INFLUENCE OF DIFFUSIVE SURFACE POSITION AND EXTENSION ON THE ACOUSTICS OF A SMALL PERFORMANCE SPACE

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1 INTRODUCTION

Diffusive surfaces have been used in different environments and several studies have been carried out to better understand their positive and negative effects through in-field[1,2] and physical-scale[3-6] measurements, simulations and perceptual tests[3,7,8]. However, very little research has been carried out in real concert halls due to many practical problems, that is technical and economical. In this study, it was possible to investigate the effects of diffusive surfaces in a real shoebox concert hall with variable acoustics.

In-situ measurements conducted by Jeon *et al*.[1] demonstrated that early decay time (*EDT*) and interaural cross correlation (*IACC*) are the most affected parameters by the use of diffusive surfaces. Furthermore, Kim *et al.*[2] found that the effects of scattered sound on acoustic parameters depend on the receiver position. Several studies have been conducted to determine the effects of diffusive surfaces by using scale models. Ryu and Jeon[3] and Kim *et al*.[4] found that hemispherical diffusers, applied to scale model surfaces, decrease reverberation time (*RT*) and early decay time (*EDT*). Different results were found for clarity (C_{80}), which increased at the front seats and decreased at the rear seats[3]. Green and Barron[5] showed the importance of the location of diffusive surfaces, which could lead to deficient sound levels at the rear of the wall when diffusive treatment are applied to the side walls. Since the use of real and scale models can be time-consuming and can often be technically difficult to perform, the use of computer modelling and acoustic simulations has been considered an acceptable and reliable alternative[9,10]. However, the modelling of diffusive surfaces needs further investigation since it is linked to the issues regarding the degree of detail of the geometrical acoustic models[11-13]. Perceptual investigation has been carried out in order to understand the relationships between subjective response and the acoustical objective measures, i.e. the quality of the listening environment. The subjective evaluation conducted by Ryu and Jeon[3] showed that the preference of diffusive sound field highly correlates with loudness and revereberance. Kim et al.[2] showed how the diffuse sound field is perceived in terms of sound strength (*G*) and number of reflected peaks. The modelling of frequency-dependent scattering was shown to be important in simulations[14] influencing the JND of diffused sound[15,16].

Finally, there is an evident need for acousticians and practitioners alike, to understand better the influence of the diffusive surface on room acoustic parameters and perception, as well as improving the way this surfaces are considered in the simulation software. In this study, the influence of diffusive surface position and extension has been investigated by means of in-situ measurements, simulations and perceptual listening tests in a real scale variable acoustic small concert hall. The objective acoustic parameters, such as reverberation time (T_{30}), early decay time (*EDT*), clarity (C_{80}) and definition (D_{50}) have been estimated in fourteen hall configurations. Subjective investigations have been carried out through headphones listening tests applying the ABX method[21].

2 EXPERIMENT

The acoustic measurements have been performed in a small variable-acoustic hall, the Espace de Projection (ESPRO) at IRCAM in Paris, in order to investigate how the position and extension of diffusive surfaces can influence the generated sound field. The ESPRO is a shoebox hall (Figure 2a) and has a capacity of about 350 seats. The variable volume is achieved by varying the ceiling height (H_{max}=10 m)[17]. Furthermore, the ceiling and the walls are made of variable panels (5.29 m^2), which contain three rotatable prisms. The three sides of these prisms are successively absorbing, specular reflecting and diffusely reflecting. This allows to obtain six different combinations of the panels acoustic characteristics. Fourteen hall configurations have been tested by modifying position and extension of the diffusive surfaces. All the other surfaces, except for the floor, have been set in absorptive mode (Figure 1).

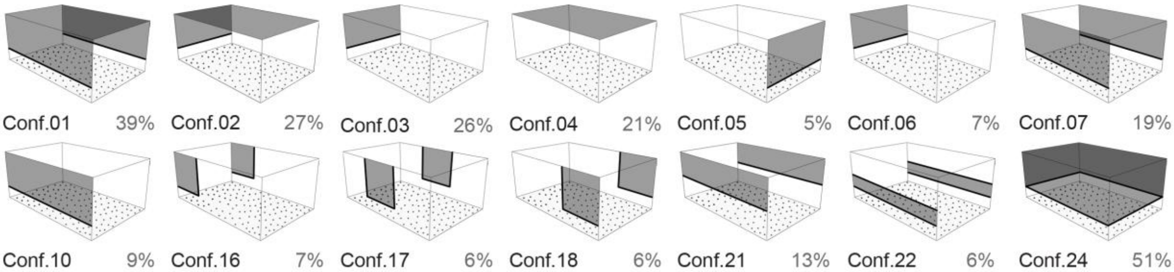

Figure 1. In each configuration the white color indicate absorptive surface, while the gray color indicate diffusive surfaces, and dotted gray pattern shows the reflective floor surface. The percentage indicates the extension of diffusive surfaces with respect to the total surface of the walls and ceiling (% = $S_{diffusive}/S_{tot,walls+ceiling}$).

