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Geometrical acoustic modelling of occupied acoustic conditions in mosques: Application to a case study ☆

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ABSTRACT

Old religious buildings represent an essential cultural heritage whatever the country or the religion they belong to. Thanks to many researches carried out in the last years, their acoustics is now considered part of this heritage. However, for practical reasons, their acoustic characterization is often made under unoccupied conditions, while, given the frequent use of hard reflecting surfaces, the occupied conditions may differ significantly. Geometrical acoustics may represent, if properly used, a valid tool to simulate how sound propagates in an occupied space, allowing to investigate the effect on the full set of acoustic parameters. Occupancy in mosques may be more challenging to simulate than in other spaces because of the different postures of the worshippers and the usually high absorption that they introduce because of high density of occupants. To correctly simulate such effects, a specific modelling approach has been proposed starting from reverberant chamber measurements and validating them against on-site measurements. Using the proposed method, the effect of occupancy in the Jedid Mosque in Algiers, which was built in 1660, in a typical Ottoman style, and later restored in 1855, was studied. The mosque was chosen because it is large and reverberant to allow a better appreciation of the variations due to occupancy. The geometrical acoustic model was first carefully calibrated against measurements in unoccupied conditions, which also pointed out a clearly non-diffuse behaviour in the space, and, finally the occupancy was added. Results showed that due to the strong concentration of absorbing elements on the floor, where carpets already contributed to absorb sound, the occupancy mostly affected reverberation parameters, while clarity for speech remained poor.

1. Introduction

The acoustics of worship buildings has been receiving increased attention only in the last two decades, when a number of works have been published in order to better understand the specific acoustic features of such buildings, and how the combination of shape and materials contributed to characterize their behaviour, also in relation to the ritual aspects and common practices. With reference to mosques, through an exploration of the acoustics of ancient places [1–7], particularly Ottoman ones, some features have been finally revealed, but several things still need to be better understood.

As with other worship spaces, mosques present interesting acoustic effects and challenges. One of the first systematic studies to explore such features was carried out within the CHARISMA project, that particularly investigated Ottoman mosques designed by Sinan [8,9]. Other researchers followed in the years. Elkhateeb and Ismail [2], studied the reverberation time and other acoustic indicators such as Speech Transmission Index (STI) in the madrasa (school) and mosque of sultan Hassan (Cairo, Egypt), using field measurements and computer simulation. Sü and colleagues [3,5] investigated the acoustics of several Turkish mosques, including both historical buildings like Kocatepe Mosque in Ankara and Hagia Sophia in Istanbul [6], and more recent buildings

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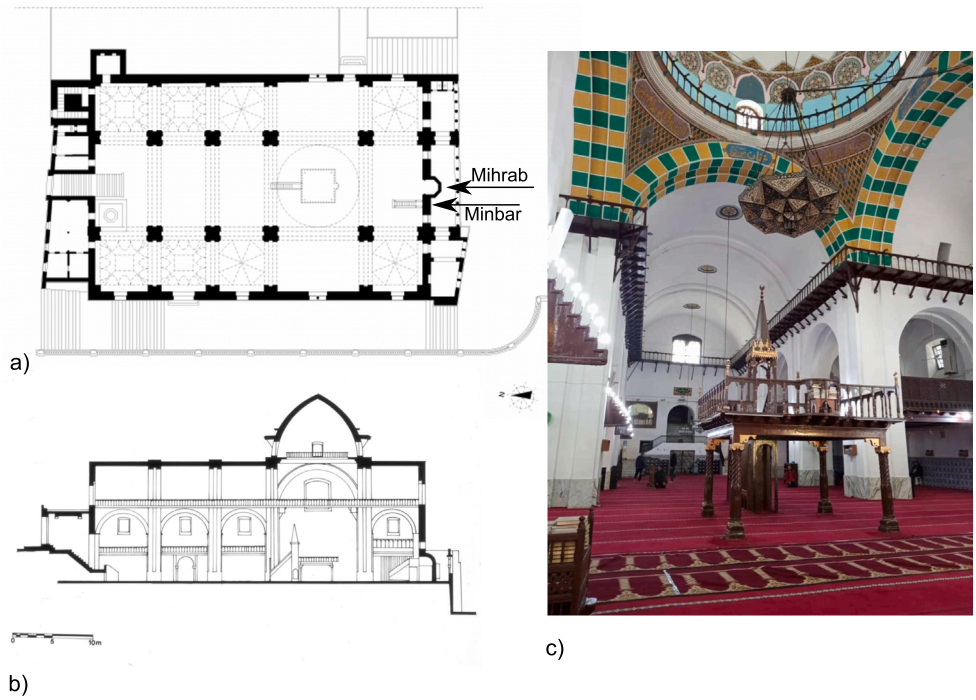

Fig. 1. Plan (a), cross section (b), and (c) interior view of Jedid Mosque, Algiers.

like Doğramacizade Ali Paşa Mosque [4]. With reference to contemporary buildings, Abdou [1] studied 21 modern mosques.

Among the elements that characterize the acoustic response of mosques, there are a few that stand out in particular. The presence of carpets on the floor is one of the major elements that characterize the acoustics of mosques as compared to other historical worship spaces, introducing an absorbing surface distributed throughout the space. The position of sound sources is another important characterizing element, related to the clear identification of the location of the Mihrab (i.e. the niche in which the Imam guides prayers toward the direction of the Sacred Mosque in Mecca), and of the Minbar (i.e. the raised pulpit at the right side of the Mihrab, where the Imam stands to deliver sermons), as shown in Fig. 1. These two source positions also correspond to different posture of the worshippers, resulting in further acoustic differences. In both cases, as music is not used in mosques, speech intelligibility is the key acoustical factor that needs to be investigated. This is a requirement that many other worship spaces, including Christian and Judaic, have in common [10]. In all the cases there are parts of the worship (usually sermons and readings) that require the highest intelligibility, while other parts (prayers or chants, depending on the rite), may accept, or require, more relaxed parameters.

The effect of occupancy is a key element that characterizes the acoustics of every worship place, because people introduce a significantly large amount of absorption that may induce large variations in acoustics compared to the unoccupied situation. This is particularly true in all those worship spaces, like churches [11], where historically, the sound absorbing surfaces were rather limited and the number of occupants could be very large. Mosques usually have carpets on the floors that certainly imply the presence of a permanent absorbing area, although concentrated on a single surface and characterized by a non-flat frequency response that mostly affects medium and high frequencies [9,12]. Thus, investigating the effect of occupancy in mosques offers interesting occasions to understand how the presence of the worshippers on the absorbing floor affects sound propagation by actually emphasizing the concentration of the sound absorption on the same surface, with all the relevant implications on sound propagation, and its relation with the rituals which require, particularly during preaching, a better speech intelligibility.

One key issue in this process is due to the difficulty of performing acoustic measurements under fully occupied conditions and, consequently, the need to rely on acoustical simulations to gain insight through some approximations. As demonstrated in several studies this process requires a careful setup of the acoustic model [11,13–15] and a proper modelling of the occupants [16] based on reliable data. To this purpose many authors measured absorption coefficients of audiences in reverberant chambers [17] and with reference to specific venues like concert arenas [18], churches [19], and mosques [12]. Some of these works considered the effect of different posture of the occupants, as well as different clothing. Based on the results of the measurements, one problem that may arise when using such absorption values in simulation tools is the difficulty of modelling the audience. In fact, in concert halls and other comparable spaces, the conventional approach is that of modelling audience as an extruded block surrounded by aisles, distributing the absorption to the exposed surfaces of such blocks, in combination with increased scattering. However, a dense audience, particularly if standing, may be very sound absorbing, resulting in an absorption per person that, when expressed in terms of absorption coefficients (referred to area projected on floor, instead of actual area of exposed body), may easily be larger than one. If this is not a big problem when performing calculations using Sabine's formula, in simulation tools where absorption coefficients cannot exceed one, poses some problems that are not yet been clarified as to which is the better modelling approach.

The present paper, starting from the acoustic measurements carried out in one of the most important historical Algerian mosques, the Jedid Mosque in Algiers, investigates the effect of the occupancy on the acoustics of the space by means of geometrical acoustic simulation, also exploring which is the best way to model such phenomena when using these tools. The results obtained in different occupancy situations are then presented together with a brief discussion.

