Acoustical prediction in some Italian theatres

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Abstract: The study examines some acoustical objective indexes in eleven Italian theatres. The influence of the diffuse-reflection factor on the acoustic modelling was particularly analysed. A room acoustic prediction and auralization software (CATT-Acoustic®) has been used, to simulate the sound field within the modelled rooms. In addition, the results of acoustical simulations were compared with experimental measurements to test the model's accuracy. The proposed approach allows the evaluation of the acoustic quality of the sound field in concert halls as a function of their shape or the diffusing material's properties.

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1. Introduction

In recent years the inadequacy of the traditional approach to the modelling of the acoustic field in concert halls has emerged.[1] This inadequacy is due to the excessively approximated view of the acoustic field on which this modelling technique relies. In fact, only the geometric properties of the room (in particular the specular reflections) are considered, whereas other aspects of the whole environment that are relevant from an acoustical standpoint, are not. For this reason, the traditional modelling technique has undergone a fundamental innovation[1], which consists of the introduction of a correction factor, namely the *diffuse-reflection factor* δ, which is used to approximate the scattering and diffracting properties of reflecting surfaces. The main problem for the modelling techniques which consider the diffuse-reflection factor relies mainly on the uncertain assessment of the optimal values of the diffuse-reflection factor for the various material surfaces. In a recent study the dependence of the diffuse-reflection factor on auditorium size for rectangular, fan, reversed fan and hexagonal shapes was investigated[4]. By comparison of experimentally measured objective indexes and those obtained using models based on three different formulations of the diffuse-reflection factor, namely the secondary randomized diffuse rays model, randomized ray directions model and modified scattered diffuse energy model, Lam[5] demonstrated that the latter ensures the best fit between experimental data and the results of the model. In this study, δ was found to be 0.1 for plain walls in scaled models and 0.7 for real-scale seating halls, which had sizes ranging from 5.050 m^3 to 29.500 m^3 and polygonal shapes ranging from rectangular to hexagonal. Finally, Lam[4] also evaluated the diffuse-reflection factor for larger halls and halls characterised by complicated shapes, which are typical of the Italian opera theatre; in both these cases δ was found to reach 0.4. The aim of this work is to extend the opera theatre halls' typology considered by Lam and determine the optimal diffuse-reflection factor by comparing experimentally measured objective indexes and those simulated using a room acoustics prediction and auralization software, which is called CATT-Acoustic ® [3]. This software was chosen because it evaluates the diffuse-reflection factor on the base of the modified scattered diffuse energy model, which is optimal according to Lam[5]. A sample of eleven musical halls was experimentally tested and modelled. These halls range in size from 4450 m^3 to 37700 m^3 and have three shapes: seven theatres are horseshoe shaped, three are pseudo-rectangular shaped and one is circular shaped. The variety of sizes and shapes of the halls considered allowed for an extensive investigation. The following section describes the experimental measurements that were analysed in this study. The third section presents a brief description of the technique used to model the acoustics of the eleven theatres and the objective indexes model-based prediction. The comparison between the experimental measurements and the results of the simulations is reported in the fourth section, which is followed by some concluding remarks.

2. Experimental measurements

A real time analyser was used to capture and filter the impulse response, which was then transferred to a computer; decay times were calculated from least-squares fits to portions of the decay curves obtained using the Schroeder backward integration technique[6].

Table 1. Measured values of acoustics parameters in eleven italian theatres (125 Hz : 8 kHz)

