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Simulated Sound-Fields in a Multi-Configurable Auditorium

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In this work, simulation techniques have been implemented to study the sound fields of a multi-configurable performance enclosure by creating computer acoustic 3D-models for each room configuration. The digital models have been tuned by means of an iterative fitting procedure that uses the reverberation times measured on site for unoccupied conditions with the orchestra shell on the stage. The initial virtual acoustic model is validated by comparing the other monaural and binaural acoustic parameters measured in the room in terms of their perception differential threshold. The procedure is applied to the Maestranza Theatre of Seville, built for the Universal Exhibition in 1992. The spatial distribution of the acoustic parameters in the audience area of the venue by measured parameters and simulation mappings enables the establishment of three zones of acoustic comfort, and are corroborated by the values of the Ando-Beranek function which provide a global quality coefficient of each zone.

Keywords: acoustic simulation; concert hall acoustics; theatre heritage; sonic metrics.

1. Introduction

Computing techniques are essential tools in the investigation of complex sound fields and are widely used in acoustic measurements to generate signals and to process impulse responses. The modelling of virtual sound fields constitutes another topic of digital application which draws increasing interest in various architectural spaces (San Martín, Arana, 2006; Galindo *et al.*, 2009; Martellotta, 2009; Sant'Ana, Zannin, 2011), designs (Mahdavi *et al.*, 2008; Berardi, 2014), and urban environments (Kang, 2005). These techniques are the most frequently used for the pre-design of performance spaces to verify their feasibility from the acoustic viewpoint (Hidaka *et al.*, 2000), and enable various design possibilities to be assessed. In these enclosures, acoustic experiments with scale models (Xiang, Blauert, 1993; Polack *et al.*, 1993; Kim *et al.*, 2011) still remain a powerful tool when a rough design of the room is already available (Hidaka *et al.*, 2000). However, as a further aspect of the widespread use of computers in architecture (Oldham, Rowell, 1987), computer simulations are replacing these physical models since their algorithms are becoming not only easier to use but also cheaper and more accurate. Nowadays, the wide range of existing commercial computer programmes, whose validity can be directed towards a variety of scientific aspects (Ermann, 2005; Rychtáriková *et al.*, 2011), incorporate high-quality auralizations. A major effort is being invested in research for the refinement of these auralizations (Torres *et al.*, 2001; Calamia *et al.*, 2008; Zahorik, 2009) in acoustic virtual-reality applications, and for the recreation of the sound of both multiple future virtual acoustic environments of spaces and of ancient scenarios for archaeological purposes (Vassilantonopoulos, Mourjopoulos, 2009).

By considering the advantages and facilities of geometrical acoustics for this type of enclosure (Vorländer, 2013), this study has created a digital acoustic model of the Maestranza Theatre in Seville (Spain), for whose tuning an iterative adjustment procedure of the unique absorption coefficients of the diffuser wooden ceiling is used. Wood is the material to which the greatest uncertainty in the literature is directed and wherein the simulated reverberation times, position-averaged at the different octave bands, differ by less than 5% from those measured. A similar approach proved highly suitable both for churches

(Galindo *et al.*, 2009) and auditoria (Garrido *et al.*, 2012).

Once the model has been validated by comparing the results of the acoustic parameters experimentally measured and simulated in terms of their difference limen, just noticeable difference (JND) (ISO 3382-1, 2009), it can be used as a reliable prediction of the acoustic behaviour of the theatre and as a means to evoke their sound environment in other physical configurations of the stage (new provision for symphonic music and opera) and/or with the maximum audience in the hall for which no experimental measurements yet exist. In this context, there is also the possibility to identify acoustic differences between the different parts of the audience zones by using the mapping possibilities offered by the simulation software.

The method is based on visually selecting from the mappings of the various parameters, where parameter can identify a suitable zone discrimination (in this case the T_S parameter), and thereafter the behaviour of the remaining parameters in each identified zone can be characterized. The analysis is complemented by the experimental results and the calculation of the Ando-Beranek function of global assessment of acoustic quality of the various established zones.

2. Experimental methods

This section first describes the features of the multi-configurable performance venue and states the procedures followed in the objective acoustic measurements. The geometric and acoustic details of the acoustic simulations performed by using commercially available software based on ray-tracing techniques are furtherly provided.

2.1. The simulated auditorium

The performance space to simulate is the Maestranza Theatre, designed by architects Aurelio del Pozo and Luis Marín in 1991, which formed part of the building work that was carried out in Seville for the Universal Exhibition in 1992 (EXPO-92). The theatre consists of a large cylindrically shaped concert room without boxes (Fig. 1a and Table 1). The multifunctional character of the hall, which stages continual performances of various musical types and scenarios, requires specific acoustic qualities depending on the nature of the performance that is to be held.

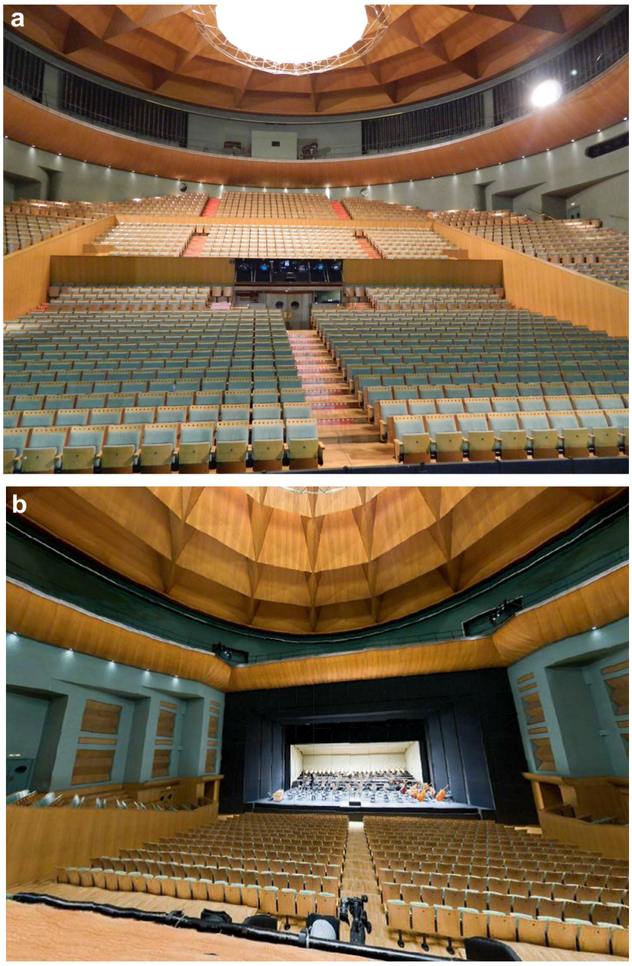

Fig. 1. The Maestranza Theatre: a) view of the hall from the stage with the absorbing cylinders deployed on the drum cover; b) view of the orchestra shell with the musician positions.

Architecturally it is possible to modify the proscenium by installing an acoustic shell for concerts (Fig. 1b) and by means of certain platforms with vertical movement invading the pit so that dancing shows may be performed and/or large orchestras may be accommodated (referred to here as the *Symphonic 1* con-

Table 1. Significant geometric, environmental and acoustic data of the hall corresponding to the configuration measured.

N	V_A [m^3]	V_S [m^3]	W [m]	D [m]	H [m]	S_A [m^2]	P_{atm} [kPa]	t [°C]	ϕ [%]	T_{mid} [s]	L_{eq} [dBA]	L_{Max} [dBA]	L_{Min} [dBA]
1,800	20,321	1,850	37	36.3	14.3	1,156	102	21	40	2.51	27.5	31.6	26

N, number of seats; V_A, audience volume; V_S, stage volume with shell; W, mean width; D, mean depth; H, mean height; S_A, seat surface area; (P_{atm}, t, ϕ), atmospheric pressure, temperature and relative humidity for in situ measurement; T_{mid}, mid-frequency reverberation time; (L_{eq}, L_{Max}, L_{Min}) equivalent, maximum and minimum sound pressure levels for a background measurement period of 3 minutes with the air-conditioning system switched off.

figuration). In the case of opera, it is viable to vary the sound absorption of the overhead drum on which the cover rests (Fig. 1a) by introducing some absorbent cylinders (up to 250 cylinders, 30 cm in diameter and 3.20 m in length) which, without modifying the reflective surfaces near the public, allow the reverberation time of the room to be reduced.

The stage of the theatre is very extensive, measuring 18.5×41 m and is 23 m high up to the flies, and completely configurable according to the performance (Fig. 2a). The latest modifications carried out in the scenic area enable its surface to be increased to 2,400 m^2.

The main surface material inside the hall is wood (plywood on the walls and parquet on the floor) and, together with the wooden structure that covers the room, "the acoustic daisy", combines functionality and aesthetics (Figs. 1 and 2a). These wooden finishings configure a topography of convex shapes and truncated flat terraces that breaks the cylindrical shape and introduces acoustic diffusing elements. The stalls, two lateral surfaces and a terrace at the rear part of the room, are composed of lightweight seats (Fig. 1). The vertical walls enclosing these terraces contribute early lateral reflections towards the central zone of the stalls. In the middle of the ceiling covering the auditorium there is a large glass lamp with convex geometry that favours the diffusion of energy reflected from it.

The latest renovation in the theatre has altered the location of the orchestra as follows: the first four rows of seats have disappeared and the fire curtain now closes the stage (referred to here as the *Symphonic 2* configuration). The orchestra shell is only installed when a choir performs. This measure encourages greater integration of the orchestra in the hall and, according to the staff, this change has been welcomed by many regular users and performers.

