Virtual acoustic environment reconstruction of the hypostyle Mosque of Córdoba.

Highlights:

- Acoustic intangible heritage of the Aljama Mosque of Cordoba is recovered
- Different spatial configurations and their acoustic environment are analysed
- Acoustic parameters are obtained by carrying out a virtual sound reconstruction
- The visual mosque space has an apreciable multiplicity of acoustic environments
- Sound source location and shape of the prayer room are determining factors

Virtual acoustic environment reconstruction of the hypostyle Mosque of Cordoba.

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ABSTRACT

Current simulation tools and virtual-reality technologies enable the reconstruction of the historical sound inside heritage buildings, and have become powerful tools in Archaeoacoustics. The sound generated within the current state of a heritage building can be used to characterize the sound of the past inside that building by using virtual sound reconstruction. In this work, this methodology is applied to one of the emblematic Islamic temples of the West: the Aljama Mosque of Cordoba. Based on the onsite acoustic measurements carried out in its current state as Mosque-Cathedral, the original state of the Mosque has been reconstructed in the different spatial configurations throughout its history from the 8th to the 10th century. By means of the acoustic simulation of the different models generated from these spatial configurations, it has been possible to reconstruct the sound of the Islamic past of this monumental building. Although the successive enlargements of the mosque managed to maintain visual unity in its interior space, its sound perception has become divided. The values of the main acoustic parameters that characterize this acoustic perception support the hypothesis that spatial division occurs from the point of view of sound.

KEYWORDS: archaeoacoustics, virtual modelling, worship acoustics, acoustic environment, Mosque of Cordoba.

1. INTRODUCTION.

The importance of intangible heritage is recognized in the Convention for the Safeguarding of the Intangible Cultural Heritage [1]. From this convention, a new scientific approach to cultural heritage emerges [2], with new methodologies that include the application of diverse computer technologies, initially focused on the visual aspect, thanks to the potential of immersive visualization and 3D reconstruction of archaeological sites [3]. Other studies took into consideration the incorporation of simulation tools by focusing on sensory features, such as acoustics and lighting [4]. In this regard, the combination of different techniques can be considered as a useful and interesting resource, since the recreation of virtual reality allows the sensory experience to be extended. In this way, the addition of a subjective component that incorporates realistic rendering techniques facilitates the virtual reconstruction of sound, understood as an intangible cultural heritage [5]. Through Archaeoacoustics, and thanks to the virtual acoustic simulation tools developed in recent decades, it is possible to study the acoustic environment of ancient sites and monuments [6], and to recover the sound of heritage spaces that have disappeared or have since undergone major transformation [7].

The recovery of the sound of the past has been applied to various types of approaches ranging from the conception of soundscapes of the past [8], to the expansion of the concept to different ages and cultural contexts [9,10], as well as several building typologies, and with various objectives [11,12,13,14]. These applications include: prehistoric constructions, such as Stonehenge [15], which are rebuilt in their original state; Greek and Roman theatres, as have been carried out in the ERATO Project [16], the Syracuse Charter [17], and by Berardi et al. [18], reconstructed from onsite measurements; ecclesial spaces in the

West that have since disappeared [19] , thereby linking the liturgy and its spatial configuration [20] by modifying the position of the choir space [21] , and analysing the functional use of these spaces for cultural purposes [22]; and ecclesial spaces in the East, such as Sinan's Mosques and the Byzantine Churches, which are reconstructed acoustically as a form of identification, revival and conservation (CAHRISMA) [23].

There is extensive scientific literature on acoustics of worship spaces, with several significant examples throughout history [24], grouped by architectural styles [25], with different measurement techniques [26,27] and simulation techniques [28] , that analyse the acoustics [29], or consider the methodology to be applied in large cathedral spaces [30]. However, acoustic studies on mosques remain scarce. Of these studies, the first work carried out by Hammad [31] stands out, as are those studies that characterize the acoustics of contemporary mosques by means of onsite measurements, through objective indicators of Reverberation Time (T_{30}), clarity index (C_{50}), and Speech Transmission Index (STI) [32], or by Reverberation and Strength (G) [33], or by analysing the degree of intelligibility, both measured and simulated [29]. Furthermore, studies that focus on subjective aspects of Ottoman mosques through subjective surveys [34] are also worthy of note.

The main aim of this work is to reconstruct the sound of the Islamic rite throughout the enlargement process of the Mosque of Cordoba, from its initial creation to the erection of one of the biggest mosques of the time, and to recover the sound of the hypostyle typology of mosques, considered as a prayer space, through the application of acoustic simulation technologies. A second objective involves both the determination of the acoustic quality of the Muslim space, according to the current evaluation criteria applied in room acoustics, and the evaluation of the differences in the acoustic behaviour of each spatial configuration associated to its liturgical function. Therefore, a paradigmatic example of this typology has been chosen, the Aljama Mosque of Cordoba, whose interior space has undergone continuual transformations since the 8th century, with three enlargements as a mosque until its transformation into the current space configuration as a Mosque-Cathedral. The main parameters that determine the acoustic behaviour of this Muslim space in each of its configurations throughout history are obtained by carrying out virtual sound reconstruction.

2. THE MOSQUE OF CORDOBA.

The Mosque of Cordoba was the largest in the western Muslim world and it consolidated the typology of hypostyle rooms. Its preservation, after more than 1200 years, has been possible thanks to its transformation into a Christian cathedral. At present, it can be contemplated as a construction of enigmatic beauty in which the Muslim space fuses with the Christian space, thereby establishing a unit of space that was declared Patrimony of Humanity by UNESCO in 1984.

The typology of a hypostyle mosque responds to the needs of the Islamic rite: it is associated to the principle of maximum simplicity and accommodates a massive congregation. It presents a series of basic elements:

- A covered prayer room divided into aisles, *haram*, preceded by a courtyard, *sahn*.
- A wall facing Mecca, *qibla*, which marks the direction of the prayer, where a small empty niche opens, the *mihrab*.

- A raised platform to the right of the *mihrab*, the *minbar*, from which the Friday sermon, *jutba*, is proclaimed in the aljamas mosques.

The ceremony of Islamic worship that takes place in the mosque establishes a relationship between the faithful and God through two rites:

- Rite of prayer, in which the imam, facing the *mihrab*, directs the collective ritual prayer, consisting of verbal sentences and gestures. The preceptive prayer is shaped by a series of cycles, *rakat*, which accompanies the prayer with repetitive movements of the faithful who are standing, sitting, or prostrated.
- Rite of the sermon, in which the *jatib* or preacher, from the *minbar*, directs the prayers, reads the Quran, and delivers the *jutba* or sermon, which is heard by the seated faithful.

The aljama Mosque of Cordoba was erected in 788 by Abd al-Rahman I, who adopted a typology of hypostyle hall that would become the pattern of the mosques of the West. This mosque is formalized by a square enclosure, where the *sahn* courtyard is located in the northern half and the rest, supported by the south wall that serves as the *qibla*, is a hypostyle space for prayer. The great prayer room, of 74 x 37 m, presents eleven aisles arranged perpendicular to the wall of the *qibla* (Fig. 1.a). The need to design the prayer room with a height of more than 9 m implies the idea of an intelligent constructive solution, with a system of double arches superimposed onto slender columns of small diameter (Fig. 2). This solution generates a diaphanous space that allows its expansion in any direction, of greater breadth than depth, and liberates the maximum surface of the floor for a large number of the faithful, while also enabling a greater visibility of the *imam*.

