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EXPERIMENTAL CHARACTERIZATION OF THE ACOUSTICAL PARAMETERS OF TWO LECTURE ROOMS

Master's Thesis

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Author’s declaration of originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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Abstract

The aim of this study is to obtain the ISO-3382 acoustic parameters, the speech transmission index (STI) and the reverberation time (T30) of two lecture rooms. The impulse response is measured by means of logarithmic sine sweep method using ARTA software for signal acquisition and processing. The two lecture rooms are situated in Tallinn University of Technology (Taltech). The obtained parameters have been analysed to understand the acoustic conditions of the rooms and to validate a numerical model of the same rooms provided by the software package CADNA-R. Finally, a solution technique has been provided for improving the acoustic behaviour of the lecture rooms based on numerical solution.

Keywords: Reverberation Time (T30), Speech Intelligibility, ARTA, sine sweep, CADNA-R.

Annotatsioon

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Lõputöö on kirjutatud Inglise keeles ning sisaldab teksti 91 leheküljel, kuus peatükki, 111 joonist, 51 tabelit.

List of abbreviations and terms

BEM	*Boundary Element Method*
CAD	*Computer Aided Design*
dB	*Decibel*
EDT	*Early Decay Time*
FEM	*Finite Element Method*
GAM	*Geometrical Acoustic Method*
IR	*Impulse Response*
LTI	*Linear and time invariant*
MTF	*Modulation Transfer Function*
MLS	*Maximum Length Sequence*
PRD	*Prime root diffusors*
QRD	*Quadratic residue diffusor*
RAM	*Room Acoustic Modelling*
RT	*Reverberation Time*
STI	*Speech Transmission Index*
TUT	*Tallinn University of Technology*

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1 Introduction

Architectural acoustic is a branch of acoustical engineering dealing with achieving a good sound and speech intelligibility within the buildings. There are different types of buildings like concert hall, churches, classroom etc., which are characterized by different levels of speech intelligibility. This thesis aims at characterizing the acoustics of two lecture rooms by means of an experimental approach and at improving the speech intelligibility by using a numerical method [1].

1.1 Problem Statement

A proposal came from my supervisors regarding investigating the acoustic conditions of two lecture rooms (U03-103, U04-103) present in TalTech university. |In fact, the students observed and reported a poor speech intelligibility of the rooms. In order to analyse the acoustic condition of the rooms the impulse response (IR) was measured using logarithmic sine sweep method. Then the analysis of the acoustic parameters was carried out from the measured IR. Finally, a technical solution was provided to improve the speech intelligibility of the lecture rooms based on a numerical approach.

1.2 Motivation and goals

The aim of this thesis is gaining the knowledge about the practical acoustic condition of the lecture rooms by analysing the influence of room shape, interiors and the presence of absorbing materials on the acoustic parameters reverberation time (RT) and the early decade time (EDT) which, ultimately affect the speech intelligibility. This was useful to validate the numerical model of the rooms which has be used to provide a practical solution for improving the speech transmission index (STI) of the two lecture rooms.

1.3 Structure of the thesis

The structure of this thesis consists of the following chapters: chapter 2 explains about the ISO-3382 parameters, the IR and different types of method for measuring IR. Chapter 3 defines the acoustic treatment elements and sound insulation concept. Chapter 4 presents the field measurements of the two lecture rooms. Later, in chapter 5, the room acoustic modelling of the lecture rooms is described, including the solutions to improve the acoustic behaviour. Finally, the summary of the work and the conclusions are provided in the chapter 6.

2 Room Acoustic Parameters

The acoustic performance of a room is defined by its acoustic parameters. The revised document which define the room acoustic parameters was released by ISO in 2009[1] which improved, with a few changes in the annexure, the previous version represented by the document ISO-3382:1997. Fig-1 below shows the various acoustic parameters of ISO-3382.

Quantity Symbol	*Subjective Aspect*
Reverberation time T_{30}, T_{20} (s)	reverberance, loudness, involvement
Early decay time EDT (s)	reverberance, clarity
Center time T_S (s)	clarity
Clarity C_{80} (dB)	clarity
Definition D_{50} (%)	speech definition
Strength G (dB)	relative sound level
Lateral energy fraction LF, LFC (%)	spatial impression
Interaural cross-correlation IACC	spatial impression

Figure 1: ISO-3382 acoustic parameters

2.1.1 **Reverberation Time**

One of the most important parameters is the reverberation time (RT), which is defined as the time taken for the sound energy to decay to 60 dB. It was first introduced by the physic researcher Wallace Clement Sabine (Father of Architectural acoustics) as follows.

$$T60 = 0.161\frac{V}{A} \qquad (2.1.1.1)$$

Where T_{60}: Reverberation Time

V: Volume of room in cubic meters

A: Total area of absorption in the room

Sabine’s RT equation is not able to provide good measurement accuracy in dead rooms[2] (Anechoic Chambers), so Carl Eyring introduced a RT equation which can provide more accurate measurements:

$$T60 = 0.049 \frac{V}{S \ln(1 - \alpha)} \qquad (2.1.1.2)$$

Here S is the surface area of the room and α is the absorption coefficient.

In 1965 Schroders[3] proposed a new method for measuring reverberation time in a practical way. Later, many modifications have been provided by scientists to provide more detailed descriptions of the acoustic behaviour of the buildings. The first standardized procedure was released by ISO in 1997 with the above mentioned ISO-3382 document [4].

2.1.1.1 Measuring Methods of Reverberation Time (RT)

The two main methods available to measure the RT are described below [1].

- **Interrupted noise method**

A steady state level of the random noise has to be achieved in the free space, then the excitation has be stopped and the subsequent sound pressure decay level is measured [5]. The noise source most commonly used for this method is pink noise, due to its greater presence of low frequency energy when compared to white noise signal. This method requires multiple measurements of a free space due to the random nature of the excitation signal [6]. The figure 2 shows an example of this type of measurement.

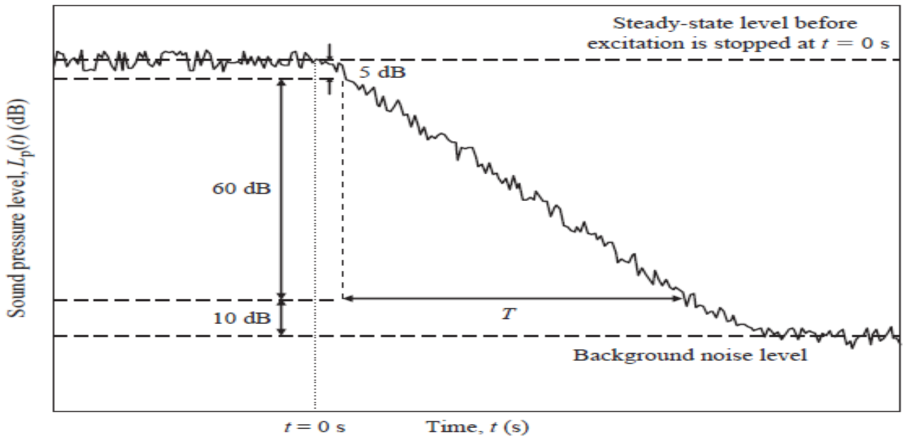


Figure 2: Example decay curve measured using the interrupted noise method

- **Integrated impulse response method**

The impulse response, h(t), is the resulting response of the acoustic system which is excited by a Dirac delta function signal. The system which is observed can be an acoustic system (e.g. a room), a mechanical structure as well as chain of measurement equipment. The integrated impulse response method involves generating an impulse and recording or sampling the response of the system to this impulse. Creating the Dirac delta function is not possible in practice due to infinite height and narrow width, but it is possible to create an impulse of short duration approximating the Dirac delta function. Traditionally, for many years the impulse source used to measure the RT of a room was generated by hand claps, pistol gunshot, balloon burst, or noise burst via loudspeaker. However, these impulse sources present the limitation of being not omnidirectional and generate a flat spectrum with high crest factors (ratio of peak to rms) [5]. To avoid the above-mentioned problems, the response of a linear acoustic system (such as a room) can be measured in time by using a swept sine signal (SSS) as impulse source or by using a maximum length sequence signal (MLS). The differences between these two approaches and the reason why the sine sweep signal has been used for in the present work are explained below.

- **Comparison of impulse source**

As previously mentioned, the most common excitation signals for measuring the IR are the SSS and MLS, as well as the Inverted Repeated Sequence (IRS) and the Time-Stretched Pulses (TSP). Comparison studies have been carried out in the past by analysing the signal parameters involved in the different methods thus, to understand the pro and cons of all of them. The results justified that the sine sweep signals has higher immunity against distortion and has more signal to noise ratio (SNR) compared to the other two signals[7]. The sine sweep has the lowest crest factor – 3db – compared to the MLS which has 8db[8].

- **Logarithmic Sine Sweep Method**

When the sine sweep is generated with instantaneous frequency varying exponentially with time, the method is referred to as logarithmic sine sweep [9].

The general form of an exponential swept sine signal is

$$S(t) = \sin\,[\theta(t) = \sin\,[K.\, e^{t/L}\text{-}1] \qquad (2.1.1.3.1)$$

Where

$$K = \frac{T.\,w1}{\ln\,(\frac{w2}{w1})} \qquad (2.1.1.1.2)$$

$$L = \frac{T}{\ln\,(\frac{w2}{w1})} \qquad (2.1.1.1.3)$$

The lower and higher extremities of the frequency range (w1 & w2), T is the time duration in seconds[10].

The instantaneous frequency w(t) can be described as:

$$w(t) = \frac{K}{L}\,.\, e^{t/L} \qquad (2.1.1.1.4)$$

2.1.2 **EDT**

In this section, another parameter introduced by the ISO standard and used in this work, the early decay time (EDT) is introduced. The EDT is defined as the time interval required for the sound energy level to decay 10 dB after the excitation has stopped. The EDT shall be evaluated from the slope of the integrated impulse response curves (as the conventional reverberation time) [1]. To enable direct comparison with the reverberation time, the result is multiplied by a factor of 6. For an ideal exponential decay in a diffuse field, the expected value of the EDT equals reverberation time. An example of EDT computation is shown in Figure 3.

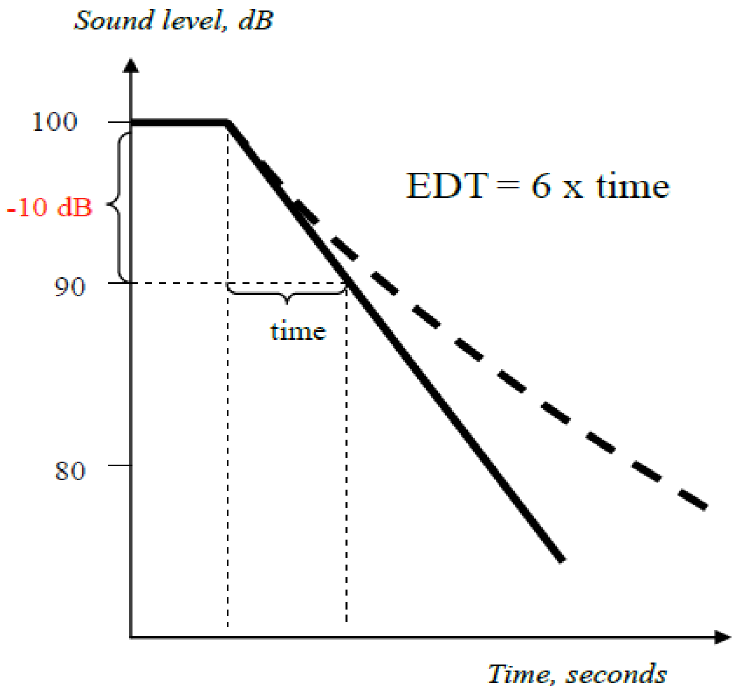


Figure 3: Example of EDT

2.1.3 **STI**

In this section, another parameter largely used in building acoustic, the speech transmission index (STI) is introduced. This parameter is not directly included in the ISO standard, but it is of practical meaning. The STI was first provided by Herman Steeneken and Tammo Houtgast in 1971. The STI has developed gradually since then, into the mature and widely recognized and applied measuring tool. It represents an objective, physical measure of speech transmission quality of a communication channel. The STI is a measured in metric index (0 to 1), indicating the degree to which a transmission channel degrades speech intelligibility. This means that perfectly intelligible speech, when transferred through a channel with an associated STI of 1[11], will remain perfectly intelligible. Instead, the closer the STI value is to zero, the more information is lost. The first STI is mathematically defines as:

$$STI = \frac{1}{\alpha}\sum_{n=1}^{5}\alpha_n\left(\frac{\Delta L\acute{}n^{p}}{\Delta L}\right)$$

Where

$\alpha = \sum_{n=1}^{5}\alpha_n$

n: number of octave bands (2.1.3.1)

$\alpha_{n:}$ octave-band weighting factor

ΔL(dB): Initial level difference in dB

P: power applied

The International Electrotechnical Commission has provided the correspondence between STI and the quality of the speech intelligibility in the document IEC60268-16. The main outcomes are summarized in the Table 1.

STI	**Speech Intelligibility**
0.00-0.30	Bad
0.30 – 0.45	Poor
0.45 – 0.60	Fair
0.60 – 0.75	Good
0.75 – 1.00	Excellent

Table 1: STI values

2.1.4 **STI measurement from impulse response**

For the purpose of this thesis, the measurement of the STI from impulse response was computed using ARTA software. The procedure is schematized in the Figure 4.

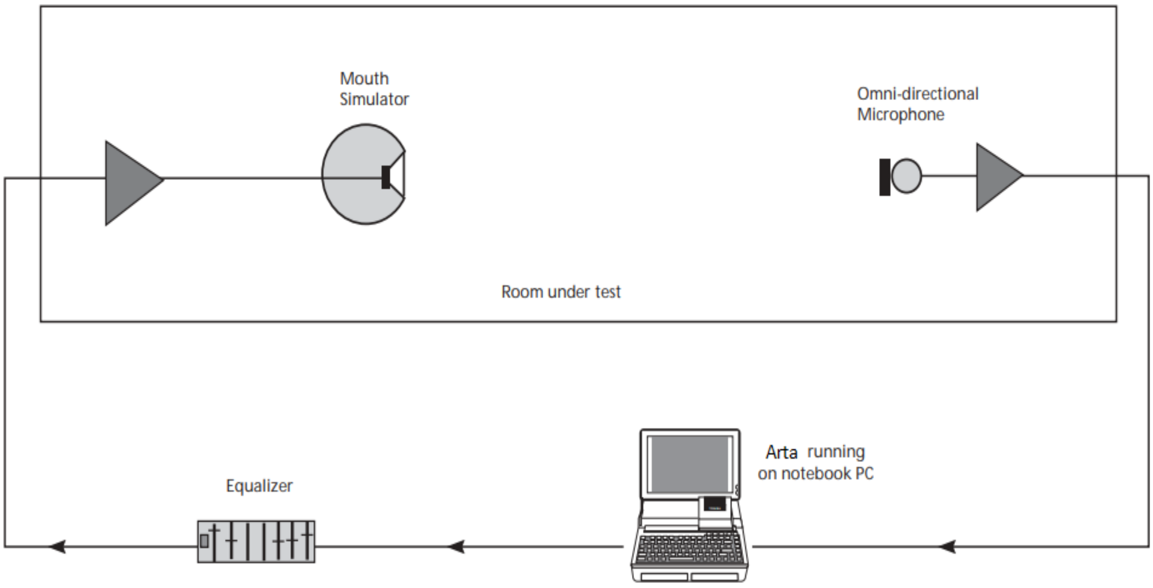


Figure 4: Measurement setup

The following steps are followed by the ARTA software.

- ➢ Calibration of the hardware equipment from ARTA software settings.
- ➢ Playing an inbuilt logarithmic sine sweep signal for 5 trials.
- ➢ Stopping the signal, automatically, after 5 trials.
- ➢ Then the best impulse response for the chosen microphone position is obtained. An example is shown in Figure 5.

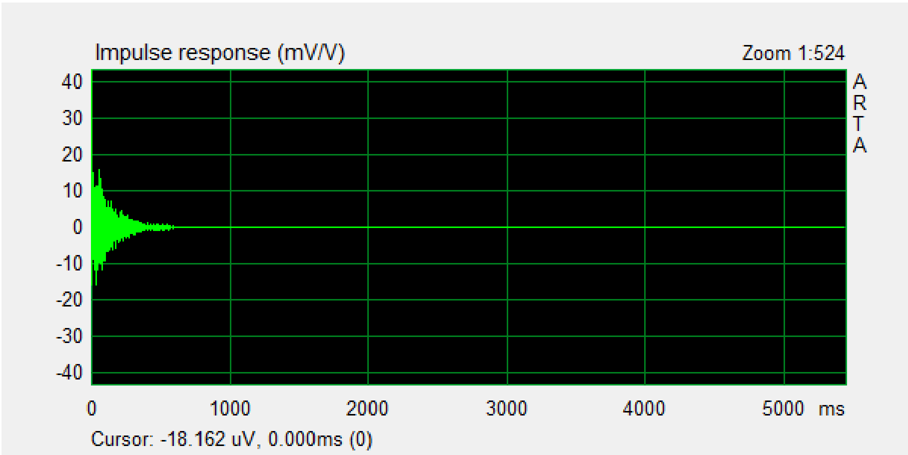


Figure 5: Impulse response

- ➢ At this stage, the values of the so-called modulation transfer function (MTF) are extracted for 7 octave bands and 14 modulation frequencies. In total, 98 values of MTF are obtained.

- MTF values are related to the signal to noise ratio (SNR), which are calculated as follows:

$$SNR = 10\log MTF/(1 - MTF) \qquad (2.1.4.1)$$

- The mean SNR are calculated for 7 octave bands.

- The mean SNRs are weighted with weighting constants which depend on the octave band.

- Then the STI is obtained from the mean weighted SNR value.

$$STI = \text{SNR} + 15/30 \qquad (2.1.4.2)$$

In the Figure 6, a typical example of STI measurement is shown, including the 98 MTF values obtained by means of impulse response based on logarithmic sine sweep.

Band	125	250	500	1000	2000	4000	8000
0.63	0.9066	0.9388	0.9469	0.9610	0.9706	0.9798	0.9976
0.80	0.8606	0.9056	0.9169	0.9385	0.9536	0.9676	0.9961
1.00	0.8122	0.8692	0.8829	0.9127	0.9341	0.9531	0.9942
1.25	0.7631	0.8315	0.8466	0.8845	0.9128	0.9367	0.9920
1.60	0.6661	0.7583	0.7721	0.8246	0.8679	0.8997	0.9868
2.00	0.5723	0.6935	0.7005	0.7643	0.8231	0.8594	0.9807
2.50	0.4413	0.6173	0.6051	0.6807	0.7603	0.7973	0.9704
3.15	0.3103	0.5517	0.5028	0.5941	0.6873	0.7180	0.9556
4.00	0.2589	0.5105	0.4284	0.5384	0.6277	0.6478	0.9410
5.00	0.2056	0.4644	0.3468	0.4850	0.5657	0.5634	0.9208
6.30	0.1309	0.3938	0.2532	0.4403	0.5159	0.4905	0.9013
8.00	0.0716	0.2558	0.1515	0.4142	0.4622	0.4261	0.8820
10.00	0.1879	0.1821	0.1805	0.3673	0.4359	0.3884	0.8654
12.50	0.0636	0.0774	0.2439	0.2500	0.4447	0.3923	0.8516
OctTI	0.4551	0.5574	0.5532	0.6245	0.6764	0.6913	0.9167

STI = 0.6654 (male), 0.6843 (female) Rating: GOOD (GOOD)

Figure 6: MTF Matrix and the resulting STI values.

2.2 Room Acoustic Modelling

Room acoustic modelling (RAM) is an established tool in architectural acoustic design for predicting the acoustic condition of the buildings with the aid of computer. It is highly supportive for acoustic researchers and consultant in their everyday approach[12].The RAM has its role in both the pre-design stage of the buildings and in the design of sound reinforcement systems [13]. The potential of computer modelling of room acoustic was first outlined by Schroder in 1960[12] and the famous paper on computer simulation was published by Krokstad, Strom and Sordal in 1968[14] boosted the replacement of scale based models with RAM. To understand the accuracy of RAM the predicted result of the existing room has to be validated by comparison with experimental results obtained by means of on-field measurements[12].

2.3 Types of Room Acoustic Modelling Methods

As shown in Figure 7, there are three most common approaches available for room acoustic modelling, i.e., wave based numerical modelling, geometrical acoustic method and artificial methods [15].

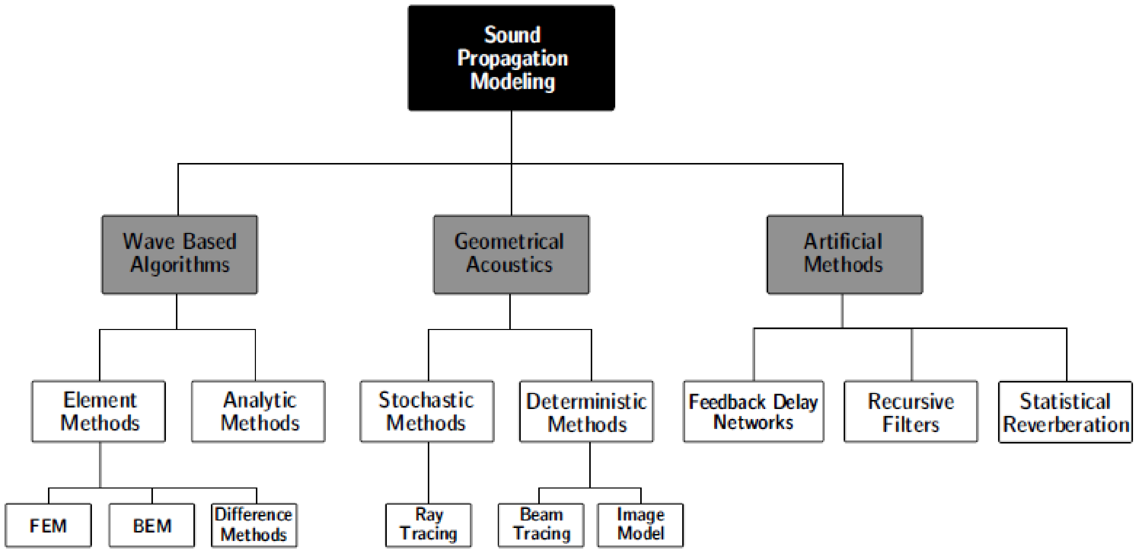


Figure 7: Classification of Acoustic Modelling Methods

The wave based modelling, such as Finite Element Method (FEM), provides high accuracy in the predicted results even though it is computationally demanding [15]. They are typically used for low-mid range frequency analyses. Instead, the geometrical acoustics modelling is more computationally efficient at mid-high frequencies. In Figure 8 it is shown how these two approaches can be combined to analyse the whole audible frequency spectrum of small environments (e.g. car compartments) and to provide the input for the binaural auralization.

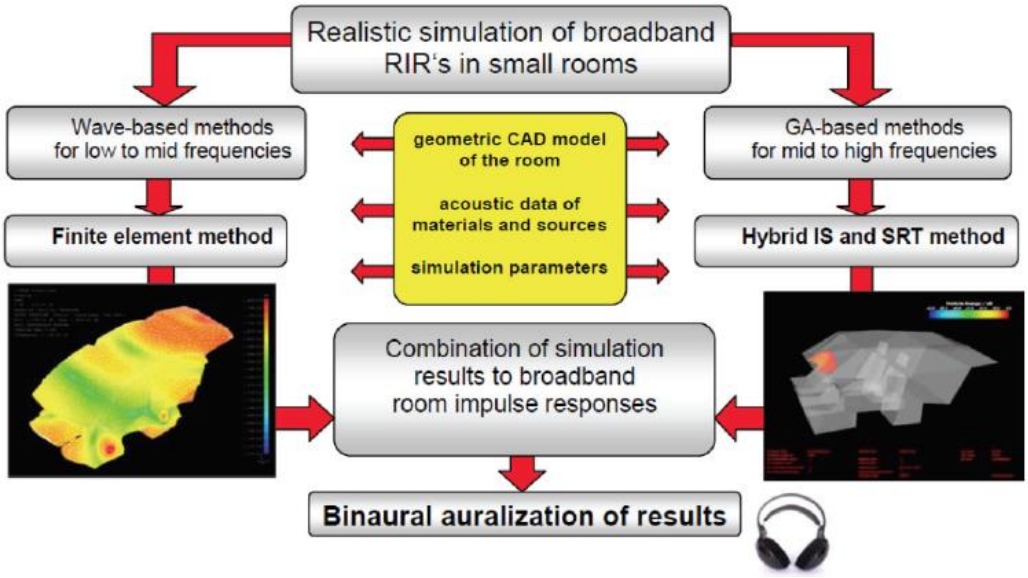


Figure 8: Combined use of wave-based and geometrical acoustic methods in small environments. [13]

2.3.1 **Geometrical Acoustic Method (GAM)**

The numerical analyses which were performed in this thesis are based on GAM. I highlight here that the main purpose of GAM is to compute the various ISO-3382 acoustic parameters from the measured impulse response or the time-energy. As mentioned, the GAM techniques are widely used in modelling the mid and high frequency behaviours of rooms. Currently, the most challenging application of GAM is providing the result for auralization, which is process of simulating the binaural listening experience at the receiver position. This can be achieved by means of physical or mathematical modelling of the sound source in the modelled acoustic space[15].

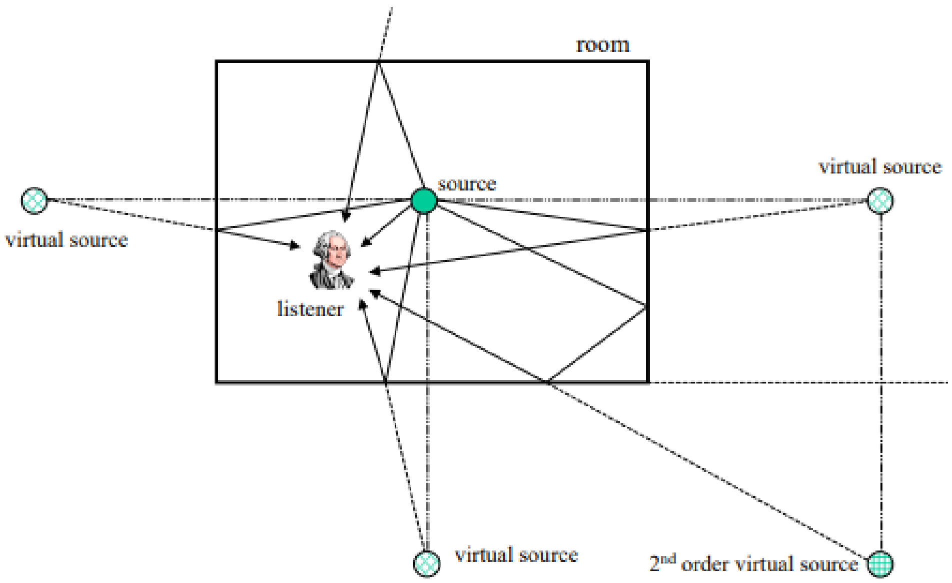


Figure 9: Example of GAM: Image source model

3 Room Acoustic Treatment

Acoustic treatment means providing technical solutions to improve the acoustic behaviour of a building. These solutions aim to control the reverberance and the sound level according to the type and the use of the building, its internal shape and furniture. Two important things must be considered while treating an acoustic space. One is to improve the speech intelligibility and the other one is to reduce the noise coming from the external environment.

There are three basic means to acoustically treat a certain building: by using sound absorption, reflection and diffusion[16]. In Figure 10, the difference between these three treatments are shown, based on the temporal and spatial response of the environment. The following section will provide further details about the acoustical treatments.

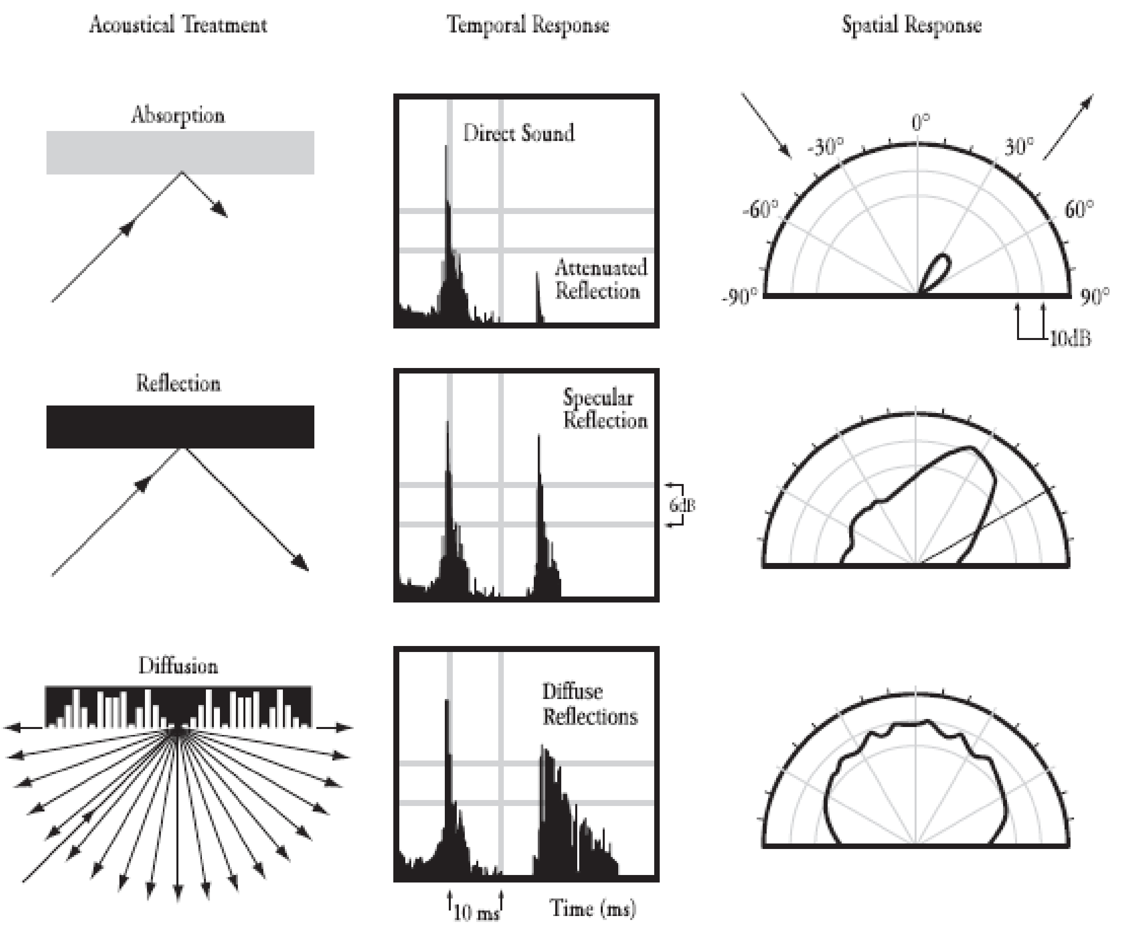


Figure 10: The temporal and spatial characteristics of absorbing, reflecting and diffusing surface

3.1 Absorption

Absorption is the process of dissipating acoustical energy by means of viscous losses. In sound absorptive materials (porous materials, wools, foams, sponges, carpets, etc.) large part of the sound wave energy is absorbed by conversion into heat, while a smaller fraction is transmitted through or reflected by (see Figure 10). The level of energy converted to heat energy depends on the sound absorbing properties of the material. Porous materials, such as mineral wool, have usually a high ratio of absorption.

