On the use of a variable acoustic solution with perforated panels for a multi-purpose auditorium

Pereira A.[1], Gaspar A.[1], Godinho L.[1], Amado Mendes P.[1], Mateus D.[1], Carbajo J.[2], Ramis J.[2], Poveda P.[2]

[1]. University of Coimbra, ISISE, Department of Civil Engineering, Coimbra, Portugal {apereira@dec.uc.pt; uc2016202135@student.uc.pt, lgodinho@dec.uc.pt; pamendes@dec.uc.pt; diogo@dec.uc.pt}
[2] University of Alicante, Department of Physics, System Engineering and Signal Theory, Spain

{jesus.carbajo@ua.es; jramis@ua.es; pedro.poveda@ua.es}

Abstract
In this paper a cost-effective variable acoustic solution, which can be used in room acoustics applications, is addressed. In the design of such solution, the surface appearance is kept unchanged, while variable acoustic behaviour is achieved either by closing the holes in the back face of the perforated panel or by placing a porous material in varying positions inside the backing cavity, thus accomplishing different acoustic requirements within a multipurpose auditorium. An analytical approach, based on the transfer matrix method, is employed for preliminary sound absorption assessment and definition of an optimized solution to be used. Diffuse sound absorption is then computed, and the result is used in the analysis of the acoustic behavior of an auditorium where this solution is prescribed. Acoustic simulations of this auditorium are performed using a ray tracing model and several room acoustics quality parameters are evaluated and compared with different acoustic requirements, in order to demonstrate adequacy and efficient acoustic performance for distinct uses (e.g. music, speech).

Keywords: sound absorption, analytical approach, ray tracing, perforated sound absorbent systems, variable acoustics design.

1 Introduction

Most of the existing auditoriums of many cities have been designed to accommodate one type of use, while in common practice these are used for different and complementary purposes. In the last years, increased attention has been given to the design of multipurpose halls, in order to be more efficient, to accommodate more than one acoustic type of performance [1]. It has also become evident that, due to economic and functional reasons, auditoriums dedicated to just one single use are not viable and, in large cities, there is also a demand for flexibility in the use of these spaces, becoming common the organization of different events with different acoustic requirements, from conferences to different types of music or theatre plays.

One way of providing a more appropriate acoustic performance for each function of the auditorium is using variable acoustics techniques to control reverberation time and other relevant acoustic phenomena. These solutions can modify the acoustic environment either through the implementation of electroacoustic systems (active variable acoustics) or through architectural changes (passive variable acoustics).

Passive variable acoustic strategies may include changing the volume of the space or varying acoustic absorption/scattering of the surfaces, allowing to reduce or increase the reverberation time, control of the direction of the early energy and other acoustic parameters, such as Clarity and Definition. To obtain an effective change in the acoustic properties, a substantial absorption variation is required [1]. Examples of solutions that can modify sound absorption in an environment are the use of retractable curtains, hinged panels, adjustable audience seats or movable reflectors [2],[3]. A concept consisting on the use of articulated panels, where one side has an absorbent material, being exposed when such space is used for theatre, while the other face has a reflective surface, being exposed when the auditorium changes for a musical concert [4], has been widely used, but it requires some significant modifications in the architecture of the room. Most of the existing solutions implemented in auditoriums in the last years are manually controlled, however, with the development of electromechanical and control systems at more affordable costs, other possibilities for the implementation of such systems have been arising [5]. In the present work, a passive variable acoustic concept will be explored, having in mind the possibility of automatization, for its implementation in multipurpose halls.

During the design of a room, the first parameter to be analysed is the reverberation time, being possible to change this metric by varying the absorption inside the auditorium. This can be accomplished by using systems composed of combinations of porous or fibrous materials, that, through their properties (such as porosity, fibre length, density or material thickness), allow to enhance absorption in the higher frequencies, volume absorbers and panel absorbers that may be used as lining panel separating porous/fibrous material and airgap from the auditorium. If this lining is composed of multiple perforated panels, the sound absorption performance of these systems depends also on the properties of each perforated panel, such as perforation type, diameter, central distance and perforation ratio [6]. By modifying some of these parameters, it is possible to achieve a range of sound absorption performance of a variable acoustic system.

In this paper, a passive variable acoustics concept, based on the ideas described, is developed and its acoustic performance is analysed. The concept herein proposed allows maintaining the architecture of the room while the acoustic environment is modified. The analysis is performed using a mathematical model based on the Transfer Matrix Method to obtain the sound absorption coefficient for normal incidence. The concept is then applied in a conceptual multipurpose auditorium where the acoustic performance is studied for different types of use by developing a model based on the ray-tracing method [7]. Several acoustic parameters are calculated and compared with different requirements, established for different types of use.

2 Concept description

The acoustic system herein developed makes use of a perforated panel facing the auditorium and an air gap with a fixed thickness, containing an absorbing material (e.g. mineral wool), whose position may vary. Figure 1 displays the configurations that may be applied depending on the space and acoustic requirements.

