz**
Window				65.08	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster					0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR				27.94	0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium				16.98	0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element					0.10	0.30	0.70	0.80	0.85	0.90
Carpet					0.01	0.02	0.06	0.15	0.25	0.45
Surface x_2	**22.00**	**5.00**	**110.00**							
Window				65.08	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster					0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR				27.94	0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium				16.98	0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element					0.10	0.30	0.70	0.80	0.85	0.90
Carpet					0.01	0.02	0.06	0.15	0.25	0.45
Surface y_1	**19.25**	**5.00**	**96.25**							
Plaster				68.10	0.01	0.01	0.01	0.02	0.02	0.03
Chalkboard				9.00	0.15	0.15	0.11	0.03	0.05	0.03
White projection board				15.75	0.20	0.20	0.20	0.20	0.25	0.25
Door aluminium				3.40	0.01	0.02	0.03	0.03	0.04	0.04
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Surface y_2	**19.25**	**5.00**	**96.25**							
Wall laminated wood				26.93	0.38	0.24	0.17	0.10	0.08	0.05
Wall acoustic				65.32	0.20	0.35	0.70	0.65	0.60	0.55
Plaster					0.01	0.01	0.01	0.02	0.02	0.03
Door wood				4.00	0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element					0.10	0.30	0.70	0.80	0.85	0.90
Carpet					0.01	0.02	0.06	0.15	0.25	0.45
Chalkboard					0.15	0.15	0.11	0.03	0.05	0.03
Window					0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Surface z_1	**22.00**	**19.25**	**709.50**							
Linoleum				418.41	0.02	0.03	0.03	0.03	0.03	0.02
Wood					0.02	0.03	0.04	0.05	0.05	0.06
Desk laminated wood				5.09	0.02	0.02	0.03	0.04	0.04	0.04
Seats and backs				286.00	0.02	0.02	0.03	0.04	0.04	0.04
Surface z_2	**22.00**	**19.25**	**423.50**							
Acoustic ceiling				423.50	0.20	0.35	0.70	0.65	0.60	0.55
Plaster					0.01	0.01	0.01	0.02	0.02	0.03

Table 8.17a: Template – Auditorium A

8.6.2. Auditorium C

Compactness	C [m]	1.50
Total surface area	S [m²]	337.49
Total volume	V [m³]	505.53

Surface	Length	Width	Surface	Surface	Absorption coefficient					
	L [m]	W [m]	S_i [m²]	S_i [m²]	α_i [-]	α_i [-]	α_i [-]	α_i [-]	α_i [-]	α_i [-]
Surfacel x1	**7.27**	**4.43**	**32.21**		**125Hz**	**250Hz**	**500Hz**	**1,000Hz**	**2,000Hz**	**4,000Hz**
Window					0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster				25.61	0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood				3.00	0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element				3.60	0.10	0.30	0.70	0.80	0.85	0.90
Carpet					0.01	0.02	0.06	0.15	0.25	0.45
Surface x2	**7.27**	**4.43**	**32.21**							
Window				9.24	0.12	0.12	0.12	0.14	0.14	0.14
Covered window (sunblocking)					0.04	0.03	0.02	0.02	0.02	0.02
Plaster				21.17	0.01	0.01	0.02	0.02	0.03	0.03
Wall laminated wood					0.24	0.17	0.10	0.08	0.05	0.05
PUR					0.55	1.00	1.15	1.15	1.20	1.20
Window: aluminium					0.02	0.03	0.03	0.04	0.04	0.04
Curtains					0.04	0.03	0.02	0.02	0.02	0.02
Door wood					0.10	0.08	0.08	0.08	0.08	0.08
Acoustic element				1.80	0.30	0.70	0.80	0.85	0.90	0.90
Carpet					0.02	0.06	0.15	0.25	0.45	0.45
Surface y1	**10.35**	**4.43**	**37.87**							
Plaster				21.87	0.01	0.01	0.02	0.02	0.03	0.03
Chalkboard				6.00	0.15	0.11	0.03	0.05	0.03	0.03
White projection board				10.00	0.20	0.20	0.20	0.25	0.25	0.25
Door aluminium					0.02	0.03	0.03	0.04	0.04	0.04
Door wood					0.10	0.08	0.08	0.08	0.08	0.08
Surface y2	**10.35**	**4.43**	**45.85**							
Wall laminated wood					0.24	0.17	0.10	0.08	0.05	0.05
Wall acoustic					0.35	0.70	0.65	0.60	0.55	0.55
Plaster					0.01	0.01	0.02	0.02	0.03	0.03
Door wood				2.11	0.10	0.08	0.08	0.08	0.08	0.08
Acoustic element				10.02	0.30	0.70	0.80	0.85	0.90	0.90
Carpet				33.72	0.02	0.06	0.15	0.25	0.45	0.45
Chalkboard					0.15	0.11	0.03	0.05	0.03	0.03
Window					0.12	0.12	0.12	0.14	0.14	0.14
Covered window (sunblocking)					0.04	0.03	0.02	0.02	0.02	0.02
Surface z1	**10.35**	**7.27**	**114.11**							
Linoleum				73.12	0.03	0.03	0.03	0.03	0.02	0.02
Wood					0.03	0.04	0.05	0.05	0.06	0.06
Desk laminated wood				2.12	0.02	0.03	0.04	0.04	0.04	0.04
Seats and backs				38.87	0.02	0.03	0.04	0.04	0.04	0.04
Surface z2	**10.35**	**7.27**	**75.24**							
Acoustic ceiling				75.24	0.35	0.70	0.65	0.60	0.55	0.55
Plaster					0.01	0.01	0.02	0.02	0.03	0.03

Table 8.17b: Template – Auditorium C

8.6.3. Auditorium D

		Compactness	**C [m]**	**1.21**						
		Total surface area	**S [m²]**	**945.29**						
		Total volume	**V [m³]**	**1141.41**						
Surface	**Length**	**Width**	**Surface**	**Surface**	**Absorption coefficient**					
	L [m]	**W [m]**	**S_i [m²]**	**S_i [m²]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**
Surfacel x1	**19.62**	**4.80**	**94.18**		**125Hz**	**250Hz**	**500Hz**	**1,000Hz**	**2,000Hz**	**4,000Hz**
Window				28.08	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster				66.10	0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element					0.10	0.30	0.70	0.80	0.85	0.90
Carpet					0.01	0.02	0.06	0.15	0.25	0.45
Surface x2	**19.62**	**4.80**	**94.18**							
Window				26.69	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster				67.49	0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element					0.10	0.30	0.70	0.80	0.85	0.90
Carpet					0.01	0.02	0.06	0.15	0.25	0.45
Surface y1	12.12	4.80	58.18							
Plaster				35.98	0.01	0.01	0.01	0.02	0.02	0.03
Chalkboard				6.00	0.15	0.15	0.11	0.03	0.05	0.03
White projection board				10.00	0.20	0.20	0.20	0.20	0.25	0.25
Door aluminium				1.66	0.01	0.02	0.03	0.03	0.04	0.04
Door wood				4.54	0.14	0.10	0.08	0.08	0.08	0.08
Surface y2	12.12	4.80	58.18							
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
Wall acoustic					0.20	0.35	0.70	0.65	0.60	0.55
Plaster				41.70	0.01	0.01	0.01	0.02	0.02	0.03
Door wood				4.00	0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element				12.48	0.10	0.30	0.70	0.80	0.85	0.90
Carpet					0.01	0.02	0.06	0.15	0.25	0.45
Chalkboard					0.15	0.15	0.11	0.03	0.05	0.03
Window					0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Surface z1	19.62	12.12	402.79							
Linoleum				235.79	0.02	0.03	0.03	0.03	0.03	0.02
Wood					0.02	0.03	0.04	0.05	0.05	0.06
Desk laminated wood				2.00	0.02	0.02	0.03	0.04	0.04	0.04
Seats and backs				165.00	0.02	0.02	0.03	0.04	0.04	0.04
Surface z2	19.62	12.12	237.79							
Acoustic ceiling				237.79	0.20	0.35	0.70	0.65	0.60	0.55
Plaster					0.01	0.01	0.01	0.02	0.02	0.03

Table 8.17c: Template – Auditorium D

8.6.4. Auditorium E

		Compactness	C [m]	0.96						
		Total surface area	S [m²]	536.81						
		Total volume	V [m³]	514.77						
Surface	**Length**	**Width**	**Surface**	**Surface**	**Absorption coefficient**					
	L [m]	**W [m]**	**S_i [m²]**	**S_i [m²]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**
Surfacel x1	**13.40**	**4.83**	**61.50**		**125Hz**	**250Hz**	**500Hz**	**1,000Hz**	**2,000Hz**	**4,000Hz**
Window				20.72	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster				12.09	0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element					0.10	0.30	0.70	0.80	0.85	0.90
Carpet				28.69	0.01	0.02	0.06	0.15	0.25	0.45
Surface x2	**13.40**	**4.83**	**62.04**							
Window				20.72	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster				12.63	0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element					0.10	0.30	0.70	0.80	0.85	0.90
Carpet				28.69	0.01	0.02	0.06	0.15	0.25	0.45
Surface y1	**8.37**	**4.83**	**39.33**							
Plaster				21.21	0.01	0.01	0.01	0.02	0.02	0.03
Chalkboard				5.00	0.15	0.15	0.11	0.03	0.05	0.03
White projection board				8.74	0.20	0.20	0.20	0.20	0.25	0.25
Door aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Door wood				4.38	0.14	0.10	0.08	0.08	0.08	0.08
Surface y2	**8.37**	**4.11**	**39.12**							
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
Wall acoustic					0.20	0.35	0.70	0.65	0.60	0.55
Plaster				2.19	0.01	0.01	0.01	0.02	0.02	0.03
Door wood				4.38	0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element					0.10	0.30	0.70	0.80	0.85	0.90
Carpet				32.55	0.01	0.02	0.06	0.15	0.25	0.45
Chalkboard					0.15	0.15	0.11	0.03	0.05	0.03
Window					0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Surface z1	**13.40**	**8.37**	**222.66**							
Linoleum				109.46	0.02	0.03	0.03	0.03	0.03	0.02
Wood					0.02	0.03	0.04	0.05	0.05	0.06
Desk laminated wood				2.70	0.02	0.02	0.03	0.04	0.04	0.04
Seats and backs				110.50	0.02	0.02	0.03	0.04	0.04	0.04
Surface z2	**13.40**	**8.37**	**112.16**							
Acoustic ceiling					0.20	0.35	0.70	0.65	0.60	0.55
Plaster				112.16	0.01	0.01	0.01	0.02	0.02	0.03

Table 8.17d: Template – Auditorium E

8.6.5. Auditorium G

Compactness	C [m]	1.13
Total surface area	S [m²]	510.62
Total volume	V [m³]	575.77

Surface	Length	Width	Surface	Surface	Absorption coefficient					
	L [m]	W [m]	S_i [m²]	S_i [m²]	α_i [-]	α_i [-]	α_i [-]	α_i [-]	α_i [-]	α_i [-]
Surfacel x1	**10.00**	**5.59**	**55.90**		**125Hz**	**250Hz**	**500Hz**	**1,000Hz**	**2,000Hz**	**4,000Hz**
Window				15.12	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster				17.77	0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element				8.20	0.10	0.30	0.70	0.80	0.85	0.90
Carpet				14.81	0.01	0.02	0.06	0.15	0.25	0.45
Surface x2	**10.00**	**5.59**	**55.90**							
Window					0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster				17.19	0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood				4.10	0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element				9.92	0.10	0.30	0.70	0.80	0.85	0.90
Carpet				24.69	0.01	0.02	0.06	0.15	0.25	0.45
Surface y1	**10.30**	**5.59**	**57.58**							
Plaster				39.58	0.01	0.01	0.01	0.02	0.02	0.03
Chalkboard				6.00	0.15	0.15	0.11	0.03	0.05	0.03
White projection board				10.00	0.20	0.20	0.20	0.20	0.25	0.25
Door aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Door wood				2.00	0.14	0.10	0.08	0.08	0.08	0.08
Surface y2	**10.30**	**5.59**	**57.58**							
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
Wall acoustic					0.20	0.35	0.70	0.65	0.60	0.55
Plaster				17.90	0.01	0.01	0.01	0.02	0.02	0.03
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element				8.20	0.10	0.30	0.70	0.80	0.85	0.90
Carpet				16.36	0.01	0.02	0.06	0.15	0.25	0.45
Chalkboard					0.15	0.15	0.11	0.03	0.05	0.03
Window				15.12	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Surface z1	**10.00**	**10.30**	**180.67**							
Linoleum				103.00	0.02	0.03	0.03	0.03	0.03	0.02
Wood					0.02	0.03	0.04	0.05	0.05	0.06
Desk laminated wood				2.67	0.02	0.02	0.03	0.04	0.04	0.04
Seats and backs				75.00	0.02	0.02	0.03	0.04	0.04	0.04
Surface z2	**10.00**	**10.30**	**103.00**							
Acoustic ceiling					0.20	0.35	0.70	0.65	0.60	0.55
Plaster				103.00	0.01	0.01	0.01	0.02	0.02	0.03

Table 8.17e: Template – Auditorium G

8.6.6. Auditorium H

		Compactness	C [m]	0.95						
		Total surface area	S [m²]	299.40						
		Total volume	V [m³]	283.50						
Surface	**Length**	**Width**	**Surface**	**Surface**	**Absorption coefficient**					
	L [m]	**W [m]**	**S_i [m²]**	**S_i [m²]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**
Surfacel x1	**9.00**	**5.00**	**45.00**		**125Hz**	**250Hz**	**500Hz**	**1,000Hz**	**2,000Hz**	**4,000Hz**
Window					0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster				40.60	0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood				4.40	0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element					0.10	0.30	0.70	0.80	0.85	0.90
Carpet					0.01	0.02	0.06	0.15	0.25	0.45
Surface x2	**9.00**	**5.00**	**45.00**							
Window				11.50	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster				33.50	0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element					0.10	0.30	0.70	0.80	0.85	0.90
Carpet					0.01	0.02	0.06	0.15	0.25	0.45
Surface y1	**6.30**	**5.00**	**31.50**							
Plaster				23.46	0.01	0.01	0.01	0.02	0.02	0.03
Chalkboard				4.80	0.15	0.15	0.11	0.03	0.05	0.03
White projection board				3.24	0.20	0.20	0.20	0.20	0.25	0.25
Door aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Surface y2	**6.30**	**5.00**	**31.50**							
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
Wall acoustic					0.20	0.35	0.70	0.65	0.60	0.55
Plaster				25.94	0.01	0.01	0.01	0.02	0.02	0.03
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element					0.10	0.30	0.70	0.80	0.85	0.90
Carpet					0.01	0.02	0.06	0.15	0.25	0.45
Chalkboard				5.56	0.15	0.15	0.11	0.03	0.05	0.03
Window					0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Surface z1	**9.00**	**6.30**	**89.70**							
Linoleum					0.02	0.03	0.03	0.03	0.03	0.02
Wood				55.70	0.02	0.03	0.04	0.05	0.05	0.06
Desk laminated wood				1.00	0.02	0.02	0.03	0.04	0.04	0.04
Seats and backs				33.00	0.02	0.02	0.03	0.04	0.04	0.04
Surface z2	**9.00**	**6.30**	**56.70**							
Acoustic ceiling					0.20	0.35	0.70	0.65	0.60	0.55
Plaster				56.70	0.01	0.01	0.01	0.02	0.02	0.03

Table 8.17f: Template – Auditorium H

8.6.7. Auditorium I

Compactness	C [m]	0.83
Total surface area	S [m²]	376.57
Total volume	V [m³]	313.50

Surface	Length	Width	Surface	Surface	Absorption coefficient					
	L [m]	W [m]	S_i [m²]	S_i [m²]	α_i [-]	α_i [-]	α_i [-]	α_i [-]	α_i [-]	α_i [-]
Surfacel x1	**14.00**	**5.00**	**68.85**		**125Hz**	**250Hz**	**500Hz**	**1,000Hz**	**2,000Hz**	**4,000Hz**
Window					0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster				17.66	0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood				8.76	0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element				8.50	0.10	0.30	0.70	0.80	0.85	0.90
Carpet				33.93	0.01	0.02	0.06	0.15	0.25	0.45
Surface x2	**14.00**	**5.00**	**68.56**							
Window				17.88	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster				13.63	0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element				8.50	0.10	0.30	0.70	0.80	0.85	0.90
Carpet				28.55	0.01	0.02	0.06	0.15	0.25	0.45
Surface y1	**6.27**	**5.00**	**31.35**							
Plaster					0.01	0.01	0.01	0.02	0.02	0.03
Chalkboard				5.00	0.15	0.15	0.11	0.03	0.05	0.03
White projection board				8.74	0.20	0.20	0.20	0.20	0.25	0.25
Door aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Surface y2	**6.27**	**5.00**	**30.41**							
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
Wall acoustic					0.20	0.35	0.70	0.65	0.60	0.55
Plaster				5.28	0.01	0.01	0.01	0.02	0.02	0.03
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element				5.40	0.10	0.30	0.70	0.80	0.85	0.90
Carpet				19.73	0.01	0.02	0.06	0.15	0.25	0.45
Chalkboard					0.15	0.15	0.11	0.03	0.05	0.03
Window					0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Surface z1	**10.00**	**6.27**	**114.70**							
Linoleum				60.98	0.02	0.03	0.03	0.03	0.03	0.02
Wood					0.02	0.03	0.04	0.05	0.05	0.06
Desk laminated wood				1.72	0.02	0.02	0.03	0.04	0.04	0.04
Seats and backs				52.00	0.02	0.02	0.03	0.04	0.04	0.04
Surface z2	**10.00**	**6.27**	**62.70**							
Acoustic ceiling					0.20	0.35	0.70	0.65	0.60	0.55
Plaster				62.70	0.01	0.01	0.01	0.02	0.02	0.03

Table 8.17g: Template – Auditorium I

8.6.8. Auditorium J

		Compactness	C [m]	0.99						
		Total surface area	S [m²]	322.63						
		Total volume	V [m³]	318.50						
Surface	**Length**	**Width**	**Surface**	**Surface**	**Absorption coefficient**					
	L [m]	**W [m]**	**S_i [m²]**	**S_i [m²]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**
Surfacel x1	**10.00**	**4.90**	**48.32**		**125Hz**	**250Hz**	**500Hz**	**1,000Hz**	**2,000Hz**	**4,000Hz**
Window					0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster				6.61	0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood				8.70	0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element				8.20	0.10	0.30	0.70	0.80	0.85	0.90
Carpet				24.81	0.01	0.02	0.06	0.15	0.25	0.45
Surface x2	**10.00**	**4.90**	**48.32**							
Window				18.30	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster				9.02	0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element				8.20	0.10	0.30	0.70	0.80	0.85	0.90
Carpet				12.80	0.01	0.02	0.06	0.15	0.25	0.45
Surface y1	**6.50**	**4.90**	**29.64**							
Plaster				23.12	0.01	0.01	0.01	0.02	0.02	0.03
Chalkboard				6.52	0.15	0.15	0.11	0.03	0.05	0.03
White projection board					0.20	0.20	0.20	0.20	0.25	0.25
Door aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Surface y2	**6.50**	**4.90**	**31.85**							
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
Wall acoustic					0.20	0.35	0.70	0.65	0.60	0.55
Plaster				6.50	0.01	0.01	0.01	0.02	0.02	0.03
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element				4.10	0.10	0.30	0.70	0.80	0.85	0.90
Carpet				9.05	0.01	0.02	0.06	0.15	0.25	0.45
Chalkboard					0.15	0.15	0.11	0.03	0.05	0.03
Window				12.20	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Surface z1	**10.00**	**6.50**	**99.50**							
Linoleum				63.00	0.02	0.03	0.03	0.03	0.03	0.02
Wood					0.02	0.03	0.04	0.05	0.05	0.06
Desk laminated wood				2.00	0.02	0.02	0.03	0.04	0.04	0.04
Seats and backs				34.50	0.02	0.02	0.03	0.04	0.04	0.04
Surface z2	**10.00**	**6.50**	**65.00**							
Acoustic ceiling					0.20	0.35	0.70	0.65	0.60	0.55
Plaster				65.00	0.01	0.01	0.01	0.02	0.02	0.03

Table 8.17h: Template – Auditorium J

8.6.9. Auditorium K

Compactness	C [m]	1.11
Total surface area	S [m²]	441.38
Total volume	V [m³]	491.53

Surface	Length	Width	Surface	Surface	Absorption coefficient					
	L [m]	W [m]	S_i [m²]	S_i [m²]	α_i [-]	α_i [-]	α_i [-]	α_i [-]	α_i [-]	α_i [-]
Surfacel x1	**9.90**	**5.27**	**51.17**		**125Hz**	**250Hz**	**500Hz**	**1,000Hz**	**2,000Hz**	**4,000Hz**
Window				15.60	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster				35.57	0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element					0.10	0.30	0.70	0.80	0.85	0.90
Carpet					0.01	0.02	0.06	0.15	0.25	0.45
Surface x2	**9.90**	**5.27**	**49.08**							
Window				15.60	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster				33.48	0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element					0.10	0.30	0.70	0.80	0.85	0.90
Carpet					0.01	0.02	0.06	0.15	0.25	0.45
Surface y1	**9.95**	**5.27**	**51.03**							
Plaster				32.47	0.01	0.01	0.01	0.02	0.02	0.03
Chalkboard					0.15	0.15	0.11	0.03	0.05	0.03
White projection board				15.00	0.20	0.20	0.20	0.20	0.25	0.25
Door aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Door wood				3.56	0.14	0.10	0.08	0.08	0.08	0.08
Surface y2	**9.95**	**4.33**	**43.08**							
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
Wall acoustic					0.20	0.35	0.70	0.65	0.60	0.55
Plaster				37.32	0.01	0.01	0.01	0.02	0.02	0.03
Door wood				5.76	0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element					0.10	0.30	0.70	0.80	0.85	0.90
Carpet					0.01	0.02	0.06	0.15	0.25	0.45
Chalkboard					0.15	0.15	0.11	0.03	0.05	0.03
Window					0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Surface z1	**9.90**	**9.95**	**148.51**							
Linoleum				96.89	0.02	0.03	0.03	0.03	0.03	0.02
Wood					0.02	0.03	0.04	0.05	0.05	0.06
Desk laminated wood				1.62	0.02	0.02	0.03	0.04	0.04	0.04
Seats and backs				50.00	0.02	0.02	0.03	0.04	0.04	0.04
Surface z2	**9.90**	**9.95**	**98.51**							
Acoustic ceiling					0.20	0.35	0.70	0.65	0.60	0.55
Plaster				98.51	0.01	0.01	0.01	0.02	0.02	0.03

Table 8.17i: Template – Auditorium K

8.6.10. Auditorium N

Compactness	**C [m]**	**1.15**
Total surface area	**S [m²]**	**869.42**
Total volume	**V [m³]**	**995.71**

Surface	**Length**	**Width**	**Surface**	**Surface**	**Absorption coefficient**					
	L [m]	**W [m]**	**S_i [m²]**	**S_i [m²]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**
Surfacel x1	**22.00**	**6.92**	**105.24**		**125Hz**	**250Hz**	**500Hz**	**1,000Hz**	**2,000Hz**	**4,000Hz**
Window				20.00	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster					0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood				40.30	0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element					0.10	0.30	0.70	0.80	0.85	0.90
Carpet				44.94	0.01	0.02	0.06	0.15	0.25	0.45
Surface x2	**22.00**	**6.92**	**105.24**							
Window				20.00	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster					0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood				40.30	0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element					0.10	0.30	0.70	0.80	0.85	0.90
Carpet				44.94	0.01	0.02	0.06	0.15	0.25	0.45
Surface y1	**9.43**	**4.77**	**43.90**							
Plaster				9.49	0.01	0.01	0.01	0.02	0.02	0.03
Chalkboard				6.50	0.15	0.15	0.11	0.03	0.05	0.03
White projection board				23.50	0.20	0.20	0.20	0.20	0.25	0.25
Door aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Door wood				4.41	0.14	0.10	0.08	0.08	0.08	0.08
Surface y2	**9.43**	**2.60**	**24.52**							
Wall laminated wood				12.75	0.38	0.24	0.17	0.10	0.08	0.05
Wall acoustic				7.35	0.20	0.35	0.70	0.65	0.60	0.55
Plaster					0.01	0.01	0.01	0.02	0.02	0.03
Door wood				4.42	0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element					0.10	0.30	0.70	0.80	0.85	0.90
Carpet					0.01	0.02	0.06	0.15	0.25	0.45
Chalkboard					0.15	0.15	0.11	0.03	0.05	0.03
Window					0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Surface z1	**22.00**	**9.43**	**383.06**							
Linoleum				202.71	0.02	0.03	0.03	0.03	0.03	0.02
Wood					0.02	0.03	0.04	0.05	0.05	0.06
Desk laminated wood				4.75	0.02	0.02	0.03	0.04	0.04	0.04
Seats and backs				175.60	0.02	0.02	0.03	0.04	0.04	0.04
Surface z2	**22.00**	**9.43**	**207.46**							
Acoustic ceiling				207.46	0.20	0.35	0.70	0.65	0.60	0.55
Plaster					0.01	0.01	0.01	0.02	0.02	0.03

Table 8.17j: Template – Auditorium N

8.6.11. Extra: auditorium B

Compactness	**C [m]**	**1.10**
Total surface area	**S [m²]**	**416.25**
Total volume	**V [m³]**	**456.51**

Surface	**Length**	**Width**	**Surface**	**Surface**	**Absorption coefficient**					
	L [m]	**W [m]**	**S_i [m²]**	**S_i [m²]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**	**α_i [-]**
Surfacel x1	**9.80**	**5.70**	**55.86**		**125Hz**	**250Hz**	**500Hz**	**1,000Hz**	**2,000Hz**	**4,000Hz**
Window				14.40	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster				10.83	0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element				0.61	0.10	0.30	0.70	0.80	0.85	0.90
Carpet				30.03	0.01	0.02	0.06	0.15	0.25	0.45
Surface x2	**9.80**	**5.70**	**55.86**							
Window				14.40	0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Plaster				10.83	0.01	0.01	0.01	0.02	0.02	0.03
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
PUR					0.10	0.55	1.00	1.15	1.15	1.20
Window: aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Curtains					0.05	0.04	0.03	0.02	0.02	0.02
Door wood					0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element				0.61	0.10	0.30	0.70	0.80	0.85	0.90
Carpet				30.03	0.01	0.02	0.06	0.15	0.25	0.45
Surface y1	**8.20**	**5.70**	**44.40**							
Plaster				30.45	0.01	0.01	0.01	0.02	0.02	0.03
Chalkboard				4.15	0.15	0.15	0.11	0.03	0.05	0.03
White projection board				8.00	0.20	0.20	0.20	0.20	0.25	0.25
Door aluminium					0.01	0.02	0.03	0.03	0.04	0.04
Door wood				1.80	0.14	0.10	0.08	0.08	0.08	0.08
Surface y2	**8.20**	**5.70**	**46.74**							
Wall laminated wood					0.38	0.24	0.17	0.10	0.08	0.05
Wall acoustic					0.20	0.35	0.70	0.65	0.60	0.55
Plaster				6.57	0.01	0.01	0.01	0.02	0.02	0.03
Door wood				4.35	0.14	0.10	0.08	0.08	0.08	0.08
Acoustic element				5.28	0.10	0.30	0.70	0.80	0.85	0.90
Carpet				30.54	0.01	0.02	0.06	0.15	0.25	0.45
Chalkboard					0.15	0.15	0.11	0.03	0.05	0.03
Window					0.14	0.12	0.12	0.12	0.14	0.14
Covered window (sunblocking)					0.05	0.04	0.03	0.02	0.02	0.02
Surface z1	**9.80**	**8.20**	**133.03**							
Linoleum				78.44	0.02	0.03	0.03	0.03	0.03	0.02
Wood					0.02	0.03	0.04	0.05	0.05	0.06
Desk laminated wood				1.92	0.02	0.02	0.03	0.04	0.04	0.04
Seats and backs				52.67	0.02	0.02	0.03	0.04	0.04	0.04
Surface z2	**9.80**	**8.20**	**80.36**							
Acoustic ceiling					0.20	0.35	0.70	0.65	0.60	0.55
Plaster				80.36	0.01	0.01	0.01	0.02	0.02	0.03

Table 8.17k: Template – Auditorium B

8.7. Product data

MACKIE. SRM450v2 PRECISION ACTIVE LOUDSPEAKER

SRM450v2

The Mackie SRM450v2 is a full-range, portable, powered loudspeaker system providing high-output, ultra-wide dispersion and low-distortion performance in a compact, lightweight design. Two Fast Recovery™ amplifiers independently power a 12-inch lightweight woofer and a precision titanium compression driver. Mackie's sophisticated Active electronics provide phase correction, crossover, time correction, equalization and protection circuitry.