2.1 Measurement set-up

The in-situ measurements have been carried out using an artificial head and an array of twenty-four omnidirectional microphones that were extended to one of the two halves of the audience area, as shown in Figure 2. Two omnidirectional dodecahedron loudspeakers were positioned on the front part of the room[18]. All the receivers and the artificial head heights were adjusted at 3.7 m above the floor level, which corresponded to the center of the first level of diffusive panels. The lower level panels were set in absorptive condition in all the measurements in order to avoid the strong reflections from the lower parts of the walls, as this configuration is not very usual for an audience in a concert hall. The ceiling was set at its maximum height of 10 m. Acoustic measurement were performed according to ISO 3382-1[19]. Measurements and post processing has been carried out using the ITA-Toolbox, which is an open source toolbox for Matlab.

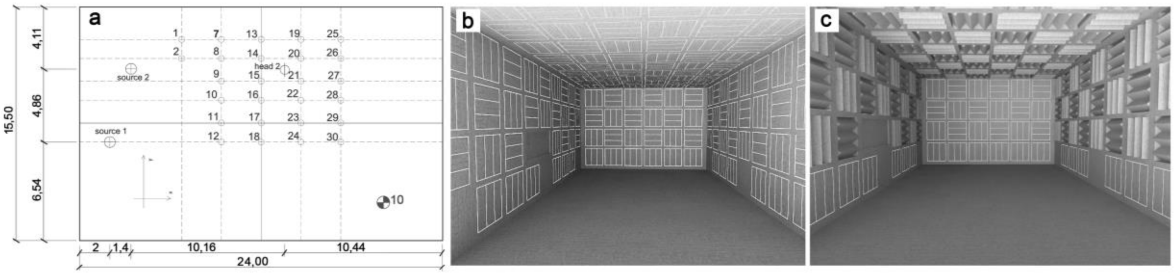

Figure 2. Measurement positions and main dimensions of the room (a). Flat surface model (b) and the 3D surface model (c) of configuration C_01 used in Odeon 12.0.

2.2 Simulations

The objective room acoustic parameters were also investigated through simulations carried out with software Odeon 12.0. This program uses a hybrid calculation method where the early reflections are calculated using a combination of Image Source method and ray-tracing, while late reflections are calculated using a special ray-tracing process generating secondary sources that radiates energy locally from the surfaces of the walls[20]. The direction of a diffusive reflection is calculated

with a probability function according Lambert's cosine-law, while the direction of a specular reflection is calculated according to Snell's law[18].
Eight configurations (Conf.01-02-03-04-05-06-07-24) have been selected for the simulations, where the diffusive surfaces have been modeled in two different ways in order to verify if a higher level of modelling detail leads to different results. In the first model (Figure 2b) the diffusive surfaces were modeled as a flat surface to which the scattering coefficient (0.7) was assigned. This value has been obtained by previous analysis through BEM simulation using AFMG Reflex software. While in the second model (Figure 2c), the diffusive surfaces are modeled as in the real hall diffusive condition and a low scattering coefficient (0.05), typical of reflective surfaces, has been assigned to each surface. The other materials in both models have been assigned after calibration of reverberation time in a 3D surface model (C_24).

2.3 Listening test

2.3.1 Method

The listening test has been conducted to investigate the listener's ability to perceive changes of diffusive surfaces position and extension. Furthermore, the effect of different source positions and type of music passages have been investigated. The ABX method[21] was considered to be suitable for the aim of the tests. This method is based on the presentation of three stimuli: stimulus "A" and stimulus "B" is known to be different in some way and the task of the listener is to identify whether stimulus "X" is the same as "A" or the same as "B".
The LIStening Test Environment (LisTEn)[22] was used to conveniently set up the ABX test. The administrator and the participant are provided with two different working panels, where the administrator builds two playlists (A and B). The test was run in random order, so that different participants did not have the same sequence of samples. The results have been analyzed applying the statistical analysis of Binomial Distribution.