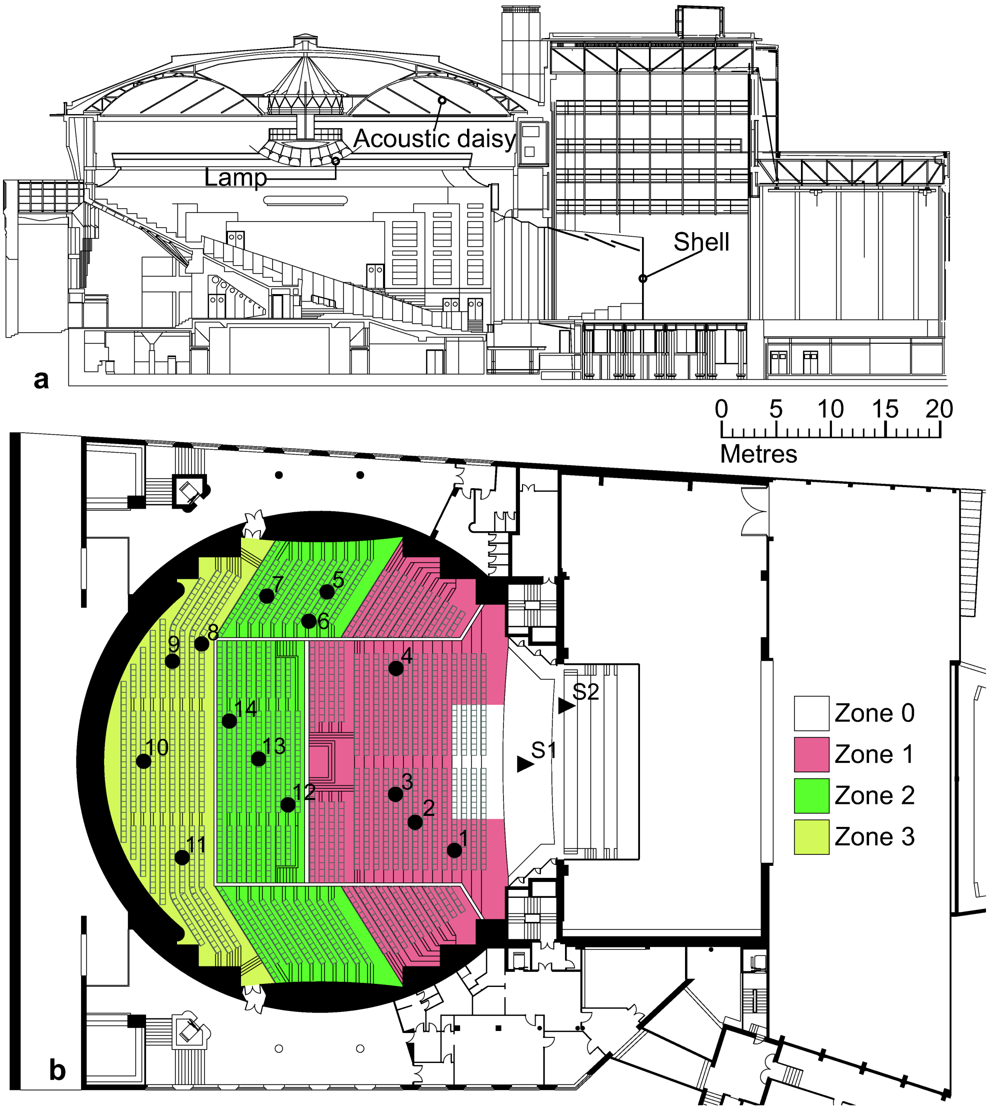

Fig. 2. The Maestranza Theatre: a) longitudinal section with the orchestra shell on the stage; b) ground plan showing the orchestra shell, and the source and receiver positions. The three zones in the audience area are also given.

2.2. Objective measurements

The objective acoustic measurements were carried out in the unoccupied room with the musician instruments on the stage, following the procedures established in the ISO 3382-1 standard. The environmental conditions were monitored during the process (see Table 1).

The monaural and binaural room impulse responses (RIR) were obtained by exciting the room with a sinusoidal sweep signal of 30 s duration running from 16 to 20,000 Hz, generated and analysed by the software 2004 WinMLS via a Digigram VX Pocket v2 soundcard. The dodecahedral omnidirectional source AVM-DO12 from 01 dB with its amplifier Inter M-1000 was placed in two positions on the stage (Fig. 2b) at 1.50 m above the ground. Various types of microphones (with appropriate amplifiers-source signal conditioning, Hearthworks and OPUS 01 dB-Stell) have been used: B&K 4190 omnidirectional 1/2 inch, Multipattern Audio-Technica AT4050/CM5, and an artificial torso HSU type III (Code 1323) from Head Acoustic, located at the height of the head of a sitting person, ∼1.20 m above the ground, in a predetermined number of positions in the seats of the audience (Fig. 2b). The background noise in the hall was recorded by the sound level meter B&K type 2215 for 3 minutes with the air-conditioning equipment offline (Table 1) and remained within the recommended range for performance spaces (Cowan, 2007) even when the system was running.

From these impulse responses, the following acoustic parameters have been obtained for each frequency between 125 Hz and 4,000 Hz and in all positions of the receivers: reverberation time (T_{30}) and early decay time (EDT), to assess the characteristics of the physical and perceived reverberation; sound strength (G), to explore the sound level distribution in the audience area; centre time (T_s), clarity (C_{80}), and definition (D_{50}), as acoustic parameters based on the acoustic energy in terms of early-to-late or early-to-total energy ratios and related with perceived clarity; and the early lateral energy fraction (J_{LF}), the late lateral sound level (L_J), and the early and late interaural cross-correlation coefficients (IACC_E and IACC_L), to study the phenomena of spatial impression in the room. The L_J and IACC_L parameters are not provided by the simulation programme and thus only in the experimental results will they be discussed. Spectral averages of the parameters studied at the reception points were made according to the suggestions of the ISO 3382-1 standard, and for the IACC parameter according to Okano *et al.* (1998) as an arithmetical average of the 500, 1,000 and 2,000 Hz octave bands.

Table 1 shows the most significant geometric, environmental and acoustic data of the hall corresponding to the configuration measured. Other information, concerning the geometric and acoustic stage parameters of the hall, can be found in Girón *et al.* (2010). In the audience area, three zones have been established in terms of spatial distribution of the values of the parameters: 706 seats in Zone 1; 588 seats in Zone 2; and 434 seats in Zone 3. There are 72 seats in Zone 0 in the first rows of the stalls where direct sound predominates, and hence they have been omitted in the set and only occasionally will be considered in the analysis (see ground plan in Fig. 2b).

2.3. Acoustic simulation

The software used is CATT-Acoustic, version 9.0, (Dalenbäck, 2011) which includes the calculation engine TUCT (The Universal Cone Tracer) version 1.0. The underlying theory relies on geometrical acoustics, and TUCT offers three different cone-tracing algorithms for source-receiver echograms and impulse responses (in terms of the objective of the calculations and the acoustic complexity of the enclosure) and one algorithm for audience area mapping. It offers many room acoustics measures and analysis functions for echograms, impulse responses and colour maps as well as direct relative calibrated impulse-response reproduction, and convolution for auralization. The simulated results for each source-receiver pair consist of energy-based 1/1-octave echograms (named E) calculated in the usual way for ray-tracing techniques, and pressure-based B-format and binaural impulse responses (named h).

The software application has proved to be robust both for the prediction of the values of the acoustic parameters and in the generation of binaural impulse responses that can be used in audible simulations (Yang, Hodgson, 2006; 2007). For this type of enclosure, Schroeder's frequency is regarded as the frequency of transition between the zone of modal behaviour and statistical behaviour and can be expressed as $f_s = 2000\sqrt{(T_{30}/V)}$ (Dance, Van Buuren, 2013). In this case, the value of f_S, for the most unfavourable configuration (*Symphonic 2*) is about 22 Hz. It is common practice to consider a value of the transition frequency as $4f_S$ in order to establish a secure limit for the reliability of the calculations by using ray-tracing techniques, which means that from 88 Hz (lower limit of the 125 Hz octave band) the calculations are acceptable. The software itself provides this value in the tuning process of the model.

The great precision is obtained by considering the diffuser ceiling as being constructed from segments of the toroidal dome intercepted by oblique planes (resembling a daisy) as shown in Figs. 1 and 2a. The study encompasses the results with two positions of the omnidirectional source and 14 receiver positions. For the simulation, the algorithm 1 from TUCT, split 1, was used. Figure 3 shows a cut perspective of the three models implemented by SKETCHUP software to be later imported to CATT-Acoustic in order to perform the simulation as shown in the set of Fig. 4. Table 2 shows data for the acoustic simulation models.

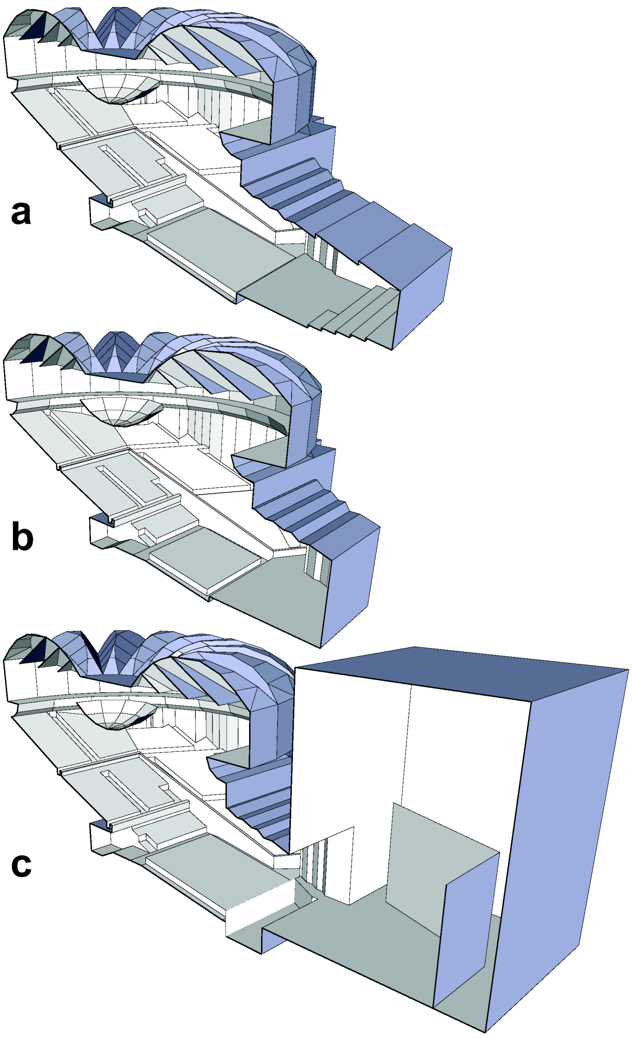

Fig. 3. Cut perspective of the 3D models of the hall implemented by Sketchup for the two symphonic configurations, labelled 1 and 2, and for opera arrangement (a), b), and c), respectively), to be imported to CATT-Acoustic.