A heat-treated titanium compression driver with multi-cell aperture directs pristine highs through an exponential high-frequency waveguide, allowing for ultra-wide dispersion. This allows the SRM450v2 to deliver clear, smooth sound to audience members up to 45° off axis.

The 12-inch lightweight woofer provides a greater magnetic field with far less material, making the woofer extremely lightweight without sacrificing performance. The 3-inch voice coil allows the driver to run cooler, delivering consistent performance even after long hours of use.

Mackie-designed Active electronics provide equalization, crossover, time alignment, and phase correction to enhance sonic performance. Protective circuitry includes over-excursion protection, low-line voltage shut-down, thermal protection, level dependent low-frequency roll-off and independent LF and HF limiters.

The SRM450v2 features a number of dedicated controls including a mic/line switch, a single microphone and line input level control, and a contour switch for low-level sound reinforcement applications. There is also a timed turnoff feature that turns off the amplifiers if the signal drops below –45 dBu for three minutes.

The center of gravity, handle locations, handle design, position of fly-points and ease of use have been ergonomically designed. There is also an integrated pole mount cup and a weather-resistant steel grille. The asymmetrical trapezoidal cabinet has been designed to provide an ideal floor monitoring position.

The cabinet is constructed of high-pressure injected polypropylene. The enclosure features ample amounts of reinforcement ribbing and structural strengthening resulting in a strong, super-rigid design providing ideal acoustical characteristics.

APPLICATIONS

Small to mid-size club/band PA systems, houses of worship, DJs, vocal/band monitor wedges, gymnasiums, banquet halls, conference rooms and many, many more.

FEATURES:

- 2-way bi-amplified, optimized powered loudspeaker system
- 300W RMS Class-D, Fast Recovery™ LF amp / 100W RMS HF amp
- 12" lightweight long-throw low-frequency transducer with 3" voice coil and servo feedback control
- High-output precision titanium compression driver
- Ultra-wide, smooth dispersion via multi-cell horn aperture and HF waveguide
- Mackie Active electronic time alignment, phase correction and EQ for studio quality sound
- Built-in phase-accurate 24 dB Linkwitz-Riley electronic crossover
- Mic/line input and pass-thru connector
- Lightweight for ultimate portability (40 lb / 18.1 kg)
- Asymmetrical trapezoidal cabinet for floor monitor positioning
- Stand / Pole-mountable
- Flyable via ten M10 rigging points using the optional eyebolt kit

I/O PAGES

MACKIE. **SRM450v2** PRECISION ACTIVE LOUDSPEAKER

SRM450v2 SPECIFICATIONS

Acoustic Performance

Frequency Response (–3 dB)	55 Hz - 18 kHz
Frequency Range (–10 dB)	45 Hz - 20 kHz
Directivity Factor; Q (DI)	9.95 (9.98), averaged 2 kHz to 10 kHz
Max SPL long-term	124 dB @ 1 m
Max SPL peak	127 dB @ 1 m
Crossover Point	Linkwitz-Riley, 24 dB/octave @ 1600 Hz

Input / Output

Input / Thru Type	Balanced Differential
Input Impedance	20 kΩ
Input Protection	RFI and level protected

Sensitivity

Line	+4 dBu (center detent)
Mic	–36 dBu
Maximum Input Level	+22 dBu
Low-Cut Frequency	75 Hz, Second-order filter
Acoustic Contour Equalization (Peaking)	+3 dB @ 100 Hz, +3 dB @ 12 kHz

Low-Frequency Power Amplifier

Rated Power	300 watts rms*
Rated THD	< 0.1%
Cooling	Convection Extrusion
Design	Class D, Parametric Servo Feedback

High-Frequency Power Amplifier

Rated Power	100 watts rms*
Rated THD	< 0.1%
Cooling	Convection Extrusion
Design	Conventional Class AB

*Rated power is continuous rms wattage into transducer's rated impedance @ 5kHz for the HF amplifier and @ 500Hz for the LF amplifier.

Low-Frequency Transducer

Diameter	12 in / 305 mm
Voice Coil Diameter	3 in / 76 mm

High-Frequency Transducer

Diaphragm Diameter	1.75 in / 44 mm
Diaphragm Material	Heat treated titanium

Horn Design

Type	Conical and Exponential
Mouth Size	12 in / 305 mm (W) x 7 in / 178 mm (H)
Throat Diameter	1 in / 25 mm
Horizontal Coverage	90° (1 kHz - 20 kHz)
Vertical Coverage	45° (2.8 kHz - 20 kHz)

Line Input Power

US, JP	100 - 120 VAC, 50 - 60 Hz
EU, UK, AU	200 - 240 VAC, 50 - 60 Hz
AC Connector	3-pin IEC 250 VAC
Power Consumption	300 watts

Control System Function

Electronic Crossover, Phase Alignment, Equalization, Parametric EQ

Safety Features

Over-Excursion Protection	Second-Order High-Pass Filter
Thermal Protection	Amplifier shutdown, auto-reset
Low-Line Voltage Shut Down	60% Nominal line
Driver Protection	Independent LF and HF compressors
Low-Freq Roll-Off	Dynamic, signal-level dependent

Construction Features

Basic Design	Asymmetrical Trapezoidal
Enclosure Alignment	Sixth-Order
Material	Polypropylene
Finish	Black, textured finish
Handles	One on each side, one on top
Grille	Perforated metal with weather-resistant coating
Display LEDs	Signal Present, Peak, Power ON, and Thermal
Operating Temperature	–10°C - 45°C 14°F - 113°F

Physical Properties (packaged product)

Height	26.5 in / 673 mm
Width	16.8 in / 427 mm
Depth	15.5 in / 394 mm
Shipping Weight	46.0 lb / 20.9 kg

Physical Properties (product)

Height	26.1 in / 663 mm
Width	16.0 in / 406 mm
Depth	14.8 in / 376 mm
Net Weight	40.0 lb / 18.1 kg

Mounting Methods

Floor mount, pole mount, or fly via 10 integrated M10 threaded inserts (two each located on each side, top, bottom and rear of enclosure)

Options

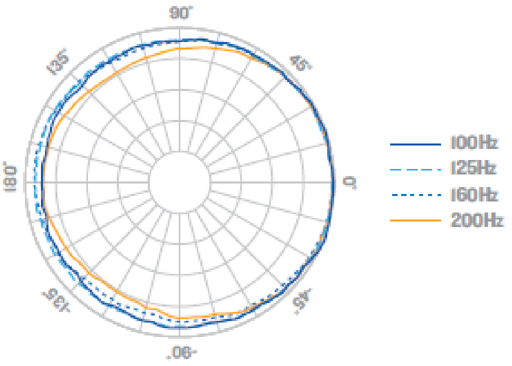
PA-A1 Forged Shoulder Eyebolt Kit	P/N 0031943
SPM200 Loudspeaker Pole Mount	P/N 2035170-01
SRM450v2 Speaker Bag	P/N 0002843

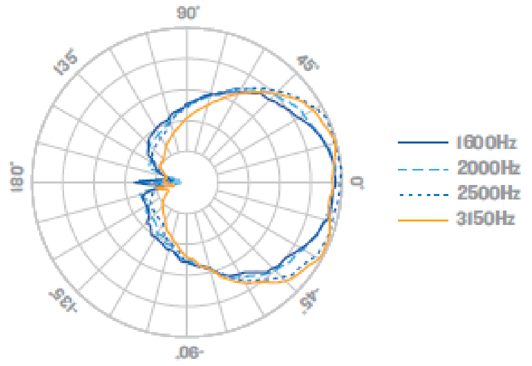
Ordering Information

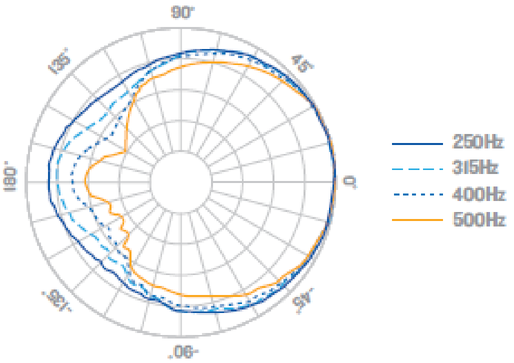
SRM450v2 12" 2-way Compact SR Loudspeaker, US	P/N 2033799-00
SRM450v2 12" 2-way Compact SR Loudspeaker, EU	P/N 2033799-01
SRM450v2 12" 2-way Compact SR Loudspeaker, JP	P/N 2033799-02
SRM450v2 12" 2-way Compact SR Loudspeaker, UK	P/N 2033799-03
SRM450v2 12" 2-way Compact SR Loudspeaker, AU	P/N 2033799-04

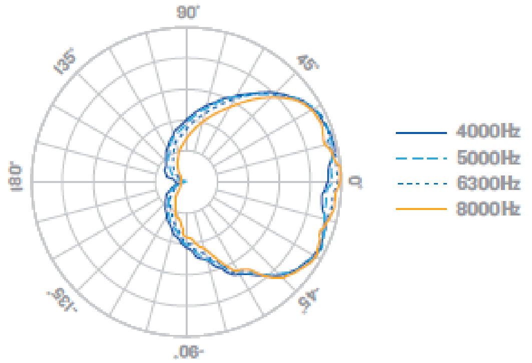
SRM450v2 HORIZONTAL POLARS

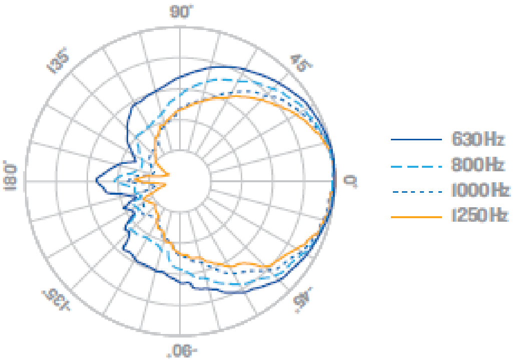
Gridlines: 6 dB axial / 15 degrees radial

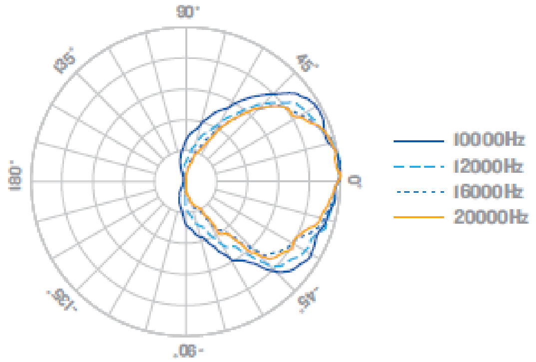






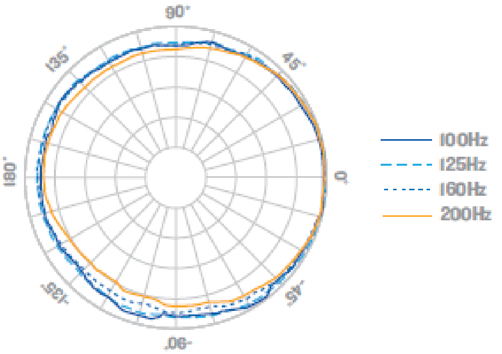


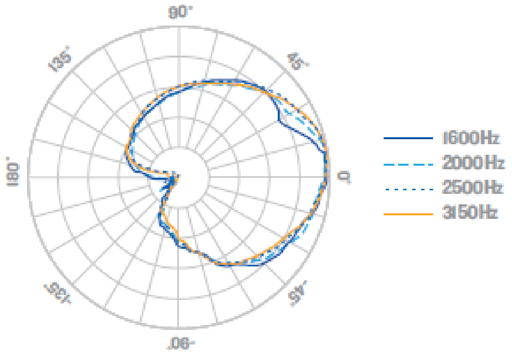


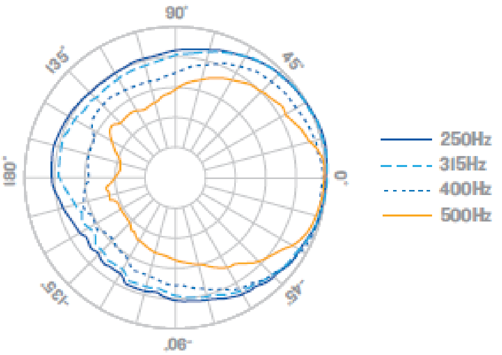


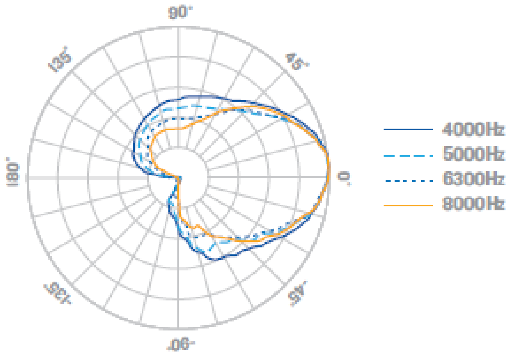
SRM450v2 VERTICAL POLARS

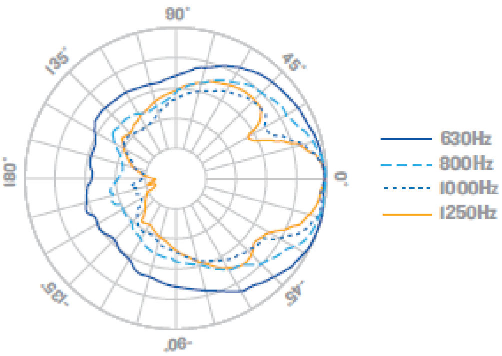
Gridlines: 6 dB axial / 15 degrees radial

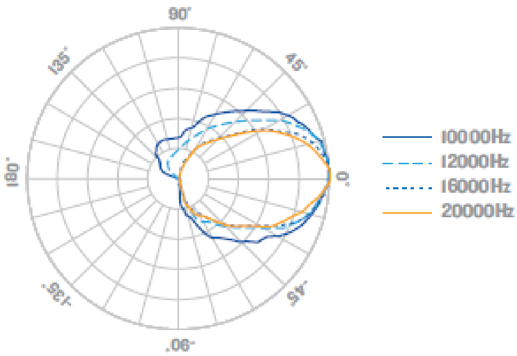












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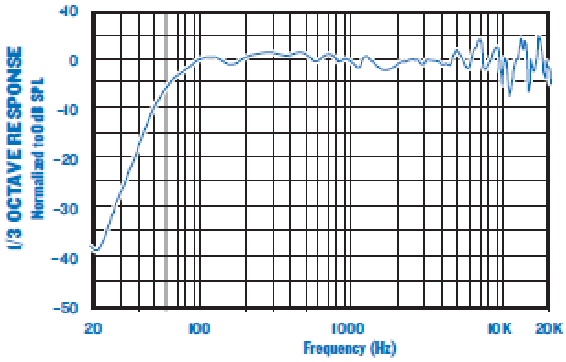
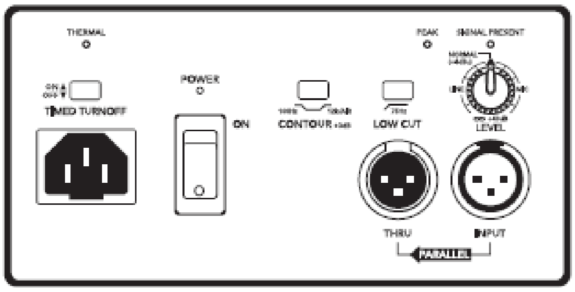
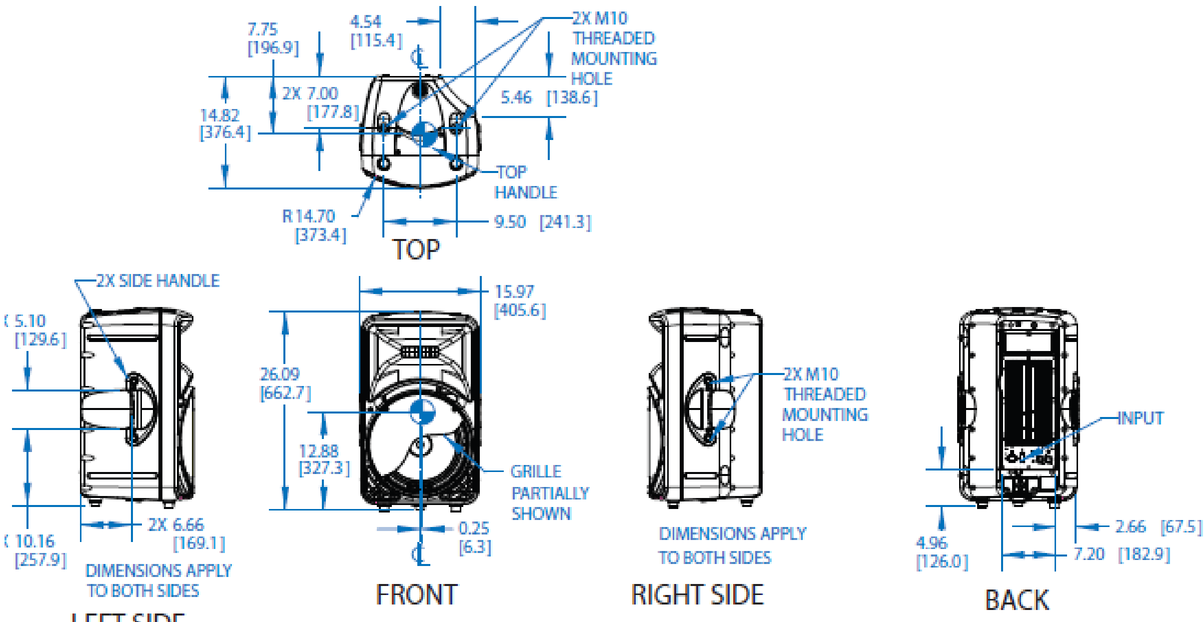
SRM450v2 FREQUENCY RESPONSE

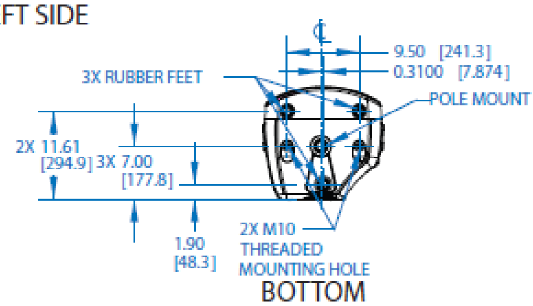


SRM450v2 INPUT PANEL



SRM450v2 DIMENSIONS



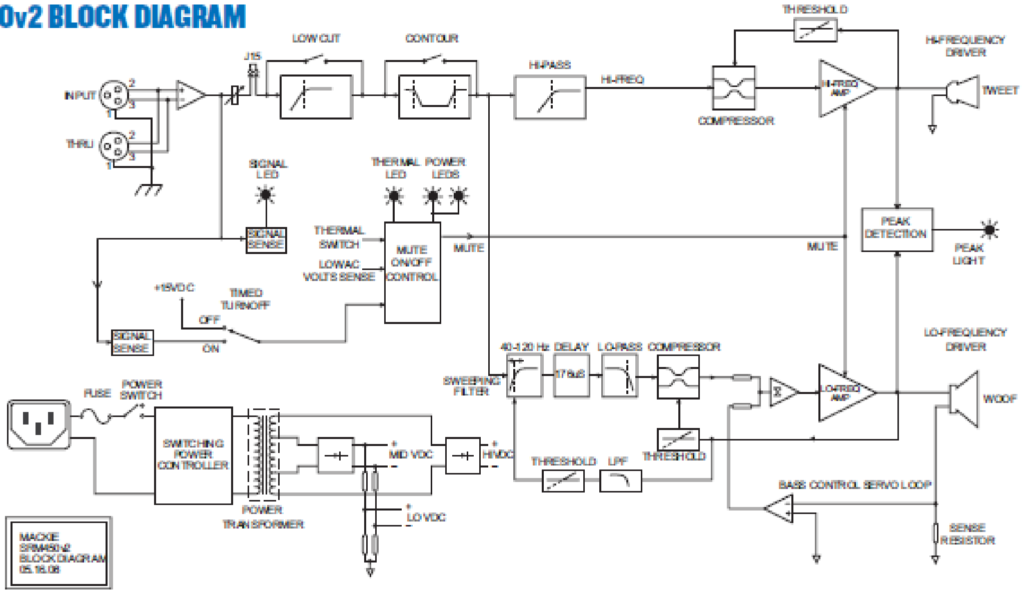


NOTES:
1. SYMBOL ◐ INDICATES CENTER OF BALANCE.
2. WEIGHT APPROX. 40.0 lb [18.1 kg].
3. SHIPPING WEIGHT APPROX. 46.0 lb [20.9 kg].

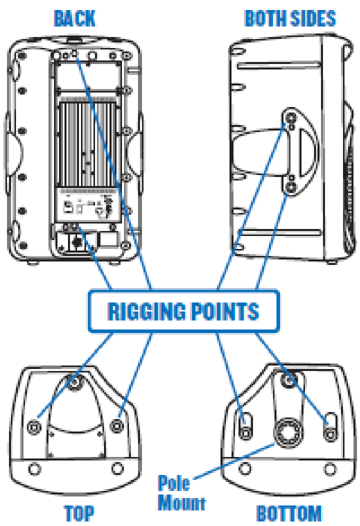
UNLESS OTHERWISE SPECIFIED: ALL DIMENSIONS ARE IN INCHES, DUAL [MM] DIMENSIONS FOR REF ONLY
TOLERANCES
LINEAR ± 0.13 in./ ± 3.3mm; ANGLES ± 1°
(X.XX) = REF DIMS
NO TOLERANCE IMPLIED
TSC=THEORETICAL SHARP CORNER
DIMENSIONS ACROSS CENTERLINES TO BE SYMMETRICAL

SRM450v2 PRECISION ACTIVE LOUDSPEAKER

SRM450v2 BLOCK DIAGRAM



SRM450v2 FLY POINTS



MACKIE.
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Part No. SW0841 Rev. B 08/11

Electronic files for this product are available at:
www.mackie.com

Specification Sheet	SRM450v2_SS.PDF
Owner's Manual	SRM450v2_OM.PDF

PRODUCT DATA

Hand-held Analyzer Types 2250 and 2270

with Sound Level Meter Software BZ-7222, Frequency Analysis Software BZ-7223, Logging Software BZ-7224, Enhanced Logging Software BZ-7225, Signal Recording Option BZ-7226 and Tone Assessment Option BZ-7231

Type 2250 and Type 2270 are the innovative, 4th generation hand-held analyzers from Brüel & Kjær. The analyzers' easy, safe and clever design philosophy is based on extensive research. Type 2250 has been awarded several prizes for its combination of excellent ergonomics and attractive design.

Both analyzers can host a number of applications, including frequency analysis, logging (profiling) and signal recording, but in addition, Type 2270 adds dual-channel capabilities such as sound intensity/sound power measurements and dual-channel building acoustics applications. Applications are available separately at any time – or you can order a fully pre-configured instrument from the factory.

The combination of application modules and innovative hardware makes these instruments into dedicated solutions for performing high-precision measurement tasks in environmental, occupational and industrial application areas. As a result, Brüel & Kjær delivers the functionality you need now, plus the capability to add more functionality later – this is a very secure investment.

Uses and Features

Uses

- Environmental noise assessment
- Occupational noise evaluation
- Reverberation Time measurements*
- Selection of hearing protection
- Noise reduction
- Product quality control
- Class 1 sound measurements to the latest international standards
- Real-time analysis of sound in 1/1- and 1/3-octave bands
- Tone assessment using 1/3-octave methods
- Loudness and noise rating measurements
- Analysis of time histories for broadband parameters and spectra (Logging)
- Documentation of measurements using text, voice and metadata annotations
- Documentation of measurements through recording of measured signals
- Logging up to 10 broadband parameters and 3 spectral parameters

* For more information, please refer to the relevant product data sheet.

Features

- Dual-channel measurement capability†
- Large, high-resolution, touch-sensitive color screen
- Data storage on high-capacity plug-in memory cards
- Communication via USB, LAN, or GPRS/3G modems
- Dynamic range in excess of 120 dB
- 3 Hz – 20 kHz broadband linear frequency range
- 24- or 16-bit recording during all or parts of a measurement (optional)
- Personalized measurement, display and job setup
- Integral digital camera for documentation and reference†
- "Smiley" quality indicators with hints and warnings
- Timers for automatic start of measurement
- PC software included for archiving, previewing and exporting data; software maintenance and remote online display
- Automatic detection of and correction for windscreen
- GPS coordinates stored with measurement data
- Simultaneous measurement of acoustic and weather parameter data
- Robust and environmentally protected (IP44)

† Type 2270 only.

