# An Attempt to Rank Italian Historical Opera Houses Based on Numerical Simulation

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Abstract

Due to the complexity of the acoustic field in articulated closed spaces, architectural acoustics is often approached as a reverse-engineering problem: criteria, reference values and analysis methods are extrapolated by comparing results from measurements in a set of case studies. Considering the methods and the results of previous works on Italian historical theatres, the present study shows the results of geometrical acoustic (GA) numerical simulations with the aim to attempt a ranking based on the subjective preference theory. The models were calibrated using several room criteria that had been previously measured in the framework of a measurement campaign performed in Italian theatres. The cluster chosen is intended to represent an adequate sample of case studies relative to different capacities and different design approaches, which were first developed in the seventeenth century.

## 1. Introduction

The theatres investigated in this study represent an adequate sample of case studies relative to the different design approaches of Italian Historical Opera Houses (D'Orazio and Nannini, 2019). These theatres shared the political events related to the foundation of the Kingdom of Italy (1861) and World War II, during which most of them were severely damaged, sacked and used as warehouses, public toilets, cellars or field hospitals. In the twenties, some of these theatres were equipped with an orchestra pit, whose construction changed the role of the proscenium arch. In particular, in many cases the stage was moved backward (D'Orazio et al., 2019) and as a consequence the proscenium arch could no longer provide the typical strong early reflection on the audience.

A synthesis of the architectural features of these theatres can be found in Table 1. By using existing categories (Prodi et al., 2015), it is possible to distinguish between large (DUS, BOL) and mid-sized theatres (ALI, BON). See also Fig. 1.

Table 1 – Architectural features of the theatres analysed

| ID | $V_{fly}$ (m$^3$) | $V_{hall}$ (m$^3$) | Shape | N |
|---|---|---|---|---|
| BOL | 19900 | 5500 | Bell | 999 |
| BON | 11630 | 3130 | Horse-shoe | 798 |
| ALI | 5300 | 3360 | Horse-shoe | 835 |
| DUS | 2800 | 7400 | Modern | 999 |

## 2. Acoustic Criteria for Opera Houses

The acoustic quality of an opera house is described using measurable quantities that are the scientific expressions of precise subjective judgements. Over the years, several scholars have investigated the relation between objective parameters and individual perceptions of sound in an enclosed space. However, different approaches to the issue and difficulties found in dissimilar evaluations have not made it possible to achieve a single method. All that has been established until now is a series of measurable room criteria, some of which are still debated by experts while others are officially defined by standards (ISO 3382-1, 2009).

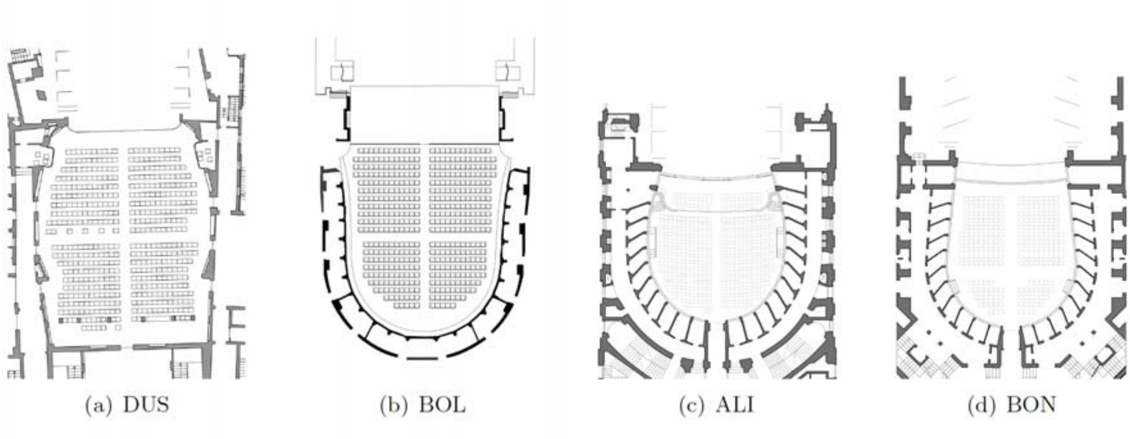



Fig. 1 – Plans of the main halls of the investigated theatres

All the indicators on which the present study is based are briefly described and commented on hereafter in relation to Italian Opera Houses. The most evident characteristic we perceive inside a hall is the reverberation, a parameter that intuitively indicates how long a sound persists in the space. For the first century of architectural acoustics (which dates back to Sabine's work) it has represented the main, if not the only, measurable descriptor used to qualify the acoustic behaviour of an enclosure.

