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Architectural Acoustic Modeling for Predicting Reverberation Time in Room Acoustic Design Using Multiple Criteria Decision Making Analysis

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Abstract**—**This paper presents architectural acoustic modeling to estimate reverberation time in room acoustic design using multiple criteria decision making analysis. First, fundamental decision criteria were determined to evaluate the reverberation time in the room acoustic design problem. Then, the proposed model was applied to a practical decision problem to evaluate and select the optimal room acoustic design model. Finally, the optimal acoustic design of the rooms was analyzed and ranked using a multiple criteria decision making analysis method.

Keywords**—**Architectural acoustics, room acoustics, architectural acoustic modeling, reverberation time, room acoustic design, multiple criteria decision making analysis, decision analysis, MCDMA.

I. INTRODUCTION

MULTIPLE criteria decision making analysis (MCDMA) is an important mathematical tool that expresses preference based on applicable attributes defined as multiple criteria in a decision analysis environment. MCDMA is a quantitative method for ranking decision alternatives and choosing the best one when the decision maker has more than one criterion.

With MCDMA, the decision maker selects the alternative that best meets the decision criteria and develops a numerical score to rank each decision alternative based on how well each alternative meets them. Also, human judgments and decisions about alternatives can be partial, and often it is difficult to choose the best alternatives.

Of the many MCDMA methods, only a few are mentioned, such as preference analysis for reference ideal solution (PARIS) [1-4], analytical hierarchical process (AHP) [5-7], VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) [8-10], preference ranking organization method for enrichment evaluation (PROMETHEE) [11-14], technique for order preference by similarity to ideal solution (TOPSIS) [15-18], ÉLimination et Choix Traduisant la REalité (ELECTRE) [19-20], and fuzzy decision making etc [21-22].

MCMDA has been effectively applied to evaluate a variety of engineering and technological decision analysis problems [1-22]. Analysis of reverberation time includes multiple decision criteria in room acoustic design modelling. Architectural acoustic evaluation of important indoor spaces, such as many concert halls, auditoriums, churches, and mosques, has been researched considering acoustic design for spatial acoustic comfort and measurement of acoustic qualities.

The comparing the acoustics of mosques and Byzantine churches project dealt with the means of qualifying and enhancing the acoustical heritage of mosques and byzantine churches. The acoustical measurements were carried out inside a selected group of spaces of worship and systematically collected their primary acoustical data. By successive processing, the main features of the two types of enclosures could be described and compared. The transition from the acoustics of a byzantine church to that of a mosque was also analyzed thanks to the architectural similarity between the former St. Segius and St. Bacchus church in Istanbul (now Kucuk Ayasofia mosque) and the Basilica of St. Vitale and St. Agricola in Ravenna, Italy [23].

Catholic churches and mosques are worship places but with different occupation modes and acoustic requirements, decoration, and architectural styles. The acoustic performance of these worship places was compared to describe main similarities and differences. It was analyzed the variability between objective acoustical parameters (Reverberation Time, Clarity C50 or C80 and STI or RASTI) and architectural parameters (volume, area, length, height, and width). Regression models were created to find the best relationships among the parameters. A comparison between the acoustics of churches and mosques was established using data analysis to allow for a discussion relating to the comprehension of those parameters' variability [24].

Auditorium evaluation was considered by four important acoustic design issues for auditoria: volume and seats; control of reverberation time (RT); diffusion of sound; elimination of defects [25]. The acoustic design of the classical concert hall and evaluation of the acoustic performance were discussed in terms of three acoustic parameters (i.e., reverberation time (RT), clarity (C80), and lateral fraction (LF)) [26].

The acoustic quality of commercial spaces and buildings is determined by speech intelligibility, which is mainly influenced by reverberation time within an enclosure. These analyses were focused on reverberation time and other parameters related to speech intelligibility [27].

The ceiling structure, which affects the acoustics of the mosque the most, is designed for mosques with either curvilinear elements or flat ceilings. Eight historical mosques with ceiling structures of different materials and types in Turkey were examined in terms of acoustic properties in the main place of worship. Acoustic data were collected by measurements to reveal how morphological differences and

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material changes in ceiling structures affect the acoustic environments of mosques with similar volumes. In order to reflect the effect of architectural features on the acoustic characteristics of the place of worship, the distribution of acoustic parameters and the suitability of the values obtained from the measurements were compared [28].