Brüel & Kjær

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Graphical templates

A critical review on the use of existing formulae for the calculation of the Reverberation Time in auditoria

Lottie Braems, Hannah De Kerpel

Supervisor: Prof. dr. ir. Marcelo Blasco

Master's dissertation submitted in order to obtain the academic degree of
Master of Science in de ingenieurswetenschappen: architectuur

Department of Architecture and Urban Planning
Chairman: Prof. dr. Pieter Uyttenhove
Faculty of Engineering and Architecture
Academic year 2013-2014

UNIVERSITEIT
GENT

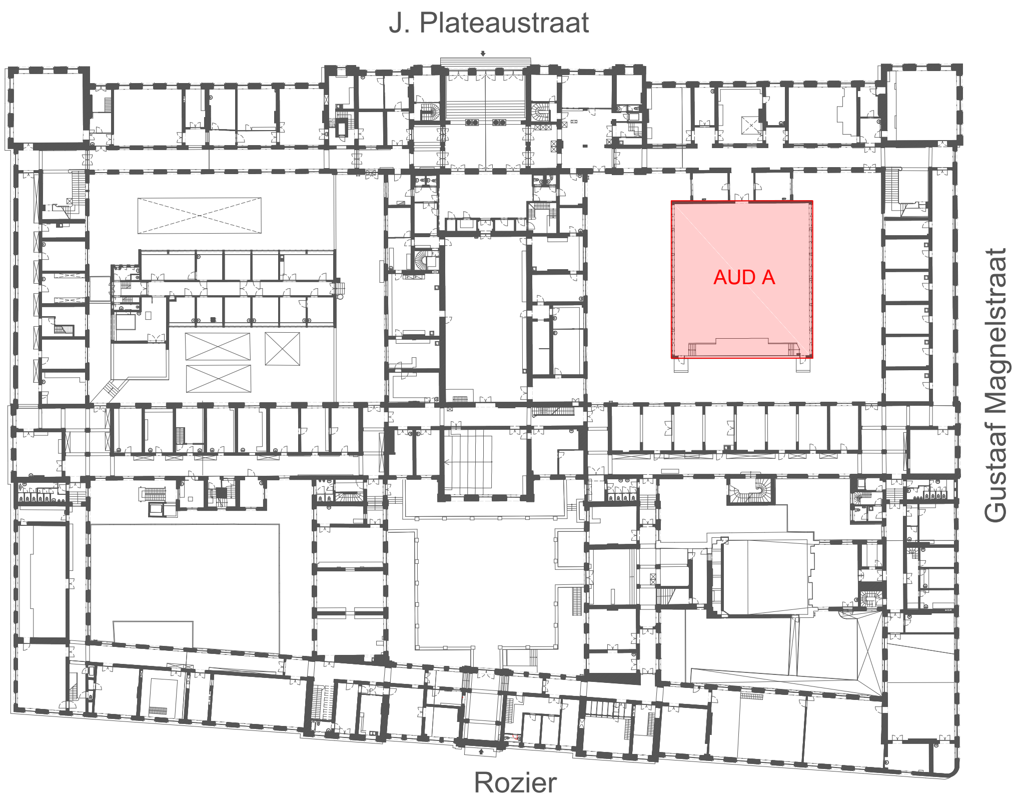
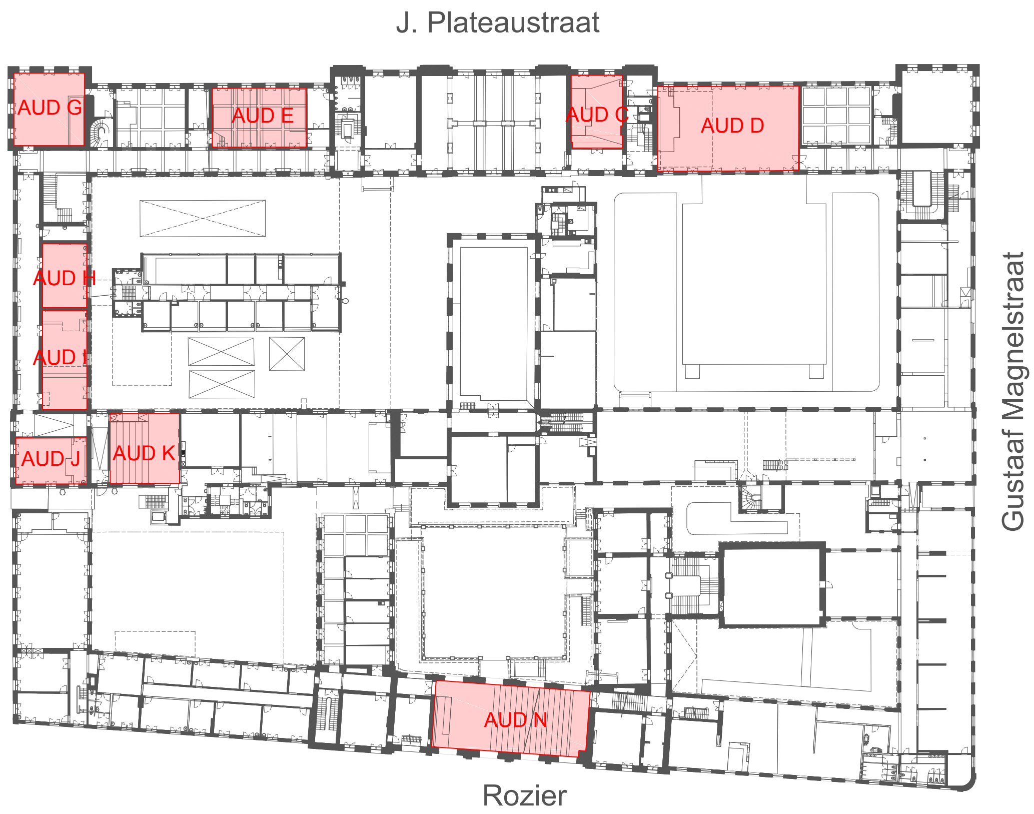
General information

General Information

Measurements			
Measuring method	Interrupted noise method	Decay curve	RT_{30}
Degree of precision	Engineering method	Equipment	Loudspeaker and amplifier: Mackie SRM 450 v2 Sonometer: Bruel & Kjaer, hand-held Analyzer Type 2250
Sound signal	White noise	Number of persons present	2

Location of the auditoria	
Location	Jozef-Plateaustraat 22, Ghent- Engineering Sciences
Auditoria	A , C, D, E, G, H, I, J, K, N

Plan

Ground floor	First floor
	

Measurements

Auditorium A - Measurements

Jozef-Plateaustraat 22, ground floor, Ghent 09/11/2013

General information

L-W-H [m]	19.62- 12.12- 4.80	Compactness [m]	1.37
Volume [m³]	2,117.50	Capacity	456 persons - 4.64 m³/person
Total surface area [m²]	1,254.41	H20 [%] / T [°C]	50-70 % / 20 °C

Surfaces

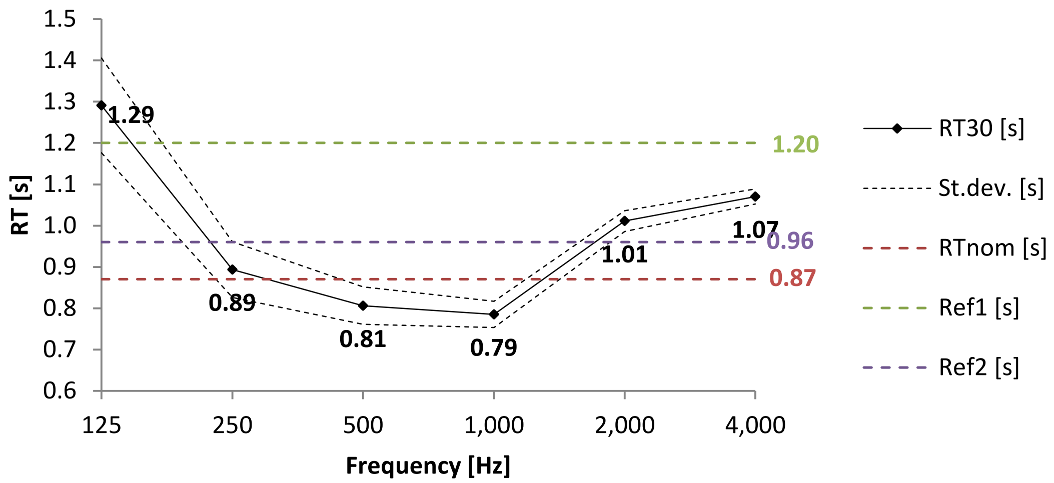
Index	Material	Surface area [m²]
1	Window	130.16
2	Plaster	68.10
3	Carpet	-
4	Wood	4.00
5	Metal	37.36
6	Chalkboard	9.00
7	Acoustic wall/element	65.32
8	Acoustic ceiling	423.50
9	Linoleum	418.51
10	PUR foam	55.88

Reverberation time

f [Hz]	RT [s]
125	1.29
250	0.89
500	0.81
1,000	0.79
2,000	1.01
4,000	1.07

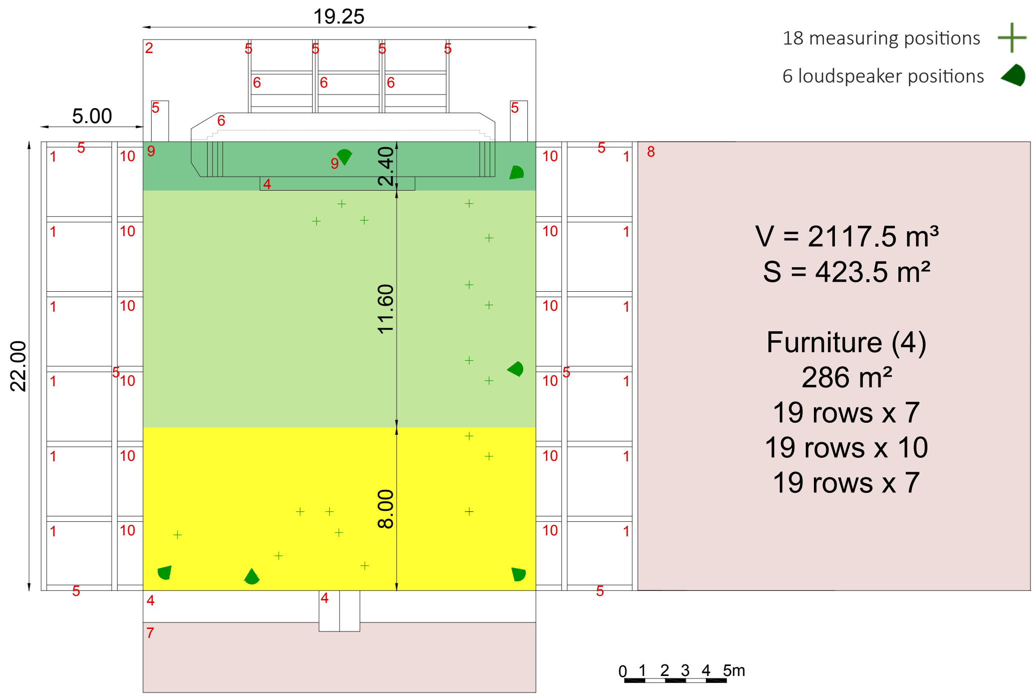
Quality	SN [dB]	C_{50} [dB]	STI
Zone 1 = Excellent	19.48	12.54	0.93
Zone 2 = Good	2.41	2.37	0.63
Zone 3 = Fair	-5.12	1.21	0.59

Graph

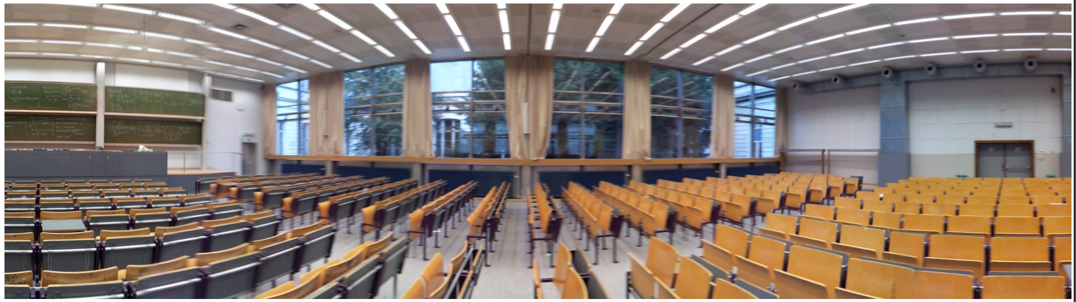


St.dev. = standard deviation Ref1 = Normal comfort (NBN S 01-400-2) Ref2 = Increased comfort (NBN S 01-400-2)

Plan



Photos



Auditorium C - Measurements

Jozef-Plateaustraat 22, first floor, Ghent 09/11/2013

General information

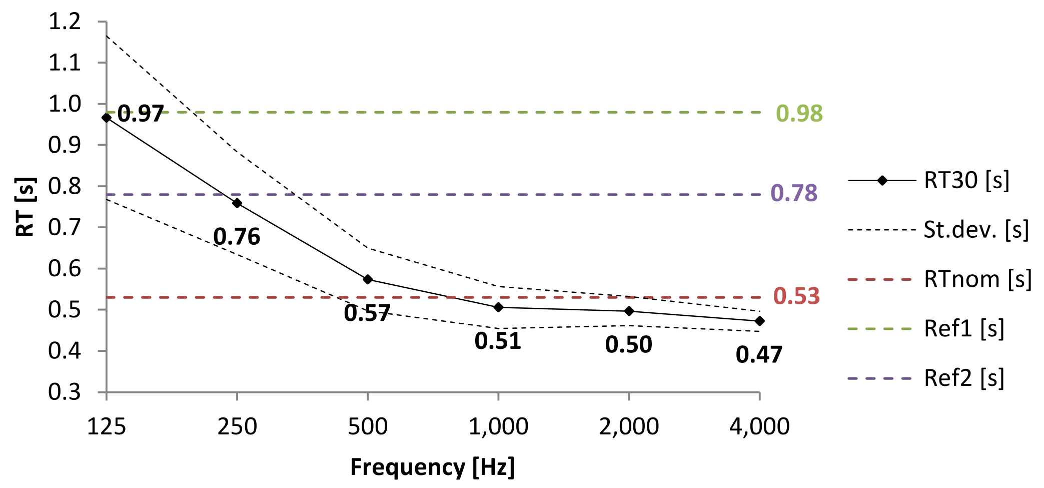
L-W-H [m]	10.35- 7.72 - 3.41	Compactness [m]	1.50
Volume [m³]	505.53	Capacity	60 persons- 8.43 m³/person
Total surface area [m²]	296.50	H20 [%] / T [°C]	50-70 % / 20 °C

Surfaces / Reverberation time

Index	Material	Surface area [m²]	f [Hz]	RT [s]
1	Window	9.24	125	0.97
2	Plaster	68.64	250	0.76
3	Carpet	33.72	500	0.57
4	Wood	46.10	1,000	0.51
5	Metal	-	2,000	0.50
6	Chalkboard	6.00	4,000	0.47

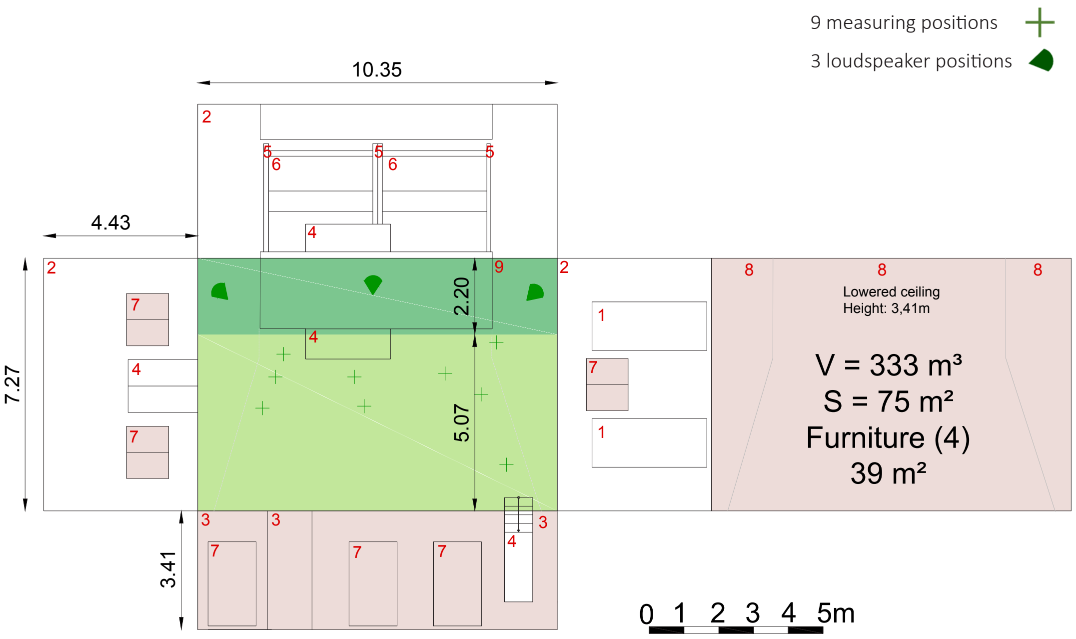
Index	Material	Surface area [m²]	Quality	SN [dB]	C_{50} [dB]	STI
7	Acoustic wall/element	15.42				
8	Acoustic ceiling	75.24	Zone 1 = Excellent	13.44	10.92	0.88
9	Linoleum	73.12	Zone 2 = Good	-2.23	4.86	0.70
10	PUR foam	-	-	-	-	-

Graph



St.dev. = standard deviation Ref1 = Normal comfort (NBN S 01-400-2) Ref2 = Increased comfort (NBN S 01-400-2)

Plan



Photos

Auditorium D - Measurements

Jozef-Plateaustraat 22, first floor, Ghent 09/11/2013

General information

L-W-H [m]	19.62- 12.12- 4.80	Compactness [m]	1.37
Volume [m³]	1,141.41	Capacity	263 persons - 4.34 m³/person
Total surface area [m²]	778.29	H20 [%] / T [°C]	50-70 % / 20 °C

Surfaces

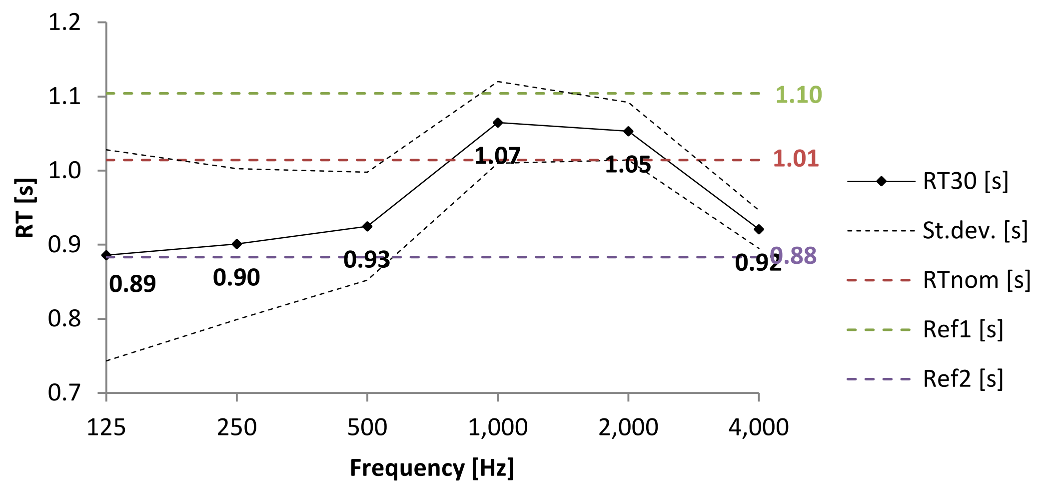
Index	Material	Surface area [m²]
1	Window	130.16
2	Plaster	68.10
3	Carpet	-
4	Wood	4.00
5	Metal	37.36
6	Chalkboard	9.00
7	Acoustic wall/element	65.32
8	Acoustic ceiling	423.50
9	Linoleum	418.51
10	PUR foam	55.88

Reverberation time

f [Hz]	RT [s]
125	0.89
250	0.90
500	0.93
1,000	1.07
2,000	1.05
4,000	0.92

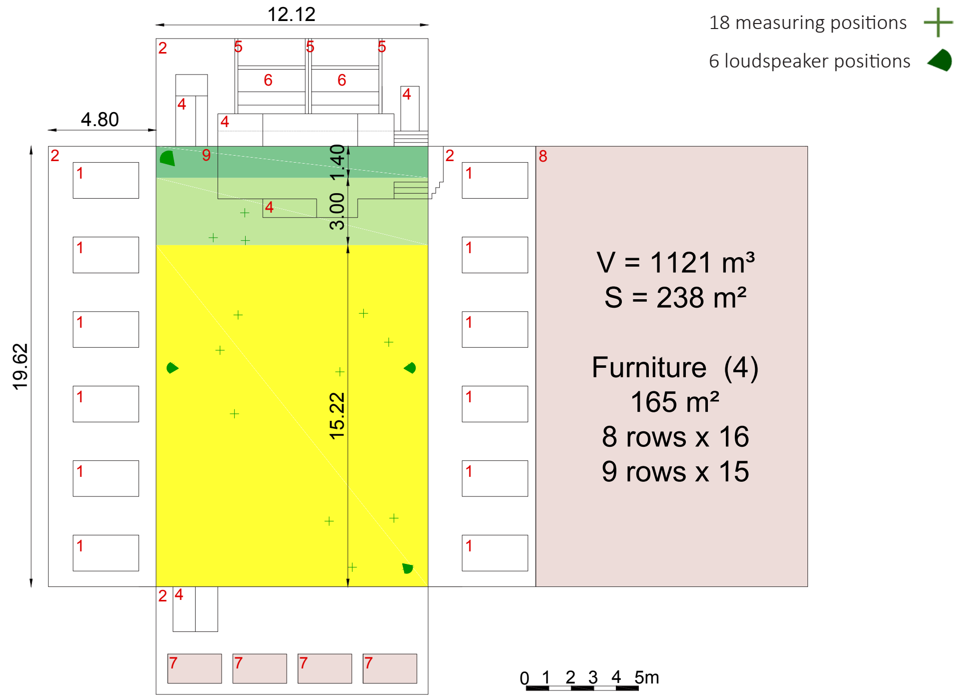
Quality	SN [dB]	C_{50} [dB]	STI
Zone 1 = Excellent	20.90	12.36	0.93
Zone 2 = Good	8.35	2.98	0.64
Zone 3 = Fair	-3.60	0.31	0.56

Graph



St.dev. = standard deviation Ref1 = Normal comfort (NBN S 01-400-2) Ref2 = Increased comfort (NBN S 01-400-2)

Plan



Photos

Auditorium E - Measurements

Jozef-Plateaustraat 22, first floor, Ghent 09/11/2013

General information

L-W-H [m]	13.40 - 8.37 - 4.83	Compactness [m]	0.96
Volume [m³]	514.77	Capacity	104 persons - 4.99 m³/person
Total surface area [m²]	423.61	H20 [%] / T [°C]	50-70 % / 20 °C

Surfaces

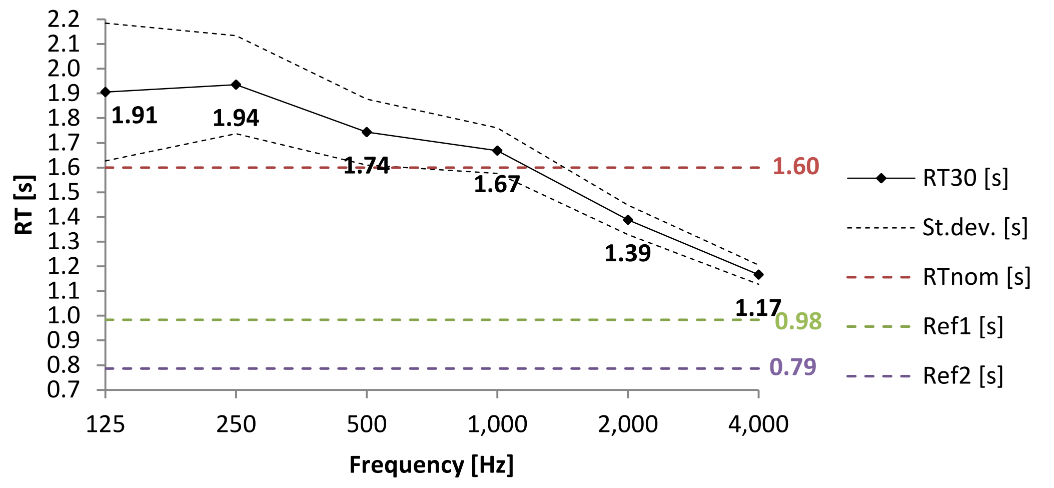
Index	Material	Surface area [m²]
1	Window	41.44
2	Plaster	48.12
3	Carpet	89.93
4	Wood	121.96
5	Metal	-
6	Chalkboard	5.00
7	Acoustic wall/element	-
8	Acoustic ceiling	-
9	Linoleum	109.46
10	PUR foam	-