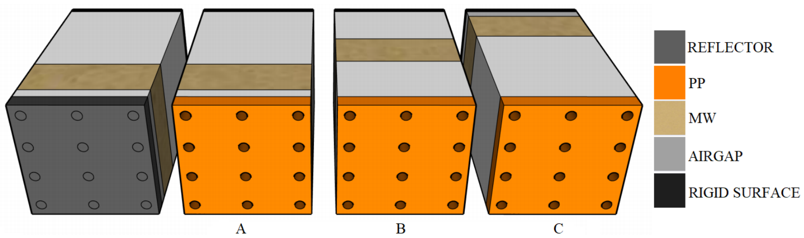

Figure 1 – Possible configurations of the variable acoustic solution (Acronyms: PP- Perforated panel; MW-Mineral wool).

Behind this perforated panel, a movable reflective panel (schematically represented in the figure by changing the colour of the panel) will allow to close the holes and change the acoustic properties to approach a reflective surface (although allowing some diffusion in the higher frequencies). As it will be shown later, these configurations can be designed so as the two extreme acoustic types of use (speech and classical music) can be provided with sound quality, but it may also allow fulfilling intermediate acoustic requirements, by appropriately configuring the panel system (changing the position of the mineral wool panel or opening/closing the holes of the perforated panel). This tuning feature can be achieved by using an

automatized system as it will be described next. It is also important to bear in mind that, although from the acoustic point of view it is possible to modify the space, from the architectural point of view the chosen solution does not change the aesthetics of the room, which may be an advantage of such a system for practical use.
The proposed acoustic solution can be easily automated through the use of an electromechanical system [8] allowing the different configurations to be activated. Note that, in order to allow for mechanization of the system, a small air gap was left in the extreme positions of the absorbing material (see Figure 1).

3 Sound absorption evaluation

The approach used in this paper to evaluate the sound absorption of a variable acoustic conceptual system is based on the evaluation of the acoustic impedance of each layer (e.g. perforated panel, porous material or air-gap) of the multilayer sound absorber. In the case of the perforated panel, the acoustic impedance of a single hole is used to obtain that of the whole panel by using its open area ratio, the panel being considered as a set of short tubes of similar length to its thickness. It is also assumed that the wavelength of the sound that propagates is sufficiently large compared with the dimensions of the tube (i.e., hole). The impedance of the panel includes terms due to the viscosity of air, radiation (from a hole in a baffle) and interaction between holes. On the other hand, an equivalent fluid is defined to describe the porous material whose skeleton is assumed to be rigid by means of its effective acoustic properties (i. e. complex characteristic impedance and wave number), and the air-gaps being modelled by means of a purely reactance term. To allow the evaluation of generic systems, with arbitrary layers, the Transfer Matrix Method (TMM) [9] has been used, where the acoustic impedance along the normal direction of an interface of a material is determined using the continuity of particle velocity (on both sides of the interface) and knowing the acoustic properties of the medium (characteristic impedance and the wavenumber or propagation constant).

4 Auditorium simulation

The conceptual auditorium used has a capacity for 409 seats, mean dimensions of 18.9(m)x16.9(m)x11.9(m), and a total volume of 3779 m³. It is composed of the stage area, with a volume of 1448 m3, and an audience area, totalizing a volume of 2331 m3. The volume per seat is approximately 9 m3. Note that this auditorium does not correspond to an existing space (see Figure 2).
Regarding the reflective configuration, sound absorption coefficients were those from experimental results obtained for similar existing commercial solutions.

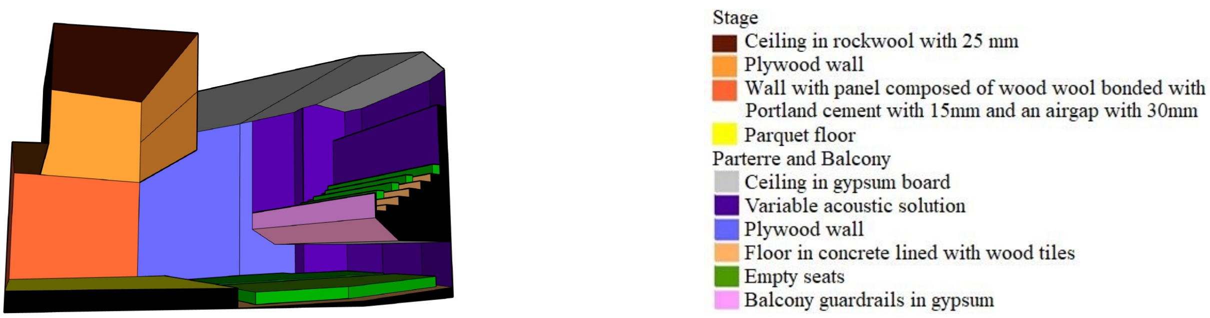

Figure 2 – Geometry of the auditorium and distribution of applied lining materials.