Dealing with the subjective perception of reverberation, the Early Decay Time EDT plays a key role. During an "aria", for instance, it is unlikely that a listener has the time to hear the whole decrease of a single note sound energy, so fast notes follow one another. In a few words, new acoustic phenomena mask the late reflections of sounds previously emitted, thus we are able to perceive only the beginning of the decay curve.

Clarity (C) is one of the parameters that describe the "balance between early and late arriving energy" (ISO, 2009) in a room. The integration time is assumed as 80 ms for music ($C_{80}$) and the integration extreme t = 0 represents the direct sound arrival time. A threshold of 50 ms was shown to be more suitable for mid-sized Italian opera houses (De Cesaris et al., 2015).

Sound strength (G) is a descriptor that quantifies the sound energy distribution in the hall; it indicates how much the hall naturally amplifies sounds (ISO, 2009). Sound strength index is one of the most important parameters to analyse and qualify the acoustics of the auditorium and the behaviour of the coupled volumes (D'Orazio et al., 2017; Garai et al., 2016).

In ISO 3382-1 (2009) besides the mentioned monaural coefficients, a binaural index is also defined: the Inter-Aural Cross Correlation (IACC). The most general form of IACC is provided with $t_1 = 0$ and $t_2 = 1$, i.e. with a time comparable with reverberation time. Moreover, the IACC can be found out both for early energy ($IACC_E$ with $t_1 = 0$ ms and $t_2 = 80$ ms) and for the reverberant field ($IACC_L$ with $t_1 = 80$ ms and $t_2$ greater than reverberation time of the hall surveyed). Rather than the IACC coefficient, an alternative parameter is usually preferred: the Binaural Quality Index (BQI), defined as: $BQI = 1 - IACC_{E,3}$ where subscript E stands for early (integration's extremes $t_1 = 0$ ms and $t_2 = 80$ ms) and subscript 3 indicates that value has been averaged over the central octave bands (500-1000-2000 Hz).

Other objective acoustic criteria are used in the present paper. The Bass Ratio (BR) is defined as the ratio of the reverberation time at 125 Hz and 250 Hz to the reverberation time at 500 and 1000 Hz, usually evaluated in occupied condition ($BR_{occ}$). The Initial Time Delay Gap (ITDG) is the time difference between the direct sound and the first reflection. The Lateral Fraction (LF) is the ratio of the early energy measured with a figure-of-eight microphone ($t_1 = 5$ ms, $t_2 = 80$ ms) and the early energy measured with an omnidirectional microphone ($t_1 = 0$ s, $t_2 = 80$ ms). Subjective LF is expressed through the Lateral Fraction Cosine (LFC). Finally, the Surface Diffusivity Index (SDI) is defined as an average value of diffusivity of all surfaces in a room.

## 3. Calibration

The theatres were investigated using monoaural and binaural techniques in an unoccupied state, according to ISO 3382 (ISO, 2009).

The IRs were measured using a custom high-SPL dodecahedron (D'Orazio et al., 2016a) as sound source. IRs were acquired using ESS test signals (Guidorzi et al., 2015) and postprocessed in order to extract ISO 3382 criteria.

In each theatre, the number and type of curtains were noted. The curtains were set for a standard performance of a medium-sized orchestra following the requirements of the minimum amount of absorptive material on the stage, suggested in the Charter of Ferrara (Pompoli and Prodi, 2000), of 500 m$^2$.

The measurement campaign was characterised by a large number of measurements. In the stalls, IRs measurements were performed at all seats for several source positions: two on the stage, one on the fore-stage, one in the centre-stage, two in the orchestra pit, one in the covered part, one in the open part of the pit – at a height of 1.2 m. In each box, measurements were performed placing the microphone in the front position. In the gallery, measurements were taken in correspondence to the seats in the boxes, with some slight differences depending on the setting of the gallery. The height of the microphone was kept at 1.2 m. Over 50,000 IRs were processed: a more complete overview of this survey was presented in (Garai et al., 2015a).

The theatres were 3D modelled starting from architectural surveys (ALI, DUS, BON) or laser scanning (BOL only (Bitelli et al., 2017)). Numerical models were then calibrated by assigning material properties in each octave band, from 63 Hz to 8 kHz, following an iterative process (ODEON, 2010). The absorption coefficients were found in reference datasets (Cox and D'Antonio, 2009; Vorländer, 2007); the scattering coefficients take into account geometry of complex surfaces and receiver-surface distances (Shtrepi and Astolfi, 2015; Shtrepi, 2019). Values of both parameters were adjusted in order to fit the measured values (Postma and Katz, 2016).