Reverberation time

f [Hz]	RT [s]
125	1.91
250	1.94
500	1.74
1,000	1.67
2,000	1.39
4,000	1.17

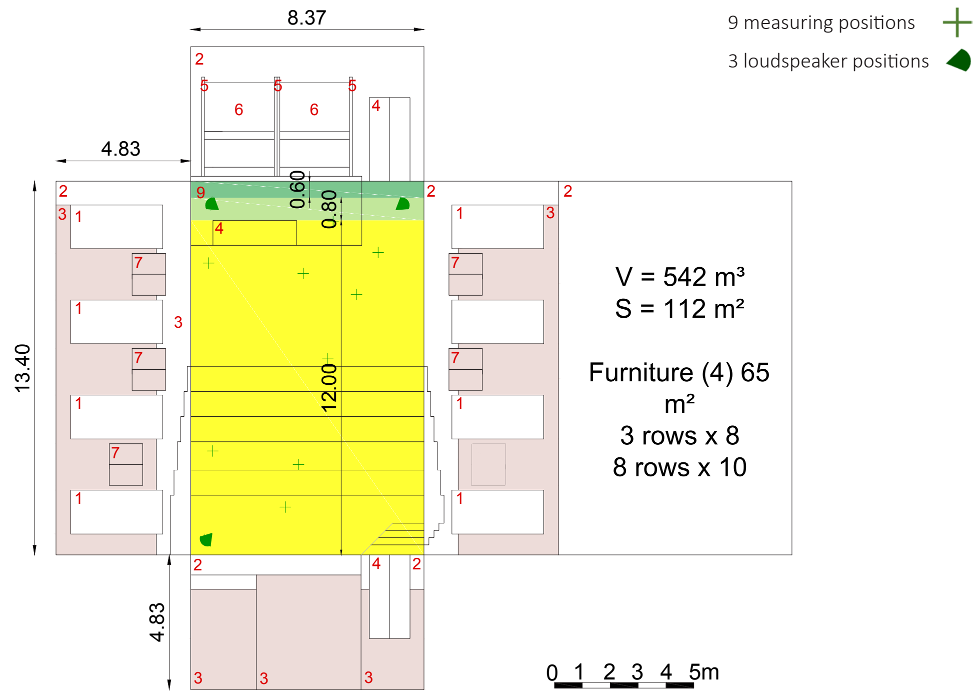
Quality	SN [dB]	C_{50} [dB]	STI
Zone 1 = Excellent	23.34	10.15	0.86
Zone 2 = Good	14.67	2.74	0.64
Zone 3 = Fair	-1.58	-2.18	0.49

Graph



St.dev. = standard deviation Ref1 = Normal comfort (NBN S 01-400-2) Ref2 = Increased comfort (NBN S 01-400-2)

Plan



Photos

AUDITORIUM G - MEASUREMENTS

JOZEF-PLATEAUSTRAAT 22, FIRST FLOOR, GHENT 09/11/2013

GENERAL INFORMATION

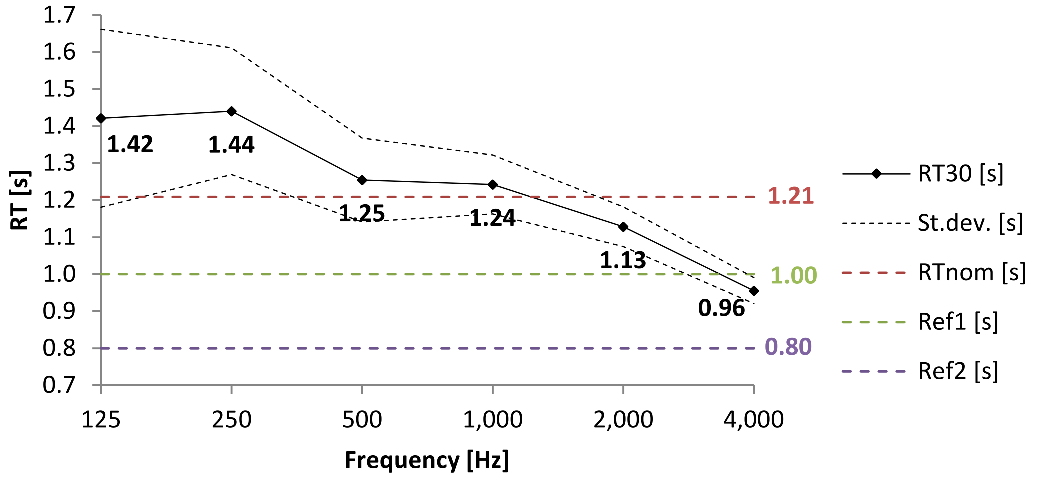
L-W-H [m]	10.30 - 10.00- 5.59	Compactness [m]	1.13
Volume [m³]	575.77	Capacity	119 persons - 4.84 m³/person
Total surface area [m²]	432.95	H20 [%] / T [°C]	50-70 % / 20 °C

SURFACES / REVERBERATION TIME

Index	Material	Surface area [m²]	f [Hz]	RT [s]
1	Window	30.24	125	1.42
2	Plaster	92.43	250	1.44
3	Carpet	55.86	500	1.25
4	Wood	83.77	1,000	1.24
5	Metal	-	2,000	1.13
6	Chalkboard	6.00	4,000	0.96
7	Acoustic wall/element	26.32		
8	Acoustic ceiling	-		
9	Linoleum	103.00		
10	PUR foam	-		

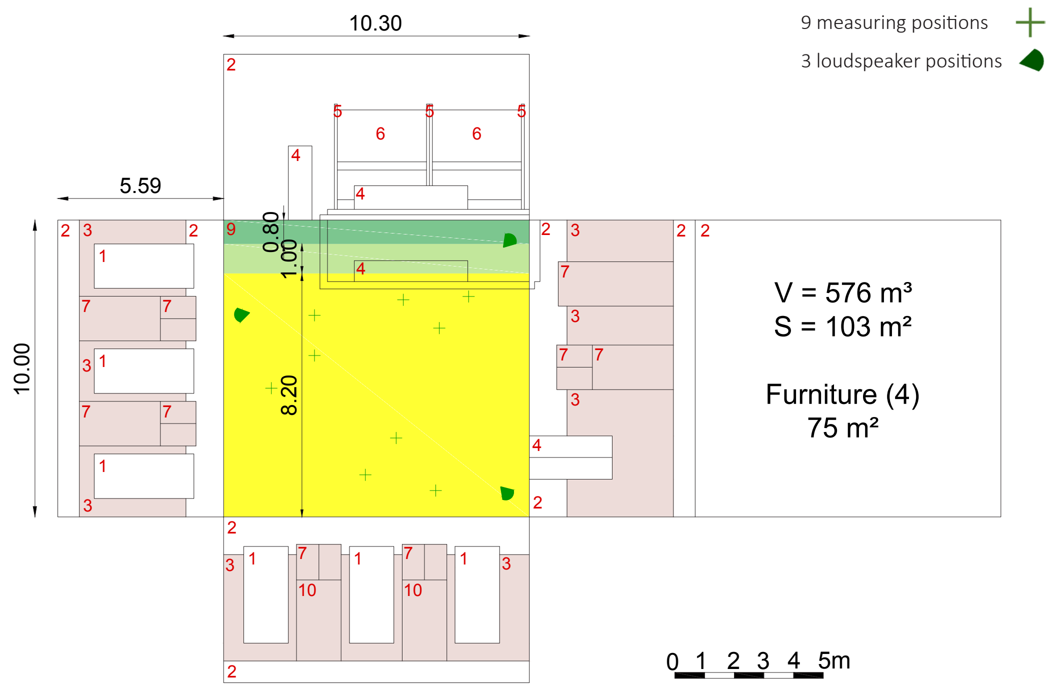
QUALITY	SN [dB]	C_{50} [dB]	STI
Zone 1 = Excellent	21.50	9.40	0.84
Zone 2 = Good	12.28	2.34	0.63
Zone 3 = Fair	-0.33	-0.69	0.53

GRAPH



St.dev. = standard deviation Ref1 = Normal comfort (NBN S 01-400-2) Ref2 = Increased comfort (NBN S 01-400-2)

PLAN



PHOTOS

Auditorium H - Measurements

Jozef-Plateaustraat 22, first floor, Ghent 09/11/2013

General information

L-W-H [m]	9.00 - 6.30 - 5.00	Compactness [m]	0.95
Volume [m³]	283.50	Capacity	52 persons - 5.45 m³/person
Total surface area [m²]	265.40	H20 [%] / T [°C]	50-70 % / 20 °C

Surfaces

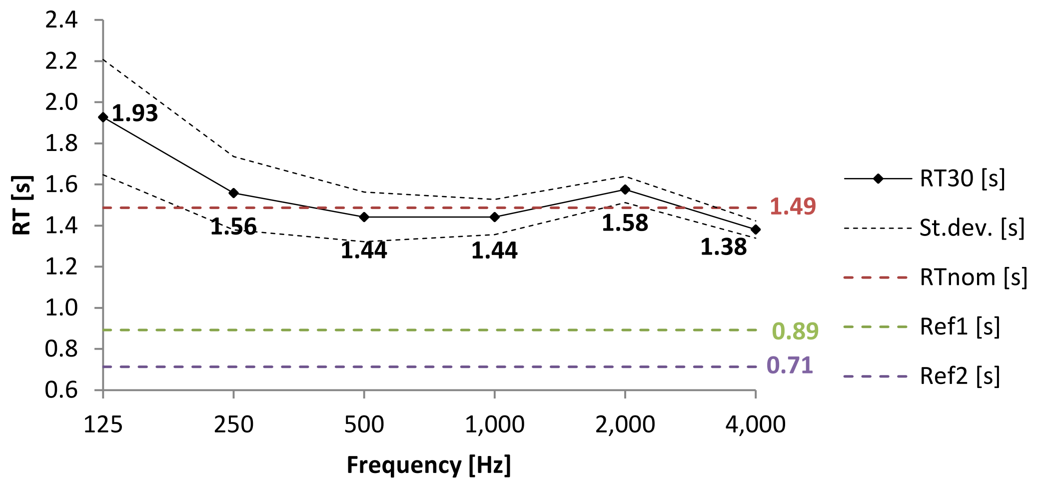
Index	Material	Surface area [m²]
1	Window	11.50
2	Plaster	123.50
3	Carpet	-
4	Wood	94.10
5	Metal	-
6	Chalkboard	10.36
7	Acoustic wall/element	-
8	Acoustic ceiling	-
9	Linoleum	-
10	PUR foam	-

Reverberation time

f [Hz]	RT [s]
125	1.93
250	1.56
500	1.44
1,000	1.44
2,000	1.58
4,000	1.38

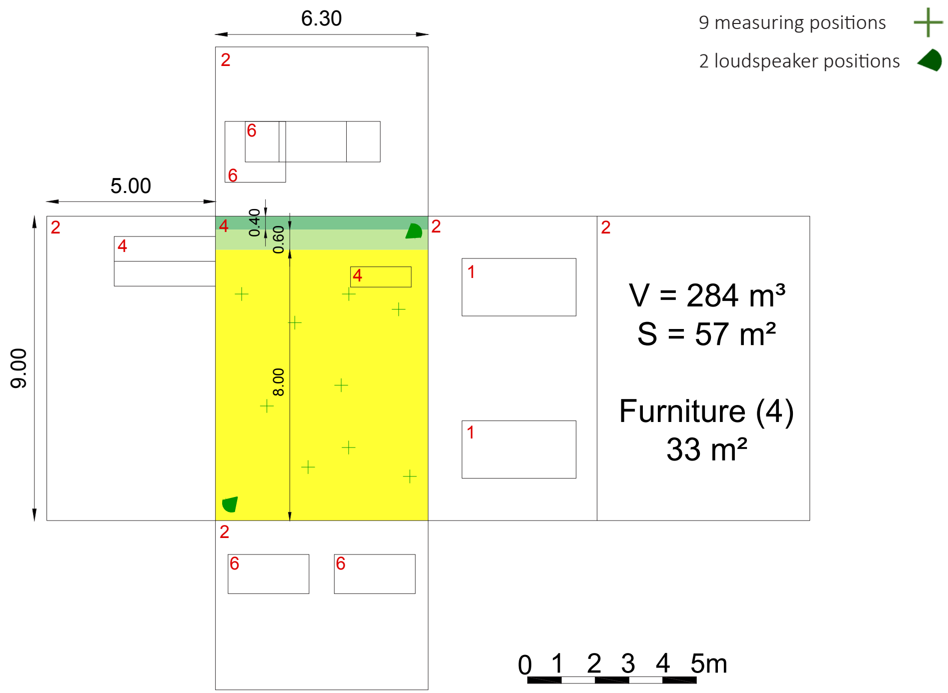
Quality	SN [dB]	C_{50} [dB]	STI
Zone 1 = Excellent	22.85	9.39	0.84
Zone 2 = Good	15.07	2.89	0.64
Zone 3 = Fair	-0.97	-1.81	0.50

Graph



St.dev. = standard deviation   Ref1 = Normal comfort (NBN S 01-400-2)   Ref2 = Increased comfort (NBN S 01-400-2)

Plan



Photos

AUDITORIUM I - MEASUREMENTS

JOZEF-PLATEAUSTRAAT 22, FIRST FLOOR, GHENT 09/11/2013

GENERAL INFORMATION

L-W-H [m]	14.00- 6.27 - 5.00	Compactness [m]	0.83
Volume [m³]	313.50	Capacity	83 persons - 3.78 m³/person
Total surface area [m²]	322.85	H20 [%] / T [°C]	50-70 % / 20 °C

SURFACES

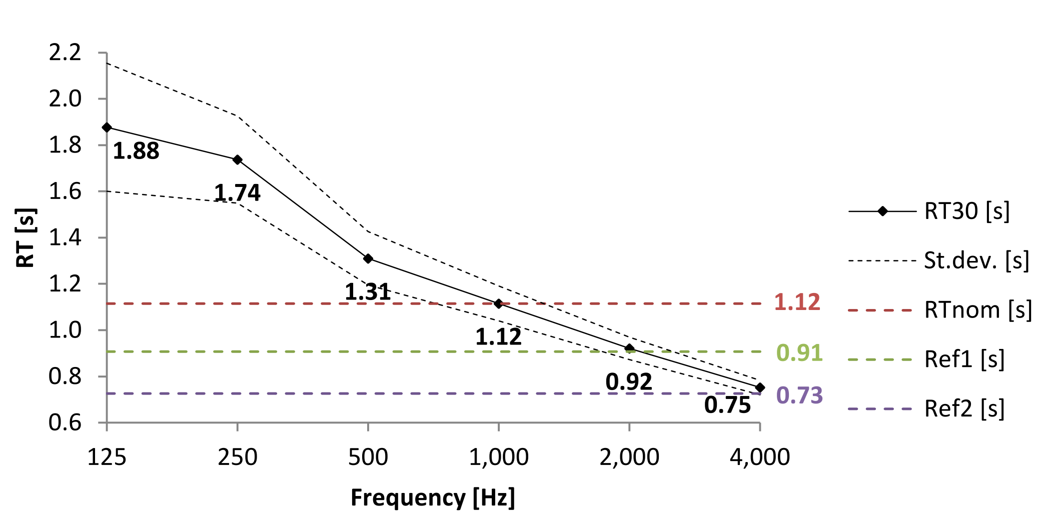
Index	Material	Surface area [m²]
1	Window	17.88
2	Plaster	36.57
3	Carpet	82.21
4	Wood	62.48
5	Metal	-
6	Chalkboard	5.00
7	Acoustic wall/element	22.40
8	Acoustic ceiling	-
9	Linoleum	60.98
10	PUR foam	-

REVERBERATION TIME

f [Hz]	RT [s]
125	1.88
250	1.74
500	1.31
1,000	1.12
2,000	0.92
4,000	0.75

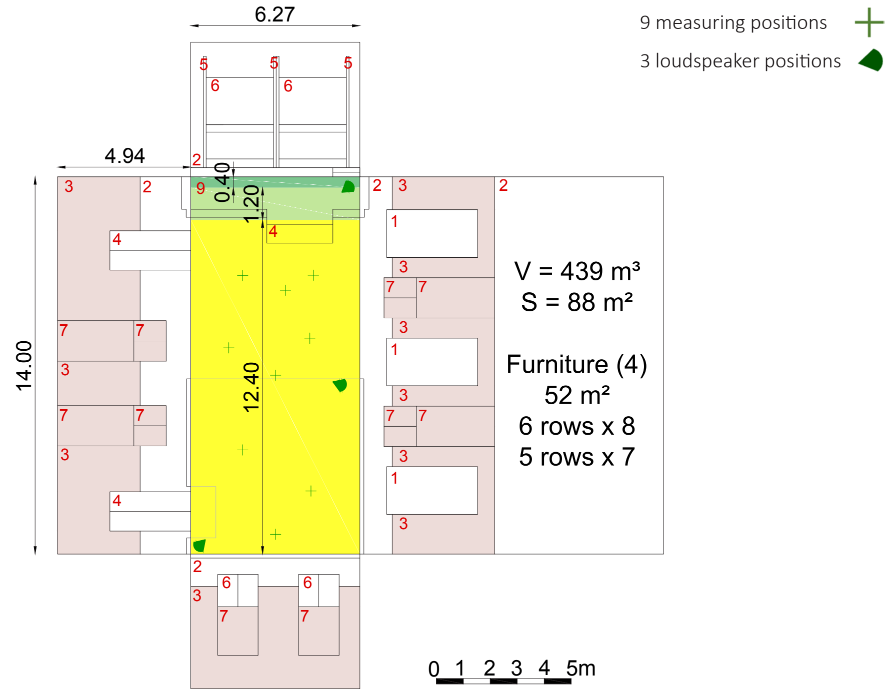
QUALITY	SN [dB]	C_{50} [dB]	STI
Zone 1 = Excellent	24.18	11.95	0.91
Zone 2 = Good	13.58	3.50	0.66
Zone 3 = Fair	-3.44	-0.40	0.54

GRAPH



St.dev. = standard deviation Ref1 = Normal comfort (NBN S 01-400-2) Ref2 = Increased comfort (NBN S 01-400-2)

PLAN



PHOTOS

Auditorium J - Measurements

Jozef-Plateaustraat 22, first floor, Ghent 09/11/2013

General information

L-W-H [m]	10.00 - 6.50 - 4.90	Compactness [m]	0.99
Volume [m³]	318.50	Capacity	55 persons - 5.79 m³/person
Total surface area [m²]	286.13	H20 [%] / T [°C]	50-70 % / 20 °C

Surfaces

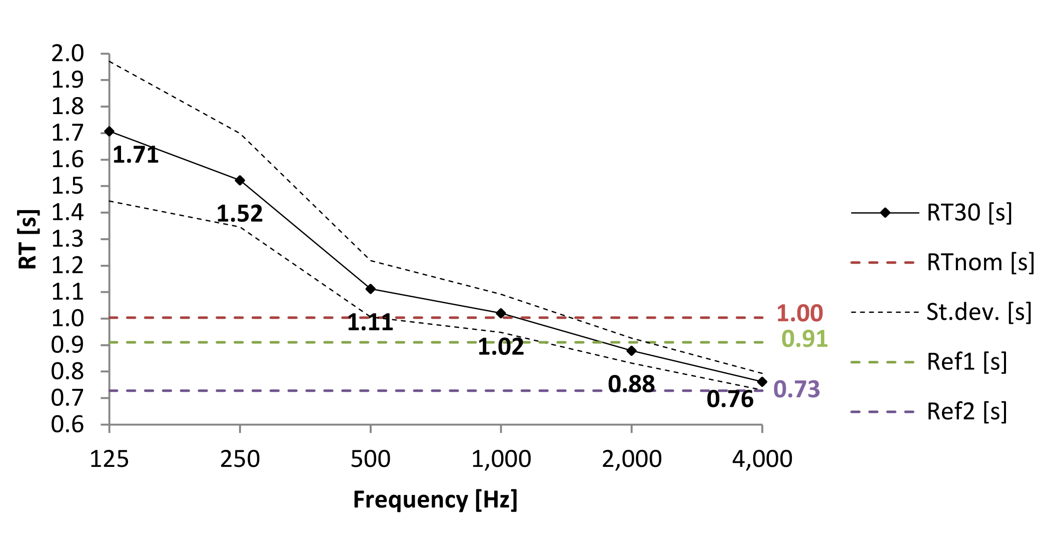
Index	Material	Surface area [m²]
1	Window	30.50
2	Plaster	42.25
3	Carpet	46.66
4	Wood	45.20
5	Metal	-
6	Chalkboard	6.52
7	Acoustic wall/element	20.50
8	Acoustic ceiling	-
9	Linoleum	63.00
10	PUR foam	-

Reverberation time

f [Hz]	RT [s]
125	1.71
250	1.52
500	1.11
1,000	1.02
2,000	0.88
4,000	0.76

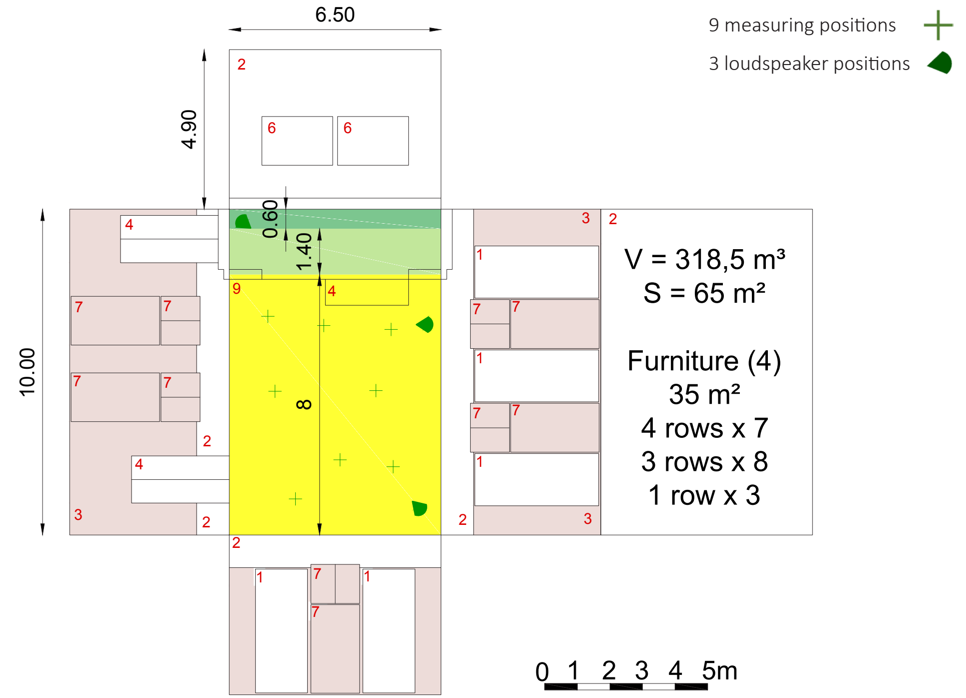
Quality	SN [dB]	C_{50} [dB]	STI
Zone 1 = Excellent	21.29	10.20	0.86
Zone 2 = Good	10.54	2.63	0.63
Zone 3 = Fair	-2.36	0.22	0.56

Graph



St.dev. = standard deviation Ref1 = Normal comfort (NBN S 01-400-2) Ref2 = Increased comfort (NBN S 01-400-2)

Plan



Photos

Auditorium K - Measurements

Jozef-Plateaustraat 22, first floor, Ghent 09/11/2013

General information

L-W-H [m]	9.95 - 9.90 - 5.27	Compactness [m]	1.11
Volume [m³]	491.53	Capacity	79 persons - 6.22 m³/person
Total surface area [m²]	389.76	H20 [%] / T [°C]	50-70 % / 20 °C

Surfaces

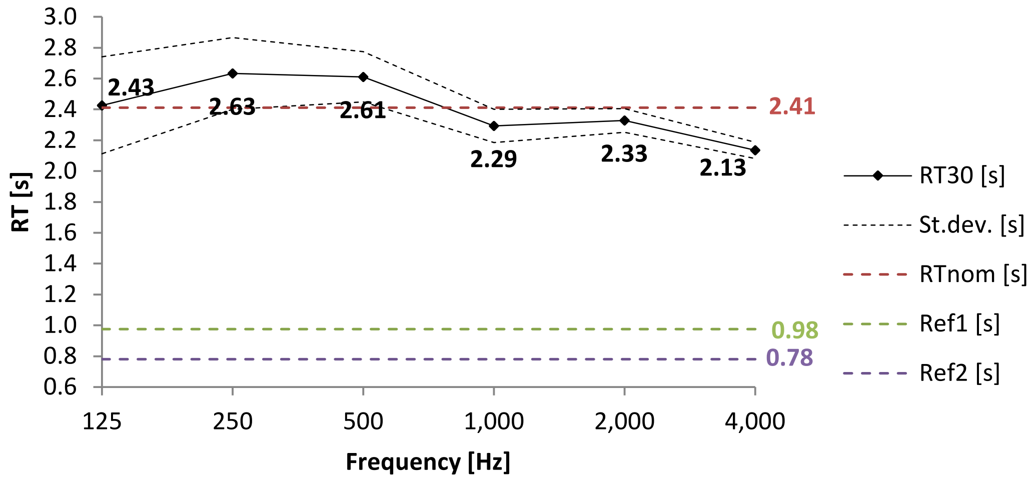
Index	Material	Surface area [m²]
1	Window	31.20
2	Plaster	138.85
3	Carpet	-
4	Wood	60.94
5	Metal	-
6	Chalkboard	-
7	Acoustic wall/element	-
8	Acoustic ceiling	-
9	Linoleum	96.89
10	PUR foam	-

Reverberation time

f [Hz]	RT [s]
125	2.43
250	2.63
500	2.61
1,000	2.29
2,000	2.33
4,000	2.13

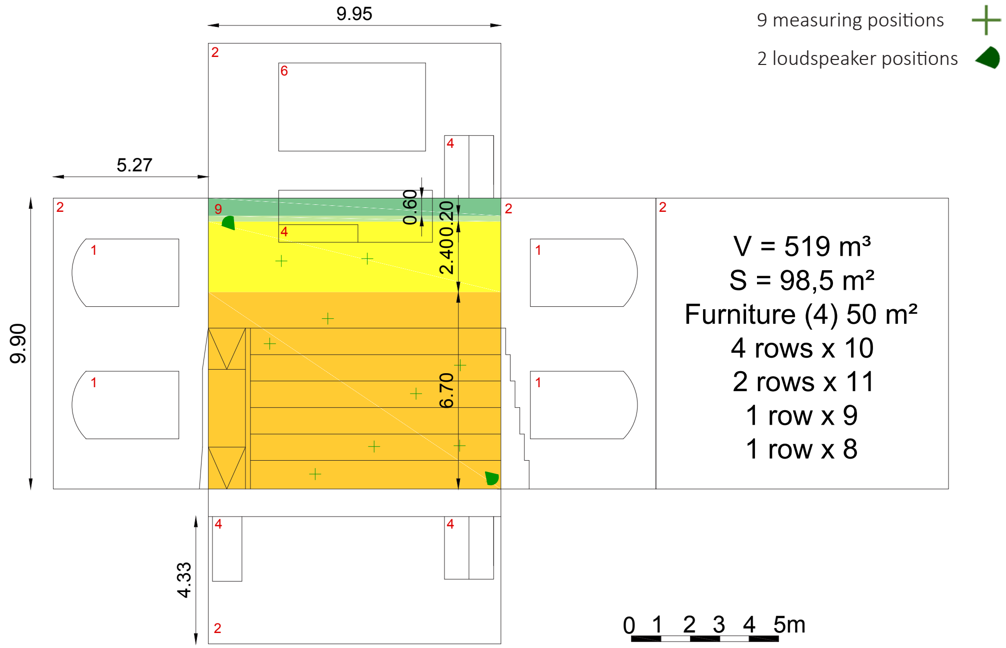
Quality	SN [dB]	C_{50} [dB]	STI
Zone 1 = Excellent	22.37	8.77	0.82
Zone 2 = Good	15.52	2.55	0.63
Zone 3 = Fair	8.04	-1.99	0.50
Zone 4 = Poor	-2.44	-4.41	0.42