2. Methods

2.1. Description of the mosque under study

The Jedid Mosque, also called Djama'a el Djedid, was built in 1660. The building was built during the reign of the Aghas, who wanted to

Fig. 2. Photographs of Mihrab (a), and Minbar (b) of the Jedid Mosque, Algiers; c) location of source and receivers in the mosque.

express their supremacy through a distinguished architectural style [20–22], as the funding for the construction work came from an association (state-affiliated institution) called Subul al Khayrat. It is worth recalling that at this time the Ottomans may have been seeking to establish a style that reflected their dominance, hence the use of Christian captives and renegades as craftsmen and masons. The Jedid Mosque represents one of the first achievements of this style in the Maghreb.

The interior of the mosque (Fig. 1) reflects an Ottoman inspiration, as it is very similar to the mosques of Brousse, especially Ulu Cami of Brousse, built in 1400 [22]. The prayer hall is rectangular in shape and measures 39.5 x 24 m, covering an area of 1371 m^2. A large ovoid dome dominates the building. It is located at the intersection of the two barrel vaults, placed above the two naves. Four small squares, covered by small octagonal domes, supported by pendentives at a lower level, result from this crossing.

The exterior of the building is decorated with merlons, reflecting the traditional Maghrebi architecture. The prayer hall has a rather sober decoration, characterized mainly by a white and blue tiled base along the walls of the prayer hall. However, the Mihrab, the Minbar and the central dome are richly decorated. The dome is decorated with openwork plaster and ceramic tiles of different designs, covering the pendentives. The minbar is in white marble, very rich in sculpted decoration.

2.2. Measurement method

Acoustic measurements were carried out in compliance with international standards and protocols in order to ensure repeatability and data comparison among different research groups [23]. Source positions were chosen considering both transformations of the structure of the building (additions, demolitions), and the possible evolution of the source location along time according to worship needs [24]. In order to balance between a more detailed survey and the need to minimize measurement time to avoid interfering with ordinary activities, two source positions were chosen corresponding to the Mihrab (A) and Minbar (B) (Fig. 2a,b). In compliance with standards, and following similar studies on mosques, the source was at 1.55 m above the floor, and at least 1.0 m from reflecting walls. Source A was at 1.5 m from the Mihrab wall.

Receivers were distributed among the different seating areas, so to have a good description of the acoustic differences (Fig. 2c). According to ISO 3382-1 [23], receivers should be placed at 1.2 m above the floor, and at least at a quarter wavelength of the lowest frequency of interest from reflecting surfaces. For mosques this recommendation was not a problem for source A (Mihrab), for which worshippers stay standing, thus distance from the floor was set to 1.65 m. Conversely, for source B (Minbar), worshippers must be seated on their knees, so, despite ISO recommendation, receivers height for source B was set to 0.85 m as proposed by other authors [1].

With reference to equipment, all the measurements were carried out strictly complying with ISO 3382-1 standard [23]. An omni-directional sound source (B&K 4292), made of twelve loudspeakers mounted on a dodecahedron, was used, with a frequency response from 50 Hz to 16 kHz. An omnidirectional microphone (Behringer ECM800, diameter 13 mm), was used to collect the signal. In order to measure the impulse responses for each source receiver combination, the open-source Audacity software with Aurora plug-in was used to generate a logarithmic sine sweep, play it back and simultaneously record the room responses using a sound card (Onyx Artist 1.2). The sine sweep was characterized by frequencies varying from 20 Hz to 10000 Hz, and 20 s duration so to cover the typical frequency range and provide a sufficiently high signal-to-noise ratio.

Acoustical parameters were calculated by means of MATLAB scripts developed in compliance with standard requirements. With reference to reverberation time, T30 was calculated at every receiver position, thanks to the good signal-to-noise ratio provided by the measurement chain. Among the other monaural acoustic parameters, early decay time (EDT), centre time (Ts), and clarity were calculated. In the latter case only C50 was considered as speech was clearly more appropriate to mosques.

2.3. Acoustic simulation of the space

In order to take into account the effect of occupancy a common research approach is that of measuring the space under unoccupied conditions and then use acoustical modelling (usually based on geometrical acoustics (GA)), to simulate the effect of the occupants [11,25]. When measurements of unoccupied conditions are available, it is customary to "calibrate" the acoustic model, so that optimal agreement between measured and simulated conditions is found (considering point by point values and not by just considering spatial averages), so that any other subsequent modification in the space should lead to reliable predictions. The discriminating criterion to evaluate the quality of the calibration process is represented by the difference between measured and predicted results expressed as a function of the just noticeable difference (JND) for the parameter under study, representing the threshold above which a change can be perceived by an average listener. Usually, an error below one JND is considered to be an excellent result if referred to point-by-point values, with 2 JNDs representing an upper limit that should not be exceeded except in the lowest frequencies [13]. For spatially-averaged values, that are meaningful only for parameters like T30 that are not supposed to change a lot, stricter limits around 0.5 JNDs have been applied recently [15,26].

CATT-Acoustic (CATT-A, v. 9.1g), a GA based software [27], was used for acoustic simulations and the "Algorithm 1" was considered as the room volume was closed and sufficiently mixing. Algorithm 1 uses a

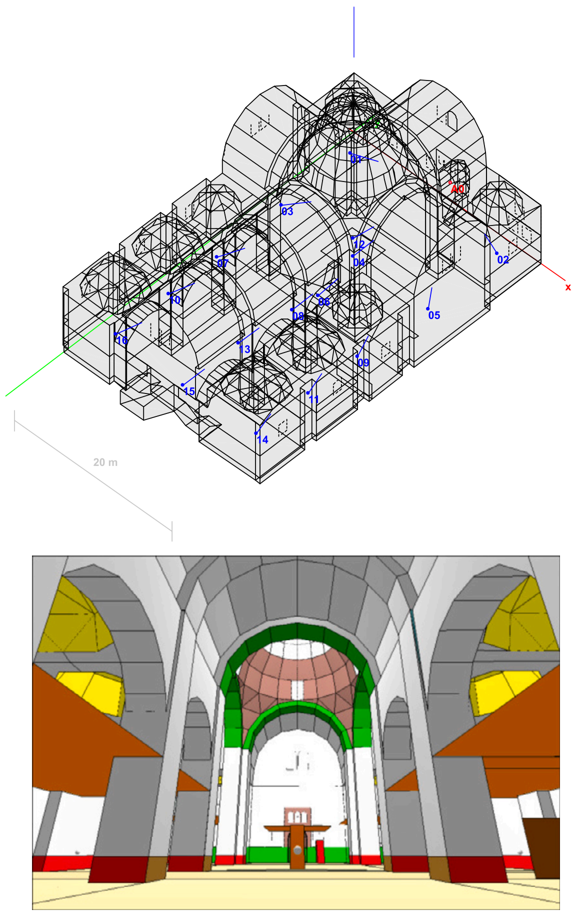

Fig. 3. GA model of the mosque.

randomized cone-tracing that switches to randomized ray-tracing when the expanding receiver sphere touches a surface. A number of rays sufficiently higher than the minimum number recommended by the software was used, equal to $2 \cdot 10^6$. Impulse response length was set equal to the longest expected T30 (i.e. 4 s and 3 s for empty and full case).

The resulting geometrical model (Fig. 3) was made of about one thousand planes, with an overall surface area of 5300 m^2 and a volume of 10500 m^3. Windows and other secondary elements were modelled as sub-planes, so to minimize the overall number of surfaces and speed up calculations. Small pillars and open balustrades were not modelled (e.g. for the Mahfil, the raised platform under the dome, only the horizontal plane was included).

As the combined effect of absorption and scattering may have significant effects in spaces with particular geometries, the calibration process cannot focus only on "fine-tuning" absorption coefficients until an agreement is found among measured and predicted parameters, but it must also involve scattering coefficients. To this purpose, at the preliminary stages, once the absorption coefficients taken from the literature were assigned to surfaces or updated, in order to understand how much sensitive the model was to scattering, three uniformly distribute values (independent of frequency) were investigated: 0.05, 0.10, and 0.99. In all of the cases, "auto-edge" was set to "on" for all pillars, arches, mezzanines, and surfaces with protruding elements. This option aims at taking into account that in GA, when a surface is small in relation to the wavelength, or is close to another one with different impedance, it cannot give a valid specular reflection, so the energy can instead be transferred to diffuse. Thus, for each selected surface, scattering coefficients are proportionally increased as a function of the extent of the frequency dependent area spanning a quarter of wavelength from each exposed edge.