	ITALIAN THEATRE		**ACOUSTICAL OBJECTIVE PARAMETERS**					
			RT60(sec)	**EDT(sec)**	**C-80(dB)**	**D-50(%)**	**S/N(dB)**	**RASTI(ratio)**
Horseshoe	a)Guerrini Benevento V=4907 m^3	Min	0.74	0.55	3.11	24.80	1.89	0.35
		Mean	1.10	0.83	6.52	57.34	6.44	0.43
		Max	2.53	1.93	8.85	82.32	9.12	0.56
		StD	0.66	0.17	2.65	18.75	3.35	0.08
	b)Regina Margherita Caltanissetta V=4962 m^3	Min	1.27	1.31	-7.32	35.09	0.74	0.42
		Mean	1.43	1.44	1.11	40.85	1.65	0.52
		Max	2.34	1.72	3.23	60.50	2.55	0.61
		StD	0.43	0.13	1.10	2.02	0.82	0.82
	c)Comunale Trento V=10060 m^3	Min	0.68	1.05	0.34	34.02	-0.86	0.42
		Mean	1.20	1.26	2.92	56.71	1.42	0.43
		Max	1.40	1.46	4.63	60.50	3.58	0.52
		StD	0.21	0.21	1.57	8.87	1.52	0.03
	d)Verdi Padova V=14895 m^3	Min	0.69	0.66	-0.50	35.24	-1.76	0.51
		Mean	0.91	1.01	3.13	63.75	2.98	0.59
		Max	1.16	1.30	8.30	82.54	8.37	0.70
		StD	0.14	0.16	1.57	7.88	2.36	0.08
	e)Bellini Catania V=17500 m^3	Min	1.20	0.75	-0.28	37.30	-0.68	0.31
		Mean	1.54	1.28	1.67	50.49	1.76	0.37
		Max	1.72	1.66	7.35	76.06	7.45	0.43
		StD	0.08	0.29	2.33	14.79	2.85	0.04
	f)Rossetti Trieste V=19835 m^3	Min	0.82	0.42	0.39	28.56	-1.52	0.52
		Mean	0.92	0.94	1.74	48.60	1.34	0.58
		Max	1.22	1.39	11.72	89.16	11.74	0.68
		StD	0.16	0.39	3.69	20.14	4.26	0.06
	g)Massimo Palermo V=37723 m^3	Min	0.80	1.30	0.06	42.41	-0.99	0.45
		Mean	1.65	1.52	1.59	51.03	1.29	0.47
		Max	2.42	2.01	5.35	70.43	5.5	0.49
		StD	0.58	0.25	1.67	7.85	1.91	0.05
Rectangular	h)Politeama Siracusa ReggioCalabria V=4441 m^3	Min	0.89	0.88	1.13	43.13	-1.45	0.28
		Mean	1.04	1.16	1.98	54.49	1.14	0.32
		Max	1.11	1.34	6.87	71.36	5.61	0.48
		StD	0.08	0.15	1.93	9.57	2.32	0.06
	i)Pollini Padova V=4686 m^3	Min	0.70	0.14	2.67	31.23	-3.71	0.50
		Mean	0.92	0.91	2.32	52.37	1.99	0.56
		Max	1.44	1.35	12.54	94.17	12.61	0.68
		StD	0.25	0.43	5.21	25.48	5.75	0.11
	l)Odeon Latisana V=6080 m^3	Min	0.70	0.97	-0.8	25.18	-3.70	0.52
		Mean	0.80	1.16	1.76	43.27	1.75	0.53
		Max	0.97	1.35	4.98	63.31	3.33	0.54
		StD	0.09	0.15	1.99	11.82	2.37	0.03
Circular	m)Viale Africa Catania V=13464 m^3	Min	1.02	1.31	0.52	37.83	-0.11	0.27
		Mean	1.45	1.58	1.68	53.65	1.53	0.30
		Max	2.00	1.71	5.46	74.46	5.52	0.37
		StD	0.27	0.15	1.72	11.82	1.82	0.04
Optimal tolerance bounds			(<1) Recital (1.2÷1.8) Opera (1.4÷2) Chamber (1.7÷2.3) Symphonic	(1.8÷2.2) ≅RT	(-2÷+2) Symphonic (÷3) Recital / Opera	(40÷60) Lyric (34) Symphonic (>50) Recital	at 1kHz (-6÷+6)	(0÷0.32) Bad (0.32÷0.45) Poor (0.45÷0.60) Fair (0.60÷0.75) Good (0.75÷1) Excellent

Ten measurements were carried out in different positions of the unoccupied halls with an empty pit for the orchestra for each theatre, except for the Bellini in which eleven measurement points were considered; moreover, because all the rooms were furnished with sound-absorbing upholstered chairs, the differences between the acoustic field measured and that predicted by the model for the fully occupied condition were neglected[7]. In addition, dB-

IMPULSE® software was used to compute objective indexes on the base of the experimental measurement of sound decay[8]; in particular, the evaluated indexes are: reverberation time (RT60), early decay time (EDT), clarity (C80), definition (D-50), signal-to-noise ratio (S/N), rapid speech transmission index (RASTI). The comparison between the measured values of these indexes and their optimal values[7] shows that most of the theatres examined present good acoustical characteristics.

