Assessment of Acoustical Characteristics for Recent Mosque Buildings in Erbil City of Iraq

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Abstract—**The study of mosque acoustics, concerning acoustical features, sound quality for speech intelligibility, and additional practical acoustic criteria, is commonly overlooked. Acoustic quality is vital to the fundamental use of mosques, in terms of contributing toward prayers and worshippers' appreciation. This paper undertakes a comparative analysis of the acoustic quality level and the acoustical characteristics for two modern mosque buildings constructed in Erbil city. This work investigates and examines the acoustical quality and performance of these two mosques and their prayer halls through room simulation using ODEON Room Acoustics Software, to assess the degree of speech intelligibility according to acoustic criteria relative to the spatial requirements and design guidelines. The sound pressure level and other room-acoustic indicators, such as reverberation time (T30), early decay time, and speech transmission index, are tested. The outcomes demonstrate the quality of acoustics in the investigated mosques during semi-occupied and fully-occupied circumstances. The results specify that the sound quality within the both mosques is displeasing as the loudspeakers were off.**

***Index Terms*—Acoustic parameters; mosque acoustics; ODEON; reverberation time; Speech Transmission Index.**

I. Introduction

The mosque is the most fundamental example of Islamic architecture that has evolved to be connected with needs of Muslim communities in diverse geographical and historical contexts. A number of various worship activities occur within these multifunctional public spaces, and such diverse functions have diverse acoustical demands and requirements. Three distinctive activities are practiced in mosques, either independently or in combination with one another, as shown in Fig. 1. The first one is carrying out prayers, individually or in congregation (led by the imam). The second is participating in preaching, particularly the Friday sermon. The third is listening as well as reciting verses from the Holy Quran. Despite the fact that mosque construction gives high emphasis to architectural esthetic, good quality levels in terms of acoustics are sorely lacking, despite the fundamental importance of this dimension for users of such structures (Wasim, 2007). Indeed, given the mosque's core functions, the most effective determining factor of its architectural design ought to be its acoustical requirements (Hammad, 1990), but little if any precise guidelines have been developed for mosques in this regard (Waseem, 2007). The previous studies reveal that appropriate interior design and wisely detailed building envelope with extensive acoustical consideration are key elements for improving the acoustical performance of mosques. However, most mosques usually have hard and reflective interior finished surfaces, hampering speech intelligibility due to echoes, and/or reverberations, because of cavernous hall spaces within mosques, and their sheltering elements such as domes.

In new-generation mosques, sound reinforcement systems have been utilized to achieve acoustical comfort levels, but this is not an adequate solution without a proper architectural design of the space (Lewers and Anderson, 1984; Suárez, Sendra, Navarro and León, 2004). Clearly, it is a significant quality requirement for mosque structures to offer satisfaction with the intelligibility and ambience of oral communication and tranquility for worshippers. Beside the main function, which is delivering the religious message, other activities conducted in mosques which require speech intelligibility include prayer, speaking publicly, education, lectures, and Quran recitation. Hence, it is undeniable that the quality of acoustics has a significant role which is related to the function of a mosque as a worship center in addition to the spread of knowledge and propagation (*da'wa*). Computer simulation techniques are mostly used in mosque renovations or investigating the acoustical quality of mosques (Orfali, 2007). Evaluated acoustical metrics are generally speech transmission index (STI), sound pressure levels (SPL), and reverberation time (RT) (early decay time [EDT], T30). The aim of this paper is to study and to compare the sound performance two major modern mosque projects in Erbil, Dayk and Altun Mosques. Computer simulation techniques (ODEON 16 Basics edition) were utilized to measure the acoustical parameters of the mosques' main prayer halls. The results indicate that the sound quality of both mosques' main prayer halls was unsatisfactory whilst the loudspeakers were

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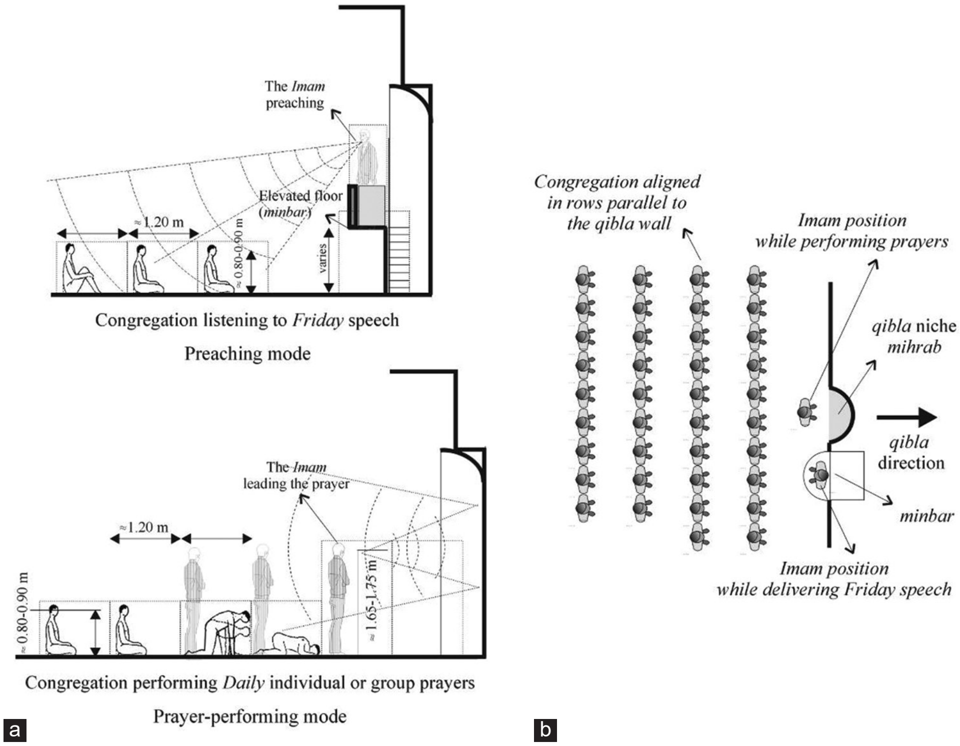

Fig. 1. Different postures and orientation of the worshippers concerning the imam in the two main religious modes. (a) Sections showing worshippers listening to the Friday sermon (that is, the preaching mode) and performing daily prayer (that is, the prayer-performing mode). (b) Plan view showing positions of the imam and worshippers in group prayer performance.

off. Moreover, in the daily prayer scenarios only worshippers in the initial rows close to the imam had a satisfactory STI score.

The essential aspects that influence sound quality inside mosques consist of physical and acoustic aspects. The former includes the form and scheme of the mosque, whereas the latter consists of user-related factors such as the occurrence of background noise and reverberation sound (Lamancusa, 2000). The most important acoustic quality level in the mosque is required during Friday sermons, when all worshippers should be able to hear the imam preaching; aside from this, it is necessary to be able to the hear the imam during the five daily prayers. This requires acoustical measures to stifle unwanted noise whereas enhancing the desired sounds. A decent acoustic design can offer an enhanced and more convenient atmosphere within the mosque concerning the clarity and intelligibility of speech (Othman, Harith, Ibrahim and Ahmad, 2016). Marie (2009) conducted a number of quantity tests to develop some practical replicas to estimate the sound levels for prayers with different parameters, for instance, the room volume, the prayers number, the room background noise without occupants, as well as the RT. Acoustic parameters refer to speech comfort and clarity in terms of the echo time and background noise (Chiang and Lai, 2008), which with reverberation substantially contribute to the effective acoustic quality level of a room. To generate a beneficial sound level, testing must consider the noise criteria (NC) based on the background noise, RT, and STI should be considered.

As previously mentioned, in designing a mosque, an effective acoustic system is necessary for the worshippers. When delivering speeches or sermons in a mosque, worshippers further from the pulpit (*minbar*) would struggle to hear clearly, and the message would not be conveniently relayed to some people. Architects in recent times usually focus more on designing buildings in accordance with appearance or forms, and the primary operation of the space is actually neglected. Poor acoustic design impairs user use and aesthetic enjoyment of the structure – regardless of its visual attractiveness – due to frustrating the primary activities of users, such as the inability to clearly hear the voice of the imam during prayers. Therefore, early consideration of acoustic design is necessary while designing mosques, including in terms of material choices, geometrical forms of spaces, and the implications of the combined factors in the design.