2.3.2 Test

The listening test was conducted in the anechoic room at Politecnico di Torino. The test lasted three days, in which the room conditions as well as the set-up have been kept unvaried. The equipment consisted of one computer, a sound card (Tascam US-144 MKII) and headphones (Sennheiser 600 HD). The listeners were seated in a chair and the environment was made comfortable for them. All listeners were familiarized with the test by an illustrated written and verbal explanation of the test's steps in order to give them an idea of what the task involved. The listeners, were asked to complete a short audiometric test through an i-pad based application (uHear).

The auditory tests consisted in 104 stimuli (52 pairs), which were created by convolving the binaural impulse responses obtained from in-situ measurements with two music passages. The two music passages were chosen based on different style, tempo and spectral contents: an orchestra track ("Water Music Suite"- Handel/Harty) and a solo instrument trumpet (Mahler). They were chosen to be long enough to give the listener the necessary time to assess the full extent of the sensation and avoid boredom. Thus, a length of 7 s for all samples was considered as suitable.

The listening test consisted of two groups of signals based on the recording in two groups of configurations, where the position and extension of diffusive surfaces has been varied. The first has a scope to investigate the listener's ability to perceive changes in diffusive surfaces position. While the second aimed at testing their capacity to detect changes of diffusive surface extension. A pair of different configurations is compared in each experiment, while the sources, the artificial head and music passage remain unvaried within each pair of samples. Figure 3 depicts the test structure.

Thirty-one listeners, who were made up of a group of research assistants and students, aged between 23 to 40 years old with normal hearing ability, were chosen as test subjects.

Fifty-two experiments with three samples (A, B and X) were presented to each listener. The test was double-blind and fully randomized: the order of A and B pairs presentation and the order of X sample i.e. X could be randomly A or B. After listening to A and B, they were asked to answer: “Which one is X?”. The listeners would then record their answer choosing “sample A”, “sample B” or “I don’t know” and move onto the next step. No answer would be registered if they did not listen all three samples and the test would not continue. The listener could chose freely the play order of three samples and they could listen to the samples again. The listeners could not take breaks during the test which lasted 30 minutes. After the test, the listeners impressions and opinions were collected. Furthermore, information on their experience with previous listening tests, on their music skills, as well as age and general health conditions (such as any recent colds or ear infections) were gathered.

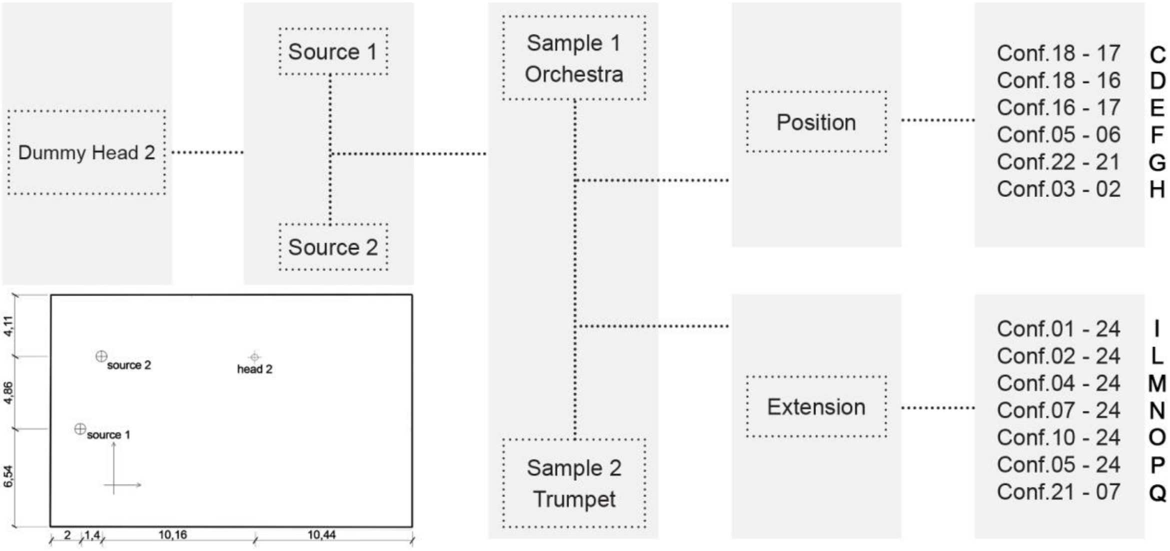

Figure 3. Listening test structure and schematic plane of the hall which shows the sources and artificial head positions.

