RENOVATION OF CLASSROOMS WITH NON-CONTINUOUS ACOUSTICAL TREATMENT MATERIAL

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ABSTRACT
Good acoustical conditions in classrooms are quite related to the learning process of the individuals. The school environment should promote an atmosphere that induces everyone's interest in listening and being involved in communication. The efficiency of the learning environment can be measured by the acoustical conditions of the c1assrooms. Following the process of renovation of two c1assrooms at the Lisbon Engineering Institute, ISEL, an alternative acoustical treatment approach was implemented. The solution usually adopted to create appropriated acoustical conditions consists on covering the ceiling area with sound absorption material distributed uniformly. Although this solution keeps the reverberation time at reasonable values it attenuates the first reflections with a loss of detail in the communication path, affecting the articulation of consonants, and consequently degrades the acoustical parameters related to the comfort in the room such as the Speech Transmition Index, and the Clarity. Therefore, part of the ceiling area was kept without acoustical treatment to enhance the reflection of the early sound energy more efficiently to the audience. The treated zones are covered with the same type of acoustical material but with different thickness to better control the reverberation. Results of the adopted solution are presented and compared with the usual acoustical treatment of classrooms by simulation and by using auralization techniques.

Keywords: Classrooms acoustics, measurements, prediction and simulation.

1. Introduction

The aim of this study is to improve the acoustical conditions of a number of the ISEL classrooms, in Lisbon. Keeping in mind that these rooms are normally used for teaching, with speech as the acoustical signal, the study follows the Portuguese recommendations given by the Building Acoustics Act, *Regulamento dos Requisitos Acústicos dos Edifícios, Decreto-Lei* nº 129/2002 of 11 of March [1].

Table 1 shows the recommended values for the Reverberation Time, RT60 (or Tr), for the octave frequency bands centered on the 500 to 2000Hz, for empty rooms.

The optimal acoustical conditions for musical performances on rooms of this geometry can be achieved following an additional acoustical approach, after implementing the solutions for speech, by using acoustical panels and bass straps devices located on the walls.

Tipo de Sala Receptora	Valores recomendados para o Tempo de Reverberação médio, T_r [s]
Salas de aula, áreas para aprendizagem em geral, salas para seminários, laboratórios de línguas:	
$V < 300$ m^3	0,6 - 0,8
300 m$^3 \leq V < 600$ m^3	0,7 - 0,9
Áreas para aprendizagem em *Open Space*	0,8 - 1,0
Salas de aulas de música	< 1,0
Salas para prática musical	< 0,8
Salas para prática musical em *ensemble*	0,6 - 1,2
Estúdios de gravação	0,6 - 1,2
Régies de gravação	< 0,5
Auditório pequeno (< 50 pessoas)	< 0,8
Auditório grande (> 50 pessoas)	< 1,0
Salas de estudo (individual, preparação de aulas)	< 0,8
Bibliotecas	< 1,0
Laboratórios de ciência e informática	< 0,8
Oficinas	1,0 - 1,2
Salas polivalentes	0,8 - 1,2
Ginásios	< 1,5
Gabinetes médicos, gabinetes para entrevistas	< 0,8
Refeitórios	< 1,0
Salas administrativas	< 1,0
Corredores, escadas	< 1,5

Table 1 – Recommended RT60 values to the different enclosures.

The volume of the rooms under study is about 250m^3. Therefore, the RT60 value should be under 0.8 seconds, considering an empty room.

2. Assessment of the acoustical conditions before acoustical treatment

In order to assess the acoustical situation of the classrooms before treatment, acoustical measurements were carried out in two rooms, rooms C3.14 and C3.16.

The RT60 and the others parameters considered important to characterize the rooms, namely the Early Decay Time – EDT, the Clarity - C80 and the Speech Transmission Index – STI, were estimated by using the results of the measurements and by simulation.

The measurement setup consisted on a dodecahedral sound source Omni-12 and a power amplifier, omnidirectional microphones ECM 8000, (Behringer), external multichannel sound board 8x8 FA101 (EDIROL), measurement framework for room acoustics developed in Matlab and the WinMLS as a complement [2-5].

Figure 1 shows the lay-out of the room C3.16 (the larger room tested) as well as the measurement points R2, R3 e R7. All the receptors marked on the dfawing were used in the simulations.