The purpose of the research is to recognize the significance of acoustic design in the mosque regarding the comfort of the worshippers. From the background research, it is anticipated to increase recognition among concerned professionals, especially architects, concerning the value of acoustic design in mosques, to provide improved user comfort and enjoyment while using the mosque. It is essential to obtain an appropriate acoustic design in mosques for user comfort, but modern mosques commonly fail to achieve this. Therefore, this study conducts simulation and testing to discover how comfortable worshippers are after getting into the mosque. This study was conducted to achieve the following objectives:

- To evaluate the acoustic quality level in the mosque using ODEON 16 Basics edition.

- To recognize the factors influencing the acoustical quality level inside the selected mosques.
- To generate awareness of the application of good acoustic design in mosques by comparing two recent common mosque designs in Erbil.

II. Importance of Acoustic Design Within Mosques

As Khabiri, et al. (2013) mentioned, mosques are a multi-function public halls hosting many worshipping activities with different acoustical requirements. Hence, every mosque has need of an acoustic design. Sü Gül and Çalıskan (2013) discussed that one of the significant features of places of worship is sound quality, and this should be considered essential in mosque design, taking into consideration speech patterns related to activities organized in those spiritual places. Ismail (2013) emphasized that the essence of speech intelligibility evolved into a bigger factor in modern-day mosque design, with the integration of further routines that include the recitation of Holy Quran, talks and speeches, as well as lectures in prayer halls becoming typical occurrences. This implies that acoustical design is important within mosques to confirm the quality of sound, to make sure that religious routines and activities are continued more efficiently.

III. RT Effect on Mosque

In an investigation by Sü Gül and Çalıskan (2013), they discovered that RT is understood to be the time needed for the sound energy density as an average to degrade by 60 dB from steadiness stage after stopping the sound source. Sabine has researched the trend since 1900, and additionally RT is incorporated as the primary method for determining the acoustic qualities of room's environment. Acoustical simulations of Doğramacızade Ali Paşa Mosque by Sü Gül and Çalıskan (2013) were connected with RT over frequency range anticipated as an interior volume global average, modeling every single recipient position by means of distribution maps. The assessments of Sü Gül and Çalıskan (2013) indicate that perforated timber utilization on inverse triangular pendentive surface areas works equally well for populated and unpopulated circumstances of the mosque, especially in the enhancement of low to middle range of frequency. They noted that with the chosen substitute design approach, all the simulation outcomes were displayed solely for perforated wooden utilization on pendentive spots. Average mid-frequency T30 for an unpopulated mosque with acoustical treatment on pendentive surfaces is 1.94 s, with an average low-frequency T30 of 2.07 s.

Mazloomi (2010) demonstrated that the uniqueness of such pendentive constructing surfaces is that they produce a huge space in the interior of the mosque. Through proper treatment, average mid-frequency T30 for an occupied mosque is 1.34 s, and the average low frequency T30 is 1.86 s. The bass ratio (BR) is required to be higher than 1.20 for music activities, and it was established that whereas speech is the basic activity in a mosque, the lower frequency and tone of the male imam's voice were relatively distinctive compared to normal speech, which makes it recommended to obtain a BR which is nearer to optimum for music. Moreover, Sü Gül and Çalıskan (2013) found that BR was 1.06 for the unoccupied mosque and 1.38 for the occupied mosque (regarding Doğramacızade Ali Paşa Mosque). The feature of the physical presence of worshippers increases absorption in the mid- to high-end frequency range of the mosque space that is occupied, generating a distinctive acoustical atmosphere.

Ismail (2013) found that an excessive RT will affect speech intelligibility. Furthermore, the decay time from 0 dB to −10 dB is EDT. An advanced technique, introduced by Schroeder, uses the squared reverse-integrated impulse response of an auditorium space. It is used as a rapid clue of the quantity of reflections, diffusion, or sound clarity. To sum up, this technique is beneficial for fast calculation of the EDT and can be applied for on-site uses.

IV. Role of Material and Shape in Mosque Acoustic Design

Speech intelligibility is the major acoustical matter for buildings used in communication, demanding appropriate designation of volume, the geometry of the primary place, and suitable utilization of acoustically absorptive and diffusive materials, such as coating surface areas (Sü Gül and Çalıskan, 2013). It is been claimed that acoustical design ought to be incorporated into mosque design in the initial phases of conceptual building design. The biggest geometrical shapes are created during the schematic stage, along with materials to resolve considerations of esthetics and acoustics. Most contemporary mosques have sound-reflecting materials on most of their internal surfaces, apart from the horizontal surfaces, which are usually carpet-finished on the floor level (Ismail, 2013). Single-glazed material is used in large openings, and wood is used for doors. The central air conditioning units or stand-alone split units, positioned on rooftops or inside chosen spaces, increase the background noise levels inside prayer areas, and affect the acoustical calmness of space. Table I shows the sound absorption and scattering coefficients of materials used in the mosque designs.

V. Methodology

From the literature review, information was gathered regarding the application of acoustic devices inside the mosques and relevant buildings. This study undertakes a comparative assessment of acoustic quality level in two mosque case studies to identify factors influencing acoustical performance. Information was collected about the Altun Mosque and Dayk Mosque, concerning the buildings' dimensions, sizes, and internal surface materials, gathered on the sites or using computer drawings and files. The main prayer halls of both mosques were modeled using

SketchUp 2018 (a 3D modeling computer program) and were then imported to ODEON 16 Basics edition to perform the acoustic simulations (Fig. 2). The material properties of all surfaces were applied (types, absorption coefficient, and scattering affect), as shown in Fig. 3. After that, the sound sources (imam and loudspeakers) and receivers (worshippers) were allocated. General settings, such as room setup, were configured for acoustical simulation as recommended in the ODEON manual. Within Point Source Editor, natural directivity patterns (BB93_Raised_Natural.So8) were selected. The BB93_Raised_Natural source type (Education Funding Agency, 2015) corresponds to a male speaker with a raised vocal effort representing an imam's voice (Fig. 4a). Similarly, Common Loudspeaker Format (CLF), an open-source format for loudspeaker data, was selected and applied inside the Point Source Editor to the other sources to represent loudspeakers, using their sound level and directivity (Fig. 4b). Finally, the simulations were performed to investigate acoustical parameters such as SPL, RT, T30, EDT, and STI for two different situations: Fully occupied (preaching during the Friday sermon) and partially occupied (during daily prayers).

VI. The Case Study Selections

As mention previously, two different mosques were chosen as representatives of the most common contemporary mosque design typologies in Erbil, Altun Mosque and Dayk Mosque. Table II summarizes the key physical features of the two selected mosques, with data on length, width, height, volume, and overall estimated capacity at peak occupancy. Only the size of the main prayer hall is used for sound analysis, as this is the acoustically functional area of the mosque (as described previously).

A. The Dayk Mosque

The second case study is located in Italian City II in Erbil, Iraq (Fig. 5). The main prayer hall has been selected for the investigation purpose in this mosque, located in the center of the mosque design, with a rectangular plan of 20 m by 31 m (area = 651 m²). It has an entry area of 5.2 m width and 9 m length (area = 46.8 m²), with an additional 22 m² for the front part of the hall for the imam to recite and prostrate during prayer, called the *mihrab* area, but this can be neglected as no worshippers go there (Fig. 6). As a result, the total area of the main prayer hall is about 700 m², which can be occupied with slightly more than 800 people. The height of the hall is generally around 4.6 m, but the central dome extends to a crown of 12 m, with a diameter of 9 m.

The inner surfaces have various finishing materials, with carpeting to cover the floor (Fig. 7). The wall finishing is gypsum plastering, wood, and glass, with window frames covering 7% of the total wall surfaces, covered by curtains. All walls are covered with wood of 1.20 m meter height, and the *mihrab* wall is also covered with gypsum plaster finishing. Gypsum board is used for the ceiling. Absorption coefficients of used materials are illustrated in Table III.