Graph



St.dev. = standard deviation Ref1 = Normal comfort (NBN S 01-400-2) Ref2 = Increased comfort (NBN S 01-400-2)

Plan



Photos

Auditorium N - Measurements

Jozef-Plateaustraat 22, first floor, Ghent 09/11/2013

General information

L-W-H [m]	22.00- 9.43 - 4.85	Compactness [m]	1.15
Volume [m³]	995.71	Capacity	280 persons - 3.56 m³/person
Total surface area [m²]	689.07	H20 [%] / T [°C]	50-70 % / 20 °C

Surfaces

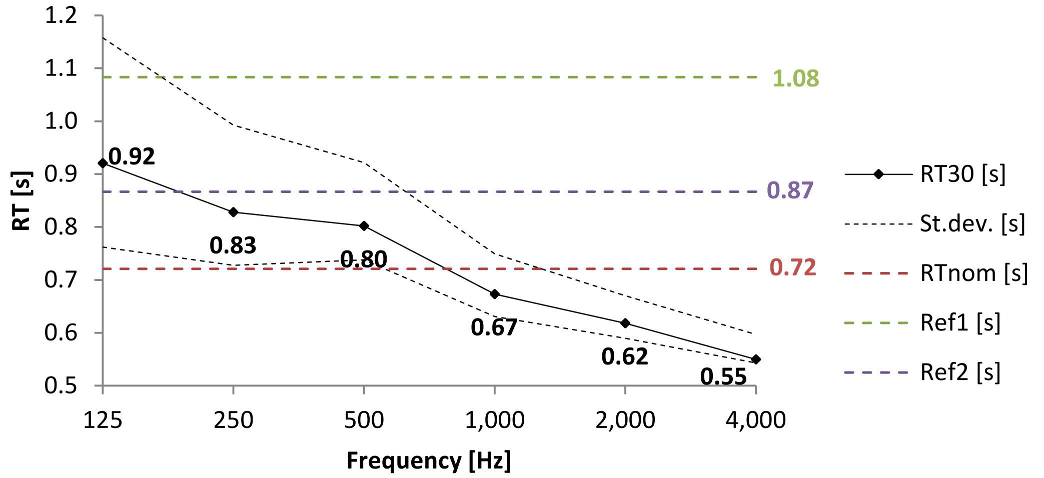
Index	Material	Surface area [m²]
1	Window	40.00
2	Plaster	9.49
3	Carpet	89.88
4	Wood	282.53
5	Metal	-
6	Chalkboard	6.50
7	Acoustic wall/element	7.35
8	Acoustic ceiling	207.46
9	Linoleum	202.71
10	PUR foam	-

Reverberation time

f [Hz]	RT [s]
125	0.92
250	0.83
500	0.80
1,000	0.67
2,000	0.62
4,000	0.55

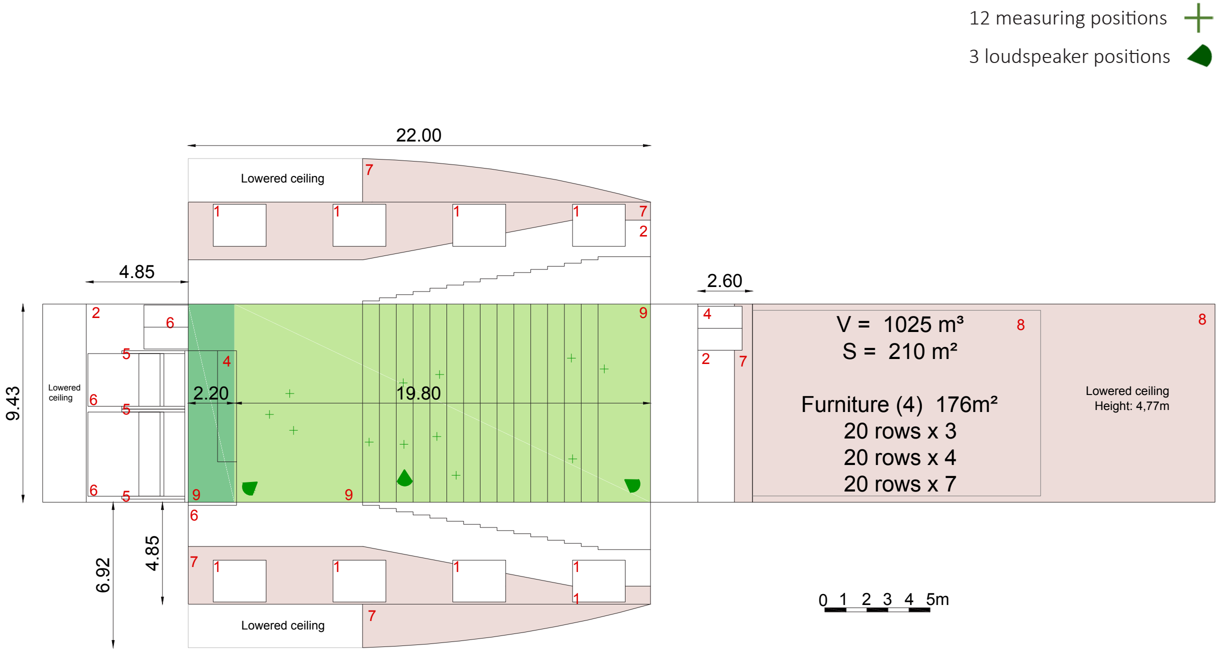
Quality	SN [dB]	C_{50} [dB]	STI
Zone 1 = Excellent	**17.42**	**12.35**	**0.93**
Zone 2 = Good	**-3.20**	**2.87**	**0.64**
-	-	-	-

Graph



St.dev. = standard deviation Ref1 = Normal comfort (NBN S 01-400-2) Ref2 = Increased comfort (NBN S 01-400-2)

Plan



Photos

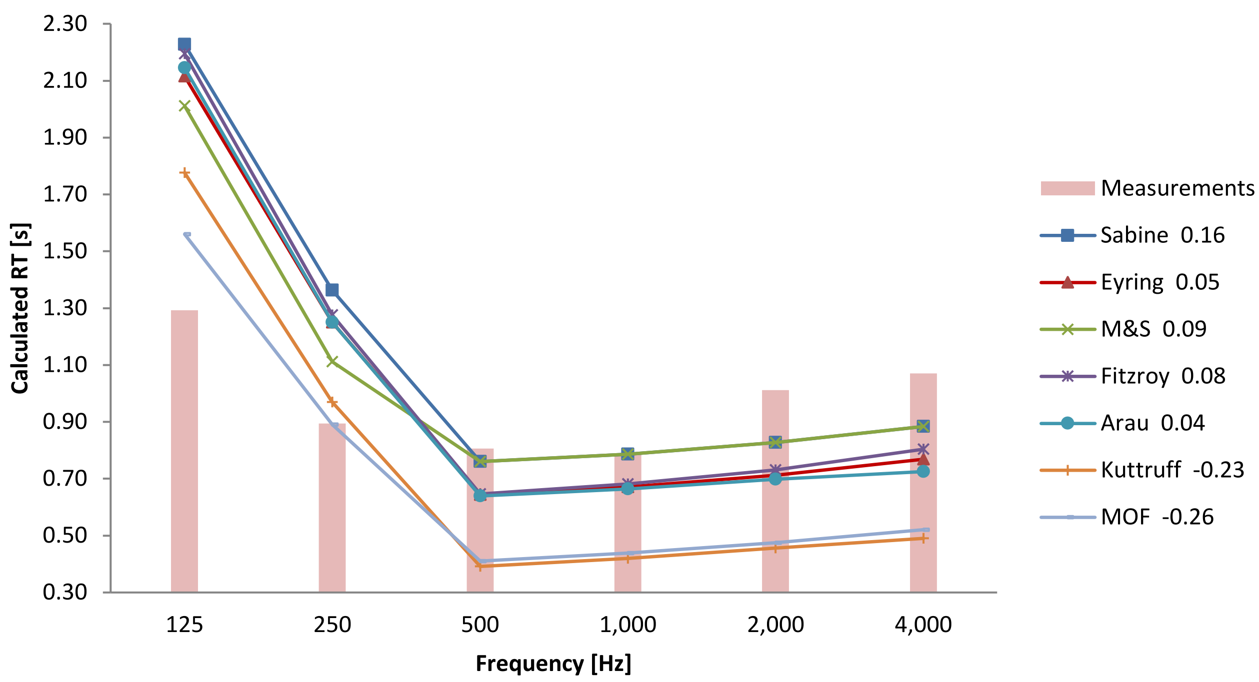
Calculations

Auditorium A - Calculations

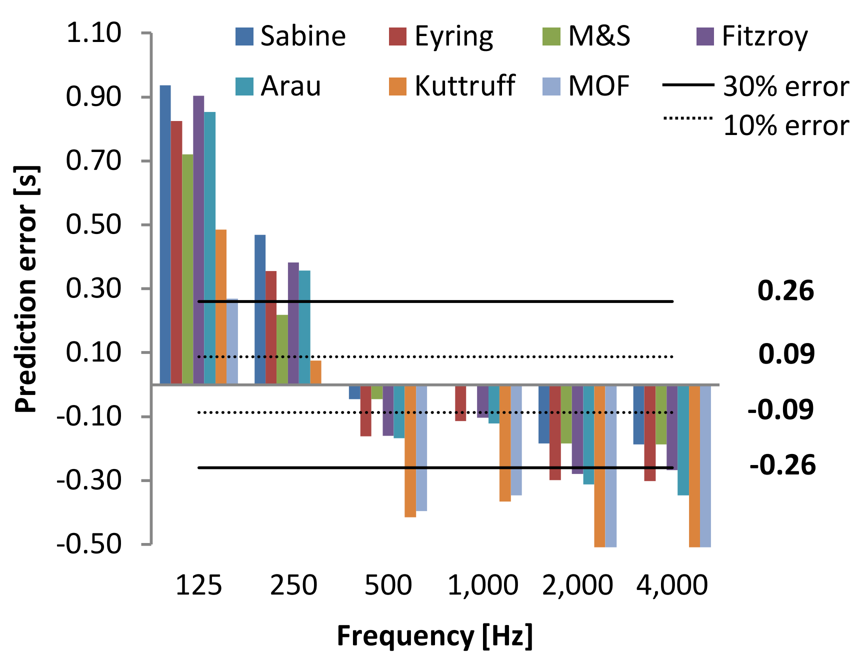
Jozef-Plateaustraat 22, ground floor, Ghent

Model \ f [Hz]	Calculated RT [s] 125	250	500	1,000	2,000	4,000	Prediction error [s] 125 - 4,000	500 - 1,000	500 - 2,000
Measurements	1.29	0.89	0.81	0.79	1.01	1.07	-	-	-
Sabine	2.23	1.36	0.76	0.79	0.83	0.88	0.16	-0.02	-0.08
Eyring	2.12	1.25	0.64	0.67	0.71	0.77	0.05	-0.14	-0.19
M&S	2.01	1.11	0.76	0.79	0.83	0.88	0.09	-0.02	-0.08
Fitzroy	2.19	1.28	0.65	0.68	0.73	0.80	0.08	-0.13	-0.18
Arau	2.14	1.25	0.64	0.66	0.70	0.72	0.04	-0.14	-0.20
Kuttruff	1.78	0.97	0.39	0.42	0.46	0.49	-0.23	-0.39	-0.44
MOF	1.56	0.89	0.41	0.44	0.47	0.52	-0.26	-0.37	-0.43

Graph calculated RT



Graph prediction error

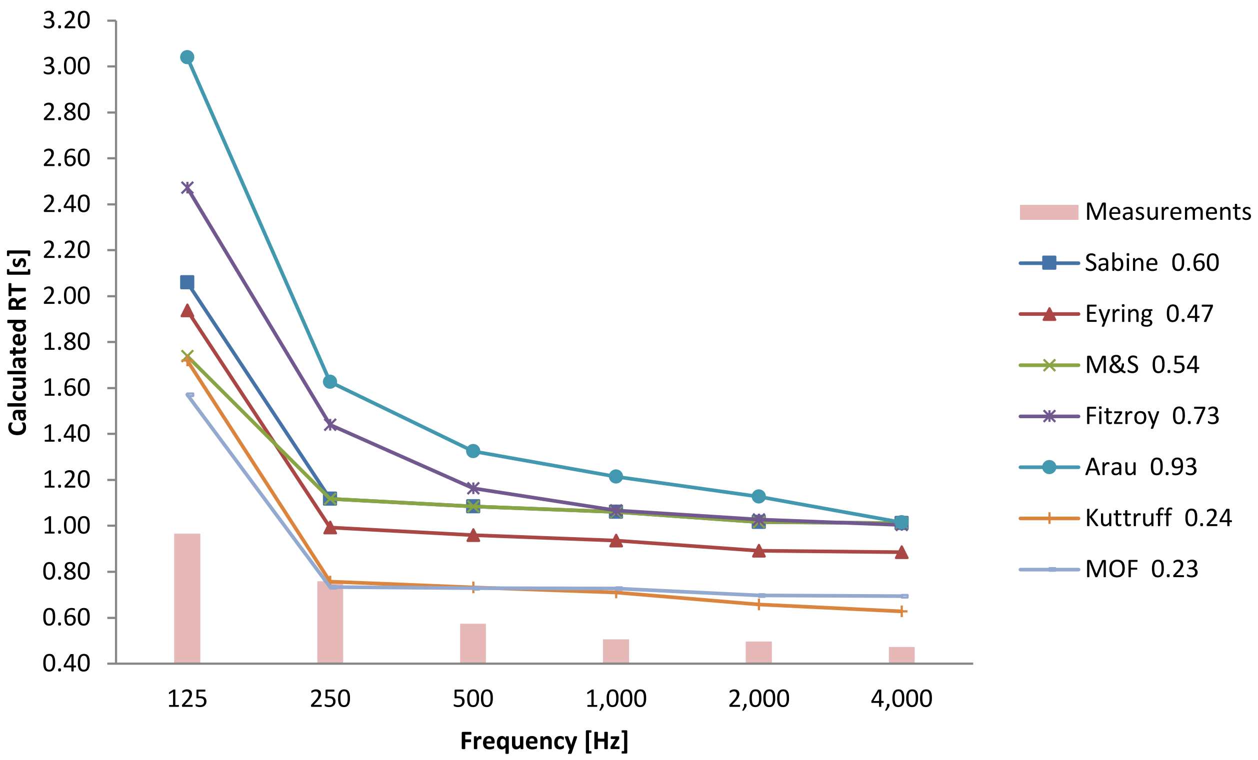


Auditorium C - Calculations

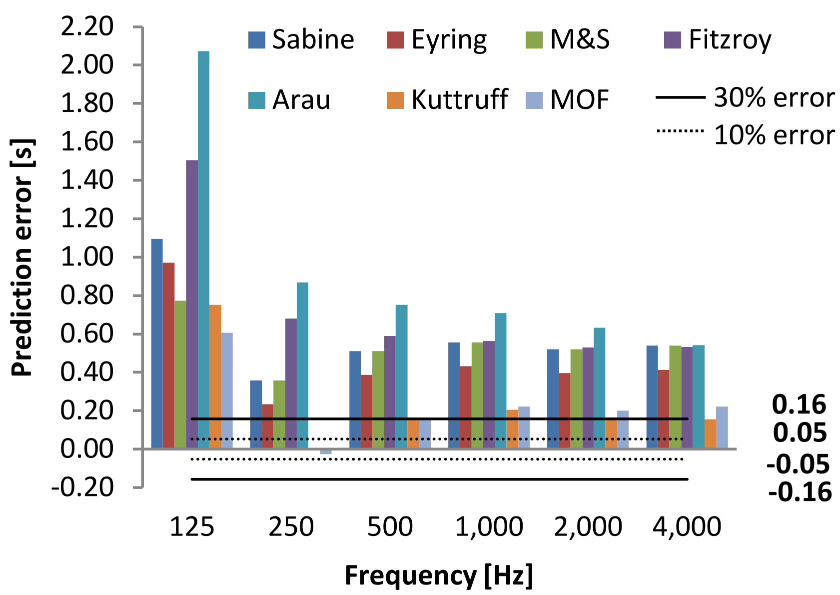
Jozef-Plateaustraat 22, first floor, Ghent

Model \ f [Hz]	Calculated RT [s] 125	250	500	1,000	2,000	4,000	Prediction error [s] 125 - 4,000	500 - 1,000	500 - 2,000
Measurements	0.97	0.76	0.57	0.51	0.50	0.47	-	-	-
Sabine	2.06	1.12	1.08	1.06	1.02	1.01	0.60	0.53	0.53
Eyring	1.94	0.99	0.96	0.94	0.89	0.89	0.47	0.41	0.40
M&S	1.74	1.12	1.08	1.06	1.02	1.01	0.54	0.53	0.53
Fitzroy	2.47	1.44	1.16	1.07	1.03	1.00	0.73	0.58	0.56
Arau	3.04	1.63	1.32	1.21	1.13	1.01	0.93	0.73	0.70
Kuttruff	1.72	0.76	0.73	0.71	0.66	0.63	0.24	0.18	0.17
MOF	1.57	0.73	0.73	0.73	0.70	0.69	0.23	0.19	0.19

Graph calculated RT



Graph prediction error

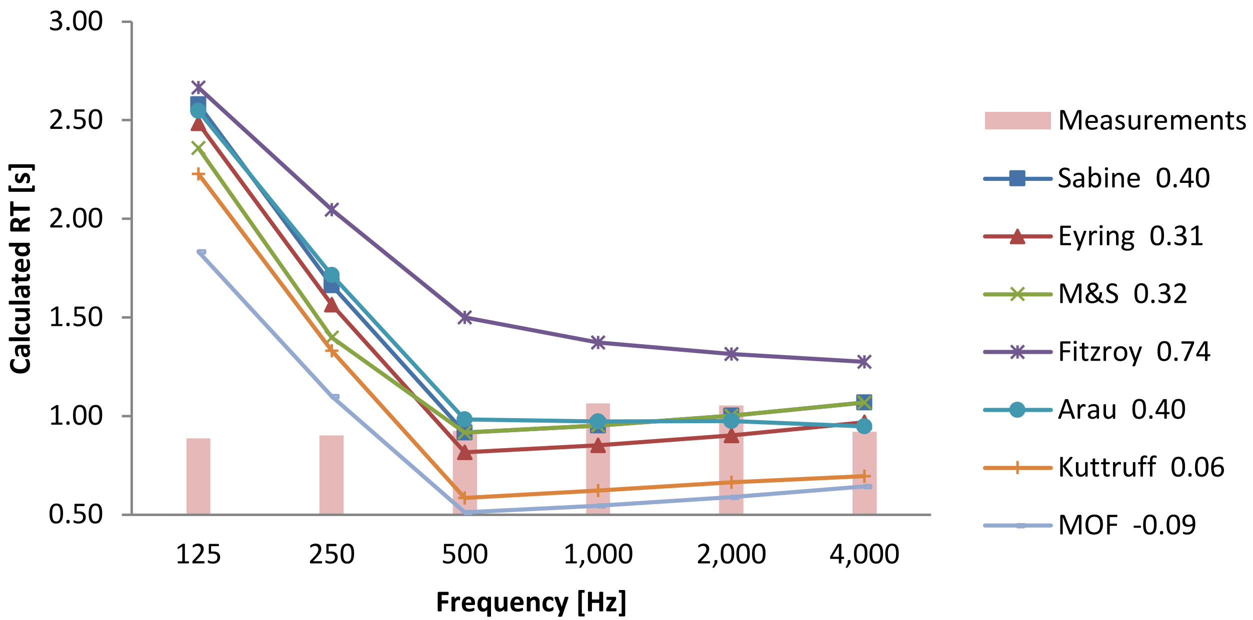


Auditorium D - Calculations

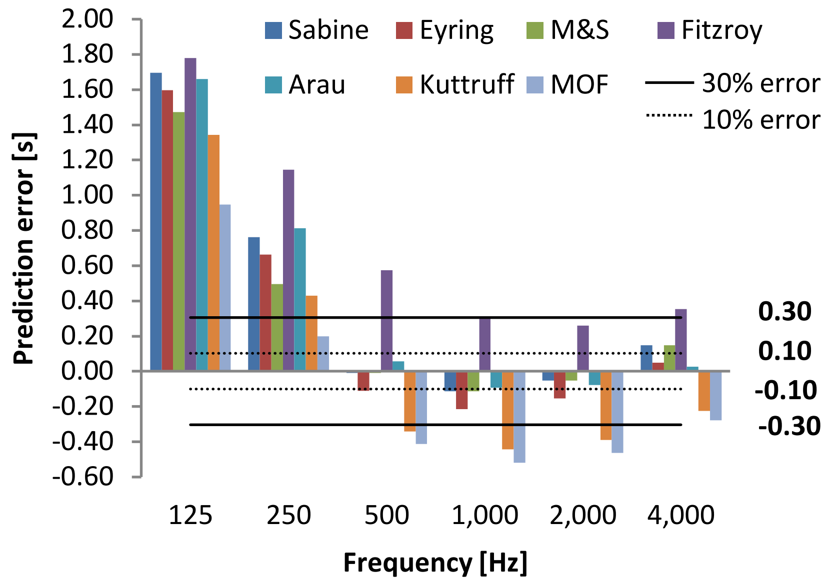
Jozef-Plateaustraat 22, first floor, Ghent

Model \ f [Hz]	Calculated RT [s]						Prediction error [s]		
	125	250	500	1,000	2,000	4,000	125 - 4,000	500 - 1,000	500 - 2,000
Measurements	0.89	0.90	0.93	1.07	1.05	0.92	-	-	-
Sabine	2.58	1.66	0.92	0.95	1.00	1.07	0.40	-0.06	-0.06
Eyring	2.48	1.56	0.82	0.85	0.90	0.97	0.31	-0.16	-0.16
M&S	2.36	1.40	0.92	0.95	1.00	1.07	0.32	-0.06	-0.06
Fitzroy	2.67	2.05	1.50	1.37	1.31	1.27	0.74	0.44	0.38
Arau	2.55	1.71	0.98	0.97	0.97	0.95	0.40	-0.02	-0.04
Kuttruff	2.23	1.33	0.58	0.62	0.66	0.70	0.06	-0.39	-0.39
MOF	1.83	1.10	0.51	0.55	0.59	0.64	-0.09	-0.47	-0.47

Graph calculated RT



Graph prediction error

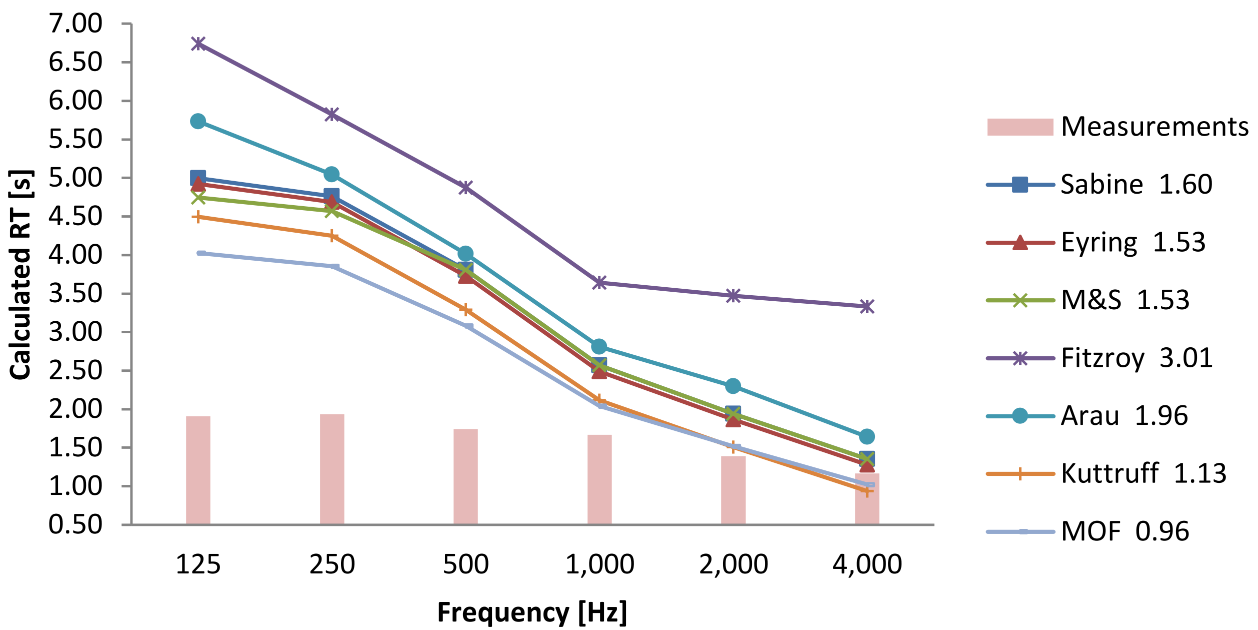


Auditorium E - Calculations

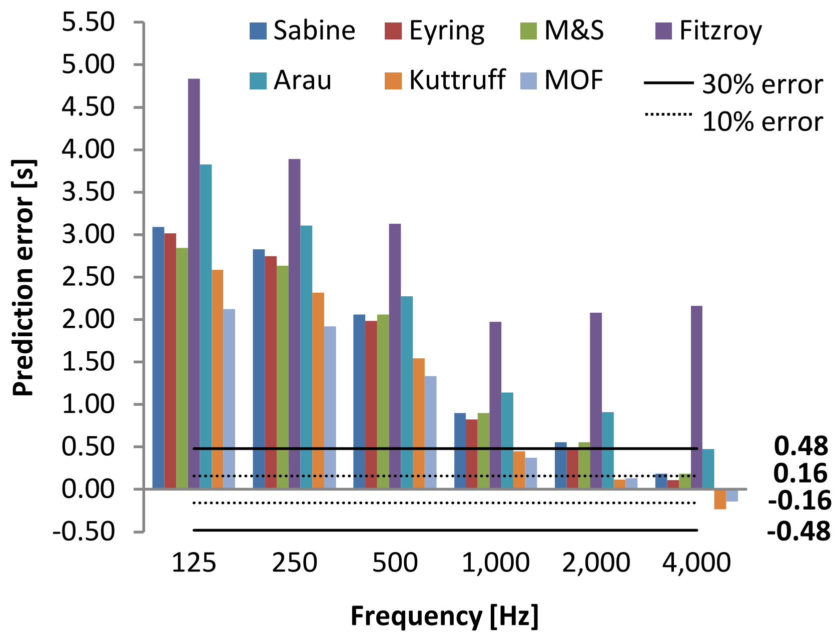
Jozef-Plateaustraat 22, first floor, Ghent