Table 1
Absorbing area per person (m^2), as a function of different posture referred to a density of 1.5 pers/m^2 of floor area as resulting from Refs. [12,19].

	Frequency bands					
	125	250	500	1k	2k	4k
Standing [12]	0.07	0.19	0.35	0.63	0.86	1.02
Sitting [12]	0.05	0.12	0.35	0.51	0.59	0.67
Standing [19]	0.12	0.20	0.47	0.76	0.84	0.89
Sitting [19]	0.12	0.20	0.47	0.68	0.76	0.80

The accuracy of the GA model was evaluated at each stage by comparing spatially averaged values of T30 and point-by-point values of EDT, Ts, and C50. For the latter parameters the mean absolute error was calculated and then expressed in terms of JND for the selected parameter.

2.4. Acoustic simulation of occupants

To account for the acoustic absorption due to the worshippers, several sources of data are available [17–19] but, in the present case the values given by Elkatheeb [12] were used as being specific for the different postures used in the mosques. As these values are given in terms of absorbing area per occupant (Table 1), in case of a dense audience they may result in an absorption per square meter higher than one that, even if acceptable when using Sabine's formula (as it is a consequence of the measuring method), is impossible to handle with simulation tools, as surfaces may only accept coefficients lower than one.

Consequently, in order to model the effect of the occupants while taking into account the energy conservation on surfaces, three approaches are possible (Fig. 4).

- One very simple possibility is to distribute the overall absorption due to occupants over the whole floor surface. In fact, there are several areas like pathways, aisles etc. that remain unoccupied, and their surface might be sufficiently large to get an absorption coefficient within the prescribed limits. However, this simplistic approach might not be easily applied in mosques because of the carpet on the floor that already adds a certain amount of absorption which limits the available headroom for the audience, although being largely covered by the audience, its effect is likely to be negligible. In addition, modelling a three-dimensional and thick (up to 1.7 m for a standing audience) like a simple flat surface cannot be recommended in acoustic modelling (and GA in particular) because it neglects all the wave interactions that might take place, also including blocking near-grazing rays that will consequently propagate freely without being absorbed or scattered.
- A second approach is derived from concert halls, performance spaces, and other venues where a seated audience occupies "blocks" that in GA modelling are reproduced by means of simple extruded volumes with borders (usually 0.5 to 0.7 m high) that may offer an extra surface where absorption may (and needs to) be applied. In this way the blocks offer a more realistic representation of the audience and, by properly adjusting absorption and scattering coefficients (also including edge effects), they proved to effectively contribute to model the effect of occupancy in such spaces. However, for a standing (and dense) audience the block height might become too large (also affecting room volume more than the actual volume occupied by the bodies would), while the border surface might not be large enough to distribute the overall absorption that pertains to the block while keeping the absorption below one [16].
- A third approach, that might help to overcome some of the limitations that have been shown by the first two methods, is to model the occupants as an array of "baffles" standing on the floor with a spacing of about 1.0 to 1.25 m. In this way the height of the baffles can

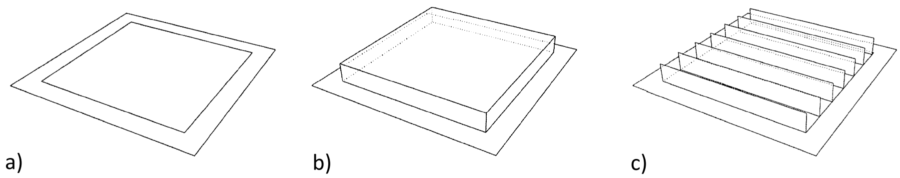

Fig. 4. Schematics of the three approaches to model occupancy in GA models.

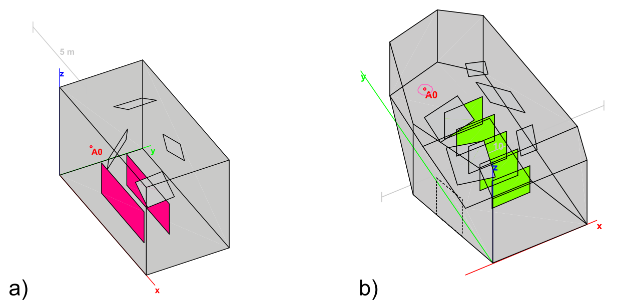

Fig. 5. GA models of (a) the 164 m^3 reverberant chamber used in Sabbagh and Elkhateeb [12], and (b) the 200 m^3 chamber used in Martellotta et al. [19].

be adapted to the actual posture of the occupants without affecting room volume. Baffles have two faces available to distribute sound absorption thus making it possible to assign absorption coefficients lower than one, even though mutual masking is likely to make some of this absorption ineffective. Scattering (or even diffraction) effects may be "crudely" accounted for and by modelling the surfaces as partly transparent it could be possible to model the sound propagation through the audience area, which is likely to happen at low frequencies where wavelengths are longer. Finally, this solution is virtually independent of the floor treatment which will remain in its place offering extra absorption as demonstrated in [12].

Of the three options, the one that seems more suitable to the case of mosques is certainly the third one. Thus, assuming that h is the baffle height (approximated by the shoulder height, equal to 1.5 m for a standing audience and 1.0 m for a seated one), N_p is the number of occupants per square meter, A_p is the corresponding absorption per person as given in Table 1, and d is the row spacing, the equivalent absorption coefficient to apply to both the faces of the baffle, can be calculated as:

$$\alpha_{occ} = \frac{A_p \cdot N_p \cdot d}{2h}, \tag{1}$$

It is important to underline that absorption per person tends to decrease when the occupant density increases [19,18], but due to the need to leave enough space to change posture during worship, the area per person is 0.5 m by 1.25 m, corresponding to a maximum density of 1.6 pers/m^2, which is very close to values given in Table 1.

Finally, in order to correctly model the occupancy in a GA tool, it is not feasible to just apply the coefficients given by Eq. (1). In fact, as said above, reciprocal masking effects are likely to come into play, and thus some preliminary testing is needed before coefficients can be assigned to surfaces.

To this purpose, the method proposed by Benedetto and Spagnolo [28] and Summers [29] was applied, by determining the absorption coefficients in a virtual reverberant chamber (reproducing the measurement setup used by Sabbagh and Elkatheeb [12]) modelled in the same GA software used for the other simulations (Fig. 5a). In this way, it was possible to account for the actual sound distribution in the space, including masking effects, and obtain more reliable coefficients and predictions. The method requires a first calibration of the "empty room" GA model, during which all the acoustic parameters pertaining to room surfaces must be defined. During this step, absorption and scattering coefficients of surfaces must be adjusted so that the predicted reverberation time matches the measured one. A realistic approach considering the nature of the chambers is to keep scattering coefficients as low as 0.05 for flat surfaces and use auto-edge for diffusers, and then adjust absorption coefficients. Once this step is completed, the "sample" to be measured is added to the model and its absorption and scattering coefficients are adjusted until the predicted reverberation time matches the one measured in the actual room with the samples inside. Clearly, in order to be effective, the method requires a sufficiently accurate modelling of the actual room behaviour, which, in such small spaces should also include a proper treatment of low frequency propagation, which is not always possible in GA models.

To further validate this approach, on-site measurements carried out by Martellotta et al. [16] were used to validate reverberant chamber measures of audience absorption [19]. First, GA absorption coefficients were obtained from the virtual reverberant chamber (Fig. 5b), with reference to a seated audience with same density as that to be used in the mosque. Then, the values were used in the GA model of one of the churches surveyed (Sant'Andrea) where the occupants' density was more similar to that used in the chamber. Details of this validation are given in Appendix A.