3 RESULTS

3.1 Measurement

The objective parameters have been analyzed comparing the variation of *EDT*, T_{30}, C_{80} and D_{50} in the front and rear part of the audience area. Standard deviations of the parameters averaged values at 500 Hz and 1 kHz have been used for an easier comparative investigation. The results showed significant variations of the parameters depending on the diffusive surface position and extension. Figure 4 depicts the standard deviation of the four objective parameters:

- Reverberation time (T_{30})

Variations in this parameter resulted within the *JND* value, thus no significant effect of the position and extension of the diffusive surfaces could be detected.

- Early decay time (*EDT*)

Standard deviations of about 1 *JND* resulted in the front part of the hall when the first sound source was used and the diffusive surfaces were positioned on:

- the ceiling (C_04)
- the rear and front wall (C_05 and C_06)

The same result could be observed in the front part of the hall when the second sound source was used and the diffusive surfaces were positioned on:

- the ceiling (C_04)
- the ceiling and lateral walls (C_01)
- the front wall (C_06)

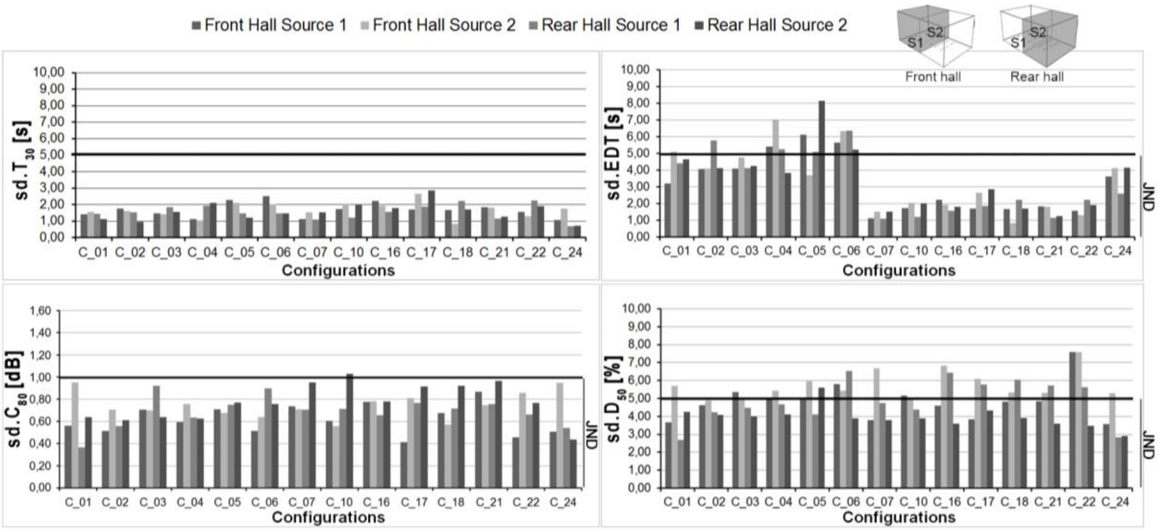

Figure 4. Standard deviation of each objective parameters in the front and rear part of the hall.

Standard deviations of about 1 *JND* resulted in the rear part of the hall when the first sound source was used and the diffusive surfaces were positioned on:

- the ceiling (C_04)
- the ceiling and front wall (C_02)
- the rear and front wall (C_05 and C_06)

The same result was obtained when the second sound source was used and the diffusive surfaces were positioned on:

- the front wall (C_06)

• Clarity (C_{80})

No significant differences resulted in the front part of the hall when the first sound source was used. Conversely, standard deviations of about 1 *JND* resulted in the front part of the hall when the second sound source was used and the diffusive surfaces were positioned on:

- the ceiling and lateral walls (C_01)
- the ceiling, lateral, front and rear walls (C_24)

Standard deviations of about 1 *JND* resulted in the rear part of the hall when the first sound source was used and the diffusive surfaces were positioned on:

- the front wall (C_06)
- the ceiling and rear wall (C_03)

The same resulted when the second sound source was used and the diffusive surfaces were positioned on the lateral walls:

- on 1/3 of the central and front area of the lateral wall (C_17 and C_16),
- on the entire surface of the lateral walls (C_07),
- on the upper part of the lateral wall (C_21)
- on only one lateral wall (C_10)

• Definition (D_{50})

Standard deviations of about 1 *JND* resulted in the front part of the hall when the first sound source was used and the diffusive surfaces were positioned on:

- the ceiling (C_04)
- the ceiling and rear wall (C_03)
- the rear and front wall (C_05 and C_06)
- one of the lateral walls (C_10)
- the upper part of the lateral wall (C_21)
- 1/3 of the rear area of the lateral wall (C_18)

In all the configurations the standard deviations of about 1 *JND* resulted in the front part of the hall when the second sound source was used.