Faced with a demographic increase in Cordoba, Abd al-Rahman II extended the prayer space in the year 848. The enlargement increased the depth of the prayer hall, breaking through the *qibla* wall and built eight new arcades to the south, and hence the original formal structure was repeated, resulting in a practically square prayer room (Fig. 1.b).

In 966, Al-Hakam II built the most important expansion of the mosque following the same approach put forward in the enlargement by Abd al-Rahman II. The wall of the *quibla* was again broken through and the building extended to the south with twelve new arches, resulting in a prayer room where the depth clearly predominates (Fig. 1.c). The formal mechanisms of the first mosque were repeated by incorporating four skylights with ribbed vaults that introduce natural daylight into the prayer room.

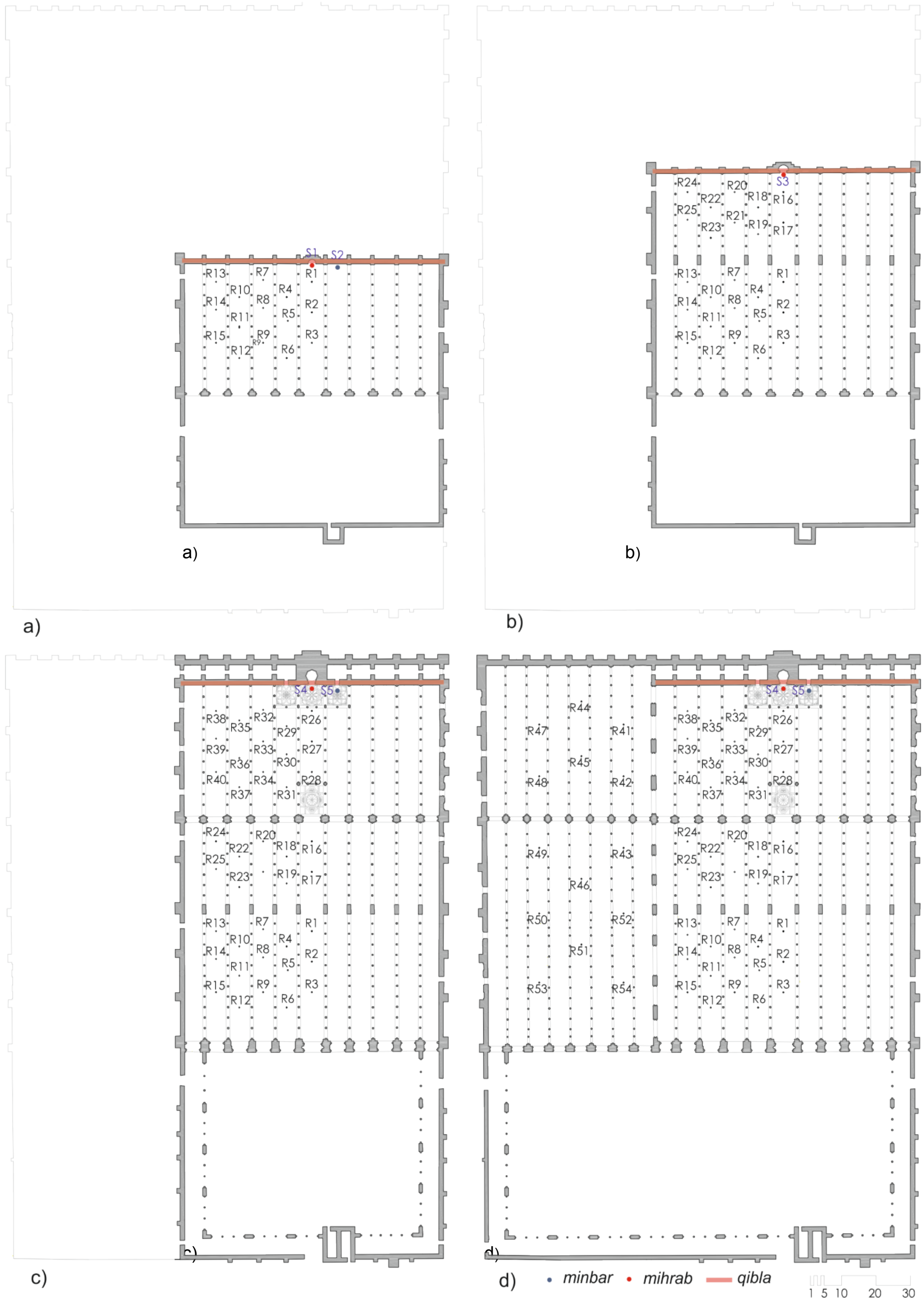

Fig. 1. Floor plans corresponding to each of the historical models: a) Abd al-Rahman I, b) Abd al-Rahman II, c) Al-Hakam II, d) Al-Mansur. Sound source (S) (located at *mihrab* and

minbar) and receiver (R) positions are shown considering each of the models simulated. See Table I for more information regarding receiver positions.

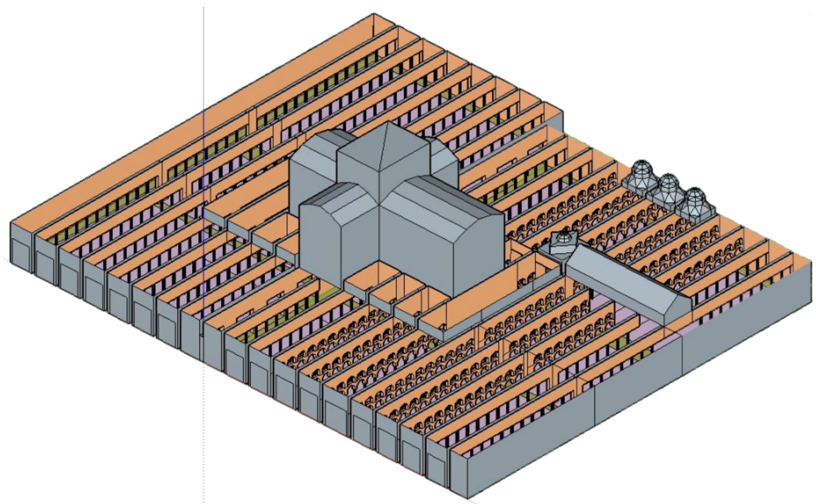

Fig. 2. Image of the current model: a) External point of view; b) Internal point of view (main nave).

The large population of Cordoba in the late X century led Al-Mansur to build the last expansion of the mosque. Faced with the impossibility of further expansion towards the south, the new enlargement was carried out to the east, whereby eight naves were added to the prayer hall throughout its length, by repeating the original formal schema. This enlargement undermines the formal unity, since it widens the building by decentring the *mihrab*, from Al-Hakam II, which is preserved. The result is a large, abstract, and nearly isotropic enclosure, with a length of 79 m and a width of 128 m (Fig. 1.d).

