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Study of energy acoustical parameters at audience area in a simulated multi-purpose hall with an articulated orchestra shell

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Abstract

The basic requirement for multi-purpose theaters is the adaptation to different musical styles that should be presented in the room. Orchestral shells provide better ensemble feeling to musicians, but also benefit listeners with closer first reflections. Nevertheless, there are few works devoted to study the acoustical influence of shells at the audience area. The Teatro Municipal de Paulinia, located in the countryside of São Paulo (Brazil), is a multi-purpose theater equipped with an articulated poly-cylindrical orchestral shell with a retractile ceiling. In previous works, the acoustic parameters TR, EDT and C80 were measured according to ISO 3382-1:2009 in two configurations of the unoccupied theater: in the presence and absence of the shell. However, energy related parameters (G, G_{early} and G_{late}) and spatiality parameters (LF and GLL) were not studied. This paper aims to assess the computational model of the theater through the measurement data and calculate these other acoustical parameters to further analyze the resulting effect of the shell upon the audience area. First, the model is validated in the configuration of the theater where the shell is not mounted, so as to estimate the absorption and scattering coefficients of the room. Then, the model is validated in the presence of the shell to estimate its absorption coefficient. The parameters G, G_{early}, G_{late}, LF and GLL are calculated in both configurations. The results indicated an improvement in the acoustical performance of listeners.

Keywords: Room Acoustics, Acoustical Simulation, Orchestra Shells

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1 Introduction

Orchestra shells are mainly intended to help musicians, providing a better ensemble feeling as they can hear each other more clearly. Shells are useful in multi-purposes halls because variability and adaptation is key to provide good (or at least, regular) acoustics for the several performance styles to be presented. However, there are not many studies aimed at the acoustical influence of orchestra shells in the audience.

The Teatro Municipal de Paulínia is a Brazilian multi-purpose hall equipped with a poly-cylindrical orchestra shell. The theatre serves for music, theatre, dance and even cinema presentations. Maiorino [1] performed measurements of three acoustic parameters, reverberation time T_{20}, early decay time *EDT* and clarity index C_{80}, according to ISO 3382-1:2009 [2] in the unoccupied theatre. Yet this study presented a limitation for a further analysis because energy and spatial parameters were not measured. Due to theatre scheduling it was not possible to perform another measurement at site. It is possible to evaluate these parameters by performing an acoustical simulation.

A common problem in the acoustical simulation of existing rooms is the correct estimation of absorption and scattering coefficients of materials. Many times, data of some materials are either unknown or it can greatly vary due to different manufactures and different mounting types at reverberation chamber's measurements. Absorption coefficients of vibrating panels, for example, can be calculated with satisfactory precision through analytical or numerical methods, but such surfaces are not the main source of absorption in large rooms. Absorption by occupied and unoccupied seats has been measured [3,4] and can be used as a first estimation for models. However, even with available data, the coefficients may not meet the (near) actual values necessary for the accurate representation of the room.

This paper proposes to calculate five acoustic parameters: sound strength *G*, early sound strength G_{early}, late sound strength G_{late}, lateral fraction *LF* and late lateral sound level *GLL* through the acoustical simulation software ODEON. Using the optimization tool implemented in the software and the previous measurements in the theatre it is possible to calibrate the model, deriving the unknown absorption coefficients of some materials.

2 Description of the theatre

The theatre has a rectangular shoebox shape symmetrical to the central vertical plane. It has a total area of 12,500 m², internal volume of approximately 16,000 m³ and a capacity of about 1,200 seats. The audience area is composed of five subareas: inferior and superior audience, central and lateral balcony and cabins. The lateral balconies are disposed over three floor levels, each one phased in four levels that follow the inclination of the inferior and superior audience. Two corridors cut the inferior and superior audience and the central balcony. There are two types of seating. The lateral balconies ones are removable chairs of metal structure lightly upholstered, while the seats of all other audience areas are wood structure retractile seating of moderate upholstery.

The lateral walls at the balconies and cabins are made of smooth and glazed wood covering, while the rear walls are lathered wood with varied spacing over mineral wool covered by black fabric. In the middle of the lateral walls, there are vibrating panels with different depth forming a repeating pattern on each lateral balcony floor. There are four reflecting panels with 4.5° of inclination above the stage and lower audience area, which extends over the lateral balconies' edge.