The first model (Fig. 4a) is tuned following an iterative process whereby the absorption coefficients of the materials that have greater uncertainty in the literature are adjusted. In this case, these absorption coefficients are of the wooden roof. The iterative process continues until the simulated reverberation times, averaged spatially for each octave band, differ by less than 1 JND (5% for T_{30}), (ISO 3382-1, 2009) from the experimentally measured average values. Although the JND is valid for the spectral mean values of the parameters, it has been accepted for each octave band.

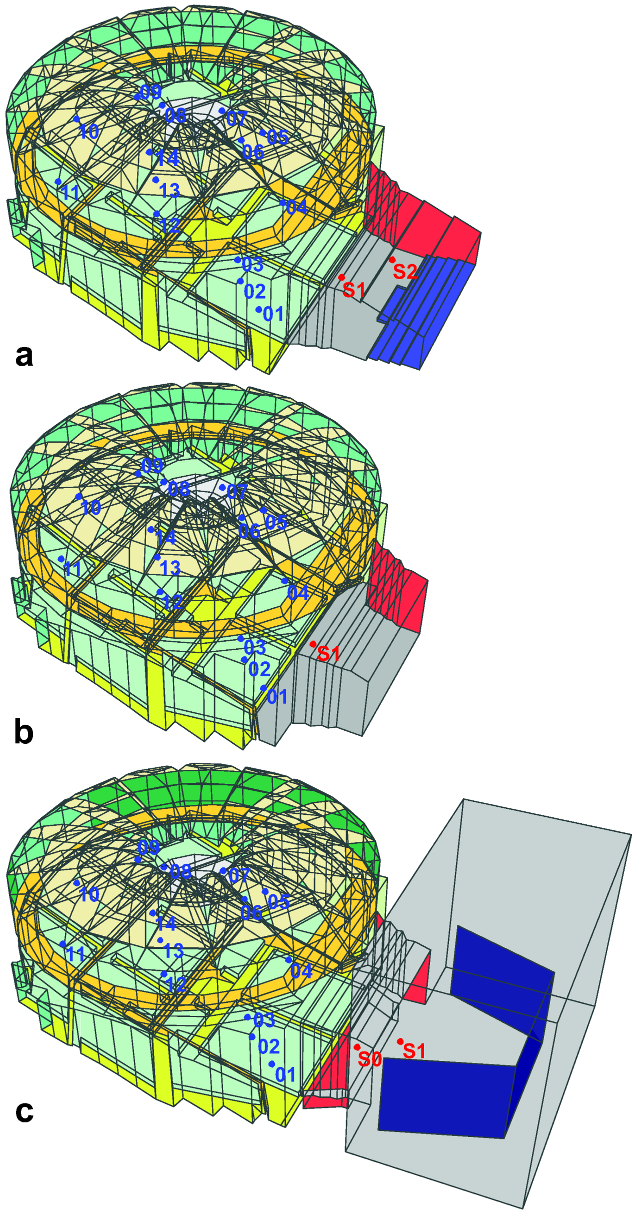

Fig. 4. 3D models of the Maestranza Theatre, showing the source positions, and the receivers: a) for *Symphonic 1* configuration; b) for *Symphonic 2* configuration; and c) for *Opera* configuration.

Table 2. Significant data for the acoustic simulation models.

	Planes	Area [m^2]	Volume [m^3]	N. of rays/cones	IR length
Symphonic 1	793	8,343	20,571		
Symphonic 2	780	7,989	20,027	2,500,000	3.5 s
Opera	787	12,064	33,493		

Table 3 shows the associated absorption and scattering coefficients in the simulations, and the relative area of each material. In the rows corresponding to *Symphonic 2* and *Opera* the change in the area of certain materials is specified with respect to the *Symphonic 1* simulation (see Figs. 4b and 4c).

Table 3. Coefficients of absorption (upper row), and dispersion (lower row) in % for each material, description of the surfaces, and references for the three hall arrangements.

	Material, description, reference	Area [m^2]	Area [%]	Octave bands [Hz] 125	250	500	1 k	2 k	4 k	Colour in Fig. 4
Symphonic 1	Empty seats, Carmen seats[a]	1,146.8	13.7	18	34	48	60	57	53	
				30	40	50	60	70	80	
	Occupied seats, Carmen seats[a]	1,146.8	13.7	33	57	72	74	78	78	
				30	40	50	60	70	80	
	Shell walls and ceiling, 16 mm wood on 40 mm studs[b]	590.3	7.1	18	12	10	9	8	7	
				15	20	25	30	35	40	
	Panel, plywood panelling 1 cm thick[c]	1,134.1	13.6	28	22	15	9	10	7	
				20	30	40	45	50	55	
	Shell platform, wood[b]	150.0	1.8	20	25	35	45	55	65	
				30	40	50	60	70	70	
	Hall ceiling[d], wood (scattering coefficient estimated[e])	3,254.5	39	30	22	13	5	7	6	
				20	25	30	35	40	45	
	Orchestra risers, wood[b]	133.3	1.6	20	25	35	45	55	65	
				30	40	50	60	70	70	
	Lamp, glass[c]	181.4	2.2	19	7	4	3	2	2	
				20	30	40	45	50	55	
	Oculus, (estimated apparent absorption)	54.5	0.7	10	10	10	8	5	4	
	Diffuser lateral wall, wood[c], (scattering coefficient estimated[e])	206.7	2.5	28	22	17	9	10	11	
				20	30	40	50	60	70	
	Hall wall, glaze, plaster[c]	1,100.2	13.2	1	1	1	2	2	2	
				10	10	15	20	25	25	
	Hall floor, wood in 2 layers[b]	391.7	4.7	9	6	5	5	5	4	
				15	20	30	35	40	40	
Symphonic 2	Empty seats	1,059.3	13.2							
	Hall floor	375	4.7							
	Orchestra risers disappear	0	0							
	Stage mouth, curtain firewall, same as shell walls	419	5.2							
	Stage floor, same as shell platform	240.6	3							
	Panel, reduced to	1,096.6	13.8							
Opera	Stage mouth, same as shell wall	281.9	2.3							
	Orchestra pit, same as shell wall	171.5	1.4							
	Panel, reduced to	1,106.5	9.2							
	Hall wall, reduced to	629.7	5.2							
	Opera stage[b]	3,645.7	30.2	18	12	10	9	8	7	
				15	20	25	30	35	40	
	Upstage[f]	307.2	2.5	8	9	10	10	10	10	
				15	20	25	30	35	40	
	Side stage[f]	489.0	4.1	15	20	25	30	35	35	
				15	20	25	30	35	40	
	Cylinders (estimated by the authors)	472.5	3.9	16	40	66	74	82	82	
				20	30	36	50	70	80	

[a] García-BBM S.A (1991), [b] textscVorländer (2008),

[c] Cox and D'Antonio (2009), [d] Absorption adjusted in the iteration

[e] Dalenbäck (2011), [f] Parati *et al.* (2007).

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

3. Results and discussion

It should be clarified, for subsequent discussion, that the experimental measurements were carried out in the hall exclusively with the orchestral shell on the stage. These measurements are compared with the computer simulation for the same scenario for validation purposes. In this comparison, the average values for the two positions of the source (S1 and S2 in Figs. 2b and 4a) are used. The configuration *Symphonic 2* is exclusively studied by computer simulation which takes place from only one source position (S1 in Fig. 4b). The corresponding arrangement for *Opera* places the source in the orchestra pit and alternatively on the stage (labelled S0 and S1, respectively, in Fig. 4c), this configuration is also studied exclusively by computer simulation and each source position is discussed individually.

3.1. Symphonic 1 configuration

The virtual acoustic research of the theatre began by implementing a geometric control model with only 409 planes, which was studied from only the position of the sound source S1, and which simplified the actual segmented ceiling of the room by assuming a flat roof. In the tuning process, based on T_{30} values, both absorption and scattering coefficients of the ceiling were adjusted, although the other parameters showed significant differences from those measured for spectral and spatial behaviour. Hence a refinement was made in order to incorporate greater detail in the definition of the diffusing surface of the roof.