Regarding the spatial division that includes all the enlargements of the Mosque, the "sea" of columns, arches and aisles that form the temple should be borne in mind, since it holds an extremely important role for visual unity and plays a significant part in the indoor acoustics.

3. METHODOLOGY.

The applied methodology aims to identify and acoustically evaluate each spatial configuration, resulting from the different enlargements previously indicated, and also to create a virtual sound environment.

This work is based on the experimental results obtained from the onsite acoustic measurements of the *mihrab* area of the current state of Mosque-Cathedral. Subsequently, based on the results obtained from the experimental technique, the created model has been calibrated in the same unoccupied conditions. The original interior space of the mosque is then reconstructed in each of its spatial configurations [35], with the presence of the audience taken into consideration. Since none of the models, that of the founding mosque and those of any of its extensions, remains available, the creation process has been carried out in an inverse way in order to achieve a proper validation of the acoustic models, that is, starting from the current model until the foundational model is attained.

From the simulations of the acoustic models, the impulse response (IR) is obtained at each of the receiver points, and the most relevant acoustic parameters of each spatial configuration are deduced. Simultaneously, the generated audio signals are used in subjective evaluations and auralizations.

The acoustic simulations were performed with the CATT-Acoustic v9 program [36] with the TUCT v1.0h (The Universal Cone Tracer) version 1.0h, using the algorithm 1, developed by CATT for the acoustic simulation and auralization of enclosures. This software is based on geometrical acoustics (GA) theory [37], which consists of energy-based octave-band echograms. These echograms are calculated in the usual way via pressure-based methods and ray-tracing techniques. These ray-racing techniques involve a ray-tracing algorithm, according to the image source method, a diffuse reflection algorithm by studying the late decay of the sound [38].

CPU-based processors, such as CATT-Acoustic, deal with complex models. In addition, thanks to the development of simulation carried out in rectangular churches, the software application has proved to be robust for the prediction of acoustic parameters [39]. These tests also enable verification of the agreement between CATT-Acoustics results and expectations with the theory of sound diffuse field.

3.1. Acoustic measurement. Calibration of the model.

In order to characterize the acoustic behaviour of the Mosque-Cathedral in its current state, we proceed to measure the various IRs in its interior space. The sound source is placed in the *mihrab* and the 8 receivers are located in the positions indicated in Fig. 3.

The measurements were carried out at night in the unoccupied temple, following the recommendations indicated in ISO 3382-1: 2009.

The generation of the exponential sine sweep signal, to excite the volume, as well as the acquisition and processing of the registered signals, have been carried out with WinMLS2004 software, using the Edirol UA-101 sound card. An AVMDO-12 dodecahedral source has been used with a B & K 2734 power amplifier for the emission of the sweep signal. A self-powered Beringher Eurolive B1800D-Pro subwoofer has been incorporated to improve the low-frequency signal-to-noise ratio.

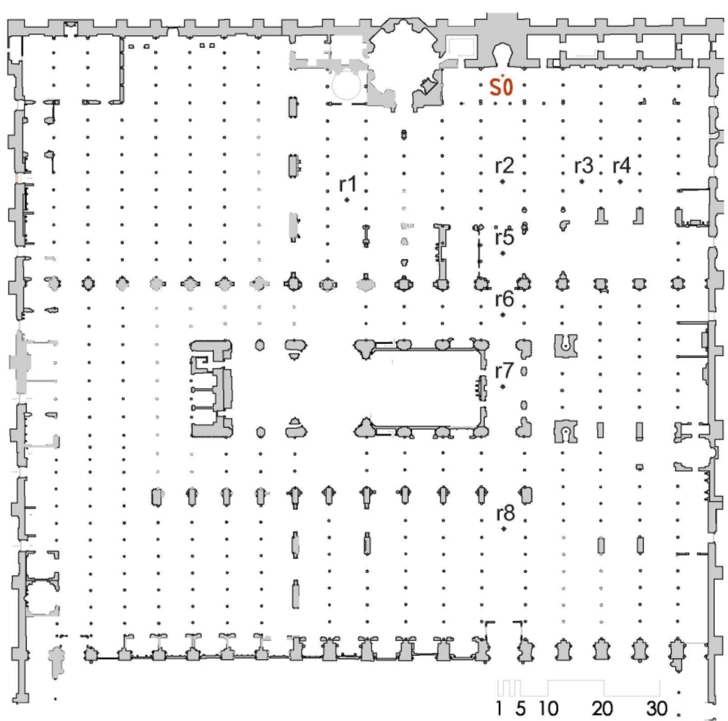

Fig. 3. Floor plan corresponding to the current state of the Mosque-Cathedral. Position of sound source (S) and receiver points during measurement (r1-r8).

Impulse responses have been collected with two types of microphone systems: on the one hand, an Audio-Technica AT4050 / CM5 multi-pattern microphone (omnidirectional and figure-of-8 for future use), was connected to a Sound Field SMP200 polarization source; on the other hand, a Binaural Head Acoustics HMS III (Code 1323) and the B & K-2829 signal conditioner were used for the capture of binaural IRs, for future use.

3.2. Acoustic simulation of the mosque.

Four models (M_) were generated that correspond to the four phases of the mosque described (AR I, AR II, AH II, AM). For each of these models, the spatial zones of each enlargement (Z_) have been differentiated:

- M_AR I: Abd al-Rahman I founding mosque (Fig 1.a).
- M_AR II: Enlargement by Abd al-Rahman II consisting of two zones: that corresponding to the founding mosque (Z_AR I) and that enlarged (Z_AR II) (Fig 1.b).
- M_AH II: Expansion by Al-Hakam II, with three zones: the two previously described and this last enlargement (Z_AH II) (Fig 1.c).
- M_AM: Enlargement by Al-Mansur, which includes the three previous zones and that corresponding to this expansion (Z_AM) (Fig 1.d).

Table 1 specifies the number of receivers considered in each of these zones of the various configurations, located as shown in Fig. 1.

Table 1. Receiver location.

Mosque	Zones	Receivers
Abd al-Rahman I (M_AR I)		R1 – R15
Abd al-Rahman II (M_AR II)	Abd al-Rahman I (Z_AR I)	R1 – R15
	Abd al-Rahman II (Z_AR II)	R16 – R25
Al-Hakam II (M_AH II)	Abd al-Rahman I (Z_AR I)	R1 – R15
	Abd al-Rahman II (Z_AR II)	R16 – R25
	Al-Hakam II(Z_AH II)	R26 – R40
Al-Mansur (M_AM)	Abd al-Rahman I (Z_AR I)	R1 – R15
	Abd al-Rahman II (Z_AR II)	R16 – R25
	Al-Hakam II(Z_AH II)	R26 – R40
	Al-Mansur (Z_AM)	R41 – R54

The sound source is placed in the two configurations of the Muslim rite: the rite of prayer, with the source in front of the *mihrab* (S_Mb), at a height of 1.55 metres, and the rite of the sermon, with the source in the *minbar* (S_Mr), elevated to 3.00 m. The receivers are distributed throughout the temple at a height of 1.65 m from the floor (the faithful, standing), when the source is arranged in the *mihrab*, and at 0.75 m off the floor (the faithful, sitting), when the source is situated in the *minbar*.