Standard deviations of about 1 *JND* resulted in the rear part of the hall when the first sound source was used and the diffusive surfaces were positioned on:

- the lateral walls (C_07)
- the upper and lower area of the lateral walls (C_21 and C_22)
- 1/3 of the front, central and rear area of the lateral walls (C_16, C_17 and C_18)
- the front and rear wall (C_05 and C_06)

Conversely, no significant differences resulted in the rear part of the hall when the second sound source was used.

As expected, increasing the diffusive surface extension with respect to the absorptive one leads to higher *EDT* and T_{30}, and lower C_{80} and D_{50}. The results highlighted the role of the lateral walls. It is well-known that the lateral walls are responsible for the generation of early reflections, thus the use of diffusive surfaces in such location easily varies the room acoustic parameters.

Finally, the choice of diffusive surfaces position and extension leads to different variations in the front and rear part of the hall. This is useful to achieve a more mindful design of concert halls and intervene in those areas that could bring to the required results.

3.2 Simulations

The average values of the objective parameters obtained by two different models have been compared to the in-situ measurement values, as shown in Figure 5, where the values are averaged through twenty-four receiver positions in the mid frequencies of 500 Hz and 1 kHz. The volume difference between flat and 3D surface model is indicated for each configuration. The comparison has been carried out for T_{30}, *EDT*, C_{80} and D_{50} and for the both source positions. Since the *EDT* and D_{50} values did not indicate any significant variations their graphs are therefore not reported here. Similar results were obtained for both source positions, thus here are reported results regarding only source 1. Figure 5a shows that the T_{30} simulated values in the flat and 3D modelled rooms are very similar to the measured values (within 1 JND) except for two configurations C_01 and C_24. This exception is due to the volume differences of the flat and 3D modelled rooms (ΔV_{C_01}=44.29 m^3 and ΔV_{C_24}=58.05 m^3).

Figure 5b shows the differences in C_{80} between the predicted and measured values. Differences of about 1 JND can be noticed for C_06 and C_02. This results suggests that beside the reverberation time, also the other parameters should be taken into account when calibrating the prediction models. As expected, extending the diffusive surfaces with respect to the absorptive ones, the reverberation time increases and the clarity decreases.

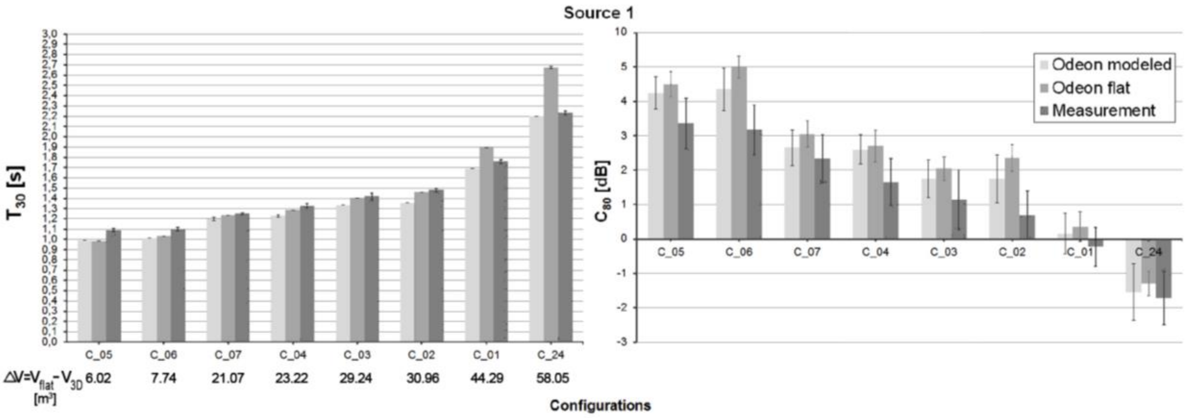

Figure 5. The comparison between simulated and measured values of T_{30} (a) and C_{80} (b) averaged at 500 Hz and 1 kHz when using source 1. The vertical bars indicate the standard deviation of the parameters considering the overall microphone positions.