3. Results

3.1. Measured acoustical parameters

An extensive analysis of measured acoustical parameters is given in [30]. Here, a brief summary of the main results is given, due to its relevance in pointing out the variations after occupancy is considered, as well as for the purpose of model calibration. Fig. 6a shows the spatially averaged values of T30 and EDT, which point out that EDT is slightly shorter across the whole spectrum of frequencies. Point-by point values of EDT (Fig. 6b) show that, as expected, EDT grows with distance. Clarity and centre time also showed strong dependence on source-receiver distance (Fig. 6c,d), with only a few odd receivers that, particularly for C50, are more sensitive to early individual reflections, and showed bigger deviations from the general trend. This variation, that appears at all the frequency bands, clearly underlines the need to perform the subsequent model calibration on a point-by-point base, as referring to spatially averaged values of such parameters would be meaningless.

3.2. Model calibration

The calibration process was started assuming literature absorption coefficients for all the surfaces and then adjusting their values (within reasonable and physically sound values) to match measured parameters. For carpets, a mildly absorbing sample was chosen, with characteristics similar to those also reported by Fausti et al. [9]. In the subsequent process, rather than aiming at exact T30 calibration and then check the point values, as anticipated before, both aspects were considered together.

The starting point was the set of absorption coefficients taken from literature [31] and given in Table 2. From these values, to explore model behaviour, three simulations were started, assuming uniform scattering coefficients of 0.05, 0.10, and 0.99 (except for the surfaces of the mezzanine and the columns that had auto-edge option turned to on), which returned the results shown in Fig. 7a suggesting that the proposed set of

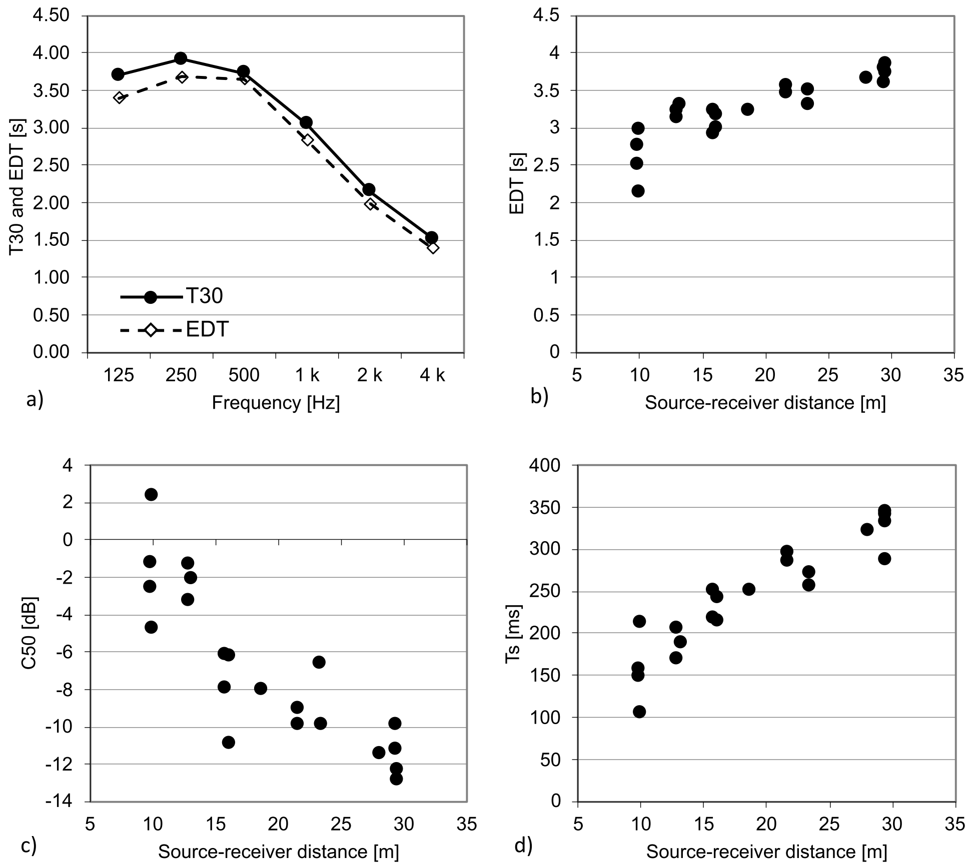

Fig. 6. Spatially averaged values of measured T30 (thick) and EDT (dashed) as a function of frequency (a), and mid-frequency (500-1000 Hz) averages of point-by point values of measured EDT (b), clarity C50 (c), and centre time (d) plotted as a function of source-receiver distance.

Table 2
Covered area of different surfaces used in the geometrical model and their absorption coefficients as taken from the literature [31] and, in brackets, the modified values used in the calibrated model.

Material	Area (m^2)	Frequency bands 125	250	500	1k	2k	4k
Plaster	2920	0.02(0.04)	0.02(0.04)	0.03(0.04)	0.03	0.04	0.05
Wooden ceiling	434	0.15(0.20)	0.11(0.13)	0.10	0.07	0.06	0.07
Carpet (6.4 mm, 1.4 kg/m^2)	888	0.15	0.17	0.12(0.19)	0.32	0.52	0.57
Carpet on wood	434	0.15(0.23)	0.17(0.20)	0.12(0.19)	0.32	0.52	0.57
Decorated/rough plaster	330	0.03(0.04)	0.03(0.04)	0.04	0.04	0.05	0.06
Marble	140	0.01	0.01	0.01	0.01	0.02	0.02
Windows	85	0.35	0.25	0.18	0.12	0.07	0.04
Wooden furniture	85	0.40(0.45)	0.30(0.35)	0.20	0.17	0.15	0.12

absorption coefficients in combination with a 0.10 scattering almost perfectly matched the measured T30 in the last three octave bands, while in the others prediction were clearly overestimating T30, suggesting that corrections were needed to increase absorption. With reference to the role of scattering coefficients, it was interesting to notice that it mostly affected frequencies above 500 Hz, resulting in shorter T30 as scattering increased, while much smaller variations were observed in the lowest bands. Reducing scattering coefficients from 0.10 to 0.05 resulted in a 10% increase in T30 on average from 1 kHz to 4 kHz. This result was expected, considering that most of the high frequency absorption, excluding air absorption (which is significant due to the large volume), is due to the carpet which is located on the floors. Thus, more scattered reflections make the floor more effective in absorbing sound. In the lowest bands, two factors concur to the substantial independence from scattering coefficients. On one side, there is a more uniform distribution of absorption on the surfaces and, on the other side, the “auto-edge” option (applied to selected planes) automatically increases scattering to account for border effects, and, being this area proportional to a quarter wavelength, it notably affects lower frequencies. Thus, the average scattering was about 0.10 independent of default values and, combined with the geometry of the space, finally resulted in the observed behaviour.

Given the discrepancy between measurements and predictions for T30, an adjustment to absorption coefficients was needed and, in order to keep their values as close as possible to the original values, while preserving the physical behaviour of the surfaces, it was decided to increase by a small amount the low frequency values for the wooden ceiling that covers the mezzanines and, consequently, also raise the low frequency values for the carpet on wood, together with the 500 Hz coefficient for the carpet, while the remaining absorption was assumed to be distributed on the plastered surfaces 2. In absolute terms, the applied variation was small, but it allowed to take into account that, in order to keep the GA model simple, many details were omitted, while, as shown in Figs. 1 and 2, such surfaces also include several elements like luminaries, shoe racks, etc, that can justify the proposed increase. Considering

