The 'Teatro Principal' of Valencia. Acoustics for Theatre or Music. Objective evaluation supported by acoustic simulation.

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Abstract

The "Teatro Principal" of Valencia, designed in 1774 and inaugurated in 1832, is one of the oldest Italian theatres in Spain. As a cultural icon in Valencia, it has been the temple of the performing arts for more than 150 years until the 1980s with the inauguration of the Palau de la Música. From that moment on, the musical performances were transferred to the new Auditorium with the consequent period of adaptation to the new acoustic conditions for both the public and the Orchestra. The aim of the present work is the evaluation of the acoustic quality of the Theatre for music and speech. As the quality is affected by the hall capacity, and as the acoustic parameters are not easily measurable in full hall conditions, the support of acoustic simulation is necessary. An acoustic model of the hall has been adjusted following the response surface methodology. On the adjusted model, simulations have been carried out with different conditions of capacity and number of instrumentalists or actors on stage. The results obtained have been evaluated with the Arau Merit Factor as an objective methodology.

Keywords: proscenium theaters, response surface methodology, simulation, merit factor.

1. Introduction

The Teatro Principal of Valencia (1832) constitutes one of the most paradigmatic Spanish examples of proscenium style together with the Gran Teatre del Liceu in Barcelona (1847) and the Teatro Real in Madrid (1850). It is one of the oldest theaters in Spain that has preserved its original configuration [1].

The Principal Theater was originally designed by the Italian architect Felipe Fontana in 1770. Some financial difficulties postponed the beginning of the construction until 1808. After a stop due to the Independence war, the building was finished and finally opened on July the 24th of 1932, without the façades. In 1933 the fourth floor was added. In the following years, the roof was fixed several times due to leaks. The venue was inaugurated definitely in 1959. For a long time, it was the most important venue in the city. In the 19th century, there was a scenic spaces construction blossom in the city of Valencia, although none of them rivaled the Principal. Many of those theaters have disappeared today.

The building of the Principal Theater has evolved throughout the years and has undergone several renovations, although none of them have changed it dramatically. The last one occurred in the 80s, was very respectful with the interior space and recovered some of the compositional aspects of the original theater and adapted it to modern regulations. Essentially the theater has maintained its geometry and characteristics. The Principal Theater (Figure 1) gathers all the attributes of a proscenium theater: the auditorium box has a horseshoe-shaped plan (with a slight slope), a flat ceiling, an orchestra pit (which can be exposed or closed and occupied by seats), a large stage fly-tower (of above 8.000m3, it is separated from the audience by the proscenium arch), side boxes in the stalls and four levels of boxes and balconies (the last two floors also have rear galleries).

This theater has a capacity of 1226 people. Four hundred and sixty of those seats are located in the stalls.

Nowadays, the fourth floor is used for technical support and is closed to the audience. The access to the room is made through numbered doors located in curved corridors, outside the room. They give independent access to the stalls, to each of the boxes, and the continuous balconies and galleries. On the last two floors, the boxes disappear to place rows of seats on the sides and galleries centered at the back.

At the beginning of the 20th century, the Principal Theater was used intermittently as a rehearsal and performance room by the Valencia Municipal Symphonic Band of Music and by the Orchestra of Valencia; until 1987, the year in which the Palau de la Música was inaugurated.

The acoustic conditions of both spaces differ greatly, this caused some controversy between aficionados and multiple opinion articles in local newspapers at the time.

Figure 1 – The Principal Theater (Source: author)

The aims of the present work are:

- To make a 3D model of the theater and to adjust it to the onsite acoustic survey using the response surface methodology.
- To simulate different conditions of room capacity.
- To evaluate the acoustic quality of the theater for music and speech at different conditions using the Merit Factor.

2. Methods

On-site measurement of the impulse response was conducted to obtain the objective parameters of the room. The field measurements were done in two different room conditions, with the curtain closed and with the curtain undrawn (as this survey is part of a broader research). The measurements were conducted using an impulsive source (a Bruel & Kjaer dodecahedral loudspeaker) and recorded in various positions of the room (Figure 2) using both omnidirectional and binaural microphone configurations (Shure KSM44A). These experimental measurements were conducted in accordance with the ISO 3382 [2]. The stage had scenography during measurements.