The simulations were performed using a ray tracing code developed in Matlab, which used around 30000 rays during the calculation and an Impulse Response (IR) length of 2 s. This method uses a large number of particles (rays) emitted by an omnidirectional sound source. Figure 2 displays the geometry of the acoustic model (built with 111 planes and a total surface area of 2008 m2) and the corresponding lining materials, where it is also possible to identify the position of the variable acoustic solution previously described in this work.

The variable acoustic solution employed in this auditorium (see Figure 1) was designed so as its two extreme types of use (speech and classic music) can be provided with enough sound quality, for the above-described auditorium, but also to allow intermediate acoustic requirements. The perforated panel has the following properties: diameter of the hole with 3mm and perforation rate of 18%. Regarding the mineral wool the following properties were assumed: density of 70 kg/m3 and flow resistivity of 28377 Pa.s.m-2. Table 1 displays other relevant properties of the analysed system.

The sound absorption and scattering coefficients used in the simulations for the materials applied on different surfaces are displayed in

Table 2, as well as the relative area of each material. For the evaluation of sound absorption provided by the perforated configurations of the variable acoustic solution, the transfer matrix method was applied and diffuse field conditions were then computed using the approach defined in [10].

Table 1 - Definition of the different layers for each system of the set of configurations.

Configuration	Layer 1	Layer 2	Layer 3	Layer 4
A	PP	Airgap e=10mm	MW e=40mm	Airgap e=100mm
B	PP	Airgap e=55mm	MW e=40mm	Airgap e=55mm
C	PP	Airgap e=100mm	MW e=40mm	Airgap e=10mm

Table 2–Sound absorption (α) and scattering (s) coefficients for each lining material.

	Materials	Area m²	Area %	Acoustic Parameter*	Octave bands [Hz] 125	250	500	1000	2000	4000
Stage	Ceiling in rockwool with 25 mm	105,2	5,2	α	0,25	0,60	0,65	0,95	0,95	0,95
	Plywood wall	267,1	13,3	α	0,20	0,10	0,07	0,05	0,05	0,05
	Wall with panel composed of wood wool bonded with cement with 15 mm and an airgap with 30 mm	182,4	9,1	α	0,10	0,15	0,40	0,75	0,45	0,55
	Parquet floor	148,1	7,4	α	0,02	0,03	0,04	0,05	0,05	0,06
Parterre and Balcony	Ceiling in gypsum board	335,0	16,7	α	0,12	0,10	0,08	0,06	0,06	0,06
	Plywood wall	223,8	11,1	α	0,20	0,10	0,07	0,05	0,05	0,05
	Floor in concrete lined with wood tiles	144,5	7,2	α	0,02	0,04	0,05	0,04	0,10	0,05
	Empty chairs, low upholstered	271,8	13,5	α	0,25	0,35	0,47	0,51	0,49	0,45
				s	*0,20*	*0,30*	*0,40*	*0,50*	*0,60*	*0,70*
	Balcony guardrails in gypsum	73,7	3,7	α	0,12	0,10	0,08	0,06	0,06	0,06
	Variable Acoustic Configuration A	256,6	12,8	α	0,88	0,99	0,99	0,92	0,48	0,24
				s	*0,12*	*0,13*	*0,14*	*0,15*	*0,16*	*0,17*
	Variable Acoustic Configuration B			α	0,63	0,92	0,90	0,55	0,37	0,27
				s	*0,12*	*0,13*	*0,14*	*0,15*	*0,16*	*0,17*
	Variable Acoustic Configuration C			α	0,20	0,42	0,49	0,53	0,48	0,24
				s	*0,12*	*0,13*	*0,14*	*0,15*	*0,16*	*0,17*
	Variable Acoustic Configuration Reflector			α	0,20	0,10	0,10	0,10	0,15	0,20
				s	*0,12*	*0,13*	*0,14*	*0,15*	*0,16*	*0,17*

*By default, scattering coefficients not shown are assumed to be 0,10.

For the acoustic simulations, 56 numerical receivers were placed in the audience seats area, grouped in 5 zones (A and B situated in the parterre and C, D and E in the balcony area), and an omnidirectional source, A0, was placed centered at 1,5 m from the front of the stage. The arrangement of the receivers and sound source are displayed in Figure 3. The arrangement of the receivers by zones was employed to assist in the data analysis and enable a better understanding of the influence of this spatial distribution on the acoustic parameters.