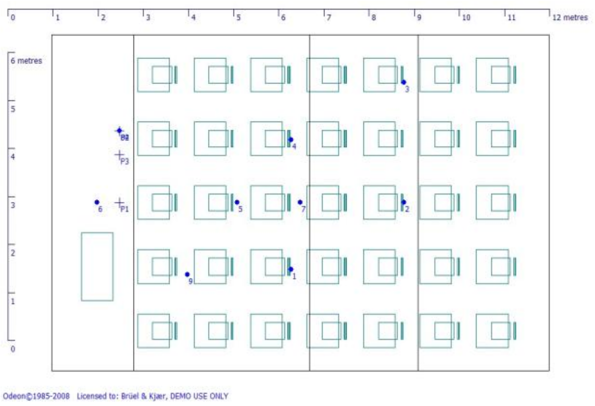


Figure 1 – Classroom C3.16 with the measurement points.

The estimated acoustical parameters for the room C3.16 are depicted in Table 2. The results show a significant deviation of the RT60 values from the recommended values for speech, which are about 2.3s for the empty room and 1.0s with 70% of audience.

Room C3.16 - No audience							
Freq (Hz)	125	250	500	1000	2000	4000	8000
EDT (s)	2,71	2,92	2,62	2,38	2,13	1,62	1,12
T30 (s)	2,65	2,56	2,41	2,23	2,06	1,58	1,10
			Ave 500-2000Hz		2,23 sec		
C80 (dB)	-2,7	-4,0	-3,4	-2,2	-0,7	0,5	2,4
D50 (%)	24,4	18,4	21,7	25,7	31,6	37,9	46,8
Ts (s)	226,6	221,1	203,1	167,4	153,3	112,2	74,0
STI							
Room C3.16 - Occupied (70%)							
Freq (Hz)	125	250	500	1000	2000	4000	8000
EDT (s)	1,56	1,53	1,08	1,06	0,94	0,84	0,76
T30 (s)	1,68	1,68	1,13	1,01	0,95	0,85	0,73
			Ave 500-2000Hz		1,03 sec		

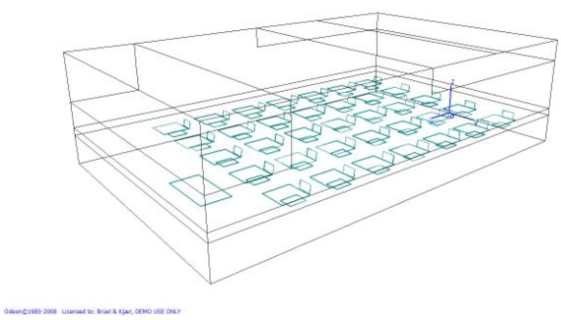
Table 2 – Results of the acoustical parameters measured in the room C3.16 before the acoustical treatment.

3. Methodology

The acoustical treatment of the classrooms C3.14 e C3.16 consisted on placing acoustically absorbent material on the part of the ceiling and walls.

The definition of the areas to be protected and the characteristics of the acoustical material were obtained by using the ODEON- Room Acoustics Software package, ver. 9.1. Thus, a 3D model of the rooms was developed for these purposes.

This prediction software has the advantage of including tools for auralization, i.e. an audio file can be selected for binaural audition taking account the acoustic environment of the enclosure. This option is very benefit to compare, virtually, different acoustic environment configurations, before implementation of the solutions. Figure 2 shows different perspectives of the classroom using the virtual 3D model.



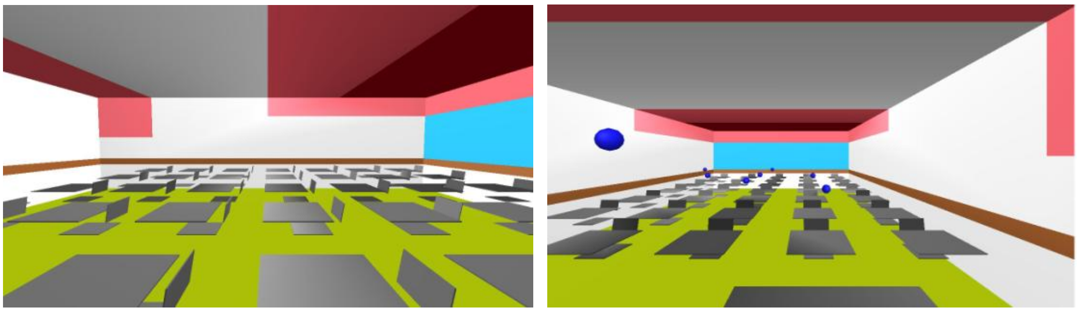


Figure 2 – Virtual 3D model used on the acoustical simulations of the rooms.