The receiver points were distributed uniformly and non-symmetrical in relation to the room axis. The source was placed in the center of the apron, which allowed us to maintain its position in the closed curtain measurement procedure. The measurements were registered with DIRAC software [3]; afterwards a file treatment has been done to obtain the room acoustic parameters.

To define the (x, y, z) coordinates of the source and receivers (Table 1), we have set the origin in the center of the apron at the lowest point, where it joins the stalls. The analysis was conducted without an audience.

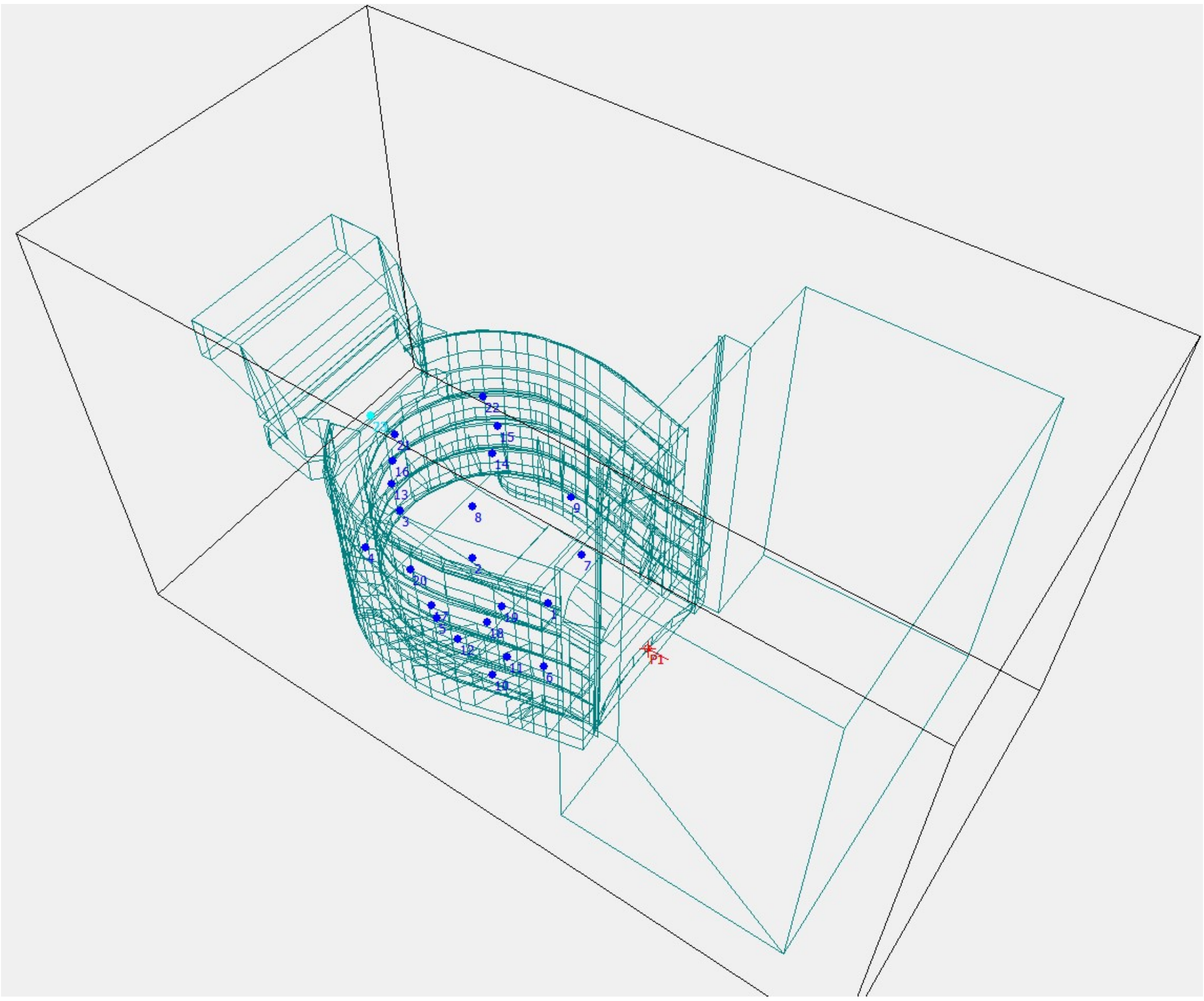

Figure 2 - Location of the source and the receivers

Table 1 - Coordinates of the source and the receivers set in the Principal Theater

	X	*Y*	*Z*		*X*	*Y*	*Z*
Source	0.90	0.28	2.47	Receiver 12	-8.71	-7.83	5.17
Receiver 1	-7.25	0.00	1.50	Receiver 13	-20.97	0.00	5.17
Receiver 2	-13.86	0.00	1.81	Receiver 14	-16.89	6.54	5.17
Receiver 3	-20.55	0.00	2.42	Receiver 15	-16.49	6.85	8.04
Receiver 4	-20.44	-4.00	2.41	Receiver 16	-20.47	0.00	8.04
Receiver 5	-12.66	-5.56	1.73	Receiver 17	-10.32	-8.22	8.04
Receiver 6	-4.39	-4.38	1.50	Receiver 18	-6.60	-7.18	8.04
Receiver 7	-7.76	4.84	1.50	Receiver 19	-5.15	-7.35	11.02
Receiver 8	-16.69	3.58	2.05	Receiver 20	-11.56	-8.34	11.02
Receiver 9	-11.20	-8.40	2,17	Receiver 21	-19.92	0.00	11.02
Receiver 10	-6.48	-7.25	2.17	Receiver 22	-17.20	6.31	11.02
Receiver 11	-5.27	-7.09	5.17	Receiver 23	-21.96	0.00	11.70

Also, we have collected information about the building materials and how they were set in place, especially those that may affect the acoustic behavior.

A 3D model of the theatre in AutoCAD software has been made. Then, it has been adjusted in Odeon software, using the response surface method (RSM). This method helps to evaluate the influence of a material in the reverberation time of a room [4].