The proscenium arch of the theatre has 15 m of width and 7.5 m of height. The stage box has unpainted, glazed brick walls and its volume is approximately 8,600 m^3. It contains lighting equipment, six sound absorbers for cinema sessions, two vertical stage regulators and the orchestra shell. There are also nine scenic curtains parallel to the proscenium arch of and two more curtains perpendicular to the arch.

Nine towers of metal structure with three semi-cylindrical (93 cm radius) wood panels each form the orchestra shell. The shell is made of 6 mm thick wood panels with a surface density of 4.5 kg/m^2. Optionally, it can be installed a retractile ceiling to the shell. The ceiling is composed by three series of three wood curved panels of 4 m x 3 m dimension and 6 mm of thickness, whose angulation and height can be varied. It is also possible to position the ensemble in different configurations.

3 Method

Figure 1 shows the CAD model of the Teatro Municipal de Paulínia. The software used for the acoustical simulation of the theatre was ODEON (version 13). Many elements of the theatre had its geometry simplified. A high detail geometry, despite the over complications, can conflict with the software's calculation methods based on geometrical acoustics, which does not improve results but increases calculation time [5,6]. The inherent fractioning of curved surfaces by CAD models affects scattering and diffusion too. Scattering effects of irregular surfaces that are lost in the process of geometry simplification can be corrected, to a certain level, by the scattering coefficient assigned to each surface. Seats were represented by the so called "audience box", a volume of approximately 0.7 m height wrapping the audience area.

As there were materials with unknown absorption coefficients, it was necessary to calibrate the model through the previous measurements and, thus, calculate the unmeasured parameters G, G_{early}, G_{late}, LF and GLL.

3.1 Source and receiver positions

Omnidirectional sources (F) and receivers (R) were positioned according to the measurement positions with the addition of three verification points (R27, R28 and R29). Figure 2 shows these positions in the three levels of the theatre's floor plans. All sources and receivers points are placed, respectively, at 1.5 m and 1.2 m above the ground.

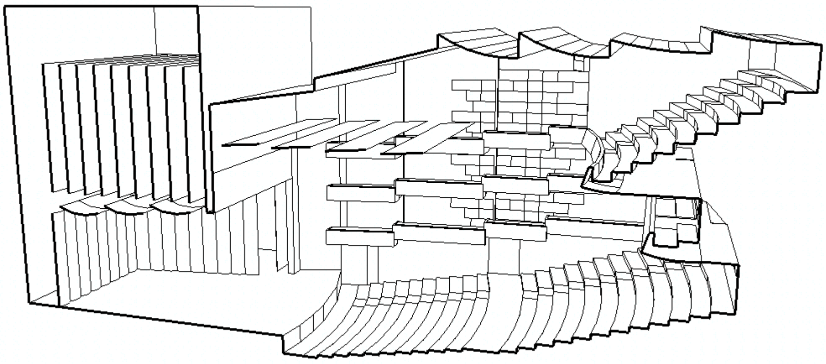

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Figure 1: Vertical section of the theatre's SketchUp 3D model used for the simulation.

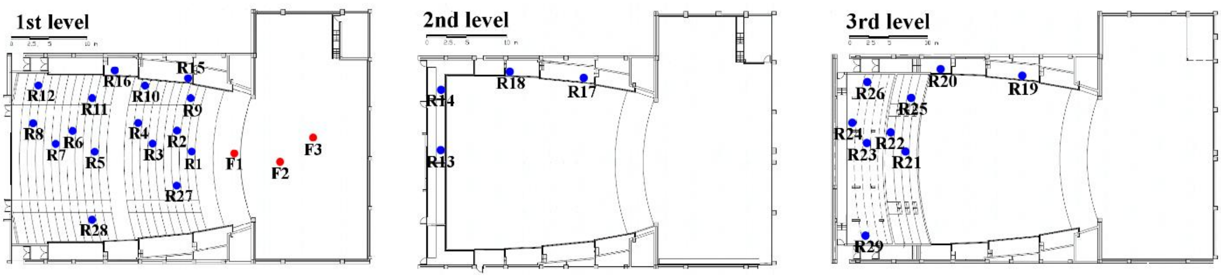

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Figure 2: Source (F1, F2 and F3) and receiver (R1 to R29) positions displayed in the three-level floor plans of the Teatro Municipal de Paulínia.