As a result of the analyses of the architectural acoustic characteristics of the three monumental Ottoman Mosques (Selimiye Mosque (Selimiye Camii) [29], Üç Şerefeli Mosque (Üç Şerefeli Camii) [30], Muradiye Mosque (Muradiye Camii) [31]) in Edirne, Turkey, it has been revealed that architectural acoustic parameters alone are not sufficient in the evaluation of indoor spaces, and that architectural acoustic parameters should be considered with the architectural characteristics of the volumes.

The literature review provides the basic acoustic design features of interiors and their measurement parameters for architectural acoustical evaluation. This paper aims to examine the objective parameters of the reverberation time of indoor spaces such as rooms, concert halls, auditoriums, churches, and mosques. Acoustic evaluation of numerical samples and comparison of results with a classification are the objectives of the MCDMA methodology.

The reminder of this paper is organized as follows: In Chapter 2, the original idea of the multiple criteria decision making analysis method is explained. In Chapter 3, a numerical example is examined. Finally, in Chapter 4, concluding evaluations and recommendations are presented.

II. METHODOLOGY

In decision theory, Bayes rule or Bayes-Laplace principle, weighted linear combination or simple additive weighting model is the best known and simplest quantitative multiple criteria decision analysis method [1-4]. The Bayes rule method combines all multiple objective functions into a single scalar, composite-objective function using the weighted sum.

Suppose that multiple criteria decision making analysis problem has I alternatives $a_i = (a_1, ..., a_i)$, $i \in \{ i = 1, ..., I \}$, and J criteria $g_j = (g_1, ..., g_j)$, $j \in \{ j = 1, ..., J \}$, and the importance weight of each criterion (ω_j, $j \in \{ j = 1, ..., J \}$) is known. The procedural steps of Bayes rule method for evaluation of the alternatives with respect to the decision criteria are presented as follows:

Step 1. Construction of decision matrix $X = (x_{ij})_{ixj}$

$$X = \begin{pmatrix} a_1 \\ \vdots \\ a_i \end{pmatrix} \left(\begin{array}{ccc} g_1 & & g_j \\ x_{11} & \cdots & x_{1j} \\ \vdots & \ddots & \vdots \\ x_{i1} & \cdots & x_{ij} \end{array} \right)_{ixj} \tag{1}$$

where $X = (x_{ij})_{ixj}$ represents the decision matrix and x_{ij} is the value of ith alternative with respect to jth indicator g_j.

In exceptional decision problems, if there are negative values in the decision matrix, first, the decision matrix is transformed by $x_{ij}^t = x_{ij} - \min_j x_{ij}$, then, the values of x_{ij}^t are used in the next procedural steps.

Step 2. Determination of reference ideal (optimal) solution elements (X_j^*)

$$x_j^* = \left\{ x_1^*, ..., x_j^* \right\} = \left\{ (max_i\, x_{ij} \mid j \in B), (\min_i x_{ij} \mid j \in C \right\} \tag{2}$$

where, B represents the benefit criteria and C represents the cost criteria.

Step 3. Normalization of the decision matrix $R = (r_{ij})_{ixj}$

$$R = \begin{pmatrix} a_1 \\ \vdots \\ a_i \end{pmatrix} \left(\begin{array}{ccc} g_1 & & g_j \\ r_{11} & \cdots & r_{1j} \\ \vdots & \ddots & \vdots \\ r_{i1} & \cdots & r_{ij} \end{array} \right)_{ixj} \tag{3}$$

If the evaluation quality is a benefit criterion g_j,

$$r_{ij} = \frac{x_{ij}}{x_j^{\max}}, \; i = 1, ..., I, \; j = 1, ..., J \tag{4}$$

If the evaluation quality is a cost criterion g_j,

$$r_{ij} = \frac{x_j^{\min}}{x_{ij}}, \; i = 1, ..., I, \; j = 1, ..., J \tag{5}$$

where, X_{ij} denotes the evaluation indices, and $i = 1, ..., I$, the number of alternatives, and $j = 1, ..., J$, the number of criteria.

When the criteria of the decision matrix are normalized, all elements are reduced to range values of [0, 1] so that all criteria have the same proportional metrics.

Step 4. Calculation of the weighted normalized matrix $Y = (y_{ij})_{ixj}$

$$Y = \begin{pmatrix} a_1 \\ \vdots \\ a_i \end{pmatrix} \begin{pmatrix} g_1 & & g_j \\ y_{11} & \cdots & y_{1j} \\ \vdots & \ddots & \vdots \\ y_{i1} & \cdots & y_{ij} \end{pmatrix}_{ixj} \tag{6}$$

$$y_{ij} = \omega_j r_{ij}, \; i = 1,\dots,I, \; j = 1,\dots,J \tag{7}$$

where $\sum_{j=1}^{J} \omega_j = 1$, ω_j, g_j importance criteria weight of attribute, r_{ij} and y_{ij} are the normalized, and weighted normalized values of the attribute/criteria g_j, respectively.