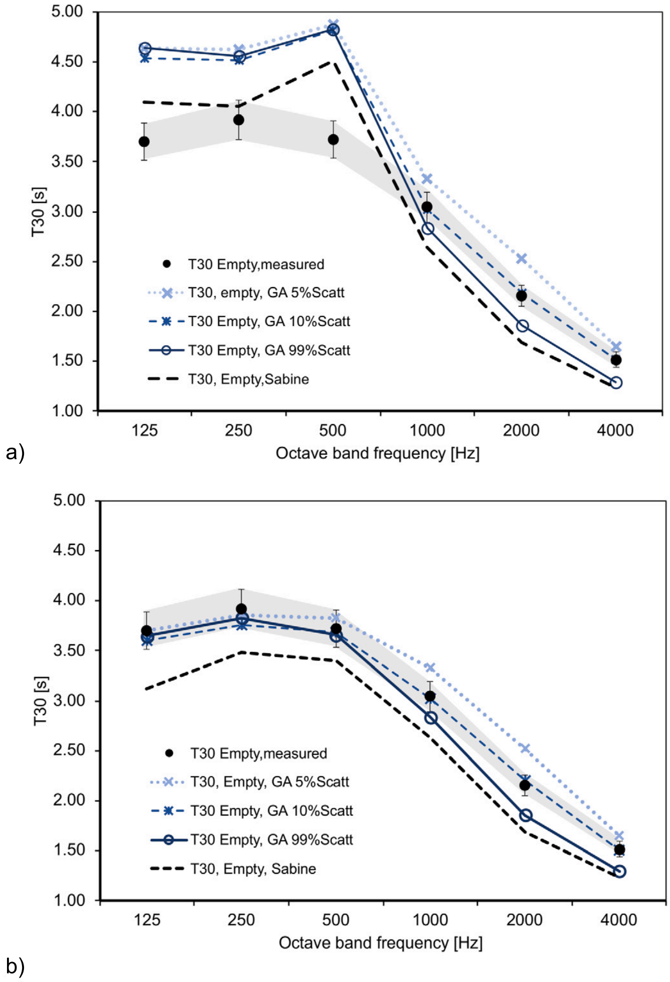

Fig. 7. Reverberation time measured and predicted using GA tools utilizing a) literature absorption coefficients and different default scattering coefficients and b) modified (calibrated) absorption coefficients and different default scattering coefficients. Grey areas correspond to 1 JND error.

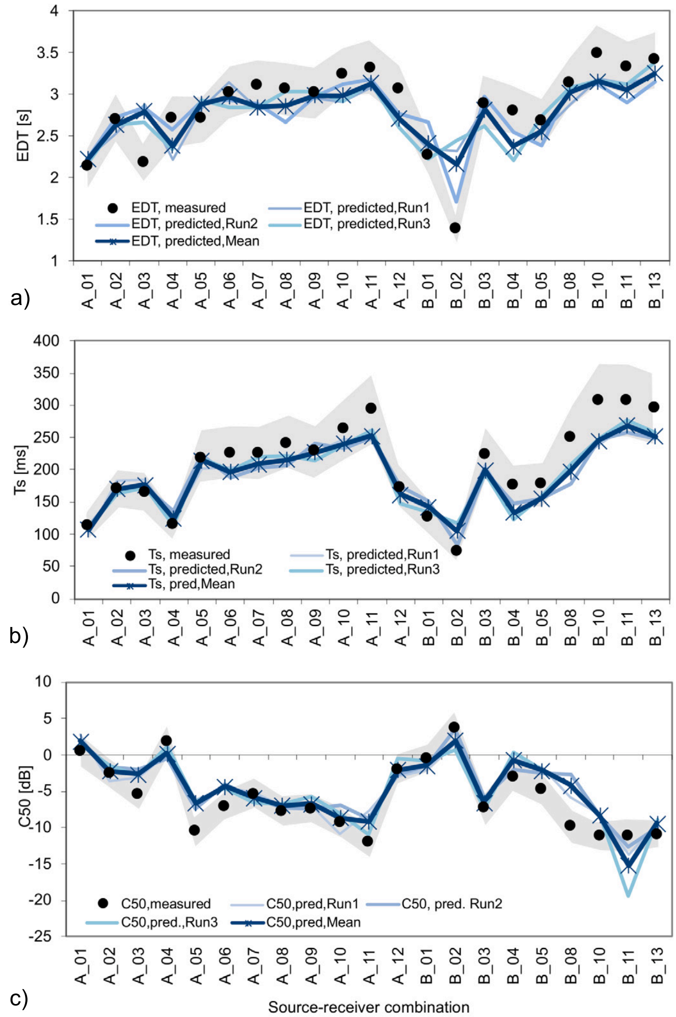

Fig. 8. Plot of mid-frequency average of point-by-point measured and predicted values (based on three different runs) for EDT (a), Ts (b), and C50 (c). Grey areas correspond to a 2 JNDs variation.

this, also with reference to scattering coefficients it seemed realistic to assume a 0.10 value for frequencies from 500 Hz on, so that no change had to be applied to absorption coefficients, while in the lowest bands a 0.05 scattering still seemed the best option for most large surfaces. After some refinements, the final absorption coefficients were found and are given in brackets in Table 2. Fig. 7b shows that a much better agreement was found in the low frequency bands, and, with the proposed assignment of default scattering coefficients JND error for T30 was below 0.5. With reference to individual position values the agreement was usually very good for T30 and Ts (Fig. 8 and Table 3), while EDT and C50 that are notably more sensitive to even small differences in early reflections pattern, showed slightly bigger errors, generally within 2 JND for EDT, and slightly above for C50. Fig. 8 shows that, with reference to mid-frequencies, the agreement was excellent in most of the receiver positions, with the only exception of a few positions when source position B was used.

At the end of the calibration it was worth noticing that, whatever the frequency considered, even assuming 0.99 scattering, GA predictions for T30 were always higher than the diffuse-field Sabine predictions, suggesting that even forcing surfaces to be fully diffusive, the geometry of the room was not so “mixing” after all. The presence of the deep mezzanines, whose upper face is covered by carpet while the lower face is made of wood, actually prevents all room surfaces from “seeing” all the others, which is one of the basic conditions on which Sabine formula relies. In fact, if a highly absorbing material is mounted in a hidden or recessed position its effect on the reverberant field will be lower, because, statistically, it will have lower probability to be hit by every sound ray propagating in the space. This was analytically demonstrated by Embleton [32], that showed that if a surface cannot be seen by the others, its absorbing effect is reduced. So, the presence of highly absorbing treatments on such surfaces clearly emphasizes this behaviour. Similar conclusions were found by Jurkiewicz et al. [33]. Fig. 6a shows that the only frequency band where GA predictions get closer to Sabine (without forcing scattering to 0.99) was 500 Hz, which was also the band where the absorption coefficients on both the faces of the mezzanine were more similar to the overall mean absorption.

To confirm that this was the correct explanation for this behaviour, two simple tests were carried out. First, the geometrical model was mod-

Table 3
Mean absolute difference (in JNDs) between predicted and measured values, averaged over individual receivers, as a function of frequency.

Parameter	Frequency bands						
	125	250	500	1k	2k	4k	Mid
T30	1.1	0.8	0.6	0.5	0.5	0.3	0.5
EDT	2.6	1.9	1.2	2.0	2.0	1.9	1.1
Ts	2.0	1.3	1.3	1.4	1.8	1.8	1.0
C50	2.4	2.4	2.3	1.9	2.5	2.6	1.8

Table 4
Reverberation time as a function of frequency, measured and predicted using GA model, Sabine and Eyring using whole GA model, Sabine and Eyring schematizing the space as a system of coupled volumes (CV).

	Frequency bands					
	125	250	500	1k	2k	4k
Measured	3.70	3.92	3.73	3.05	2.16	1.52
GA	3.72	3.95	3.75	3.07	2.22	1.57
GA, Sabine	3.14	3.52	3.43	2.66	1.76	1.30
GA, Eyring	2.98	3.37	3.28	2.52	1.64	1.22
CV, Sabine	4.02	4.32	4.01	3.22	2.28	1.69
CV, Eyring	3.84	4.15	3.83	3.04	2.10	1.55

ified by removing all the dividing surfaces of the mezzanine. Under these conditions, no difference appeared between GA predictions and Sabine values when scattering coefficients were set to 0.99, and mean-free-path also increased from 8 m in the original model to 9.5 m in the new model. The agreement was perfect across the whole spectrum, with only a small overestimation at 125 Hz.

A second, more interesting test, was carried out by considering that as the surfaces of the mezzanine cannot see each other and also prevent other surfaces from fully participating to the sound propagation, it might be possible to treat the room as a combination of several sub-volumes connected by apertures and coupled together. For the sake of brevity, details of the calculation method are given in Appendix B. Results, summarized in Table 4, confirmed that this model correctly reproduced the sound propagation in the room, yielding reverberation time values that, particularly when Eyring's formula was used, were much more similar to measured ones than those based on a single volume.