The RSM explores the relationships between several explanatory variables and one or more response variables. The goal is to use a sequence of designed experiments to obtain an optimal response using a second-degree polynomial. The response, in room acoustics, is the reverberation time of the enclosure. To apply this method, the absorption coefficient of every surface of the space must be known except for two independent variables, whose values determine the response.

The RSM can be applied to obtain a study region per surface. Then they are combined to get 9 absorption spectrum combinations.

The study region definition in the RSM application:

$$X_{1i} = B_{1i} \pm R_{1i} \tag{1}$$

Being:

B_{1i}, values taken from the bibliography,

R_{1i}, increments which vary from 0 to 0,5

Analogously X_{2i}

The new absorption spectrum couples are introduced in Odeon to calculate the reverberation time of each combination. The Just Noticeable Difference (JND) has been considered to fit the adjusted simulation results to the RT30 measured onsite. The JND indicates the minimum variation an acoustic parameter can have to be subjectively perceivable [5], in this case, this minimum variation of the RT30 is a 5%. The combinations are acceptable when they fit between the maximum and minimum JND values of the onsite measured reverberation time.

The reverberation times obtained are grouped by frequencies, creating nine combinations of three points by frequency. The response surfaces which fit with those combinations are drawn. New couples of points from each surface that satisfy the target are obtained. We make a Table of the pairs by frequency, and we create new absorption spectrum coefficients combinations of the unknown surfaces. We calculate the reverberation time of each combination, and then we compare the results with the onsite measurement.

After the RSM application process, an adjusted model of the room is obtained for both the curtain of the stage opening drawn and undrawn.

With the adjusted model of the previous step, several acoustic simulations with different occupancy percentages will be carried out:

- Audience only in the stalls (approximately 37 % occupancy)
- Audience in every seat (100 % occupancy)
- Orchestra on the stage and 100% occupancy.