The sound absorbing properties of materials are expressed by the sound absorption coefficient, α, (alpha), as a function of the frequency. α is the ratio between the reflected and the incident sound power when the material is backed by a rigid surface. α ranges from 0 (total reflection) to 1.00 (total absorption).

There are three types of sound absorbing materials: porous materials, vibrating panels and resonating absorbers [16]. These tree types are schematized in Figure 11 and detailed in the following sections.

Other important parameters used to describe the behaviour of acoustical materials are the equivalent density (ρ) and bulk modulus (K), which can be used to describe the material as an equivalent fluid [17]. Semi-phenomenological methods exist to describe these properties as functions of non-acoustical quantities such as flow resistivity, thickness, density, porosity and tortuosity.

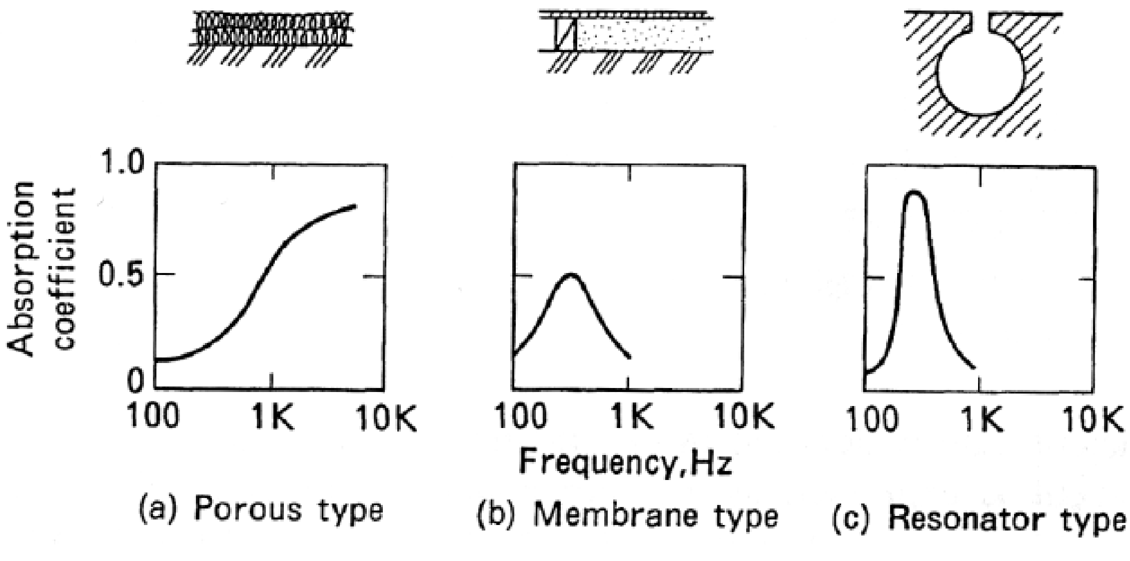


Figure 11: Three types of absorbers

3.1.1 **Porous Type**

The porous type absorbers are mineral wools, fibreglass, carpets, acoustic tiles, curtains, cushions, cotton and acoustic foams[16]. Air molecules at the surface and within the pores are forced to vibrate and the sound energy is transformed/dissipated by thermal and viscous losses within the pores into heat energy[16][18]. The absorption of the porous media changes according to the frequency, thickness, composition, surface finishing and method of mounting. The figure below shows the absorption of curtain for differential weights,

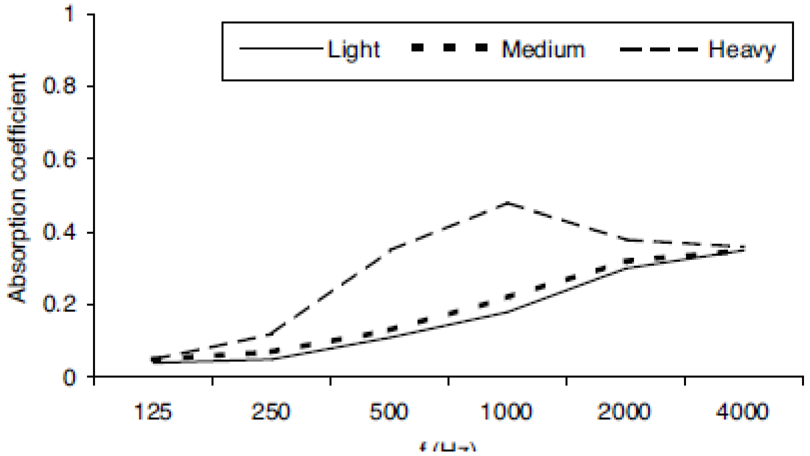


Figure 12: Curtain absorption [14]

3.1.2 **Vibrating Panel Type**

The vibrating panel absorbers also constituted by a thin plate or a membrane backed by an air cavity or by a light membrane in front of a porous absorber [17]. Thin plates are supported along the edges and can oscillate at frequencies which are determined - among other things - by the ratio between the bending stiffness and the mass of the plate[19], [20]. Membrane absorbers have bending stiffness which is very small compared to the stiffness of the air enclosed in the cavity. Light membranes of plastic (or similar type of thin foil) in front of a porous absorber, constitute a special variant of the membrane absorbers as shown in Figure 13.

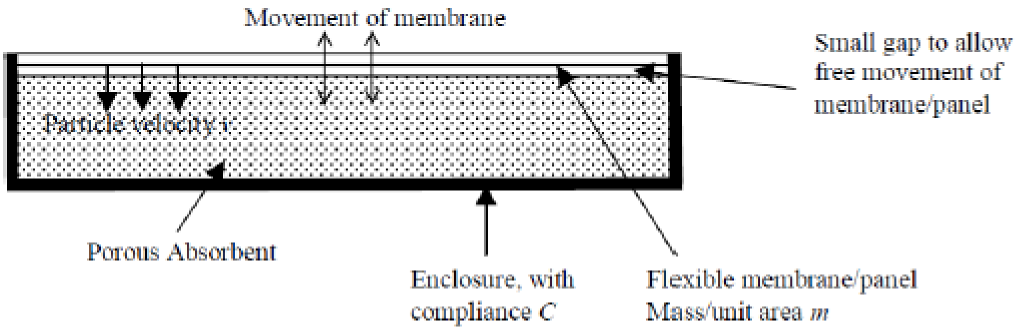
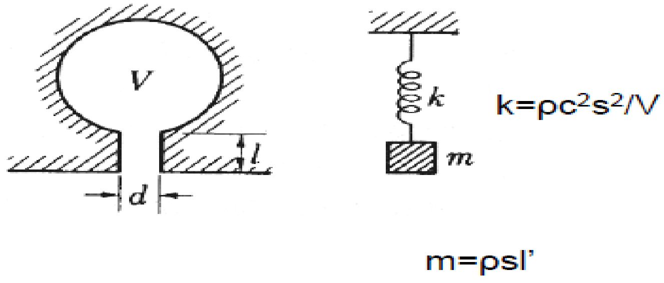


Figure 13: Example of membrane absorber

3.1.3 **Resonating Absorbers**

The resonating absorbers are based on the principle of the Helmholtz resonator, which was named after the German physician and physicist Hermann von Helmholtz (1821–94). This is acoustic equivalent of a mass-spring system and it is made of a cavity with one (or more) openings, as shown in Figure 14. At the resonance frequency of the air in the cavity, the air within the openings oscillates with high velocity. However, by definition, a Helmholtz resonator is a purely reflective element. In order to absorb or dissipate acoustic energy one must include a resistive component. For this reason, resonating absorbers are made of perforated plates (the openings can be holes or slots) backed by a cavity which is partially of fully filled with a porous material, where the absorption takes place[21]. More recently, resonator absorbers are made of plates with sub-millimetre sized perforations (micro-perforated panels)[22][23], [24], where the viscous losses occur. These panels do not necessarily require to fill the cavity with another absorber [17].

A characteristic feature of the resonating absorbers is the distance between the openings being small compared to the wavelength whereby a certain interaction between individual resonators should be expected.



Resonance frequency:

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{S}{V(l+\delta)}}$$

s: area of opening (m²) = $\pi d^2/4$
V: volume of resonator (m³)
l: length of the neck (m)
δ: end correction: $= 0.8\ d$ (m)

Figure 14: Helmholtz resonators

3.2 Reflectors

When the sound travels in a medium, it strikes the surface of the object and bounces back in some other direction, this phenomenon is called reflection of sound. The waves are called the incident and reflected sound waves.

The acoustic reflectors are an acoustic tool which provides as much natural reinforcement for the unamplified voice as possible. An example is shown in Figure 15. Reflectors can be used for the following purposes: to support a weak sound source, to improve the sound balance between different sound sources, to block echo paths, to create lateral reflections, to create diffuse reflections[25].

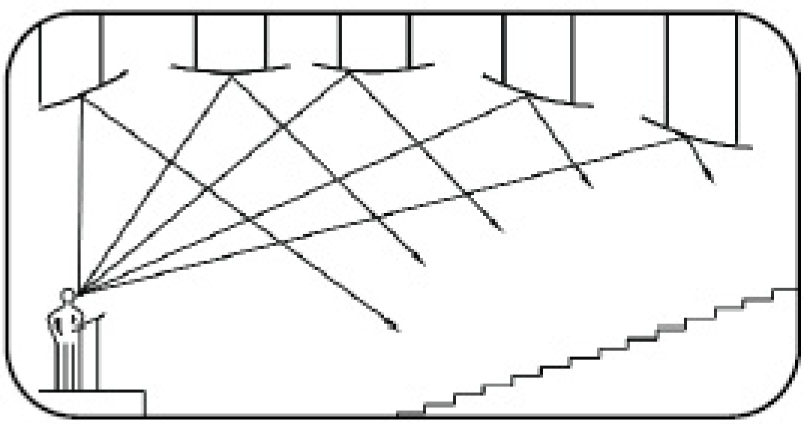


Figure 15: Example of Reflectors

3.2.1 **Types of Reflectors**

There are two common types of reflectors: plane reflectors, curved reflectors [26].

- **Plane reflectors**

The plane reflectors are often used above the auditorium stage to provide an early reflection into the audience. The reflected sound must not be delayed so the width of the reflector should be wide enough[26].

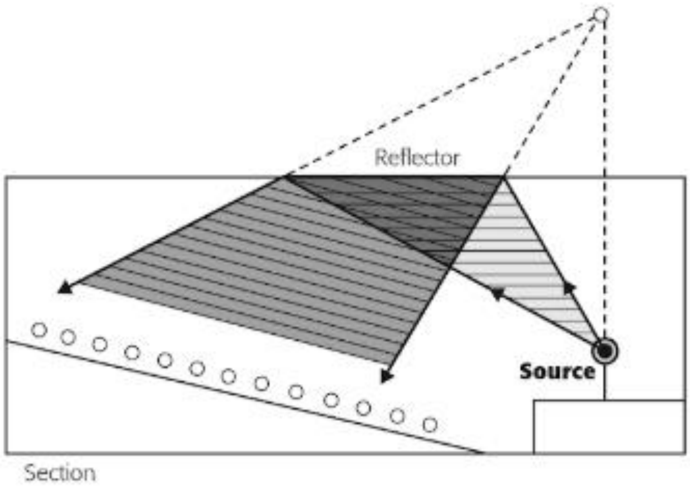


Figure 16: Plane reflector

- **Curved reflector**

There are two types of curved reflectors, concave and convex reflectors, according to the shape of the reflecting surface. Respective examples are shown in Figures 17 and 18. A concave surface focusses the sound, thus tends to concentrate sound energy areas, whilst a convex surface disperses the sound. Convex surfaces reflectors are more commonly used in building acoustics, especially when there is the necessity of distributing sound over the large areas. The ornaments and plasterwork were example of convex surface which provide the useful effect of scattering the sound at random manner.

Figure 17: Example of concave reflector

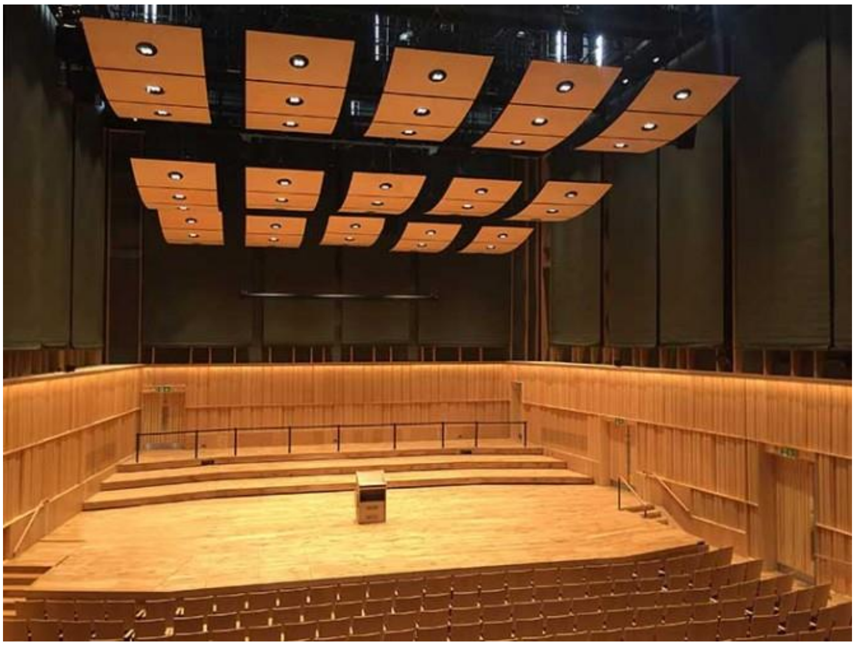


Figure 18: Example of convex reflector

3.3 Diffusors

Diffusors are used to treat sound abnormality, such as echoes in rooms. They are an excellent alternative to sound absorption because they do not remove sound energy but can be used to effectively reduce distinct echoes and reflections. In most cases, the use of diffusers panels is carried out in combination with acoustic panels to absorb sound and avoid reverberation. So, diffuser panels and acoustic panels work together absorbing and distributing sound for contributing to achieve the sound uniformity for undertaking the acoustic conditioning of a room.

3.3.1 Types of diffusors

There are two type of diffusers: geometrical and mathematical diffusors.

- **Geometrical diffusor**

It is the simplest type of diffusor, constituted by a simple reflective surface with different geometric shapes. The different shapes of the reflective surface provide different types of angle of incidence and angle of reflection. Performance of diffusion is good for normal incidence where sound comes from front of the diffusor. Diffusion performance for oblique incidence is generally poor.

The different types of geometric shapes are simply curved surfaces, irregular structures, and periodic geometric structure. An example is shown in Figure 19.

Figure 19: Example of geometric diffusor

- **Mathematical diffusor**

These diffusors are designed with the application of mathematical equations, thus referred to as mathematical diffusors. They consist of a series of wells of the same width and different depths (see Figure 20). The wells are separated by thin fins. The depths of the wells are determined by a mathematical number sequence[16].

The different types of diffusors are the Schroeder diffusor (shown in Figure 21), the quadratic residue diffusor (QRD), the Prime root diffusor (PRD) and the maximum length sequence diffusor (MLS).

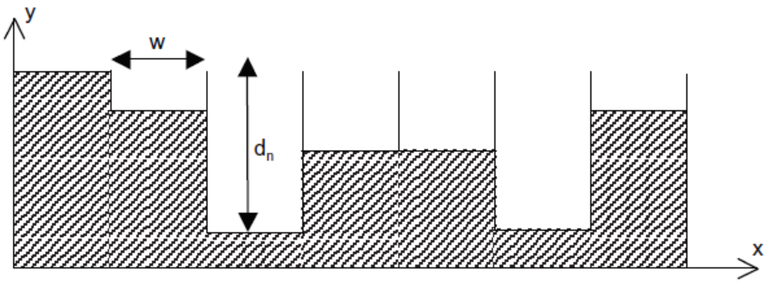


Figure 20: Example of diffusor well

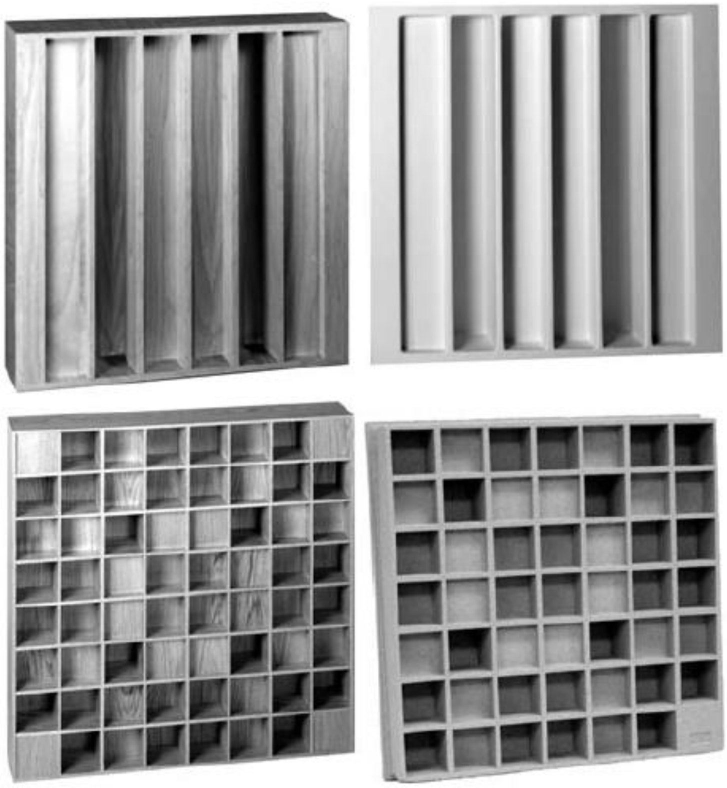


Figure 21: 1D, 2D Schroeder diffusors

4 Acoustic space measured results

The acoustic spaces investigated in this study are two lecture rooms (U03-103 & U04-103) located in Tallinn University of technology (TalTech). Both of the rooms have the following dimensions: 13.15m length, 13m width and 3.5m height. The total volume is 598.325m^3. The two rooms have different interiors. The U03-103 has less furniture compared to the U04-103 but U03-103 has an absorptive material which partially covers the back wall. The measurement equipment used for measuring the impulse response is described here:

- One Behringer ECM-8000® microphone
- A laptop with ARTA® software package,
- The BRUEL & KJAER® omnidirectional speaker.

The measuring equipment is calibrated based on IEC 61672 and IEC 61260 standards.

Each measurement campaign consists of several tests where the microphone is positioned in different locations in the rooms, chosen to cover the entire space, and the loudspeaker is fixed in front of the audience. This is schematically shown in Figure 24.

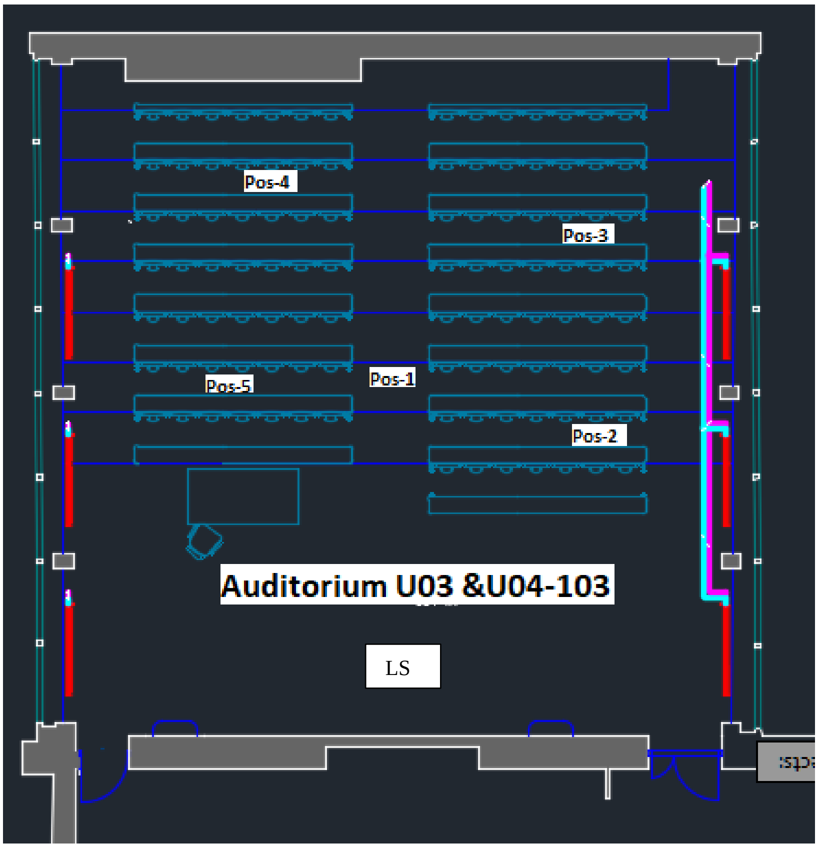


Figure 22: Microphone and loudspeaker positions.

4.1 Measurement of Lecture Room U03-103

The results for the room U03-103 in terms of RT and STI are presented in this section for the five different microphone locations shown in Figure 22. The RT and STI are obtained from the impulse response measurements by using the procedure described in (chapter 2.1.4). The RT is expressed as T30, which refers to a sound decay of 30 dB, because measuring RT in practice difficult to reach full 60 dB decay due to e.g. background noise, so decay range of 20 or 30 dB are commonly used. The range of 30 dB the corresponding time must be multiplied by two.

For each position the Figures 23, 25, 27, 29, 31 show the measured IR for the microphone position 1 to 5. The trends, in time domain, appear similar to each other and show the typical logarithmic decay of sound.

The Tables 2, 4, 6, 8, 10 show the T30 and EDT results at 7 discrete frequencies. In all cases, the RT and EDT values are close enough to each other to indicate that the measurements are reliable. The T30 and EDT are plotted in the 20-8000 Hz frequency range in the graphs in Figures 24, 26, 28, 30, 32. In all cases, the shorter sound decay measured at higher frequencies is due to the highest dissipation rate at high frequencies, which is confirmed by literature.

The STI values measured at the 5 positions are listed in the Tables 3, 5, 7, 9, 11.

The results at different positions are similar to each other, with the extreme cases represented by position 2, which shows the highest STI (0.64), and by position 3, which shows the longest time decay and the lowest STI (0.58). This is in agreement with the shortest and the longest time decays respectively shown in position 2 and 3 by the Figures 26 and 28.

The overall averages of the results obtained for the 5 positions have been carried out, for the T30 and EDT, shown in Table 12 and plotted in Figure 33, and for the STI (Table 12) which has a value 0.59. According to Table 1, this value corresponds to a “fair” acoustic behaviour of the room, which could be not tolerable for long listening times and justifies the necessity of improving the speech intelligibility.

Position-1

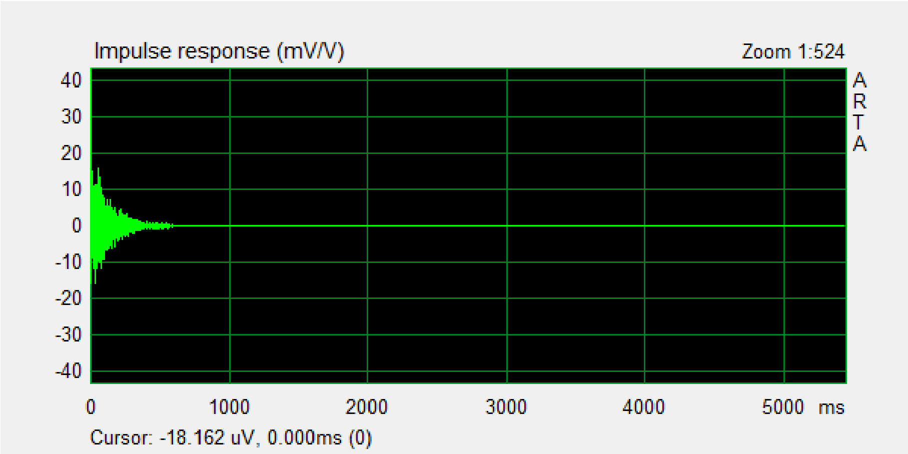


Figure 23: IR at POS-1

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Measured Pos-1 (s)	1.95	1.33	1.13	1.07	0.97	0.74	0.53
EDT Measured Pos-1 (s)	1.523	1.16	1.078	1.05	0.935	0.808	0.584

Table 2: Position-1 RT & EDT

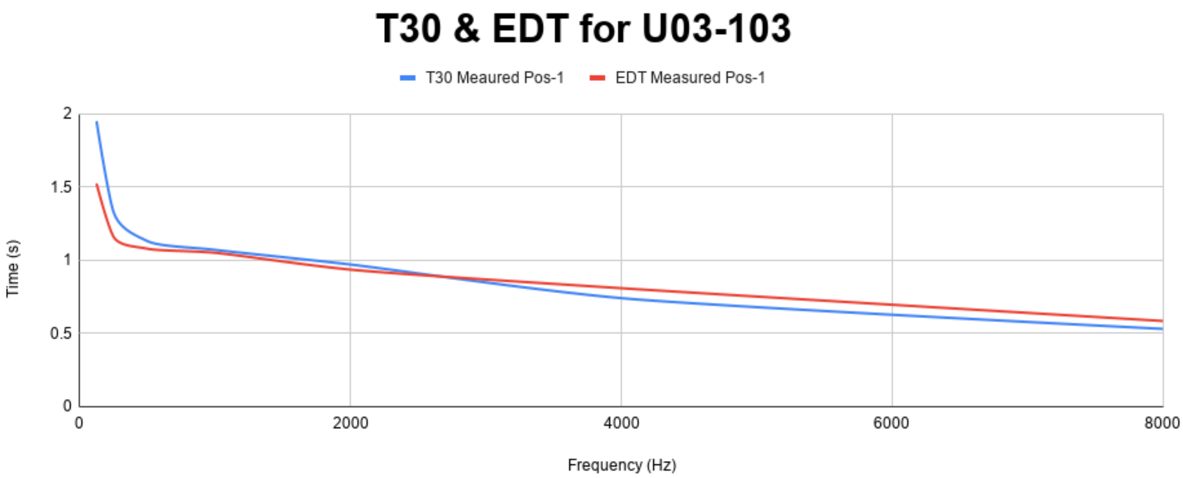


Figure 24: Position-1 RT & EDT graph

STI	0.59

Table 3: Position-1 STI

➢ **Position-2**

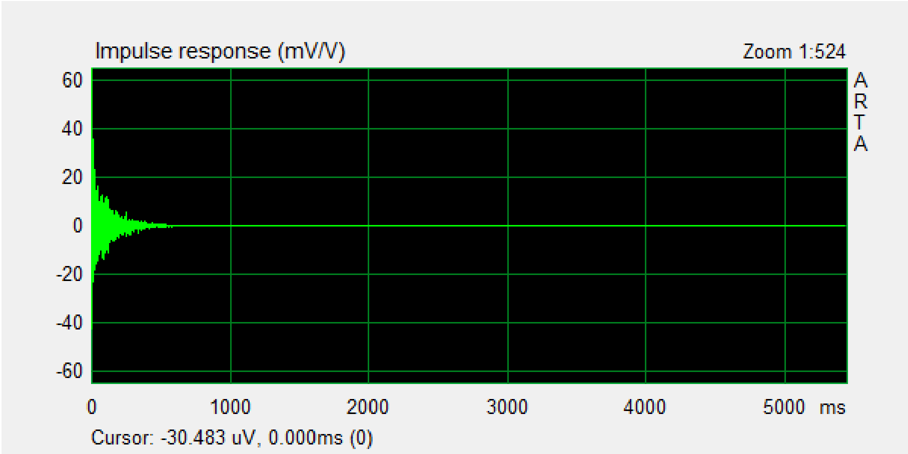


Figure 25: IR of POS-2

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Measured Pos-2 (s)	1.88	1.38	1.15	1.04	0.97	0.71	0.5
EDT Measured Pos-2 (s)	1.528	1.027	1.187	1.033	0.925	0.652	0.422

Table 4: Position-2 RT & EDT

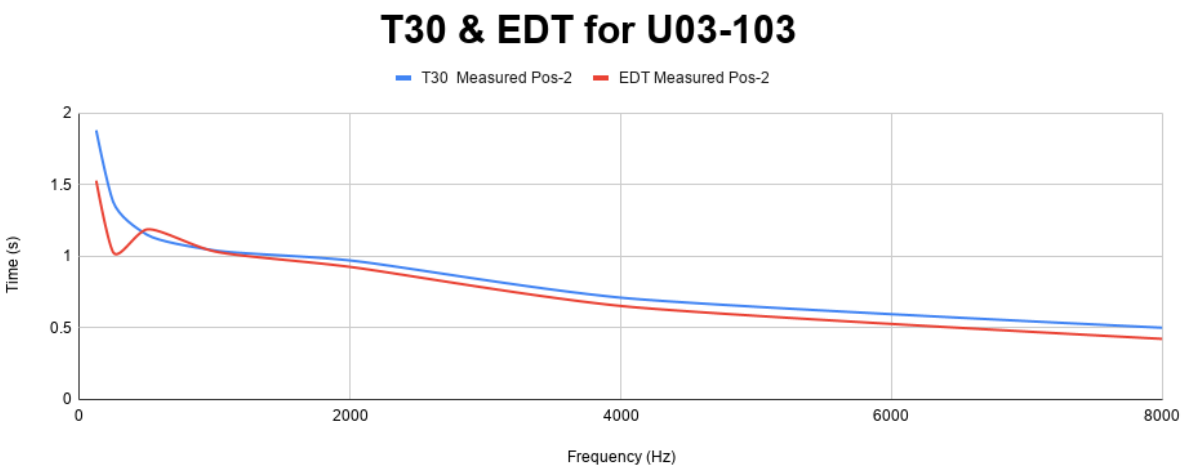


Figure 26: Position-2 RT & EDT graph

STI	0.64

Table 5: Position-2 STI

➢ Position-3

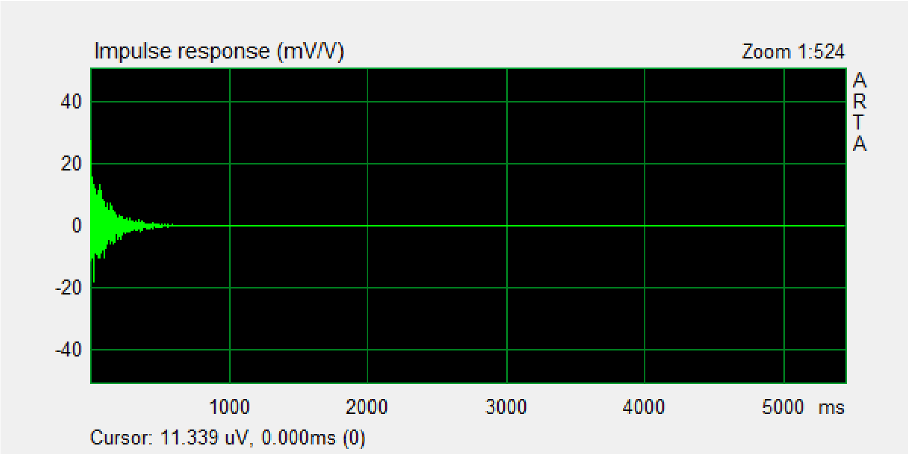


Figure 27: IR at POS-3

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Measured Pos-3 (s)	1.55	1.39	1.19	1.09	0.96	0.75	0.51
EDT Measured Pos-3 (s)	1.728	1.062	0.967	0.967	0.936	0.717	0.538