B. Altun Mosque

Altun Mosque is located in Bnaslawa Old Road in Erbil, Iraq (Fig. 8). The main prayer hall area is 968.2 m² with dimensions of 29 × 33.2 m, which can be occupied by slightly more than 980 persons. The ceiling height is 11 m

Table I
Sound absorption and scattering coefficients of materials

Material	63 Hz	125 Hz	250 Hz	500 Hz	1 k Hz	2 k Hz	4 k Hz	8 k Hz	Scatte-ring factor
Sand blasted travertine	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.15
Solid timber door	0.14	0.14	0.10	0.06	0.08	0.10	0.10	0.10	0.25
Double glazing	0.10	0.10	0.07	0.05	0.03	0.02	0.02	0.02	0.10
Single glazing	0.08	0.08	0.04	0.03	0.03	0.02	0.02	0.02	0.10
Ceramic tiles	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.15
2×13 mm gyps. Board on frame	0.15	0.15	0.10	0.06	0.04	0.04	0.05	0.05	0.10
12 mm wood on studs	0.28	0.28	0.22	0.17	0.09	0.10	0.11	0.11	0.10
Perforated MDF panel (TopAkustik 5/3T)	0.20	0.30`	0.80	0.95	1.00	0.80	0.60	0.60	0.10

Source: Sü Gül and and Çalıskan (2013)

Fig. 2. AutoCAD 2020, Bosch Laser Distance, SketchUp, and ODEON 16

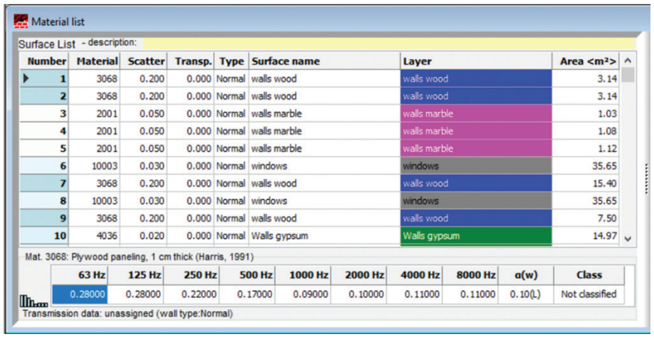

Fig. 3. Material list in ODEON, showing material properties and area.

Fig. 4. Point source editor setup in ODEON, (a) imam source, and (b) loudspeaker source.

Fig. 5. Exterior and interior views of the Dayk Mosque.

and the dome height is 7.7 m, with a diameter of 20 m (approximately one-third of the ceiling area, as shown in Fig. 9). The mosque has different types of internal surface finishing materials (Fig. 10), with carpeting on the floor. The wall finishing is gypsum plastering, wood, and marble, with fenestration covering 20% of the total wall surfaces, covered by curtains. All walls are covered with wood of 1.20 m meter height, and the *mihrab* wall is clad in marble. Gypsum board and wood material are used for the ceiling. Absorption coefficients of the used materials are illustrated in Table III.

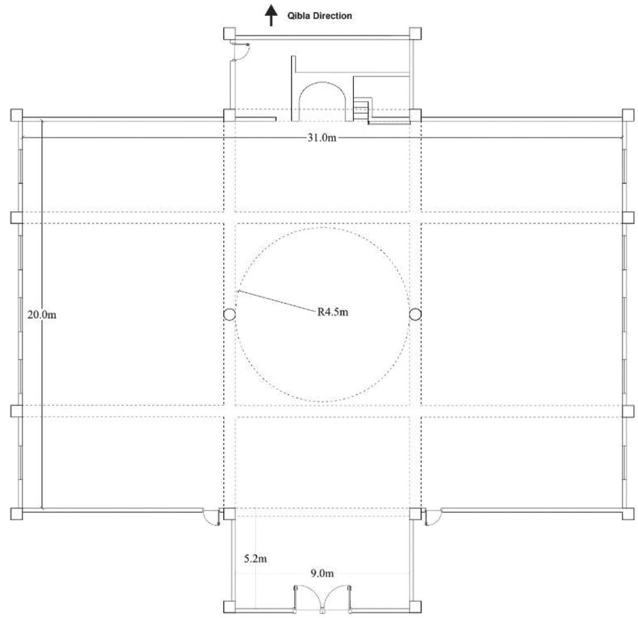

Fig. 6. Main floor plan of the main prayer hall, Dayk Mosque.

TABLE II
CASE STUDIES MEASUREMENT

No.	Mosque name	Floor plan measurement			Parameters for main prayer activities room	
		Prayer room dimension (m)				
		Length	Width	Height	Volume (m^3)	Expected capacity
1	Dayk Mosque	20	31	4.6	3650	800
2	Altun Mosque	29	33	11	13000	980

C. Interior Materials and Noise Reduction Coefficient (NRC)

A variety of materials have typically been used in the interior of the mosques' main prayer halls, presumably to achieve best quality acoustic performance. Some materials that have been used can be categorized as reflective, and others as absorbent, according to their NRC rate. Designers, whether architects or interior designers, need to select the appropriate materials to offer balance to achieve the eligible RT. Table III illustrates the common existing materials of the interior building fabric in main prayer halls regarding their specification and absorption coefficient.

D. Computer Simulation (ODEON)

Technological developments provide new opportunities for acoustical design. The acoustical assessment of a space in the design phase used to be done with scale models, which was time-consuming and impractical. It is now possible to use computer simulations to analyze acoustical properties before the actual construction of buildings, and acoustical design can thereby become an integral part of the architectural design process from its inception. Computer simulation has proven to be a viable tool in designing music buildings, such as concert halls, opera houses, and multi-purpose auditoria, minimizing hitherto unexpected acoustic

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TABLE III
THE LIST OF MATERIALS AND THEIR PROPERTIES OF DAYK AND ALTUN MOSQUES (ODEON USER'S MANUAL, 2020)

Materials	Absorption coefficient (α)							
	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Plaster, gypsum, or lime, smooth finish on lath (Harris, 1991)	0.14	0.14	0.10	0.06	0.04	0.04	0.03	0.03
Gypsum board (Ref. Dalenbäck, CATT)	0.28	0.28	0.12	0.10	0.17	0.13	0.09	0.09
Plywood paneling (Harris, 1991)	0.28	0.28	0.22	0.17	0.09	0.10	0.11	0.11
Carpet heavy, on concrete (Harris, 1991)	0.02	0.02	0.06	0.14	0.37	0.06	0.65	0.65
Solid wooden door (Bobran, 1973)	0.14	0.14	0.10	0.06	0.08	0.10	0.10	0.10
Single pane of glass (Ref. Multiconsult, Norway)	0.18	0.18	0.06	0.04	0.03	0.02	0.02	0.02
Double glazing, 2-3 mm glass, 10 mm gap (Kristensen, 1984)	0.10	0.10	0.07	0.05	0.03	0.02	0.02	0.02
Single pane of glass, 3 mm (Fasold and Winkler, 1976)	0.08	0.08	0.04	0.03	0.03	0.02	0.02	0.02
Marble or glazed tile (Harris, 1991)	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
Audience, 1 per sq. m (Meyer, Kunstmann, and Kuttruff, 1964)	0.16	0.16	0.24	0.56	0.69	0.81	0.78	0.78

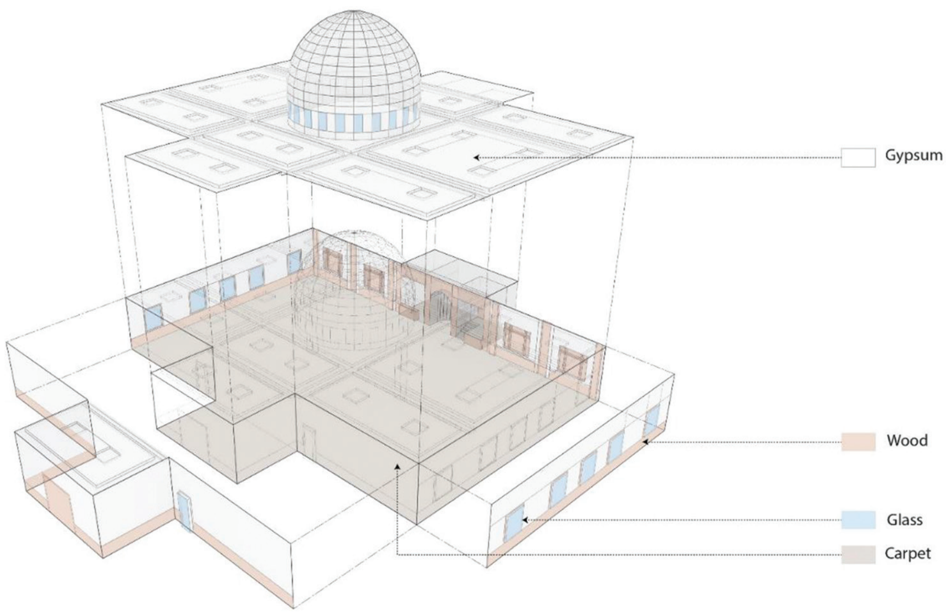

Fig. 7. Exploded diagram showing the internal surface material of the main prayer hall, Altun Mosque.

Fig. 8. Exterior and interior view of the Altun Mosque.

problems (that can now be anticipated), and allowing many alternatives to be tested in a short time span (Schmidt and Kirkegaard, 2004). Computer simulations of the studied Mosques were carried out using ODEON Room Acoustics Program 6 software, which was released by the Technical University of Denmark (Naylor, 1993) (Figs. 11 and 12). The calculation method of this software is based on prediction algorithms including the image-source method and ray tracing. The ODEON Room Acoustics Program also takes into account the statistical properties of room geometry and absorption (Rindel, 2000).