Step 5. Determining the values of the optimality function

$$\pi_i = \sum_{j=1}^{J} y_{ij} = \sum_{j=1}^{J} \omega_j r_{ij}, \; i = 1,\dots,I, \; j = 1,\dots,J \tag{8}$$

where, π_i is the value of the optimality function of the alternative *i*.

Step 6. Ranking the alternatives in ascending order (Q_i)

Among the candidate alternatives, the alternative with the highest valuation score is the best choice.The degree of utility of the alternative a_i is determined by comparing it with the ideally best value of the candidate π_i^o being analyzed. Q_i calculates the degree of utility of an alternative a_i.

$$Q_i = \frac{\pi_i}{\pi_i^o} \tag{9}$$

where π_i and π_i^o are the optimality criteria values.

Step 7. Identifying the most acceptable alternative

$$a_i^* = \left\{ a_i \mid \max_i \mu_i \right\}, i = 1,\dots,I \tag{10}$$

where a_i^* denotes the most acceptable alternative.

Step 8. Risk assessment analysis

$$\kappa_i^* = \left\{ \kappa_i \mid \max_i \left[\lambda \sum_{j=1}^{J} \omega_j r_{ij} + (1-\lambda) \min_j \omega_j r_{ij} \right] \cap 0 \le \lambda \le 1 \right\} \tag{11}$$

where, κ_i optimality criterion, $\lambda \in [0,1]$ risk assessment factor, ω_j criteria weight,

$$\kappa_i^* = \left\{ \kappa_i \mid \max_i \kappa_i \right\} \tag{12}$$

where, κ_i^* is the optimal alternative, λ = 0 (no confidence) gives the solution according to Wald's rule. λ = 1 (great confidence) gives the solution according to Bayes' rule.

Step 9. Calculation of Spearman Correlation (ρ_s)

The Spearman correlation method calculates the correlation between the rank of *x* and the rank of *y* variables.

$$\rho_s = \frac{\sum_{i=1}^{n} (r(x_i) - r(\bar{x}))(r(y_i) - r(\bar{y}))}{\sqrt{\sum_{i=1}^{n} (r(x_i) - r(\bar{x}))^2} \sqrt{\sum_{i=1}^{n} (r(y_i) - r(\bar{y}))^2}} \tag{13}$$

where $r(x_i)$ and $r(y_i)$ observations in the sample.

The hierarchy of the MCDMA model is constructed to represent the evaluation and selection process, as shown in Fig. 1.

Level 1: Goal	Architectural Acoustic Modeling			
Level 2: Criteria	g_1	g_2	$\cdots$	g_j
Level 3: Criteria weights	ω_1	ω_2	$\cdots$	ω_j
Level 4: Alternatives	a_1	a_2	$\cdots$	a_i
Level 5: Selection and analysis	$a_i^* = \left\{ a_i \mid \max_i \left(\sum_{j=1}^{J} \omega_j y_{ij} \right) \cap \sum_{j=1}^{J} \omega_j = 1 \right\}$			

Fig. 1. Evaluation and selection hierarchy multiple criteria decision making analysis

III. APPLICATION

A. Parameters for Room Acoustics Quality

According to the ISO 3382-1 standard [32], reverberation time is a predominant indicator of the acoustic quality of a music or speech room. Although Reverberation Time continues to be recognized as an important parameter, there is consensus that other measures such as early/late energy ratios, specific intelligibility indices and background noise level are necessary for a more complete assessment of the acoustic quality of speech rooms.

The Reverberation Time (T), in seconds, is the measure of time elapsing between the disarming of a sound source and the moment when the sound level is decreased by 60 dB.

Reverberation Time can be evaluated based on a smaller dynamic range than 60 dB and extrapolated to a decay time of 60 dB. Particularly, Reverberation Time is evaluated from the time at which the decay curve reaches 5 dB and 25 dB below the initial level for T20, and 5 dB and 35 dB for T30, respectively.