Table 6: Position-3 RT & EDT

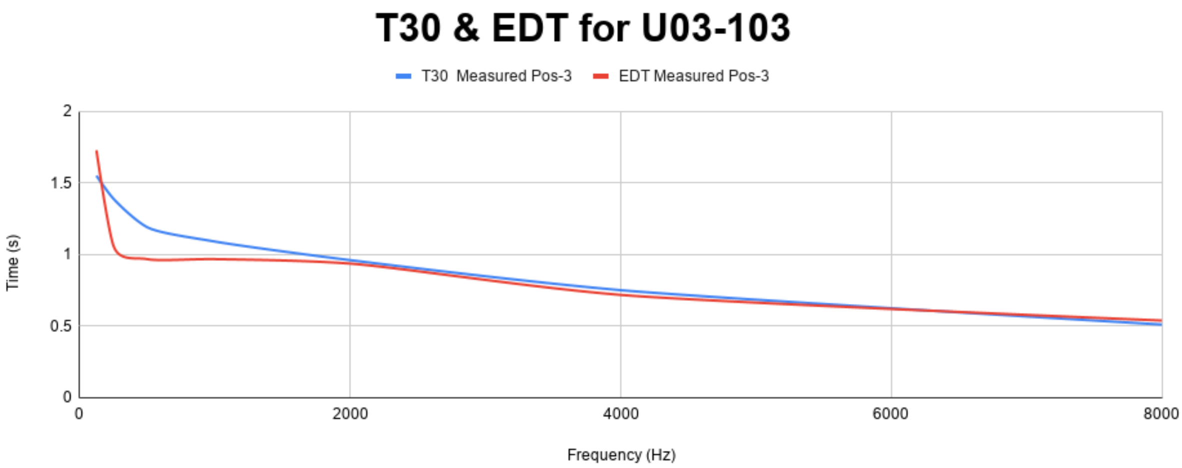


Figure 28: Position-3 RT & EDT graph

STI	0.58

Table 7: Position-3 STI

➢ **Position-4**

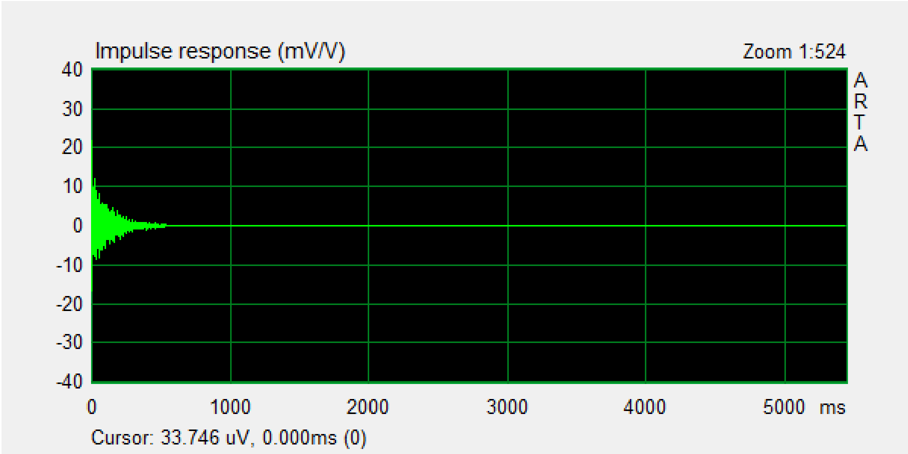


Figure 29: IR at POS-4

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Measured Pos-4 (s)	1.55	1.40	1.15	1.11	0.96	0.74	0.51
EDT Measured Pos-4 (s)	1.242	1.282	1.225	1.034	0.988	0.804	0.527

Table 8: Position-4 RT & EDT

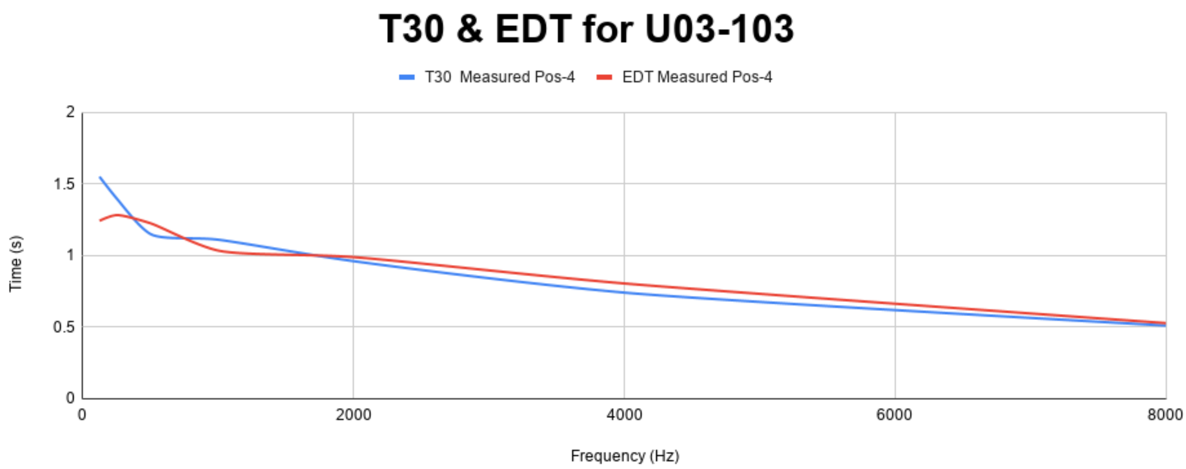


Figure 30: Position-4 RT & EDT graph

STI	0.59

Table 9: Position-4 STI

➢ Position-5

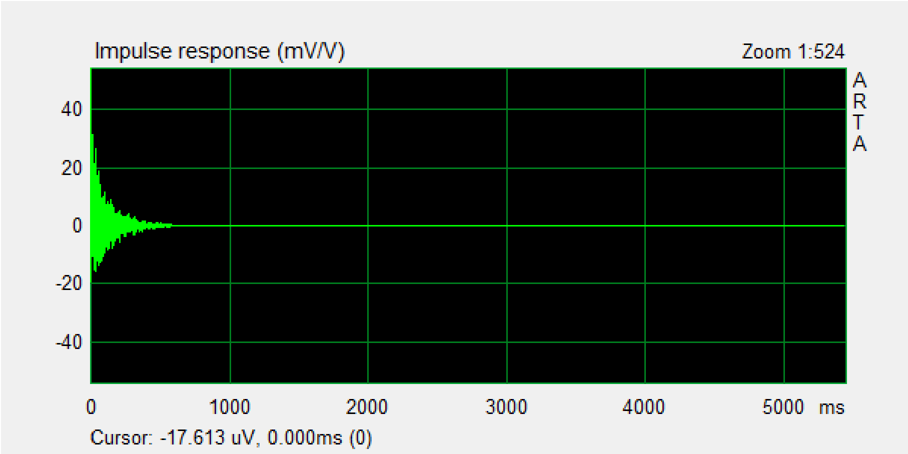


Figure 31: IR at POS-5

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Measured Pos-5 (s)	1.82	1.41	1.07	1.04	0.91	0.71	0.48
EDT Measured Pos-5 (s)	2.111	1.082	1.323	1.05	0.967	0.666	0.501

Table 10: Position-5 RT & EDT

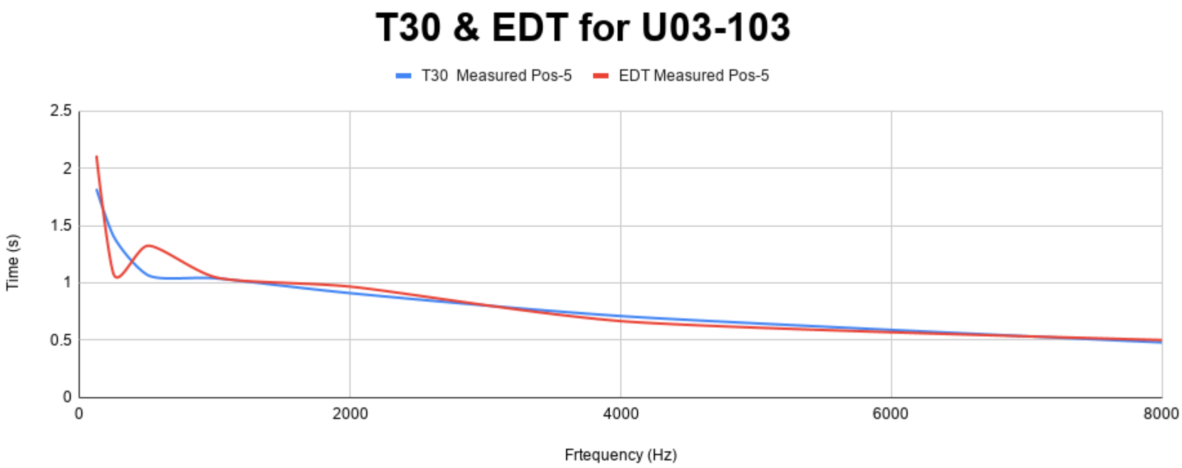


Figure 32: Position-5 RT & EDT graph

STI	0.60

Table 11: Position-5 STI

➢ Averaged results

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Average (s)	1.75	1.382	1.138	1.07	0.954	0.73	0.506
EDT Average (s)	1.62	1.12	1.15	1.02	0.95	0.72	0.51

Table 12: Average RT & EDT

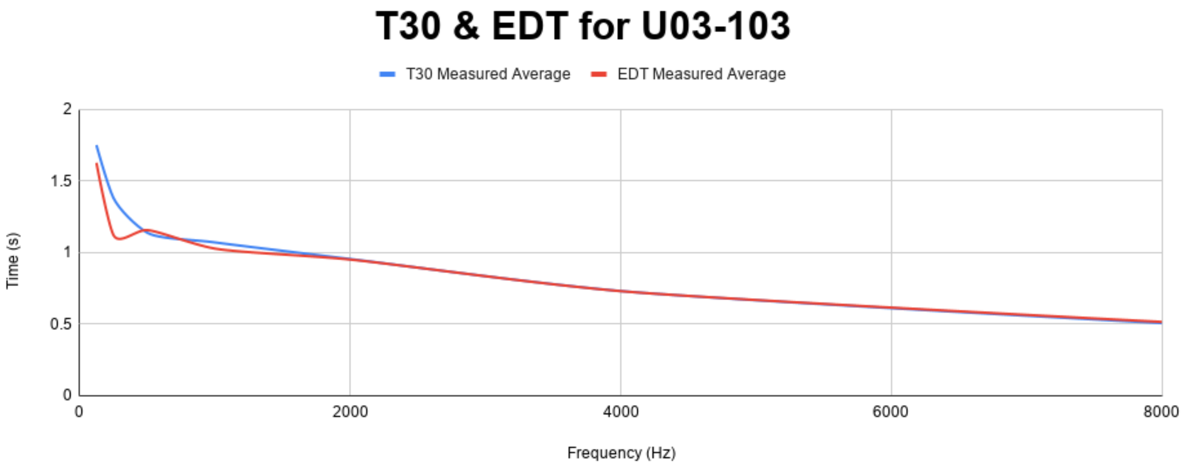


Figure 33: Average RT & EDT graph

STI	0.59

Table 13: Average STI

4.2 Measurement of Lecture Room U04-103

The results for the room U04-103 in terms of RT and STI are presented in this section for the five different microphone locations shown in Figure 22. The RT and STI are obtained from the impulse response measurements by using the procedure described in (chapter 2.1.4).

For each position the Figures 32,36, 38, 40, 42, show the measured IR for the microphone position 1 to 5. The Tables 14, 16, 18, 20, 22 show the T30 and EDT results at 7 discrete frequencies. The T30 and EDT are plotted in the 20-8000 Hz frequency range in the graphs in Figures 35, 37, 39, 41, 43. The STI values measured at the 5 positions are listed in the Tables 15, 17, 19, 21, 23.

All the trends are similar to the ones obtained for room U03-103. However, differently from U03-103, the room U04-103 has no absorptive materials on its wall. This results in longer time decays, i.e. higher values of T30 and lower STI in basically all microphone positions. In fact, the STI results at different positions now vary from (0.51 to 0.54). The position-2 attains the highest STI value of (0.54) therefore the shortest decay time. The position-1 obtained the second highest STI value of (0.53). The lowest values are presented in the position-3&4 (0.51) where the strong influence of noises is observed.

Regarding the averaged results, shown in Tables 24 and 25 and Figure 44, we can see here longer T30 and a global STI which is 0.07 less than the previous room.

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- **Position-1**

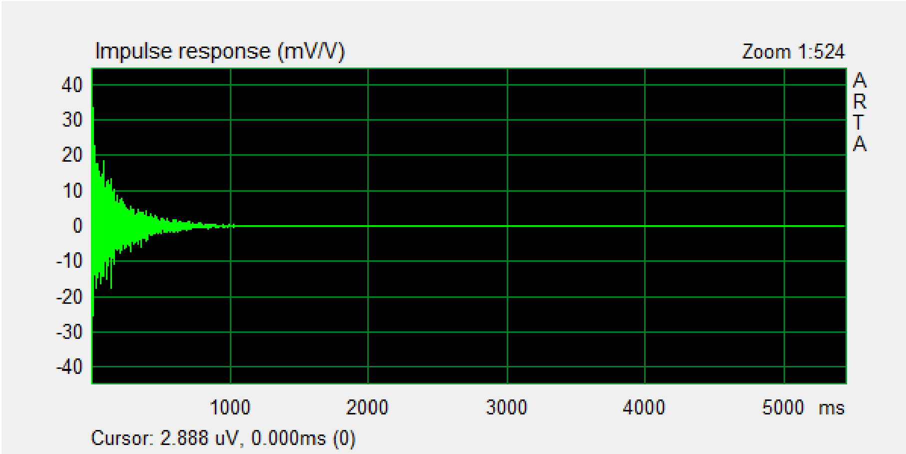

Figure 34: IR at POS-1

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Measured Pos-1 (s)	2.189	2.223	1.953	1.66	1.425	1.028	0.656
EDT Measured Pos-1 (s)	1.562	2.111	2.066	1.522	1.386	0.988	0.647

Table 14: Position-1 RT & EDT

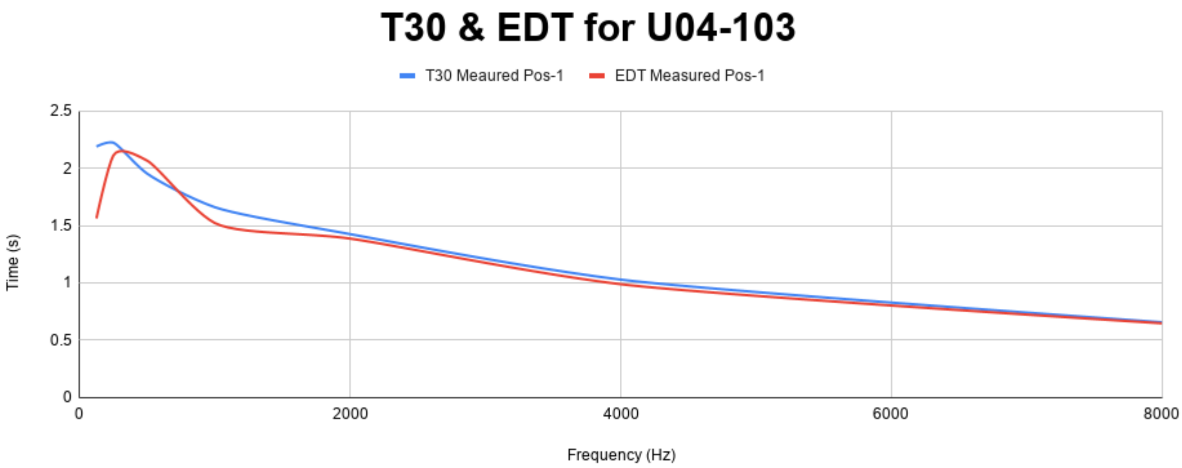

Figure 35: Position-1 RT & EDT graph

STI	0.53

Table 15: Position-1 STI

- **Position-2**

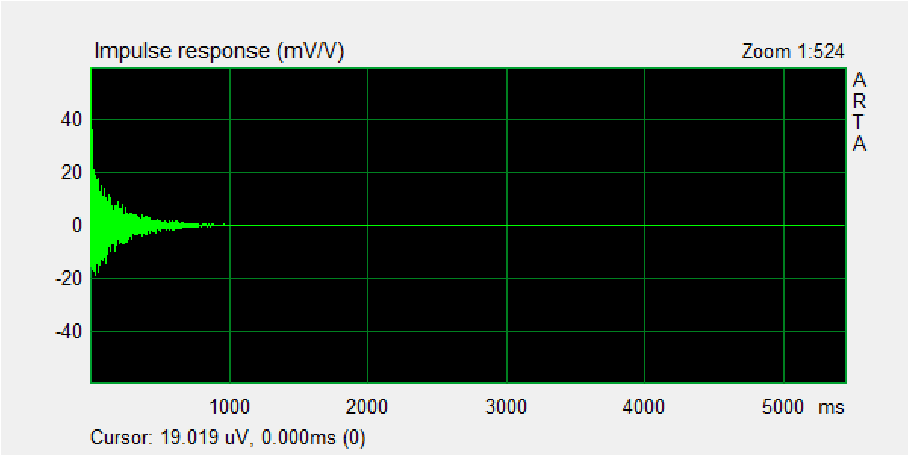

Figure 36: IR at POS-2

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Measured Pos-2 (s)	2.374	2.251	1.932	1.65	1.45	1.061	0.693
EDT Measured Pos-2(s)	1.87	2.38	1.935	1.694	1.441	0.947	0.602

Table 16: Position-2 RT & EDT

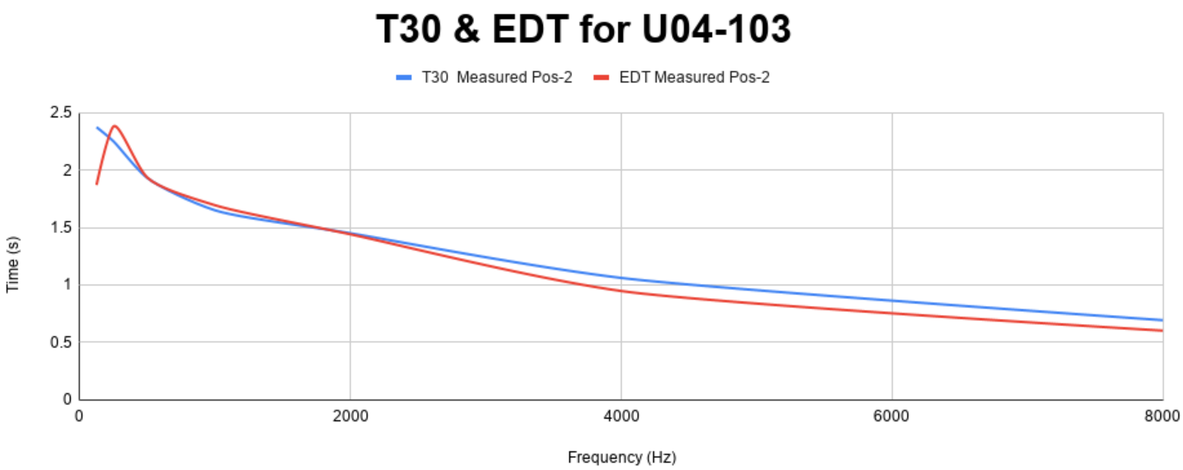

Figure 37: Position-2 RT & EDT graph

STI	0.54

Table 17: Position-2 STI

➢ **Position-3**

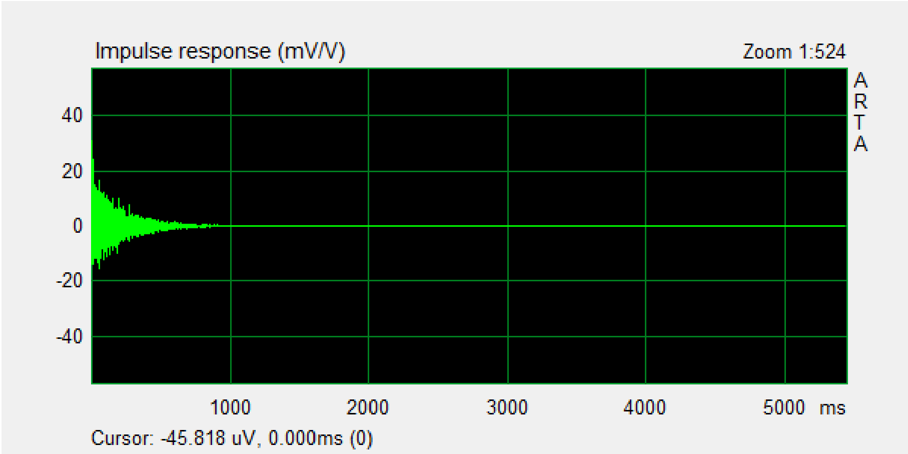

Figure 38: IR at POS-3

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Measured Pos-3 (s)	2.235	2.326	1.999	1.655	1.453	1.079	0.711
EDT Measured Pos-3 (s)	2.089	2.355	2.022	1.668	1.55	1.022	0.681

Table 18: Position-3 RT & EDT

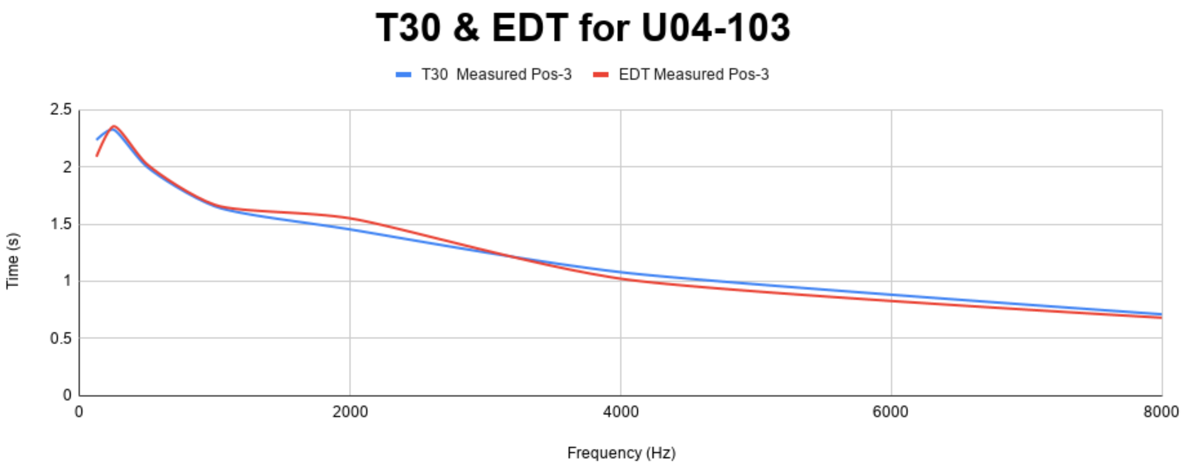

Figure 39: Position-3 RT & EDT graph

STI	0.51

Table 19: Position-3 STI

- **Position-4**

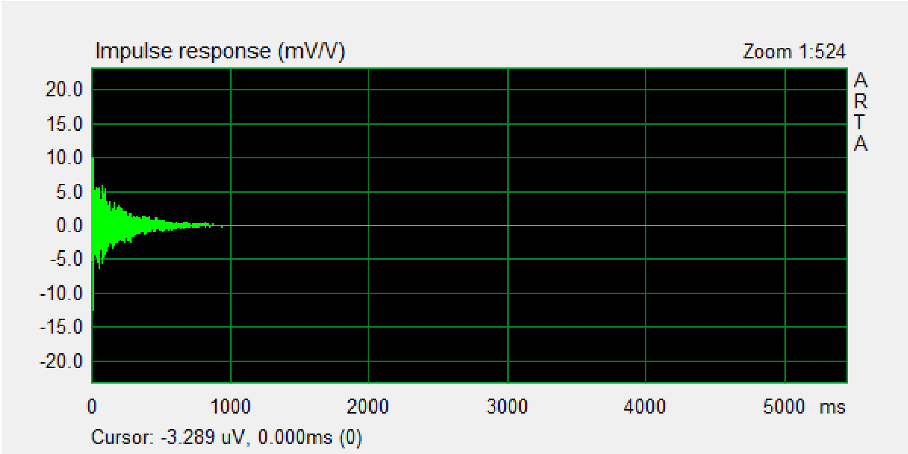

Figure 40: IR at POS-4

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Measured Pos-4 (s)	2.298	2.317	2.064	1.702	1.474	1.089	0.73
EDT Measured Pos-4 (s)	2.304	2.373	1.986	1.655	1.465	1.108	0.697

Table 20: Position-4 RT & EDT

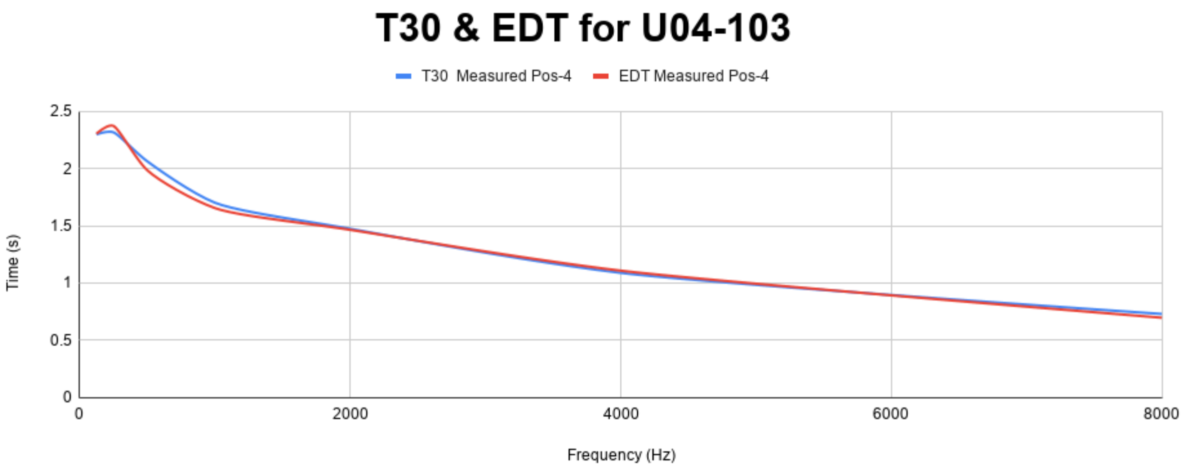

Figure 41: Position-4 RT & EDT graph

STI	0.51

Table 21: Position-4 STI

- **Position-5**

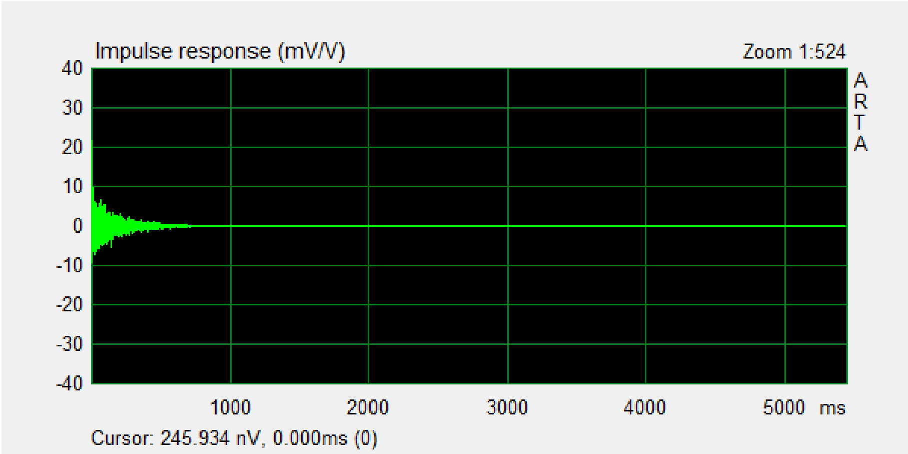

Figure 42: IR at POS-5

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Measured Pos-5 (s)	2.124	2.313	1.952	1.952	1.952	1.072	0.717
EDT Measured Pos-5 (s)	2.046	2.155	1.9	1.668	1.453	1.057	0.6631

Table 22: Position-5 RT & EDT

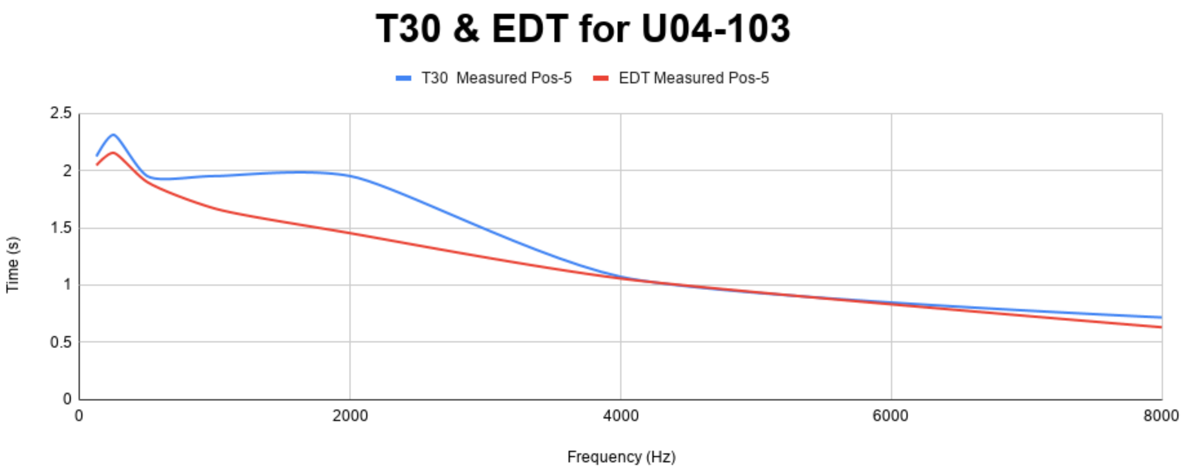

Figure 43: Position-5 RT & EDT graph

STI	0.52

Table 23: Position-5 STI

➢ **Averaged results**

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Average (s)	2.244	2.286	1.98	1.723	1.550	1.065	0.701
EDT Average (s)	1.974	2.27	1.981	1.641	1.459	1.024	0.651

Table 24: Average RT & EDT

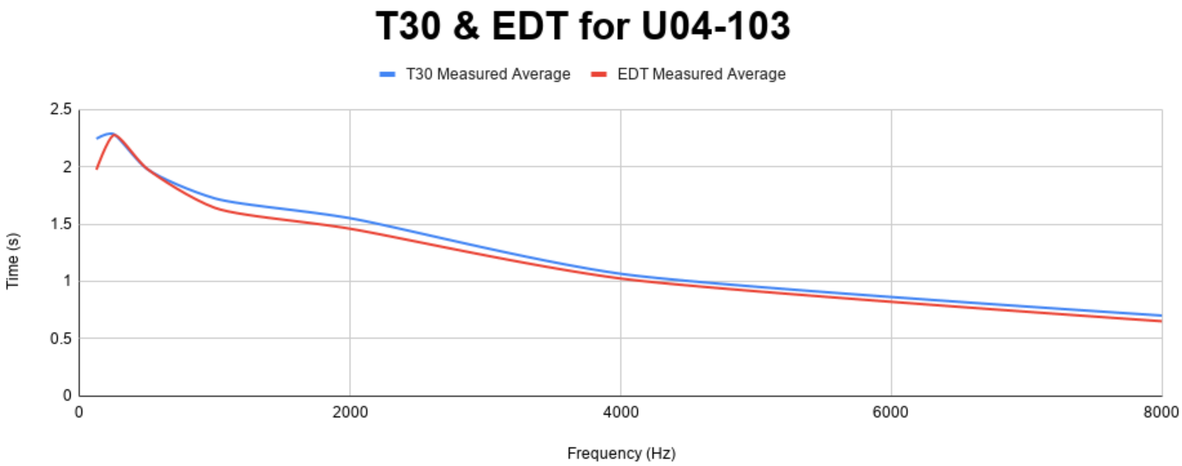

Figure 44: Average RT & EDT graph

STI	0.52

Table 25: Average STI

4.3 Comparison of Sound Sources

In order to assess the potentialities of low cost devices [27] in the process of estimating the acoustic performance of the two lecture rooms, the omnidirectional loudspeaker used for the test described in the previous sections has been replaced by a USB type Logitech® loudspeaker (shown in Figure 45) . The results, in terms of T30 and EDT measured in the two rooms by using the two different loudspeakers are compared in Figure 46 and 47 and commented below.