E. Sound Source and Receiver Points

Two different scenarios were examined for both mosques by the simulation. The first scenario discusses the case where worshippers are performing the prayer behind the imam. The imam recites in a standing position facing the *qibla* (the prayer direction, facing toward Mecca), and uses a raised voice, without using any electro-acoustic sound system. The worshippers are assumed to be also standing listening to the imam while performing the daily prayers. Their ear height is taken to be 1.65 m from the floor based on average human height. In the second scenario, the khatib is assumed to be delivering the Friday speech in a raised voice, with the aid of sound reinforcement system as in the case of loudspeaker usage, from the *minbars*, elevated about 1.3 and 1.0 m from the mosque floor in the Altun Mosque and Dayk Mosque, respectively. The mouth height is around 2.80 m from the floor in the Altun Mosque, and 2.50 m in the Dayk Mosque. Worshippers sit on the floor to listen to the *khatib* during the Friday sermon, with ear height of about 1.0 m from the mosque floor. Simulations were run with two assumptions: Mosques being fully or partially occupied.

Figs. 13 and 14 demonstrate the positions of sound sources and receptor points for all configurations.

F. Simulation Procedure

The main research aim is studying and exploring the acoustical performance of contemporary mosque types in Erbil. To achieve this goal, STI, EDT, RT (T30), and SPL in the chosen mosques were simulated and measured. Simulations were carried out using ODEON Room Acoustics software. The calculation method of this software is based on prediction algorithms including the image-source method and ray tracing. "The ODEON Room Acoustics software also takes into account the statistical properties of the room's geometry, materials, and absorption" (Rindel, 2000). As mentioned previously, a 3D model of a mosque with a dome was obtained using SketchUP Software. The model was imported to the ODEON Room Acoustics Program. In Dayk Mosque five point sources and 48 receivers are specified for each activity; the first source presents the imam and the other four sources refer to the loudspeakers. Similarly, for Altun Mosque one source as imam and five others as loudspeakers were specified, and the other 56 points were specified as receivers.

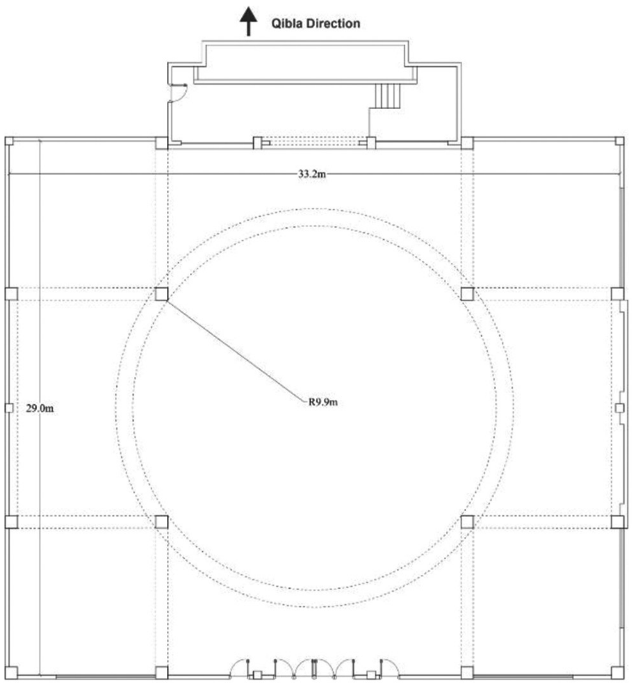

Fig. 9. Main floor plan of the prayer hall, the Altun Mosque.

The loudspeakers in both mosques are activated or turned off according to activity in the daily prayers or Friday sermon. Whereas different materials with different sound absorption coefficients have be assigned and the calculation parameters have been selected, the receiver surfaces have been divided into grids surfaces of 6 rows for Dayk Mosque and 7 rows for Altun Mosque, having 8 points in each row, as shown in Figs. 13 and 14, illustrating the locations of the sound sources and receivers. To obtain the results of different acoustical parameters, the contour maps and graphs for calculated parameters were obtained for all scenarios and cases. This process was repeated and simulated in both mosques, which have different dome areas. SPL, RT (T30), EDT, and STI were simulated in the main prayer hall when fully and partially occupied.

It is important to mention that acoustic parameters of EDT, SPL, and T30 in ODEON are calculated for eight octave

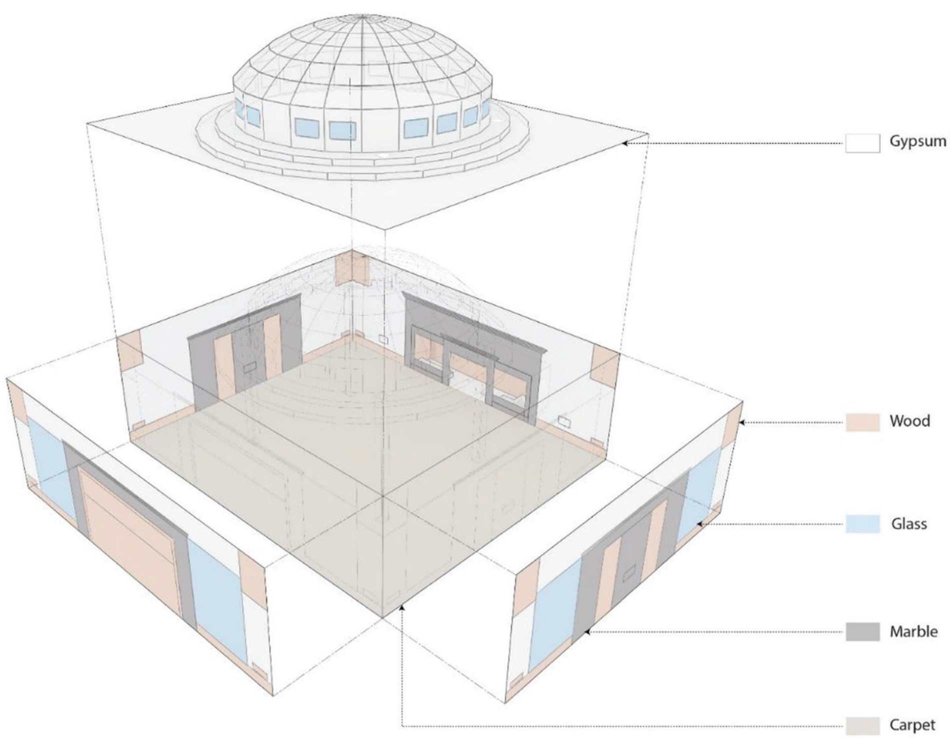

Fig. 10. Exploded diagram showing the internal surface material of the main prayer hall, Altun Mosque.

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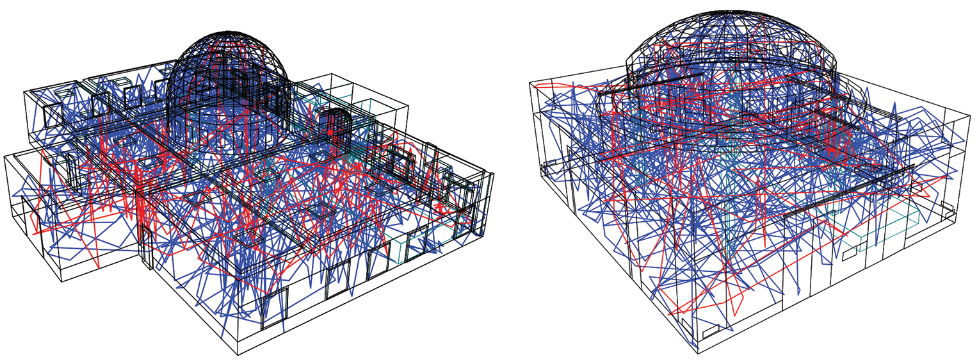

Fig. 11. 3D investigation ray tracing view in ODEON (left: Dayk Mosque, right: Altun Mosque).

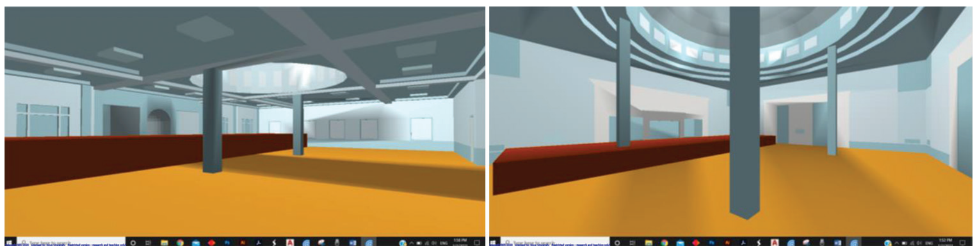

Fig. 12. Interior 3D Open-GL views of modeled mosques (left: Dayk Mosque, right: Altun Mosque).