	Calculated RT [s]						Prediction error [s]		
Model \ f [Hz]	125	250	500	1,000	2,000	4,000	125 - 4,000	500 - 1,000	500 - 2,000
Measurements	1.91	1.94	1.74	1.67	1.39	1.17	-	-	-
Sabine	5.00	4.76	3.80	2.57	1.94	1.35	1.60	1.48	1.17
Eyring	4.92	4.68	3.73	2.49	1.86	1.28	1.53	1.40	1.09
M&S	4.75	4.57	3.80	2.57	1.94	1.35	1.53	1.48	1.17
Fitzroy	6.74	5.83	4.87	3.64	3.47	3.33	3.01	2.55	2.39
Arau	5.73	5.04	4.02	2.81	2.30	1.64	1.96	1.71	1.44
Kuttruff	4.49	4.25	3.29	2.12	1.51	0.94	1.13	1.00	0.70
MOF	4.03	3.85	3.08	2.04	1.52	1.02	0.96	0.85	0.61

Graph calculated RT



Graph prediction error

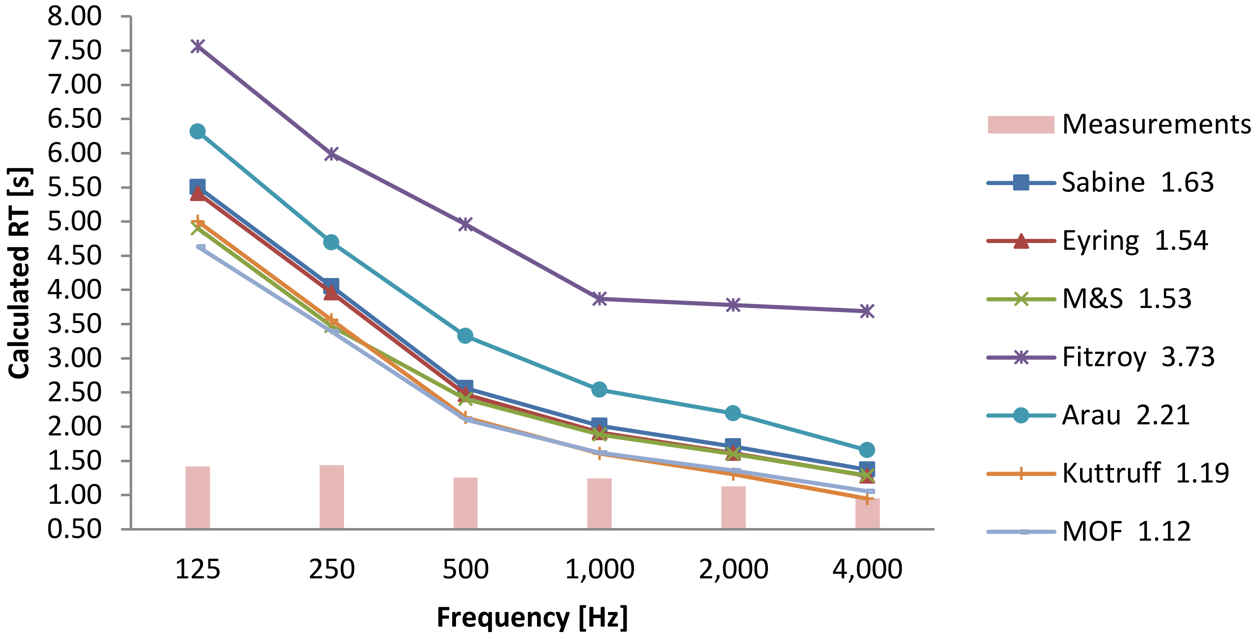


Auditorium G - Calculations

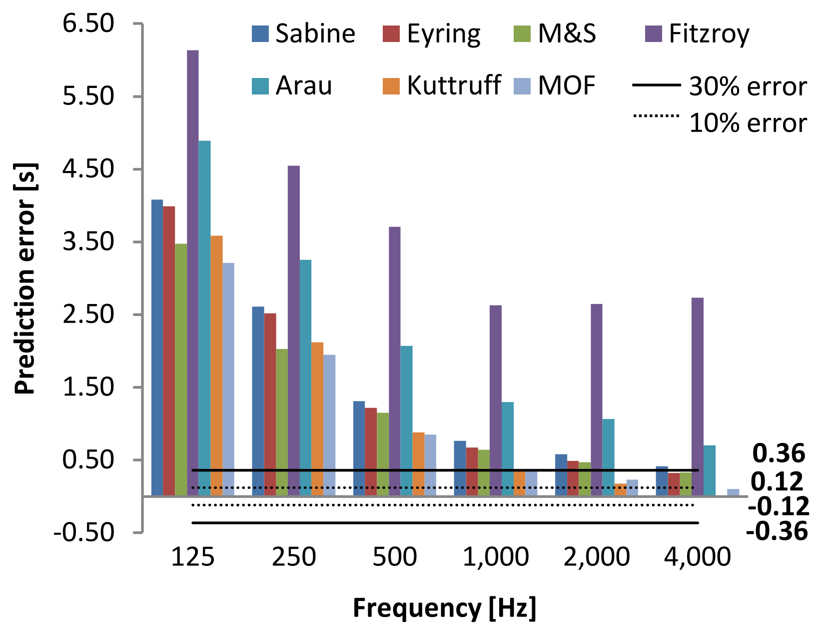
Jozef-Plateaustraat 22, first floor, Ghent

Model \ f [Hz]	Calculated RT [s] 125	250	500	1000	2000	4000	Prediction error [s] 125 - 4000	500 - 1000	500 - 2000
Measurements	1.42	1.44	1.25	1.24	1.13	0.96	-	-	-
Sabine	5.50	4.05	2.56	2.01	1.71	1.37	1.63	1.04	0.89
Eyring	5.41	3.96	2.47	1.92	1.62	1.28	1.54	0.95	0.79
M&S	4.90	3.47	2.40	1.88	1.60	1.28	1.35	0.90	0.75
Fitzroy	7.56	5.99	4.96	3.87	3.78	3.69	3.73	3.17	2.99
Arau	6.31	4.69	3.32	2.54	2.19	1.66	2.21	1.68	1.48
Kuttruff	5.00	3.56	2.13	1.61	1.30	0.95	1.19	0.62	0.47
MOF	4.63	3.39	2.10	1.62	1.36	1.06	1.12	0.61	0.48

Graph calculated RT



Graph prediction error

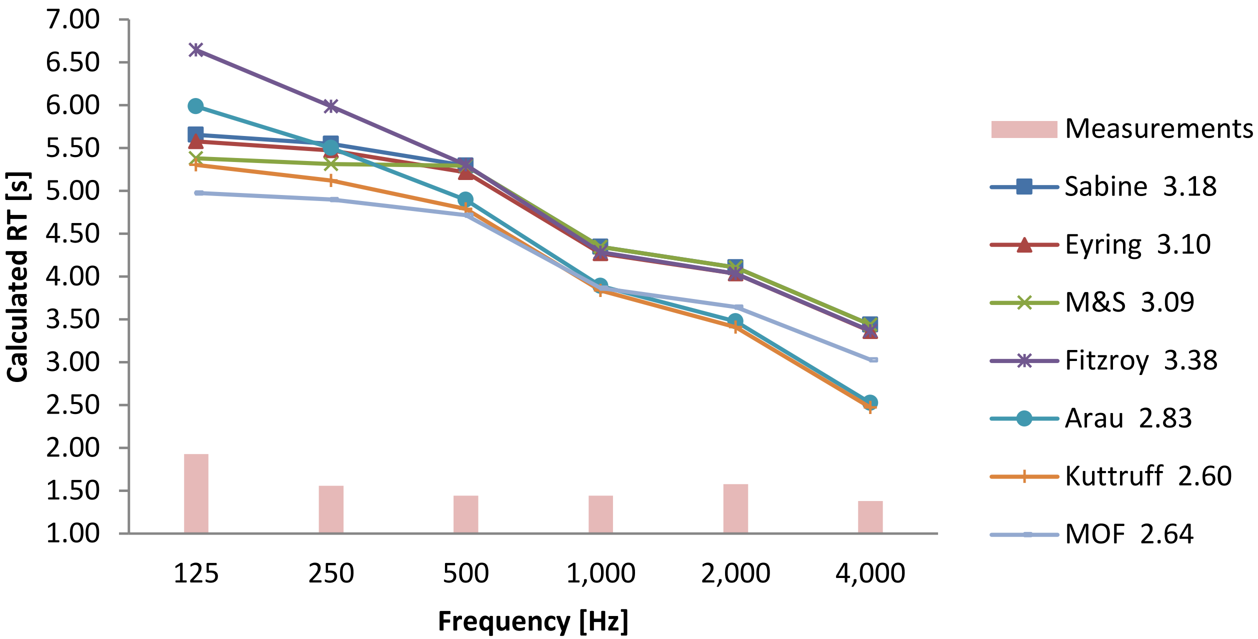


Auditorium H - Calculations

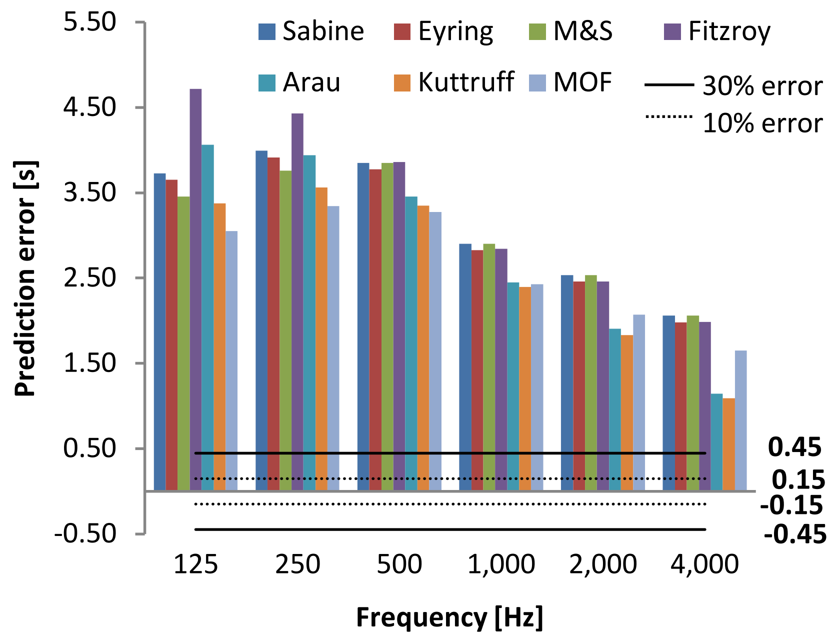
Jozef-Plateaustraat 22, first floor, Ghent

Model \ f [Hz]	Calculated RT [s] 125	250	500	1,000	2,000	4,000	Prediction error [s] 125 - 4,000	500 - 1,000	500 - 2,000
Measurements	1.93	1.56	1.44	1.44	1.58	1.38	-	-	-
Sabine	5.65	5.55	5.29	4.34	4.11	3.44	3.18	3.38	3.10
Eyring	5.58	5.47	5.22	4.27	4.03	3.36	3.10	3.30	3.02
M&S	5.38	5.31	5.29	4.34	4.11	3.44	3.09	3.38	3.10
Fitzroy	6.64	5.99	5.30	4.29	4.04	3.37	3.38	3.35	3.06
Arau	5.99	5.50	4.90	3.89	3.48	2.53	2.83	2.95	2.60
Kuttruff	5.30	5.12	4.79	3.84	3.41	2.47	2.60	2.87	2.53
MOF	4.98	4.90	4.72	3.87	3.65	3.03	2.64	2.85	2.59

Graph calculated RT



Graph prediction error

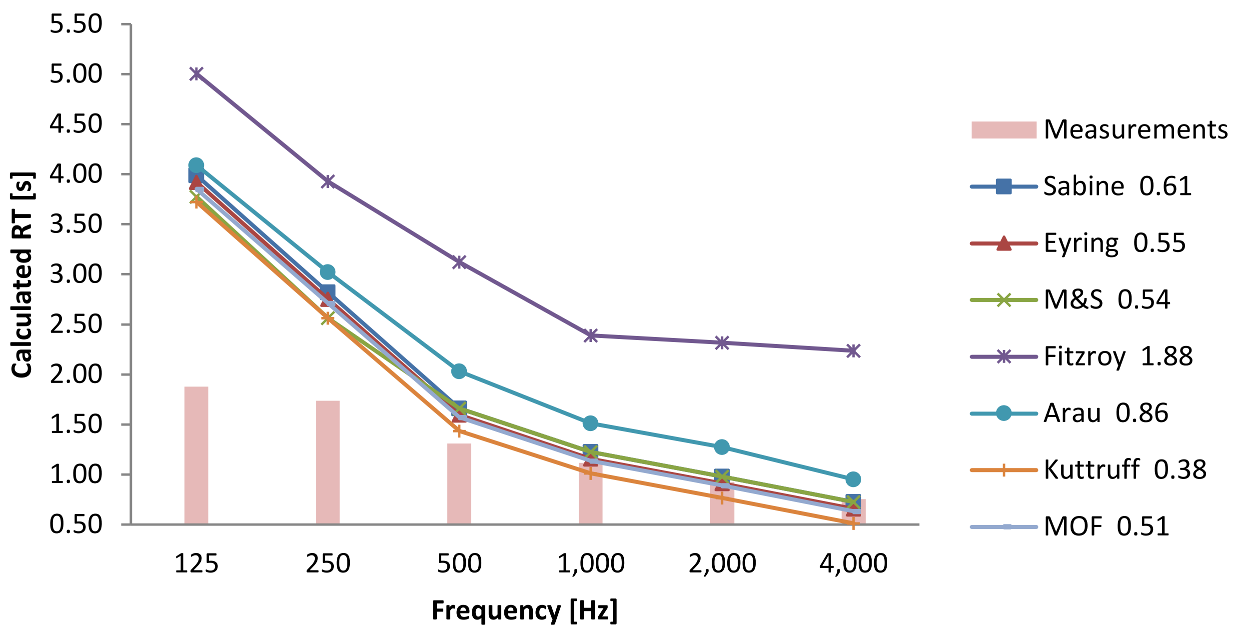


Auditorium I - Calculations

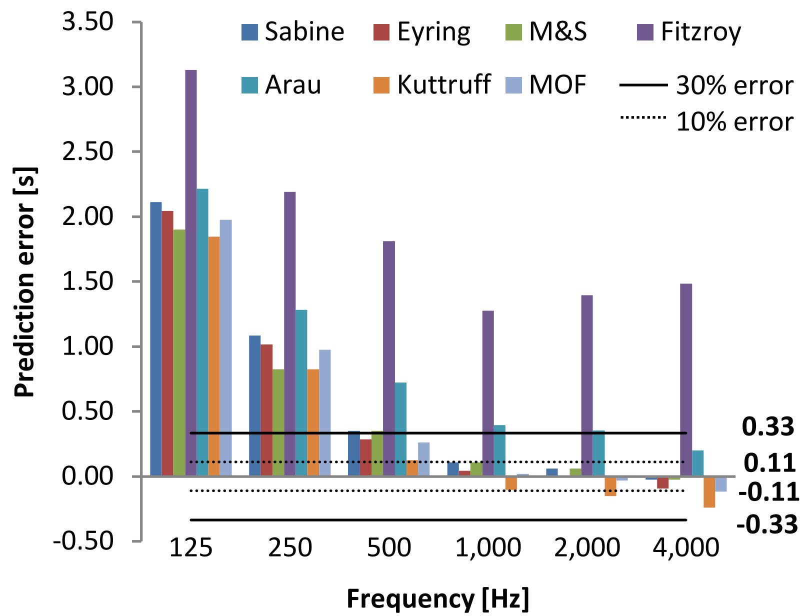
Jozef-Plateaustraat 22, first floor, Ghent

Model \ f [Hz]	Calculated RT [s] 125	250	500	1,000	2,000	4,000	Prediction error [s] 125 - 4,000	500 - 1,000	500 - 2,000
Measurements	1.88	1.74	1.31	1.12	0.92	0.75	-	-	-
Sabine	3.99	2.82	1.66	1.22	0.98	0.73	0.61	0.23	0.17
Eyring	3.92	2.75	1.59	1.16	0.91	0.66	0.55	0.16	0.11
M&S	3.78	2.56	1.66	1.22	0.98	0.73	0.54	0.23	0.17
Fitzroy	5.01	3.93	3.12	2.39	2.32	2.24	1.88	1.54	1.49
Arau	4.09	3.02	2.03	1.51	1.28	0.95	0.86	0.56	0.49
Kuttruff	3.72	2.56	1.43	1.01	0.77	0.51	0.38	0.01	-0.04
MOF	3.85	2.71	1.57	1.14	0.89	0.63	0.51	0.14	0.08

Graph calculated RT



Graph prediction error

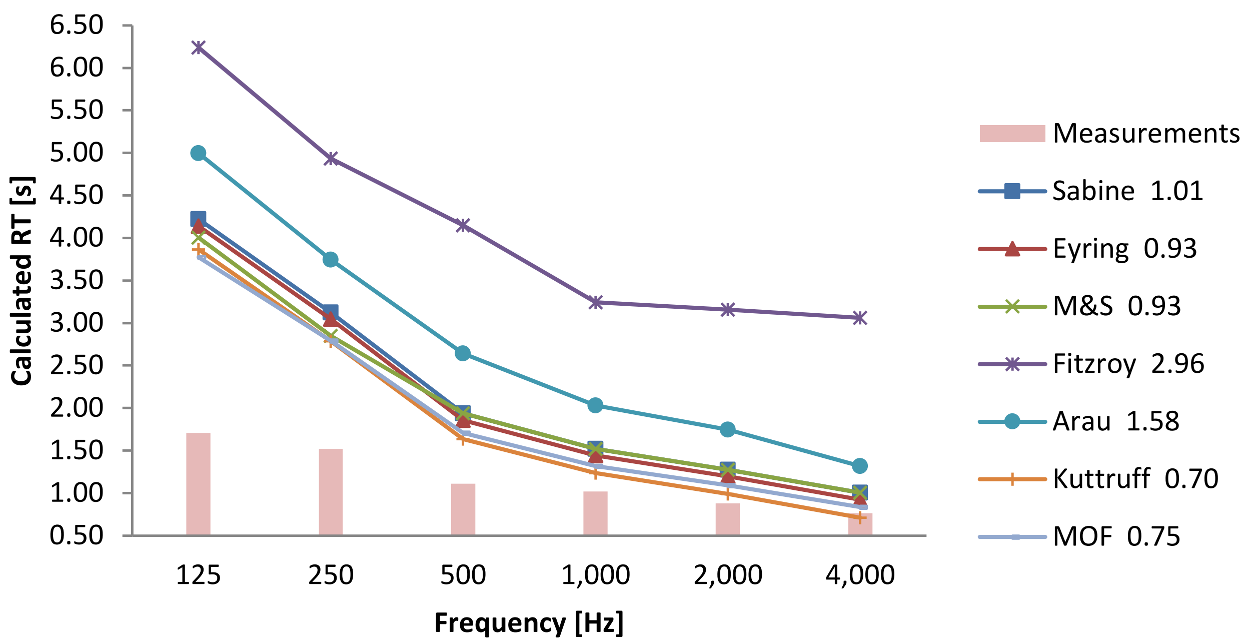


Auditorium J - Calculations

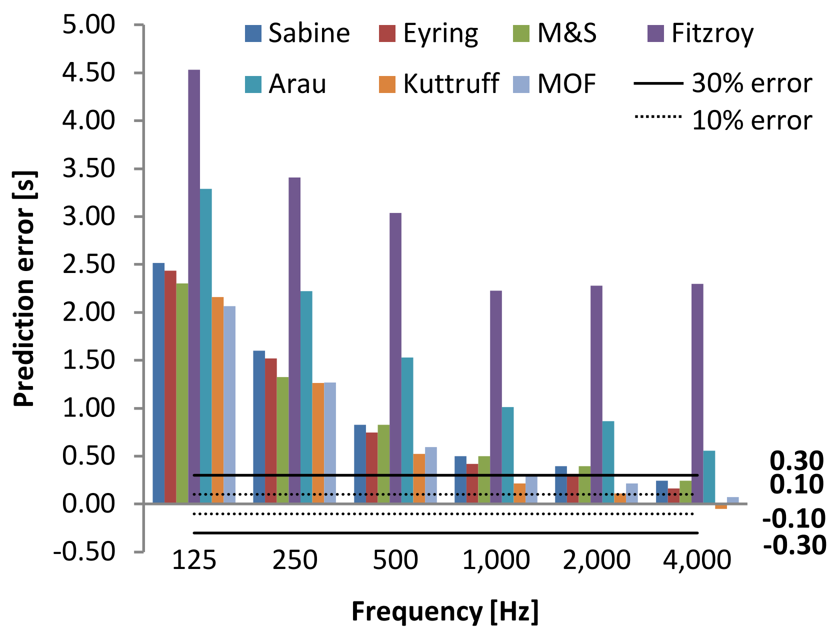
Jozef-Plateaustraat 22, first floor, Ghent

Model \ f [Hz]	Calculated RT [s] 125	250	500	1,000	2,000	4,000	Prediction error [s] 125 - 4,000	500 - 1,000	500 - 2,000
Measurements	1.71	1.52	1.11	1.02	0.88	0.76	-	-	-
Sabine	4.22	3.12	1.94	1.52	1.28	1.01	1.01	0.66	0.57
Eyring	4.14	3.04	1.86	1.44	1.20	0.93	0.93	0.58	0.49
M&S	4.01	2.85	1.94	1.52	1.28	1.01	0.93	0.66	0.57
Fitzroy	6.24	4.93	4.15	3.25	3.16	3.06	2.96	2.63	2.51
Arau	5.00	3.74	2.64	2.03	1.74	1.32	1.58	1.27	1.14
Kuttruff	3.87	2.79	1.64	1.24	0.99	0.71	0.70	0.37	0.28
MOF	3.77	2.79	1.71	1.32	1.09	0.84	0.75	0.45	0.37

Graph calculated RT



Graph prediction error

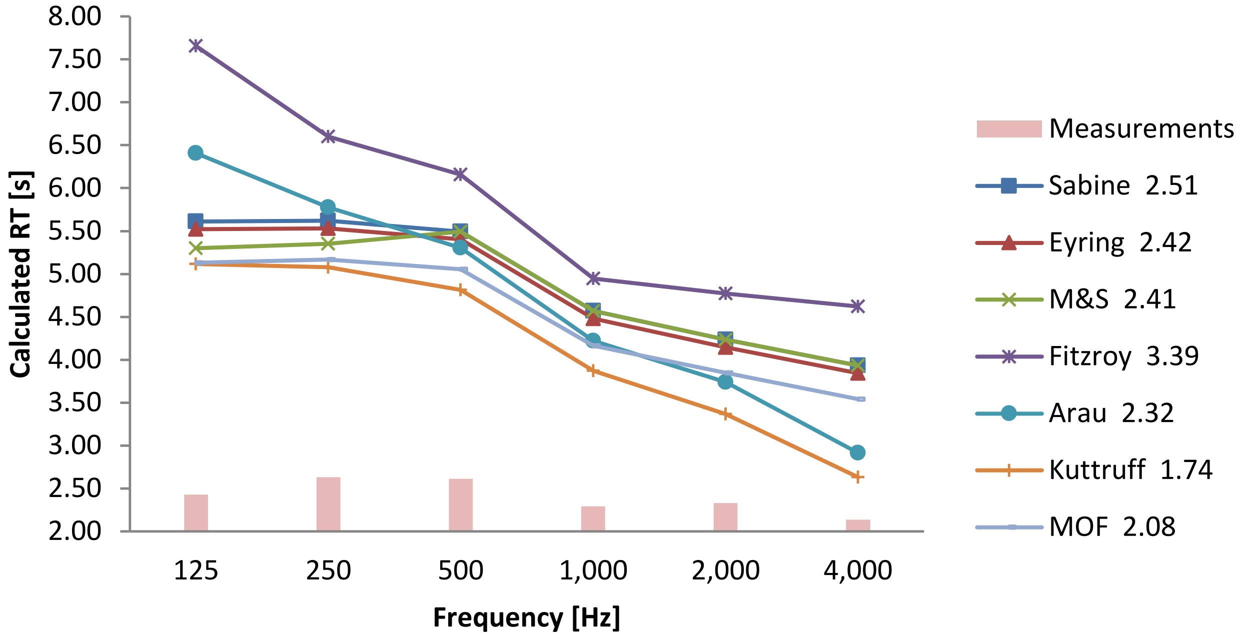


AUDITORIUM K - CALCULATIONS

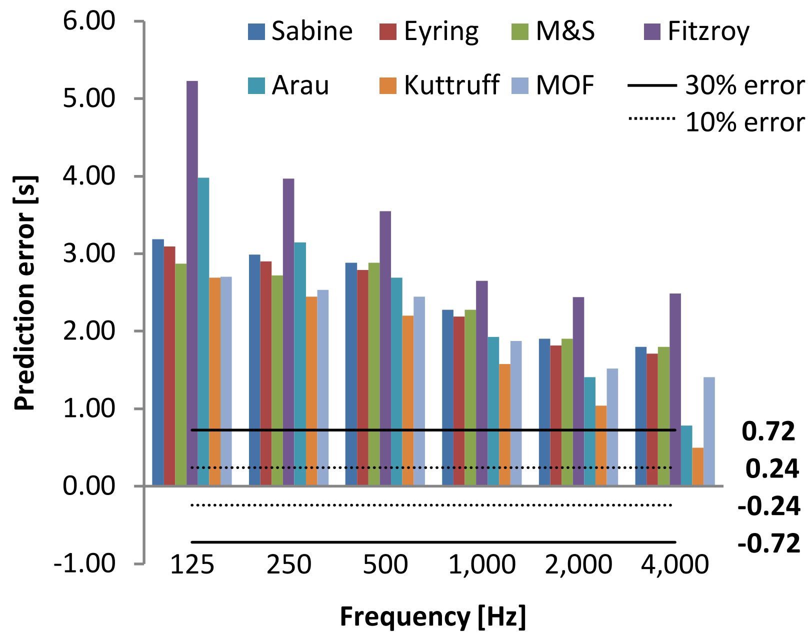
JOZEF-PLATEAUSTRAAT 22, FIRST FLOOR, GHENT