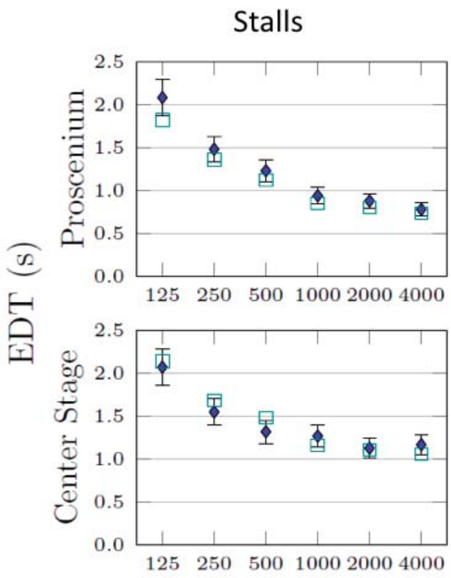



Fig. 2 – Calibration of ALI theatre, considering two source positions and three receivers areas (only stalls are displayed here). Comparison between measured and simulated values is provided in octave bands; error bars refer to 2 times the JND

The iterative process involved EDT and $C_{80}$ criteria: for each sound source, the simulation results were averaged for each group of receivers, respectively: stalls, boxes and gallery. The calibration process was concluded when the differences in each octave were within 2 JNDs, which were, respectively, 10% for EDTs and 2 dB for $C_{80}$. An example of calibration results for EDT in the ALI theatre is shown in Fig. 2.

According to state-of-the-art practice (Lokki and Pätynen, 2009), simulations were carried out in hybrid mode, combining the mirror source method and ray-tracing techniques and setting a transmission order of 2. In other words, the first two simulated reflections preserve the phase information, which may be useful when the numerical models are used to auralise anechoic signals (D'Orazio et al., 2016b).

Fig. 3 shows how each layer influences the equivalent acoustic absorption area. The incidence of four layers covers the whole absorption: plaster (which involves all the surfaces covered by plaster), wood (the wooden stage), drapes (curtains and scenarios in the fly tower), and seats. Air absorption is negligible at low and mid frequencies.

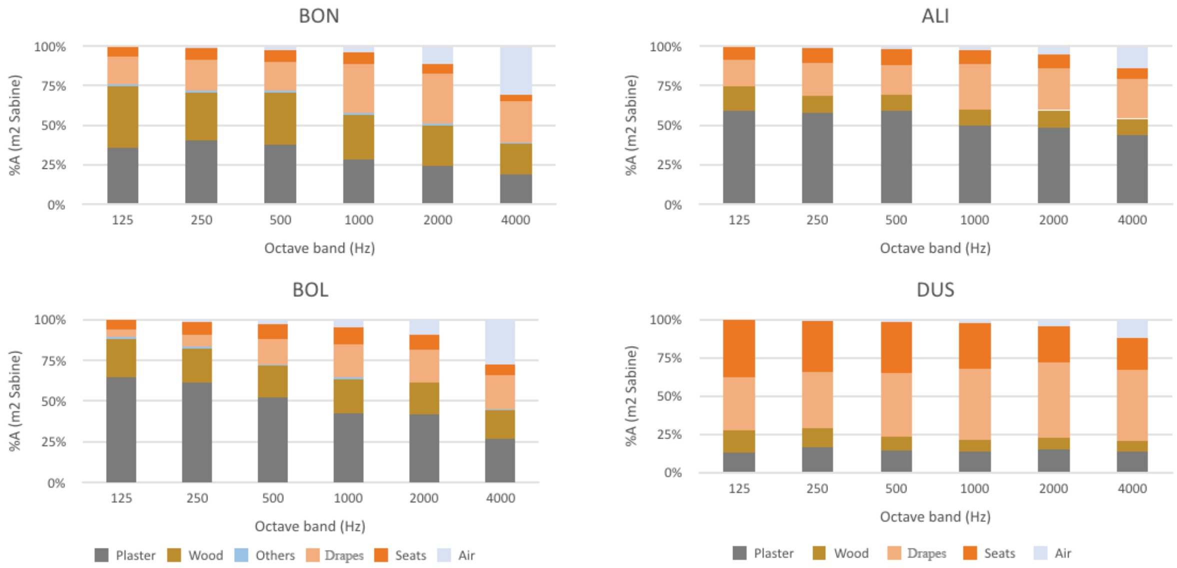



Fig. 3 – Percentage of equivalent absorption area of each layer in unoccupied conditions