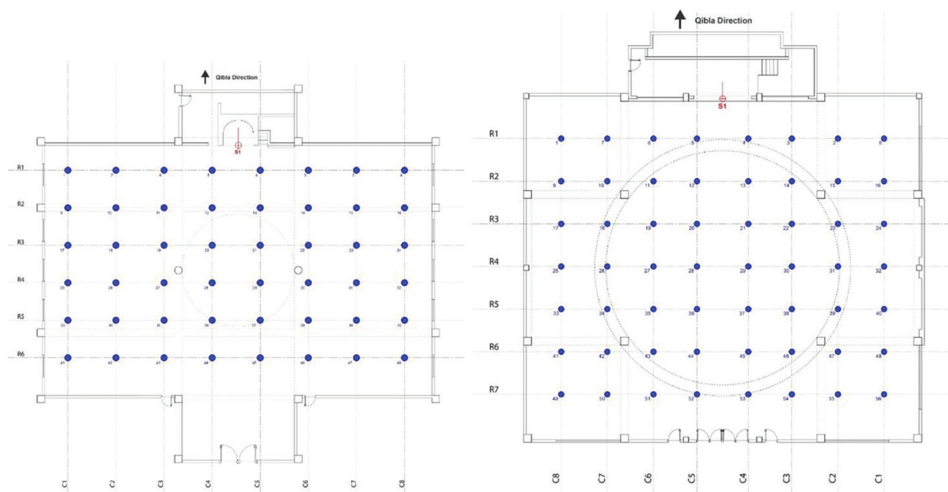

Fig. 13. Receiver points in plan view in 1st scenario with imam position source (left: Dayk Mosque, right: Altun Mosque).

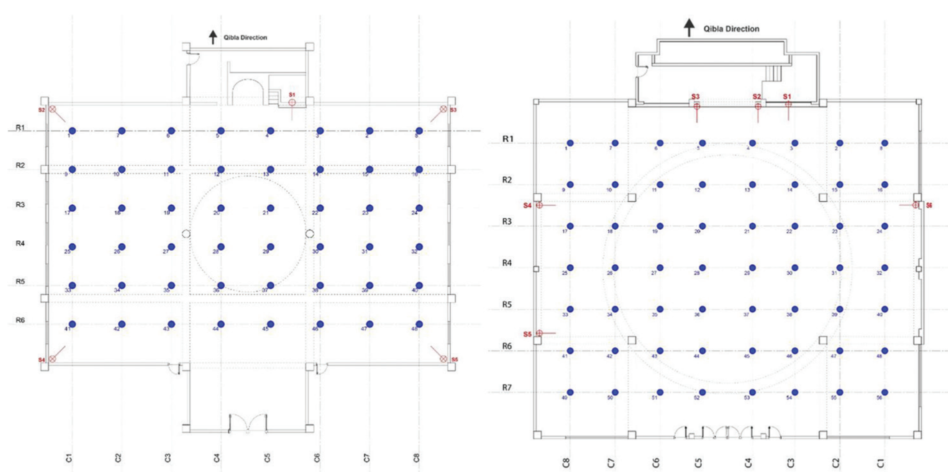

Fig. 14. Receiver points in plan view in 2nd scenario with loudspeakers and *khatib* position source (left: Dayk Mosque, right: Altun Mosque).

bands (63 Hz-8000 Hz) separately; hence, it was not possible to present all the data in this research; only the frequency of 1000 Hz is being discussed, and EDT with some other bands is presented in the Appendix. The background noise in the mosque is assumed to reach an NC rating of NC15. To include the background noise for the calculations in ODEON, NC15 was applied in the room setup. The first activity indicates the prayer mode; for this, the source is the imam in the *mihrab*, facing toward the *qibla* set at a height of 1.65 m. The *mihrab* space is highlighted in Fig. 15. The second activity is the preaching mode and the recital of the Holy Quran. The source is the *khatib* in the *minbar*, facing the worshippers, supported with four loudspeakers. The receiver height for this activity presents the seating level of approximately 1.65 m. For the two different activities, speech-related parameters are analyzed.

VII. Results and Discussion

A. STI (imam and loudspeaker)

To investigate how well speech is understood for a receiver in a room, STI can be used as a quantifying method of speech transmission intelligibility. Flawless speech transmission indicates that the temporal speech envelope at the audience location replicates the speech envelope at the mouth of speaker. The intelligibility of speech can be quantified regarding the progressions achieved in the adjustment of the speech envelope as a result of reverberation and noise in the space (Davis, Patronis and Brown, 2013). Barnett (1999) suggested that the STI subjective scale differs from 0 = bad to 1 = excellent. According to this scale, an STI of at least 0.5 is appropriate for most applications, as shown in Table IV.

1) STI measurement during daily prayer (imam position)

As presented in Fig. 16, STI ratings are indicated on the value colored scale bar in each mosque. As it can be seen in both mosques, the closer the worshippers are to the source, the better the STI score. The zones that are considered as poor and bad in STI ratings are located in the center of the rear half of the floor area, with some other poor zones near the middle-side walls, behind the column zones, and at the far front corners.

For the first activity mode, which is the most critical case when the imam is performing alone (that is, without the loudspeakers), as in the daily prayers, with one-third of the mosque occupied, the STI ranges from 0.23 to 0.65 in Dayk

Table IV
STI-subjective values for syllable intelligibility (STI reference values according to Barnett, 1999)

No	Subjective scale	STI value
1	Bad	0.00-0.30
2	Poor	0.30-0.45
3	Fair	0.45-0.60
4	Good	0.60-0.75
5	Excellent	0.75-1.00

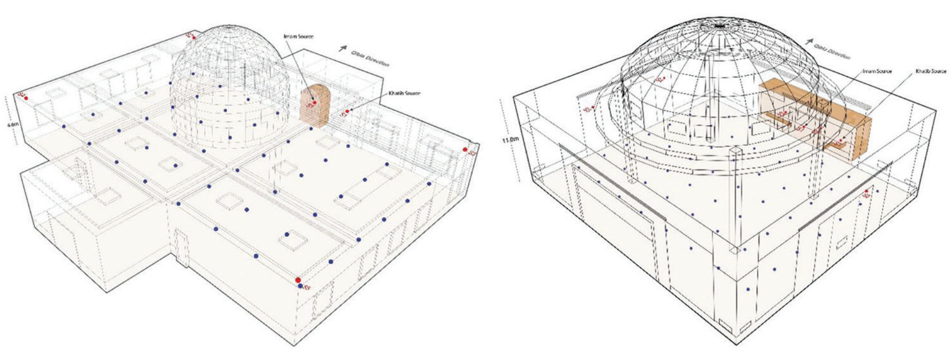

Fig. 15. All source and receiver points in 3D view in both imam and *khatib* position scenarios, highlighting the *mihrab* location (left: Dayk Mosque, right: Altun Mosque).

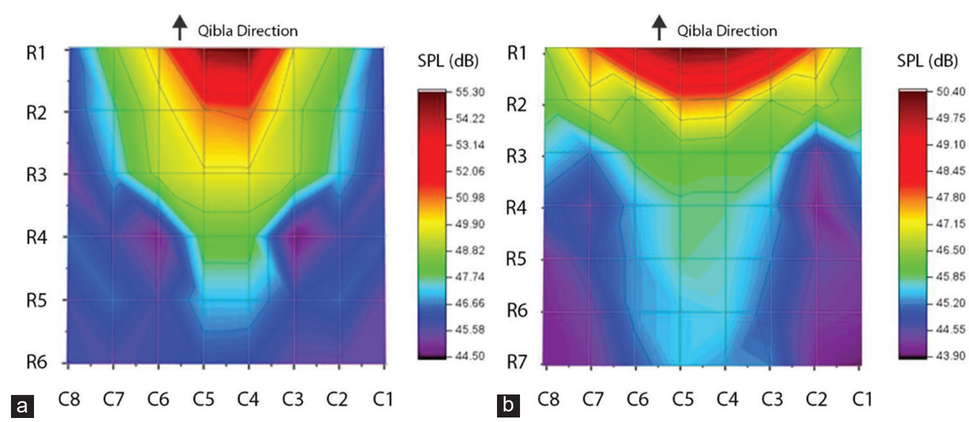

Fig. 16. Speech transmission index contour map in the case of daily prayer (imam position): (a) Dayk Mosque, (b) Altun Mosque.