3.2 Orchestra shell's configurations

Maiorino [1] measured the acoustical parameters T_{20}, *EDT* and C_{80} in octave band from 125 to 4000 Hz according to ISO 3382-1:2009 in two configurations: in the absence and in the presence of the orchestra shell. These configurations (Figures 3 and 4) were reproduced in the simulation model but simulation results will be shown by octave band frequencies from 63 to 8000 Hz.

Configuration 1: Orchestra shell absent. Three scenic curtains are moved down, bounding the orchestra space.

Configuration 2: Complete orchestra shell with retractile ceiling angled at -5° in relation to the audience. Four scenic curtains are removed from the stage box for better adjustment of the retractile ceiling.

The audio tracks of the measured impulse response of each source-receiver position combination and each configuration were added in the simulation software to gather automatically the measured parameters' results.

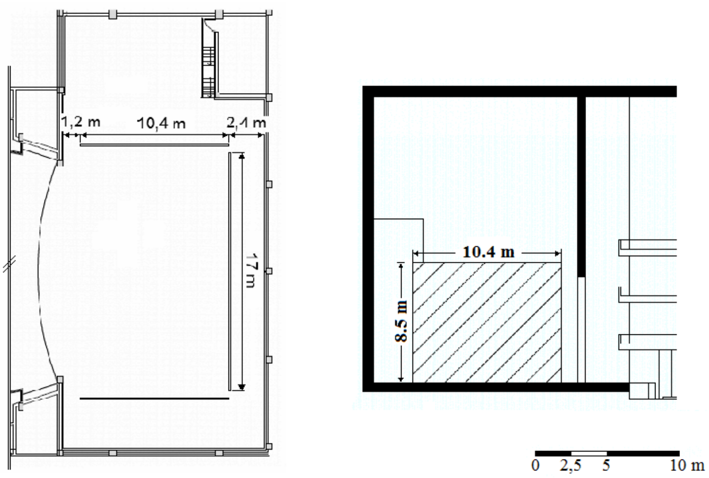

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Figure 3: Floor plan and lateral section of Configuration 1 used in the measurements and simulation.

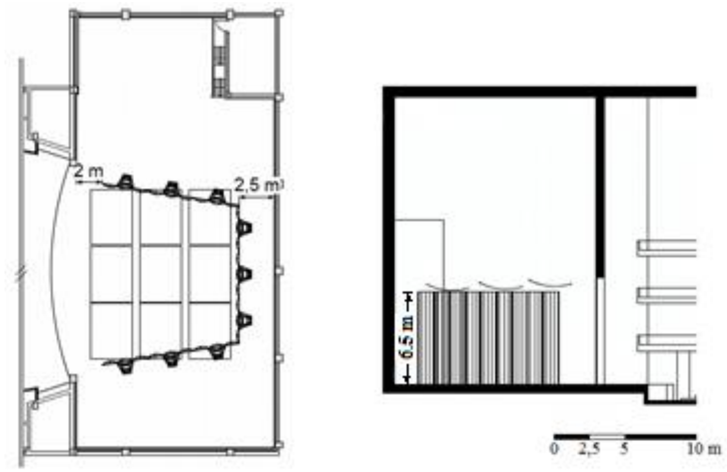

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Figure 4: Floor plan and lateral section of Configuration 2 of the orchestra shell and retractile ceiling used in the measurements and simulation.

3.3 Model calibration

In the modelling of the theatre, it was found that four groups of surfaces had absorption coefficients that could not be directly estimated with a reasonable level of confidence: the audience areas (lightly upholstered chairs and medium upholstered seats), the scenic curtains in the stage box and the orchestra shell with retractile ceiling. Absorption data highly depends on manufacturer's choice of materials, measurement method and mounting. The curtains' absorption coefficient, for example, depends on draping percentage and distance to walls [7]. However, the absorption coefficients of these surface groups can be indirectly determined by using the measured data of the theatre in the model validation process.