It is important to bear in mind that the Christian reconquest resulted in a significant transformation of the ancient Mosque. The development of previous work that evaluates the acoustic environment of Cathedrals [22, 27] has determined the need to simplify this type of acoustic models of large-scale by simplifying the interior geometry and the degree of detail. In this work, the degree of precision in the approximation of the geometric surfaces of the ceiling, arches and columns is greater in the aisles close to the sound source, and it loses precision as the source-receiver distance increases. In this regard, the assignment of sound diffraction coefficients to the aforementioned surfaces takes on a special role (Table 2). Therefore, for the development of the work, a simplified geometric model has first been created, with an approximate volume of 155,000 m^3, which reproduces the Mosque-Cathedral in its current state.

In order to calibrate the acoustic behaviour of the virtual model to the real model as precisely as possible, an iterative process of adjusting the absorption and scattering coefficients was carried out. On the one hand, data collection of absorption coefficients was carried out by categorizing the existing materials in the space after a visual inspection in the current model. On the other hand, the values of the coefficients of materials of ancient models were largely extracted from the scientific literature specified in Table II. Regarding materials employed to calibrate the model, the reference upon which the coefficient adjustment has been based is indicated.

In relation to scattering coefficients, the assignment was carried out in terms of the roughness of the surfaces of the model. The previous calibration of other Andalusian cathedrals facilitated the work by establishing baseline values [22]. In the case of there being an audience present, coefficients were determined following considerations of other studies with similar complex models , and values were set between 0.55 (125 Hz) and 0.80 (4 kHz) for an audience present, and between 0.25 (125 Hz) and 0.50 (4 kHz) for vaults. It should be borne in mind that the simulation model was resimulated using auto-edge scattering and previous results and there is hardly any variation in relation to the former model in terms of the results of the acoustic parameters.

Table 2. Sound absorption and scattering coefficients associated with the main materials used.

Material	S [%]	Coeff.	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Stone* [38]	42.8	α	0.02	0.02	0.03	0.03	0.04	0.05
Wood* [40]	25.8	α	0.15	0.11	0.10	0.07	0.06	0.07
		s	0.25	0.25	0.25	0.25	0.25	0.25
Standing congregation [41]	23.5	α	0.15	0.38	0.90	0.99	0.99	0.99
		s	0.55	0.60	0.65	0.70	0.75	0.80
Sitting congregation [42]		α	0.21	0.47	0.84	0.99	0.99	0.99
		s	0.55	0.60	0.65	0.70	0.75	0.80
Carpet [42]	4.4	α	0.11	0.14	0.37	0.43	0.62	0.75
Lime plaster [38]	2.2	α	0.02	0.02	0.03	0.03	0.04	0.05
Stone vaults*	1.3	α	0.12	0.14	0.16	0.16	0.16	0.16
		s	0.25	0.30	0.35	0.40	0.45	0.50

* Materials employed to calibrate the model. α represents the absorption coefficients, and s the scattering coefficients (value of flat surfaces: 0.1).

The calibration process carried out with TUCT v1.0h is considered complete when the averaged acoustic parameters considered in the study differ from the measured values by no more than 1 JND in the case of T_{30} (5%), and by no more than 2 JNDs in the case of D_{50}. These ranges are acceptable for this type of large-volume space [22]. Figure 4 presents the comparison of results attained from these two parameters on considering the source located at *mihrab* and all receiver points used during measurements, as shown in Figure 3. Regarding the boundary conditions, the number of rays used in the calculations was established according to the size of the space. Firstly, a ratio of 1.5 times the number of rays was considered, previously having verified that the rays converge and are based on a recommendation of the software. Secondly, the length of the room impulse response was set individually, since it was longer than the measured reverberation time. Based on the aforementioned assumptions, in this work the calculations were obtained with the TUCT v1.0h (The Universal Cone Tracer) engine, using 500,000 rays and a 6-second truncation time.

On the other hand, a simplification of the model was conducted and a removal of the exhaustive details was carried out, since geometrical simplification of the model has been proved to not affect the results and to significantly reduce the computation time. In this regard, after proving that the arrival of very late reflections from farther surfaces did not exert any influence on the values of the acoustic parameters, the degree of detail of superimposed double arcs of the farthest aisles was reduced in order to significantly decrease the number of planes involved.

Once the current model has been validated, the following models can be created: M_AR I, M_AR II, M_AH II, and M_AM.

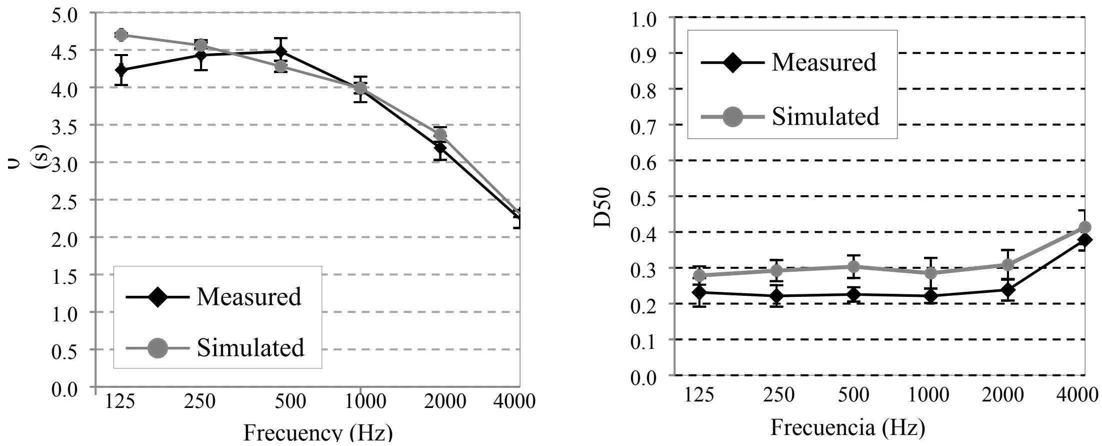

Fig. 4. Comparison between measured and simulated results obtained for T_{30} and D_{50}.

3.3. Evaluation of acoustic parameters.

The acoustic evaluation of the space is carried out from the main objective acoustic parameters defined in ISO 3382-1: 2009 that are associated to the use of this space: prayer, preaching, lecturing, and recitations from the Quran. The quantification of the reverberation is presented by the analysis of the time parameters, reverberation T_{30} and EDT; the definition of the recited word is determined using the parameter D_{50} and the STI parameter, which allow the degree of intelligibility of the word to be quantified. Regarding information that affects the calculation of acoustic parameters, a white spectrum was considered for the sound source, where the SPL values at a height of 1m on the axis of the natural source were 94 dB at 1 kHz. However, in the case of the STI parameter, sound source characteristics must meet the specifications of the human voice, and estimated background noise should be taken into account. Therefore, a specific speech spectrum whose directivity "*Singer_on axis. SD1*" was downloaded and imported from the CATT website. In addition, the coordinates of a point located in the occupied zone was determined in order to establish the point of view of the source. In relation to the background noise, a NCB 28 curve (Balanced Noise Criteria) was considered since it was set according to the spectrum of the NCB Curve recommended for concert halls or similar (less than 30 NCB).