3.3. Acoustic simulation of occupancy

As anticipated in Sec. 2.4, the starting point for the analysis of the effect of occupancy was the identification of the correct values of the absorption coefficients to use in the GA model. First of all, the measurement setup used by Sabbagh and Elkhateeb [12] was modelled in CATT-A using published data and the effect of the 15 occupants was modelled by means of two double-sided vertical surfaces 1.5 m high. The initial values $\alpha_{S+E,RC}$ of the absorption coefficients were calculated by dividing the absorption per person given in Table 2 by the total area of the baffles. Then, values were adjusted until the GA predictions of T30 matched the values measured or, in case of Ref. [12], derived from application of Sabine's formula using the published data. To partly account for diffraction effects around real bodies, the surfaces were given both scattering and transparency coefficients summarized in Table 5 and assigned considering the ratio between wavelength and body dimensions. In order to accurately determine the absorption coefficients, the maximum error in T30 during the calibration steps (for both empty and occupied conditions) was limited to 1%. Results are shown in Table 5 and suggest that, independent of the starting values that showed some small differences, by adopting the proposed approach, an increase in absorption coefficients by about 30-40% is needed at medium and high frequencies, while in the lowest bands, the requested increase was lower. This increase was somewhat expected because, particularly at high frequencies, where mutual shading is stronger, given the dimension of the planes, many portions will remain mostly ineffective, particularly in the first configuration where large rows are used. In the other case α_{Mart} values [19] showed a slightly different behaviour. In fact, for the standing audience an increase appeared in GA absorption coefficients by about 20% compared to $\alpha_{Mart,Stand,RC}$ values, while seated values were again about 30% higher. A possible explanation is that as the occupation density was taken as close as possible to the values tested by Sabbagh [12], but the reverberant chamber layout was arranged to reach a density of 2.3 pers/m^2 (16 occupants against 10), this yielded a lower (initial) absorption coefficient which resulted in more reflected/scattered energy which consequently made the whole audience surface more effective.

Table 5
Absorption coefficients applied to baffled surfaces obtained from standardized reverberant chamber (RC) measurements and from iterative adjustment in a GA model of the same room (GA), referred to a standing (Stand) and sitting (Sit) audience, based on measurements carried out by Sabbagh and Elkhateeb [12] (S+E) and Martellotta et al. [16] (Mart).

Parameter	Frequency bands					
	125	250	500	1k	2k	4k
Scattering	0.30	0.40	0.50	0.60	0.70	0.80
Transp.	0.70	0.60	0.40	0.30	0.30	0.30
$\alpha_{S+E,Stand,RC}$	0.044	0.12	0.22	0.39	0.54	0.64
$\alpha_{S+E,Stand,GA}$	0.045	0.13	0.25	0.52	0.76	0.96
Var.	+4%	+7%	+13%	+32%	+41%	+51%
$\alpha_{S+E,Sit,RC}$	0.047	0.19	0.33	0.47	0.55	0.63
$\alpha_{S+E,Sit,GA}$	0.05	0.20	0.39	0.60	0.75	0.90
Var.	+7%	+7%	+19%	+26%	+36%	+43%
$\alpha_{Mart,Stand,RC}$	0.06	0.098	0.23	0.37	0.41	0.44
$\alpha_{Mart,Stand,GA}$	0.062	0.102	0.26	0.44	0.51	0.55
Var.	+4%	+5%	+12%	+18%	+24%	+26%
$\alpha_{Mart,Sit,RC}$	0.09	0.15	0.35	0.50	0.56	0.59
$\alpha_{Mart,Sit,GA}$	0.09	0.16	0.39	0.69	0.77	0.83
Var.	-	+2%	+8%	+34%	+29%	+35%

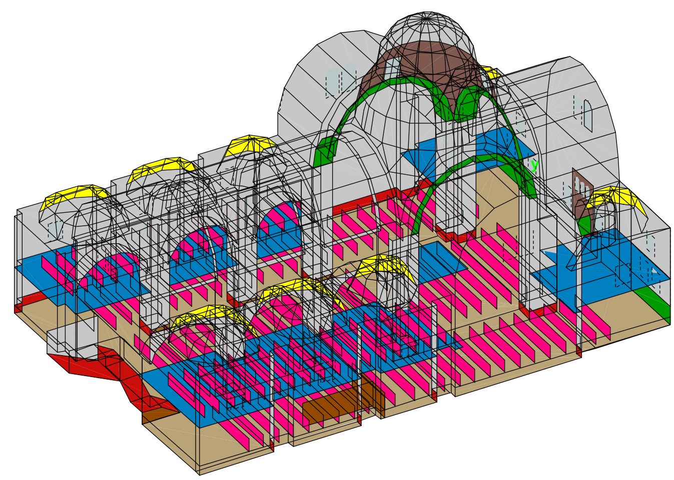

Fig. 9. GA model of the Mosque with the array of baffles reproducing the audience in place.

To provide a further validation of the proposed approach, the absorption coefficients determined from the virtual reverberant chamber were used "as is" in the model of the church of Sant'Andrea, where fully occupied measurements were available [16] for a seated audience, with comparable occupants density (1.4 pers/m^2) as those tested in the chamber. As discussed in Appendix A, an excellent agreement between measured and predicted results appeared, particularly if the low-frequency correction suggested in Ref. [16] was applied. It is important to point out that the medium-high frequency correction appears when measured absorption is applied to the baffled audience but, due to the reciprocal masking that is accounted by GA model, an increased absorption is needed to produce the same T30. If the audience was modelled conventionally such correction would not be needed. Conversely, the low frequency correction that is suggested in Ref. [16] is related to a limitation in the reverberant chamber method that, by considering a small sample, is probably unable to account for larger scale effect in that frequency range, and it should be used even when modelling audience as a box.

Finally, once the preliminary validation was completed, the proposed approach was applied to the original case study in order to discuss

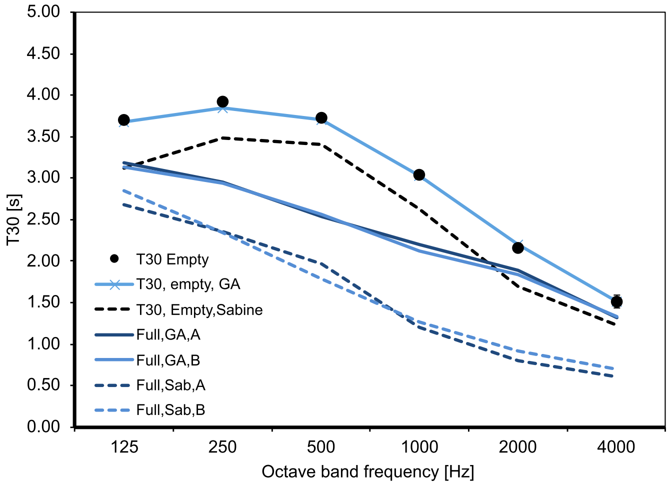

Fig. 10. Plot of spatially averaged, measured and predicted reverberation time (T30) under empty and occupied conditions in Jedid Mosque.

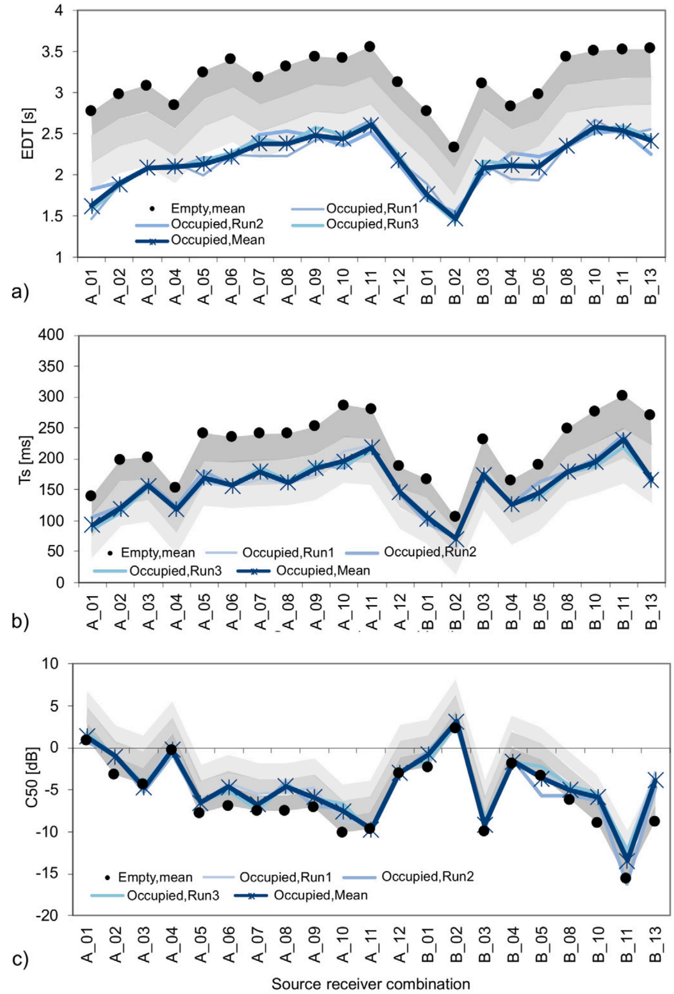

Fig. 11. Plot of mid-frequency point by point values a) EDT, b) Ts, c) C50, predicted using GA with and without occupancy. Grey areas correspond to 2 JNDs intervals.