The treated areas, characteristics and thickness of the acoustical material were achieved by the results of the simulation considering the cost/benefit aspects. A cellulose fiber spray was applied Table 3 shows the characteristics of the sound absorption coefficients, α, for the most representative octave frequency bands and for different thicknesses. These results were obtained in a reverberant chamber following the norm EN-ISO 20354.

Cellulose fiber spray on solid support							
Thickness (mm)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NRC
12	0,08	0,16	0,46	0,87	1,07	1,12	0,65
16	0,16	0,22	0,57	0,95	1,09	1,12	0,7
19	0,18	0,27	0,67	1,02	1,11	1,12	0,75
25	0,22	0,38	0,88	1,16	1,15	1,15	0,9

Table 3 – Acoustical characteristics of the acoustical material used in the classrooms.

The areas covered with acoustical material are represented by pink color tonalities in the Figure 2. The location of the receptors used on the simulations is shown on the bottom figure.

Figure 3 shows the location areas of the acoustical material in the treated rooms. The thickness of 16 and 19 mm were used to smooth the transition between materials with different acoustical characteristics, creating a more uniform sound field. The material with higher thickness is applied to the rear part of the room in order to reduce the diffuse acoustical field on the rear part of the room. This methodology reduces the reverberation, and the perceived rear acoustic wave.

Additional treatment material such as bass traps systems and movable acoustic absorbent panels on the walls was applied to create better acoustical conditions for listening to the music (this photo was taken during a session of the 10th Meeting of AES Portugal, December, 12 and 13, 2008).

The location for the acoustical treatment materials was based on the following criteria:

1- The rear area of the room – reduction of the acoustic energy of the diffuse sound field in the room, to increase the intelligibility of the speech, STI (Speech Transmission Index), by reducing the RT60. The front ceiling area, almost up to the middle of the room, is left untreated to increase the sound propagation path from the speaker to all the audience area by reflection on the ceiling. Thus, the early reflections are less attenuated, increasing the detail of the sound material by unchanging the transients characteristics of the signal. The parameters directly related to the speech intelligibility, such as the D50 and the STI are increased;

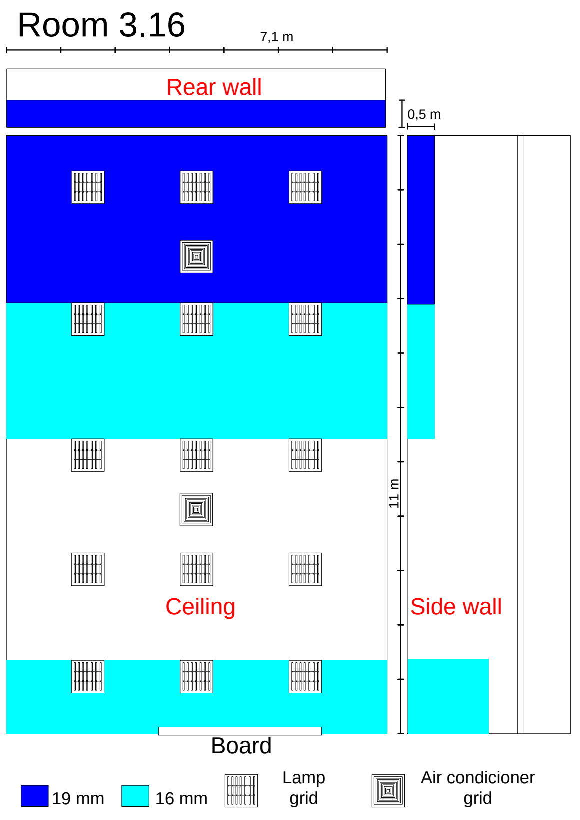


Figure 3 – Location of the acoustical treated areas, walls and ceiling, showing the different thickness of the material.