An acoustic simulation, better tuned to the experimental results of acoustic quality parameters, is performed with the 3D model as shown in Figs. 3 and 4 which approaches “the acoustic daisy” of the ceiling, as the model shows. In Fig. 5 the results for all acoustic parameters studied are presented in their spatial mean values in each octave band, corresponding to the on-site measured results, and to simulated results both for the unoccupied theatre in exactly the same way as the experimental measurements were conducted and for 100% occupancy in the theatre. Spatial averages

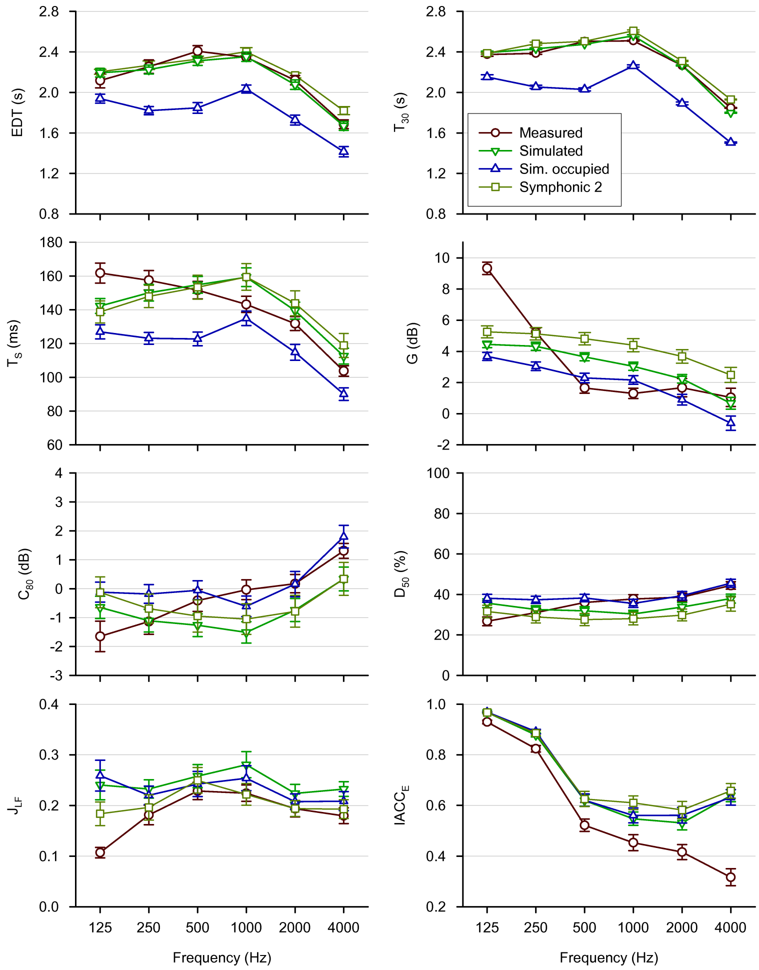

Fig. 5. Spectral values of the various acoustic parameters studied, averaged over the two source positions, corresponding to experimental measurements, and to acoustic simulations for the unoccupied hall and with 100% occupancy, all for *Symphonic 1* configuration. The simulated results for the *Symphonic 2* configuration (only for S1) are also shown. The magnitude of the vertical bars, equal to the standard error, quantifies the spatial dispersion.

correspond to the results obtained with the two source positions. For reasons of space, the detailed study of the separate results for each source has been omitted both for measured and simulated values. In this case, changes in parameters are very small and are mainly found at low frequencies.

In this plotted graph, it can be noted that the only differences in the mean values appear at low frequencies in every room acoustic metric except those which qualify reverberation, and a certain deviation from the trend at high frequencies for the parameter IACC_E. The presence of the public supposes a noticeable change in the parameters of reverberation, EDT and T_{30} (about 0.35 less on average at mid-frequencies), and in those of music sound quality, Ts (a diminution around 25 ms) and C_{80} index (an increment of about 1 dB); the perceived level quantified in terms of G diminishes by approximately 1 dB. The incidence on the speech intelligibility parameter, D_{50} is almost imperceptible and even smaller in the spatial impression parameters such as J_{LF} and IACC_E. The spatial dispersion is quantified in terms of standard errors, and is in all cases small except for low frequencies in certain acoustic parameters. In Subsec. 3.3 single values of the parameters in the room for the various configurations and experimental and simulated results are compared.

The information provided in the graph above is completed by the spatial information in each receiver of the differences between measured and simulated values of the parameters (spectrally averaged at each receiver in accordance with ISO and other authors: ISO 3382-1 (2009), Okano *et al.* (1998), Vorländer (2008) (see Table 4) that are shown in the bar chart of Fig. 6. These differences are studied in terms of accepted JNDs: the minimum perceptible variation of the value of each parameter, which is shown in Table 4, in order to be related with the differences in perceived sensations.

Calculations show that, in all acoustic parameters and most receptors, differences fall within the range of ±2 JND, whereby the greatest differences occur in the receivers next to the sound sources, and also show how, for parameters which correspond to spatial impression, the simulation overestimates the apparent source width (assessed in terms of J_{LF}, and IACC_E) compared to experimental results in most of the receivers.

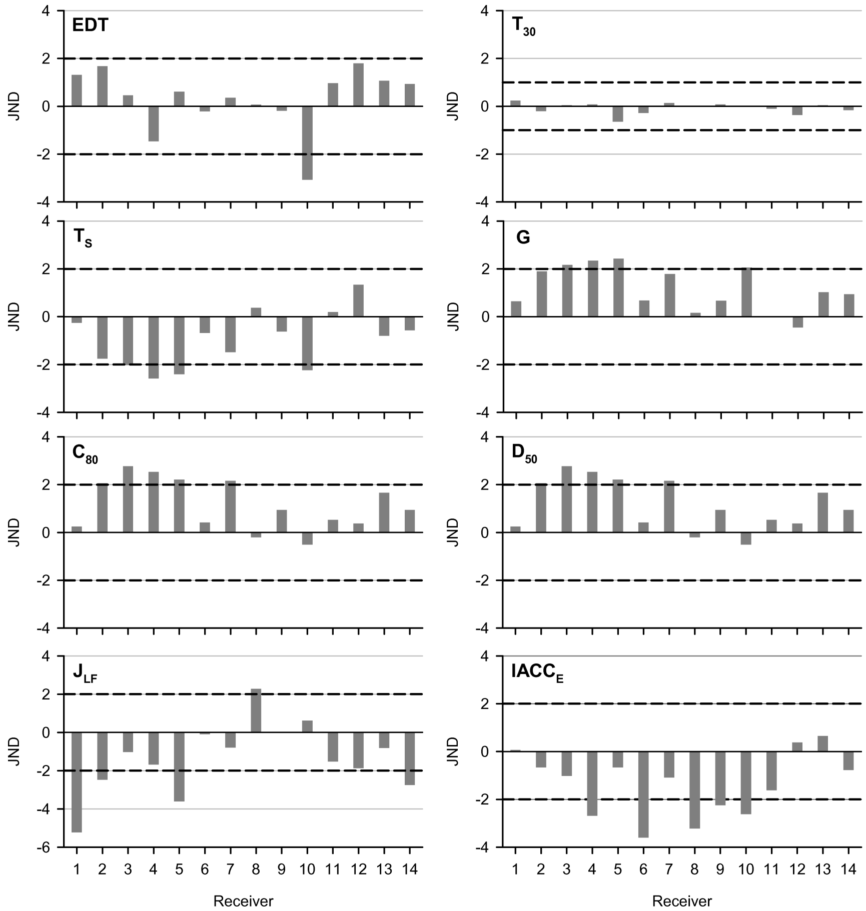

Fig. 6. Differences of spectral average values between measured and simulated results (for the two source positions) in terms of JND for each acoustic parameter studied at the various reception points. Horizontal dashed lines show the ±2 JND interval for each parameter, except for T_{30} which is ±1 JND interval.

Table 4. Bands used for spectral averaged values and just noticeable differences (JND) of subjective room acoustical impressions.

Subjective listener aspect	Acoustic parameter	Frequency range for average[a] [Hz]	JND
Subjective level of sound	G [dB]	500–1000	1 dB
Perceived reverberance	EDT [s]	500–1000	5%
Perceived clarity of sound	C_{80} [dB]	500–1000	1 dB
	D_{50}	500–1000	5
	T_S [ms]	500–1000	10 ms
Apparent source width (ASW)	J_{LF}	125–1000	0.05
	IACC_E	500–2000	0.075
Listener envelopment (LEV)	L_J [dB]	125–1000	1 dB

[a] Arithmetic average except for L_J which is energy averaged.

Moreover, in the plotted graph of Fig. 7, the differences between experimental and simulated results for each source-receiver pair, in terms of JNDs, are presented for EDT and C_{80} parameters in the six octave bands. Data shows that for both parameters 69.6% of values present differences up to ±2 JND at all frequencies; the result that is extended to 81.25% of receivers if the range ±2.5 JND is considered. For differences up to ±3 JND, the percentage of receivers for both parameters would be 88.4%.

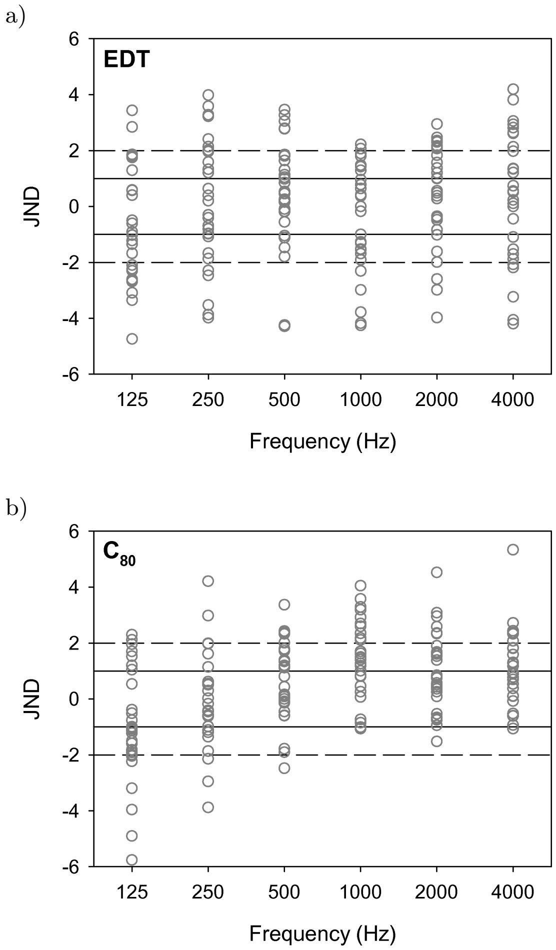

Fig. 7. Differences between measured and simulated results in terms of JND for EDT parameter (a); and for C_{80} parameter (b) at the various source-receiver pairs for each octave band. Horizontal dashed lines show the ± 2JND interval for each parameter.