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Mosque, and 0.12 to 0.42 in Altun Mosque, both of which are considered poor ratings. The best values were found at locations just around the source (imam) and in the first row, where the STI is considered fair and good (respectively).

It is shown in Fig. 16a that for the imam position in Dayk Mosque, only 5% of the area has good STI values, and about 10% of the area is covered in the fair zone. The remaining area (85%) lies between the poor and bad zones. Altun Mosque generally has low STI values, as shown in Fig. 16b; only 2% of the area lies in the fair zone, whereas the remainder lies in the poor zone (8%) and the bad zone (90%).

In general, STI values are affected by the hall size, *mihrab* geometry, and the dome-to-ceiling ratio (greater dome-to-ceiling ratio provides better STI values). The size and geometry of the *mihrab* have a significant impact in the prayer mode, where the imam is facing the *mihrab*, and the proper sound reflection is essential to obtain decent speech clarity, especially with regards to the early reflections. The overall dome-to-ceiling ratio and height of the space could cause lower STI values due to the delay in reflected sound, as shown in the contour maps of Fig. 16. For instance, Dayk Mosque, which has a semicircular niche *mihrab* (Fig. 15), has a better STI value than Altun Mosque, in which no consideration has been given to the geometry and size of its *mihrab* (Fig. 15), reflected in the unnecessary scattering of sound in the case of daily prayer.

2) STI measurement in Friday sermon (khatib position)

Fig. 17 shows the case colored scale bar and contour map indicating STI ratings. Overall, during Friday sermon activity the support of loudspeaker drastically improved the STI values, especially in Dayk Mosque. In the Altun Mosque, only the areas near the end of the side walls, rear corners, and the far front corners were zones of poor STI rating, whereas the rest of the space had decent STI values. This is mainly because this wall side had one loudspeaker compared to the parallel side. As in the first scenario, STI values were influenced by the dome-to-ceiling ratio and the space size, in addition to loudspeaker locations and distribution.

It is shown in Fig. 17a that for the sermon case in Dayk Mosque, which is the best case, most STI values are in the satisfactory (good) zone, covering 100% for Dayk Mosque. For Altun Mosque, as shown in Fig. 17b, the acceptable zone comprises about 70% of the area, with 55% being the fair zone, and 15% considered as a good zone. The remaining area comprises the poor zone (30%).

Dayk Mosque's STI values increased to the range of 0.6-0.69, which are considered good to excellent levels. Although using a greater number of loudspeakers greatly improved the STI levels in Altun Mosque, reaching a range of 0.4-0.6, this is not as good as the Dayk Mosque due to unusual distribution of loudspeakers, as shown in Figs. 14 and 15. The better location of loudspeakers in Dayk Mosque includes positioning all speakers in the four top corners of the main hall, each facing the audience near them in a balanced manner, which resulted in better STI scores.

B. Reverberation Time (RT) and Early Decay Time (EDT)

RT is defined as the time it takes for a sound to decay by 60 dB after the sound source has been switched off. This is noted as T60. RT is the most frequently used parameter in room acoustics. Some acousticians rely only on RT when evaluating room acoustics, but for most cases this is not sufficient in itself. RT can reveal information about the size of a room and sound absorption within it. When measuring RT in practice there is always a considerable level of background noise in the recording (for example, ambient acoustic noise, electric noise in microphone, electronics, and cables), which reduces the range of 60 dB required to derive T60. Therefore, RT is calculated based on smaller decay ranges (10 dB, 15 dB, 20 dB, and 30 dB) instead, which are well above the background noise level. However, the corresponding time it takes for each decay range is always multiplied by an appropriate factor to extrapolate the time for 60 dB decay (Davis, Patronis and Brown, 2013). Calculating RT in this way results in multiple different numbers for RT, as shown in Fig. 18. EDT is obtained from the initial 10 dB drop of the backward-integrated decay curve, by applying the best-fit linear regression line between 0 and −10 dB. Assuming that decay is linear, extrapolation of 10 dB range and 60 dB requires multiplication by 6, EDT is related to the first −10 dB. Since the early part of the decay is dominated

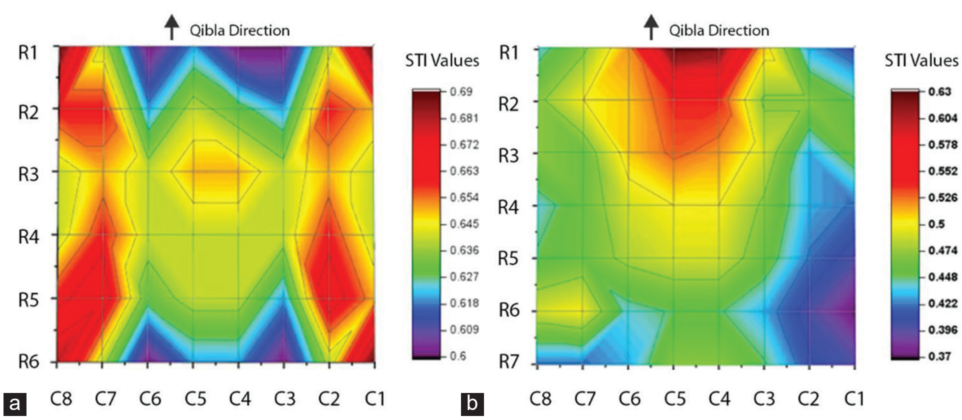

Fig. 17. Speech transmission index contour map in the case of Friday sermon (*khatib* position): (a) Dayk Mosque, (b) Altun Mosque.

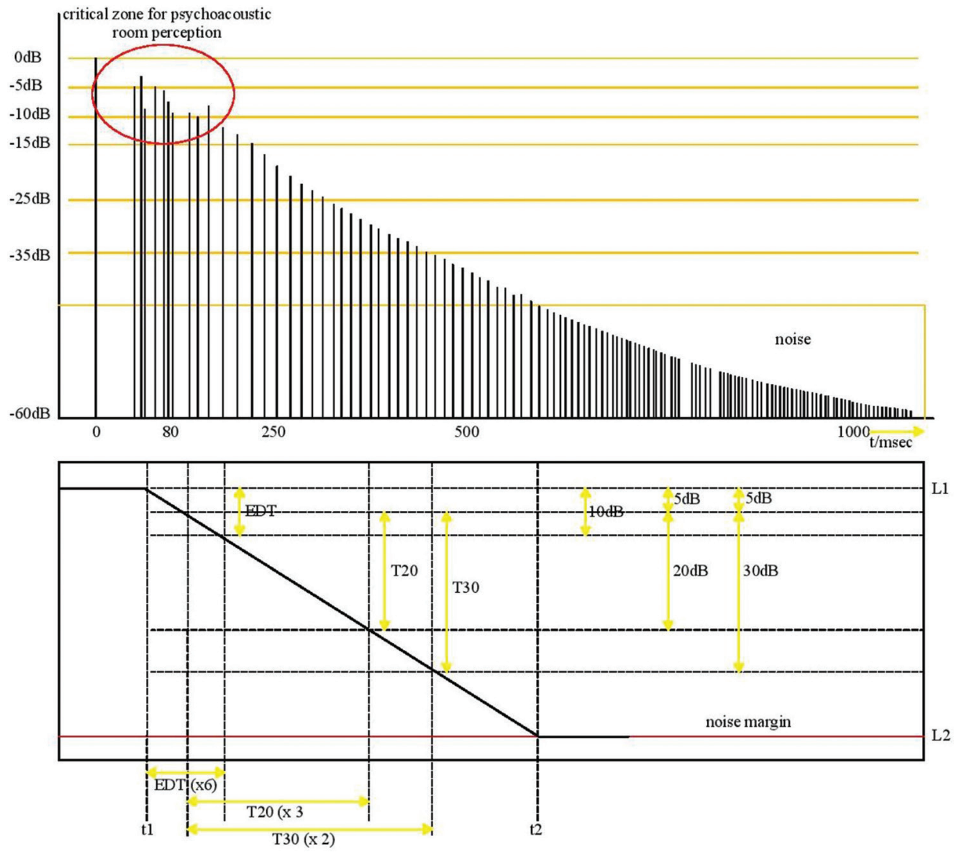

Fig. 18. The relationship among RT (T30, T20, T15) and early decay time.

by the direct sound, and it is much steeper than the rest of the decrescendo, EDT is usually shorter than the other types of RT (Barron, 2009).