the effect of the occupancy on the acoustics of the mosque (Fig. 9). With reference to reverberation time it can be observed (Fig. 10) that the largest variations appear at medium frequencies (from 3.4 s to 2.4 s), where the added absorption due to the occupants is larger compared to the empty conditions. At high frequencies, given the already significant absorption due to carpets and air volume, the variation was comparatively lower (from 1.9 s to 1.6 s). No significant difference was observed between configuration with source A (occupants standing) and source B (occupants seated on their knees) across the whole spectrum of frequencies, suggesting that the differences found in the reverberant chamber become less evident when a large area is occupied. In addition, the presence of carpet, although not particularly absorbing, might have contributed to somewhat flatten the results. The analysis of reverberation times calculated using Sabine's formula shows that at high frequencies, where absorption per person is about 50% higher for a standing person compared to a seated one, a small difference can be observed but remains very small. The very large difference between Sabine and GA predictions is not surprising, considering what was observed in the empty space that is now clearly emphasized by the even higher absorption located only on horizontal surfaces, resulting in a clearly non-diffuse behaviour.

With reference to individual position values of the other acoustical parameters, averaged over mid-frequencies as recommended by ISO 3382-1 [23], Fig. 11 shows that, following the variation observed for T30, also EDT was reduced by about 1 s, corresponding to 6.3 JNDs. Similarly, also Ts was reduced by about 100 ms, corresponding to 3.2 JNDs, while C50 showed an average variation of 1.4 dB, corresponding to 1.4 JNDs, with larger variations observed at farthest or more recessed receivers, where the role of the reverberant reflections is stronger compared to early reflections which, clearly, were less affected by the occupancy. It is interesting to point out that when changing source position from A to B (and changing occupants height from 1.5 m to 1.0 m), the variations between unoccupied and occupied values remained mostly the same, suggesting that in this frequency range, the changes were mostly due to the reduced late reverberation rather than to significant changes in the early reflections.

It is worth noticing that a similar behaviour was also observed in a previous study on the effect of occupancy applied to Catholic churches [11], where, among the six building surveyed, C80 changed by about 1 JND or less, while EDT changed by 3 to 6 JNDs and Ts varied by 2 to 4 JNDs, confirming that clarity is less sensitive to variations taking place in the late part of the IRs (which have a negligible impact on the energetic sum appearing at the denominator).

4. Conclusions

The paper presented an investigation on the effect of occupancy on the acoustics of mosques, by taking as a reference the case of Jedid Mosque in Algiers. The investigation was carried out by means of a geometrical acoustic simulation of the space which was first calibrated by taking as a reference the unoccupied measurements, and then including the effect of worshippers.

Some interesting phenomena related to a combination of geometrical issues (mostly related to the presence of a large mezzanine that divides the space into many sub-volumes) and non uniform concentration of absorption on the floor and on the same mezzanine, were investigated during the calibration phase that, consequently, required a careful setup. In fact, the absorbing surfaces, being unable to be seen from every surface in the model, were less effective in reducing the reverberation time which was longer than the Sabine value resulting from considering the room as ideally diffuse space.

Another interesting aspect that was discussed was related to the fact that worshippers in mosques tend to introduce a significant absorption and, if this was to be applied to an audience block or even to the floor, this would result in absorption coefficients greater than one. To properly account these aspects, the occupants were modelled as a series of “baffles” or arrays of vertical surfaces whose height can be adapted to the specific posture of the occupants (1.5 m if standing and 1.0 m if seated). However, in order to assign such surfaces the most appropriate absorption coefficients for a GA model, they were not given the absorption coefficients resulting from the use of Sabine's formula in the reverberant chamber, but were indirectly derived from a GA model of the same chamber to properly take into account the masking effect introduced by the array of surfaces.

Results showed that absorption coefficients determined in this way were higher than the measured ones by about 30 to 40% in the high frequency range, while they showed negligible variations in the lowest frequency bands. To validate this approach, results from measurements carried out in an occupied Catholic church were used, showing that the agreement between measured and predicted reverberation time was very good.

However, considering the greater complexity resulting from this method and the need to start from raw data obtained in a reverberant chamber to carry out the requested determination of GA-based absorption coefficients, this procedure should be limited to cases where high occupant density and posture would result in absorption coefficients higher than one, which would make it impossible to use the conventional "box" audience modelling, or to cases, like mosques, where the audience is standing in regular and well-spaced rows that would make this model more physically suitable than the others.

Finally, the calibrated GA model of the mosque was modified to account for the presence of the occupants and results showed that T30 dropped from 3.4 s to 2.4 s at mid frequencies, while in the other frequencies variations were smaller. In terms of position sensitive acoustic parameters, variations were very large for EDT which decreased in a similar way as T30, and centre time which was reduced accordingly (by about 100 ms) corresponding to about 3 JNDs compared to unoccupied values. Clarity values showed the lowest variations (around 1.4 dB on average), in agreement with both the findings observed in Catholic churches and the logarithmic nature of the parameter.

Further investigations are under way to extend the same methodology which was successfully tested here to other mosques, possibly combining with on-site measurements under occupied conditions.

CRediT authorship contribution statement

Francesco Martellotta: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Mohamed Ladaoui Benferhat:** Writing – review & editing, Visualization, Software, Resources, Investigation, Conceptualization. **Chiara Rubino:** Writing – review & editing, Validation, Investigation, Formal analysis. **Abdelouahab Bouttout:** Writing – review & editing, Resources. **Samira Debache Benzagouta:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. GA validation of absorption coefficients

The church of Sant'Andrea is characterized by a shoebox shape, hard reflecting walls and ceiling, and scarcely diffusing elements. The floor

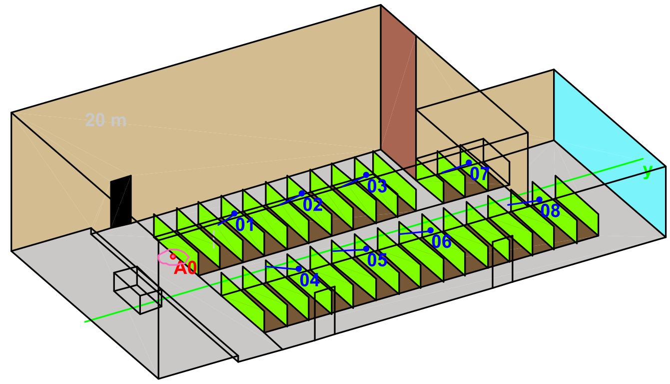

Fig. A.12. Plot of measured and predicted reverberation time (T30) under empty and occupied conditions in the church of Sant'Andrea in Bari. Error bars correspond to 1 JND.