In this regard, Fig. 8 also shows the correlation of the measured results for the two positions of the sound source on the stage and the simulated results for the parameters of musical quality C_{80} and T_S, the sound level G, and intelligibility of the speech D_{50}, in the enclosure frequency averaged according to ISO 3382-1 (2009), as a function of source-receiver distance. In addition, for the sake of comparison, the predicted values calculated from Barron's revised theory for concert halls (Barron, Lee, 1988) and other proportionate spaces (Chiles, Barron, 2004) have been included where only the total hall volume (hall plus stage, $V = 20,571$ m^3) and reverberation time averaged at mid-frequencies of 500 and 1000 Hz octave band ($T_{\mathrm{mid}} = 2.51$ s, Table 1) are needed. It can be seen how Barron's theoretical model fits qualitatively to the behaviour of the parameters against source-receiver distance except the G parameter, where there are differences around 2–3 dB for distances greater than 10 m. The good agreement of the remaining acoustic parameters and the fact that the accuracy of G measurements depends on the accuracy with which the power level of the sound source can be determined, or, in other words, with which the measurement system can be calibrated (Hak *et al.*, 2010), support the conclusion that the difference is related to errors in the reference level, since these reference values were obtained from the registered IR on site.

All these results indicate that the computational model reliably represents the sound field of the enclosure by evaluating both the spatial average of each parameter at the various octave bands and their spectral average value calculated at each reception point.

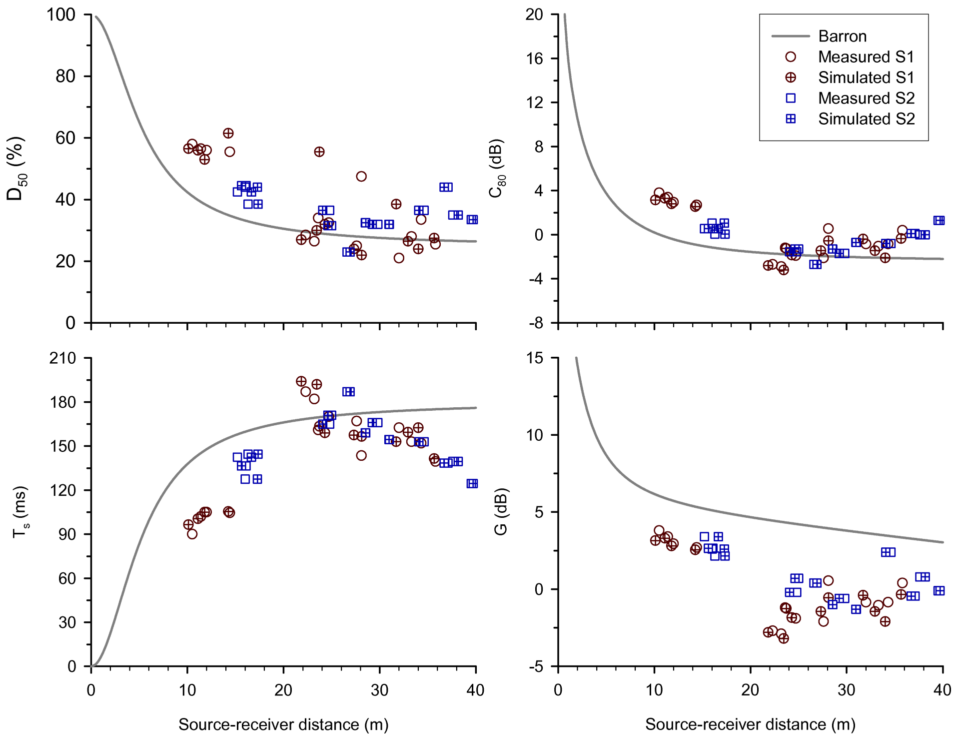

Fig. 8. Dependence on source-receiver distance of measured and simulated values, for *Symphonic 1* arrangement, for the two source positions, and for D_{50}, C_{80}, T_S and G parameters, where Barron's theoretical predictions are also shown.

3.2. Symphonic 2 configuration

This configuration corresponds to the latest remodelling undertaken in recent years to perform symphonic concerts in the hall (Fig. 4b). This provision for the orchestra on the stage was set up subsequent to this acoustic measurement campaign.

In order to quantify, through simulation, the effect of this intervention on the perception of the audience in terms of the values of the acoustic parameters, the position-averaged results in the various octave bands for comparison with the other arrangement studied so far are included in Fig. 5. The results show a great similarity with the results of the simulation *Symphonic 1*. An increased sound level at all frequencies is only slightly perceptible as is a certain decrease in the intelligibility of speech D_{50} and in the apparent source width quantified by J_{LF}.

The values, depicted in Fig. 9, are itemized in each receiver by considering the differences in the results of frequency averaging parameters for both symphonic configurations (*Symphonic 1 – Symphonic 2*), and these differences are quantified in terms of JNDs. These results indicate a slight increase in reverberation, valued in terms of EDT and T_{30}, of the sound level in terms of G, and a decrease in speech intelligibility in most receivers as well as a decrease in apparent source width in terms of a J_{LF} decrease or an increase in the IACC_E parameter for the *Symphonic 2* relative to configuration *Symphonic 1*. In all cases, the differences reached for the majority of receivers are found within the range of ±2 JND for all acoustic parameters.

It should be mentioned that the conditions may change more drastically for those musicians in the orchestra who can better perceive the room response to their music played in configuration *Symphonic 2*. The acoustic parameters of the stage support that could constitute descriptors of this change will be the subject of future work.

3.3. Opera configuration

The results of various simulations carried out in the hall, considering opera settings, displayed in Fig. 4c (absorbent cylinders on the drum, the complete stage up to the flies with sets, and the pit for the orchestra) are presented in Fig. 10 for all the acoustic parameters studied. From their analysis, the following can be highlighted:

- If the absorbent cylinders are not deployed on the drum of the roof dome, then the acoustic conditions are more unfavourable in terms of an increase in EDT at all frequencies. There is also an increment, although smaller than before, in T_{30}, a remarkable increase in T_S, and an appreciable decrease in C_{80} and D_{50} (especially the latter at 1,000 and 2,000 Hz), but no special change in G nor in the parameters that describe the apparent source width.

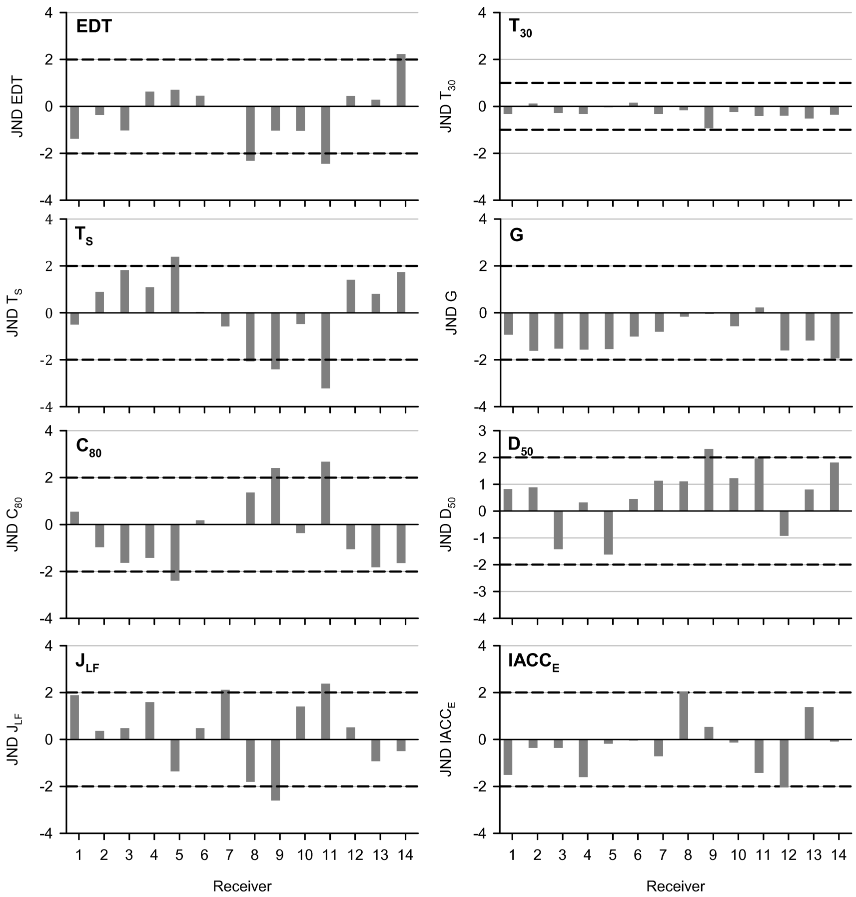

Fig. 9. Differences of spectral average values between the simulated results for *Symphonic 1* (with shell configuration) and simulated results for *Symphonic 2* (with backdrop) in terms of JND for each acoustic parameter studied at the various reception points. Horizontal dashed lines show the ±2 JND interval for each parameter, except for T_{30} which is ±1 JND interval.