3.3.1 Genetic algorithm optimization tool

ODEON offers a useful tool that uses a genetic algorithm to estimate absorption of an existing room. The genetic algorithm applied in the software seeks to minimize the fitness function ϵ, which is the difference between simulated and measured values of a given set of acoustic parameters, normalized by the just noticeable difference JND. This function, therefore, represents the average error of simulated parameters compared to measurements and is given by [8]:

$$\epsilon[JND] = \frac{\sum_{k=1}^{K}\sum_{i=1}^{I}\left|\left[Par_i^k\right]_{Sim} - \left[Par_i^k\right]_{Meas}\right|}{K \cdot I} \tag{1}$$

where $[Par_i^k]_{Sim}$ and $[Par_i^k]_{Meas}$ are the simulated and measured values of the normalized acoustic parameter i for the source-receiver combination k, K is the total number of source-receiver combinations and I is the total number of used acoustic parameters. The tool runs one algorithm for each selected frequency band simultaneously.

In the following applications of the algorithm, only the measured acoustic parameters (T_{20}, *EDT* and C_{80}) were selected for the calibration over all source-receiver positions. The two model configurations were separately used in order to decrease the number of independent variables of the optimization.

3.3.2 Calibration of absorption coefficients

The absorption coefficient of the two types of audience area and the scenic curtains were initially set to typical values given by ODEON, as manufacturer's data of seating and curtains could not be obtained. The curtains' absorption, due to its large area, showed to be one of the main sources of absorption in the theatre. Small variations of 0.1 in the absorption coefficient generated variations of 0.5-1.0 s in the T_{20} parameter for low frequencies.

In Configuration 1, it was used the genetic algorithm along with the measured parameters for the calibration of the absorption coefficients with a 50-75% search range in the octave band frequencies from 63 to 8000 Hz. Despite the good agreement between the measured and simulated results, the coefficients generated had unreal values when compared to measured absorption found on literature for materials alike. For this reason, some refinements were done to these results by using the genetic algorithm with more limited search ranges (50% or less) and for specific frequencies or by manually changing some coefficients before running the algorithm again.

When completed the calibration of the audience area and curtains, Configuration 2 was used to estimate the absorption coefficient of the orchestra shell with the same procedure as before.

Refinement by comparison was less effective this time, as only one absorption coefficient data was found for acoustical shells.

After established the model calibration, the unmeasured parameters were calculated by octave band for frequencies from 63 to 8000 Hz in both configurations in order to analyse the influence of the shell in the audience area.

4 Results and analysis

4.1 Calibration and validation results

Table 1 shows the absorption coefficients of the four groups of surfaces selected for the calibration of the model as function of the octave band frequencies from 63 to 8000 Hz. The coefficients are presented in three stages, as described in subsection 3.3.2: the initial values of similar materials, values optimized by a single run of the genetic algorithm and the final, refined values.

Table 1: Absorption coefficients of initial material ($\alpha_{initial}$), optimized material with the genetic algorithm (α_{GA}) and after refinements ($\alpha_{refined}$) for the four groups of surfaces.

		Octave band frequency (Hz)							
Material	α	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Medium upholstered seats	$\alpha_{initial}$	0.560	0.560	0.640	0.700	0.720	0.680	0.620	0.620
	α_{GA}	0.597	0.524	0.759	0.757	0.699	0.583	0.545	0.506
	$\alpha_{refined}$	0.487	0.427	0.699	0.757	0.655	0.519	0.556	0.554
Lightly upholstered chairs	$\alpha_{initial}$	0.350	0.350	0.450	0.570	0.610	0.590	0.550	0.550
	α_{GA}	0.464	0.254	0.525	0.520	0.568	0.651	0.341	0.540
	$\alpha_{refined}$	0.415	0.370	0.482	0.473	0.633	0.629	0.513	0.569
Scenic curtains	$\alpha_{initial}$	0.030	0.030	0.120	0.150	0.270	0.370	0.420	0.420
	α_{GA}	0.062	0.049	0.069	0.120	0.177	0.306	0.302	0.184
	$\alpha_{refined}$	0.051	0.057	0.069	0.120	0.177	0.306	0.302	0.279
Orchestra shell and ceiling	$\alpha_{initial}$	0.100	0.100	0.010	0.017	0.030	0.060	0.083	0.083
	α_{GA}	0.042	0.056	0.004	0.030	0.009	0.031	0.042	0.033
	$\alpha_{refined}$	0.051	0.018	0.017	0.023	0.009	0.046	0.021	0.018

The calibration of the model was based on the measured acoustical parameters T_{20}, *EDT* and C_{80}. For short, it is presented the calibration result for T_{20} only (Figure 5). Low frequency simulation values was generally more inaccurate due to the very nature of the calculation method of the software [8]. Configuration 2 had four curtains removed, which can cause a change in the absorption coefficient of the set as a whole. Table 2 contains the average deviations in terms of JND for Configuration 1 and Configuration 2 of the calibrated parameters. EDT parameter is very sensitive to random decay fluctuations, which contributes to its relatively high deviation. Measurements of C_{80} in the 63 Hz octave band had distinctively higher values and were considered unreliable. Calibration can still be considered satisfactory.