In respect to RT (T30) simulation in both mosques, In general, we can compare the case in two different ways. First method is comparing the T30 of one mosque, either Dayk or Altun, according to the different activity of daily prayer of one-third occupied space, with sound emanating from the imam position; or the Friday sermon with a fully occupied hall, when the imam is preaching from the minbar (khatib position) with loudspeaker support. The difference in audience number (that is, user density) affects the overall absorption coefficient, and consequently the T30.

Second, comparison between both mosques can be undertaken, as each has a different size, geometry, materials, design, and even allocation of loudspeakers. T30 data for all octave frequency bands were attained from the simulation results. For the purpose of this discussion, the mid-frequency of 1000 Hz is considered.

The T30 of Dayk Mosque with the frequency of 1000 Hz is around 1.2 s-1.4 s during the partially occupied daily prayer of the imam position, and about 0.98 s-1.22 s with the support of all four loudspeakers in the case of fully occupied Friday preaching scenario. Similarly, the Altun Mosque T30 ranges mostly from 2.65 s to nearly 3.4 s whereas performing the daily prayer led by the imam, and 2.23 s to around 3.15 s with the loudspeakers on during the Friday sermon.

It is observed that generally T30 is longer during the daily prayer when only the imam is reciting the Quran, compared to the case of the presence of all loudspeakers for both mosques, as the imam is standing in one location facing the *mihrab*, thus sound has to be reflected on the surfaces in front of him to bounce back to the worshippers. Moreover, the greater the audience the higher the absorption coefficient, and the lower the T30.

In the Dayk Mosque, in both scenarios during the daily prayer and Friday sermon, the highest T30 value is in the center of the hall, compared to the corners and edges, as shown in Fig. 19a and Fig. 20a. This is due to the presence of the dome in the center of the ceiling, which causes a delay in the reflected sound; in other words, this area receives long-delayed reflections from the dome. Conversely, Altun Mosque has more even T30 values in each activity, as shown in Fig. 19b and Fig. 20b, whether in daily prayer or the Friday sermon, because the dome-to-ceiling ratio is greater compared to the Dayk Mosque, and the ceiling is a hard surface with reflective characteristics, hence the dome directly affects all parts of the room, causing homogenization and similar T30 values. The effect of the dome could be intensified when all the loudspeakers are used, as their allocations are not ideally distributed. However, the dome compensates for this problem by standardizing the room with similar RT values at all points, consequently resulting in similar STI. EDT has also been simulated for all the cases (Appendix M1, M2, M3, and M4).

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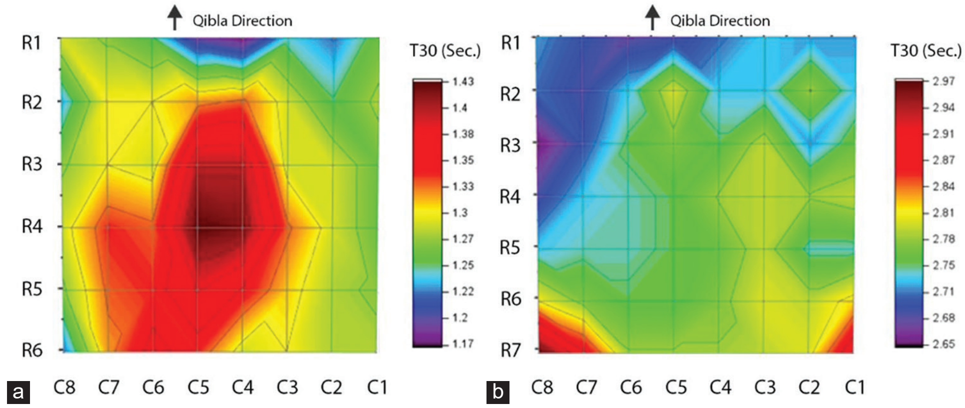

Fig. 19. T30 contour map (1000 Hz) in the case of daily prayer (imam position): (a) Dayk Mosque (b) Altun Mosque.

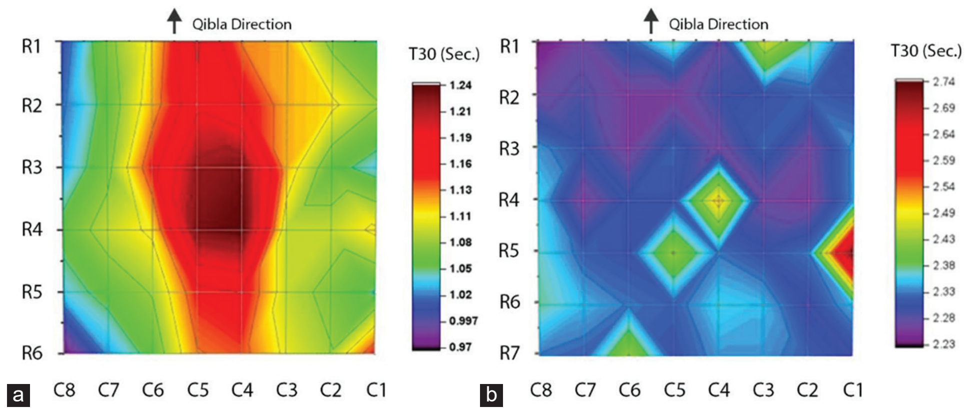

Fig. 20. T30 contour map (1000 Hz) in the case of Friday sermon (*khatib* position): (a) Dayk Mosque, (b) Altun Mosque.

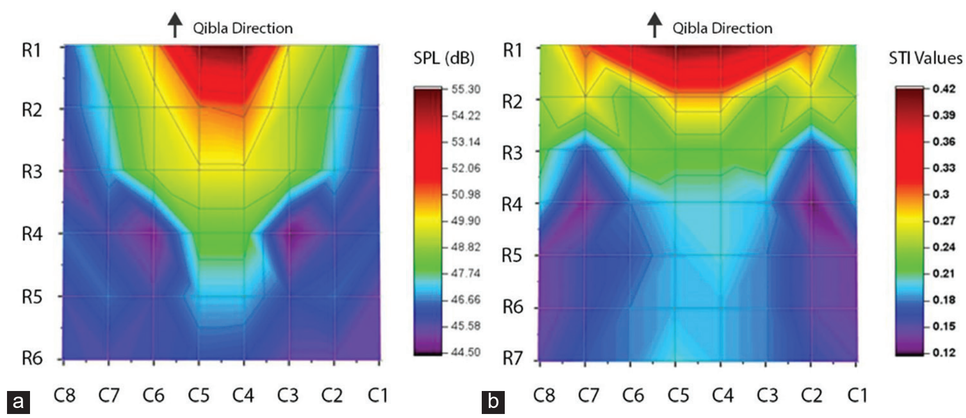

Fig. 21. Sound pressure levels contour map (1000 Hz) in the case of daily prayer (imam position): (a) Dayk Mosque, (b) Altun Mosque.

C. Sound Pressure Level (SPL)

1) SPL measurement at daily prayer (imam position)

Simulation data indicate that the values of SPL range between 45-55.30 dB in Dayk Mosque, and 44-50.40 in Altun Mosque, with a frequency of 1000 Hz for speech (imam position) (Fig. 21).

The most revealing case investigated is the first, when the imam is performing alone (that is, without the loudspeaker) in both mosques the results show that the SPL value decreases gradually as we get farther away from the imam. According to the worshipper's location, the SPL in the front rows are in the highest level as compared to the back rows, as direct sound decays in the hall. Moreover, the irregularity of the maps for both mosques occurring close to the center of the room is because of the existing columns supporting the ceiling, which create acoustic shadows in the area just behind them, as shown in the SPL contour maps (Fig. 21). These shadows are due to the columns' positions and mass relative to the position and orientation of the imam.

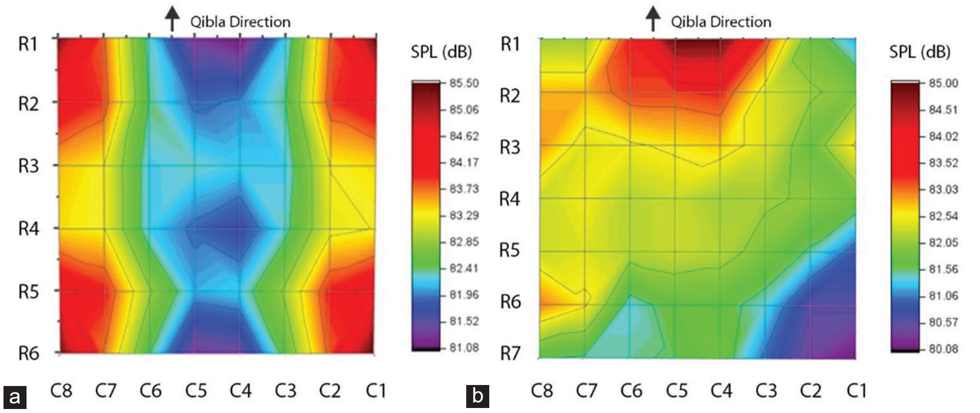

Fig. 22. Sound pressure levels contour map (1000 Hz) in the case of Friday sermon (*khatib* position): (a) Dayk Mosqu

2) SPL measurement in Friday sermon (khatib position)

From the SPL point of view, the situation is better for the imam with loudspeaker configuration for the Friday sermon. As expected, the introduction of the loudspeakers in the second case helps in the distribution of the sound more evenly throughout the space, minimizing the shadow area behind the columns, in addition to increasing SPL values in both mosques (Fig. 22). It is noticeable that the SPL range is increased to 80-85 and 81-85 dB in Dayk and Altun Mosque, respectively.