Figure 45: Logitech Z120® mini stereo speaker

4.3.1 T30 and EDT comparison of two sound sources

The reverberation and early decay time measured by the two-sound source is compared and reliability of the measurement is analysed (see Figure 48 & 49).

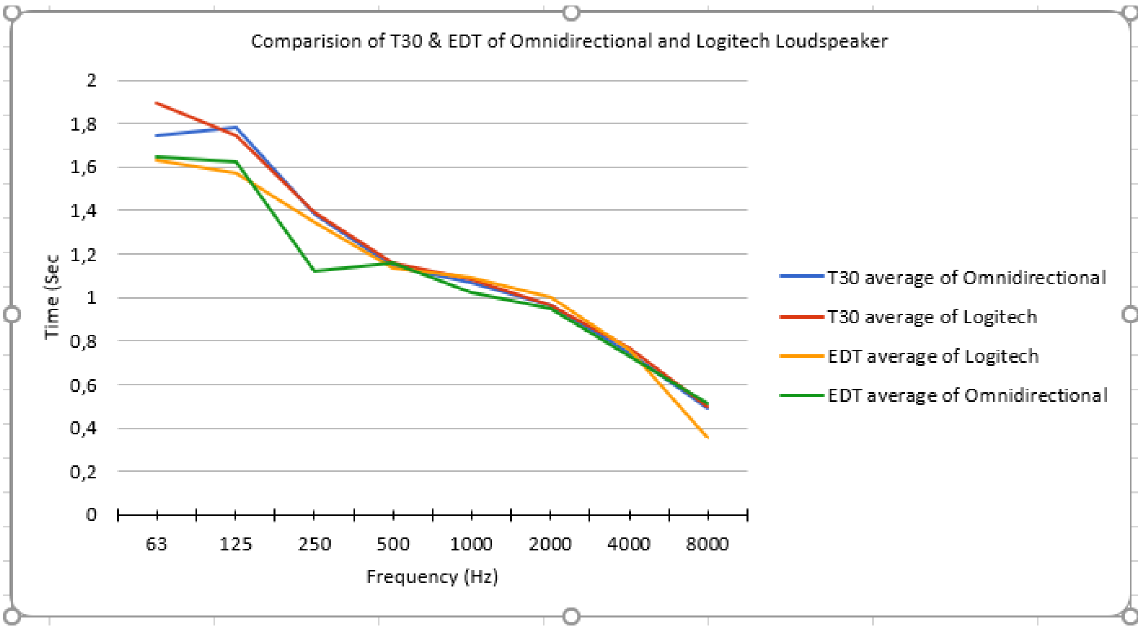

Figure 46: Comparison for U03-103 lecture room

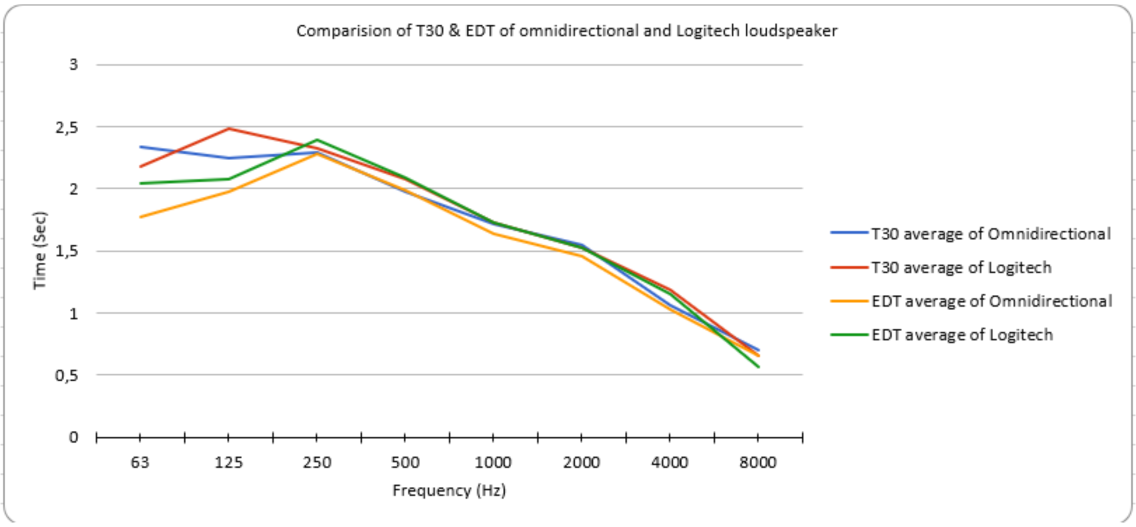

Figure 47: Comparison for U04-103 lecture room

As clearly noticeable, small discrepancies are visible only at low frequencies but, in general, the curves are overlapping. In conclusion, the Logitech USB type loudspeaker has shown a good reliability in the measurement of the acoustic behaviour of the room examined.

5 Rooms 3D simulated results

To improve the acoustic behaviour of the lecture rooms the geometrical acoustic method (GAM) was used. The room acoustic modelling software used is CADNA-R from DATAKUSTIK®, which uses image source model and particle model for calculating the required parameters[28]. The numerical analyses shown in this section consisted of two main steps. First, the acoustic models of the two rooms were prepared and validated by the experimental data. Second, absorptive panels were added in the numerical model to improve the STI. The acoustic performance of the two rooms was simulated by using different numbers of absorptive panels in order to find the solution which provided a satisfactory STI with the minimum number of panels.

To begin with room acoustic modelling a proper CAD model of lecture rooms is required[12]. The CAD model of the lecture rooms was developed with the support of AutoCAD® and SketchUp® software packages. In chapter-4, (see Figure-19) the 2D CAD wireframe schematic of the lecture rooms is shown. By using that 2D file, the proper 3D CAD model was developed using SketchUp software and shown in Figure 50 and 51.

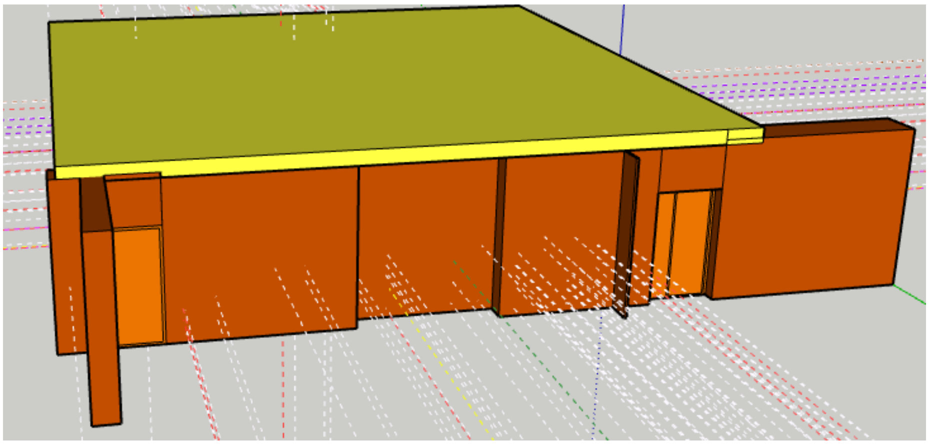

Figure 48: Isometric view of lecture room

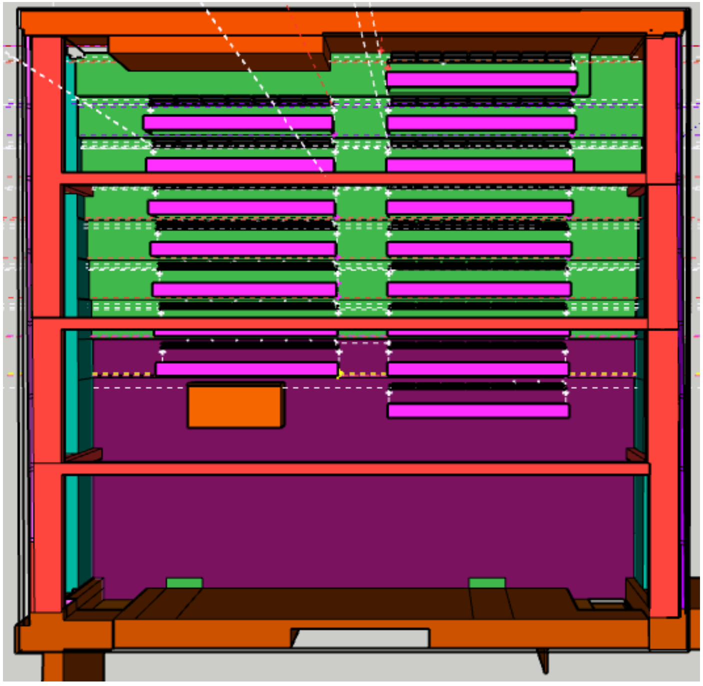

Figure 49: Top view of lecture room

The room 3D GAM model was setup by adding measurement point in the same 5 positions used for the *real* tests (see Figure 50).

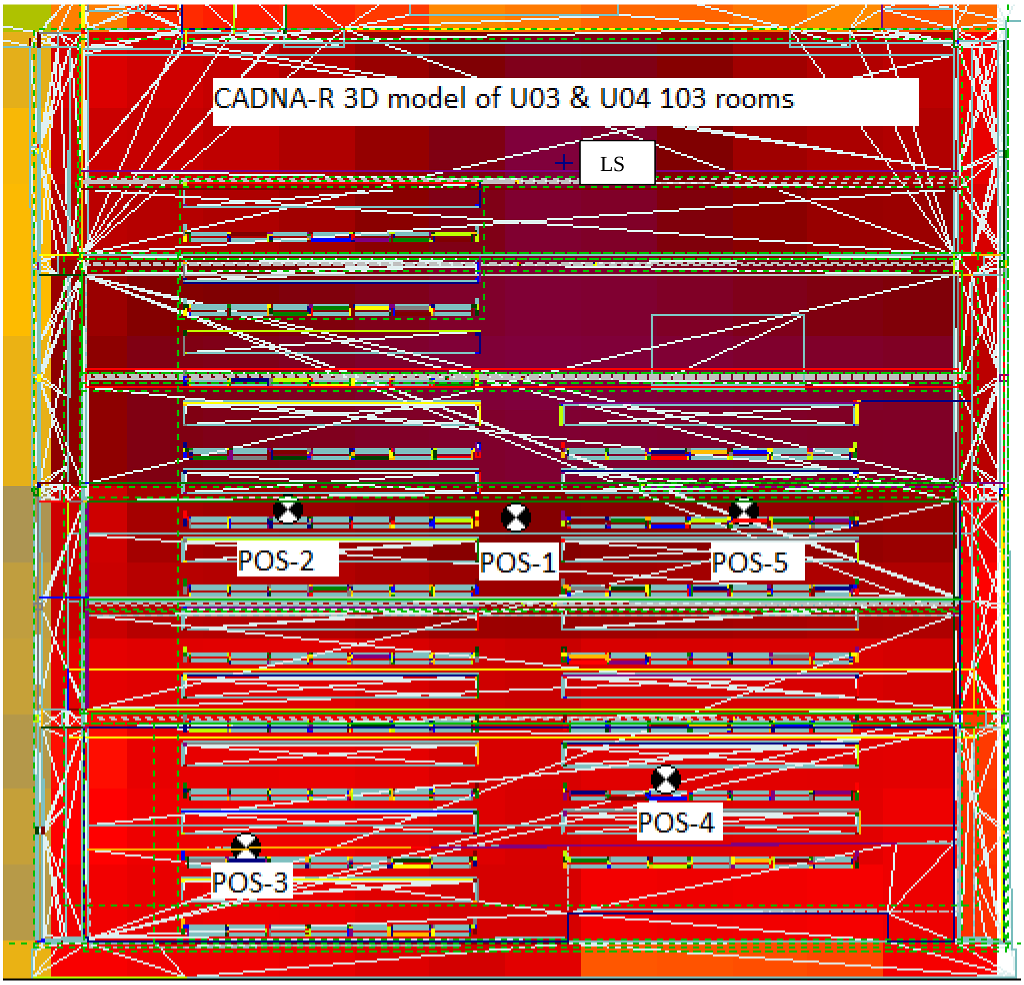

Figure 50: Microphone and loudspeaker positions of rooms in 3D model

5.1 Solution steps

The detailed steps for the implementation of the numerical analyses are listed here:

- The two rooms already designed by SketchUp software and then converted into CADNA-R model.
- The two rooms were modelled to simulate the real acoustic conditions.
- Then the acoustic parameters obtained from the measured and modelled scenarios were compared in order to validate the 3D numerical model of the rooms.
- From the sound treatment solutions described in chapter-3, the porous absorber type was chosen to improve the acoustic behaviour of the rooms.
- The rooms 3D numerical model was updated by adding ceiling absorbers and baffles. Different simulations were performed where a different number of absorbers (referred to as "1, 2, … rows ") were included.
- The obtained acoustic parameters data were compared between ceiling absorbers and baffles and between different number of rows.

5.1.1 **Simulated results**

The acoustic parameters were obtained from the CADNA-R software for the five microphone positions for the two rooms (U03-103 & U04-103). The 3D model simulation calculations for two rooms were carried out based on the steps described in (chapter 5.1).

Comments about the validation of the model will be presented in the section 5.1.2. Here the numerical results are simply described.

The Tables 26, 28, 30, 32, 34 show the T30 and EDT results at 7 discrete frequencies for both rooms. In all cases, the RT and EDT values are close enough to each other to indicate that the calculations are reliable. The T30 and EDT are plotted in the 20-8000 Hz frequency range in the graphs in Figures 51 to 60. The RT and EDT in low frequencies are below 1 second in low frequencies, where small discrepancies with the experimental results are visible.

The STI values measured at the 5 positions for both rooms are listed in the Tables 27, 29, 31, 33, 35.

The results at different positions are vary from (0.59 to 0.61) STI for room U03-103. The position-2 attains the highest STI value of (0.61) due to the shortest decay time. The position-1,4 &5 obtained the second highest STI value of (0.60). The lowest values are presented in the position-3 (0.59).

The results at different positions are vary from (0.52 to 0.56) STI for room U04-103. The position-1&2 attains the highest STI value of (0.56) due to the shortest decay time. The position-5 obtained the second highest STI value of (0.54). The lowest values are presented in the position-3&4 (0.52).

According to the Table 1, the measured value results in a "fair" acoustic behaviour of the rooms, which confirms the measured and modelled results are like each other and the rooms are needs to be improve in speech intelligibility.

The overall average data values of the room are shown in the Table 36 & 37. The obtained STI value is fair (refer Table 1) so the room needs improvement in the acoustic behaviour. The solution for the room is described in chapter 5.2.

- **Position-1**

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Modelled Pos-1 (U03) (s)	0.87	0.86	1.14	1.14	1.1	0.92	0.67
EDT Modelled Pos-1 (U03) (s)	0.8	0.84	0.84	0.85	0.84	0.77	0.67
T30 Modelled Pos-1 (U04) (s)	0.89	0.95	1.09	1.3	1.21	1.12	0.72
EDT Modelled Pos-1 (U04) (s)	0.88	0.92	0.93	0.95	0.97	0.91	0.77

Table 26: Position-1 RT & EDT for U03 & U04 rooms

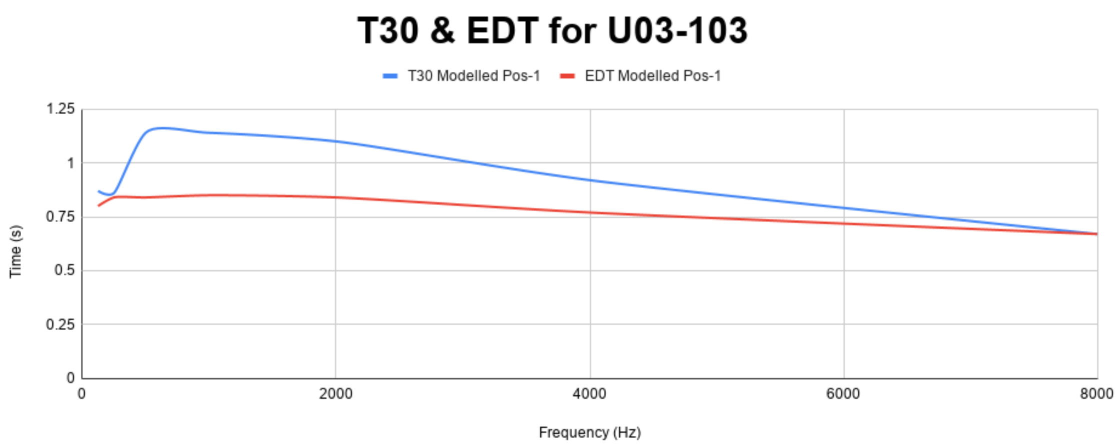

Figure 51: RT & EDT for U03 graph

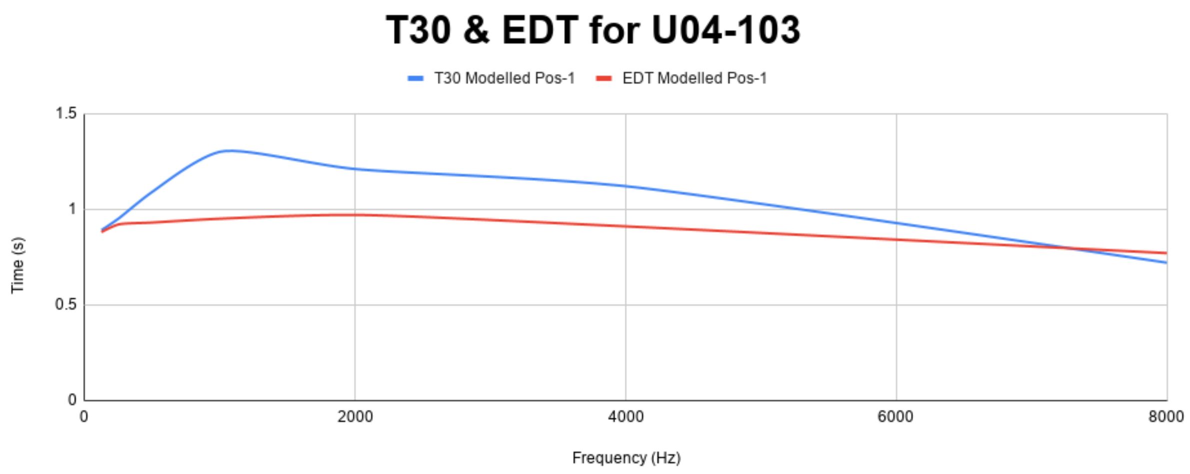

Figure 52: RT & EDT for U04 graph

STI Modelled Pos-1 (U03)	0.6
STI Modelled Pos-1 (U04)	0.56

Table 27: STI for U03 & U04

- **Position-2**

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Modelled Pos-2 (U03) (s)	0.81	0.93	1.31	1.17	1.03	0.99	0.74
EDT Modelled Pos-2 (U03) (s)	0.84	0.88	0.89	0.93	0.9	0.84	0.73
T30 Modelled Pos-2 (U04) (s)	0.93	1.05	1.14	1.38	1.12	1.15	0.67
EDT Modelled Pos-2 (U04) (s)	0.88	0.93	0.92	0.98	0.95	0.9	0.77

Table 28: Position-2 RT & EDT for U03 & U04 rooms

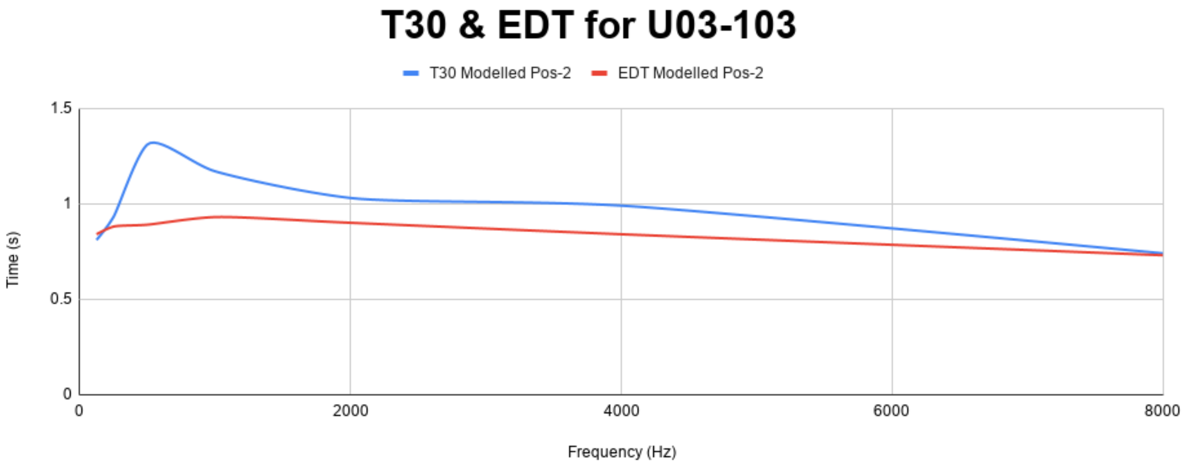

Figure 53: RT & EDT for U03 graph

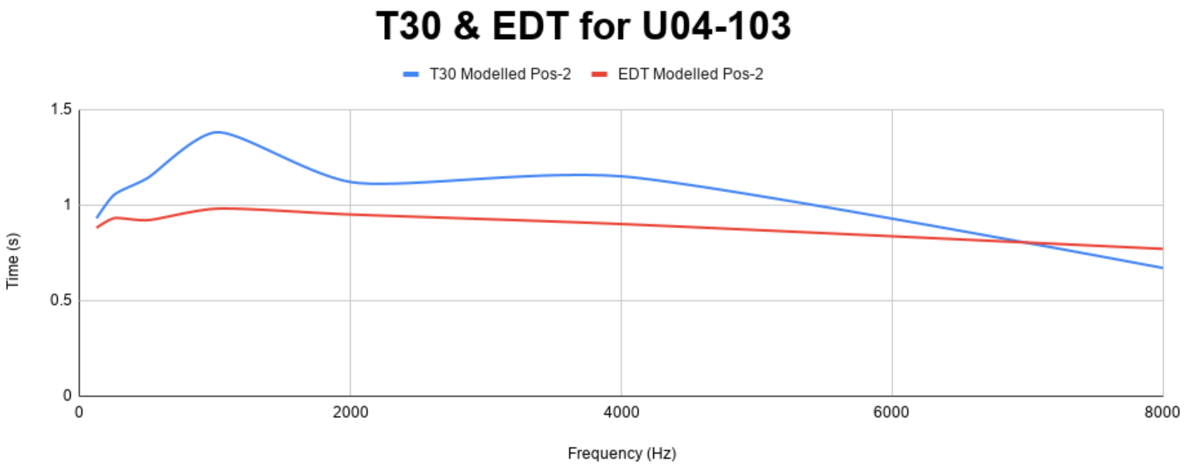

Figure 54: RT & EDT for U04 graph

STI Modelled Pos-2 (U03)	0.61
STI Modelled Pos-2 (U04)	0.56

Table 29: STI for U03 & U04

- **Position-3**

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Modelled Pos-3 (U03) (s)	0.71	0.93	1.02	1.06	1.03	0.91	0.63
EDT Modelled Pos-3 (U03) (s)	0.81	0.83	0.9	0.86	0.88	0.78	0.72
T30 Modelled Pos-3(U04) (s)	0.93	1.04	1.1	1.35	1.68	1.15	0.76
EDT Modelled Pos-3 (U04) (s)	0.94	0.98	1.01	1.04	1.09	0.98	0.83

Table 30: Position-3 RT & EDT for U03 & U04 rooms

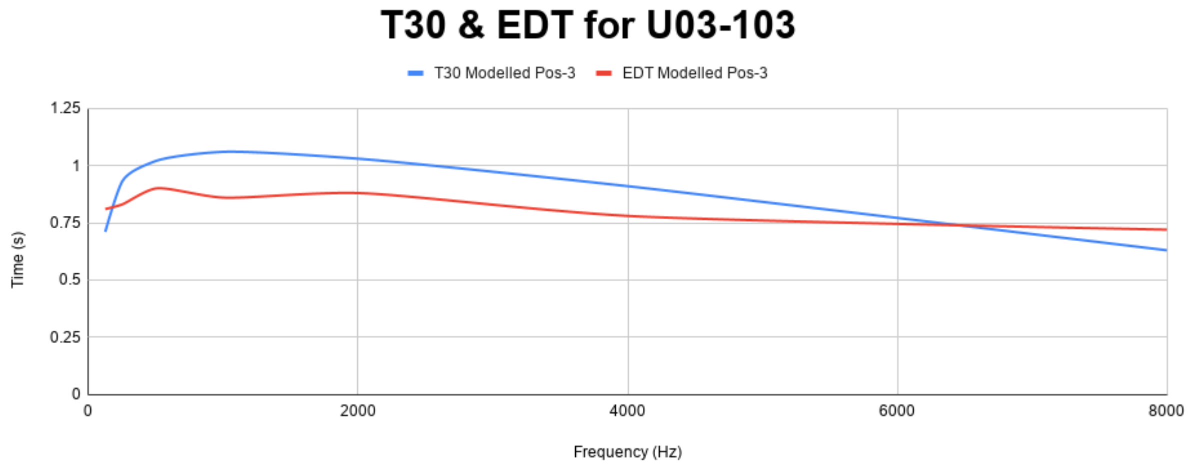

Figure 55: RT & EDT for U03 graph

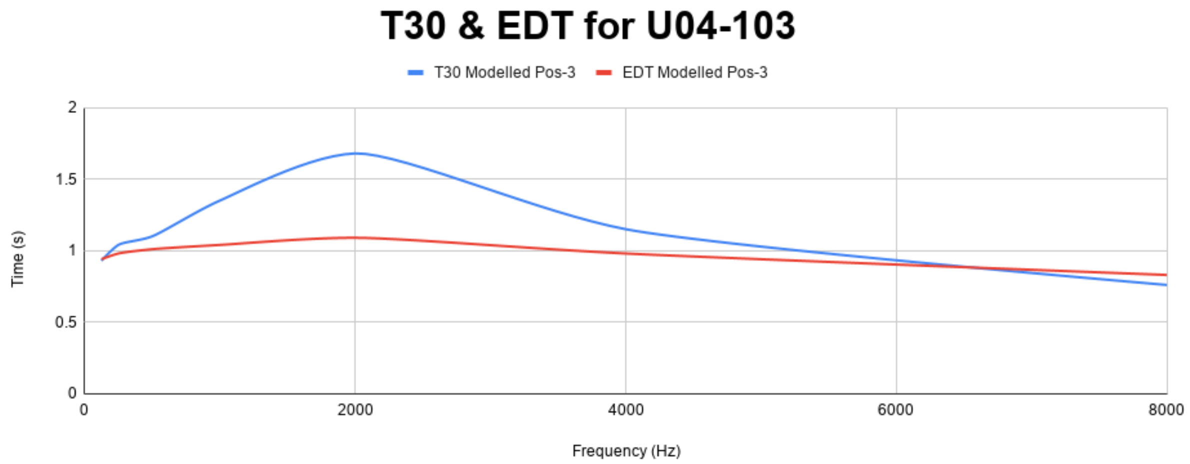

Figure 56: RT & EDT for U04 graph

STI Modelled Pos-3 (U03)	0.59
STI Modelled Pos-3 (U04)	0.52

Table 31: STI for U03 & U04

- **Position-4**

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Modelled Pos-4 (U03) (s)	1.21	0.95	0.97	1.08	1.16	0.94	0.58
EDT Modelled Pos-4 (U03) (s)	0.83	0.86	0.89	0.9	0.87	0.87	0.7
T30 Modelled Pos-4 (U04) (s)	0.82	0.94	1.25	1.26	1.47	1.09	0.73
EDT Modelled Pos-4 (U04) (s)	0.9	0.95	0.96	0.99	1.02	0.94	0.79