Model \ f [Hz]	Calculated RT [s] 125	250	500	1,000	2,000	4,000	Prediction error [s] 125 - 4,000	500 - 1,000	500 - 2,000
Measurements	2.43	2.63	2.61	2.29	2.33	2.13	-	-	-
Sabine	5.61	5.62	5.49	4.57	4.23	3.93	2.51	2.58	2.35
Eyring	5.52	5.53	5.40	4.48	4.14	3.85	2.42	2.49	2.26
M&S	5.30	5.35	5.49	4.57	4.23	3.93	2.41	2.58	2.35
Fitzroy	7.65	6.60	6.16	4.95	4.77	4.62	3.39	3.10	2.88
Arau	6.41	5.78	5.30	4.22	3.74	2.92	2.32	2.31	2.01
Kuttruff	5.12	5.08	4.81	3.87	3.37	2.63	1.74	1.89	1.61
MOF	5.13	5.17	5.06	4.17	3.85	3.54	2.08	2.16	1.95

GRAPH CALCULATED RT



GRAPH PREDICTION ERROR

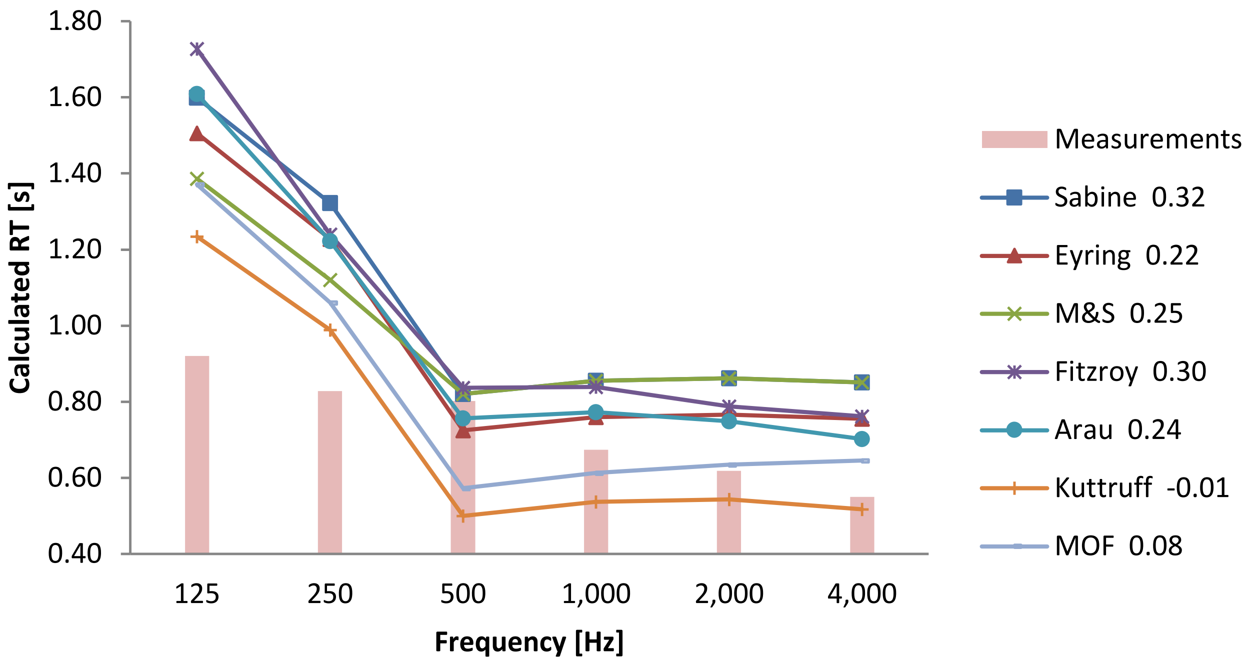


Auditorium N - Calculations

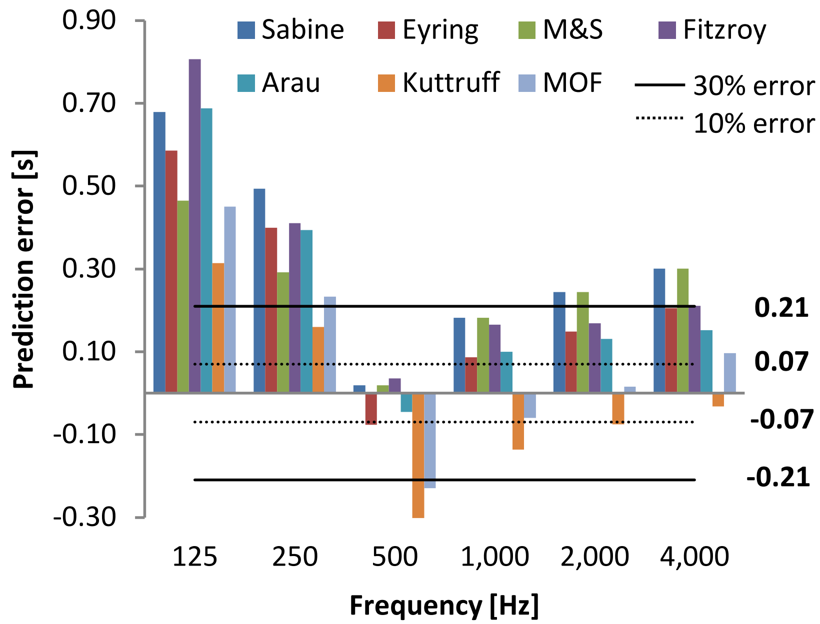
Jozef-Plateaustraat 22, first floor, Ghent

Model \ f [Hz]	Calculated RT [s]						Prediction error [s]		
	125	250	500	1,000	2,000	4,000	125 - 4,000	500 - 1,000	500 - 2,000
Measurements	0.92	0.83	0.80	0.67	0.62	0.55	-	-	-
Sabine	1.60	1.32	0.82	0.86	0.86	0.85	0.32	0.10	0.15
Eyring	1.51	1.23	0.73	0.76	0.77	0.76	0.22	0.00	0.05
M&S	1.39	1.12	0.82	0.86	0.86	0.85	0.25	0.10	0.15
Fitzroy	1.73	1.24	0.84	0.84	0.79	0.76	0.30	0.10	0.12
Arau	1.61	1.22	0.76	0.77	0.75	0.70	0.24	0.03	0.06
Kuttruff	1.23	0.99	0.50	0.54	0.54	0.52	-0.01	-0.22	-0.17
MOF	1.37	1.06	0.57	0.61	0.63	0.65	0.08	-0.14	-0.09

Graph calculated RT



Graph prediction error



Survey

Auditorium A - Survey

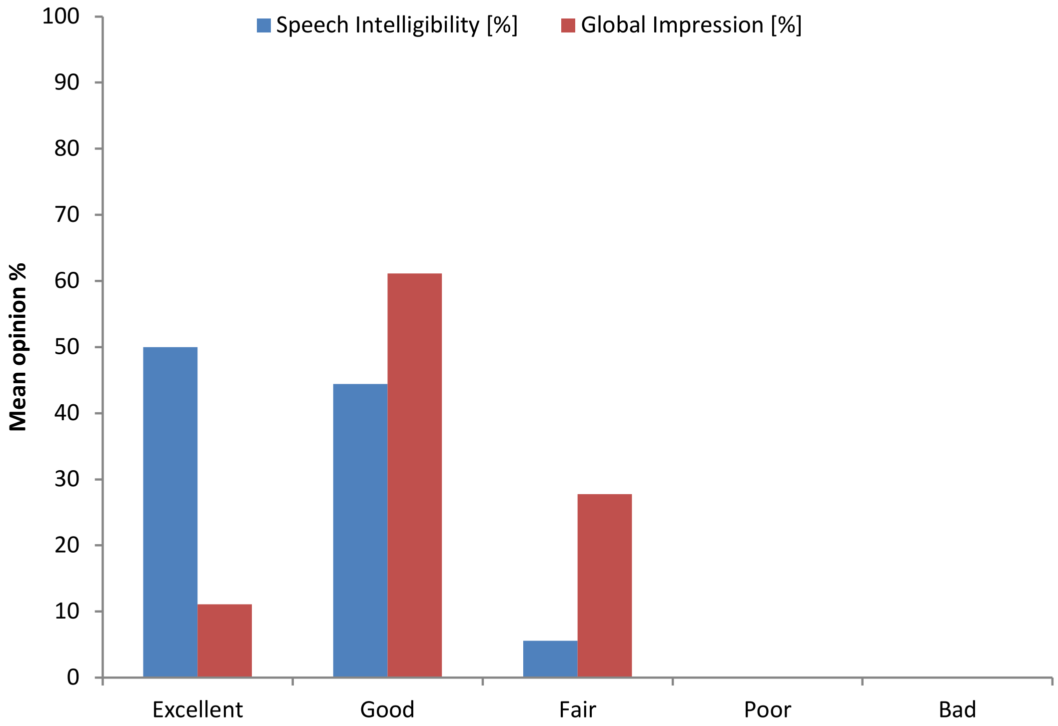
Jozef-Plateaustraat 22, ground floor, Ghent

Number of opinions	18
Use of microphone	Yes

Speech Intelligibility WITH micro				Global Impression			
STI	Rate	# students	%	STI	Rate	# students	%
Excellent	5	9	50	Excellent	5	2	11
Good	4	8	44	Good	4	11	61
Fair	3	1	6	Fair	3	5	28
Poor	2	0	0	Poor	2	0	0
Bad	1	0	0	Bad	1	0	0
Mean Speech Intelligibility [1 - 5]				Mean Global Impression [1 - 5]			
4.44 Good/Excellent				3.83 Fair/Good			

Plan - SI

Graph



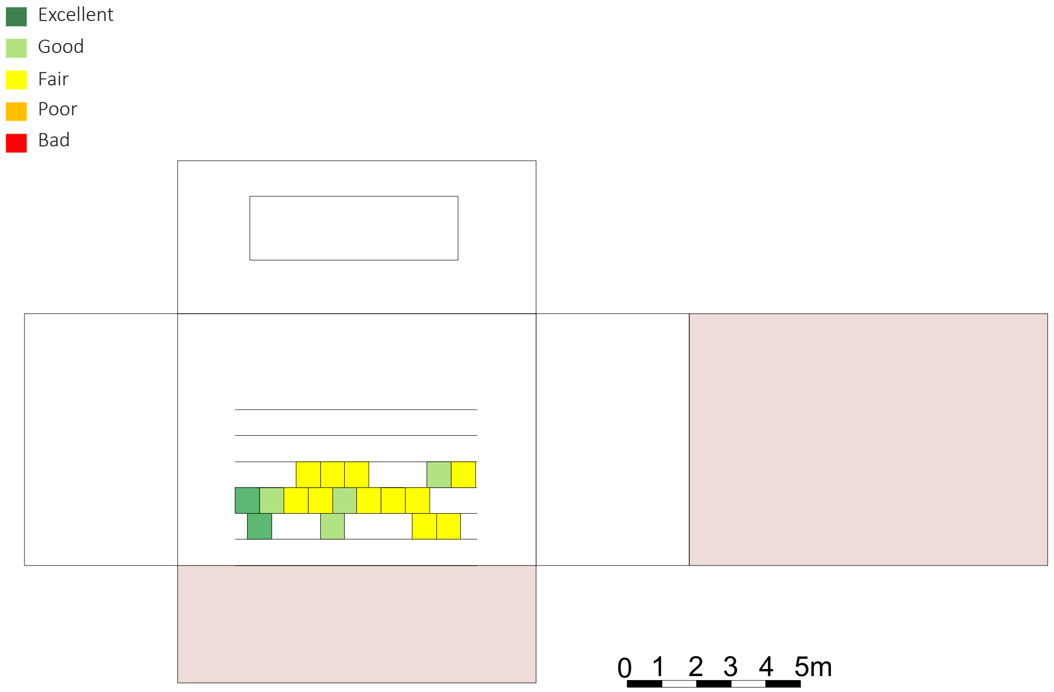
Auditorium C - Survey

Jozef-Plateaustraat 22, first floor, Ghent

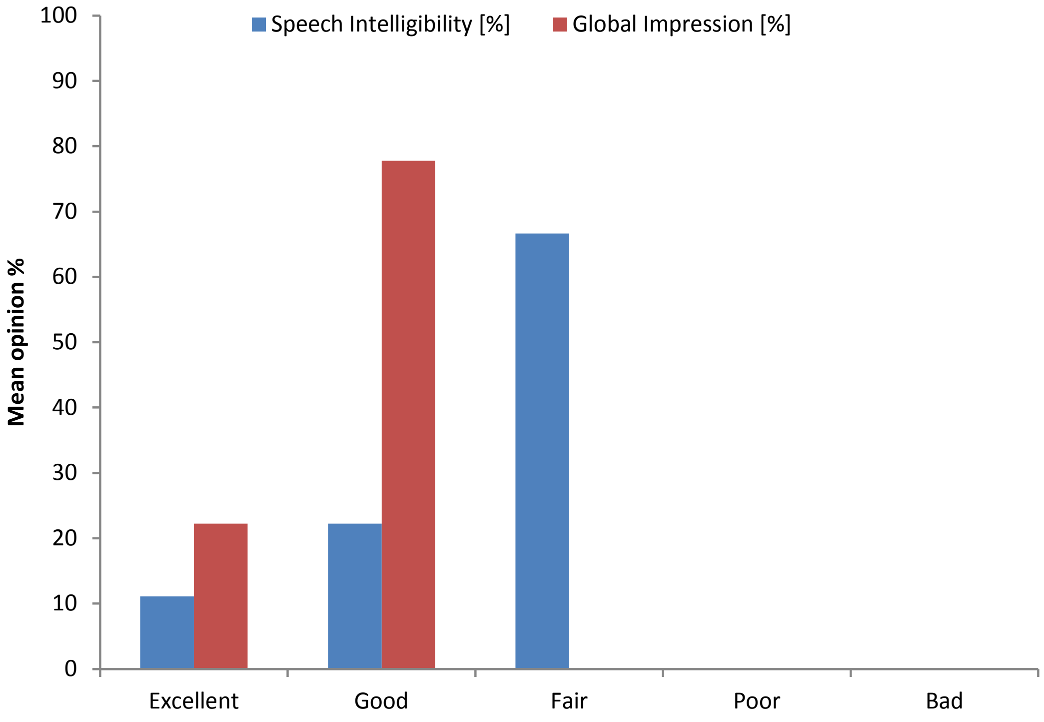
Number of opinions	18
Use of microphone	No

Speech Intelligibility WITHOUT micro				**Global Impression**			
STI	Rate	# students	%	STI	Rate	# students	%
Excellent	5	2	11	Excellent	5	4	22
Good	4	4	22	Good	4	14	78
Fair	3	12	67	Fair	3	0	0
Poor	2	0	0	Poor	2	0	0
Bad	1	0	0	Bad	1	0	0
Mean Speech Intelligibility [1 - 5]				**Mean Global Impression [1 - 5]**			
3.91				3.56			

Plan - SI



Graph



Auditorium D - Survey

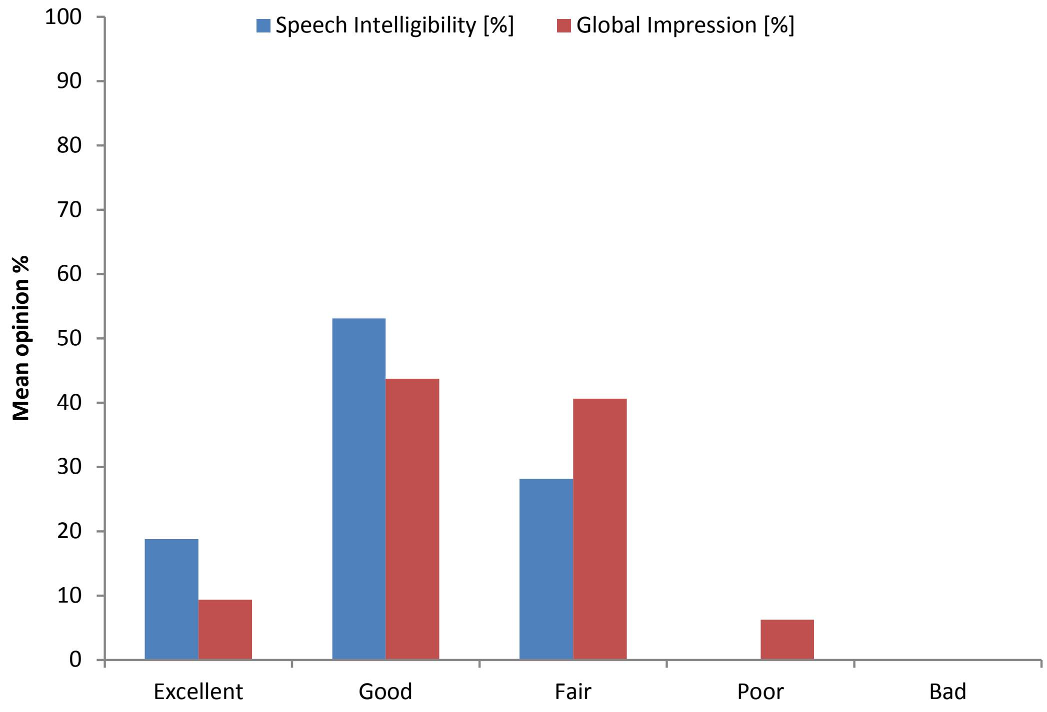
Jozef-Plateaustraat 22, first floor, Ghent

Number of opinions	32
Use of microphone	No

Speech Intelligibility WITHOUT micro				**Global Impression**			
STI	Rate	# students	%	STI	Rate	# students	%
Excellent	5	6	19	Excellent	5	3	9
Good	4	17	53	Good	4	14	44
Fair	3	9	28	Fair	3	13	41
Poor	2	0	0	Poor	2	2	6
Bad	1	0	0	Bad	1	0	0
Mean Speech Intelligibility [1 - 5]				**Mean Global Impression [1 - 5]**			
3.91				3.56			

Plan - SI

Graph



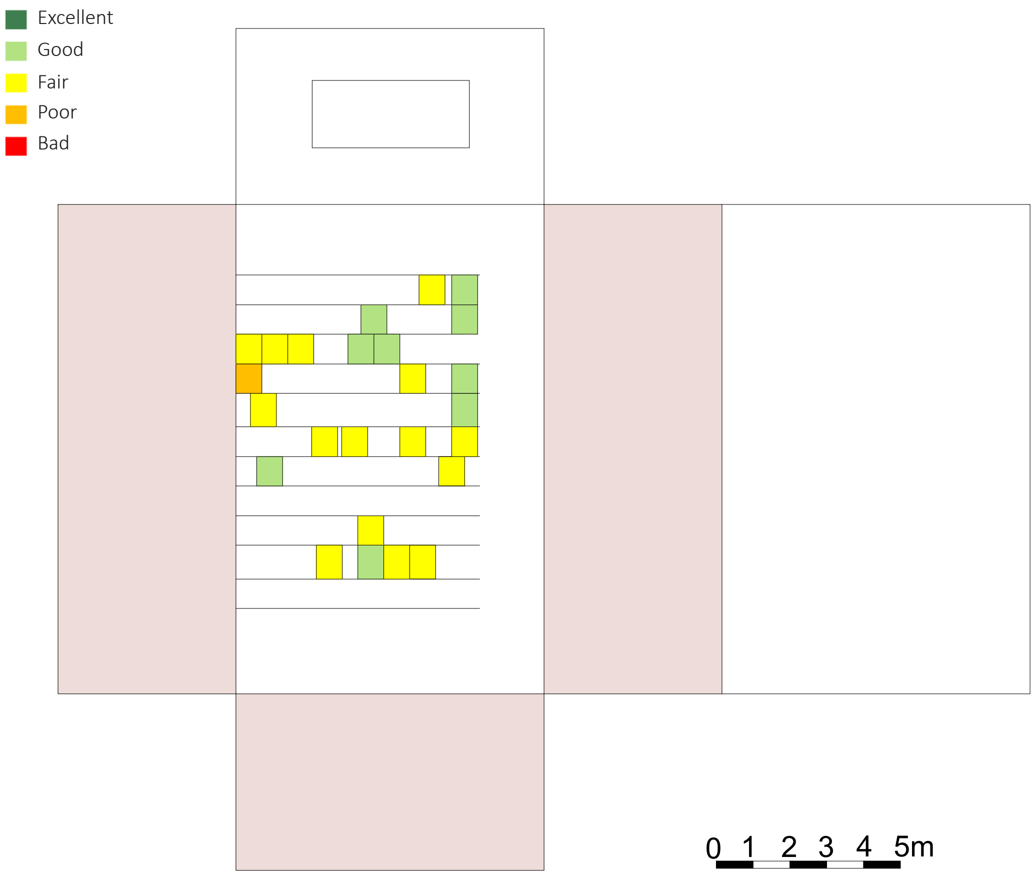
Auditorium E - Survey

Jozef-Plateaustraat 22, first floor, Ghent

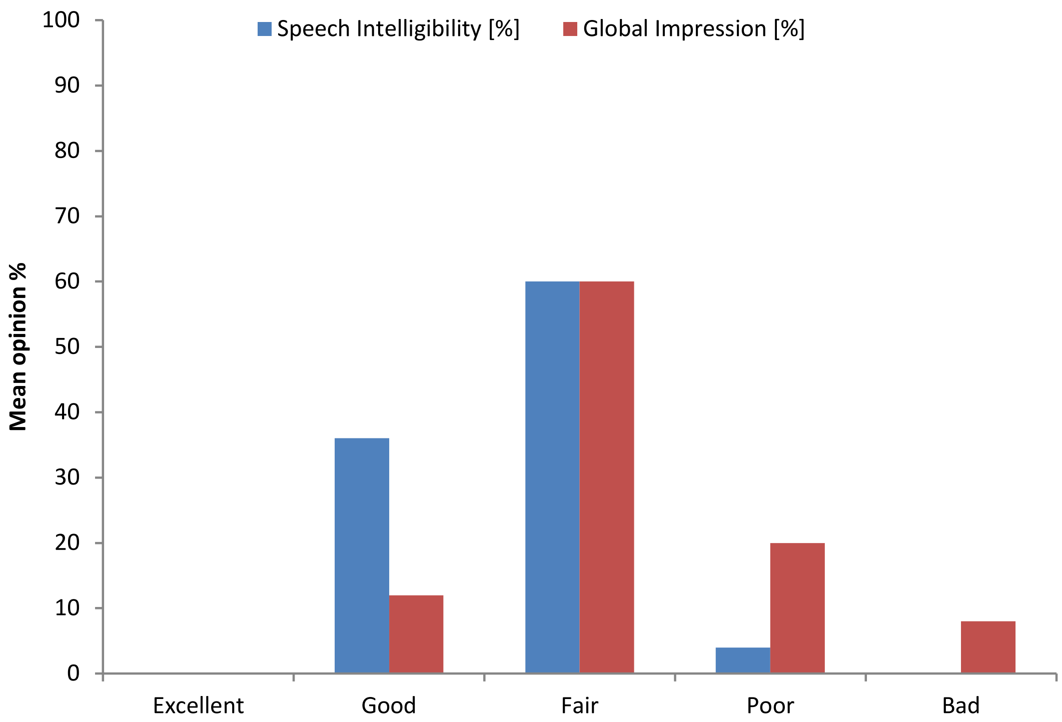
Number of opinions	25
Use of microphone	No

Speech Intelligibility WITHOUT micro				Global Impression			
STI	Rate	# students	%	STI	Rate	# students	%
Excellent	5	0	0	Excellent	5	0	0
Good	4	9	36	Good	4	3	12
Fair	3	15	60	Fair	3	15	60
Poor	2	1	4	Poor	2	5	20
Bad	1	0	0	Bad	1	2	8
Mean Speech Intelligibility [1 - 5]				**Mean Global Impression [1 - 5]**			
3.32				2.76			

Plan - SI



Graph

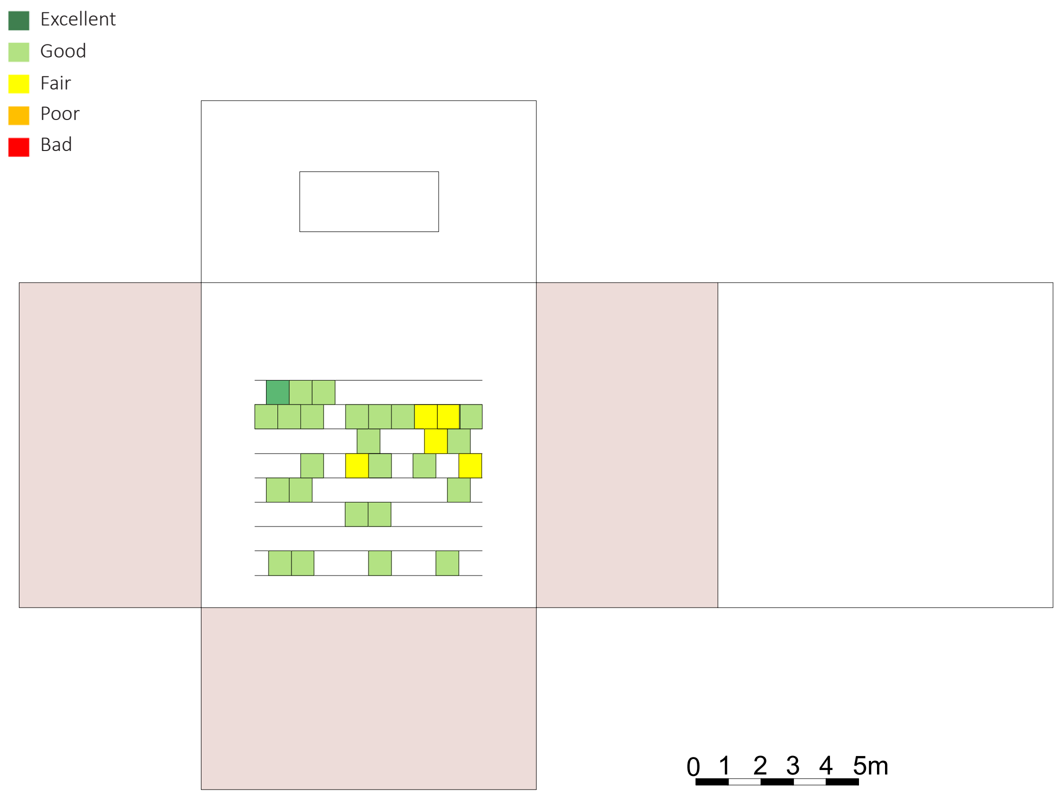


Auditorium G - Survey

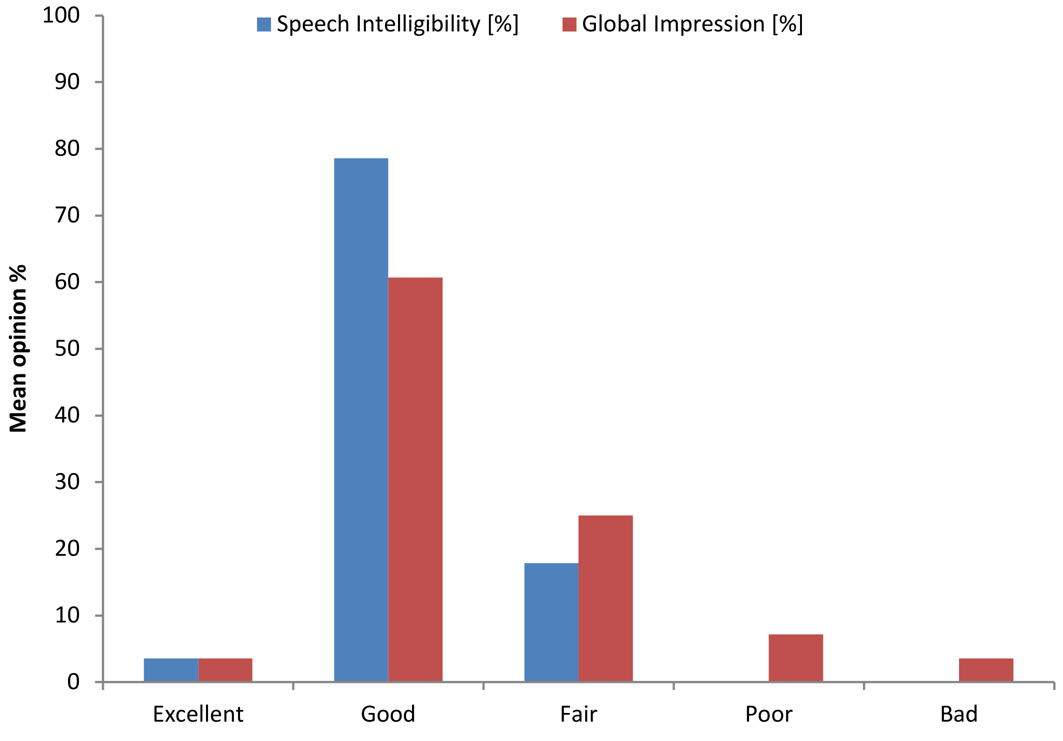
Jozef-Plateaustraat 22, first floor, Ghent