Figure 4 – Photograph view of the room C3.16 and C3.14 with acoustical treatment applied (gray color). Room C3.14 with supplemental acoustical treatment based on absorbed and diffusers panels (right).

2- The surrounding area of the speaker – due to the room geometry, parallel and acoustical reflective walls, the sound field near the speaker achieves significant sound levels, for the most important frequency bands regarding the speech signal, caused by the generation of standing waves and the reverberation. These sound levels are responsible for an uncomfortable sensation and stress to the speaker. Several approaches can be stated to overcome this situation, such as installing diffusers, resonators or absorbent material. The adopted solution is covering with the same acoustical treatment some of the areas of the front room, ceiling and walls, maintaining the uniformity of the materials in the classroom. The treated areas were carefully defined by simulation in order to reduce the reflection of the sound to the speaker, however, allowing the convenient propagation of the sound energy to the audience area.

Table 4 shows the recommended acoustical parameters values for the classrooms for the situation of no audience.

The parameter JND, Just-Noticeable Difference or Subjective Limen, indicates the maximum deviation on a parameter before being perceived by the majority of the people. This measure holds an important significance on dealing with subjective parameters. It states how the deviation of some acoustical parameter influences the perceived acoustical environment by the people, for different conditions. For example, based on the contents of the Table 4, if the parameter C80 changes less than 1dB, after the renovation, this means that the benefits of the renovation works had minor impact on the perceived results, at least regarding this specific parameter.

	Average frequency bands	Recommended value	Subjective Limen / JND (Just-Noticeable Difference)
T30 (s)	500 - 2000 Hz	< 0,8	5%
STI (%)	NA	>60	5%
EDT (s)	500 - 2000 Hz	< 0,8	5%
C80 (dB)	500 - 1000 Hz	>4	1dB

Table 4 – Maximum recommended values adopted for the acoustical parameters for the classrooms.

4. Results

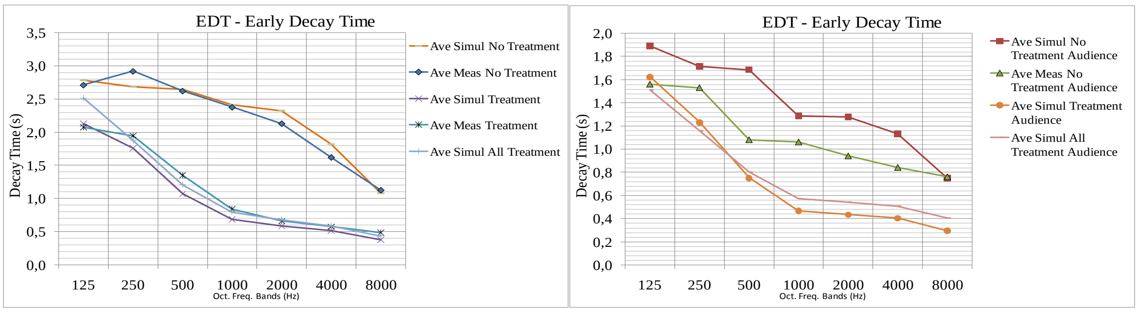
The study herein reported makes a comparative analysis showing the recommended average values for each acoustical parameter, for different situations.

The usual acoustical treatment approach used on the renovation of classrooms corresponds to the application of some kind of absorbent material to almost all the extension of the ceiling, distributed uniformly. That solution usually guaranties the recommended RT60. However, the rest of the parameters related with the acoustic comfort inside the room (perceived by the audience and the speaker) are not considered in detail.

In order to have a better understanding of the variations of the parameters considered important to classrooms for different typologies of acoustical treatment and conditions of use, the study was based on the followed conditions:

1. No acoustical treatment
   - empty
   - with an audience
2. with acoustical treatment
   - empty
     - adopted solution (partial treatment of the ceiling and the walls)
     - with treatment on all extension of the ceiling
   - with an audience
     - adopted solution (partial treatment of the ceiling and the walls)
     - with treatment on all extension of the ceiling

The results of the acoustical measurements and the simulations, for different conditions and for the receptors stated above, are depicted in Figure 6.