First, an overall analysis of each of the configurations is made whereby all measurement points in each zone are considered. Subsequently, a zonal analysis is performed within each spatial configuration, whereby only the receiver points of each zone are taken into account. This analysis has been used in ecclesial spaces in order to ascertain the acoustic complexity of these spaces [43], and has been associated with an analysis regarding liturgical uses [44,45].

3.4. Auralizations

The acoustic analysis is complemented by auralizations, which can be defined as the technique of creating audible sound files from numerical (simulated, measured, or synthesized) data [37]. Auralizations allow the subjective perception of the sound by a specific receiver to be attained and the acoustic differences of the various spatial configurations of the Mosque to be appreciated.

As complementary material, the study includes four audio files that reproduce the acoustic conditions of the four spatial configurations of the Mosque, whereby the sound source in the *mihrab* of each configuration is considered: the founding mosque (ABD I_S1_R10.wav), the enlargement by Al-Rahman II (ABD II_S3_R10.wav), the expansion by Al-Hakam II (ALH II_S4_R10.wav), and the last expansion by Al-Mansur (ALM S4_R49.wav).

The files are the result of the convolution of an anechoic recording with binaural simulated responses, processed with MultiVolver software, which is a complementary tool for CATT-Acoustic. The anechoic signal is a fragment of 1:01 minute of a *salat* (salat_anechoic.wav) recording for the CAHRISMA project by the Acoustic Research Group of the Engineering Department of the University of Ferrara, Italy, headed by Roberto Pompoli.

4. ANALYSIS OF RESULTS.

4.1. The founding mosque of Abd al-Rahman I

The founding mosque of Abd al-Rahman I (M_AR I) (Fig. 1a), with a volume of 23,429 m^3, obtained a T_{30} value of 2.2 s in mid frequencies when the prayer room was occupied by about 2500 worshippers (Fig. 5.a). This value of T_{30} would be high for the transmission of the verbal message with normal diction when the words overlap. For this reason, the *imam*, located in front of the *mihrab*, recited the sacred word of the Quran in a solemn way, and adapted the recitation of the text to the reverberation of the mosque, using the *taywid* rules, as heard in the complementary ABD I_S1_R10.wav audio. Following these rules, the imam recites the Quran slowly and clearly, with a syllabic style, differentiating the words, using the so-called *tartil* technique.

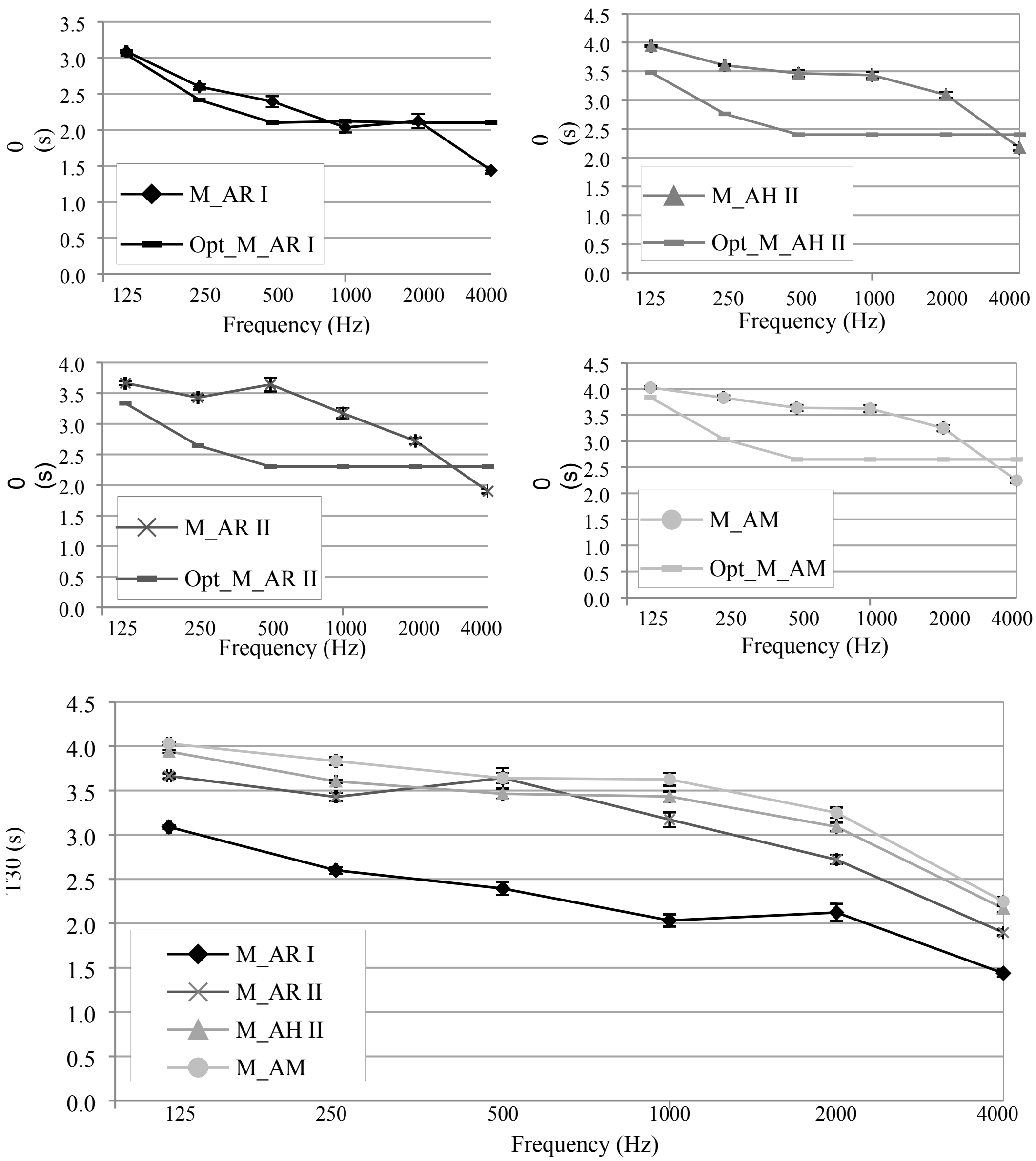

Fig. 5. Comparison between simulated and optimal results for T_{30} [46] : a) Abd al-Rahman I; b) Abd al-Rahman II; c) Al-Hakam II; d) Al-Mansur; and e) comparative T_{30} of all extensions.

With STI values higher than 0.6, the intelligibility is considered as GOOD in the central nave and this rating decreases with depth within each of the rows, due to the increasing distance from the sound source. This intelligibility, however, can be considered as FAIR in most areas of the prayer room (Fig. 6). The lowest STI values are obtained at the R12 and R15 receivers, where the intelligibility is considered to be POOR. There are points located at shorter distances from the source and with better behaviour; however, the nearby location of the columns can generate a virtual wall that makes intelligibility difficult, especially at those points located in the furthest aisle, where the number of virtual walls is multiplied. On the other hand, the Definition decreases at the back of the room, with D_{50} values lower than 0.3 (Fig. 7.a), due to the decrease of reflections from the furthest wall, since the room is open to the courtyard, which causes a loss of part of the comprehension of the verbal message.