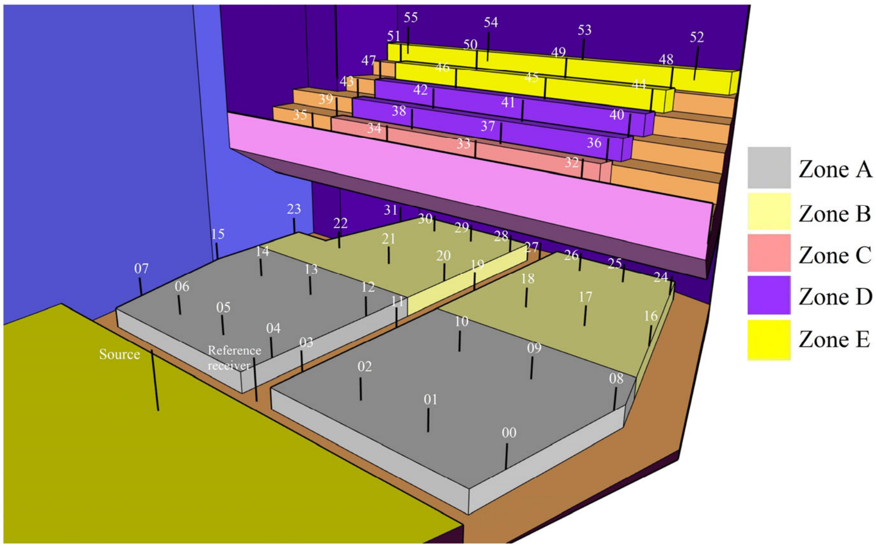

Figure 3– Position of sound source and numerical receivers.

4.1 Preliminary evaluation

Since the reverberation time is initially used in a preliminary acoustic evaluation of a closed space, it is a fundamental indicator regarding the type of space. For the case of speech use, low reverberation times are required to have a better intelligibility of words, whereas, for environments intended for music, higher values are recommended, since it is necessary to create more "live" environments, with greater sound diffusion [1].
Several published works indicate acoustic requirements for the reverberation time depending on the use of the closed space. For example, according to the Portuguese Acoustic Code for Buildings RRAE [11], in its article 10.º-A, the average reverberation time in the frequency bands of 500Hz, 1000Hz and 2000 Hz, evaluated with the room furnished but without an audience, and assumed a use for speech purposes, should be less or equal than that obtained by the following expression: $T = 0.32 + 0.17\log\left(V\right)$ for $V<9000\text{m}^3$, with V being the volume for the space in cubic meters. For the present case study, this average reverberation time should be less or equal to 0.9s.
For music and speech uses, Arau [12] suggests requirements for the reverberation time depending on the type of use and the volume of the space. The standard NS 8178 [13] is also an interesting reference to evaluate the specific case of music rooms. This standard provides a reference for the average reverberation time for performance rooms, as a function of this volume, according to three different types of music classified as amplified music, powerful acoustic music and weak acoustic music. For the analyzed performance room, with a volume of 3779 m^3, the average recommended reverberation times, are displayed in Table 3, according to these references.
Figure 4a shows the average reverberation times obtained from the values registered at all receiver positions, for four possible variable acoustic perforated system configurations (Configurations R, A, B and C). It is possible to verify that, except for the octave band of 4000 Hz, there is a significant variation in the reverberation time of the auditorium between the two extreme configurations (Configuration R and Configuration A). The remaining configurations allow the reverberation to fall in intermediate values.

Table 3 – Recommended reverberation times (mid-frequency octave bands 500 and 1000 Hz) suggested by Arau [12] and by standard NS 8178 [13], according to the type of use.

Type of use	**Reverberation time**	**Recommended Value (s)**	**Reference**
Theatre	Tmax	1,3	*Arau* [12]
	Tmin	0,8	
Opera	Tmax	1,5	*Arau* [12]
	Tmin	1,1	
Chamber music	Tmax	1,5	*Arau* [12]
	Tmin	1,3	
Concerts Acoustic powerful music	Tmax	1,8	*Arau* [12]] *Standard NS 8178* [13]
	Tmin	1,5	
Acoustic quiet music	Tmax	2.2	*Standard NS 8178* [13]
	Tmin	1.8	
Amplified music	Tmax	1.0	*Standard NS 8178* [13]
	Tmin	0.8	

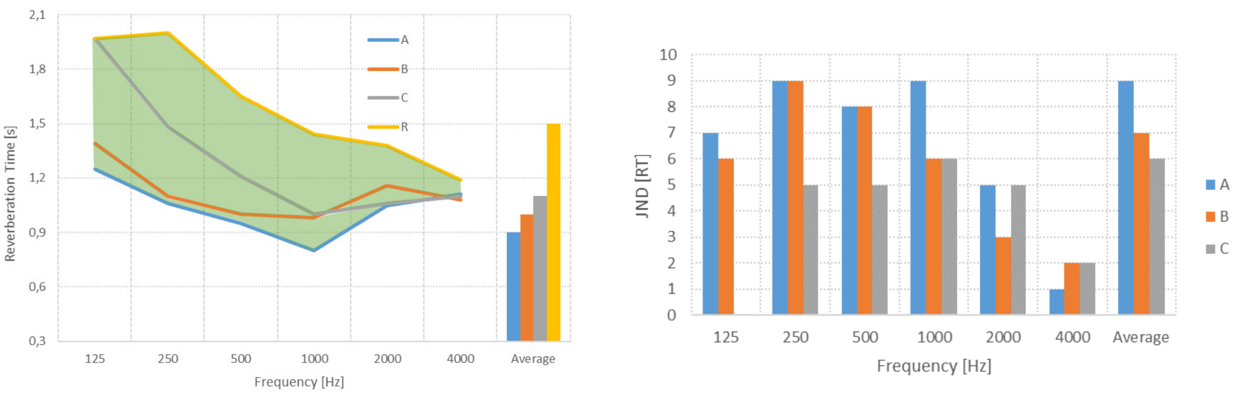

Figure 4–Average Reverberation Time (a) and corresponding JND (b) obtained for the variable acoustic perforated systems analyzed (Configurations R, A, B and C).