These occupancy variations will be simulated increasing the absorption coefficient of the seats, estimating this increment based on the bibliography [6], [7],[8].

The global merit factor, allows the evaluation of the acoustic quality of a venue [9]. The merit factor of each parameter takes values from 0 to 1. When the value of an acoustic parameter is considered excellent for the intended use of the space, then the merit factor of this parameter is 1. When the acoustic parameter is out of the margins considered optimal for a determined use, then the merit factor of this parameter is 0.

The merit factor of the reverberation time is obtained by comparing the $RT30_{mid}$ with the optimal reverberation time, $RT30_{opt}$. The optimal reverberation time depends on the use and volume of the space. The Principal Theater has a general room volume of approximately 6300m^3.

In general, EDT values are lower than RT30 values. The EDT is more related to the subjective impression of the reverberation of a room than the reverberation time [10]. When the EDT is much lower than RT30, the subjective impression of the space for music is that is dead, but more intelligible for speech [11]. The merit factor of the EDT is related to the RT30 and depends on the use of the room. For theater, it is adequate that the EDT_{mid} is between 0.6 $RT30_{mid}$ and 0.75 $RT30_{mid}$, and for concert it has to be between 0.9 $RT30_{mid}$ and $RT30_{mid}$[9].

The bass ratio reverberation time shows the affluence of low frequencies. The acoustic criteria are very strict for music, as only values of BR around 1.2 are valid. While in the case of speech, BR values can be between 0.9 and 1.3.

A brilliant sound is clear and rich in harmonics. The brilliance, Br, is the response to treble frequencies. Its value should be as high as possible, near one, and no less than 0.8 [9]. The merit factor for brilliance is shared both for music and theater. The presence of sound-absorbent materials as carpets, draperies can negatively affect the brilliance of a space.

The clarity, C_{80}, is inversely correlated with RT30 in concert halls [7]. When clarity is high, the EDT will be much lower than RT30. This effect can be easily detected in balconies and amphitheaters with a low ceiling. For music, the clarity must stay between -2 dB and 4 dB. In the case of theater, it must be above 6 dB [9].

The definition, D50, is the relation between the energy that arrives at the listener in the first 50ms from the arrival of the direct sound and the total amount of energy received [12]. It is directly related to the intelligibility of speech and the reverberation time. A value of definition above 0.7 is adequate for speech. For music, it is recommended to be less than 0.5.

The intelligibility index, STI, is determinant in theaters but not in concert halls. The STI of a theater must be above 0.75, to be considered excellent.

The global merit factor is the arithmetic media of the summation of the merit factors obtained for each of the objective acoustic parameters considered in the evaluation of the acoustic quality of the room.

$$FM_{Global} = \Sigma \, FM/n \quad (2)$$

3. Results

3.1. Objective parameters

The reverberation time, RT30, obtained after processing the data acquired during the field measurements can be seen in Table 2. As it was mentioned in previous sections, the measurements were conducted both with the curtain closed and undrawn. The reverberation time was used to adjust the simulated room.

Table 2 - Measured RT30 with closed curtain and undrawn curtain.

	Stage Opening	*125 Hz*	*250 Hz*	*500 Hz*	*1 kHz*	*2 kHz*	*4 kHz*
RT30(s)	*Closed*	*1,286*	*1,052*	*0,984*	*0,993*	*0,99*	*0,863*
	Opened	*1,286*	*1,075*	*1,037*	*1,035*	*1,005*	*0,886*

As it can be seen in Table 2 the values of RT30 for both configurations are very similar.

3.2. Validated model

Two adjusted models have been obtained, one with the proscenium curtain drawn (Figure 3) and another with the curtain undrawn (Figure 4). The adjustment process has been done comparing the average RT30 simulated with the average RT30 measured onsite considering JND. For the final adjusted model, the values of the RT30 simulated have been compared for every receiver with the onsite measurements. The adjusted model with the curtain opened has been used to perform the simulations. The materials used in the simulation (Table 3) have been taken from literature and from laboratory tests [7], [9], [13].