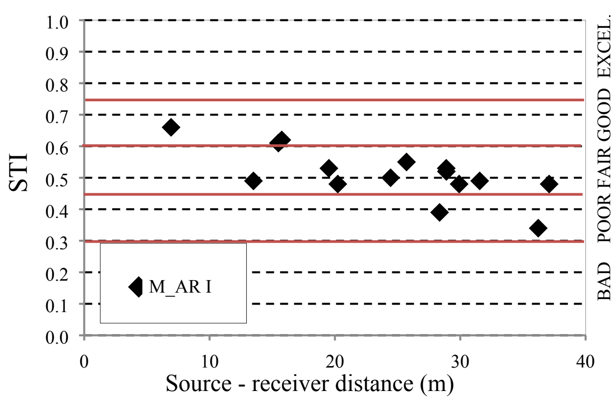

Fig. 6. STI value with respect to distance. Abd al-Rahman Mosque I.

When the sermon was delivered from the *minbar*, the sound source A2 was elevated to a height of approximately three metres (Fig. 1a), and it became more audible, with an improvement of 1 JND in the average values of D_{50} (Table 3). The voice of the *jatib* travelled over a greater distance and covered a larger area of the congregation, since sound was distributed in the naves thanks to the diffused reflections of the coffered wooden ceiling, which favour the intelligibility of the verbal message to the listeners sitting on the floor (Fig. 8).

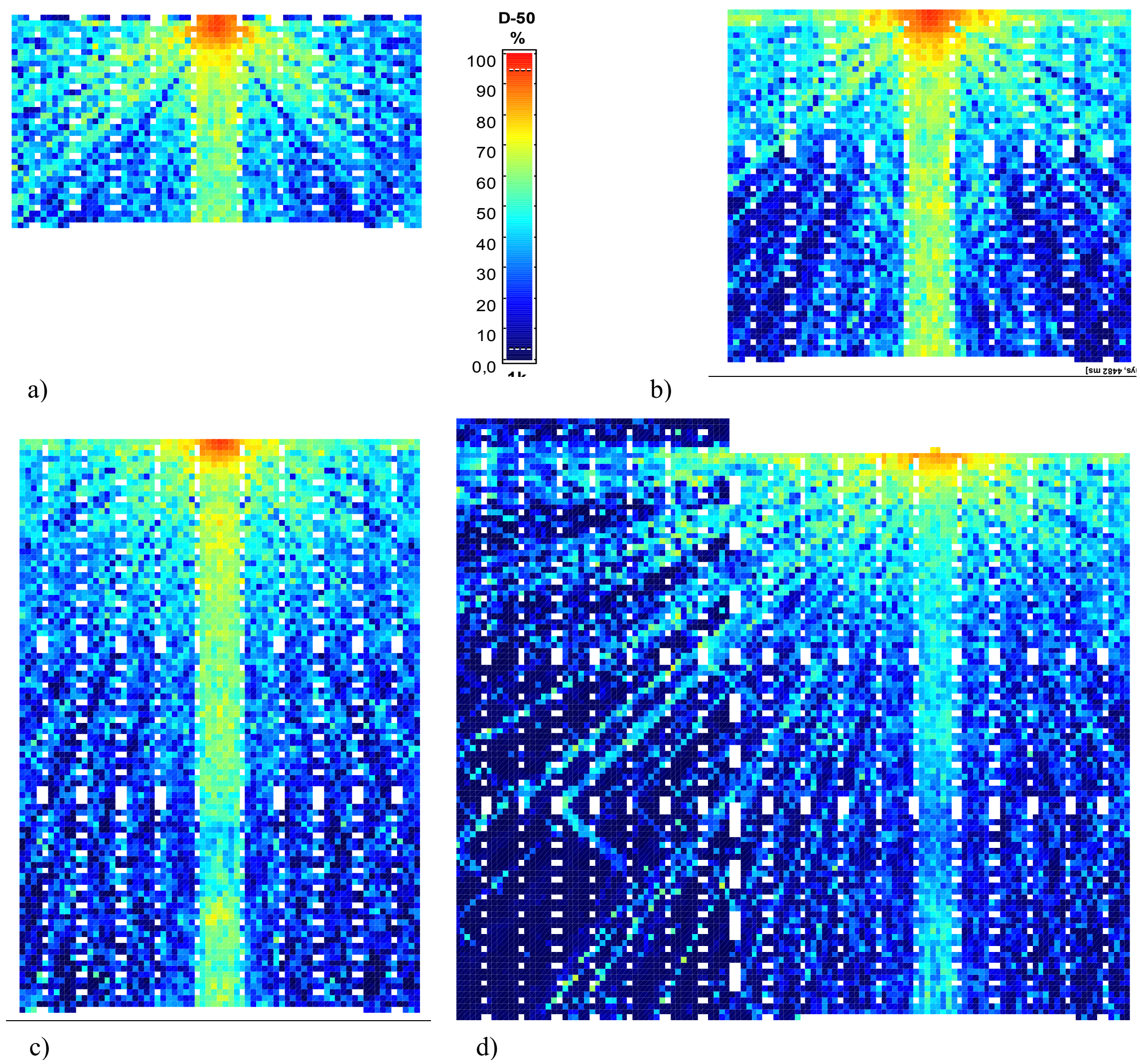

Fig. 7. Mappings of D_{50} for 1kHz: (a) Abd al-Rahman I; (b) Abd al-Rahman II; (c) Al-Hakam II; (d) Al-Mansur.

Table 3. Summary of average values and standard deviations of acoustic parameters analysed. Spatial average values by model and zone.