The differences among these solutions are also studied in terms of Just Accepted Noticeable Difference (JND) [14], which indicates the perceptible variation achieved with the variable acoustic solution. Higher values of JND indicate that the variable acoustic solution will allow to significantly modify the sound quality of space. For the reverberation time parameter, the differences in the results are calculated concerning the reflective configuration (Configuration R) and are then quantified in terms of the JND, according to the reference value defined in the ISO 3382-1-2009 [14] (JND of 5%). Figure 4b shows the octave band results and also the average at frequency bands of 500Hz and 1000Hz.

From the previous analysis, it is possible to verify that the greater JND values are found for configuration A for all frequency bands, varying between 1 and 9 JND. Configuration B follows, displaying lower JND values, in octave bands, although always greater than 2. The configuration with lower values of JND is configuration C. Looking at the average value, the JND values of the three configurations, in comparison with the reflective one are quite expressive, ranging from 6 to 9.

Comparing the average reverberation times with the reference ones (see Table 3), configuration A would be adequate for speech use or amplified music, configuration R for acoustic loud music, and configuration C could be applied for opera music, while for quiet music the auditorium would not provide good sound quality (higher reverberation times are required). The extreme configurations will be further discussed regarding other relevant acoustic parameters.

4.2 Speech Assessment

The Definition (D50) is related to speech intelligibility and is measured in linear scale, as the ratio between the energy contained in the time interval of the first reflections (50 ms) and the total energy of the impulse response. The higher the value of D50, the better the listener capacity to distinguish each syllable, with values above 50% being considered as acceptable [15].
Figure 5 shows the Definition values (expressed in %), which correspond to average values on several receiver positions, according to the above-defined zones. For the majority of the frequency bands, the values are situated above 50%, varying from 48% to 74%. Values slightly below 50% are registered in zone D (48%), for a frequency of 125 Hz, and in zone C (49%), at frequency 4000 Hz. The average definition value (at frequencies 500Hz and 1000Hz) in the several zones is situated between 70% and 71%, indicating a very good spatial distribution of this indicator.

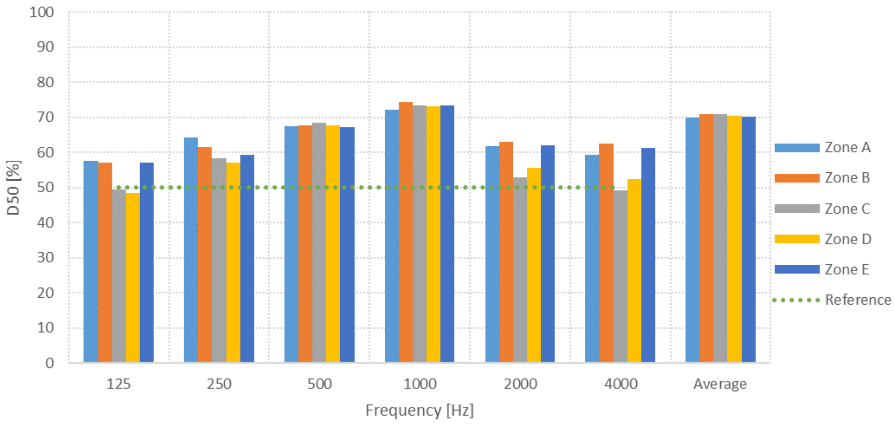

Figure 5 – Definition (D50) obtained, when the variable acoustic solution provides maximum absorption (Configuration A).

The Speech Transmission Index (STI) is a criterion used to quantify the measure of intelligibility of words, with values varying between 0 (null intelligibility) and 1 (optimum intelligibility) (see Table 4). The STI is measured by the speech signal modulation, starting from the condition that the speech signal is amplitude modulated, and to have good intelligibility one should have the minimum possible deformation [15].

Table 4 - Relation between speech transmission quality and Speech transmission index (STI).

STI	< 0,30	0,30 – 0,45	0,45 – 0,60	0,60 – 0,75	≥ 0,75
Score	Bad	Poor	Fair	Good	Excellent

The analysis of this parameter is essential in the case of the use of the space for speech purposes, to verify the measure of speech intelligibility in the sound environment. In the present case study, STI values range between 0.62 and 0.66, as evidenced by the analysis of Figure 6, with the solution being characterized as Good to oratory, according to Table 4. It is also important to note that a good spatial distribution of this parameter was found.
Although STI is a parameter used to evaluate speech intelligibility, and therefore important in the case of oratory/speech use, this value was also obtained for music configuration in order the evaluate its variation (see Figure 6). In the case of the selection of the reflective configuration (Configuration R), the STI values varied between 0.51 and 0.59, as shown in Figure 6. According to Table 4, this range is considered Fair.