The results of the experimental measurements are showed in Table 1, in which *min*, *max, mean* and *StD* indicate the values of the indexes measured respectively in the worst position, in the best position and the mean value and the standard deviation of the measures in the 10 positions. As Table 1 shows, the pseudo-rectangular halls of the *Politeama Siracusa (Reggio Calabria)* and *Pollini (Padova),* with volumes of about 5000 m^3, present mean values of RT60 respectively 1.0s and 0.9s, which is typical for recital performances where speech intelligibility is important. The "horseshoe" halls of the *Guerrini (Benevento)* and *Regina Margherita (Caltanissetta)* theatres, with the same volumes, have reverberation times that are perfectly appropriate for opera music for which they were built: 1.1s and 1.43s. The rectangular space of the *Odeon Theatre (Latisana)* has a volume of 6080 m^3 and is characterised by a RT60 mean value equal to 0.8s, which appears satisfactory when the dimensions of the hall and its multipurpose destination are taken into account. In the *Verdi Theatre (Padova)*, the reverberation time is 0.9s (the mean between the reverberation time evaluated at 500 Hz and that evaluated at 2000 Hz), but it was necessary to consider that the presence of curtains, which significantly reduced the hall volume to about 14.100 m^3 instead of 14.895 m^3. Furthermore, the mean measured value of RT60 index was about 0.9s, which is still a typical value for opera performances. The measurements performed at *Bellini Theatre* (Catania) produced a value of RT60 equal to 1.5s, which is within the optimal range for a lyric theatre[9] if the room's volume (17500m^3) is taken into account. For the *Rossetti Theatre* (Trieste), which is characterised by a greater volume (19.835m^3), a reverberation time of 0.9s was measured; this result is justified by the presence of absorbing scenery, which delimited the stage during the measurements. The *Massimo Theatre (Palermo)* also presents a great volume (V=13464 m^3) and a RT60 index of 1.65s, which is typical of a symphony hall; for this reason, the volume is often reduced (by the scenery on the stage) to obtain a lower reverberation time, which is usually required for opera music. Finally, the pseudo-circular hall of the modern theatre in *Viale Africa (Catania)* was also examined. This theatre has a volume of 13500 m^3 and presents a value of RT60 equal to 1.45s, which is more suitable for musical performances than recitals, because in the former, speech intelligibility represents a less stringent requirement.

Table 1 also shows that most of the theatres examined in this study are characterised by mean values of EDT and RT60 that are quite close to one another, in accordance with what Jordan[7] suggests for rooms with linear sound decay. In the theatres where this similarity does not hold (e.g. *Guerrini*, *Bellini*, *Massimo,* and *Odeon*), the differences between EDT and RT60 can be attributed[9] to the existence of coupled volumes or to substantial irregularity of the diffusion and absorption coefficients of the various materials. The same reasons can explain the differences existing in most of the theatres between the *min* and *max* values of EDT and RT60.

The objective indexes clarity (C-80) and definition (D-50) describe the quality of sound perception, which is linked to the initial energy reflection.[10-13] As Table 1 shows, the theatres herein considered present C-80 within the optimum range for a concert hall (-2÷4dB) and for recital or opera music (>3dB), although in some, C-80 seems to be quite high due to the absorbing effect of curtains, which were on the stage during the measurements.

The D-50 index for the theatres in the study assumed values that are generally within the tolerance bound; in the *Verdi* Theatre, they are higher than the other rooms (>50%), again due to the presence of curtains. Finally, Table 1 reports that the experimentally measured RASTI index in four of the opera theatres with a horseshoe plant (*Guerrini, Municipal,* *Bellini, Massimo*) assumed values that are in the "poor/fair" region of the admitted range; for the others, horseshoe theatres (*Verdi, Rossetti* and *Regina Margherita*) the RASTI index was found in the "fair/good" region. The explanation for these results may be that the influence of this index is not relevant for musical performance. The RASTI index becomes important when the words' intelligibility is one of the main requirements. In fact, it is in the highest range ("good/excellent") for the *Pollini* Theatre, because this theatre is mainly an auditorium for recital music, and words intelligibility is therefore an important requisite. Also the multipurpose *Odeon* Theatre presents a value on the RASTI index in the "fair" range, which ensures a good performance for a different kind of music, whereas the auditorium *Politeama Siracusa* presents a low value in the "bad" range, which is not sufficient for a theatre designation. Finally, the *Viale Africa* Theatre has a RASTI index in the "bad/poor" range, which is due to the acoustical drawbacks typical of the circular plan.