- The best sound conditions occur when the source is in the pit with the cylinders deployed and in empty conditions, in relation to when the source is on the stage, since with a certain rise of the sound level in terms of G in the first case, there is also a diminution in EDT and T_{30}, an increase in C_{80}, and even greater increase in D_{50}. However, the conditions for the apparent source width improve with the sound source on the stage (soloist) in terms of the J_{LF} parameter.
- Both when the orchestra is in the pit and when the source is on the stage, the presence of the public in the hall represents an improvement in the acoustics, since although 100% occupancy results in a small reduction of the sound level in terms of G, there remains a notable increase in C_{80} and D_{50}, and a decrement in the EDT and T_S parameters.
- A slight decrease in EDT results regarding reverberation times T_{30} at all frequencies is produced; this decrease is of greater magnitude than that obtained in the configurations *Symphonic 1* and 2 (see Fig. 5). The reason lies in the large increase in the volume of the stage, without the provision of an increment of early reflections to the audience area but of an increase of reverberant energy, resulting in differences greater than 0.5 s.

As a summary of the above, in relation to the three configurations of the hall and stage analysed, Table 5 shows the value of all single-number acoustic parameters studied by actual measurement or simulation as well as position-averaged and spectrally averaged suggested values of objective room acoustic parameters in unoccupied halls for classical music, from Gade (2007). The D_{50} values greater than 35 correspond to syllable intelligibility above 80%, according to Kuttruff (2009), and for T_S the desirable interval for music is provided by Hoffmeier (1996).

It is assumed that the seats are highly absorptive, and hence, when the hall is fully occupied with musicians and audience, the T_{30} values are reduced by no more than 0.2 s. The upper limit of 2.4 s should be regarded as largely suitable for the terraced arena or directed reflected sequence halls with large volumes per seat, whereas 2.0 s is more suitable for shoe-box-shaped halls.

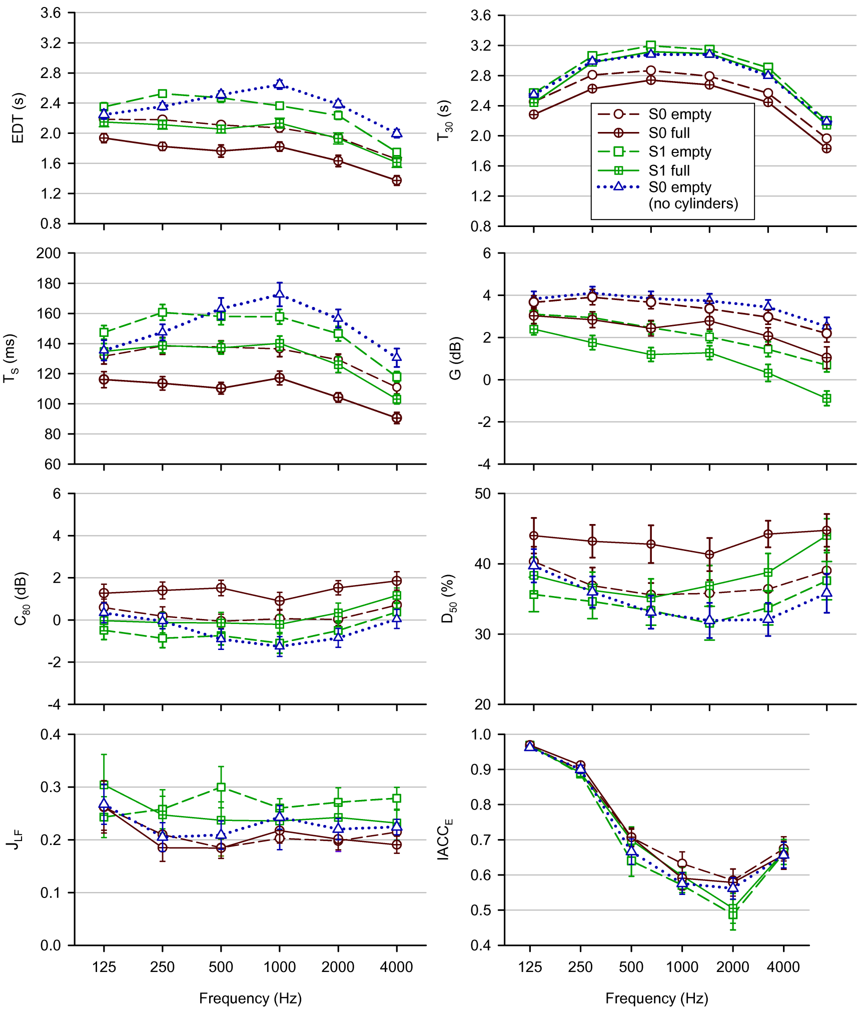

Fig. 10. Spectral values of the acoustic parameters for *Opera* configuration with the source in the pit, S0, and on the stage, S1, and in the both cases for an empty and occupied hall. The results with the source in the pit without the absorbent cylinders are also shown. The magnitude of the vertical bars, equal to the standard error, quantifies the spatial dispersion.

Table 5. Position-averaged spectrally averaged parameters for measured and simulated conditions in each arrangement of the hall. Suggested values from the literature are also included in the last column.

	Symphonic 1			*Symphonic 2*	*Opera*				Suggested
	Experimental	Simulated empty	Simulated full	Simulated empty	S0 pit empty	S0 pit full	S1 stage empty	S1 stage full	
V/N	–	20,571[a]/1,800		20,027[a]/1,656	33,493[a]/1,800				25,000/2,000
EDT [s]	2.36	2.33	1.94	2.37	2.09	1.79	2.42	2.09	2.2
T_{30} [s]	2.51	2.52	2.15	2.56	2.83	2.71	3.17	3.10	2.0–2.4 (Classical) 1.4–1.8 (Opera)
T_S [ms]	148.4	157.1	128.8	156.4	137.1	113.8	157.9	138.7	70–150
C_{80} [dB]	−0.36	−1.39	−0.33	−1.0	0.00	1.21	−0.91	−0.17	−1
D_{50}	37.0	31.0	37.0	27.9	35.7	42.1	32.5	36.0	>35
G [dB]	1.67	3.35	2.23	4.60	3.52	2.61	2.25	1.24	3
J_{LF}	0.19	0.25	0.24	0.21	0.21	0.21	0.27	0.26	0.20–0.25
1-IACC$_E$	0.53	0.43	0.42	0.39	0.36	0.37	0.43	0.40	0.3–1

[a] Volumes are estimated by the simulation software.

For opera, one may aim towards the same desired values of EDT, C_{80} and G, for symphonic halls; but the goal for the reverberation time is normally set vaguely lower, at 1.4–1.8 s, in order to obtain a certain intelligibility of the lyrics and to render the sound of breaks in the more dramatic music (Gade, 2007).

The comparison of the results for the two symphonic configurations corroborates the comments of the previous two sections. In relation to the change in reverberation time when the hall is fully occupied to when it is empty, this comparison of results indicates that seats in the hall are relatively light since the reverberation time decreases by approximately 0.10–0.38 s according to the simulation when the room is occupied. The configuration *Symphonic 2* also equals *Symphonic 1* in terms of EDT, T_{30}, with a small decrease in D_{50} and an increase in sound levels measured by G, as discussed in the previous subsection.

The decrease in EDT values relative to T_{30} values for all the simulations carried out in the *Opera* configuration (between 0.74 s and 1.01 s) is again remarkable here, although it has no place in the two symphonic configurations studied (differences between 0.19 s and 0.21 s). This is attributable to the large increase in volume for the opera stage with no significant increase of early reflections, but an increase in reverberant energy in the audience area, quantified by the T_{30} parameter.

Although a value of T_{30} between 1.4–1.8 s for opera is desirable, the large increase in volume of the stage up to the flies in this room causes T_{30} to lengthen, despite the effect of the absorbing cylinders deployed and the public. Likewise, the large increase in volume of the room when the whole stage is included takes it outside the proposed range of V/N. In addition, it should be noted that the estimation of absorption for the stage sets are conservative since they are highly dependent on the type of scene set in each case.

3.4. Acoustic zones in the audience area: simulation mappings

It is customary for managers of auditoria to establish various audience zones, according to the performance, and assign different prices. This zoning process is usually carried out based on visual criteria and proximity to the stage. This information is available on the MAESTRANZA THEATRE site. In this context, there is the possibility of identifying acoustic differences between the audience zones by using the mapping possibilities offered by the simulation software.

The method is based on a visual inspection of the mappings at 1 kHz octave band of the various parameters, and on the selection of the parameter that can identify a suitable zone discrimination. Thereafter, the behaviour of the remaining parameters in each identified zone can be characterized. The area close to the sound source has been removed from the analysis since the prevalence of direct sound in this area could affect the analyses of mappings. In this case, the T_S parameter has been utilized to identify the three zones shown in Fig. 2b.

This zone identification is spectrally analysed from experimental measures for the *Symphonic 1* configuration and finally characterised by using unique indexes, according to the proposal of Ando (1985) and Beranek (1996), for the qualification of the acoustics of auditoria.

Advantage has been taken of the mapping capability of the software used, by means of the corresponding algorithm, in order to both identify the zones as marked on the ground plan of Fig. 2b and to show them in greater detail. The mapping is configured with a grid (step) of 0.5 m and of height 0.25 m above the planes of the audience, elevated 0.85 m above the ground, which means that the centre of the receivers is placed approximately at the ear height of a seated person. A truncated time of 3,378 ms and 1,000,000 rays are used. For the sake of space, simulated mappings are chosen for the 1 kHz octave band, for the most significant acoustic parameters (EDT, T_S, C_{80}, and J_{LF}), displayed in Fig. 11 for each stage and hall configuration. Beside each map, the statistical distribution of the corresponding values for each zone is shown, and that of the whole room (excluding Zone 0, see Fig. 2b). The amplitude of the intervals (bin range) in each horizontal axis is chosen as equal to half the JND of each parameter, and the percentages of the vertical axis for each zone are calculated in relation to the total receptors evaluated in the mapping (2,977, 2,695 and 2,976 respectively for each hall configuration) for a visual display of the contribution of each zone to the total distribution. Table 6 summarizes the characteristic data of the zones from the simulation mappings: the average values and the evaluation of the spatial dispersion in each zone, expressed by the standard deviations at 1 kHz octave band for each hall configuration.