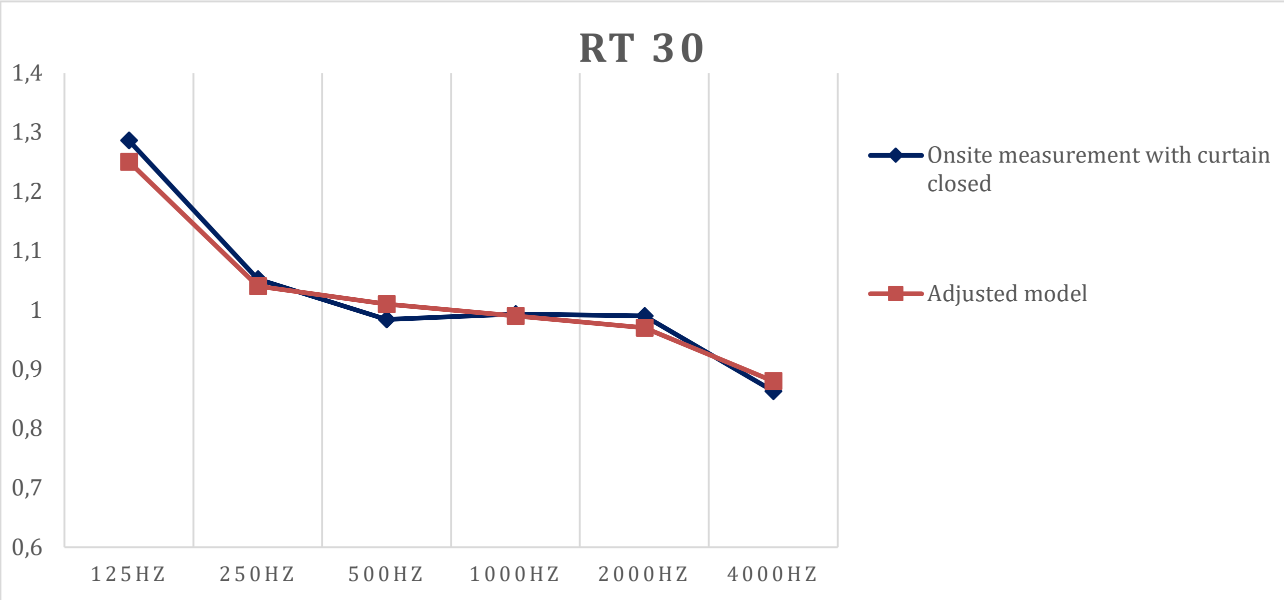

Figure 3 - Reverberation time (RT30) of the onsite measurements with curtain closed and of the adjusted 3D model.