Model	Source		T_{30}		σ	EDT		σ	D_{50}		σ	STI		σ
M_AR_I	S1	S_Mb	2.21	±	0.07	1.59	±	0.08	0.44	±	0.04	0.51	±	0.02
M_AR_I	S2	S_Mr	2.10	±	0.09	1.23	±	0.09	0.56	±	0.05	0.49	±	0.02
M_AR_II	S3	S_Mb	3.41	±	0.10	2.08	±	0.10	0.33	±	0.04	0.45	±	0.02
Z_AR_I	S3	S_Mb	3.31	±	0.13	2.26	±	0.11	0.26	±	0.05	0.40	±	0.02
Z_AR_II	S3	S_Mb	3.55	±	0.14	1.79	±	0.15	0.44	±	0.04	0.53	±	0.03
M_AH_II	S4	S_Mb	3.45	±	0.06	2.58	±	0.11	0.26	±	0.03	0.41	±	0.02
Z_AR_I	S4	S_Mb	3.52	±	0.11	3.05	±	0.14	0.17	±	0.04	0.32	±	0.03
Z_AR_II	S4	S_Mb	3.45	±	0.07	2.84	±	0.12	0.21	±	0.04	0.41	±	0.02
Z_AH_II	S4	S_Mb	3.38	±	0.08	1.95	±	0.12	0.38	±	0.04	0.51	±	0.03
M_AM	S4	S_Mb	3.63	±	0.06	3.01	±	0.15	0.26	±	0.02	0.38	±	0.02
Z_AR_I	S4	S_Mb	3.70	±	0.12	3.34	±	0.19	0.20	±	0.04	0.30	±	0.02
Z_AR_II	S4	S_Mb	3.61	±	0.10	2.68	±	0.12	0.27	±	0.05	0.42	±	0.02
Z_AH_II	S4	S_Mb	3.34	±	0.12	1.81	±	0.18	0.43	±	0.04	0.53	±	0.03
Z_AM	S4	S_Mb	3.92	±	0.15	4.26	±	0.20	0.13	±	0.04	0.26	±	0.03
M_AM	S5	S_Mr	4.12	±	0.22	3.16	±	0.14	0.30	±	0.03	0.35	±	0.02
Z_AR_I	S5	S_Mr	4.12	±	0.45	3.53	±	0.19	0.20	±	0.03	0.27	±	0.02
Z_AR_II	S5	S_Mr	4.14	±	0.34	2.96	±	0.15	0.25	±	0.04	0.34	±	0.03
Z_AH_II	S5	S_Mr	3.62	±	0.26	2.16	±	0.21	0.47	±	0.04	0.50	±	0.03
Z_AM	S5	S_Mr	4.74	±	0.70	4.02	±	0.31	0.23	±	0.06	0.28	±	0.03

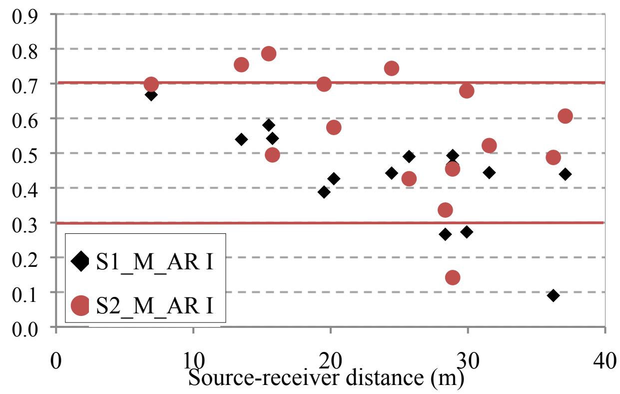

Fig. 8. D_{50} value with respect to distance, with sound source in *mihrab* (S1) and *minbar* (S2). Abd al-Rahman Mosque I.

4.2. Enlargement by Abd al-Rahman II

With the extension by Abd al-Rahman I (M_AR I) (Fig. 1.b), the proportion of the prayer room is modified, resulting in an almost square enclosure with a volume of 38,915 m^3. The new dimensions represent a clear variation of the acoustic conditions. The reverberation time increases T_{30} mean values to the order of 3.4 seconds, which is far from optimum conditions (Fig. 5.b), although the subjective sensation of the room reverberation is lower, with EDT mean values of approximately 2 seconds (Table III). The liveliness of the room would be neutralized with the emphasized recitation performed by the *imam*, as could be heard in the ABD II_S3_R10.wav audio file. The characteristics of the recitation, such as the high-pitched voice recording, together with the combination of sound effects, such as nasalization, extension of phonemes, pauses and repetition, promote the intelligibility of the text, and result in STI values greater than 0.50 in most areas of the prayer room.

However, the increase of depth, together with the acoustic shadows produced by the buttresses of the ancient *qibla* of Abd al-Rahman I, lead to an attenuation of sound and a decrease in early reflections in the more remote areas of the *qibla*. D_{50} values were lower than 0.30 in the area of the Abd al-Rahman I mosque (Z_AR I), except in the central nave (Fig. 7.b). This in turn leads to a spatial hierarchy, due to a sound differentiation in the prayer room.

4.3. The expansion by Al-Hakam II

The new expansion of Al-Hakam II (M_AH II) (Fig. 1. c) introduces a new spatial order in the Mosque as a whole, due to the variation of the dimensions of the Mosque by creating a space of great depth and a volume of 61,781 m^3. Despite the increase in volume, the T_{30} values show no significant increase, although the reverberation sensation increases slightly with EDT mean values of 2.58 s (Table III). This sensation would increase the appearance of a greater spatial dimension, since the sound extinction is prolonged beyond the action of the *imam*'s voice in the recitation of the Quran, as can be perceived in the audio of complementary material (ALH II_S4_R10.wav). This increase of reverberation promotes a feeling of proximity to the divine, with a diffuse sound devoid of clear directionality that is rhythmic and rich in harmonics.

The increase in the depth of the mosque leads to a variation of the acoustic behaviour, with a greater time delay and the appearance of different levels of sound perception.

The spatial distribution of the intelligibility is not uniform, and decreases with the distance from the *qibla*, with an STI average of 0.47. Although it can generally be described as

FAIR, major dispersion occurs, as can be observed between the maximum and minimum values (Fig. 9 and Table III).

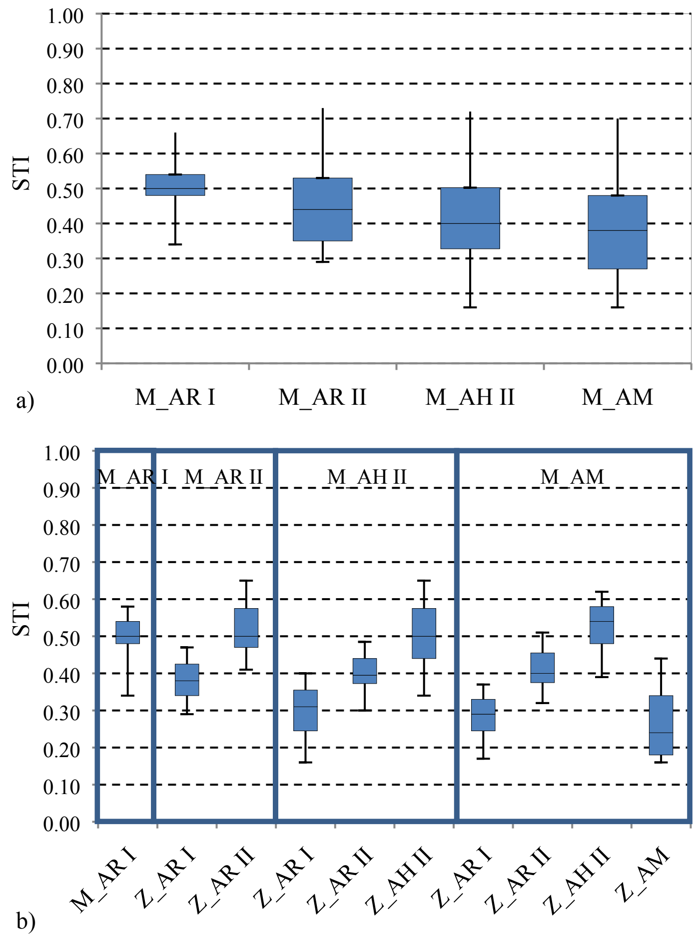

Fig. 9. Typical deviation values of the STI parameter in: a) each mosque model; b) each zone of each model.