In general, the ranges of the distribution of the parameter values for Zone 1 are broader than for Zone 2 and Zone 3, as shown by the maps and the statistical distributions of Figs. 11, and by the largest standard deviation values of Table 6, and by the most appropriate value of the acoustic parameters. Distributions of Zones 2 and 3 are similar but with a certain shift: with the maximum of the distribution and more appropriate values of the acoustic parameters in Zone 3 than in Zone 2, for the three studied configurations: EDT and T_S values are higher for Zone 2, while for C_{80}, the values of Zone 3 are higher than those of Zone 2. Finally, the distribution of the values of the parameter related to the sense of spatiality, J_{LF}, presents behaviour of a more complex nature and only the distribution of Zone 3 shows more uniformity and higher values of this parameter in all zones.

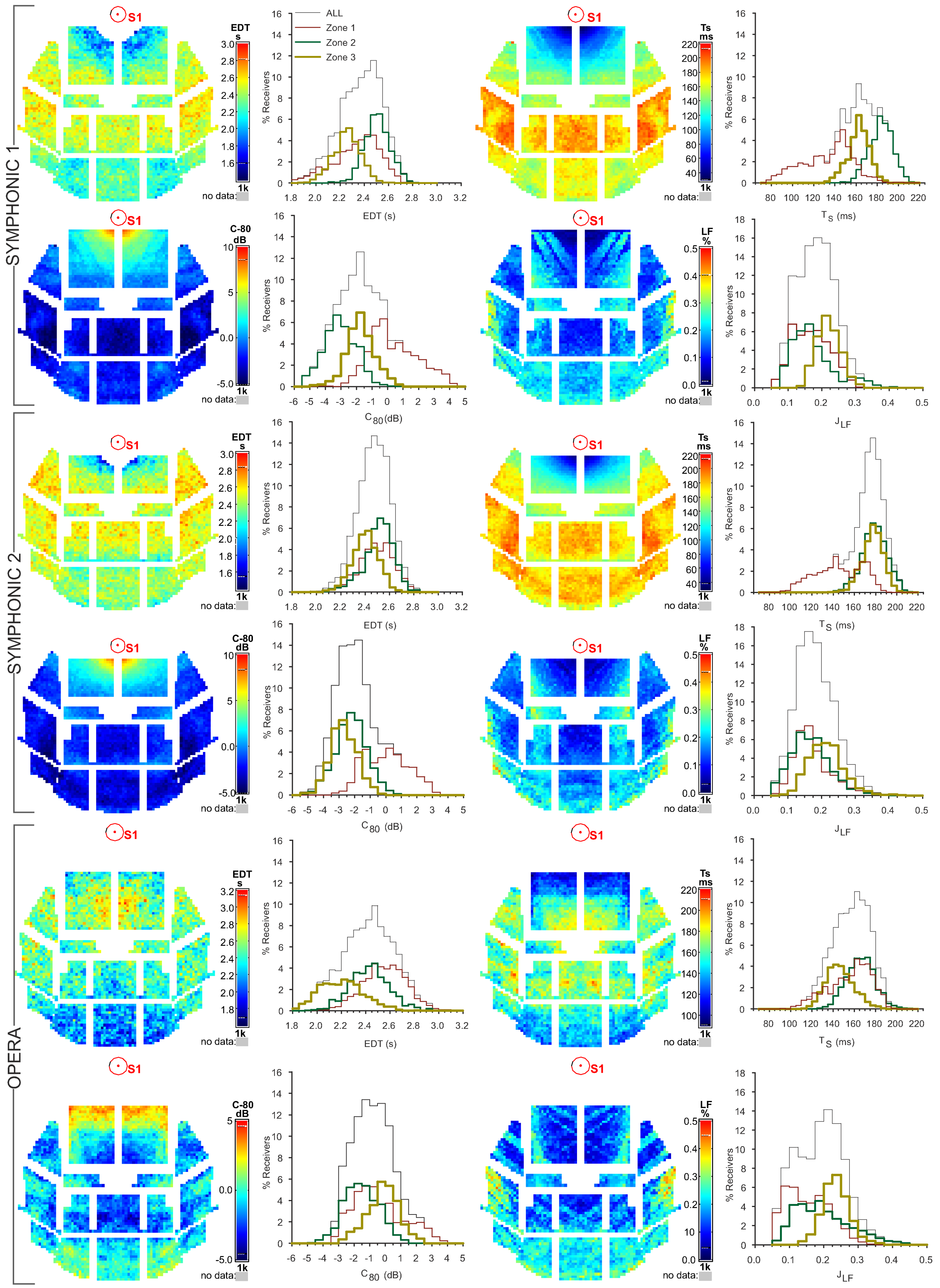

Fig. 11. Spatial distribution maps at 1 kHz, of EDT, T_S, C_{80}, and J_{LF} parameters in the three configurations of the theatre: *Symphonic 1*, *Symphonic 2*, and *Opera*; and their statistical distribution in each zone and in the whole hall (without Zone 0).

Table 6. Average values and standard deviation (at 1 kHz octave band) to evaluate the spatial dispersion for each parameter and zone from the simulation mappings. The rows labelled "All" exclude the receptors of Zone 0 (see Fig. 2b).

	Zones	Receptors	Values	EDT [s]	T_S [ms]	C_{80} [dB]	J_{LF}
Symphonic 1	Zone 1	1,176	Av. value	2.33	132.9	0.44	0.17
			Std. dev.	0.19	23.5	1.54	0.05
	Zone 2	989	Av. value	2.50	183.6	−3.06	0.17
			Std. dev.	0.10	11.1	1.00	0.06
	Zone 3	812	Av. value	2.25	162.3	−1.74	0.22
			Std. dev.	0.11	10.0	0.91	0.03
	All	2,977	Av. value	2.36	157.7	−1.32	0.18
			Std. dev.	0.18	27.5	1.94	0.06
Symphonic 2	Zone 1	876	Av. value	2.48	145.4	0.04	0.17
			Std. dev.	0.14	22.2	1.41	0.05
	Zone 2	1,020	Av. value	2.50	178.8	−2.21	0.17
			Std. dev.	0.13	11.9	1.00	0.06
	Zone 3	799	Av. value	2.40	177.1	2.69	0.21
			Std. dev.	0.11	10.0	0.85	0.05
	All	2,695	Av. value	2.47	167.4	−1.62	0.18
			Std. dev.	0.13	21.9	1.62	0.06
Opera	Zone 1	1,176	Av. value	2.55	155.8	−0.44	0.15
			Std. dev.	0.18	20.0	1.61	0.06
	Zone 2	989	Av. value	2.43	166.0	−1.51	0.20
			Std. dev.	0.16	13.25	1.09	0.08
	Zone 3	811	Av. value	2.20	146.6	−0.16	0.24
			Std. dev.	0.18	13.3	1.01	0.04
	All	2,976	Av. value	2.41	156.7	−0.44	0.19
			Std. dev.	0.22	17.9	1.62	0.07

In order to corroborate these facts, for *Symphonic 1* configuration, in Fig. 12, the experimental spectral results (spatial averages) for the 10 acoustic parameters studied are depicted and averaged for the receptors in each zone of the audience area (for the values obtained with the two source positions) as marked on the ground plan of Fig. 2b. Results show that, with the exception of reverberation time which remains highly uniform throughout the performance space at all frequencies, all the remaining parameters present appreciable changes when moving from one zone to another.

In particular, the reverberation perceived, valued by EDT, shows the shortest values for Zone 3 and the longest for Zone 2, while those of Zone 1 lie somewhere between these two values with differences of approximately 0.2 s. Zone 1 shows appropriate values of the parameters that assess the clarity and the definition; with respect to Zone 2, there is a decrease of Ts values of the order of 40 ms at medium frequencies and an increase of 2 dB for C_{80} and of 35% for D_{50}; while Zone 3 presents intermediate values. Zone 1 also has the highest sound level, exceeding, at medium frequencies, those of Zone 3 by about 2 dB, and those of Zone 2 by about 3 dB. This, in addition to the fact that the spatial dispersion in each zone is small, means that the sound level is very uniform, for all frequencies, in most of the audience area. However, for the apparent source width, as assessed by acoustic parameters J_{LF} and 1-IACC$_E$, seats of Zone 3, the furthest from the stage, are those that have the highest number of early lateral reflections. There is also a noticeable effect from the vertical walls of Zone 1 (see Fig. 1a) that facilitate lateral reflections on a portion of Zone 1. In relation to the sense of music envelopment, as qualified through the late lateral sound level L_J, and 1-IACC$_L$; L_J detects a higher value (of approximately 1 dB at medium frequencies) in Zone 1, although 1-IACC$_L$ discriminates less and shows a very similar value for all three zones at all frequencies.