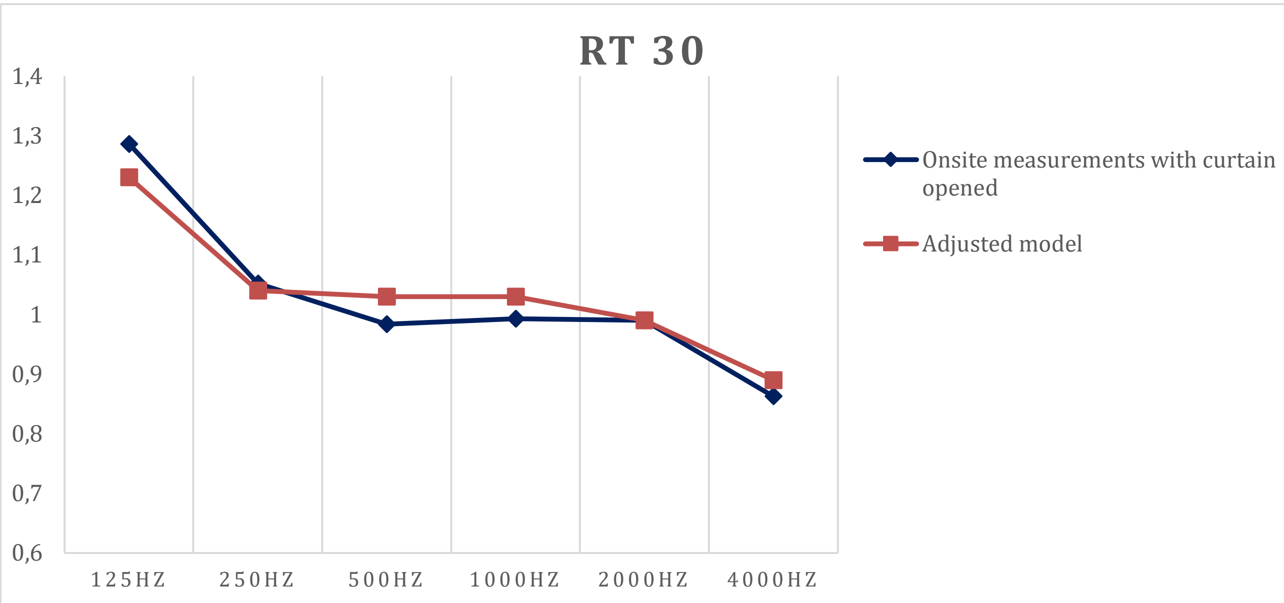

Figure 4 - Reverberation time (RT30) of the onsite measurements with curtain undrawn and of the adjusted 3D model.

Table 3 - Zone, materials, and absorption coefficient of the surfaces of the adjusted model.

Zone	Materials	125 Hz	250 Hz	500 Hz	1 KHz	2 KHz	4 KHz
Stage floor	Wooden platform with air camera	0.40	0.30	0.20	0.17	0.15	0.10
Ground floor	Tongue and groove wooden floorboards	0.05	0.03	0.06	0.09	0.10	0.20
Corridors	Carpet	0.11	0.14	0.37	0.43	0.27	0.25
Balconies floors	Ceramic pavement	0.01	0.01	0.01	0.02	0.02	0.02
Hollow wall solution	Plasterboard with air camera	0.29	0.10	0.05	0.04	0.07	0.09
Walls	Solid ceramic brick	0.025	0.026	0.06	0.085	0.043	0.05
Balconies decoration	Plaster molding	0.13	0.13	0,25	0.28	0.30	0.30
Ceiling decoration	Plaster molding	0.20	0.20	0.25	0.28	0.30	0.30
Stage opening		0.30	0.35	0.40	0.45	0.50	0.55
Ceiling main area	Reed with paster	0.30	0.20	0.10	0.07	0.05	0.05
Ceiling under balconies	Plaster on slab	0.14	0.10	0.06	0.04	0.04	0.03
Balconies seats	Medium upholstered seats	0.56	0.64	0.70	0.72	0.68	0.62
Perimeter ceiling	13mm plaster on 25mm studs (with mineral wool)	0.29	0.20	0.15	0.10	0.05	0.05
Back amphitheater ceiling	Plasterboard on frame 13mm board, 100mm empty cavity	0.08	0.11	0.05	0.03	0.02	0.03
Stalls	High upholstered seats	0.72	0.79	0.81	0.82	0.80	0.76
Curtains covering walls	Hanging velvet separated from the wall	0.40	0.80	0.44	0.35	0.32	0.32

3.3. Merit Factor of the simulations

Using the adjusted model with undrawn curtains, we have made acoustic simulations of different cases of occupation and use of the theater.

We have considered three cases:

- Case 1:
  - Use of the space: Theater
  - Occupation: only the stalls (37 % occupancy)
- Case 2:
  - Use of the space: Theater
  - Occupation: 100%
- Case 3:
  - Use of the space: Concert
  - Occupation: Orchestra on the stage and 100% of the seats of audience occupancy.

For concerts, the $RT30_{opt\ max}$ is 1.91 and the $RT30_{opt\ min}$ is 1.64. For theater the $RT30_{opt\ max}$ is 1.37 and the $RT30_{opt\ min}$ is 0.89.