Table 32: Position-4 RT & EDT for U03 & U04 rooms

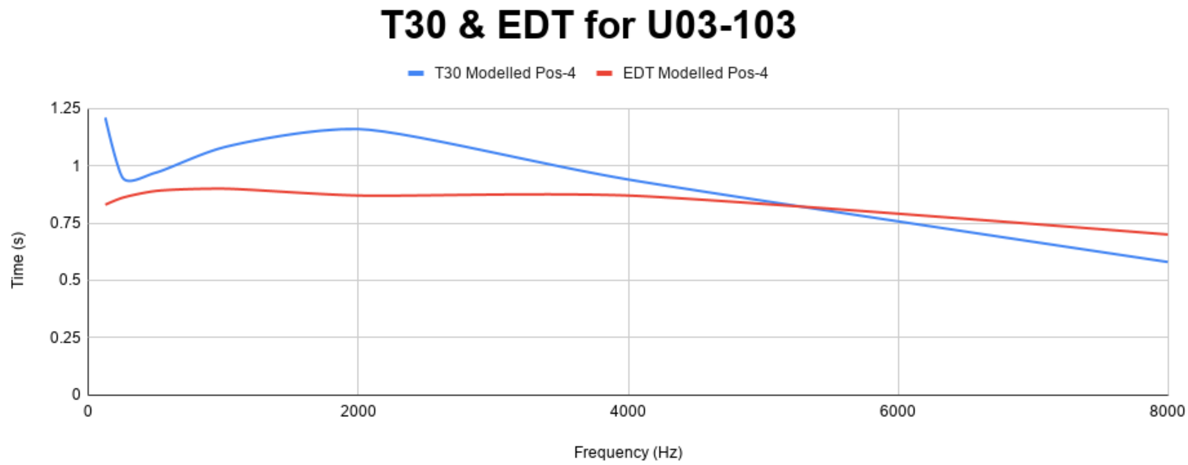

Figure 57: RT & EDT for U03 graph

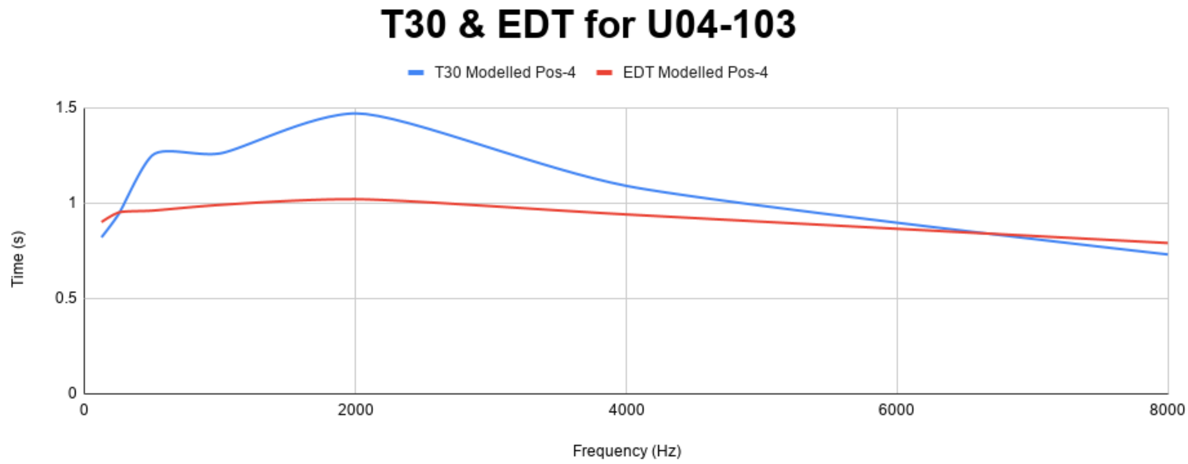

Figure 58: RT & EDT for U04 graph

STI Modelled Pos-4 (U03)	0.6
STI Modelled Pos-4 (U04)	0.52

Table 33: STI for U03 & U04

- **Position-5**

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Modelled Pos-5 (U03) (s)	0.82	0.9	1.28	1.15	1.08	0.93	0.73
EDT Modelled Pos-5 (U03) (s)	0.85	0.89	0.92	0.94	0.92	0.86	0.74
T30 Modelled Pos-5 (U04) (s)	0.86	1.09	1.12	1.41	1.17	1.18	0.71
EDT Modelled Pos-5 (U04) (s)	0.86	0.91	0.93	0.94	0.97	0.9	0.79

Table 34: Position-5 RT & EDT for U03 & U04 rooms

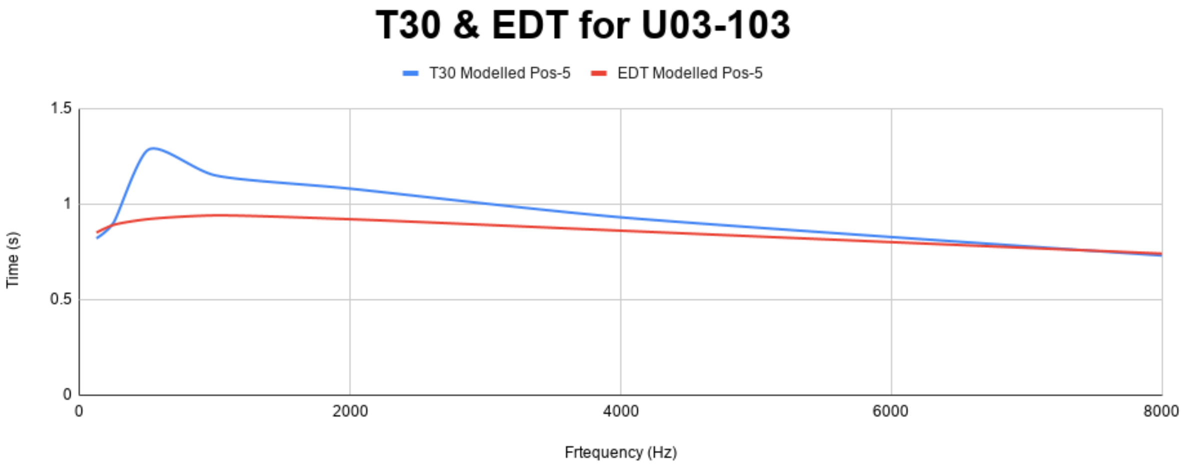

Figure 59: RT & EDT for U03 graph

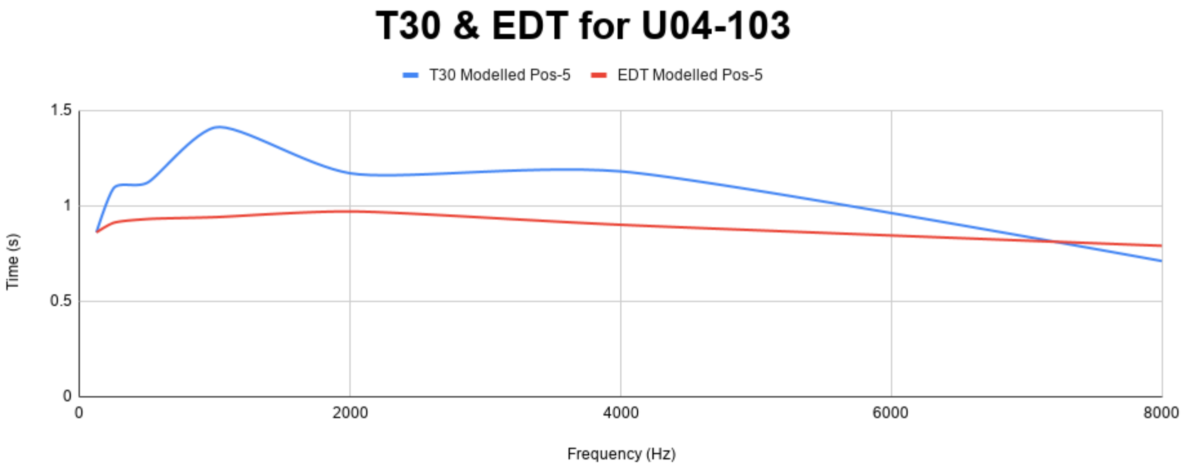

Figure 60: RT & EDT for U04 graph

STI Modelled Pos-5 (U03)	0.6
STI Modelled Pos-5 (U04)	0.54

Table 35: STI for U03 & U04

- **Average**

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Modelled Average (U03) (s)	0.884	0.914	1.144	1.12	1.08	0.938	0.67
EDT Modelled Average (U03) (s)	0.826	0.86	0.888	0.896	0.882	0.824	0.712
T30 Modelled Average (U04) (s)	0.886	1.014	1.14	1.34	1.33	1.138	0.718
EDT Modelled Average (U04) (s)	0.892	0.938	0.95	0.98	1	0.926	0.79

Table 36: Average RT & EDT for U03 & U04 rooms

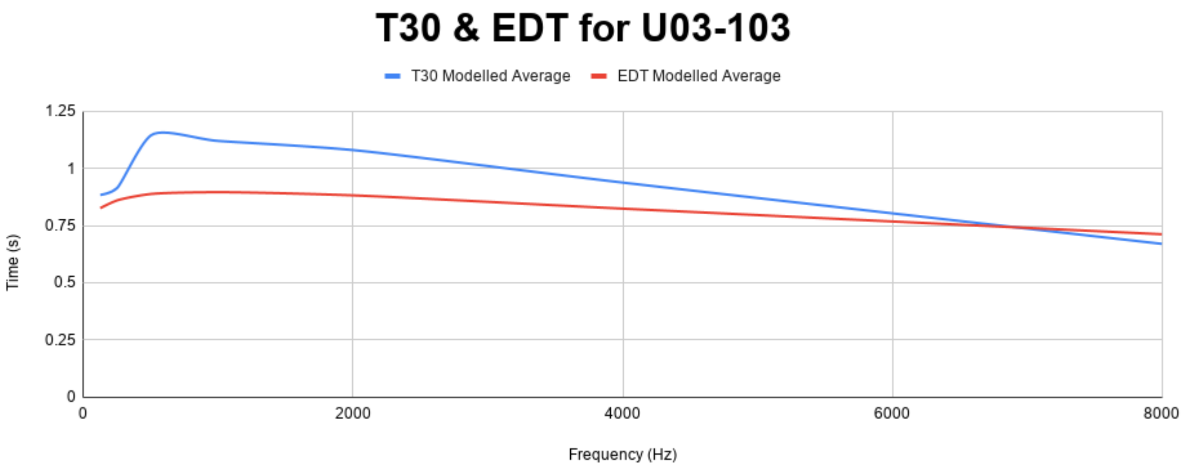

Figure 61: RT & EDT for U03 graph

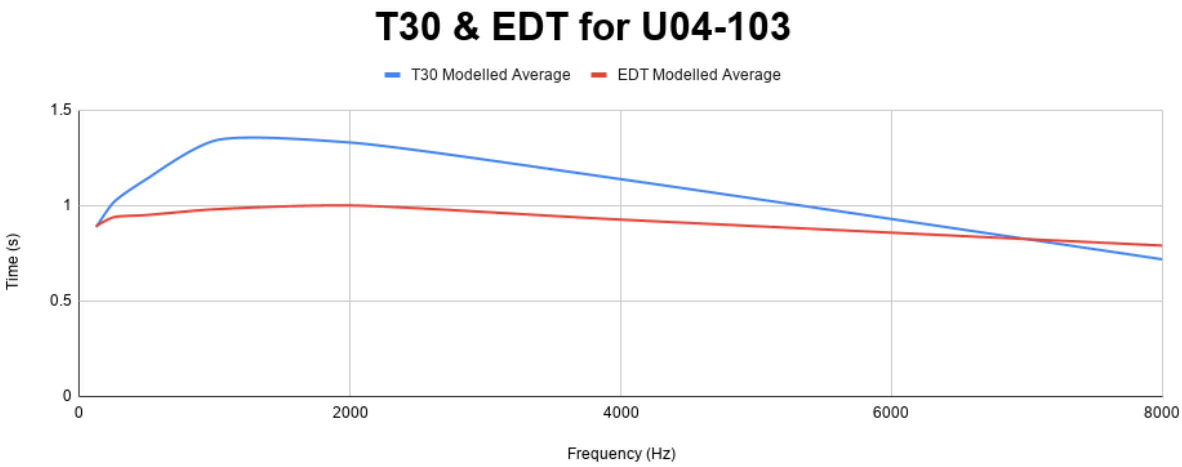

Figure 62: RT & EDT for U04 graph

STI Modelled Average (U03)	0.6
STI Modelled Average (U04)	0.54

Table 37: STI for U03 & U04

5.1.2 **Comparison between measured and calculated data**

In this section the comparison between the measured and calculated data is analysed for both rooms U03-103 & U04-103. The calculated data of the parameters RT and EDT are close enough (see Table 38) to the measured values. The STI values of the both calculated and measured rooms (see Table 39) are matching and that proves the 3D model of the room is reliable for further calculation for the solution analysis.

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 Measured Average (U03) (s)	1.75	1.382	1.138	1.07	0.954	0.73	0.506
T30 Modelled Average (U03) (s)	0.884	0.914	1.144	1.12	1.08	0.938	0.67
EDT Measured Average (U03) (s)	1.6264	1.1226	1.156	1.0268	0.9502	0.7294	0.5144
EDT Modelled Average (U03) (s)	0.826	0.86	0.888	0.896	0.882	0.824	0.712
T30 Measured Average (U04) (s)	2.244	2.286	1.98	1.7238	1.5508	1.0658	0.7014
T30 Modelled Average (U04) (s)	0.886	1.014	1.14	1.34	1.33	1.138	0.718
EDT Measured Average (U04) (s)	1.9742	2.2748	1.9818	1.6414	1.459	1.0244	0.6516
EDT Modelled Average (U04) (s)	0.892	0.938	0.95	0.98	1	0.926	0.79

Table 38: RT & EDT for U03 & U04 rooms measured and modelled

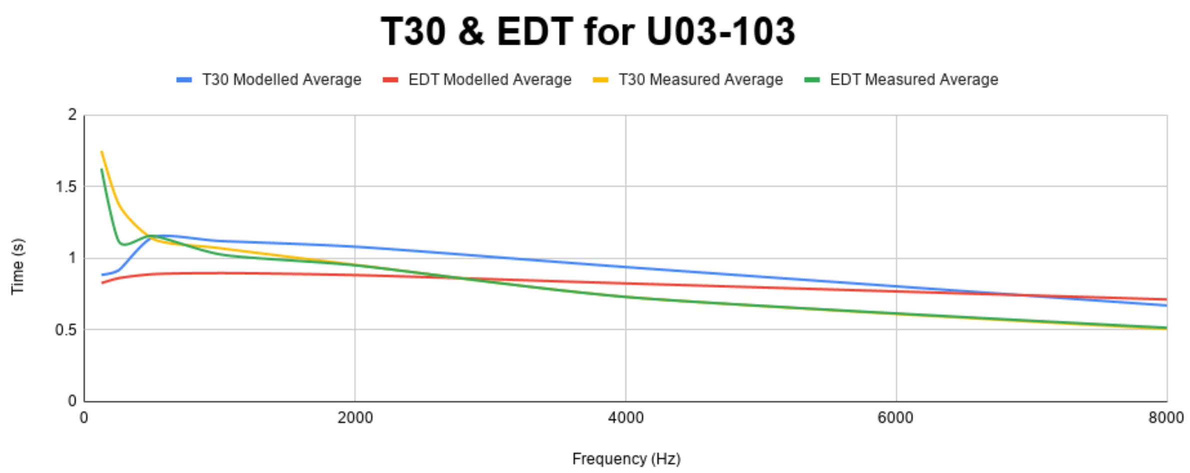

Figure 63: RT & EDT for U03 graph

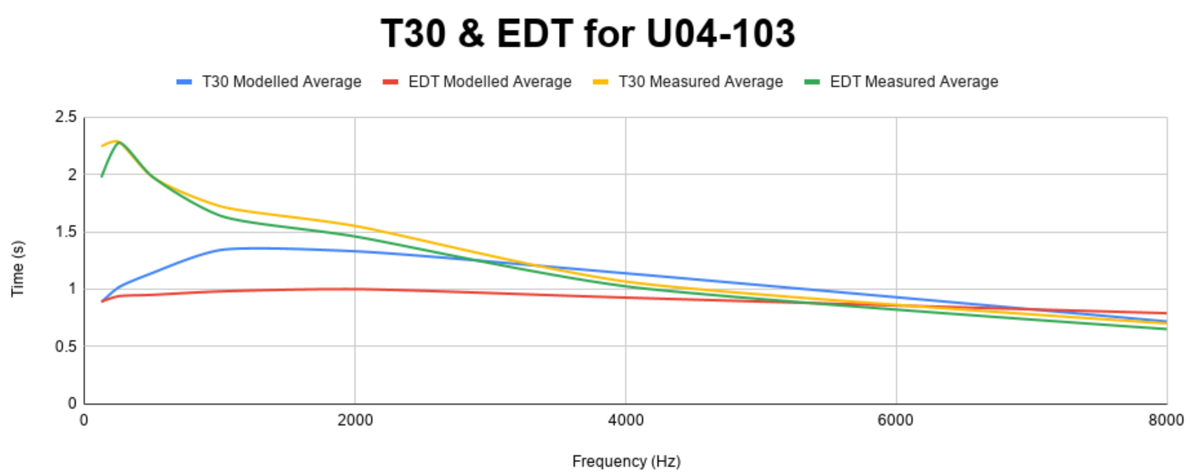

Figure 64: RT & EDT for U04 graph.

STI Measured Average (U03)	0.6
STI Modelled Average (U03)	0.6
STI Measured Average (U04)	0.52
STI Modelled Average (U04)	0.54

Table 39: STI for U03 & U04 of measured and modelled

5.1.3 Comparison between acoustic ceiling and baffle

As stated earlier in this chapter the acoustic treatment technique is used to improve the acoustic condition of the rooms in 3D model. The presence of two different type of absorbers were simulated: The Ecophon® ceiling absorbers and The Ecophon® baffles. Different numbers of absorbers (ceilings and baffles) are simulated. The room geometry includes 6 parallel "beams" with 1-meter height supporting the ceiling. In 3D model of the rooms the ceiling absorbers were placed horizontally between two consecutive beams and backed by the ceiling. The acoustic baffles were placed vertically and backed by the beams. Initially, only the 2 rows of absorbers were included in the models, then 4 and 6 rows in order to find the best trade-off between cost of the treatment and performance of the rooms.

5.1.3.1 Two Row Comparison

In the 3D model, two rows of absorbers wee included and placed in back side of the rooms (U03-103 & U04-103). The calculation took place for baffles and ceilings separately. The obtained RT, EDT and STI values for each microphone position are listed in Tables 40,41,42 &43. The graphs of RT and EDT are plotted in Figures 65 to 75. The performance of both ceiling absorber and baffle are same in the value of STI (0.62) for both rooms (refer Tables 42 &43) and the STI value increases, in comparison with the measured values, for both rooms. According to the Table 1, the measured values result in a "good" acoustic behaviour of the room, which confirms the improvement in the speech intelligibility.

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 (5th &6th Row Baffle) Pos-1 (s)	0.76	0.8	0.98	1.36	1.41	1.04	0.69
T30 (5th &6th Row Baffle) Pos-2 (s)	0.8	0.99	1	1.38	1.15	1.12	0.69
T30 (5th &6th Row Baffle) Pos-3 (s)	0.81	1.06	1	1.06	1.25	0.91	0.76
T30 (5th &6th Row Baffle) Pos-4 (s)	0.74	0.9	0.99	1.28	1.07	0.98	0.71
T30 (5th &6th Row Baffle) Pos-5 (s)	0.82	0.82	1.02	1.01	1.14	1	0.65
T30 (5th &6th Row Baffle) Average (s)	0.786	0.914	0.998	1.218	1.204	1.01	0.7
T30 (5th &6th Row Cabsorb) Pos-1 (s)	0.82	1.03	1.16	1.28	1.19	1.11	0.7
T30 (5th &6th Row Cabsorb) Pos-2 (s)	0.81	0.82	1.06	0.98	1.27	0.96	0.72

T30 (5th &6th Row Cabsorb) Pos-3 (s)	0.85	0.86	1.32	1.57	1.2	1.08	0.71
T30 (5th &6th Row Cabsorb) Pos-4 (s)	0.77	0.92	1.24	1.39	1.04	1.1	0.7
T30 (5th &6th Row Cabsorb) Pos-5 (s)	0.81	0.98	1.03	1.19	1.36	0.97	0.72
T30 (5th &6th Row Cabsorb) Average (s)	0.812	0.922	1.162	1.282	1.212	1.044	0.71
EDT (5th &6th Row Baffle) Pos-1 (s)	0.82	0.86	0.86	0.84	0.88	0.81	0.78
EDT (5th &6th Row Baffle) Pos-2 (s)	0.81	0.87	0.85	0.87	0.85	0.82	0.77
EDT (5th &6th Row Baffle) Pos-3 (s)	0.85	0.91	0.86	0.86	0.9	0.82	0.81
EDT (5th &6th Row Baffle) Pos-4 (s)	0.82	0.88	0.85	0.88	0.88	0.82	0.78
EDT (5th &6th Row Baffle) Pos-5 (s)	0.82	0.87	0.84	0.86	0.87	0.84	0.77
EDT (5th &6th Row Baffle) Average (s)	0.824	0.878	0.852	0.862	0.876	0.822	0.782
EDT (5th &6th Row Cabsorb) Pos-1 (s)	0.85	0.85	0.87	0.87	0.88	0.84	0.78
EDT (5th &6th Row Cabsorb) Pos-2 (s)	0.83	0.85	0.87	0.9	0.91	0.84	0.79
EDT (5th &6th Row Cabsorb) Pos-3 (s)	0.9	0.9	0.94	0.94	0.95	0.84	0.81
EDT (5th &6th Row Cabsorb) Pos-4 (s)	0.88	0.88	0.86	0.92	0.95	0.84	0.81
EDT (5th &6th Row Cabsorb) Pos-5 (s)	0.83	0.86	0.85	0.89	0.92	0.84	0.8
EDT (5th &6th Row Cabsorb) Average (s)	0.858	0.868	0.878	0.904	0.922	0.84	0.798

Table 40: Comparison for U03

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 (5th &6th Row Baffle) Pos-1 (s)	0.79	0.9	1.16	1.33	1.39	1	0.72
T30 (5th &6th Row Baffle) Pos-2 (s)	0.94	1.12	1.28	1.66	1.39	1.12	0.71
T30 (5th &6th Row Baffle) Pos-3 (s)	0.82	0.94	1.02	1.34	1.96	1.15	0.77
T30 (5th &6th Row Baffle) Pos-4 (s)	0.82	1.02	1.32	1.22	1.64	1.14	0.76
T30 (5th &6th Row Baffle) Pos-5 (s)	0.86	1.09	1.23	1.75	1.43	1.13	0.71
T30 (5th &6th Row Baffle) Average (s)	0.846	1.014	1.202	1.46	1.562	1.108	0.734
T30 (5th &6th Row Cabsorb) Pos-1 (s)	0.88	1.04	1.17	1.33	1.49	1.19	0.74
T30 (5th &6th Row Cabsorb) Pos-2 (s)	0.89	1.02	1.11	1.57	1.19	1.08	0.71
T30 (5th &6th Row Cabsorb) Pos-3 (s)	1.02	0.91	1.41	1.38	1.9	1.49	0.76
T30 (5th &6th Row Cabsorb) Pos-4 (s)	0.87	0.98	1.44	1.25	1.7	1.4	0.74
T30 (5th &6th Row Cabsorb) Pos-5 (s)	0.87	0.98	1.21	1.47	1.12	1.1	0.69
T30 (5th &6th Row Cabsorb) Average (s)	0.906	0.986	1.268	1.4	1.48	1.252	0.728
EDT (5th &6th Row Baffle) Pos-1 (s)	0.84	0.88	0.85	0.86	0.87	0.82	0.77
EDT (5th &6th Row Baffle) Pos-2 (s)	0.86	0.89	0.85	0.89	0.88	0.83	0.79
EDT (5th &6th Row Baffle) Pos-3 (s)	0.9	0.92	0.9	0.92	0.92	0.89	0.85
EDT (5th &6th Row Baffle) Pos-4 (s)	0.89	0.89	0.87	0.89	0.9	0.84	0.8
EDT (5th &6th Row Baffle) Pos-5 (s)	0.85	0.89	0.84	0.87	0.88	0.83	0.78
EDT (5th &6th Row Baffle) Average (s)	0.868	0.894	0.862	0.886	0.89	0.842	0.798
EDT (5th &6th Row Cabsorb) Pos-1 (s)	0.83	0.85	0.82	0.86	0.88	0.83	0.78
EDT (5th &6th Row Cabsorb) Pos-2 (s)	0.83	0.87	0.85	0.9	0.9	0.84	0.79
EDT (5th &6th Row Cabsorb) Pos-3 (s)	0.88	0.92	0.94	0.99	0.94	0.91	0.82
EDT (5th &6th Row Cabsorb) Pos-4 (s)	0.83	0.89	0.89	0.92	0.91	0.86	0.8
EDT (5th &6th Row Cabsorb) Pos-5 (s)	0.83	0.84	0.85	0.86	0.89	0.83	0.78
EDT (5th &6th Row Cabsorb) Average (s)	0.84	0.874	0.87	0.906	0.904	0.854	0.794