As a complement to the results of the simulation mappings of Fig. 11 and the spectral behaviour of the zones shown in Fig. 12, an objective assessment by a single numerical value, proposed by Ando (1985), adapted by Beranek (1996), and based on numer-

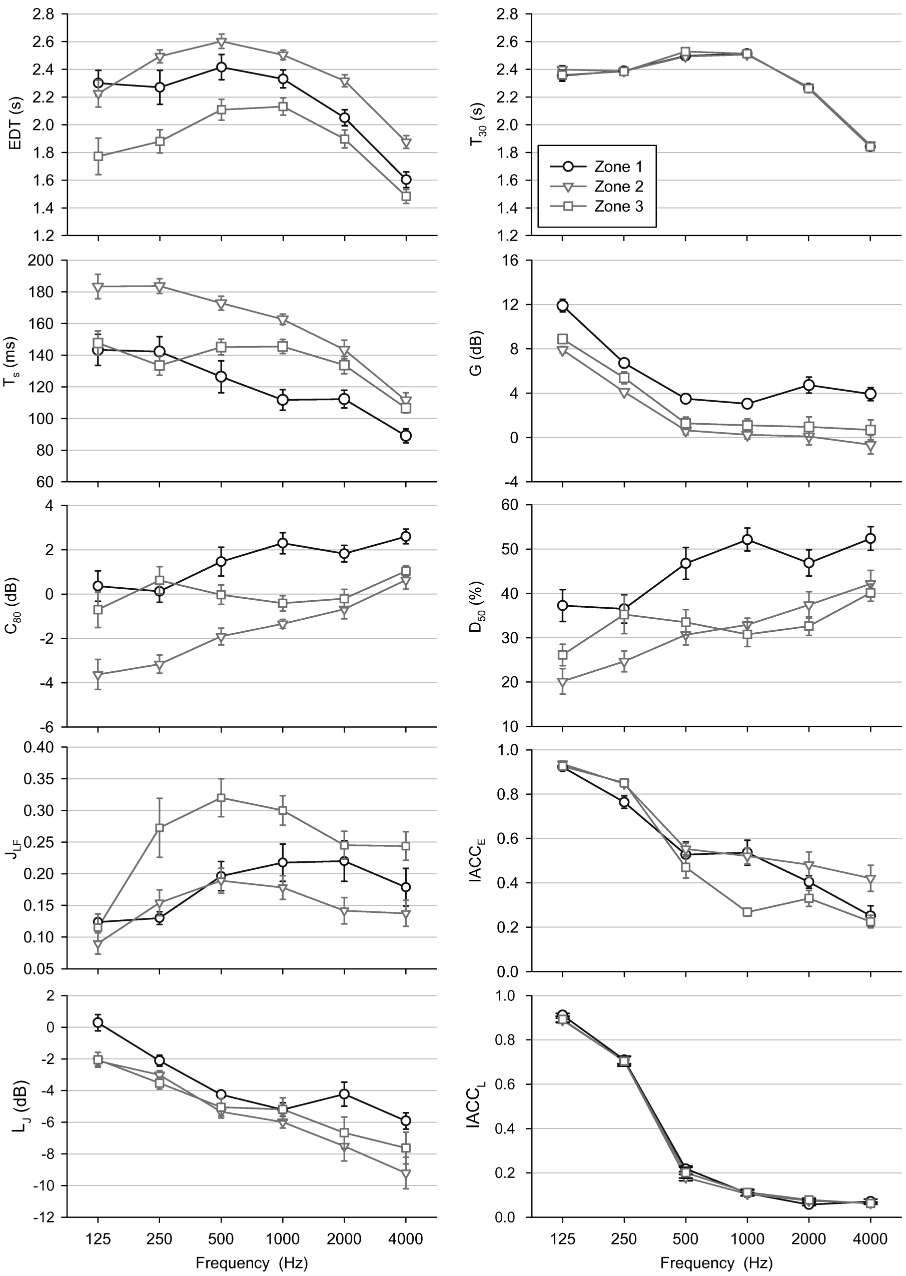

Fig. 12. Spectral results of the measured parameters in the three Zones 1, 2, and 3 in the audience area. The magnitude of the vertical bars, equal to the standard error, quantifies the spatial dispersion.

ous psychoacoustic experiments, has been carried out. For the assessment, Ando considered the four independent acoustic parameters: 1-IACC$_E$; ITDG (initial time delay gap), defined as the time at which the first reflection reaches the receiver after the direct sound; G_{mid}; and EDT$_{mid}$. Beranek, on the other hand, introduces two other orthogonal parameters: Bass Ratio, $BR = \left(T_{30}^{125\text{ Hz}} + T_{30}^{250\text{ Hz}}\right) / \left(T_{30}^{500\text{ Hz}} + T_{30}^{1\text{ kHz}}\right)$; and the Surface Diffusivity Index, SDI, which is determined through visual inspection of the room in order to ascertain the degree of irregularity of the side walls and the ceiling, and to assign different weights to these surfaces.

Table 7 depicts the results of these acoustic parameters in the three zones of the audience area, and the results of each of the six weights S_i and the final numerical values S, representative of the acoustic quality of each zone (the more negative the coefficient, the worse the acoustics of the hall). Results show once again that, both from Beranek's and Ando's models, the best valuation is first for Zone 1, then Zone 3, and finally for Zone 2. When the whole theatre in conjunction is considered, then the overall objective coefficients are very similar to those of Zone 1, although they remain slightly higher.

Table 7. Values of each acoustic parameter and their corresponding S_i factor, for each zone and for the whole hall, in order to determine the global factors from Beranek's and Ando's models.

Parameter/Factor	Zone-1		Zone-2		Zone-3		Hall	
	Parameter value	Factor value	Parameter value	Factor value	Parameter value	Factor value	Parameter value	Factor value
1-$IACC_E$/S_1	0.51	−0.41	0.48	−0.46	0.64	−0.25	0.54	−0.37
ITDG (ms)/S_2	31	−0.13	37	−0.22	51	−0.4	37	−0.21
G_{mid} (dB)/S_3	3.28	−0.04	0.45	−0.27	1.2	−0.2	1.47	−0.17
EDT_{mid} (s)/S_4	2.37	−0.04	2.55	−0.17	2.12	0	2.38	−0.04
BR/S_5	0.95	−0.15	0.96	−0.13	0.94	−0.16	0.95	−0.15
SDI/S_6	0.7	−0.06	0.7	−0.06	0.7	−0.06	0.7	−0.06
Beranek $S_B = \sum_{i=1}^{6} S_i$		−0.83		−1.31		−1.07		−1.00
Ando $S_A = \sum_{i=1}^{4} S_i$		−0.62		−1.12		−0.85		−0.79

4. Conclusions

This paper describes and applies a methodology to quantify the properties of the sound field in a performance venue in terms of those commonly accepted acoustic parameters in room acoustics that relate to the sensations perceived by the audience. To this end, a 3D geometric model of the room has been created. This demands the detailed introduction of its segmented ceiling, and has been adapted geometrically and acoustically to three configurations of the room and stage which are commonly used in the venue. The first case corresponds to the symphonic configuration available to the theatre when the acoustic measurements on site are performed (with orchestral shell). This configuration constitutes the basis for the validation of the model. The second case is a new configuration for the orchestra without shell which brings the stage forward; this arrangement has been implemented in recent years in the theatre for symphonic concert use of the hall. The third configuration for opera and ballet involves: placing the orchestra in the pit; including the total box stage up to the flies with sets; and deploying the absorbent cylinders on the drum supporting the toroidal dome.

The first case is that which has served to iteratively adjust the absorption coefficients of the segmented wooden ceiling of the room so that spatially averaged reverberation times in both simulated and measured cases remain very similar (differences smaller than 5% in all octave bands). Experimental results have been compared with the predictions of the virtual model both for the spatial averages in its spectral behaviour of all studied parameters that quantify the sensation perceived by the audience and which are provided by the simulation software, and for the values in each spectrally averaged receiver according to consensual suggestions in room acoustics. The study of differences in values of these last two sets concluded that these differences are smaller than ±2 JND in almost all receivers, except for the $IACC_E$ binaural parameter, which nevertheless represents an acceptable degree of accuracy in these processes of simulation.

The study based on source-receiver distances also confirms the very good agreement of the experimental results and the simulation for the two positions of the source under study and their suitability for the theoretical model proposed by Barron. The virtual model has also analysed the effect of the inclusion of 100% of the public in the room, since in such a situation it is unfeasible to carry out experimental measurements. The analysis shows how this intervention provides substantial positive changes in the parameters related to reverberation, both physically (T_{30}), and perceived (EDT), and for the parameters related to clarity, especially in T_S; whereby there is a certain improvement in C_{80} and D_{50}. However there is a little impact on the parameters of the spatial impression descriptors. The perceived level, measured in terms of factor G, decreases slightly as would be expected.

Once validated, the virtual model is modified to analyse the sound field perceived by the audience for configuration *Symphonic 2* which is studied exclusively by simulation and corresponds to the current provision in the theatre. The results show that this provision fails to lead to substantial changes in the acoustic parameters except for the sound strength G, for which an increase in the audience area at all frequencies can be observed, due to the further integration of the orchestra in the room. The differences between the two symphonic configurations in terms of JNDs of the acoustic parameters studied are small (< ±2 JND). For future work, a study of the possible change of stage parameters is proposed in order to assess the impact of this reform of the orchestra position on the perception of performers.

Again, the model was modified to opera settings and the results show that the insertion of the absorbent cylinders on the drum offers remarkable and positive changes in the acoustic conditions of the audience area for the perception of the performance. These results also show that the best acoustic conditions alter in relation to which parameter is studied, to the location of the source in either the pit or on the stage, and to whether the room is unoccupied or fully occupied. In all cases, the variations in the reverberation time and the early lateral reflected acoustic energy, which value the apparent source width, remain low with regard to changes in the degree of occupation and source location, although changes are more noticeable in the parameters which evaluate the perceived reverberation (EDT), clarity and definition (C_{80}, D_{50}, and T_S), and the perceived level assessed in terms of sound strength (G).

The last part of the work has shown that it is possible to establish three acoustically distinct zones in the audience area in terms of the values of the experimentally measured parameters and the simulation mappings, for the three configurations of stage and hall, and through the histogram of statistical distribution which accompanies each map. Finally, an analysis of the objective assessment is tackled of the various established zones by using a unique numerical value from Beranek's and Ando's models. All these different methodologies confirm that Zone 1 has the highest evaluation, followed by Zone 3, and finally by Zone 2.

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