3.3 Listening test

The data gathered by listening tests has been elaborated through Binomial Distribution[21]. The inverse cumulative probability is evaluated in order to obtain the minimum number of correct answers, which are needed to indicate a perceptual difference. The inverse cumulative probability is a function of trials (corresponding to the thirty-one listeners), probability of correct responses (0.5) and confidence level (95%). Therefore, the number of correct responses necessary to obtain a 95% confidence level was found to be twenty. Figure 6 depicts the pair configurations, divided by music passages and sources, which obtained twenty or more correct answers.
The listeners were able to hear variations in extension of diffusive surfaces for all pairs of configurations. Meanwhile, changes in position of diffusive surfaces were audible only for a few pairs:

- C_16 and C_18, where the diffusive surface covers 1/3 of the lateral walls at the front and rear part, respectively.
- C_05 and C_06 where the diffusive surface covers front and rear walls, respectively.

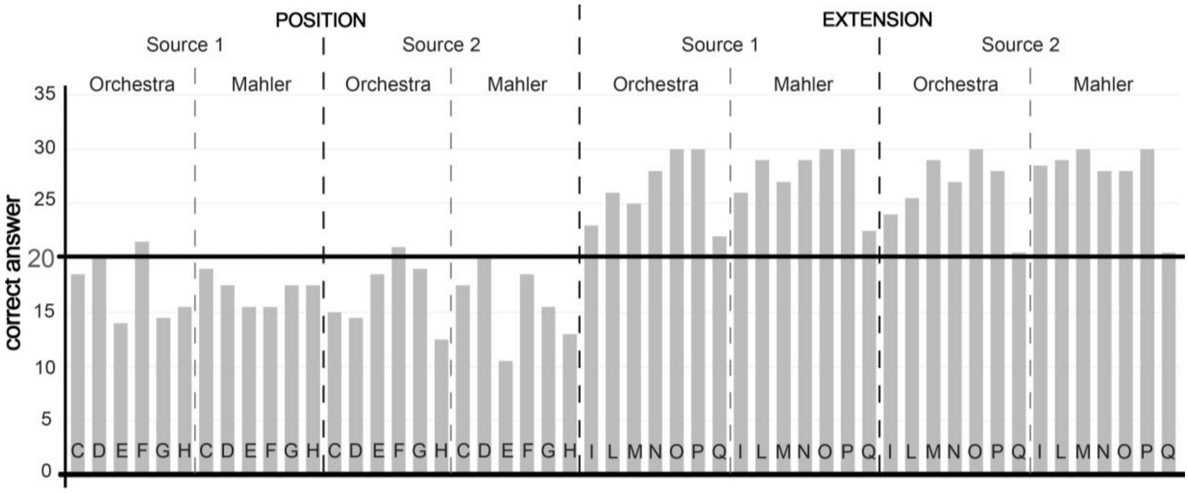

Figure 6. Listening test results. Black horizontal line indicates the minimum number of correct answers necessary to indicate a perceptual difference between configurations in one pair. X-axis indicate the pairs compared in each trial (C, D, E, F, G, H, I, L, M, N, O, P, Q).

4 CONCLUSION

In-situ measurements, simulations and perceptual listening test have been used to investigate the influence of diffusive surface position and extension on the acoustic parameters and perception in a real scale variable acoustic concert hall. In-situ measurements analysis showed different tendencies for the spatial distribution of EDT, C_{80} and D_{50} in the front and rear part of the hall depending on the diffusive surfaces position and extension. Thus, this is useful to achieve a more mindful design of concert halls and intervene in those areas which could bring to the required results. Conversely, no significant effect could be observed on the spatial distribution of T_{30}.
The results comparison between measurement and the two different prediction models showed that there is still a lot of work to do on the determination of the degree of the model detail. It has been highlighted the importance of volume determination when simplifying the room geometry.
The perception investigation showed that variations in the position of vertical diffusive surfaces on the lateral walls could be heard by subjects when comparing front to rear configurations. Furthermore, the subject could detect differences in all the cases of presenting variations in the extension of the diffusive surface.
Future works could concentrate on the determination of the thresholds concerning the minimum extent of diffusive surface in a concert hall which would be necessary to obtain the required acoustic quality. The possibility of designing variable panels within a hall could be considered as an

alternative that allows to choose the best position and extension of diffusive surfaces depending on the use of the hall and on the listeners preferences.

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