Table 41: Comparison for U04

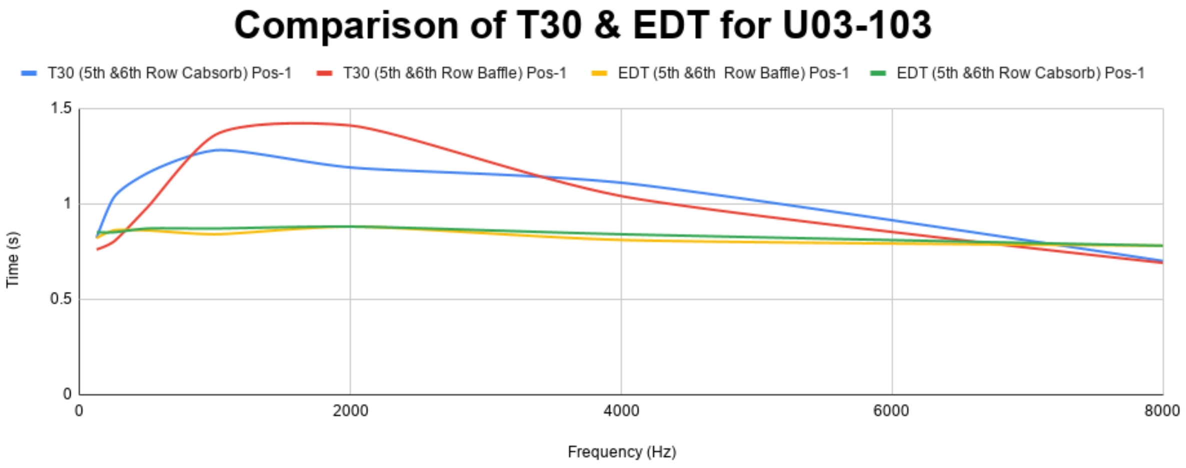

Figure 65: RT & EDT graph for Position-1

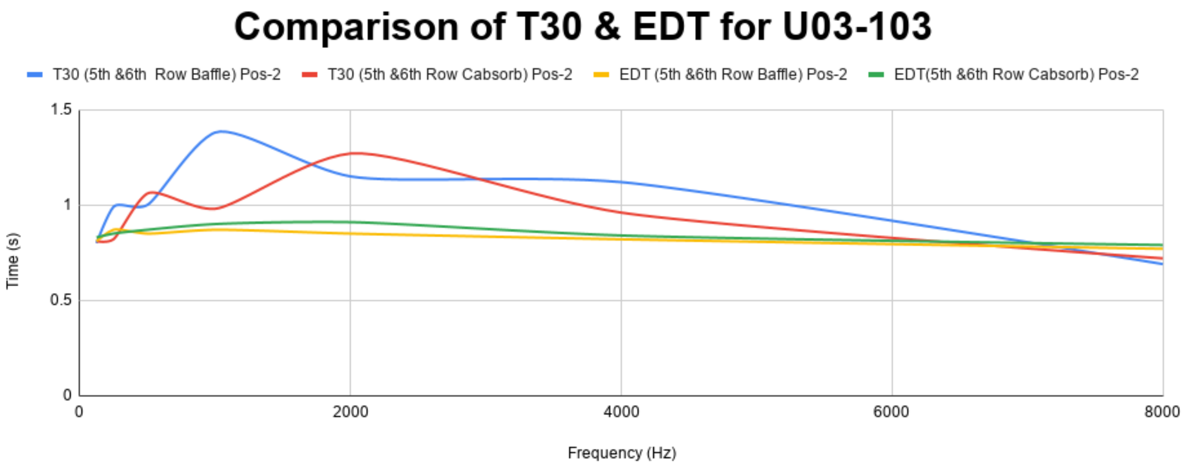

Figure 66:RT & EDT graph for Position-2

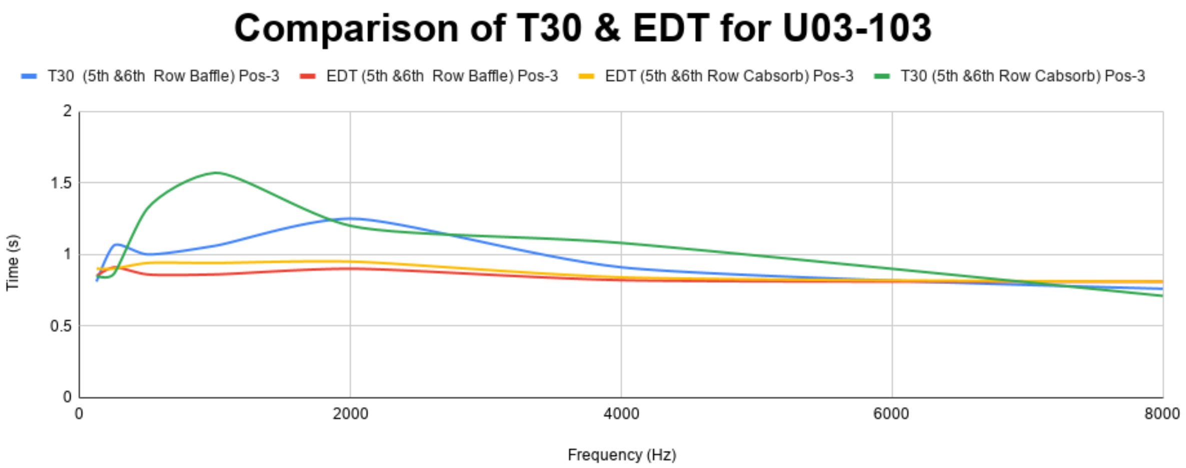

Figure 67: RT & EDT graph for Position-3

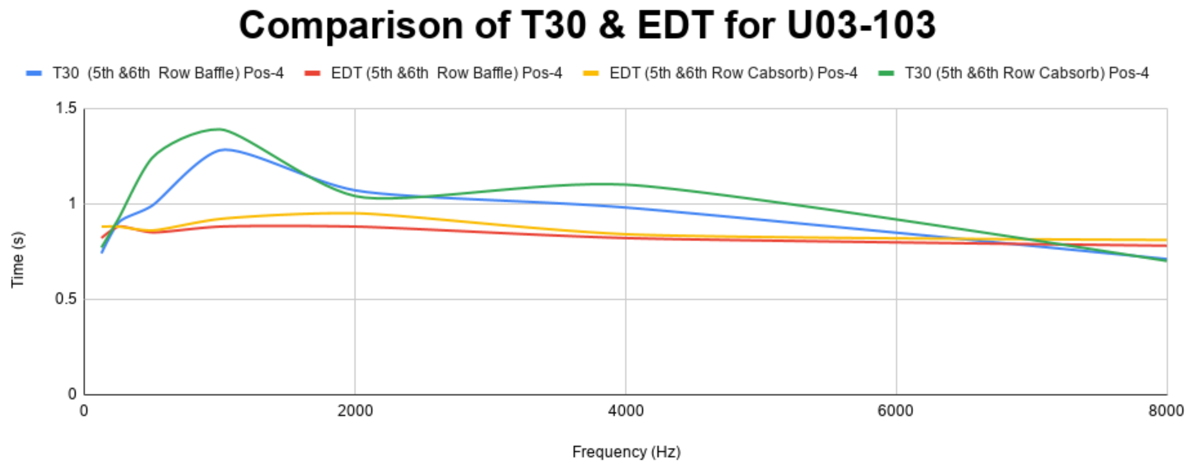

Figure 68: RT & EDT graph for Position-4

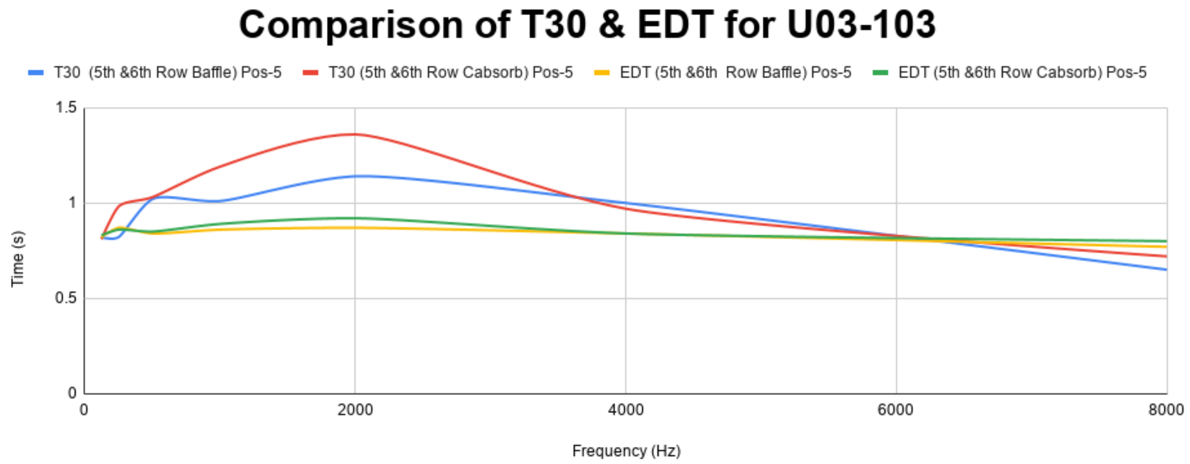

Figure 69: RT & EDT graph for Position-5

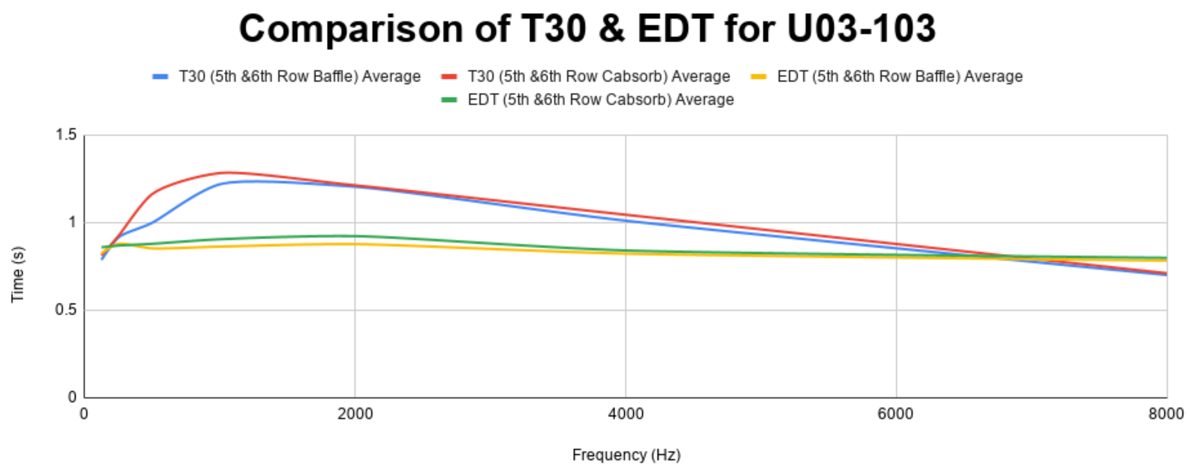

Figure 70: Average RT & EDT graph

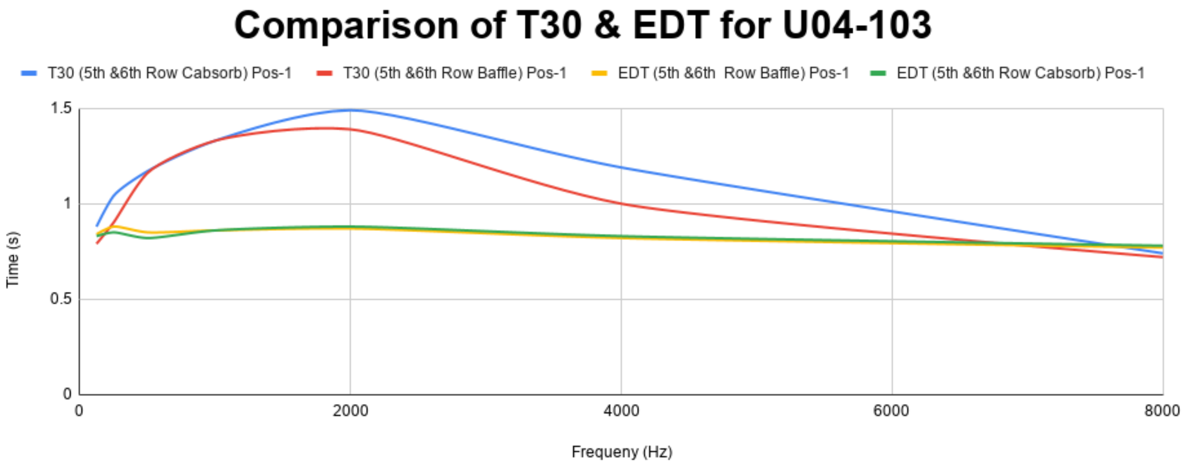

Figure 71: RT & EDT graph for Position-1

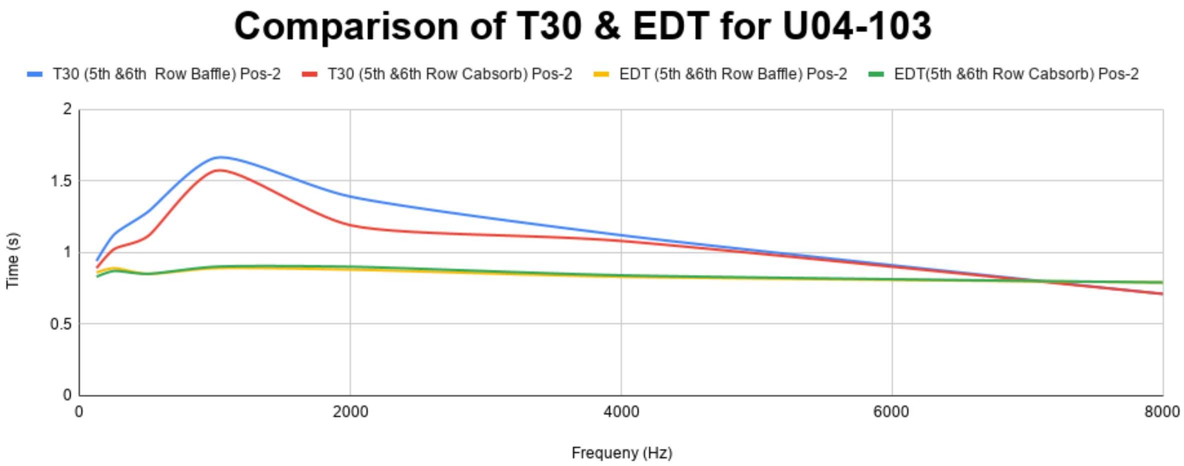

Figure 72: RT & EDT graph for Position-2

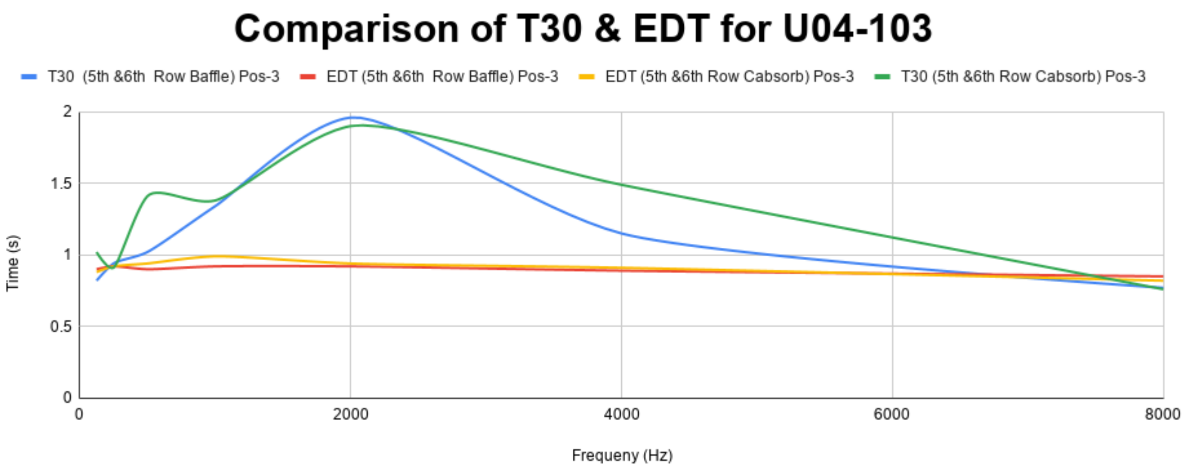

Figure 73: RT & EDT graph for Position-3

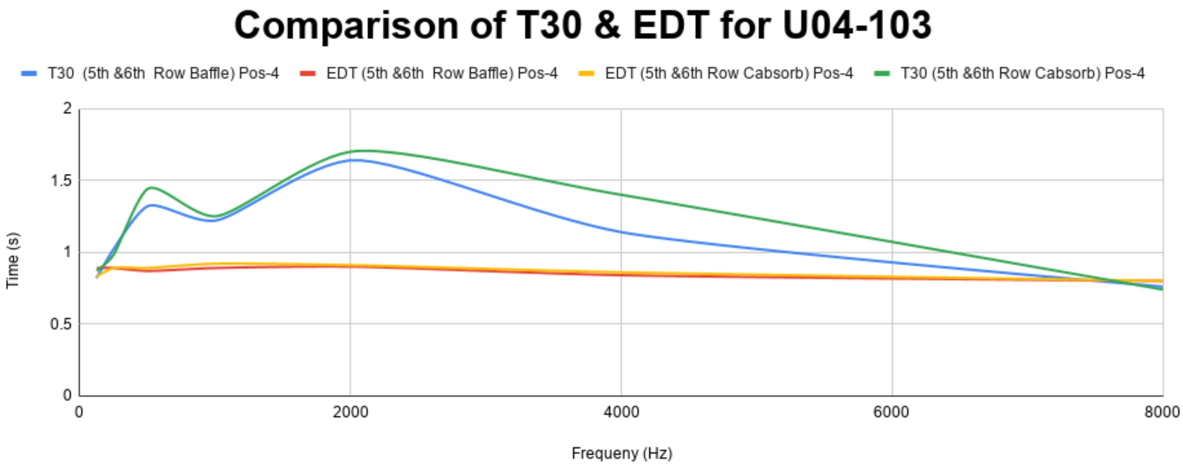

Figure 74: RT & EDT graph for Position-4

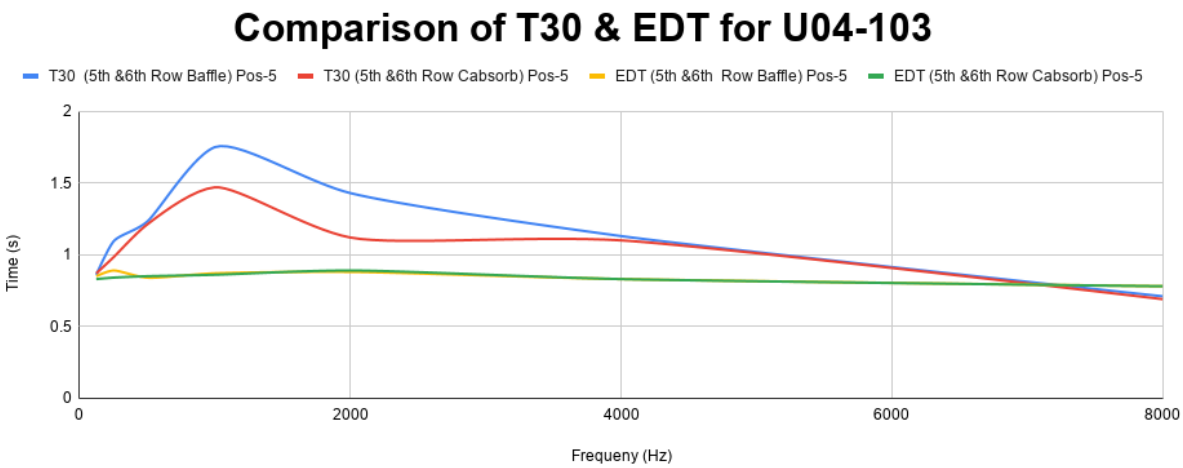

Figure 75: RT & EDT graph for Position-5

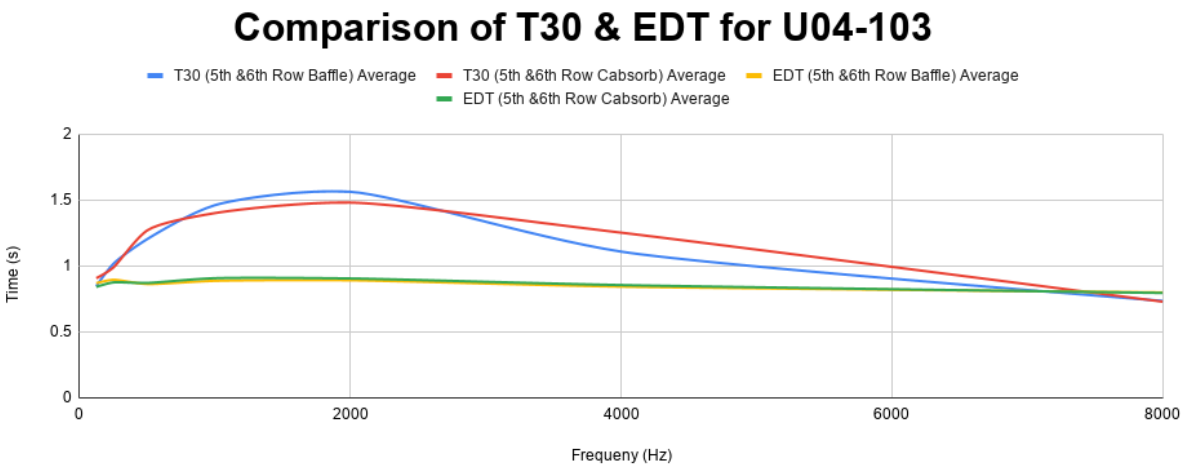

Figure 76: Average RT & EDT graph

STI (2 Row Baffle) Pos-1	0.62
STI (2 Row Baffle) Pos-2	0.61
STI (2 Row Baffle) Pos-3	0.62
STI (2 Row Baffle) Pos-4	0.62
STI (2 Row Baffle) Pos-5	0.62
STI (2 Row Baffle) Average	0.618
STI (2 Row Cabsorb) Pos-1	0.62
STI (2 Row Cabsorb) Pos-2	0.62
STI (2 Row Cabsorb) Pos-3	0.61
STI (2 Row Cabsorb) Pos-4	0.63
STI (2 Row Cabsorb) Pos-5	0.62
STI (2 Row Cabsorb) Average	0.62

Table 42: STI for U03

STI (2 Row Baffle) Pos-1	0.63
STI (2 Row Baffle) Pos-2	0.62
STI (2 Row Baffle) Pos-3	0.6
STI (2 Row Baffle) Pos-4	0.62
STI (2 Row Baffle) Pos-5	0.63
STI (2 Row Baffle) Average	0.62
STI (2 Row Cabsorb) Pos-1	0.63
STI (2 Row Cabsorb) Pos-2	0.62
STI (2 Row Cabsorb) Pos-3	0.61
STI (2 Row Cabsorb) Pos-4	0.63
STI (2 Row Cabsorb) Pos-5	0.63
STI (2 Row Cabsorb) Average	0.624

Table 43: STI for U04

5.1.3.2 Four Row Comparison

The 3D model was designed also with the inclusion of four rows of ceiling absorber and baffles, placed in the back side of the rooms (U03-103 & U04-103). The calculation took place for baffles and ceilings separately. The obtained RT, EDT and STI values for each microphone position are described in Tables 44,45,46 &47. The graph of RT and EDT are plotted in Figures 77 to 87. The STI value when the baffles are included is 0.62 for both rooms, whilst the ceiling absorber design provides the STI value 0.64. The performance of ceiling absorber is better than the acoustic baffles in the value of STI for both rooms and the STI value increased gradually compared to the measured value for both rooms. Compared with the case of baffles, the STI obtained by including ceiling absorbers is 0.2 higher for both rooms, thus the speech intelligibility greatly improves.

According to the Table 1, the measured value result in a “good” acoustic behaviour of the room, which confirms the improvement in the speech intelligibility.

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 (3rd to 6th Row Baffle) Pos-1 (s)	0.76	1.09	1.02	1.18	1.1	1.04	0.69
T30 (3rd to 6th Row Baffle) Pos-2 (s)	0.9	0.81	1.28	1.73	1.01	1.04	0.67
T30 (3rd to 6th Row Baffle) Pos-3 (s)	0.89	0.88	1.12	1.01	1.23	1.17	0.77
T30 (3rd to 6th Row Baffle) Pos-4 (s)	0.81	0.87	0.97	0.99	1.12	1.23	0.7
T30 (3rd to 6th Row Baffle) Pos-5 (s)	0.89	0.87	1.33	1.76	1.04	0.97	0.67
T30 (3rd to 6th Row Baffle) Average (s)	0.85	0.904	1.144	1.334	1.1	1.09	0.7
T30 (3rd to 6th Row Cabsorb) Pos-1 (s)	0.94	0.97	1.28	1.22	1.86	1.23	0.73
T30 (3rd to 6th Row Cabsorb) Pos-2 (s)	0.87	1.23	1.28	1.12	1.16	1.24	0.68
T30 (3rd to 6th Row Cabsorb) Pos-3 (s)	1.02	0.93	1.63	1.32	1.4	1.21	0.72
T30 (3rd to 6th Row Cabsorb) Pos-4 (s)	0.85	0.94	1.39	1.31	1.43	1.09	0.74
T30 (3rd to 6th Row Cabsorb) Pos-5 (s)	0.85	1.12	1.29	1.05	1.12	1.32	0.7
T30 (3rd to 6th Row Cabsorb) Average (s)	0.906	1.038	1.374	1.204	1.394	1.218	0.714
EDT (3rd to 6th Row Baffle) Pos-1 (s)	0.83	0.86	0.81	0.83	0.85	0.79	0.81
EDT (3rd to 6th Row Baffle) Pos-2 (s)	0.84	0.89	0.83	0.85	0.84	0.79	0.81
EDT (3rd to 6th Row Baffle) Pos-3 (s)	0.86	0.85	0.84	0.8	0.86	0.75	0.83
EDT (3rd to 6th Row Baffle) Pos-4 (s)	0.82	0.86	0.84	0.82	0.87	0.81	0.84
EDT (3rd to 6th Row Baffle) Pos-5 (s)	0.83	0.88	0.83	0.85	0.87	0.82	0.82
EDT (3rd to 6th Row Baffle) Average (s)	0.836	0.868	0.83	0.83	0.858	0.792	0.822
EDT (3rd to 6th Row Cabsorb) Pos-1 (s)	0.79	0.78	0.79	0.8	0.81	0.75	0.78
EDT (3rd to 6th Row Cabsorb) Pos-2 (s)	0.77	0.77	0.76	0.81	0.84	0.73	0.77
EDT (3rd to 6th Row Cabsorb) Pos-3 (s)	0.84	0.91	0.9	0.93	0.94	0.86	0.79
EDT (3rd to 6th Row Cabsorb) Pos-4 (s)	0.81	0.85	0.86	0.89	0.92	0.85	0.78
EDT (3rd to 6th Row Cabsorb) Pos-5 (s)	0.77	0.75	0.76	0.81	0.8	0.72	0.77
EDT (3rd to 6th Row Cabsorb) Average (s)	0.796	0.812	0.814	0.848	0.862	0.782	0.778

Table 44: Comparison for U03

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 (3rd to 6th Row Baffle) Pos-1 (s)	0.87	1	1.14	1.09	1.52	1.09	0.71
T30 (3rd to 6th Row Baffle) Pos-2 (s)	1.04	0.95	1.51	1.5	1.32	1.13	0.67
T30 (3rd to 6th Row Baffle) Pos-3 (s)	0.83	0.84	1.36	1.63	1.7	1.15	0.76
T30 (3rd to 6th Row Baffle) Pos-4 (s)	0.8	0.86	1.31	1.52	1.44	1.05	0.7
T30 (3rd to 6th Row Baffle) Pos-5 (s)	0.95	0.88	1.56	1.27	1.4	1.12	0.68
T30 (3rd to 6th Row Baffle) Average (s)	0.898	0.906	1.376	1.402	1.476	1.108	0.704
T30 (3rd to 6th Row Cabsorb) Pos-1 (s)	0.98	1.01	1.08	1.53	1.37	1.15	0.73
T30 (3rd to 6th Row Cabsorb) Pos-2 (s)	1.07	0.96	1.38	1.43	1.44	1.07	0.71
T30 (3rd to 6th Row Cabsorb) Pos-3 (s)	0.87	1.01	1.24	1.38	1.68	1.26	0.79
T30 (3rd to 6th Row Cabsorb) Pos-4 (s)	0.94	1.04	1.33	1.25	1.56	1.14	0.8
T30 (3rd to 6th Row Cabsorb) Pos-5 (s)	1.03	1.01	1.36	1.43	1.6	1.05	0.69
T30 (3rd to 6th Row Cabsorb) Average (s)	0.978	1.006	1.278	1.404	1.53	1.134	0.744
EDT (3rd to 6th Row Baffle) Pos-1 (s)	0.84	0.86	0.81	0.81	0.83	0.78	0.79
EDT (3rd to 6th Row Baffle) Pos-2 (s)	0.84	0.86	0.81	0.83	0.81	0.78	0.81
EDT (3rd to 6th Row Baffle) Pos-3 (s)	0.87	0.87	0.89	0.9	0.89	0.76	0.85
EDT (3rd to 6th Row Baffle) Pos-4 (s)	0.86	0.84	0.82	0.82	0.84	0.8	0.83
EDT (3rd to 6th Row Baffle) Pos-5 (s)	0.85	0.87	0.82	0.82	0.84	0.77	0.8

EDT (3rd to 6th Row Baffle) Average (s)	0.852	0.86	0.83	0.836	0.842	0.778	0.816
EDT (3rd to 6th Row Cabsorb) Pos-1 (s)	0.77	0.76	0.77	0.76	0.81	0.72	0.76
EDT (3rd to 6th Row Cabsorb) Pos-2 (s)	0.77	0.77	0.76	0.79	0.81	0.73	0.77
EDT (3rd to 6th Row Cabsorb) Pos-3 (s)	0.83	0.87	0.93	0.89	0.96	0.87	0.82
EDT (3rd to 6th Row Cabsorb) Pos-4 (s)	0.8	0.85	0.88	0.88	0.89	0.85	0.78
EDT (3rd to 6th Row Cabsorb) Pos-5 (s)	0.76	0.74	0.75	0.74	0.75	0.7	0.76
EDT (3rd to 6th Row Cabsorb) Average (s)	0.786	0.798	0.818	0.812	0.844	0.774	0.778