When compared with the values obtained using the most absorbent configuration, there is an increase in this indicator of about 10%.

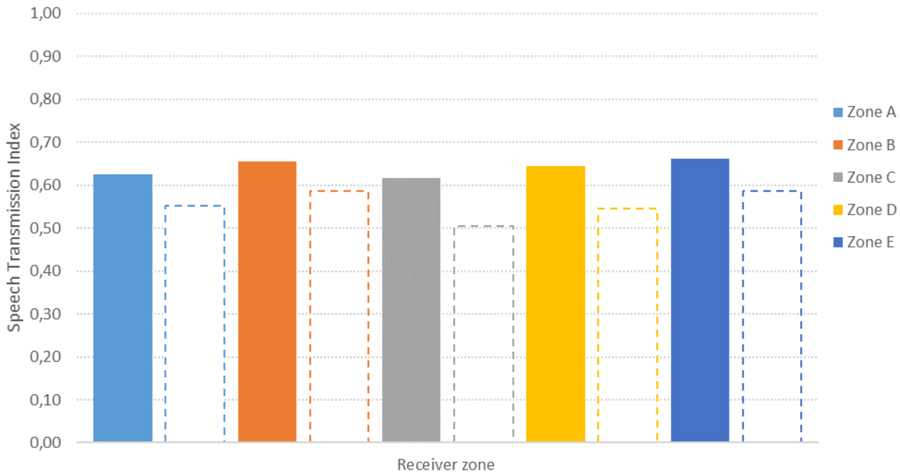

Figure 6 – Speech transmission index (STI), when the variable acoustic solution provides maximum absorption (solid columns – Configuration A) and when the variable acoustic solution provides maximum reflection (dashed columns – Configuration R).

4.2.1 Concert Assessment

The Clarity (C80) is a parameter associated with the characterization of a given space for music. According to Arau [12], a classification of values can be defined which depends on the type of use of the indoor space. For opera the recommended values vary between 2dB < C80 < 6dB, while for concerts values should lay within -2 dB < C80 < 4dB.

Figure 7 shows the indicator C80, in octave frequency bands, by zones. It can be seen that, as the distance from the source increases, the curves also increase in amplitude. The average values in the frequency bands between 500Hz and 2000 Hz (also displayed in Figure 7) vary between 1 and 4 dB complying with the recommended values proposed by Arau, for concerts.

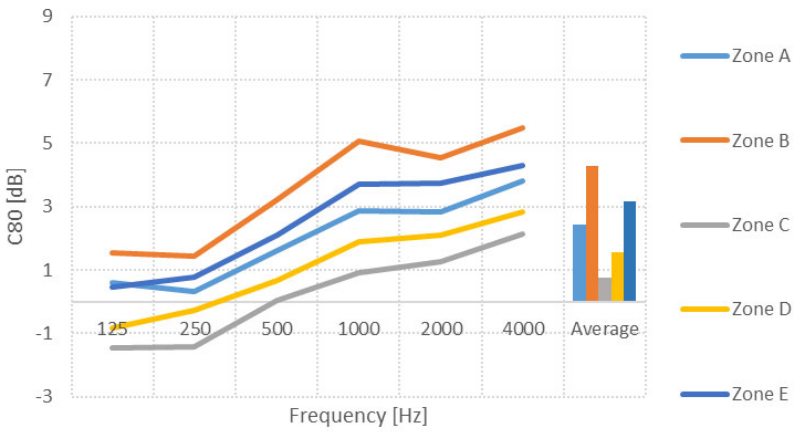

Figure 7 – Clarity (C80) obtained in the auditorium, when the variable acoustic solution provides minimum absorption (Configuration R), by zones.

The “amplification” of the sound by the room is described by the parameter Strength (symbol G), in dB, and is defined in the ISO 3382-1 [14]. The strength is the sound pressure level in the room relative to the sound pressure level in the free field at a distance of 10 m from the same source, which must be omnidirectional.

When Strength, G, of a room is known, it is possible to estimate the sound pressure level at *forte* (f) in the room when the emitted sound power at *forte* of the music ensemble, $L_w(f)$, is known, by using the following relation from ISO 3382-1 [14]: $L_p(f) = L_w(f) + G - 31$, in dB.

The perceived acoustics of the room for music is characterized by the Reverberation Time (RT) and the Strength (G) as a function of the space volume, and there is an optimum range for these values to have proper acoustics. If the Reverberation Time is too high the sound would be too muddy and if it is too low, it would be too dry. On the other hand, if the room has too high Strength the music will sound too loud and maybe quite annoying, and if the Strength is too low the music will sound weak and maybe disappointing to listen to it [16].

According to the standard NS 8178 [13], the reference for the acoustic evaluation of a music room is the sound pressure level at *forte*, Lp(f), within the range 85-90 dB for performance rooms. For a classical symphony orchestra playing at *forte,* the sound power level is around 110 dB at *forte* and around 120 dB at *fortissimo*. With these sound power levels, to obtain a sound pressure level at *forte*, a Strength (G) between 6 and 11 dB is required.