The results of the acoustic parameters of the simulations and the merit factor of each parameter can be seen in Table 4. In table 5 the global merit factor of the three cases is shown. As said before, the calculation of the merit factor depends on the use of the venue

Table 4 - Simulations results.

Parameters	Case	1	2	3
EDT	EDT_{mid}	0.795	0.78	0.635
	MF_{EDT}	0.967	0.966	0.558
RT30	$RT30_{mid}$	1.015	0.995	0.935
	MF_{RT30}	0.989	0.949	0.000
C_{80}	C_{80}	6.350	6.550	8.100
	MF_{C80}	1.000	1.000	0.304
D_{50}	D_{50}	0.670	0.675	0.750
	MF_{D50}	1.000	1.000	0.700
BR	BR	1.118	1.116	1.144
	MF_{BR}	1.000	1.000	1.000
Br	Br	0.911	0.899	0.904
	MF_{Br}	1.000	1.000	1.000
STI	STI	0.670	0.670	0.710
	MF_{STI}	0.817	0.817	0.906

Table 5 – Global merit factor of the simulations for theater configuration (1 and 2) and concert (3).

	1	2	3
MF_{GLOBAL}	0.968	0.962	0.638

4. Conclusions

The adjusted model of the theater was obtained by taking the onsite reverberation time measurements as a reference. The adjusted values of the RT30 are within the 5% established by the JND. The adjustments were done using the RSM.

The $RT30_{mid}$ results obtained in simulations 1 and 2 are within the values of the $RT30_{opt.max}$ and the $RT30_{opt.min}$ for theater use. Meanwhile, the $RT30_{mid}$ obtained in simulation 3, is out of the range of the $RT30_{opt.max}$ and the $RT30_{opt.min}$ for concert use. That means that the configuration of the space is not adequate for music.

In general, the room has a low $RT30_{mid}$, which is adequate for speech but not for music. This can be appreciated since the Merit Factor of the $RT30_{mid}$ in the third case is 0.

The EDT_{mid} and $RT30_{mid}$ values of the space configured as a theater (case 1 and 2) are quite similar, although the occupancy differs significantly. That means that the diffusion is very homogeneous (it can be verified with the D_{50} values). This is coherent with the presence of diffusor elements, such as the decorated curved balconies, the plaster decoration on the ceiling and the stage opening, and the curved joints between the ceiling and walls. On the contrary, in case 3, where the stage is occupied by an orchestra, the merit factor of EDT_{mid} and $RT30_{mid}$, are very low or zero. That shows that the theater is not adequate for concerts with the present configuration.

The merit factor of clarity is very high in the case 1 and 2, but very low in the case 3.

The definition, D_{50}, has values around 0.70, which are very good for speech but bad for music, since it is above 0,5. That is reflected in the merit factor of the definition in each case, value 1 for cases 1 and 2, meaning the D_{50} value is adequate, and penalizing the value of D_{50} in the third case.0

The merit factor of bass ratio and brilliance is 1 in every case. The theater presents an excellent performance at low and high frequencies.

The STI merit factor indicates a good behavior in the room for speech.

The presence of a virtual audience in the space or the stage does not appreciably change the RT30 values. While the results are correct for theater use, similar ones are very undesirable for concerts. Based on the simulation results, it can be said that, in general, the venue is ideal for theater, not for music. For concerts, the positioning of an acoustic shell would improve the performance of the room. Also, the curtains that cover the perimeter of the balconies on the ground floor and the first floor could be removed, which will improve the presence of treble frequencies.

To complete the survey, an on-site acoustic measurement with an audience would be desirable, to test the theatre in the standard use conditions. Also, an onsite measurement without scenography would be interesting to evaluate the fly tower contribution to the acoustic parameters. Furthermore, a comparative analysis with other concert halls and theatre spaces of the city should be relevant.

Acknowledgements

We want to thank the Deputy Director of Artes Escénicas of the Institut Valencià de Cultura of the Conselleria d'Educació, Investigació, Cultura i Esports, for letting us visit the theater and perform the measurements.

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