Table 45: Comparison for U04

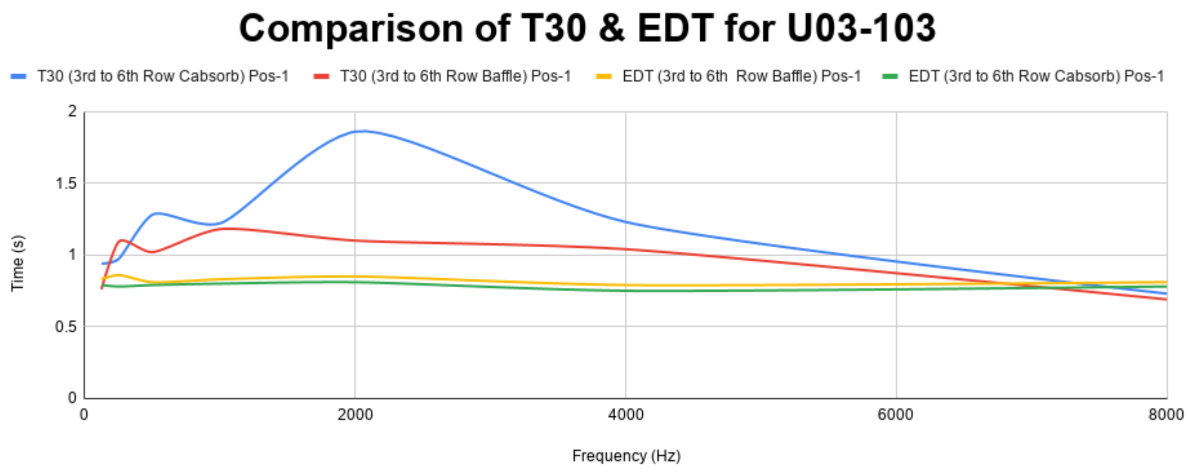

Figure 77: RT & EDT graph for Position-1

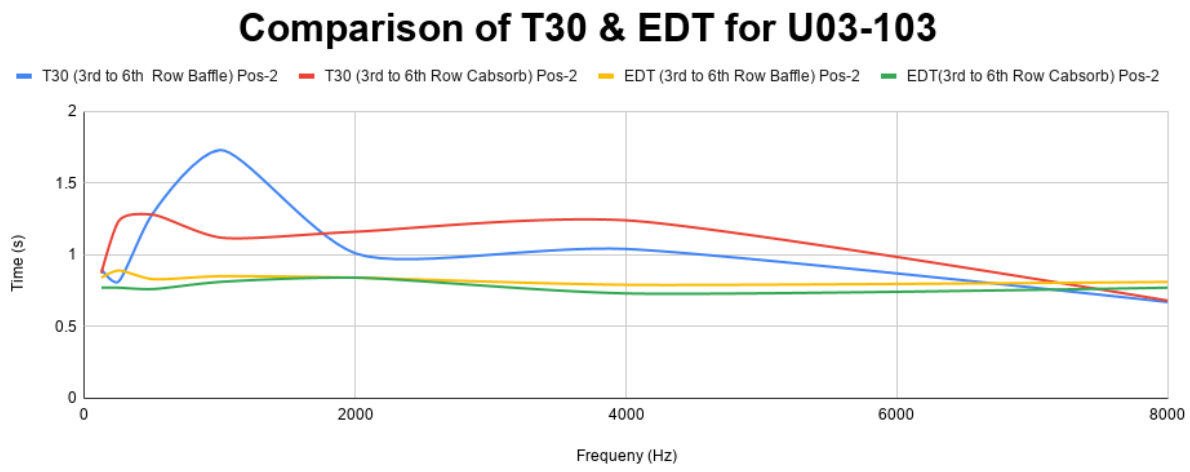

Figure 78: RT & EDT graph for Position-2

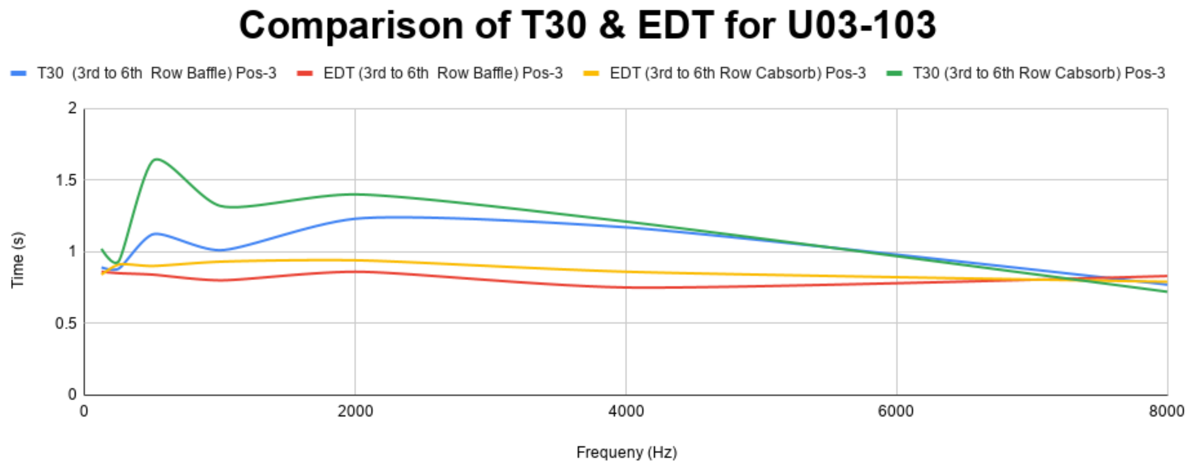

Figure 79: RT & EDT graph for Position-3

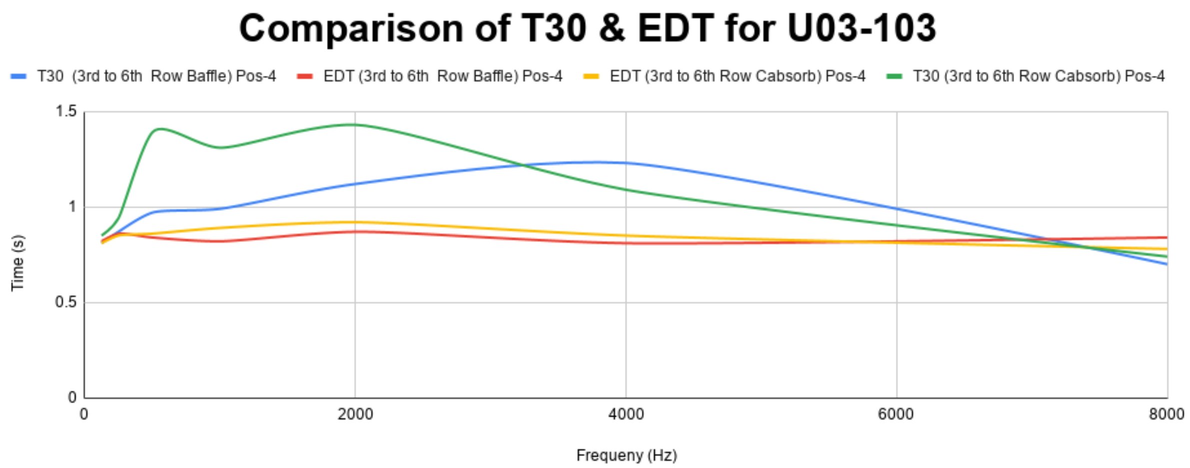

Figure 80: RT & EDT graph for Position-4

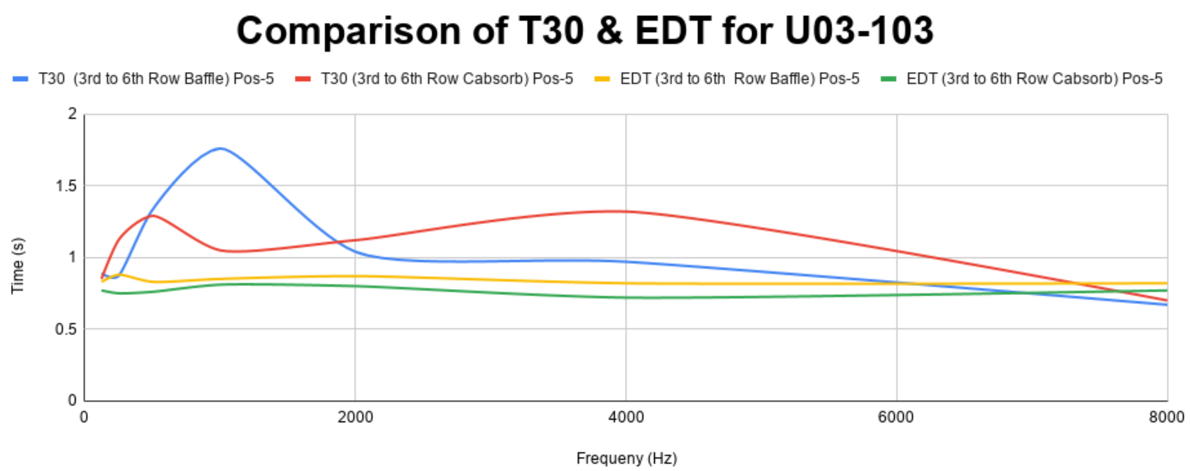

Figure 81: RT & EDT graph for Position-5

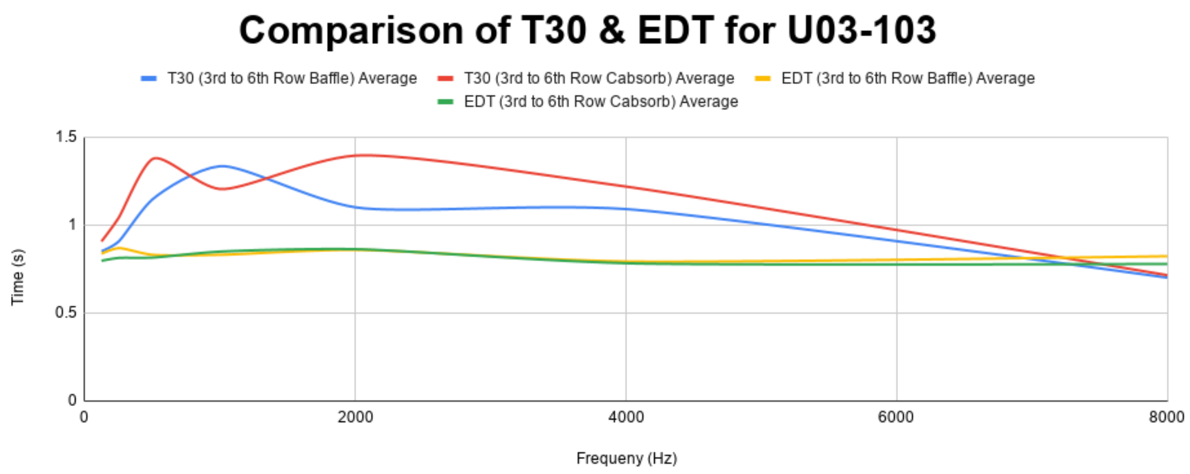

Figure 82: Average RT & EDT graph

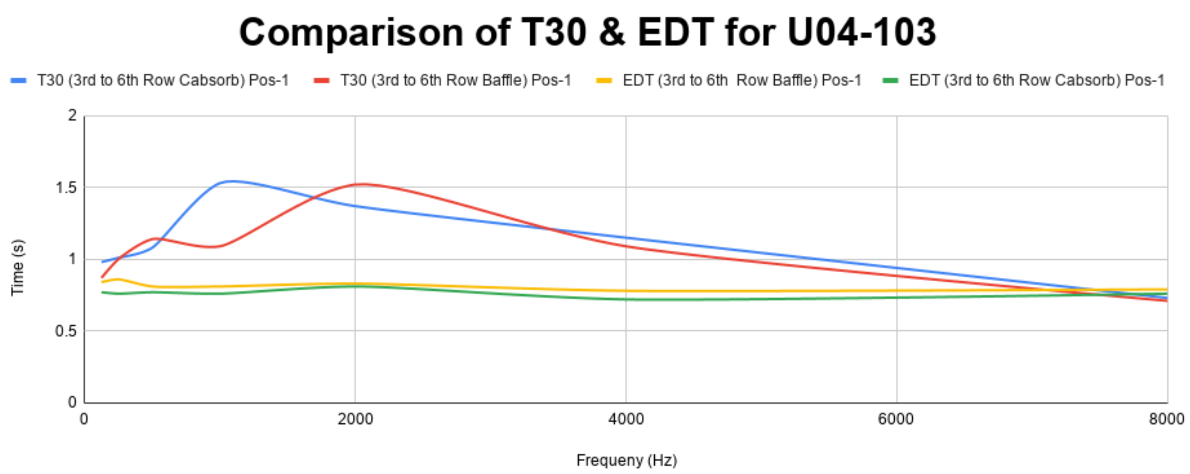

Figure 83: RT & EDT graph for Position-1

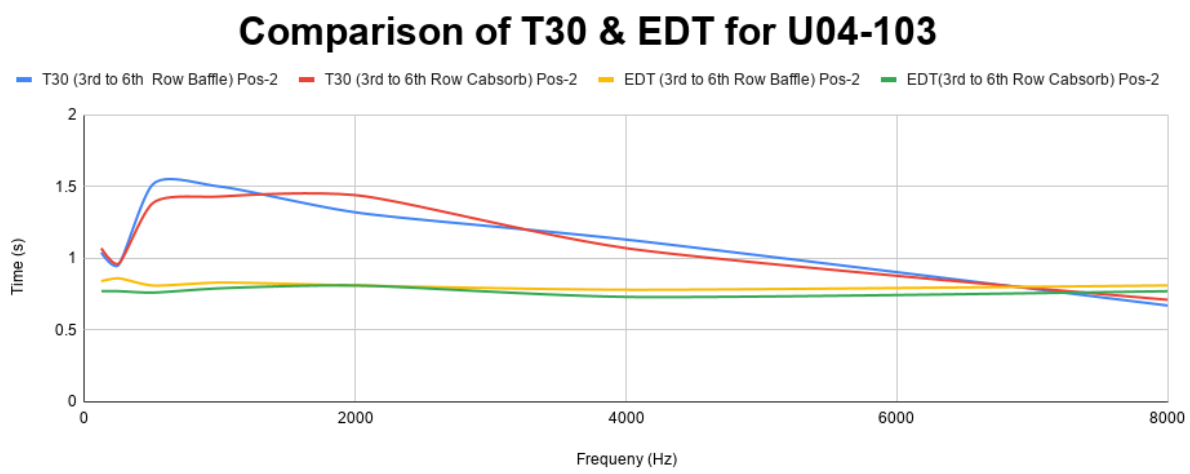

Figure 84: RT & EDT graph for Position-2

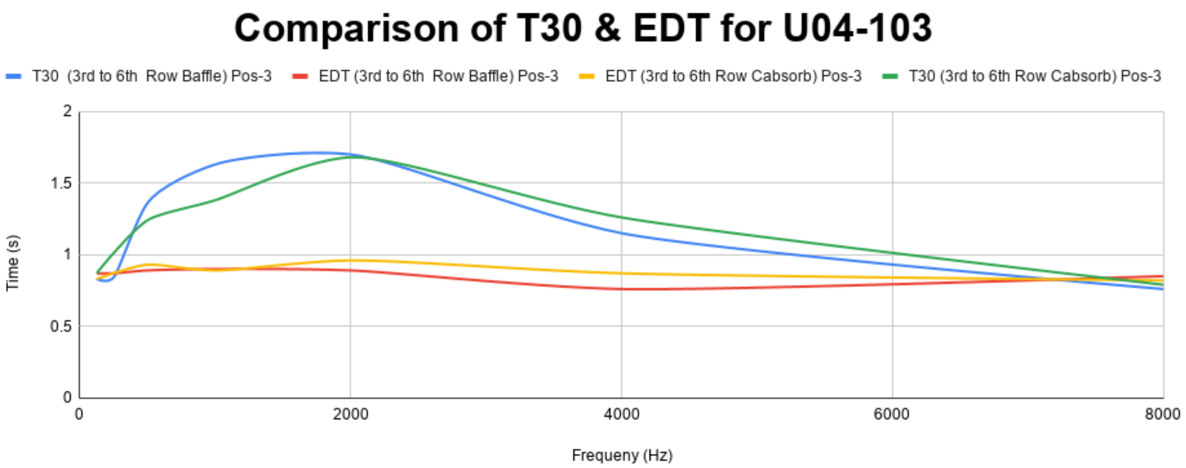

Figure 85: RT & EDT graph for Position-3

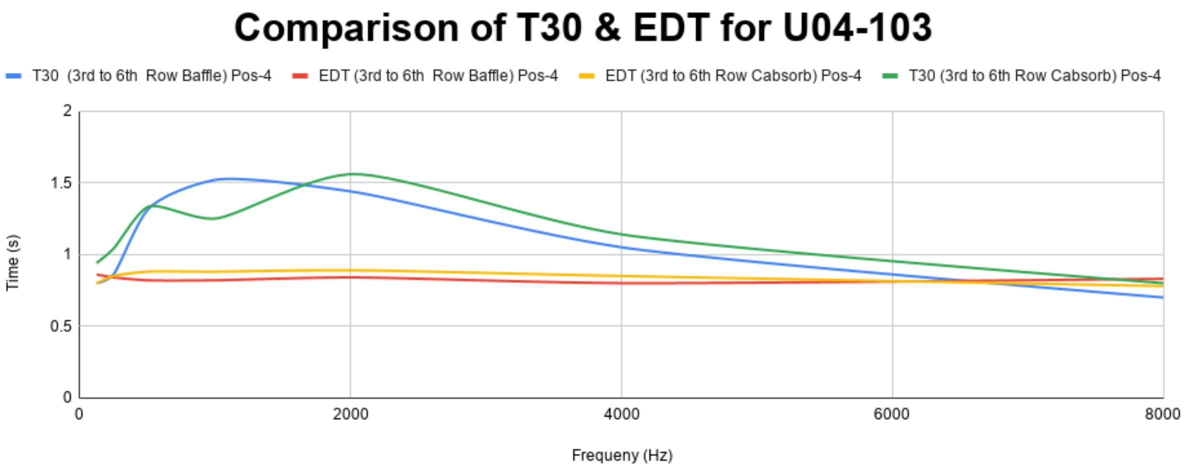

Figure 86: RT & EDT graph for Position-4

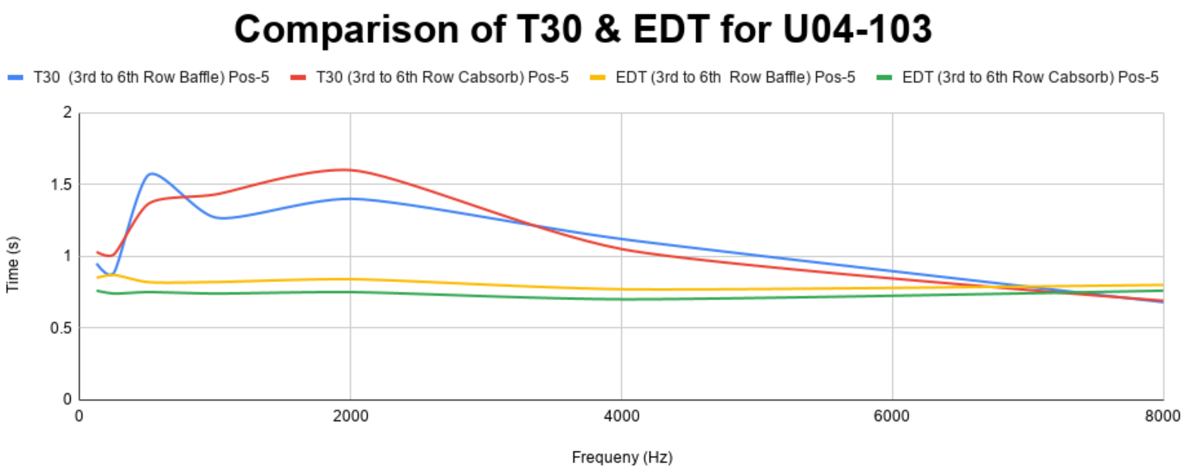

Figure 87: RT & EDT graph for Position-5

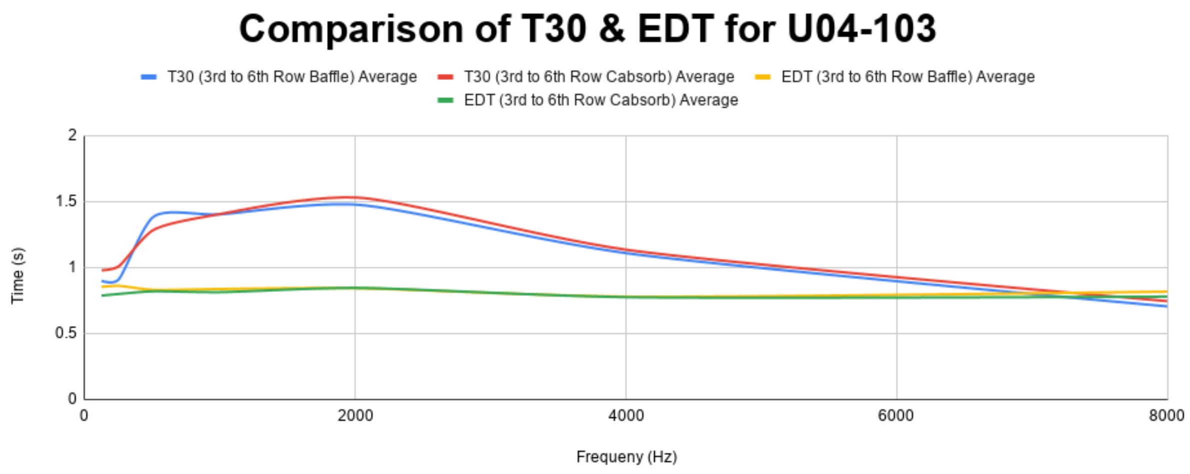

Figure 88: Average RT & EDT graph

STI (4 Row Baffle) Pos-1	0.63
STI (4 Row Baffle) Pos-2	0.63
STI (4 Row Baffle) Pos-3	0.62
STI (4 Row Baffle) Pos-4	0.63
STI (4 Row Baffle) Pos-5	0.62
STI (4 Row Baffle) Average	0.626
STI (4 Row Cabsorb) Pos-1	0.65
STI (4 Row Cabsorb) Pos-2	0.65
STI (4 Row Cabsorb) Pos-3	0.62
STI (4 Row Cabsorb) Pos-4	0.64
STI (4 Row Cabsorb) Pos-5	0.65
STI (4 Row Cabsorb) Average	0.642

Table 46: STI for U03

STI (4 Row Baffle) Pos-1	0.63
STI (4 Row Baffle) Pos-2	0.63
STI (4 Row Baffle) Pos-3	0.61
STI (4 Row Baffle) Pos-4	0.63
STI (4 Row Baffle) Pos-5	0.63
STI (4 Row Baffle) Average	0.626
STI (4 Row Cabsorb) Pos-1	0.66
STI (4 Row Cabsorb) Pos-2	0.65
STI (4 Row Cabsorb) Pos-3	0.63
STI (4 Row Cabsorb) Pos-4	0.64
STI (4 Row Cabsorb) Pos-5	0.66
STI (4 Row Cabsorb) Average	0.648

Table 47: STI for U04

5.1.3.3 Six Row Comparison

Finally, the 3D model is designed also to account for the presence of six rows of ceiling absorber and baffles which are placed by starting from the back side of the rooms (U03-103 & U04-103). The calculation took place for baffles and ceilings separately. The obtained RT, EDT and STI values for each microphone position are described (see Table 48,49,50 &51). The graph of RT and EDT is plotted (see Figures 89 to 99). The STI value obtained by using baffles is 0.64 for room U03-103 and 0.65 for room U04-103. The ceiling absorber design provides the STI value 0.70 for the room U03-103 and the STI value 0.71 for room U04-103. In terms of STI, the performance of ceiling absorber is better than the acoustic baffles for both rooms. As expected, at increasing the number of absorptive rows, the STI value increases gradually compared to the measured value for both rooms. Compared with baffles, the ceiling absorber are 0.6 STI higher for both rooms. According to the Table 1, the measured value results in a "good" acoustic behaviour of the rooms, which confirms the improvement in the speech intelligibility.

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 (1st to 6th Row Baffle) Pos-1 (s)	0.84	0.93	1.21	1.29	1.2	1.19	0.63
T30 (1st to 6th Row Baffle) Pos-2 (s)	0.93	1.02	1.3	1.25	1.35	1.01	0.66
T30 (1st to 6th Row Baffle) Pos-3 (s)	0.79	0.81	1.15	1.55	1.4	1.34	0.8
T30 (1st to 6th Row Baffle) Pos-4 (s)	0.79	1.13	1.34	1.49	1.49	1.98	0.7
T30 (1st to 6th Row Baffle) Pos-5 (s)	0.84	0.92	1.09	1.08	1.26	1.01	0.65
T30 (1st to 6th Row Baffle) Average (s)	0.838	0.962	1.218	1.332	1.34	1.306	0.688
T30 (1st to 6th Row Cabsorb) Pos-1 (s)	0.89	1.16	1.6	1.76	1.38	1.51	0.73
T30 (1st to 6th Row Cabsorb) Pos-2 (s)	1.69	1.03	1.97	1.71	1.21	1.12	0.69
T30 (1st to 6th Row Cabsorb) Pos-3 (s)	0.93	1.03	1.25	1.7	0.98	0.99	0.77
T30 (1st to 6th Row Cabsorb) Pos-4 (s)	1.05	1	1.57	1.87	1.28	1.15	0.73
T30 (1st to 6th Row Cabsorb) Pos-5 (s)	1.07	0.99	1	1.14	1.16	1.13	0.74
T30 (1st to 6th Row Cabsorb) Average (s)	1.126	1.042	1.478	1.636	1.202	1.18	0.732
EDT (1st to 6th Row Baffle) Pos-1 (s)	0.78	0.83	0.76	0.74	0.76	0.71	0.8
EDT (1st to 6th Row Baffle) Pos-2 (s)	0.8	0.85	0.82	0.79	0.79	0.74	0.82
EDT (1st to 6th Row Baffle) Pos-3 (s)	0.77	0.82	0.75	0.75	0.83	0.79	0.8
EDT (1st to 6th Row Baffle) Pos-4 (s)	0.79	0.79	0.74	0.76	0.78	0.76	0.8
EDT (1st to 6th Row Baffle) Pos-5 (s)	0.83	0.86	0.8	0.81	0.82	0.73	0.83
EDT (1st to 6th Row Baffle) Average (s)	0.794	0.83	0.774	0.77	0.796	0.746	0.81
EDT (1st to 6th Row Cabsorb) Pos-1 (s)	0.59	0.52	0.48	0.52	0.52	0.53	0.7
EDT (1st to 6th Row Cabsorb) Pos-2 (s)	0.63	0.57	0.53	0.56	0.57	0.51	0.72
EDT (1st to 6th Row Cabsorb) Pos-3 (s)	0.69	0.65	0.7	0.75	0.72	0.64	0.76
EDT (1st to 6th Row Cabsorb) Pos-4 (s)	0.68	0.64	0.63	0.71	0.76	0.63	0.71
EDT (1st to 6th Row Cabsorb) Pos-5 (s)	0.6	0.57	0.54	0.53	0.55	0.53	0.72
EDT (1st to 6th Row Cabsorb) Average (s)	0.638	0.59	0.576	0.614	0.624	0.568	0.722

Table 48: Comparison for U03

Frequency (Hz)	125	250	500	1000	2000	4000	8000
T30 (1st to 6th Row Baffle) Pos-1 (s)	0.73	1	1.07	1.27	1.2	0.98	0.65
T30 (1st to 6th Row Baffle) Pos-2 (s)	0.79	1.39	1.29	1.22	1.2	1.08	0.68
T30 (1st to 6th Row Baffle) Pos-3 (s)	0.84	0.91	1.16	1.23	1.37	1.09	0.7
T30 (1st to 6th Row Baffle) Pos-4 (s)	0.86	0.87	1.41	1.18	1.87	0.97	0.7
T30 (1st to 6th Row Baffle) Pos-5 (s)	0.76	1.44	1.37	1.1	1.42	1.09	0.67
T30 (1st to 6th Row Baffle) Average (s)	0.796	1.122	1.26	1.2	1.412	1.042	0.68
T30 (1st to 6th Row Cabsorb) Pos-1 (s)	1.15	1.16	1.08	1.5	1.65	1.15	0.74
T30 (1st to 6th Row Cabsorb) Pos-2 (s)	1.47	1.34	1.23	1.14	1.81	1.01	0.69
T30 (1st to 6th Row Cabsorb) Pos-3 (s)	0.92	1.24	1.02	1.51	2.2	1.3	0.79
T30 (1st to 6th Row Cabsorb) Pos-4 (s)	1.07	1.14	1	1.43	2	1.17	0.75
T30 (1st to 6th Row Cabsorb) Pos-5 (s)	1.3	1.29	1.16	1.67	1.8	0.93	0.68
T30 (1st to 6th Row Cabsorb) Average (s)	1.182	1.234	1.098	1.45	1.892	1.112	0.73
EDT (1st to 6th Row Baffle) Pos-1 (s)	0.8	0.81	0.71	0.71	0.72	0.65	0.81
EDT (1st to 6th Row Baffle) Pos-2 (s)	0.82	0.87	0.77	0.79	0.77	0.73	0.82
EDT (1st to 6th Row Baffle) Pos-3 (s)	0.82	0.82	0.74	0.75	0.79	0.7	0.84
EDT (1st to 6th Row Baffle) Pos-4 (s)	0.79	0.82	0.74	0.75	0.78	0.72	0.79
EDT (1st to 6th Row Baffle) Pos-5 (s)	0.8	0.84	0.73	0.76	0.76	0.7	0.82
EDT (1st to 6th Row Baffle) Average (s)	0.806	0.832	0.738	0.752	0.764	0.7	0.816
EDT (1st to 6th Row Cabsorb) Pos-1 (s)	0.57	0.52	0.48	0.53	0.46	0.46	0.68
EDT (1st to 6th Row Cabsorb) Pos-2 (s)	0.62	0.56	0.52	0.52	0.59	0.51	0.71
EDT (1st to 6th Row Cabsorb) Pos-3 (s)	0.68	0.67	0.63	0.69	0.68	0.63	0.75
EDT (1st to 6th Row Cabsorb) Pos-4 (s)	0.63	0.63	0.62	0.63	0.65	0.63	0.72
EDT (1st to 6th Row Cabsorb) Pos-5 (s)	0.62	0.51	0.51	0.52	0.57	0.45	0.71
EDT (1st to 6th Row Cabsorb) Average (s)	0.624	0.578	0.552	0.578	0.59	0.536	0.714