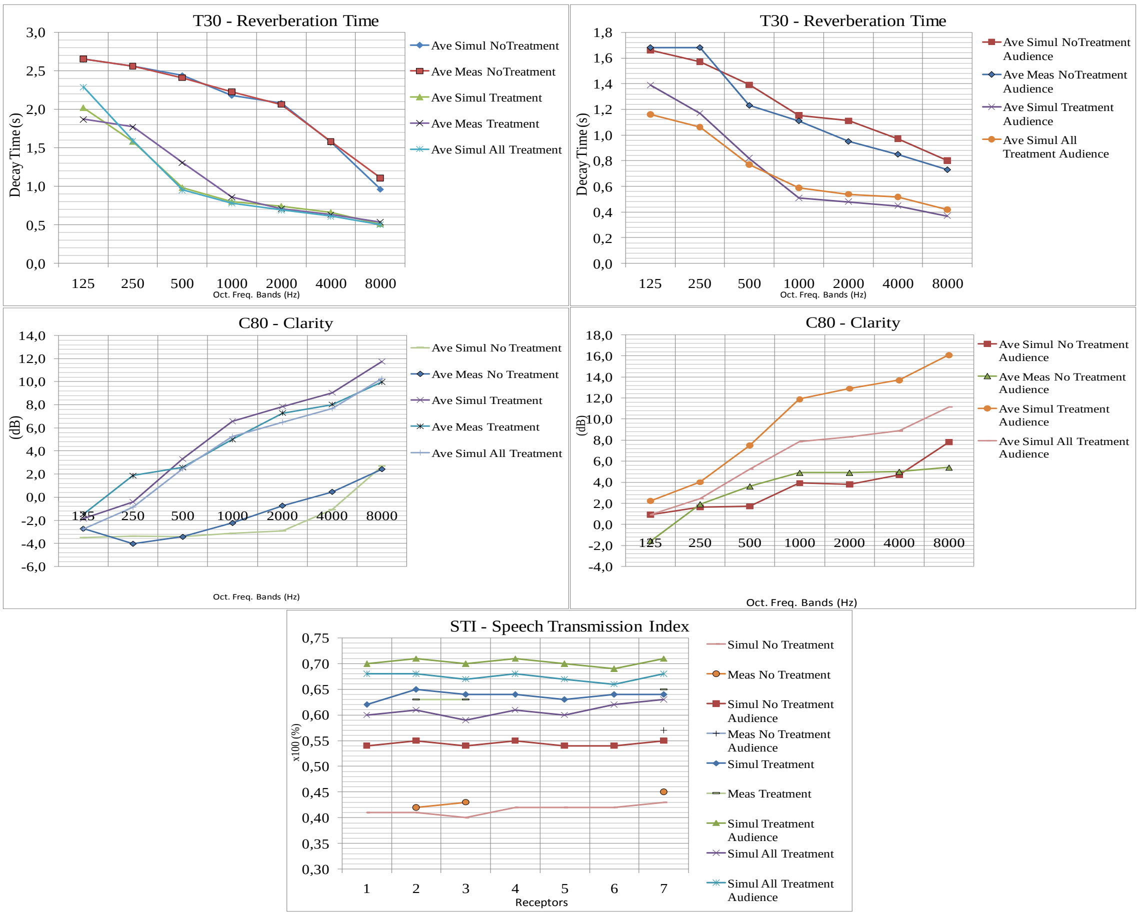


Figure 6 – Comparative results of the analysis covered by this study for the situation of without an audience and with an audience, except for the STI analysis. (i) *Treatment* corresponds to the adopted acoustical treatment solution and (ii) *All Treatment* corresponds to treatment material on all the area of the ceiling (simulation only).

EDT

This parameter is related to the perception by the auditory human system on the interpretation of the reverberation of a space based on the first reflections. It is an objective parameter which describes a subjective effect of the sound field.

The results show a significant decrease after the acoustical treatment, achieving approximately 0.8s, without an audience. The difference between the measured and simulated results is not significant. The deviation is kept within the JND for this parameter, proofing the validity of the model used on the simulations.

RT60

The reverberation times decreases to the values stated by the recommendations. Before the renovation took place, the RT60 was about 2.3s, and after treatment this value decreased to 0.85s. This value remains on the limit recommended if the JND is considered, 5% applied to 0.8s (0.04s). It can be stated that the RT60 (without an audience) follows the specifications of the project.