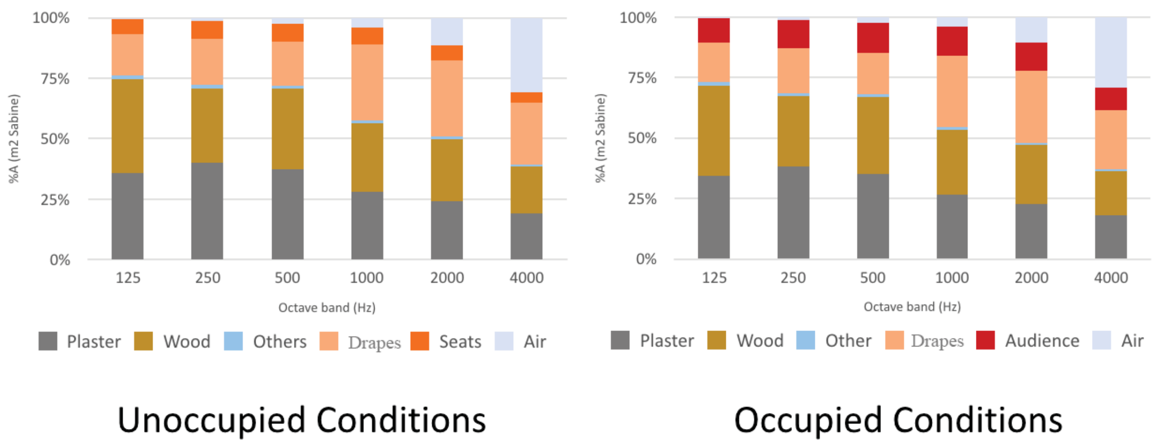



Fig. 4– Percentage of equivalent absorption area of each layer in BON in unoccupied and occupied conditions

There was a significant difference between modern (DUS) and historical theatres (ALI, BON, BOL), concerning the weight of the seats and the plaster. The acoustic absorption of DUS is mainly characterised by chairs and drapes: it means that the acoustic behaviour depends on the mounting of scenarios, more than the occupied/unoccupied conditions. Indeed, the absorption of the upholstered chairs may be comparable to the absorption of the occupancy.

Conversely, in the historical theatres, the plaster and the wood characterise the acoustic absorption of the theatres.

In each theatre the plaster coefficient was set differently depending on the materials on which the plaster was fixed: wood (as the case of ALI and BON), masonry (BOL) or concrete (DUS). Finally, the wooden stage may play a relevant role if the stage is large as the case of BON. Indeed, wooden layers may be absorbent at low frequencies due to the resonances of light parts (D'Orazio et al., 2018; Fratoni et al., 2019; Garai et al., 2015b). It can be noted that opera houses are coupled volumes, so the absorption of the fly tower does not necessarily influence the main hall (Garai et al., 2016).

## 4. Listener Absorption

Listener absorption may influence the reverberation time values of the hall (Beranek, 2006). Furthermore, frequency behaviour of listener absorption differs from the materials one, so the reverberation times may also change in frequency.

Absorption coefficients of the theatre layers should consider the orchestra occupancies too (Jeon et al., 2015, 2018). In an opera house the orchestra is placed in the pit, so the absorption of the musicians also influences the acoustic coupling between the pit and the hall.

Fig. 5 shows the differences between the equivalent absorption areas of BON theatre, respectively, in unoccupied and occupied conditions. It should be noted that in the historical theatres (BON, BOL, ALI), the audience absorption influences the octave bands between 125 and 8000 Hz, while in the modern theatres (DUS) the absorption of chairs is quite similar to that of listeners. Consequently, $BR_{occ}$ values of the historical theatres span from 1.1 to 1.3, while $BR_{occ}$ = 1.5 in DUS (see Table 2).