Consequently, a sound hierarchy of the prayer room is detected, which is configured as the sum of two juxtaposed mosques. The faithful located in the area expanded by Al-Hakam II could hear the voice of the *imam* with average STI values of 0.52 and D_{50} of 0.38 (Table III). The rest of the faithful, in addition to being unable to see the *imam*, would experience difficulties in hearing clearly from a distance of over 30 metres, with differences in mean values of 1.5 JNDs in the zone of Abd al-Rahman II (Z_AR II) and of 2 JNDs in the zone of Abd al-Rahman II (Z_AR I) (Fig. 7.c). In spite of these differences, the acoustic conditions remain more favourable in the central nave, where the sound is trapped in, and hence the reflections would provide suitable intelligibility to a greater distance, close to 80 m, with average D_{50} values of 0.38, thus rendering the Islamic liturgical axis acoustically perceptible.

4.4. The expansion of Al-Mansur

The last expansion by Al-Mansur (M_AM) (Fig. 1.d), reinstates the importance of the width, despite having the *mihrab* off-centre, with the subsequent loss of symmetry. The result is a large enclosure of 108,854 m^3: an undefined space to accommodate about 11,500 faithful. The significant dimensions of the mosque imply an increase of the T_{30} mean value, at approximately 3.5 s, which is far from the optimum values (Fig. 5.d). The main consequence of enlargement is the loss of the unity of the prayer space; the sound fragmentation of the area is now more evident. The new space is, in effect, the grouping of several mosques, each with their own levels of sound perception (Fig. 7.d), with different subjective reverberation in each area of the prayer room (Fig. 10), up to 8 JNDs of difference, and a high variability of the standard deviation values of the STI parameter (Fig. 9 and Table III).

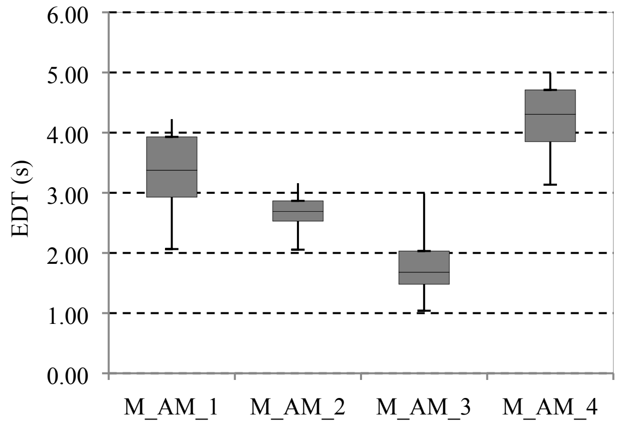

Fig. 10. EDT values for each area of the Al-Mansur mosque.

When enlarging laterally, the Al-Hakam II mosque (M_AH II) was maintained, and the acoustic behaviour is very similar to that described previously. The buttresses of the former eastern façade of the Al-Hakam II mosque, now traversed from the last enlargement, generate major acoustic shadow zones in the new area added by Al-Mansur (Z_AM), which makes the arrival of direct sound impossible in certain zones. This results in average D_{50} values of 0.13, and a difference of 3 JNDs with respect to the mean values of zone Z_AH II. This D_{50} value, together with an average EDT value of more than 4 s (Table III), results in the perception of a distant reverberant sound that seems to come from above, partly due to the significant sound absorption of the floor surface occupied by the faithful, as can be heard in the auralization of this space (ALM S4_R49.wav).

Therefore, the functionality of the Muslim rite, which fixes the sound source to the wall of the *qibla*, establishes a sound differentiation which configures the space of the Aljama Mosque. As in other worship spaces [20], the increase in the size of the prayer room promotes the multiplicity of the acoustic environments. The faithful lose their visual contact with respect to the source, and the sound acquires a new dimension thanks to the reverberation. The intelligibility loses prominence in the face of sensory experience. The reverberation stands out as the condition of a sacred place, by managing the perception of the faithful who are immersed in an enveloping environment as that which brings them closer to the presence of God.

5. CONCLUSIONS

The hypostyle mosque model that represents the founding mosque of Abd al-Rahman I responds acoustically to the Islamic liturgical requirements, and provides a living space that promotes the sense of majesty of these spaces, without the excessive reverberation that its greater volume implies. The enlargements of the mosque that follow the model of the founding mosque adopt an overlap mechanism, which gives it the same appearance obtained by repetition. However, these enlargements imply clear variations in relation to sound.

The variation of the proportions of the floor plan supposes a significant change in the sound perception. The mosque cannot be extended laterally, since in the Islamic ceremony of radial character, the extremes of the space would be practically invisible and inaudible. In the same way, the depth of the space is conditioned, a preponderance of sound in the area closest to the *qibla* appears, along with the increased importance of the central nave, and a progressive sound inferiority of the rows furthest from the *qibla* wall.

The horizontal interior space of the mosque, with a large visual unit, has an appreciable multiplicity of sounds. The mean values of T_{30} in each zone of the various extensions vary from 3.3 to 4.7 s, while the mean values of the first mosque of Abd al-Rahman I were of

2.2 s, which approaches optimum reverberation time values. This disparity between the mean values of each zone becomes more pronounced when the other parameters are analysed, with mean EDT values of the different zones ranging from 1.79 to 4.26 s and mean values of D_{50} ranging from 0.13 to 0.47, which is indicative of different acoustic behaviour. The standard deviation of the values of these parameters in each zone is greater than that corresponding to the global analysis of each enlargement. This statement verifies the fact that each zone can be considered as a separate acoustic environment that is more homogeneous than that of the whole enclosure.

From the acoustic point of view, two of the determining factors of this spatial fragmentation are the location of the sound source, which is associated with the position of the *mihrab*, and the shape of the prayer room. In the founding mosque of Abd al-Rahman I, the sound source is located at the midpoint of the longest side of a rectangle, which contributes towards providing suitable intelligibility that is consistent with the occupation of the mosque with rows in the direction the *qibla* wall. In the first extension of Abd al-Rahman II, the sound source is located at the midpoint of the side of a square, with an increase in depth, which leads to greater sound attenuation and a decrease in the first reflections in the zones furthest away from the *qibla*. Consequently, the D_{50} values are lower than 0.30. With the subsequent extension of Al-Hakam II, the sound source is located at the midpoint of the shortest side of a rectangle, which supposes a noticeable increase in the depth and a decrease in the intelligibility of the spoken word at distances greater than 30 m. Finally, in the extension of Al-Mansur, the sound source is located at a point displaced from the midpoint of the side of a square, thereby generating a decoupling of the amplified zone due to the decrease in direct sound, and the acoustic behaviour of a reverberant field, which implies an even greater degradation of the perception of the verbal message.

In the light of these results, the increase in area and, consequently, in the volume of the temple, has generated significant deterioration of the acoustic conditions. The enlargement interventions failed to take the functional aspect of the mosque and gave the highest priority to mainly the aesthetic aspect. It would be advisable to provide practical recommendations of potential improvements, which could be classified largely through the incorporation of ephemeral decoration, however, the ceremonial nature of the Islamic rite provides no solutions that can be incorporated.

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