The DIN 18041 standard [33] defines optimal T values according to the different activities in a room for speech or music, the room volume, and the frequency in octave bands. The standard always refers to occupied rooms. The following equation is applied to calculate optimal occupied T values in the frequency range 0.125 kHz–4 kHz in case of occupied rooms, starting from the volume V or the room itself [34]:

Communication

$$T_{opt,occ} = 0.32\lg V - 0.17\ [s] \qquad (14)$$

Speech

$$T_{opt,occ} = 0.37\lg V - 0.14\ [s] \qquad (15)$$

Music Performance

$$T_{opt,occ} = 0.45\lg V + 0.07\ [s] \qquad (16)$$

Music Rehearsal

$$T_{opt,occ} = 0.47\lg V - 0.37\ [s] \qquad (17)$$

High reverberation times are perfect for large music halls. Low reverberation times are preferable for lecture halls or recording studios. If there is no reverberation whatsoever, the sound levels are subject to the inverse square law. In literature, the improvement of the room acoustic quality of two medium sized meeting rooms through the investigation of the optimal placement of absorption and diffusive panels on the walls and ceiling was considered, and the acoustic measurements reveal that the Speech Transmission Index (STI) is a less sensitive parameter for the different acoustic scenarios, compared to Reverberation Time (T) and Clarity (C50) [34]. The assessment of acoustic quality indicators of enclosures, such as early/late energy ratios, certain intelligibility indices, and background noise level etc. are defined by various acoustic standards, specifications, instructions, and requirements [35-43].

B. Architectural Acoustic Modeling for Predicting Reverberation Time

In the application of the proposed MCDMA model, the equations from (14) to (17) were used to calculate optimal occupied T values in the frequency range 0.125 kHz–4 kHz in case of meeting rooms, starting from the volume V (1000 m^3) to V (2000 m^3) as shown in Table 1.

Table 1. Decision matrix

	g_v	g_1	g_2	g_3	g_4
a_0	2000	0,886	1,081	1,555	1,181
a_1	1000	0,79	0,97	1,42	1,04
a_2	1100	0,803	0,985	1,439	1,059
a_3	1200	0,815	0,999	1,456	1,077
a_4	1300	0,826	1,012	1,471	1,094
a_5	1400	0,837	1,024	1,486	1,109
a_5	1500	0,846	1,035	1,499	1,123
a_7	1600	0,855	1,046	1,512	1,136
a_8	1700	0,864	1,055	1,524	1,148
a_9	1800	0,872	1,064	1,535	1,160
a_{10}	1900	0,879	1,073	1,545	1,171

The evaluation criteria determined to predict reverberation time [s] for various rooms are volume [m^3] (g_v), communication (g_1), speech (g_2), music performance (g_3), and music rehearsal (g_4). The decision matrix was established using equations from (1) to (3).

The decision matrix was normalized using equations (4) and (5), and the normalized decision matrix is shown in Table 2.

Table 2. Normalized decision matrix

	g_v	g_1	g_2	g_3	g_4
a_0	2000	1	1	1	1
a_1	1000	0,891	0,897	0,913	0,880
a_2	1100	0,906	0,911	0,925	0,897
a_3	1200	0,920	0,924	0,936	0,912
a_4	1300	0,932	0,936	0,946	0,926
a_5	1400	0,944	0,947	0,955	0,938
a_5	1500	0,955	0,957	0,964	0,950
a_7	1600	0,965	0,967	0,972	0,961
a_8	1700	0,975	0,976	0,980	0,972
a_9	1800	0,983	0,984	0,987	0,982
a_{10}	1900	0,992	0,992	0,994	0,991

The normalized matrix was weighted by the mean weight method $\sum_{j=1}^{J} \omega_j = 1$, $\omega_j = \frac{1}{J} = \frac{1}{4} = 0,25$.

Table 3. Weighted normalized decision matrix

	g_v	g_1	g_2	g_3	g_4	Q_i	R_i
a_0	2000	0,25	0,25	0,25	0,25	1	optimal
a_1	1000	0,223	0,224	0,228	0,220	0,895	10
a_2	1100	0,227	0,228	0,231	0,224	0,910	9
a_3	1200	0,230	0,231	0,234	0,228	0,923	8
a_4	1300	0,233	0,234	0,236	0,231	0,935	7
a_5	1400	0,236	0,237	0,239	0,235	0,946	6
a_5	1500	0,239	0,239	0,241	0,238	0,957	5
a_7	1600	0,241	0,242	0,243	0,240	0,966	4
a_8	1700	0,244	0,244	0,245	0,243	0,975	3
a_9	1800	0,246	0,246	0,247	0,245	0,984	2
a_{10}	1900	0,248	0,248	0,248	0,248	0,992	1

The weighted normalized decision matrix was established using equations (6) and (7) shown in Table 3. The values of the optimality function were calculated, and ranking results were calculated using equations from (8) to (12), as well as Spearman ranking order correlation equation (13). a_0 denotes the optimal values of decision criteria. Q_i is the degree of utility of the optimality function, and R_i is the ranking order of the alternative room volumes ranging from 1000 m^3 to 2000 m^3.