Comparing the SPL contour map of both mosques, another advantage is observed for Dayk Mosque over Altun in terms of the equal distribution of SPL within the space, which is due to the loudspeaker positioning in all four corners of the hall (Figs. 14 and 15). It is important to mention that if Altun Mosque did not have a significantly greater dome-to-ceiling ratio, this problem (which is fundamentally due to the unequal distribution of the loudspeakers) would not be so obvious.

VIII. Conclusion

Sound fields of the main prayer halls in the case studies were tested for RT and sound distribution. The main prayer halls' geometries combined with existing speakers showed the advantages of uniform spatial distribution of sound, attaining proper sound supply over the whole space. However, overcoming RT problems effectively requires a holistic understanding of the material usage and properties in the initial design stages, supported by forming suitable space geometry. Furthermore, whereas almost all of the rows have acceptable sound levels, in the case of loudspeakers being absent, the imam's position within the mosque geometry negatively affected sound fields in the middle and back rows for all receivers' positions. In that case, only the front raw had appropriate levels of sound.

The research investigation conducted within this paper is anticipated to serve architects to have an enhanced understanding of the acoustical impacts of initial architectural design decisions relating to space, material, and forms of mosque architecture to incorporate necessary elements for superior quality acoustics to be enjoyed by users of structures, increasing the satisfaction of worshippers' hearing and comfort. Considering the results in this study, aside from the mosques' physical components (especially the floor plan design and volume), various aspects affect the acoustic environment, including the area, utilized building materials, and occupant number and density. The majority of the mosque designers or architects absolutely prioritize visual esthetics and form, and some mosques merely focus on providing as much space as possible to cater for more worshippers, with no specific acoustical design consideration.

This study analyzed the acoustical characteristics of main prayer halls of two most common mosque types in Erbil during two main usage scenarios: Fully occupied during the Friday sermon, and partially occupied during daily prayers. Room simulation utilized ODEON to assess the degree of intelligibility. Good acoustic criteria were compared with the requirements of space and design guidelines.

The analysis of two mosques main prayer halls indicated that quality of sound was insufficient without using loudspeakers. In Dayk Mosque, the acoustical properties were better than in Altun Mosque, due to the even distribution of loudspeakers in the former, located in the four corners of the prayer hall for the Friday sermon. In general, areas beneath the dome had longer RT. Moreover, in Dayk Mosque in both the imam and *khatib* positions the central area had longer T30 compared to Altun Mosque, which had more even distribution of T30 for both scenarios. The more appropriate *mihrab* design for the imam's position in the Dayk Mosque had a noticeable impact on the sound distribution in daily prayer. In this scenario, the SPL and consequently the STI were clearly decreased behind the structural columns, and the closer the worshippers were to the imam, the better the SPL and STI. Due to this, the worshippers in some receiver points could not follow and understand what was said clearly in the *mihrab*. Due to the limited number of chosen mosques and limited acoustical parameters in ODEON 16 Basics to determine acoustical performance, further analyses are required on the topic of common mosque designs.

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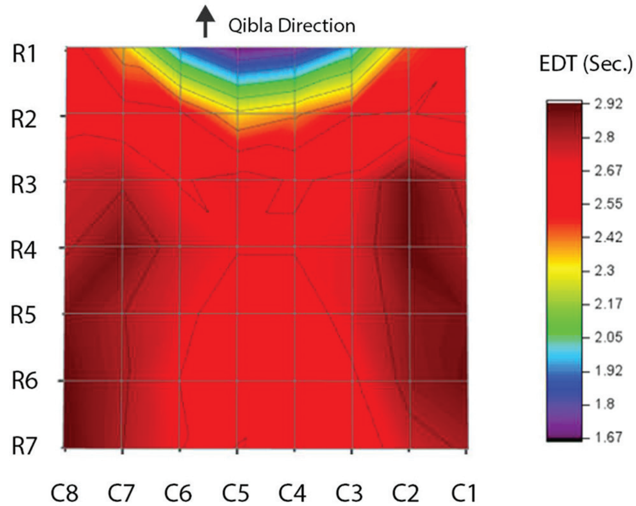
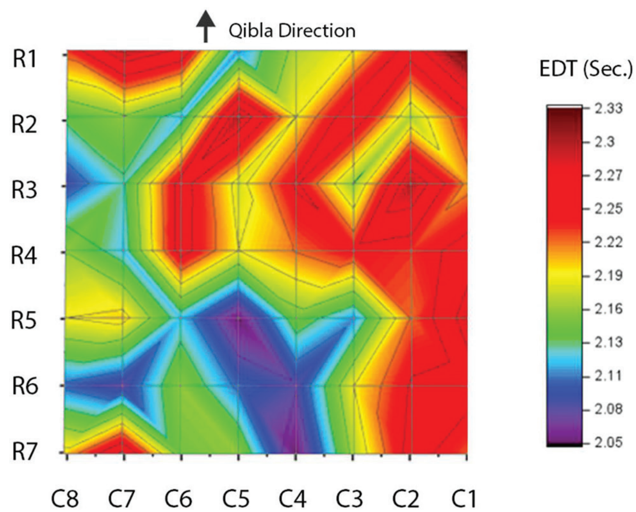
Appendix

Simulated parameter heat maps for different activities:



M1. Early decay time contour map (1000 Hz) in the case of daily prayer (imam position): Altun Mosque



M2: Early decay time contour map (1000 Hz) in the case of Friday sermon (*khatib* position): Altun Mosque

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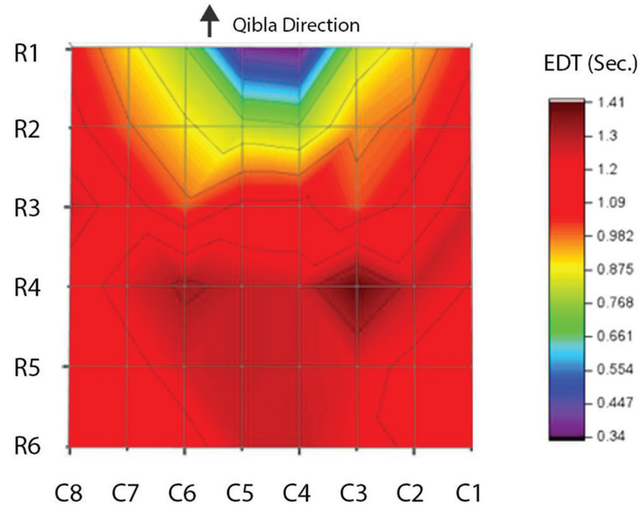
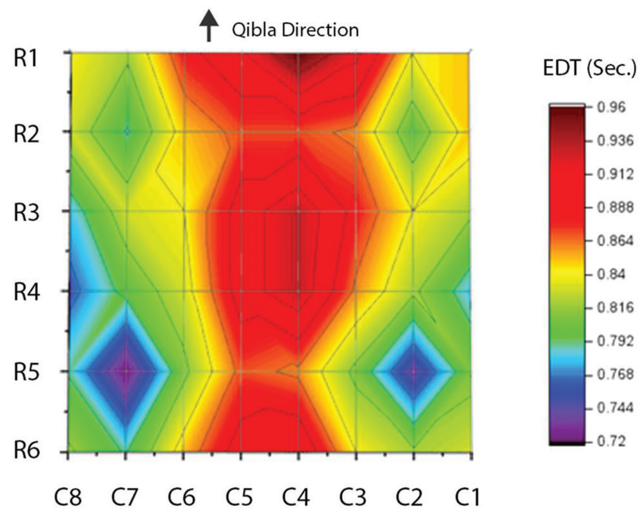


M3: Early decay time contour map (1000 Hz) in the case of daily prayer (imam position): Dayk Mosque



M4: Early decay time contour map (1000 Hz) in the case of Friday sermon (*khatib* position): Dayk Mosque