## 5. Ranking

Subjective preference theory dates back to the 1970's from studies on European Concert Halls (Schroeder et al., 1974), and has since been improved by Ando (Ando, 2015). Methods and results of the subjective preference are related to concert hall and music signals. Beranek (2003) extended Ando's subjective preference for concert halls, taking into account EDT at mid frequencies instead of $T_{30}$, BQI as a description of the cross correlation of early reflections, BR and SDI (Sound Diffusion Index). To go to the opera, or generally to stay in a theatre, is an experience which involves visual, musical, and literary experiences. Cirillo et al. (2011) adapted the Ando-Beranek approach to Italian opera houses, also taking into account the Balance (B) for the opera. A synthesis of preference models is shown in Table 3, considering the case of a soloist voice as signal source (D'Orazio et al., 2011; D'Orazio and Garai, 2017).

Table 2 – Reverberation time and bass ratio values of the theatres under study

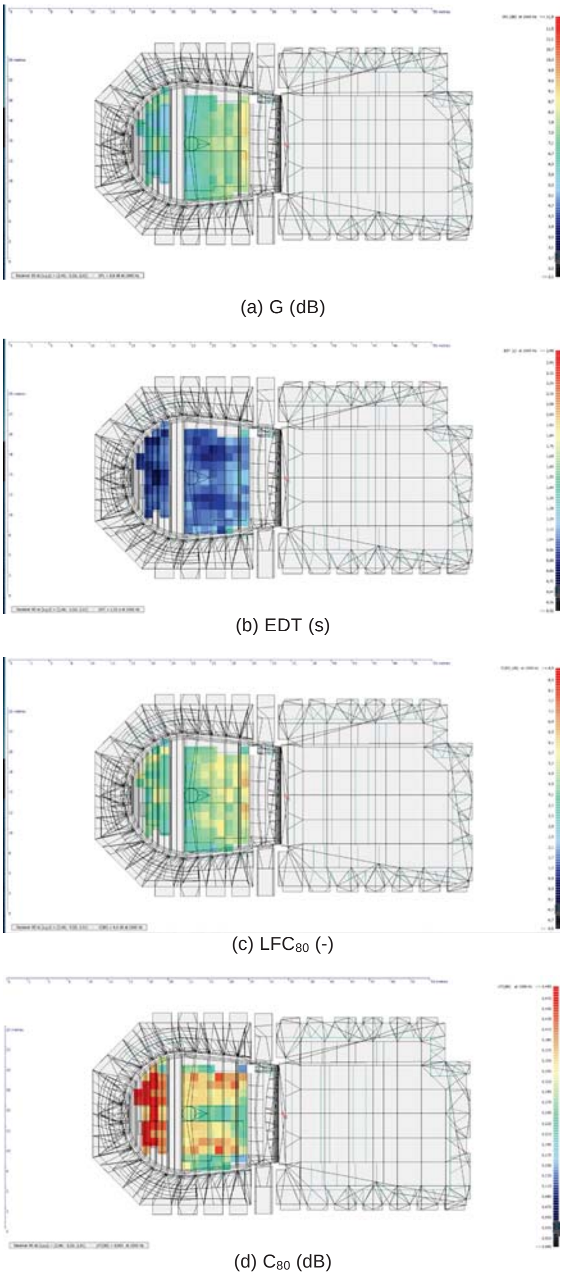
| ID | $T_{30,M,unocc}$ (s) | $BR_{occ}$ (-) |
|---|---|---|
| BOL | 1.53 | 1.1 |
| BON | 1.77 | 1.3 |
| ALI | 1.37 | 1.3 |
| DUS | 1.32 | 1.5 |

Table 3 – Criteria and preferred values of subjective preference theories. A $\tau_e$ = 20 ms was assumed for opera singers. The reverberant-to-direct ratio was defined according to (Ando, 1983)

| Criterion | Ando 2015 | Beranek 2003 | Cirillo et al. 2011 |
|---|---|---|---|
| Listening level (dB) | Bin. Level ≈ 79 | $G_{mid}$ > 1 | $G_{mid}$ 1÷8 |
| Spatiality (-) | IACC lowest | BQI 0.7 | BQI > 0.7 |
| Reverberation (s) | $T_{30}$ $23\tau_{e,min}$ | EDT 2.5 | EDT 1.4÷1.6 |
| Intimacy (ms) | ITDG $(1-\log A)\tau_{e,min}$ | ITDG 20 | ITDG < 20 |
| Clarity (dB) | - | - | $C_{50}$ 1÷5 |
| Warmness (-) | - | $BR_{occ}$ 1.1÷1.2 | BR 1.05÷1.25 |
| Diffusivity (-) | - | SDI 1 | SDI 1 |

For the purpose of this analysis, the positions of the virtual sound source were chosen similarly on the proscenium in all the theatres under study: on the longitudinal axis of the stage at 1 m from the edge. Fig.s 5 and 6 show the maps of simulated values of four criteria involved in the subjective preference models in the stalls of two theatres:

- G for natural gain of the hall;
- EDT for subjective reverberation;
- $LFC_{80}$ for spatiality;
- $C_{80}$ for clarity and early-to-late ratio.