3. Acoustic modelling

A three-dimensional model of each theatre was made using *CATT-Acoustic®* software[3]. One of the main problems in modelling real halls is the difficulty to obtain accurate material characteristics, because absorption data are unknown for most of the materials. Therefore, typical absorption coefficients[14,15], which are reported in Table 2, were considered in this study. Some approximations were considered in acoustical modelling: details of the global structure were smoothed; the ceiling was chosen highly diffusing[4], namely δ=0.7, to simulate the presence of decorations (especially for opera theatres); the boxes were assumed to behave like strongly absorbing walls (considering an absorption coefficient of 0.6).

Table 2. Sound absorption coefficients for materials and audience areas.

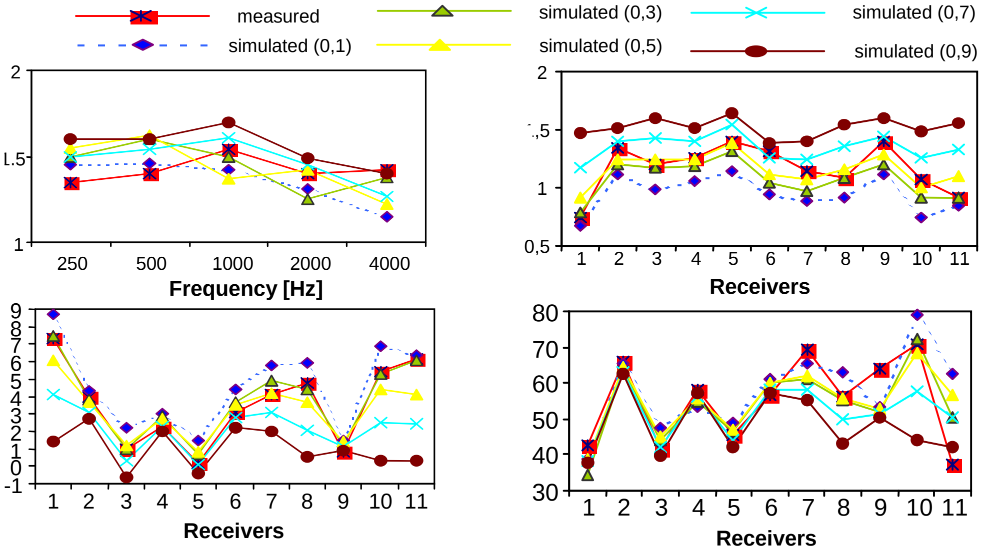
Materials	Frequency [Hz]					
	125	250	500	1000	2000	4000
Gypsum	0.29	0.10	0.05	0.04	0.07	0.09
Parquet	0.04	0.04	0.07	0.06	0.06	0.07
Plaster	0.01	0.01	0.02	0.03	0.04	0.05
Moquette	0.05	0.08	0.17	0.30	0.48	0.72
Linear-wood	0.43	0.40	0.36	0.44	0.33	0.27
Concrete block, unpainted	0.36	0.44	0.31	0.29	0.39	0.25
Upholstered seats	0.54	0.66	0.78	0.85	0.83	0.75
Velour	0.14	0.35	0.55	0.72	0.70	0.65

CATT-Acoustic® software uses the image source (*ISM*) in the early part of the echogram and ray-tracing for the later part; the algorithm considers both specular and diffuse reflection properties of the material surfaces of the modelled room. Unlike those methods that rely only on specular reflections, acoustical prediction based on this algorithm improves as diffuse-reflection combinations are taken into account.[4] A series of simulations was performed considering various diffuse-reflection factors for the materials to analyse its influence on acoustic indexes. The sound source was an omnidirectional loudspeaker system and was placed in different positions on the stage; ten receivers were placed in the audience area, which were supposed to have a very high diffusion coefficient (i.e. δ=0.8), to simulate the presence of listeners in significant spots.