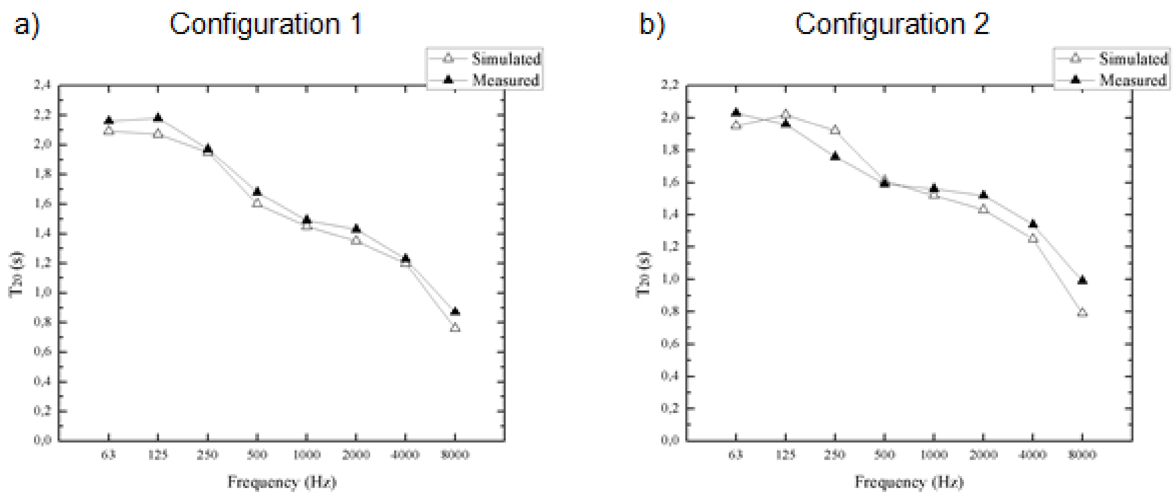

Figure 5: Simulated and measured values of T_{20} parameter of a) Configuration 1 and b) Configuration 2 as a function of octave band frequencies.

Table 2: Average deviation between measured and simulated parameters in terms of JND for both model configurations.

Acoustic parameter	Configuration 1	Configuration 2
Reverberation time, T_{20}	1.74	1.92
Early decay time, *EDT*	3.69	2.64
Clarity index, C_{80}	1.82	1.80

The proposed parameters were calculated for both configurations maintaining the calibrated absorption coefficients. Figure 6 shows the results obtained for energy parameters G, G_{early} and G_{late} as a function of frequency. An increase in all three parameters values was observed in all frequencies from changing Configuration 1 to Configuration 2, that is, the addition of the orchestra shell increased the sound strength of early and late reflections received by the audience and the overall sound strength.

Table 3 presents two spatiality parameters as single numbers: LF as the arithmetic average and GLL as the logarithmic average of octave band frequencies of 125 to 1000 Hz values. LF, which is most correlated to the apparent source width (ASW), increased 0.01 by the addition of the shell to the theatre. The listener, as the JND for that parameter is 0.05, does not perceive this change. GLL, generally correlated to listener's envelopment (LEV), had an increase of 0.65 dB from Configuration 1 to Configuration 2. JND value for this parameter is not established yet [2], but if one considers the JND for sound strength (1.0 dB), the listener would also not notice this change.