For the variable acoustic configuration R, the values of G given by zones are shown in Figure 8, in octave bands and also after performing the average in the frequency bands of 500Hz and 1000 Hz. The average G varies between 9.4 dB and 10.4 dB among different zones. The major difference is equal to 1 JND, according to the reference provided in standard ISO 3382-1 [14] (for G, that standard indicates a JND of 1 dB), meaning that there is a good distribution of this indicator within the auditorium. Analysing the reference provided in the standard NS 8178 [13], we may conclude that the auditorium will provide good acoustics for loud music.

The Strength provided by configuration A, which could be used for amplified music, was also computed and is also displayed in Figure 8 (dashed columns). Comparing the results provided by this configuration with the reflective one, the differences are very clear. In this case, the average result varies between 5 dB and 9 dB, and the greater differences are found to be at seats near the stage, which are more influenced by direct sound. In this zone (Zone A) the sound may appear too loud compared to the other zones where the maximum differences are of 1 JND and Strength values decrease to 5 dB and 6 dB.

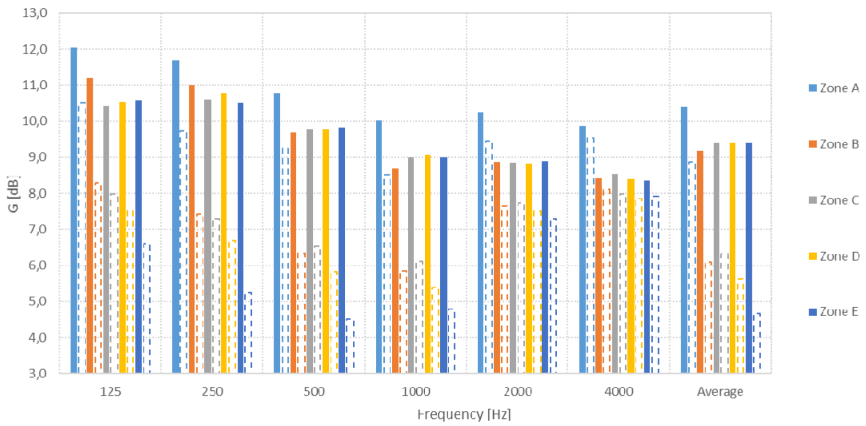

Figure 8 – Strength parameter (G) obtained in the auditorium, when variable acoustic solution provides maximum reflection (solid columns – Configuration R) and when the variable acoustic solution provides maximum absorption (dashed columns – Configuration A), by zones.

The early Lateral Energy Fraction (LF) is a parameter for the spatial impression of the room (a sense for the listener to be surrounded by the sound). A room is acoustically very spacious if it makes a sound source be perceived as “wider”. The LF is the linear ratio of sound which arrives laterally to the ear in the time interval between 5 ms and 80 ms concerning the total sound from all directions, within the first 80 ms. In other words, the LF shows the sense of sound spatiality. LF is generally measured from the impulse responses

obtained using a "figure-of-8" microphone (to measure the lateral energy), in conjunction with an omnidirectional microphone (to measure the total energy).
According to ISO 3382-1 [14], the recommended LF for music venues varies between 5% and 35%. A too high proportion of lateral sound can be disturbing since it compromises identification with the performers. The average value of LF is obtained from frequencies between 125 Hz and 1000Hz. This parameter is displayed below (Figure 9) for Configuration R. For the present case study, this value varies between 0.19-0.32, which falls within the recommended range.

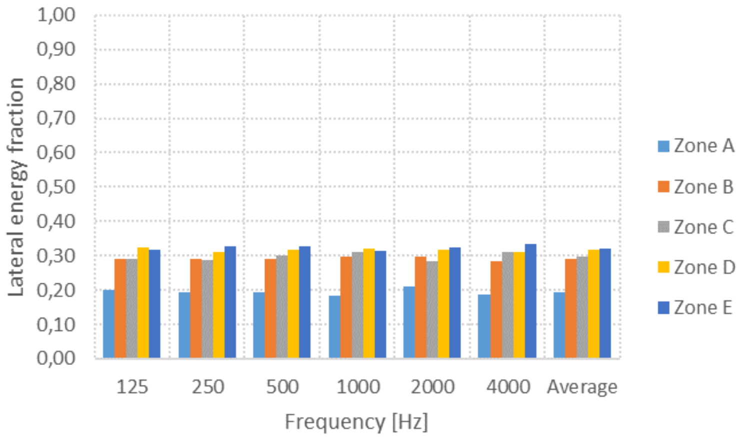

Figure 9 – Early lateral energy fraction (LF) obtained in the auditorium, when the variable acoustic solution provides minimum absorption (Configuration R), by zones.