Table 49: Comparison for U03

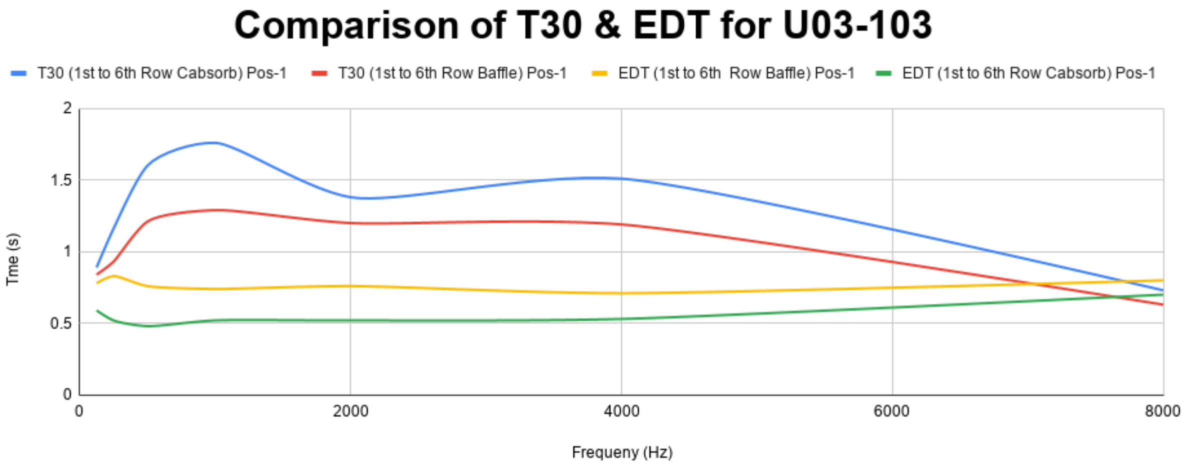

Figure 89: RT & EDT graph for Position-1

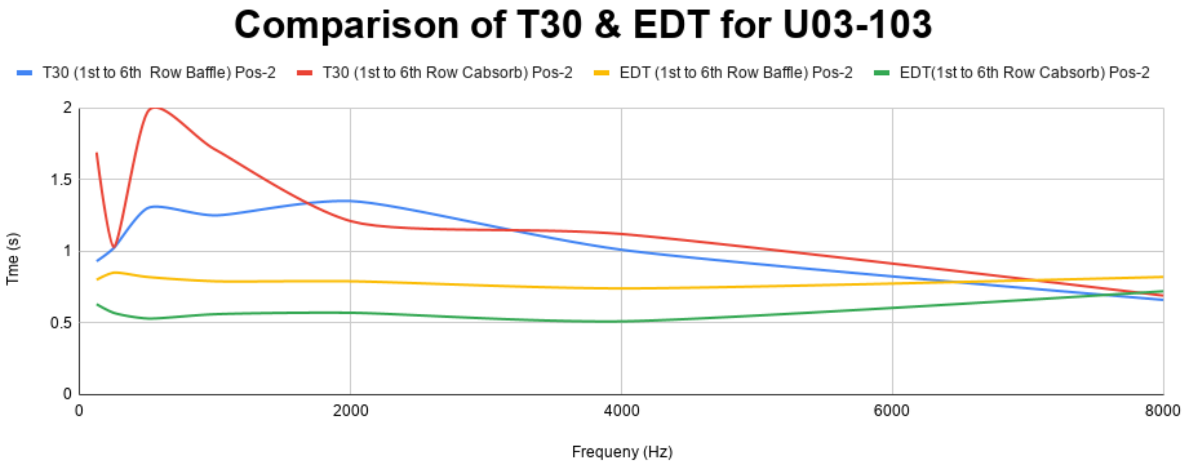

Figure 90: RT & EDT graph for Position-2

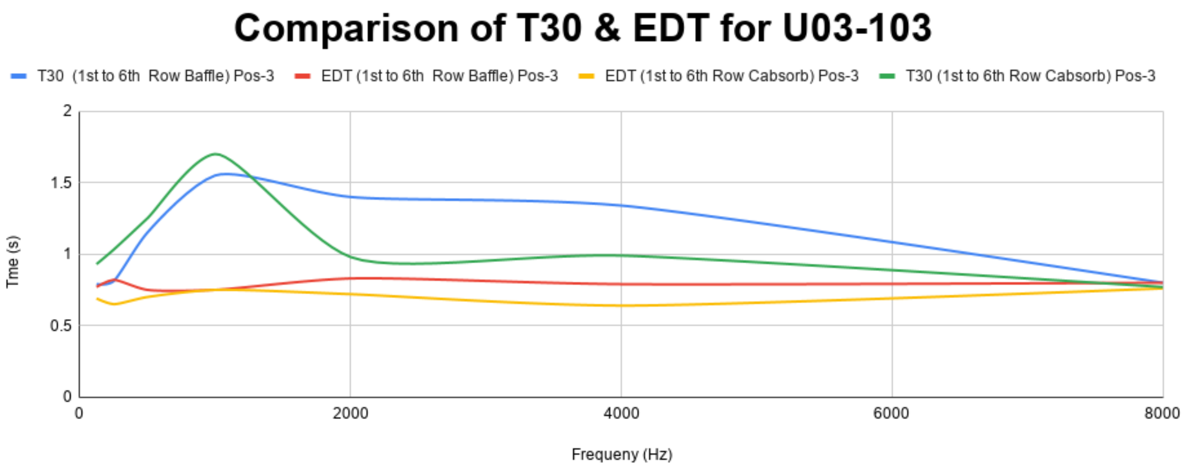

Figure 91: RT & EDT graph for Position-3

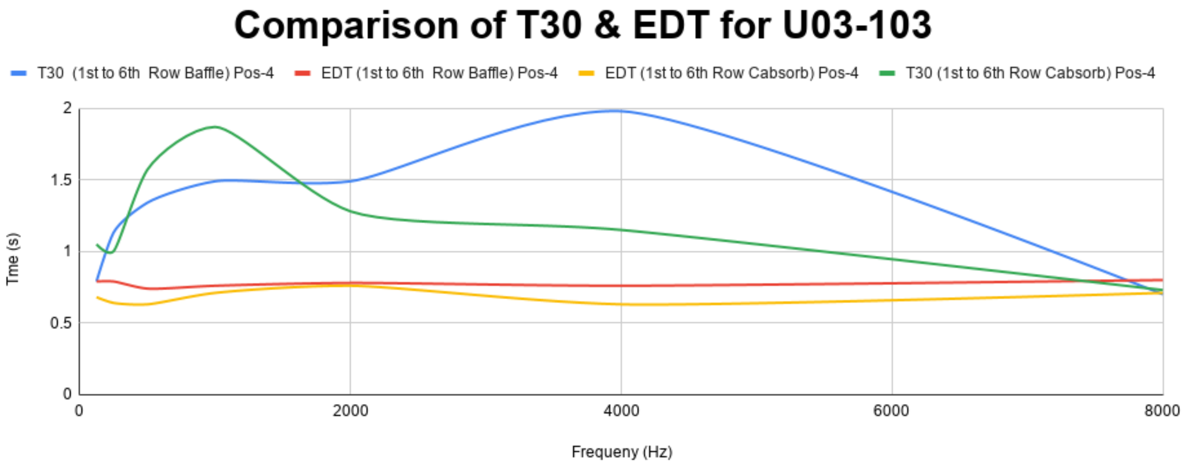

Figure 92: RT & EDT graph for Position-4

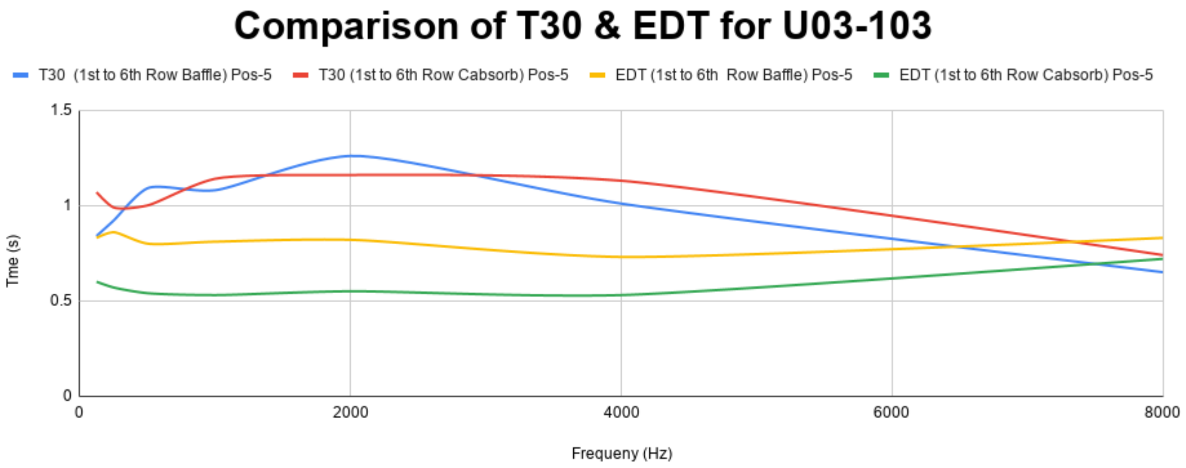

Figure 93: RT & EDT graph for Position-5

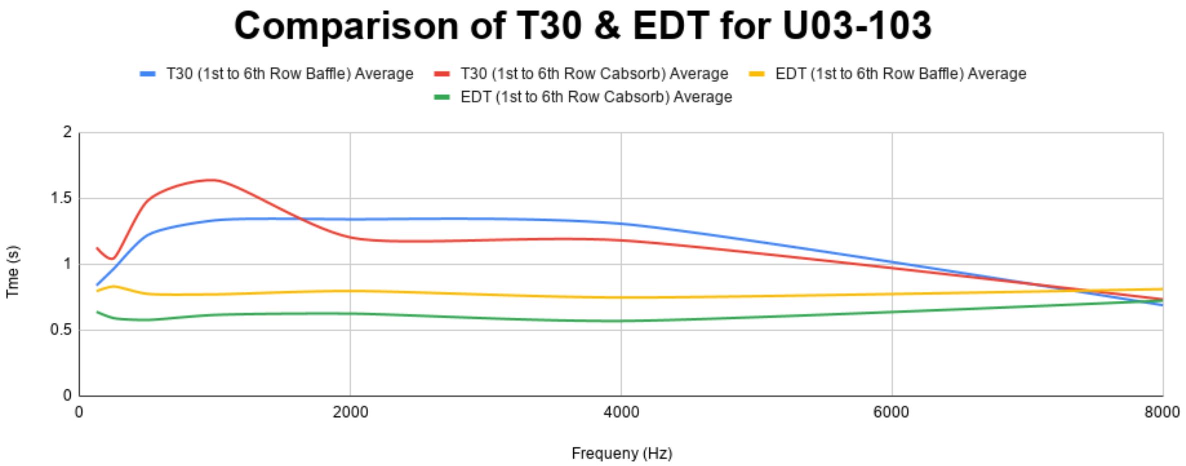

Figure 94: Average RT & EDT graph

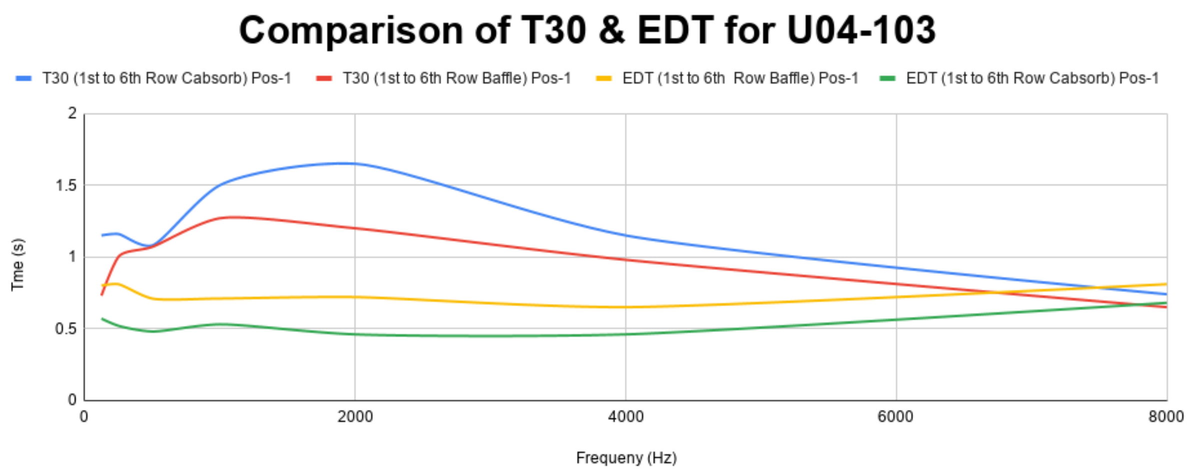

Figure 95: RT & EDT graph for Position-1

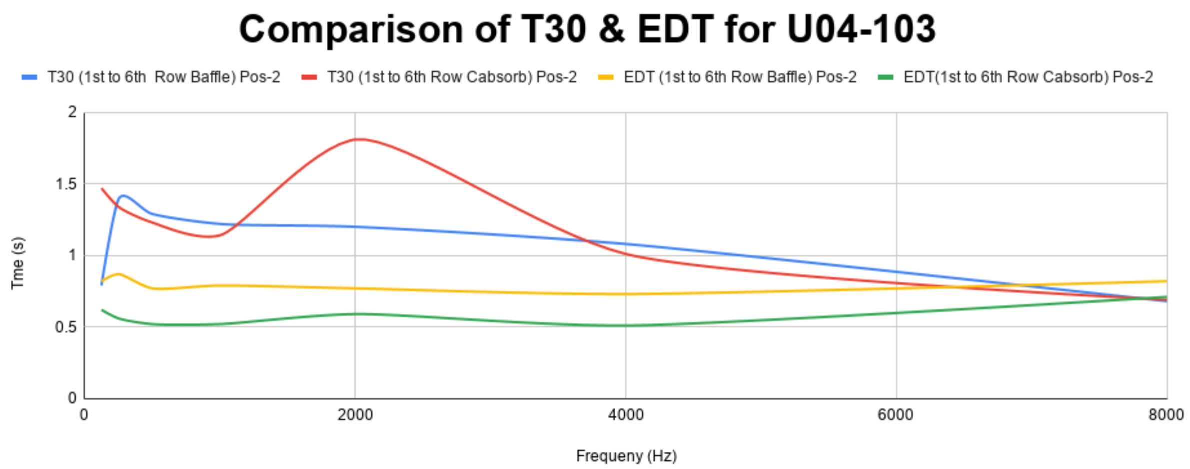

Figure 96: RT & EDT graph for Position-2

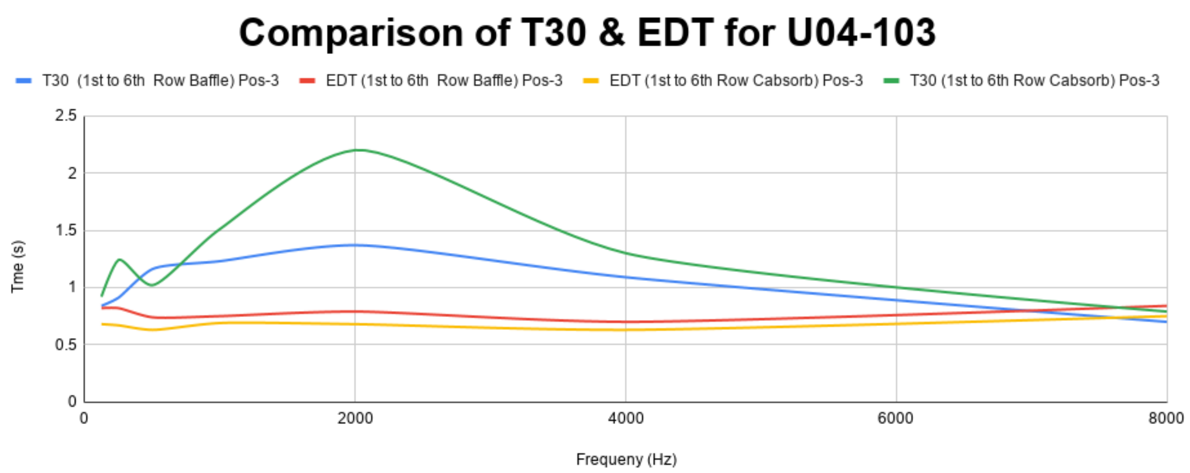

Figure 97: RT & EDT graph for Position-3

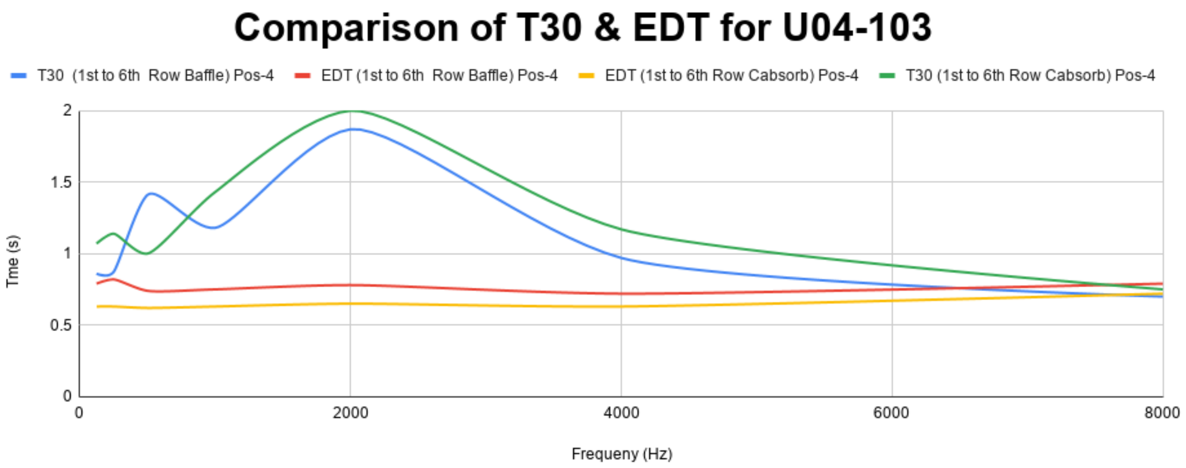

Figure 98: RT & EDT graph for Position-4

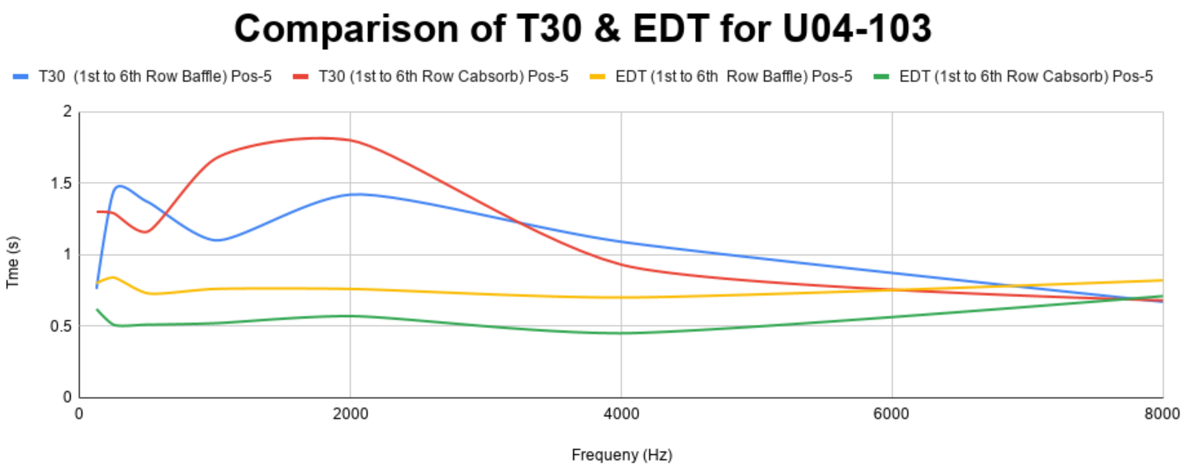

Figure 99: RT & EDT graph for Position-5

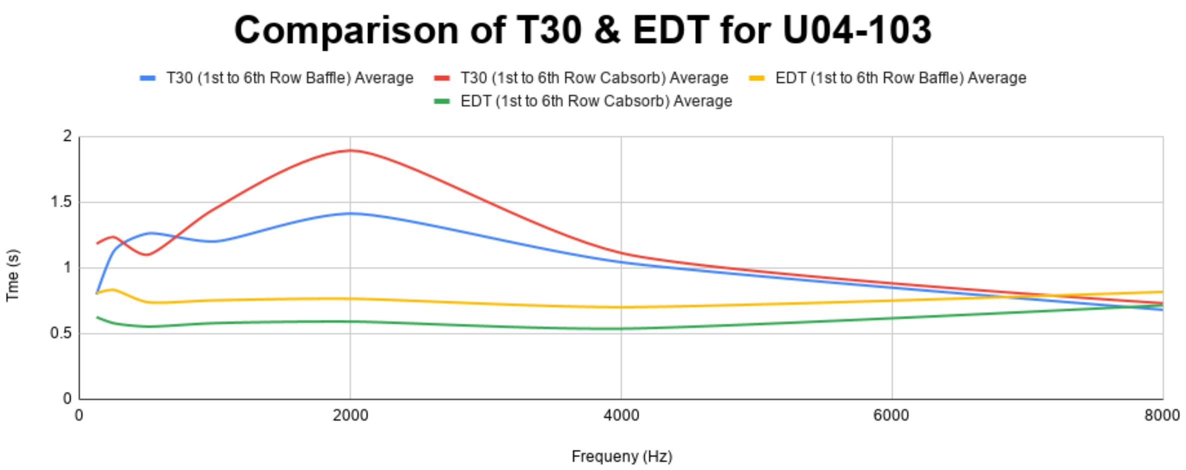

Figure 100: Average RT & EDT graph

STI (6 Row Baffle) Pos-1	0.65
STI (6 Row Baffle) Pos-2	0.63
STI (6 Row Baffle) Pos-3	0.64
STI (6 Row Baffle) Pos-4	0.65
STI (6 Row Baffle) Pos-5	0.64
STI (6 Row Baffle) Average	0.642
STI (6 Row Cabsorb) Pos-1	0.73
STI (6 Row Cabsorb) Pos-2	0.72
STI (6 Row Cabsorb) Pos-3	0.67
STI (6 Row Cabsorb) Pos-4	0.7
STI (6 Row Cabsorb) Pos-5	0.72
STI (6 Row Cabsorb) Average	0.708

Table 50: STI for U03

STI (6 Row Baffle) Pos-1	0.66
STI (6 Row Baffle) Pos-2	0.64
STI (6 Row Baffle) Pos-3	0.64
STI (6 Row Baffle) Pos-4	0.66
STI (6 Row Baffle) Pos-5	0.65
STI (6 Row Baffle) Average	0.65
STI (6 Row Cabsorb) Pos-1	0.74
STI (6 Row Cabsorb) Pos-2	0.72
STI (6 Row Cabsorb) Pos-3	0.67
STI (6 Row Cabsorb) Pos-4	0.7
STI (6 Row Cabsorb) Pos-5	0.73
STI (6 Row Cabsorb) Average	0.712

Table 51: STI for U04

6 Summary and Conclusion

In this thesis, the acoustic behaviour of the two-lecture rooms is analysed by using an experimental approach and numerically modelled. The numerical model has been validated and used to improve the acoustic behaviour of the rooms by simulating the presence of acoustic absorbers.

The acoustic parameters of the rooms (RT, EDT and STI) were measured by interrupted noise method. The measured parameters of the rooms showed that both auditoriums required an acoustic treatment to improve the speech intelligibility. At this stage, the acoustic treatment for the rooms could only be simulated. To this aim, the 3D models of the rooms were first created by using the CAD. Afterwards, the acoustic parameters of the rooms were simulated by using geometrical acoustic modelling (CADNA-R software package). The acoustic parameters obtained experimentally validated the numerical models of both rooms.

To improve the speech intelligibility of the two rooms, the validated numerical models were modified by including the presence of additional sound absorbers. An increasing number of rows of acoustic baffles and ceiling absorbers was added, which resulted in a gradual improvement of the speech intelligibility of both rooms. The performance of baffles and ceiling absorbers were compared. When only two rows of absorbers were used, the results were similar for both baffles and ceiling absorbers. However, when four and six rows of absorbers were added to the room models, the performance of the ceiling absorber was increasingly better than that of the baffles. The simulated speech intelligibility of both rooms was greatly improved by means of the acoustic treatment suggested. In future, baffles and ceiling absorbers must be installed in the rooms to verify the simulated results and to improve the acoustic comfort of the audience.

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Appendix 1 –Acoustic Glossary

ACOUSTICS: The science of Sound. Its production, transmission and effects. The branch of physics that treats the phenomena and laws of sounds as its effects people.

AIRBORNE NOISE: Noise that arrives at a point of interest by propagation through the air.

AIRBORNE SOUND: Sound that reaches the point of interest by propagation through air.

BACKGROUND NOISE: The sum of the noise which present in the acoustic space and generated by the sound sources.

Crest Factor: It is a parameter of waveform, such as alternating current or sound, which shows the ratio of peak value to the effective value.

DECIBEL (dB): The decibel (dB) is used to measure sound level. The dB is a logarithmic way of describing a sound pressure ratio.

Dirac Delta: The function $\delta(x)$ has the value zero everywhere except at $x = 0$, where its value is infinitely very large and such that its total integral is equal to one.

ECHO: Reflected sound producing a distinct repetition of the original sound.

Noise reducing co-efficient: A parameter used to compare the sound absorbing characteristic of building materials.

OCTAVE BANDS: Sounds that contain energy over a wide range of frequencies are divided into sections called bands.

Pink noise: It is acoustical energy distributed uniformly by octave throughout the audio spectrum (the range of human hearing, approximately 20 Hz to 20 kHz).

SIGNAL TO NOISE RATIO: It is the sound level at the listeners ear of a speaker above the background noise level.

VIBRATION: A force which oscillates about some specified reference point.

White Noise: It is signal which has equal intensity at different frequencies.

Appendix 2 – ISO-3382 parameters

Centre time (Ts)

Centre time is the time of the centre of gravity of the squared impulse response.

Strength (G)

Sound strength (G) is a room acoustical parameter, which describes the perceived loudness in the measured space. It is defined as the sound pressure level caused by an omnidirectional sound source on the stage, measured at a listener position in the hall, with reference to the sound pressure level at 10 m distance from the same sound source in a free field.[1]

Clarity (C_{50})

Clarity is the ratio between early received sound energy (first 50ms or 80ms of the impulse response) and the rest of the sound energy (time after the 50ms or 80ms).

Definition (D_{50})

Definition is the ratio of early received sound energy (first 50ms or 80ms of the impulse response) and the total energy of the impulse response.

Appendix 3 – Measured results from Logitech speaker

F (Hz)	63	125	250	500	1000	2000	4000	8000
T30 (s)	2.378	2.081	1.320	1.130	1.062	0.988	0.780	0.442
rT30	-0.988	-0.994	-0.999	-0.999	-0.998	-0.999	-0.999	-0.999
T20 (s)	2.378	1.841	1.321	1.161	1.003	1.003	0.738	0.426
rT20	-0.988	-0.993	-0.999	-0.999	-0.998	-0.999	-0.999	-0.999
T10 (s)	1.951	1.413	1.368	1.161	1.035	0.919	0.711	0.390
rT10	-0.992	-0.993	-0.995	-0.997	-0.996	-0.998	-0.999	-0.995
EDT (s)	1.551	1.476	1.350	1.185	1.051	0.884	0.705	0.305
C80 (dB)	-2.27	-2.28	3.33	2.17	4.66	6.82	7.24	18.90
C50 (dB)	-4.55	-4.59	0.28	-1.06	2.73	3.93	3.83	14.46
D50 (%)	25.99	25.78	51.64	43.94	65.21	71.21	70.71	96.55
Ts (ms)	252.946	138.443	82.707	79.014	54.987	40.921	38.431	5.802

Figure 101: T30 & EDT measured using Logitech speaker at POS-1 of U03-103

F (Hz)	63	125	250	500	1000	2000	4000	8000
T30 (s)	2.039	1.838	1.435	1.154	1.061	0.897	0.684	0.390
rT30	-0.996	-0.998	-0.997	-0.999	-1.000	-0.999	-0.999	-1.000
T20 (s)	2.039	1.801	1.306	1.124	1.049	0.931	0.711	0.387
rT20	-0.996	-0.997	-0.998	-0.998	-1.000	-0.998	-0.999	-0.999
T10 (s)	2.069	1.999	1.215	1.043	1.053	1.049	0.720	0.410
rT10	-0.987	-0.988	-0.997	-0.995	-0.998	-0.999	-0.999	-0.998
EDT (s)	1.621	1.650	1.207	1.046	1.137	1.050	0.742	0.363
C80 (dB)	-0.51	3.15	0.64	-0.02	2.86	4.83	6.37	15.62
C50 (dB)	-2.78	0.30	-1.86	-2.39	0.28	2.85	3.43	10.50
D50 (%)	34.52	51.73	39.43	36.58	51.60	65.83	68.80	91.82
Ts (ms)	307.435	98.911	95.632	90.634	78.238	52.847	41.821	13.932

Figure 102: T30 & EDT measured using Logitech speaker at POS-2 of U03-103

F (Hz)	63	125	250	500	1000	2000	4000	8000
T30 (s)	1.680	1.507	1.383	1.164	1.102	0.971	0.753	0.445
rT30	-0.994	-0.998	-0.998	-0.999	-1.000	-1.000	-0.999	-1.000
T20 (s)	1.680	1.629	1.448	1.205	1.103	0.964	0.733	0.437
rT20	-0.994	-0.998	-0.997	-0.999	-0.999	-0.999	-0.999	-0.999
T10 (s)	1.566	1.656	1.639	1.137	1.022	0.923	0.710	0.441
rT10	-0.991	-0.995	-0.991	-0.998	-0.997	-0.998	-0.998	-0.994
EDT (s)	1.532	1.429	1.285	1.102	0.979	1.014	0.810	0.343
C80 (dB)	-1.51	3.35	1.82	1.94	2.75	2.24	6.88	15.15
C50 (dB)	-3.16	-1.85	-2.21	-2.66	-0.45	-0.86	4.14	10.87
D50 (%)	32.57	39.49	37.56	35.15	47.41	45.04	72.18	92.44
Ts (ms)	441.462	104.452	101.948	89.469	75.965	77.260	36.388	13.328

Figure 103: T30 & EDT measured using Logitech speaker at POS-3 of U03-103

F (Hz)	63	125	250	500	1000	2000	4000	8000
T30 (s)	1.539	1.418	1.417	1.174	1.096	0.978	0.796	0.441
rT30	-0.989	-0.998	-0.997	-0.999	-0.999	-1.000	-1.000	-0.998
T20 (s)	1.558	1.376	1.474	1.191	1.084	0.976	0.788	0.406
rT20	-0.987	-0.995	-0.996	-0.998	-0.999	-0.999	-1.000	-0.999
T10 (s)	1.364	1.092	1.331	1.262	1.147	1.032	0.802	0.424
rT10	-0.956	-0.992	-0.989	-0.993	-0.998	-0.999	-1.000	-0.993
EDT (s)	1.584	1.472	1.521	1.074	1.155	1.027	0.753	0.387
C80 (dB)	-1.26	0.94	0.45	1.88	3.27	4.32	5.45	15.74
C50 (dB)	-2.83	-1.25	-3.57	-0.93	0.97	1.74	2.08	10.13
D50 (%)	34.29	42.84	30.52	44.66	55.57	59.91	61.74	91.16
Ts (ms)	337.185	130.704	111.555	81.996	71.036	60.264	53.633	13.445

Figure 104: T30 & EDT measured using Logitech speaker at POS-4 of U03-103

F (Hz)	63	125	250	500	1000	2000	4000	8000
T30 (s)	1.846	1.891	1.396	1.181	1.082	1.002	0.819	0.463
rT30	-0.993	-0.997	-0.997	-0.999	-0.999	-1.000	-1.000	-0.999
T20 (s)	1.846	1.744	1.277	1.199	1.136	1.010	0.817	0.436
rT20	-0.993	-0.996	-0.998	-0.998	-0.999	-0.999	-1.000	-0.999
T10 (s)	2.053	1.757	1.355	1.293	1.133	0.994	0.796	0.432
rT10	-0.991	-0.995	-0.992	-0.998	-0.999	-0.996	-0.999	-0.997
EDT (s)	1.886	1.820	1.391	1.287	1.132	1.051	0.799	0.390
C80 (dB)	-0.92	-0.39	1.20	1.12	3.18	5.08	7.87	17.09
C50 (dB)	-4.83	-2.83	-0.14	-0.89	0.74	2.93	5.33	12.46
D50 (%)	24.76	34.24	49.19	44.91	54.23	66.27	77.35	94.63
Ts (ms)	379.243	128.352	97.979	94.183	75.585	54.395	33.135	8.964

Figure 105:T30 & EDT measured using Logitech speaker at POS-5 of U03-103

F (Hz)	63	125	250	500	1000	2000	4000	8000
T30 (s)	2.013	2.501	2.241	2.001	1.725	1.532	1.143	0.620
rT30	-0.990	-0.995	-0.999	-0.999	-1.000	-1.000	-1.000	-0.999
T20 (s)	2.013	2.294	2.172	2.027	1.673	1.538	1.116	0.596
rT20	-0.990	-0.998	-0.998	-0.999	-0.999	-1.000	-1.000	-1.000
T10 (s)	1.887	2.412	2.312	2.006	1.668	1.587	1.087	0.597
rT10	-0.993	-0.995	-0.996	-0.997	-0.999	-1.000	-1.000	-0.999
EDT (s)	1.470	1.744	2.236	2.268	1.693	1.407	1.009	0.576
C80 (dB)	-4.77	-3.18	-3.29	-1.43	2.60	4.35	5.05	13.31
C50 (dB)	-7.28	-7.81	-5.66	-3.29	0.61	2.14	2.02	9.98
D50 (%)	15.74	14.22	21.36	31.92	53.53	62.05	61.45	90.86
Ts (ms)	732.122	179.301	171.114	158.990	85.668	66.612	56.947	12.428

Figure 106: T30 & EDT measured using Logitech speaker at POS-1 of U04-103

F (Hz)	63	125	250	500	1000	2000	4000	8000
T30 (s)	4.616	2.476	2.370	2.199	1.739	1.520	1.197	0.650
rT30	-0.987	-0.995	-0.999	-0.999	-1.000	-1.000	-1.000	-0.998
T20 (s)	4.616	2.253	2.343	2.137	1.696	1.506	1.163	0.599
rT20	-0.987	-0.994	-0.998	-0.998	-1.000	-1.000	-1.000	-0.999
T10 (s)	4.616	1.863	2.631	1.867	1.661	1.498	1.178	0.540
rT10	-0.987	-0.994	-0.996	-0.996	-0.999	-0.999	-1.000	-0.999
EDT (s)	3.114	1.892	2.380	1.778	1.733	1.506	1.195	0.606
C80 (dB)	-4.16	-2.40	-3.06	-0.30	-0.14	0.25	3.35	10.33
C50 (dB)	-7.86	-4.83	-3.69	-1.74	-3.02	-1.90	0.93	6.02
D50 (%)	14.06	24.74	29.95	40.14	33.30	39.25	55.35	79.98
Ts (ms)	783.241	171.142	176.111	123.570	127.009	105.542	69.289	25.925

Figure 107: T30 & EDT measured using Logitech speaker at POS-2 of U04-103

F (Hz)	63	125	250	500	1000	2000	4000	8000
T30 (s)	0.781	2.266	2.278	2.054	1.719	1.540	1.186	0.666
rT30	-0.947	-0.998	-0.998	-1.000	-1.000	-1.000	-1.000	-0.998
T20 (s)	0.891	2.189	2.080	1.996	1.690	1.509	1.163	0.610
rT20	-0.978	-0.998	-0.998	-0.999	-0.999	-1.000	-1.000	-0.999
T10 (s)	0.886	1.990	2.222	2.099	1.798	1.455	1.112	0.559
rT10	-0.971	-0.998	-0.990	-0.998	-0.999	-0.999	-1.000	-0.999
EDT (s)	1.566	2.225	2.572	2.336	1.802	1.515	1.152	0.605
C80 (dB)	-5.73	-1.44	-3.78	-1.63	-1.07	-1.38	2.72	9.15
C50 (dB)	-7.80	-4.23	-6.30	-3.95	-4.84	-4.62	-0.14	5.64
D50 (%)	14.23	27.40	18.98	28.72	24.70	25.65	49.20	78.55
Ts (ms)	888.489	192.164	200.019	159.981	135.318	128.712	74.201	29.660

Figure 108: T30 & EDT measured using Logitech speaker at POS-3 of U04-103

F (Hz)	63	125	250	500	1000	2000	4000	8000
T30 (s)	1.816	2.468	2.340	2.113	1.721	1.501	1.218	0.674
rT30	-0.987	-0.998	-0.998	-0.999	-1.000	-1.000	-1.000	-0.999
T20 (s)	1.816	2.354	2.349	2.198	1.660	1.546	1.198	0.647
rT20	-0.987	-0.998	-0.997	-0.999	-1.000	-0.999	-1.000	-0.999
T10 (s)	1.621	2.321	1.999	2.115	1.636	1.613	1.182	0.580
rT10	-0.993	-0.995	-0.996	-0.997	-0.999	-0.999	-0.999	-0.999
EDT (s)	2.014	2.519	2.511	1.939	1.733	1.660	1.191	0.542
C80 (dB)	-1.29	0.31	-2.13	-3.50	-1.15	0.69	1.45	11.04
C50 (dB)	-3.01	-3.04	-5.25	-7.22	-4.11	-1.73	-1.40	7.39
D50 (%)	33.36	33.18	22.98	15.96	27.94	40.15	42.01	84.56
Ts (ms)	643.325	191.663	181.306	166.996	135.068	108.517	90.162	23.025

Figure 109: T30 & EDT measured using Logitech speaker at POS-4 of U04-103

F (Hz)	63	125	250	500	1000	2000	4000	8000
T30 (s)	1.667	2.728	2.370	2.038	1.747	1.538	1.209	0.654
rT30	-0.994	-0.993	-0.999	-0.999	-1.000	-1.000	-1.000	-0.998
T20 (s)	1.667	2.397	2.231	2.011	1.722	1.527	1.216	0.604
rT20	-0.994	-0.999	-0.999	-0.998	-1.000	-0.999	-1.000	-0.999
T10 (s)	1.402	2.347	2.148	2.242	1.734	1.444	1.222	0.564
rT10	-0.993	-0.996	-0.996	-0.999	-0.998	-0.999	-1.000	-0.999
EDT (s)	2.043	2.024	2.264	2.108	1.654	1.515	1.203	0.509
C80 (dB)	-2.07	-1.04	-1.44	-2.16	-2.03	1.25	3.81	11.52
C50 (dB)	-5.48	-3.71	-2.96	-4.87	-4.36	-1.20	1.18	7.64
D50 (%)	22.05	29.87	33.57	24.56	26.82	43.11	56.75	85.31
Ts (ms)	660.458	154.381	151.195	148.669	136.330	98.362	67.511	21.869

Figure 110: T30 & EDT measured using Logitech speaker at POS-5 of U04-103

Figure 111: U03 & U04 lecture rooms, omnidirectional and Logitech measurement