The results with an audience show, as expected, a supplemental reduction on the RT60. This result is more prominent in the low frequency bands (up to 500Hz) due to the higher values of the effective absorption coefficients of the people for this frequency range and the low performance of the acoustic materials for these frequency bands.

Comparing the results of the RT60 between the adopted solution, *Treatment*, and for all the ceiling treated, *All Treatment*, taking account the JND, neglect differences are perceived.

C80

The sensation of clarity of the sound, perceived by the hearing human system, is usually assessed by this parameter. The results show a significant increase of this parameter after implementing the acoustical treatment. A figure of 3dB before and 5dB after is expected, thus, following the recommended value.

Regarding the situation of *All Treatment*, an increase of 1.5dB is observed. Although this difference is not apparently significant, it is noticeable for a binaural audition (simulated) using auralization techniques applied to a piece of music track or speech. In case of the room with an audience a supplemental increase of 3dB is expected.

STI
The intelligibility of the speech reported in this study by the Speech Transmission Index is one of the most important parameter used to quantify the quality of the acoustical ambience in an enclosure devoted to the speech signal.

The results of the measurements and simulations show that, with the adopted acoustical treatment, the STI is about 65% (before the renovation this value was less than 45%). The deviation noticed is within the JND for this parameter, proofing the validity of the model used on the simulations. With an audience, this parameter achieves 70%.

Comparing the situations for the adopted solution, *Treatment*, and for the treatment on almost all the ceiling area, *All Treatment*, a figure of 5% is reported. Therefore, this difference should be already noticeable on the detail of the speech, specially, for the percussive states of the consonants. The simulated tests with binaural audition reveal this finding.

The measurements were performed for a considerable SNR value. Thus, it will be expected that for real situations the STI will decrease due to the background noise generated by the audience and machinery present in the room, such as the air conditioned systems. The STI depends on the background noise and the reverberation.

Binaural Audition
The prediction and simulation software package used in this study, as mentioned before, includes the auralization module allowing the binaural audition, meaning that the results of the simulations can be heard on a stereo playback audio system. Thus, several simulations were made with the purposes of comparing perceptually the acoustical environments with different treatment solutions, namely, (i) empty room, (ii) with the adopted solution and (iii) with all the extension of the ceiling treated.

The results of the auralization are available in format WAVE. The audition should be made by using headphones due to the crosstalk between channels in a typical configuration of two loudspeakers in a room.

The segments of audio for different situations are in some cases shown alternate in the audio file to facilitate the judgment (ex: room with the adopted treatment and room with all area of the ceiling treated). Audio tracks of music and speech were used in the simulations.

Original audio (recorded in a professional studio)

- Speech (SomOriginalFala.mp3)
- Music (SomOriginalMusica.mp3)

Room with adopted acoustical treatment (original audio filtered by the room)

- Music (TratAdoptadoMusica.mp3)

Room with acoustical treatment on all area of the ceiling (original audio filtered by the room)

- Music (TratTodoTectoMusica.mp3)

Sequence of audio tracks. Room without treatment -> Room with acoustical treatment on all area of the ceiling -> Room with adopted acoustical treatment (original audio filtered by the room)

- Speech (No_All_AdoptedTreatFala.mp3)
- Music (No_All_AdoptedTreatMusica.mp3)

Simulations on all the area of the audience
The acoustical simulations were also evaluated on the all area of the audience with a grid of points with 20cm2 and at a height of 1.2m above the floor. These analyses give supplementary information about the stationary sound field inside the room. Figure 7 depicts the results of the more relevant parameters considered on the study of classrooms for the room C3.16 (the larger studied room) after renovation.

The interpretation of the results confirms the conclusions stated in the Figure 6.