Number of opinions				28			
Use of microphone				No			
Speech Intelligibility WITHOUT micro				**Global Impression**			
STI	Rate	# students	%	STI	Rate	# students	%
Excellent	5	1	4	Excellent	5	1	4
Good	4	22	79	Good	4	17	61
Fair	3	5	18	Fair	3	7	25
Poor	2	0	0	Poor	2	2	7
Bad	1	0	0	Bad	1	1	4
Mean Speech Intelligibility [1 - 5]				**Mean Global Impression [1 - 5]**			
3.86				3.54			

Plan - SI



Graph

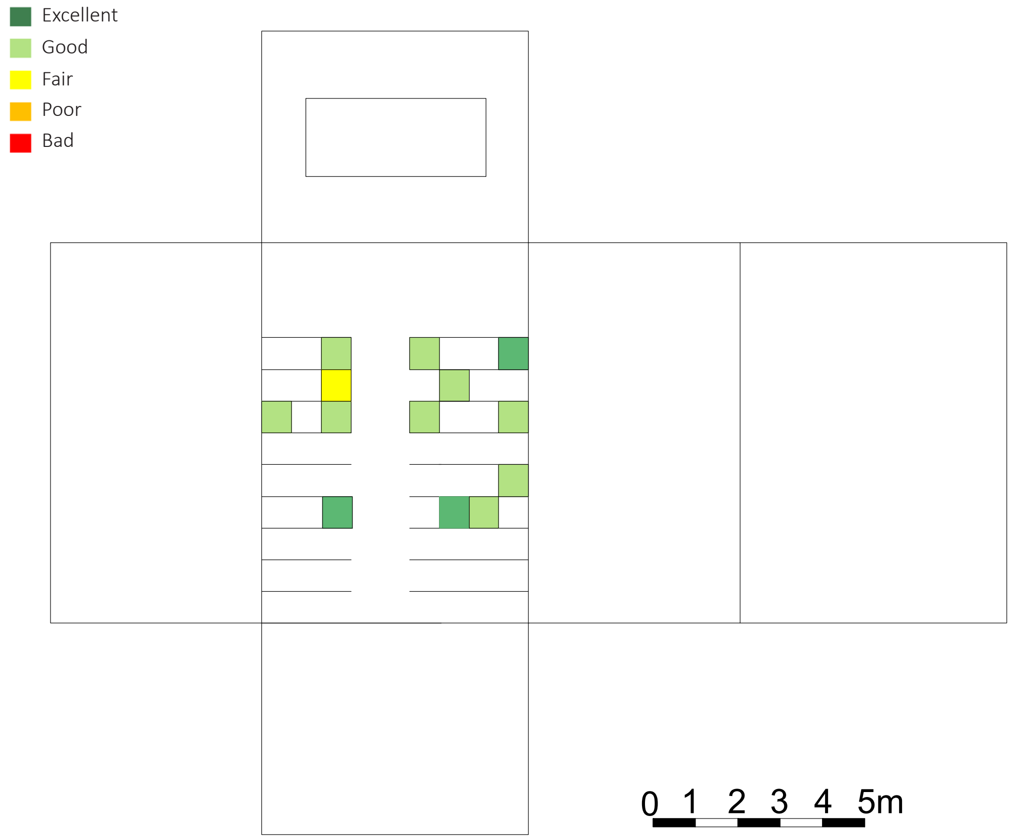


AUDITORIUM H - SURVEY

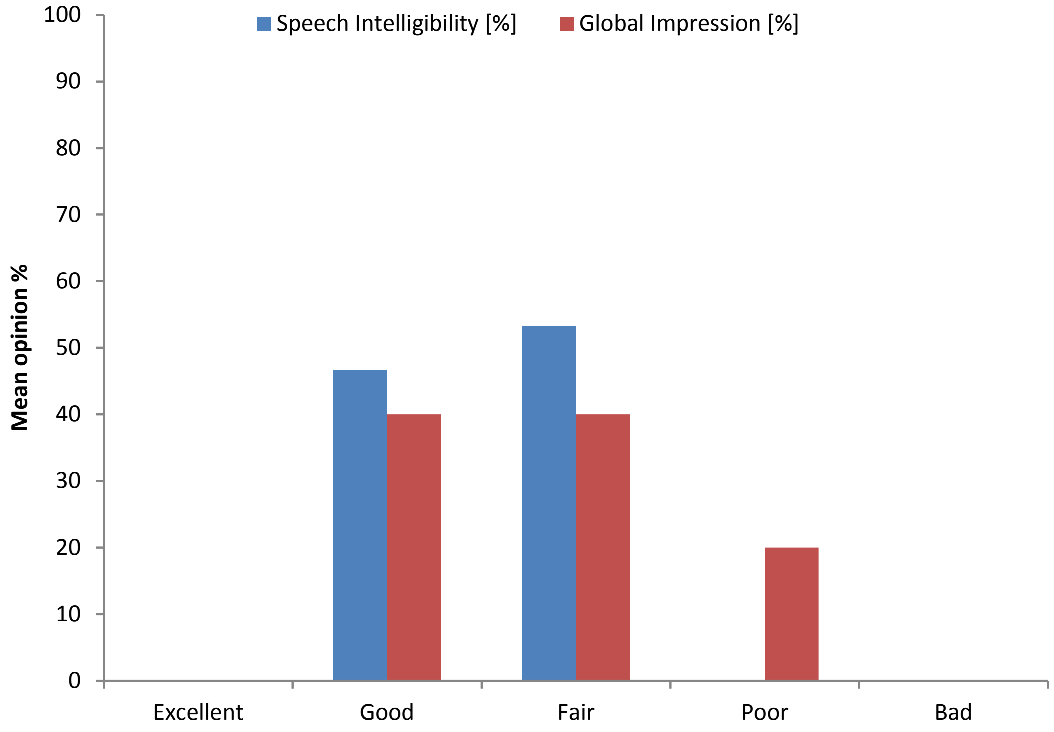
JOZEF-PLATEAUSTRAAT 22, FIRST FLOOR, GHENT

Number of opinions				15			
Use of microphone				No			
SPEECH INTELLIGIBILITY WITHOUT MICRO				**GLOBAL IMPRESSION**			
STI	Rate	# students	%	STI	Rate	# students	%
Excellent	5	0	0	Excellent	5	0	0
Good	4	7	47	Good	4	6	40
Fair	3	8	53	Fair	3	6	40
Poor	2	0	0	Poor	2	3	20
Bad	1	0	0	Bad	1	0	0
MEAN SPEECH INTELLIGIBILITY [1 - 5]				**MEAN GLOBAL IMPRESSION [1 - 5]**			
3.47				3.20			

PLAN - SI



GRAPH



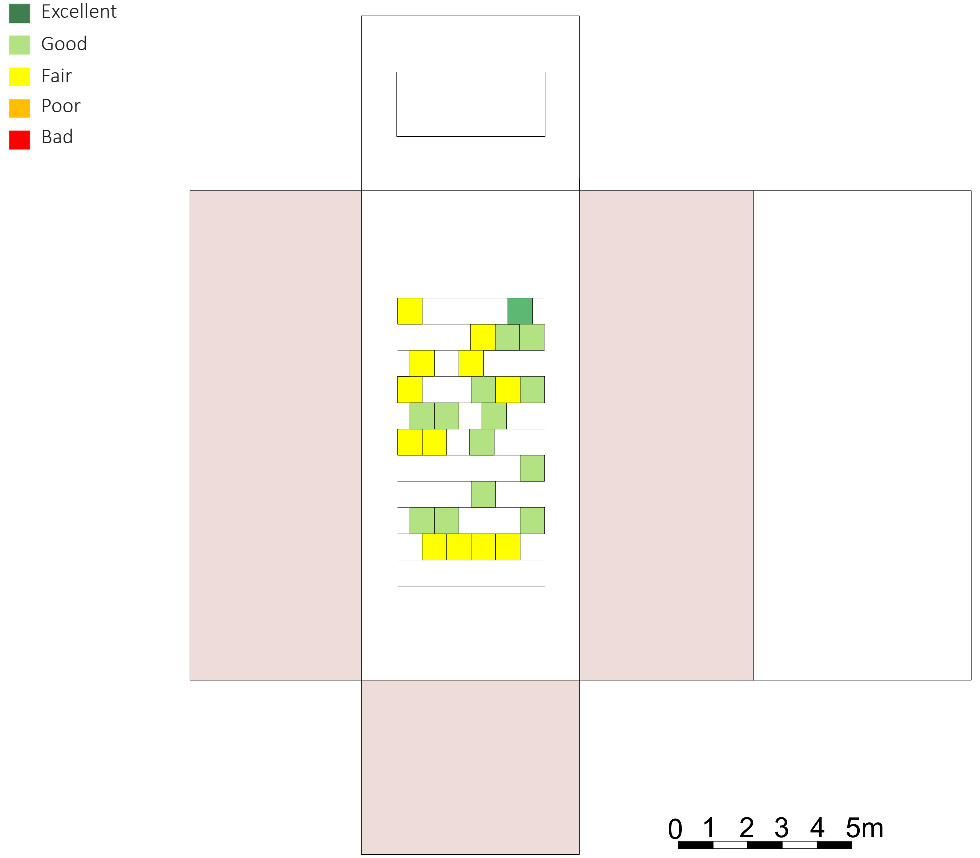
AUDITORIUM I - SURVEY

JOZEF-PLATEAUSTRAAT 22, FIRST FLOOR, GHENT

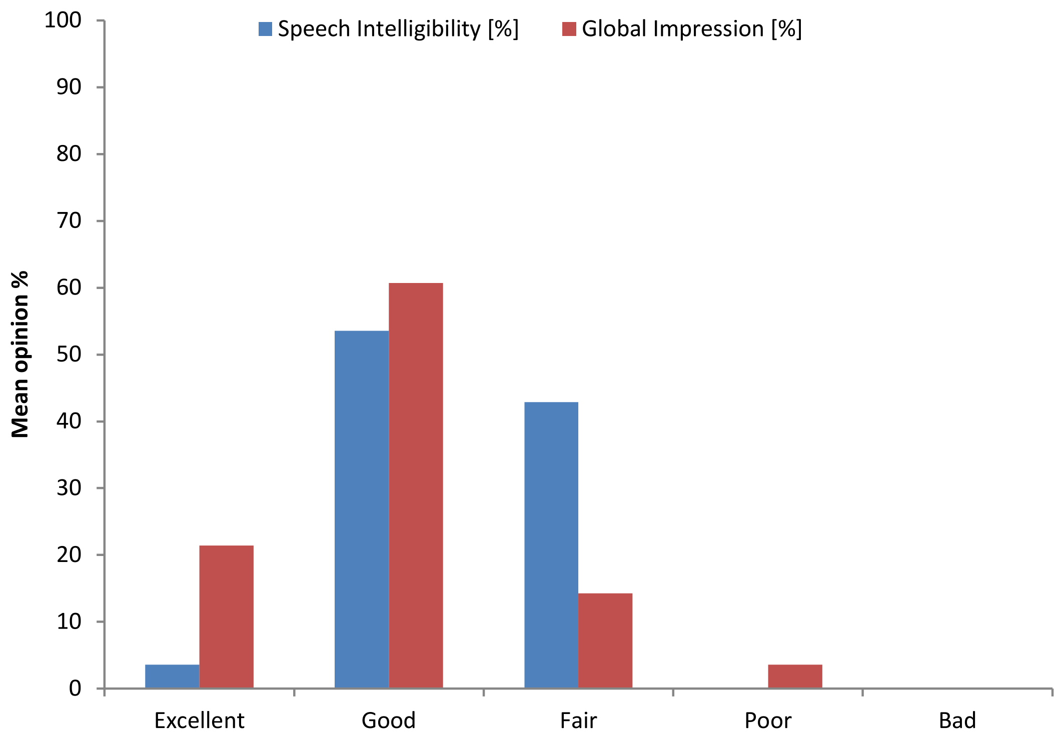
Number of opinions	28
Use of microphone	No

SPEECH INTELLIGIBILITY WITHOUT MICRO				GLOBAL IMPRESSION			
STI	Rate	# students	%	STI	Rate	# students	%
Excellent	5	1	4	Excellent	5	6	21
Good	4	15	54	Good	4	17	61
Fair	3	12	43	Fair	3	4	14
Poor	2	0	0	Poor	2	1	4
Bad	1	0	0	Bad	1	0	0
MEAN SPEECH INTELLIGIBILITY [1 - 5]				MEAN GLOBAL IMPRESSION [1 - 5]			
3.61				4.00			

PLAN - SI



GRAPH

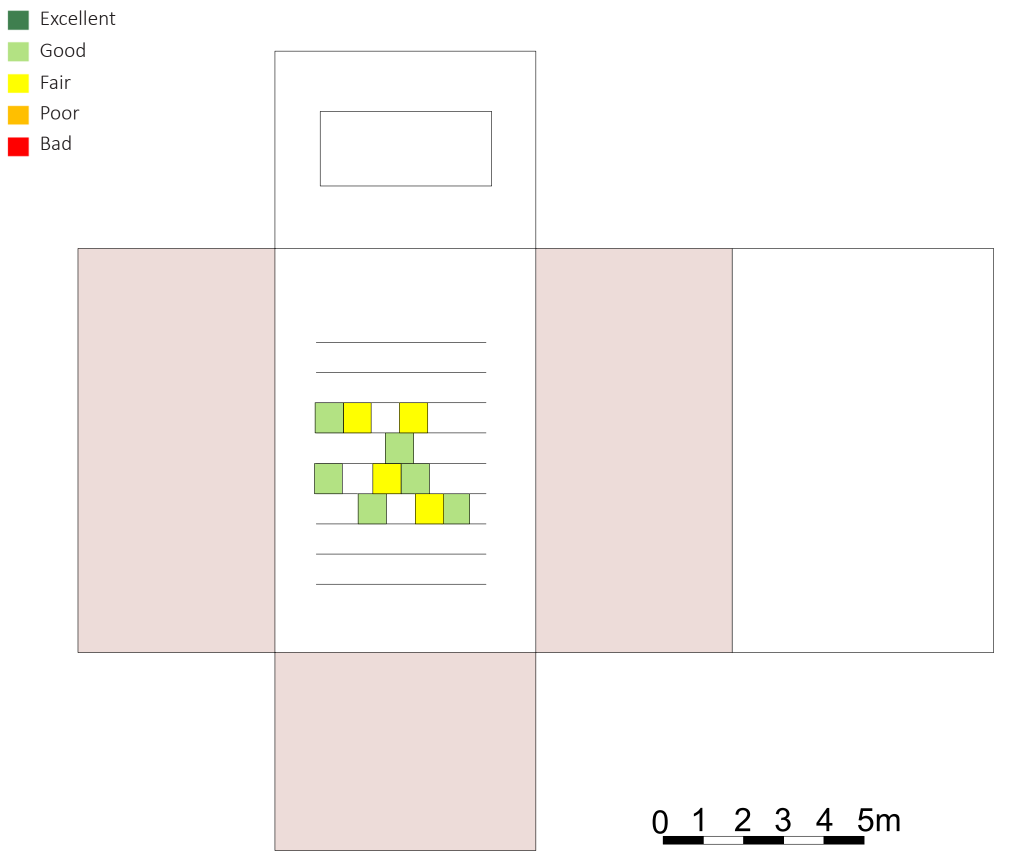


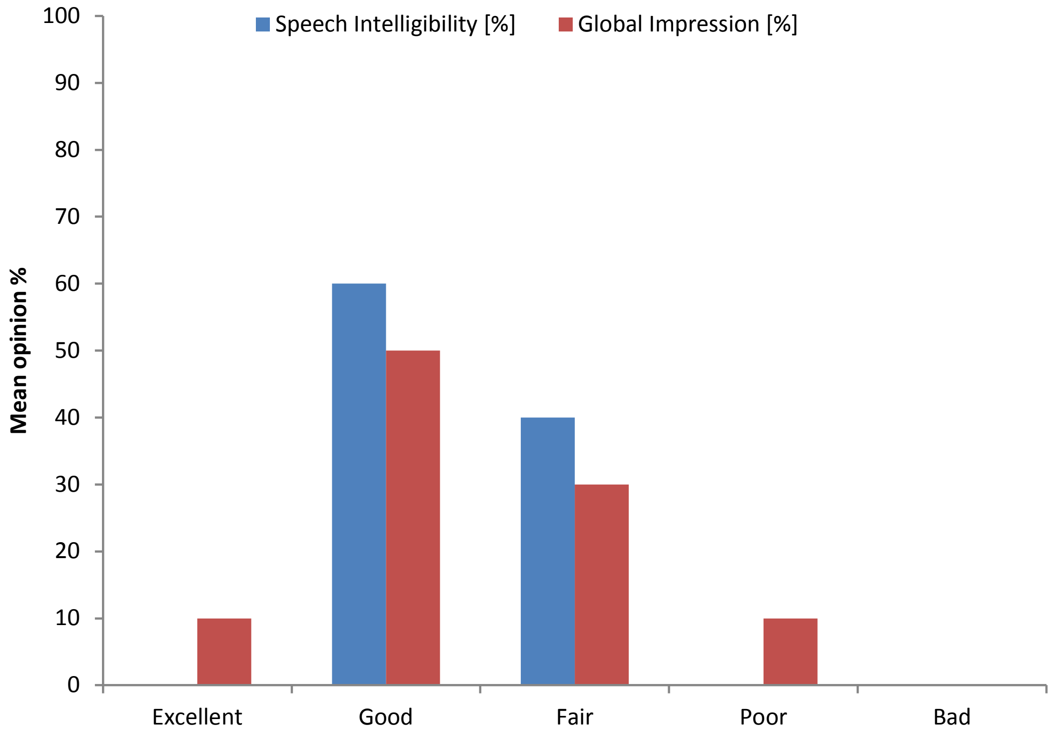
Auditorium J - Survey

Jozef-Plateaustraat 22, first floor, Ghent

Number of opinions				10			
Use of microphone				No			
Speech Intelligibility WITHOUT micro				**Global Impression**			
STI	Rate	# students	%	STI	Rate	# students	%
Excellent	5	0	0	Excellent	5	1	10
Good	4	6	60	Good	4	5	50
Fair	3	4	40	Fair	3	3	30
Poor	2	0	0	Poor	2	1	10
Bad	1	0	0	Bad	1	0	0
Mean Speech Intelligibility [1 - 5]				**Mean Global Impression [1 - 5]**			
3.60				3.60			

Plan - SI	Graph





Auditorium K - Survey

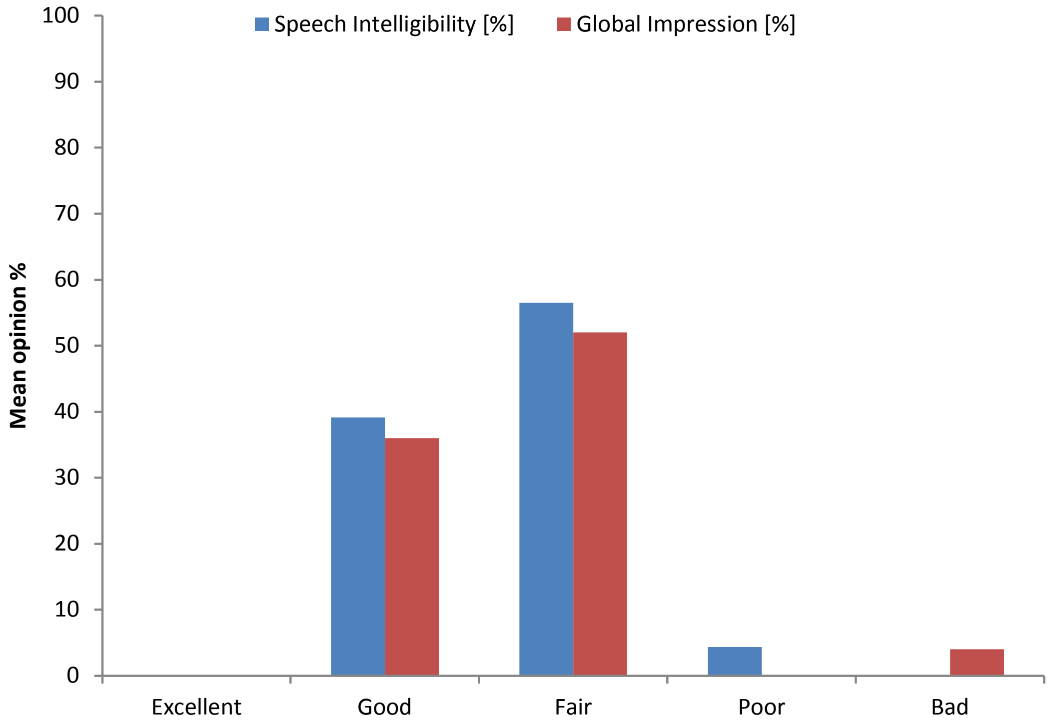
Jozef-Plateaustraat 22, first floor, Ghent

Number of opinions	23
Use of microphone	No

Speech Intelligibility WITHOUT micro				Global Impression			
STI	Rate	# students	%	STI	Rate	# students	%
Excellent	5	0	0	Excellent	5	0	0
Good	4	9	39	Good	4	9	36
Fair	3	13	57	Fair	3	13	52
Poor	2	1	4	Poor	2	0	0
Bad	1	0	0	Bad	1	1	4
Mean Speech Intelligibility [1 - 5]				Mean Global Impression [1 - 5]			
3.35				3.30			

Plan - SI

Graph



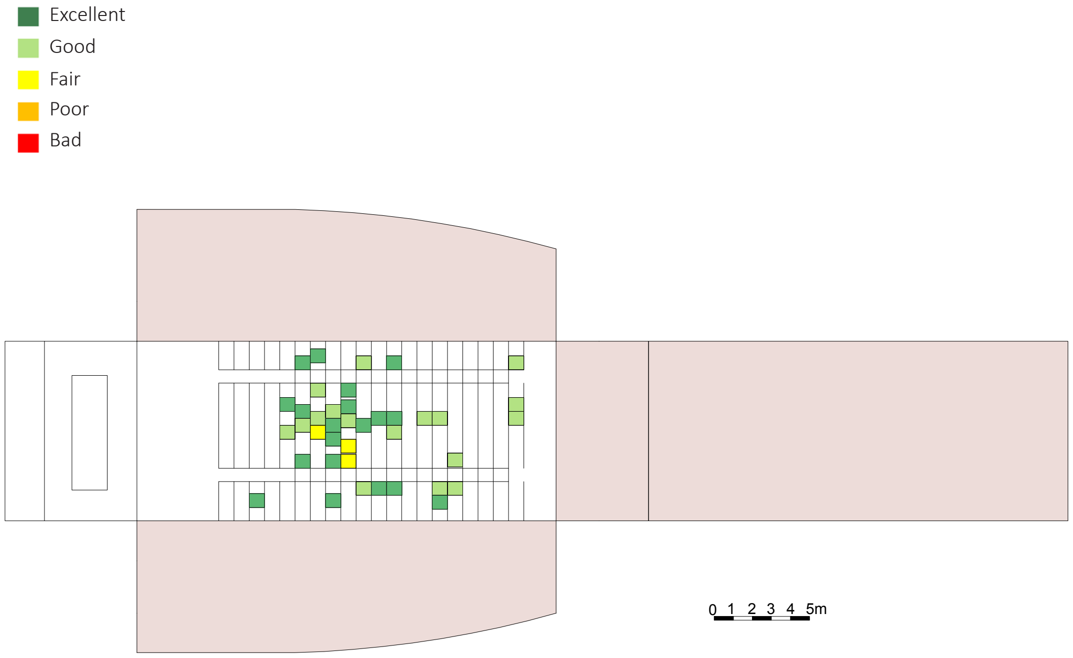
Auditorium N - Survey

Jozef-Plateaustraat 22, first floor, Ghent

Number of opinions	39
Use of microphone	Yes

Speech Intelligibility WITHOUT micro				Global Impression			
STI	Rate	# students	%	STI	Rate	# students	%
Excellent	5	19	49	Excellent	5	4	10
Good	4	17	44	Good	4	31	79
Fair	3	3	8	Fair	3	4	10
Poor	2	0	0	Poor	2	0	0
Bad	1	0	0	Bad	1	0	0
Mean Speech Intelligibility [1 - 5]				Mean Global Impression [1 - 5]			
4.41				4.00			

Plan - SI



Graph