The major difference among zones is higher than 1 JND, but less than 3 JND according to the reference provided in standard ISO 3382-1 (for LF, the standard indicates a JND of 0.05), meaning that, except for zone A (near the stage), where the sound from source may be more prominent, in general, there is a good distribution of this indicator within the auditorium and the sound will be perceived as "wider".

5 Conclusions

In this paper, a variable acoustic solution, based on the use of perforated panel systems that may be suitable to adapt the auditorium acoustic conditions to different types of use was addressed. While its surface appearance is kept constant, the acoustic properties may vary by either closing the holes of the perforated panel or changing the position of a porous material embedded inside the air gap. Sound absorption provided by possible configurations was calculated using an analytical approach based on the Transfer Matrix Method (TMM). Ray tracing simulations of an auditorium were employed to analyse the different possibilities in terms of the room acoustic behaviour. Configurations providing maximum absorption and minimum absorption of the proposed concept solution were discussed in detail through the evaluation of important acoustic indicators for each type of use and allowed for the conclusion that sound quality may be achieved for types of use such as speech, amplified music or acoustic ensemble music. It was also interesting to note that a good spatial distribution of the calculated parameters was obtained for the configuration related with speech use. Regarding music configuration, in general, the indicators display also a good spatial distribution, although differences in some indicators were found, mainly bellow the balcony where less early reflections reach this zone. Spatial impression of the room is also perceived as "wider" in the back seats than in the front seats where sound energy that reaches this zone is mainly that from the stage.

Acknowledgements

This work is financed by FEDER funds through the Competitivity Factors Operational Programme - COMPETE within the scope of the project ADJUST - Development of acoustic panels progressively adjustable with smart acting – SII &

DT Project CENTRO-01-0247-FEDER-033884. This work was partly financed by FCT / MCTES through national funds (PIDDAC) under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UIDB / 04029/2020 and by Regional Operational Programme CENTRO2020 within the scope of project CENTRO-01-0145-FEDER-000006 (SUSpENsE).

References

[1] Barron, M. Acoustics for multi-purpose use, in *Auditorium Acoustics and Architectural Design*, 2nd ed., London and New York: Spon Press, 2010; pp. 385-408.

[2] Everest, F. A.; Pohlmann, K. C. . Adjustable Acoustics, in *Master Handbook of Acoustics*, 6th ed., McGraw-Hills, 2009; pp. 375-390.

[3] Cairoli, M. Architectural customized design for variable acoustics in a multipurpose auditorium. *Applied acoustics,* Vol 140, pp. 167-177.

[4] Beranek, L. *Concert halls and opera houses: music, acoustics, and architecture*, 2nd ed.; Springer-Berlang, New York, 2004; pp. 549-550.

[5] Thün, G.; Velikov, K.; Sauvé, L.; McGee, W. *Design Ecologies for Responsive Environments: Resonant Chamber, an Acoustically Performative System*. ACADIA 12: Synthetic Digital Ecologies, San Francisco, USA, 2012.

[6] Cox, T.; d'Antonio, P. *Acoustic absorbers and diffusers: theory, design and application*, 3rd ed. Crc Press, 2017; pp. 225-255.

[7] Vorländer, M. Auralization. *Fundamentals of acoustics, modelling, simulation, algorithms and acoustic virtual reality*; Springer, Berlin, Heidelberg, Germany, 2008; pp. 181-196.

[8] Lo Turco, M.; Zich, U.; Astolfi, A.; Shtrepi, L.; Poaola B. M. From digital design to physical model. Origami techniques applied to dynamic panelling shapes for acoustic performance control. In proceedings of the *35th International Conference on Education and Research in Computer Aided Architectural Design in Europe*. Sept 2017.

[9] Patraquim, R.; Godinho, L.; Tadeu, A.; Amado-Mendes, P. Influence of the presence of lining materials in the acoustic behaviour of perforated panel Systems. *ICSV 18*, Rio de Janeiro, Brazil, 2018.

[10] Larner, D; Davy, J. The prediction of the diffuse field sound absorption of perforated panel systems. In *Proceedings of the 44th InterNoise Congress and Exposition on Noise Control Engineering*, San Francisco, CA, United States, 2015.

[11] Decree-Law n.º 96/2008, June 9th, Regulamento dos Requisitos Acústicos dos Edifícios (RRAE), 2008 [in Portuguese].

[12] Arau, H. *ABC de la acústica arquitectónica*; CEAC Eds., Barcelona, 1999; pp. 217-288.

[13] NS 8178:2014, *Acoustic criteria for rooms and spaces for music rehearsal and performance*. (In Norwegian). Standard Norge, Oslo, 2014.

[14] ISO 3382-1:2009, *Acoustics - Measurement of room acoustic parameters - Part 1: Performance spaces*. International Organization for Standardization, Brussels, Belgium, 2009.

[15] Isbert, A. C. *Diseño acústico de espacios arquitectónicos*; Universidad Politécnica de Catalunya, 1998; pp. 34-35, 184.

[16] Rindel, J. H. Rooms for music – Acoustical needs and requirements. *Baltic-Nordic Acoustic Meeting*, Tallinn, Estonia, 2014.