4. Comparison of experimental and simulated acoustic indexes

The aim of comparing experimentally measured objective indexes and those obtained by modelling the various theatres for different diffuse-reflection factors δ was to determine an optimal value for this parameter to address the problem of its choice. In other words, the accuracy of theatre's modelling depends on the choice of the diffuse-reflection factor that can therefore be correctly found by determining the model whose fitting with experimental measurements is optimal. For brevity, the results of the comparisons are presented for the *Bellini Theatre* only. In fact, this theatre well represents the typology of an opera theatre with a horseshoe-shaped plant, boxes and decorated (i.e. highly diffusing) ceilings, which this study wishes to analyse. Fig. 1 reports the plots for the *Bellini Theatre* of measured and predicted values for four objective indexes. The analysis of these plots shows that both the RT60 and *EDT* increase for a higher diffuse-reflection factor, whereas a higher diffuse-reflection factor generally reduces both the *C-80* and *D-50*. Fig. 1 also shows that the diffuse-reflection factor, which allowed us to adequately predict RT60, C-80, and D-50, was δ= 0.3, whereas δ= 0.5 ensures a better fit of experimental and simulated values of EDT (though the fit obtained with δ= 0.3 is on average acceptable). Therefore, the comparison of experimental and simulated objective indexes leads us to chose δ= 0.3 for the *Bellini Theatre*.

Fig. 1. Comparison between measured and predicted indexes (RT60, EDT, C-80, D-50).



From a general standpoint, although some uncertainties due to geometric and absorption data approximations influence the results, the predictions of the acoustic objective indexes for the eleven theatres were reasonably good for diffuse-reflection factors mainly in some specific ranges. In particular, it was found that for horseshoe-shaped halls the optimal diffuse-reflection factor to be considered is mainly constant in the range of 0.3-0.4, except for the ceiling and seating to which was assigned a value of 0.7 to account for the decorations. The choice of this value was a good compromise to avoid the underestimation of reverberation time RT and simulate a realistic diffuse sound field. A slight increase of the optimal value (δ = 0.5) was necessary to ensure a good fitting of the simulated to the experimental indexes for halls with greater volumes and for the circular-shaped hall. Finally, for halls with a rectangular shape, it was confirmed the value of 0.2, which was found by Lam[4].

Table 3. Simulation errors for selected acoustic objective parameters

THEATRE	δ_{opt}	E(RT60) [s]	E(EDT) [s]	E(C-80) [dB]	E(D-50) %
a) **Guerrini**	0.3	0.08	0.06	0.36	7.01
b) **Regina Margherita**	0.3	0.04	0.07	0.10	7.58
c) **Comunale**	0.3	0.12	0.15	0.36	5.26
d) **Verdi**	0.4	0.17	0.18	0.40	7.30
e) **Bellini**	0.4	0.16	0.14	0.56	7.44
f) **Rossetti**	0.4	0.06	0.13	0.33	9.12
g) **Massimo**	0.3	0.28	0.14	0.32	6.99
h) **Politeama**	0.2	0.11	0.15	0.35	5.06
i) **Pollini**	0.2	0.18	0.20	0.62	10.3
j) **Odeon**	0.2	0.10	0.12	0.31	7.07
k) **Viale Africa**	0.5	0.23	0.26	0.24	1.83

Table 3 reports the simulation errors for selected objective indexes; the simulations considered for the comparison were those performed with diffuse-reflection factors ensuring the best fitting between experimental and simulated objective indexes, which are also reported in Table 3. It is mentioned that the errors were calculated as the sum over the whole set of measurement points of the absolute values of the difference between the experimental acoustic objective indexes and those simulated, divided for the number of measurement points. Finally, the sufficiently low errors reported in Table 3 for the acoustic objective indexes demonstrate that satisfactory predictions were obtained.

5. Conclusion

In this study a systematic investigation of eleven concert halls and auditoria in Italy was shown to determine an optimal range of the diffuse-reflection factor to be used in the acoustic modelling of these halls. The acquisition of experimental data was followed by computer modelling of the acoustic behaviour of the eleven halls, through a room acoustics prediction model (CATT-Acoustic®) that considered both specular and diffuse acoustic reflections. The results for rectangular and pseudo-rectangular halls show that the optimal value for δ was 0.2, which is in accordance with the range found by Lam[4], (i.e., [0.1-0.2]); for horseshoe-shaped halls the optimal range for δ is [0.3-0.4], whereas for the circular shape with big volume, δ=0.5 allows good accordance between experimental and simulated data.

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