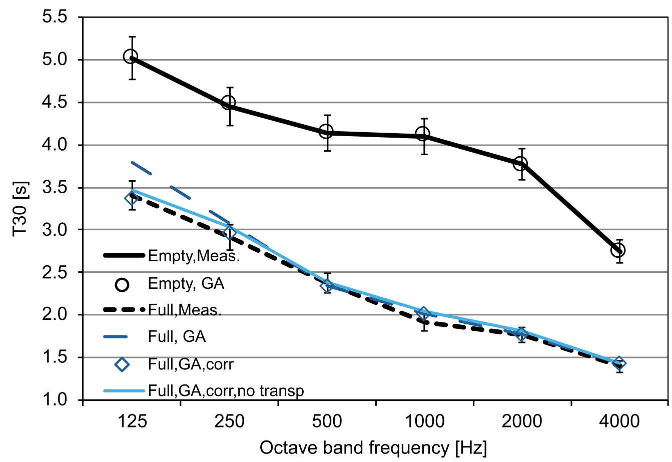

Fig. A.13. Plot of measured and predicted reverberation time (T30) under empty and occupied conditions in the church of Sant'Andrea in Bari. Error bars correspond to 1 JND.

is mostly covered by pews so that it is responsible for most of the scattering in the room as well as for the absorption under fully occupied conditions. Its volume is 1300 m^3 and its floor surface is 225 m^2 covered by pews that can seat 126 persons with a density of 1.4 pers/m^2. Acoustic measurements were carried out with and without occupancy, according to the procedures described in detail in Ref. [16], in compliance with ISO 3382-1 [23]. The geometrical acoustic model of the space (Fig. A.12) was carefully calibrated against the unoccupied T30 values (Fig. A.13), reducing the error below 1% for each frequency band. The resulting absorption and scattering coefficients are summarized in Table A.6. Higher scattering coefficients were only assigned to pews that were modelled as a sub-surface of the floor so that the baffles representing the occupants could be just overlapped without changing the previous model. The auto-edge option was turned on and applied to all surfaces having protruding edges and where discontinuities between surface treatments appeared. Calculations were carried out in both unoccupied and occupied conditions using 500k rays and a truncation time equal to the longest expected T30 (5 s and 3.5 s respectively for empty and full conditions).

Starting from the calibrated mode, the audience was then modelled according to the previously proposed layout, assuming 1 m high baffles (as the occupants were seated), and assigning the absorption coefficients obtained from the GA chamber and given in Table 5. Simulations were carried out with and without the low-frequency correction proposed in Ref. [16] (increasing absorption coefficients respectively by 50% and by 25% at 125 Hz and 250 Hz) and with and without transparency.

Table A.6
Absorption and scattering coefficients used to model a standing audience in GA model. Average scattering values represent grand average among all surfaces including auto-edge effects.

	Frequency bands					
	125	250	500	1k	2k	4k
Doors	0.18	0.22	0.16	0.10	0.10	0.10
Floor	0.01	0.02	0.03	0.03	0.03	0.03
Glass	0.35	0.30	0.20	0.10	0.03	0.03
Gypsum panels	0.28	0.28	0.22	0.10	0.06	0.06
Plaster	0.04	0.04	0.042	0.044	0.047	0.048
Pews	0.02	0.06	0.09	0.10	0.09	0.08
Scattering coefficients						
Default	0.05	0.06	0.07	0.10	0.13	0.15
Pews	0.30	0.40	0.50	0.60	0.70	0.80
Avg empty	0.25	0.20	0.18	0.19	0.21	0.23
Avg occup	0.28	0.26	0.26	0.28	0.31	0.36

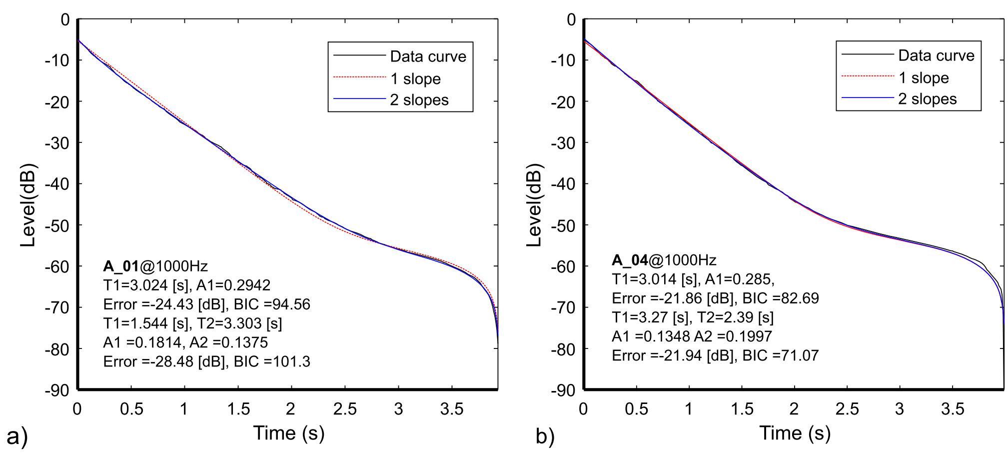

Fig. B.14. Results of Bayesian analysis of multiple slopes performed when source was in position A and receivers where at points a) 01 and b) 04.

Results shown in Fig. A.13 showed an excellent agreement with an error around 5% at medium-high frequencies, increasing to 11% at 125 Hz, when no low frequency correction was applied, while correction provided an almost perfect match between measurements and predictions. It was interesting to notice that modelling the vertical baffles as semi-transparent surfaces contributed to lower reverberation times in the lowest bands (where transparency coefficients are higher and absorption coefficients are lower), providing a generally better agreement with measured results, while in the medium-high frequencies variations were mostly negligible. Thus, based on the validation example, and considering that in this case the baffles were only 1 m high (compared to 1.5 m baffles representing a standing audience), it can be concluded that adding transparency may positively contribute to have more reliable results.

Appendix B. Coupled volume modelling

Sound propagation in complex and articulated spaces, under cartain conditions, can be mathematically modelled by considering the non-stationary processes of sound energy decay, following either steady state or impulse excitations. The sound energy decay in the whole interior, divided into m acoustical subspaces, is described by a system of m sound energy balance equations: [34]

$$V_i(d\epsilon_i/dt) = -cA_i\epsilon_i/4 + \sum cS_{ij}(\epsilon_j - \epsilon_i)/4, \tag{B.1}$$

where c is the sound speed, ϵ_i denotes the average sound energy density in the ith subspace, V_i is the volume of the ith subspace, and A_i is the equivalent absorption area of the ith subspace. The coupling area between subspace i and adjacent subspace j is denoted S_{ij}. Such a model is most accurate when applied to systems where energy lost via coupling is not substantially larger than the energy lost via absorption. Cremer and Muller [34] provided a coupling factor defined as:

$$k_i = \frac{S_{ij}}{A_i + S_{ij}} \tag{B.2}$$

In the case of Jedid Mosque, the presence of coupling effects was investigated by means of Bayesian methods [35,36], which pointed out that double slopes appeared, and were significant, only in recessed spaces very close to the sound source (Fig. B.14,a), while in the remaining parts of the mosque a single slope appeared (Fig. B.14,b). However, it is important to point out that the scope of the analysis was that of understanding if sub-volumes that are not mutually connected are responsible of the longer reverberation. Thus, by properly identifying absorption, volume and coupling areas it was possible to check if this model could better explain the non-diffuse behaviour of the volume taken as a whole. The same procedures widely discussed in previous research [37] were used, taking advantage of the GA model as a source of data for absorption and surface areas pertaining to the 22 sub-volumes distributed as shown in Fig. B.15 and supposed to be connected by means of apertures corresponding to actual opening areas. In this way the overall absorption was exactly the same as in the GA model. The mean coupling factor was 0.452, with a standard deviation of 0.15 (with a maximum of 0.82 between sub-volumes 1 and 2 and a minimum of 0.24 between main hall and side volumes). For the purpose of this analysis only the coupled-volume reverberation was useful, so no particular effort was taken to

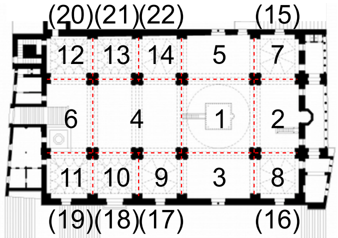

Fig. B.15. Schematic view of the subdivision of the mosque space into sub-volumes. Each sub-volume is identified by a different number. Values in brackets correspond to the subspace above the mezzanine.

model non-diffuse energy transfer and fraction of direct sound assigned to each sub-space.

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