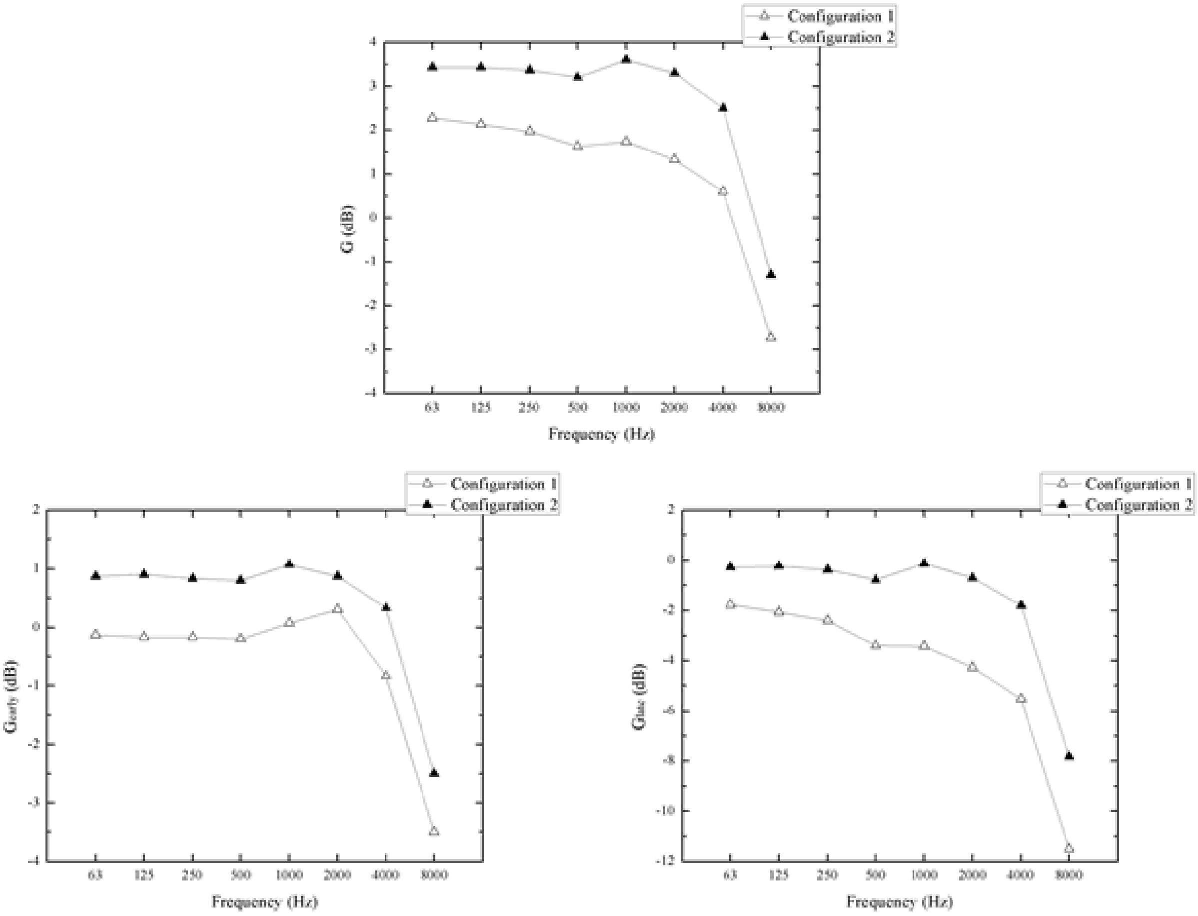

Figure 6: G, G_{early} and G_{late} values of Configuration 1 and Configuration 2 as a function of octave band frequencies.

Table 3: Single number values of simulated acoustic parameters *LF* and *GLL* for both model configurations.

Acoustic parameter	Configuration 1	Configuration 2
Lateral fraction, *LF*	0,18	0,19
Late lateral strength, *GLL*	-9,70 dB	-9,05 dB

5 Conclusions

Acoustical simulations are one of Room Acoustics’ most powerful research methods in development today. Accuracy of simulations is yet hard to determine, as both measurements and simulations have its sources of systematic and stochastic uncertainties [9,10]. In addition, absorption coefficients databases need to be in constant expansion and improvement and its use cautiously adapted into the modelling process. An improvement of this model would be to apply transparency coefficients to the freely hanged scenic curtains in order to get absorption coefficients nearer to real values as, in this way, its mounting and porosity properties are better represented.

The simulated acoustic parameters, within their imprecisions, showed some of the orchestra shell's influence in the audience area. The orchestra shell contributes for the overall gain in sound strength, increasing both early and late reflections. On the other hand, spatiality perceptions seemed not to be affected. In general, acoustical shells benefit both musicians and listeners. Audience's musical experience may yet be improved by searching new configurations for the orchestra shell.

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