(a) G (dB)

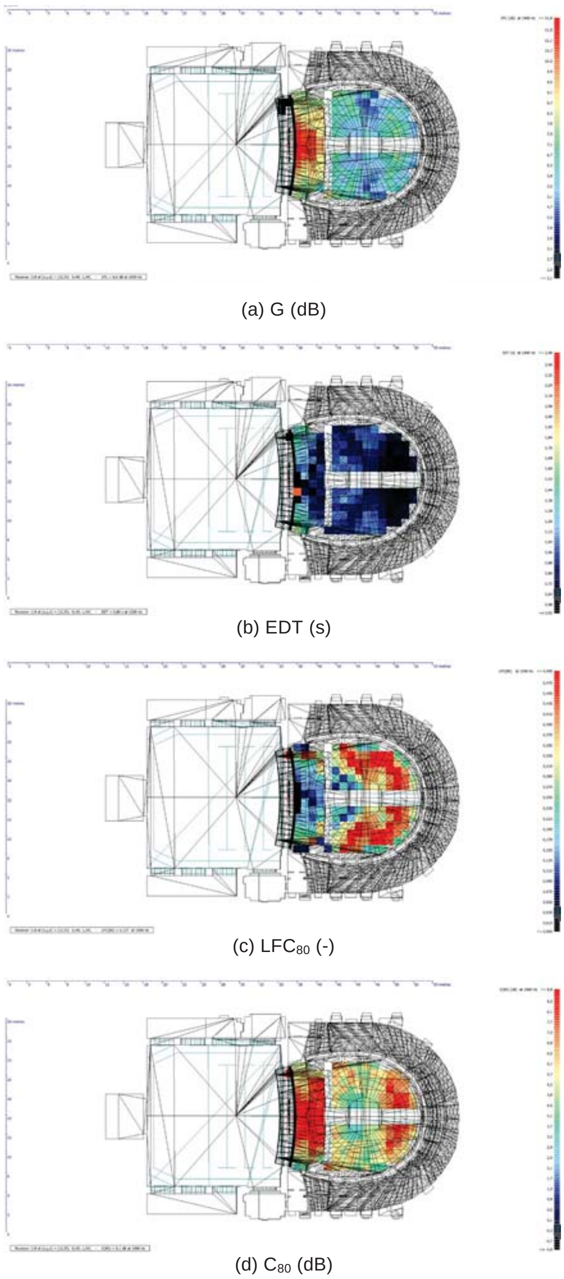
(b) EDT (s)

(c) $LFC_{80}$ (-)

(d) $C_{80}$ (dB)

Fig. 5 – Maps of the distribution of G (dB), EDT (s), LFC80 (-) and $C_{80}$ (dB) in the stalls area of the BON theatre. Sound source on the stage, at 1m from proscenium border

Stage acoustics was not taken into account in this work: an analysis of two halls (ALI, BON) was shown in a previous study (D'Orazio et al., 2015). Taking into account the subjective models and the simulation results, a preliminary ranking of the three historical opera houses is shown in Table 4. The DUS theatre, being a modern one, is not shown in this table.



(a) G (dB)

(b) EDT (s)

(c) $LFC_{80}$ (-)

(d) $C_{80}$ (dB)

Fig. 6 – Maps of the distribution of G (dB), EDT (s), LFC80 (-) and $C_{80}$ (dB) in the stalls area of the ALI theatre. Sound source on the stage, at 1m from proscenium border

## 6. Conclusion

A detailed measurement campaign was carried out in three historical opera houses and one modern theatre. ISO 3382 monaural criteria were used in order to calibrate numerical models, which were used to extract room criteria in occupied conditions. Criteria in both conditions (unoccupied and occupied) were used in subjective preference models previously proposed by scholars. Results show pros and cons of each theatre, making it possible to validate the perceived acoustic quality of theatre under study when they are used for opera.

Table 4 – Quality classes (from D to A+) of the three historical opera houses studied

| ID | Ando/Beranek | Cirillo | pros | cons |
|---|---|---|---|---|
| BOL | A | B | IACC | |
| BON | B | A | EDT | |
| ALI | B | B | | Low G |

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