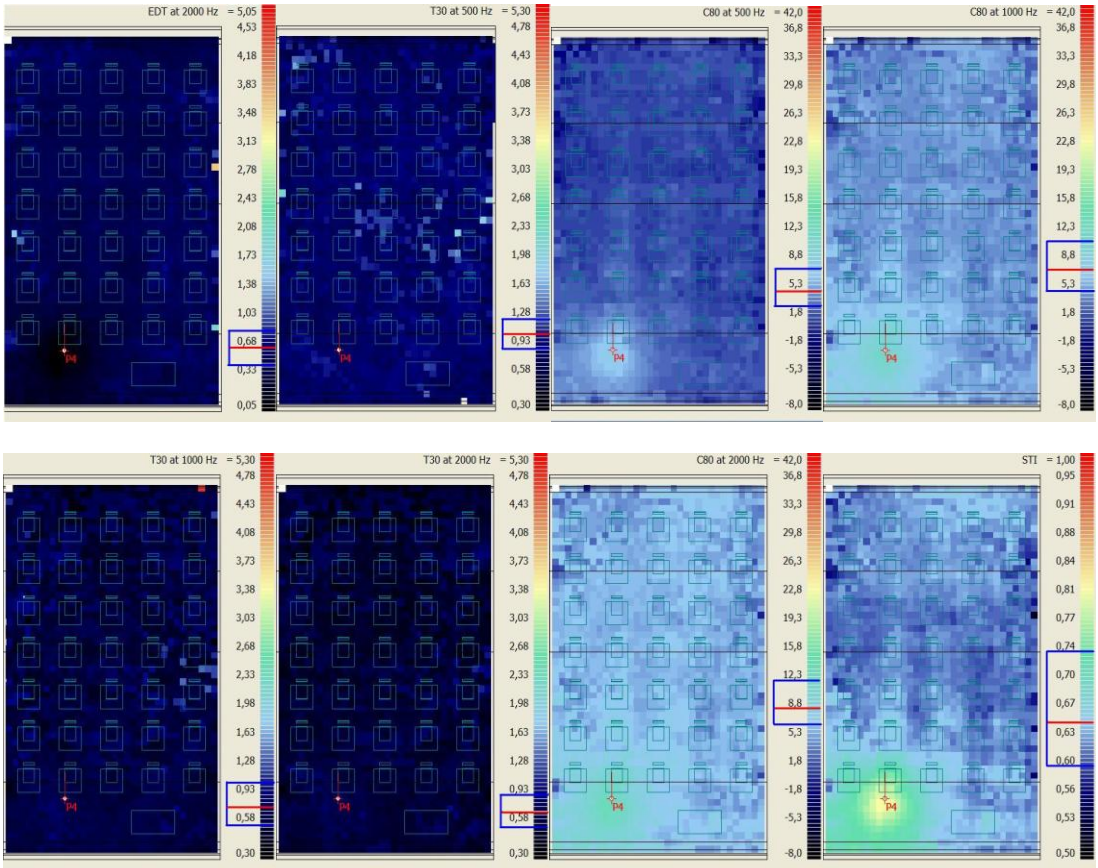


Figure 7 –Results of the analyses of the acoustical parameters for all the area of the audience with renovated room. Placed on the color scale, on the right side of each figure, are the bounds for each parameter (blue color). The lower value indicates that only 5% of the grid results are bellow, and the upper value assures that more than 95% of the grid results are bellow. The red segment shows the average value.

5. Conclusions

An alternative acoustical treatment approach is proposed and implemented on the process of renovation of two classrooms at the Lisbon Engineering Institute, ISEL.

This solution consists on keeping part of the ceiling area without treatment, in order to enhance the early reflections more efficiently to the audience, and covering the treated zones with the same type of acoustical material. Different thickness is applied to better control the reverberation.

It is shown that this solution has advantages when compared with the usual approach corresponding to cover almost all the ceiling area with absorbent material with the same thickness and distributed uniformly. Although this solution usually guaranty the reverberation time at reasonable values it attenuates the first reflections with a loss of detail in the communication path, affecting the articulation of consonants, and consequently a degradation of the acoustical parameters related to the comfort in the room, specially at the rear area of the classroom.

The benefits of the adopted acoustical solution are shown by results of the acoustical parameters EDT, RT60, C80 and STI. In terms of absolute values the differences are not significant regarding to the JND parameter. However, with the binaural audition of the sound tracks of speech and music, there is a subtle but noticeable improvement on the detail of the sound in the case of the adopted solution, specialty on the consonants of speech and the attack and onsets of the musical notes.

With the implementation of the adopted solution the cost is reduced in about 20%.

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