Table 4. Risk assessment analysis

	g_v	$\lambda = 1$	$\lambda = 0$	κ_i
a_0	2000	1	0,25	optimal
a_1	1000	0,895	0,220	10
a_2	1100	0,910	0,224	9
a_3	1200	0,923	0,228	8
a_4	1300	0,935	0,231	7
a_5	1400	0,946	0,235	6
a_5	1500	0,957	0,238	5
a_7	1600	0,966	0,240	4
a_8	1700	0,975	0,243	3
a_9	1800	0,984	0,245	2
a_{10}	1900	0,992	0,248	1

The systematic simulation of acoustical design data of various rooms gives the possibility of a scientific qualification and comparison of the acoustics of those rooms for multipurpose functions. The experimental result is that better acoustic design configurations can be established using the proposed MCDMA model. Dealing with both the physical and psychological aspects of the acoustics of rooms, concert halls, auditoriums, churches, and mosques, research is concerned with these findings about what is being measured and observed in existing halls of various sizes, shapes and details, and guiding future design more precisely towards increasingly successful results.

IV. CONCLUSION

This study aims to lead a mathematical MCDMA systematic approach to acoustic design and deliberate application of acoustic modeling in rooms for public speaking and professional meetings, such as meeting rooms with a volume of 1000-2000 m^3. The first part included a comprehensive review of the literature aimed at collecting useful guidelines on optimal occupied T values in different rooms used for multipurpose functions. The second part covered methods and results related to the acoustic modeling of various rooms of different volumes.

Simulations were carried out using four different acoustic function in the rooms, and results were compared and ranked using the proposed MCDMA model. Simulations of different occupied room configurations of various acoustic functions have been carried out with the proposed MCDMA model. Reverberation Time can be obtained in the frequency range 0.125 kHz–4 kHz in case of occupied rooms. Results from the different configurations simulated in the rooms recommend optimal T values. The research also outlined an acoustic design scheme, useful to successfully design various rooms, which allows to determine the optimal T values using architectural acoustic modeling.

REFERENCES

[1] Ardil, C. (2020). A Comparative Analysis of Multiple Criteria Decision Making Analysis Methods for Strategic, Tactical, and Operational Decisions in Military Fighter Aircraft Selection. International Journal of Aerospace and Mechanical Engineering, 14(7), 275 - 288.

[2] Ardil, C. (2020). Aircraft Selection Process Using Preference Analysis for Reference Ideal Solution (PARIS). International Journal of Aerospace and Mechanical Engineering, 14(3), 80 - 93.

[3] Ardil, C. (2020). Regional Aircraft Selection Using Preference Analysis for Reference Ideal Solution (PARIS). International Journal of Transport and Vehicle Engineering, 14(9), 378 - 388.

[4] Ardil, C. (2020). Trainer Aircraft Selection Using Preference Analysis for Reference Ideal Solution (PARIS). International Journal of Aerospace and Mechanical Engineering, 14(5), 195 - 209.

[5] Saaty, T. L. (1990). How to make a decision: The Analytic Hierarchy Process. European Journal of Operational Research, 48(1), 9-26. doi: 10.1016/0377-2217(90)90057-I

[6] Saaty, T. L. (2008). Decision making with the analytic hierarchy process. International Journal of Services Sciences, 1(1), 83-98. doi: 10.1504/IJSSCI.2008.017590

[7] Saaty, T.L. (1980). Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. McGraw-Hill, New York.

[8] Opricovic, S. (1998). Multicriteria Optimization of Civil Engineering Systems. PhD Thesis, Faculty of Civil Engineering, Belgrade (in Serbian).

[9] Opricovic, S. (2007). A fuzzy compromise solution for multicriteria problems. International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems, 15(3), 363–380.

[10] Opricovic, S., Tzeng, G.-H. (2004). Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. European Journal of Operational Research, 156(2), 445–455.

[11] Brans JP., Mareschal B. (2005). Promethee Methods. In: Multiple Criteria Decision Analysis: State of the Art Surveys. International Series in Operations Research & Management Science, vol 78, pp 163-186. Springer, New York, NY. https://doi.org/10.1007/0-387-23081-5_5.

[12] Brans, J., Ph. Vincke. (1985). A Preference Ranking Organisation Method: (The PROMETHEE Method for Multiple Criteria Decision-Making). Management Science, 31(6), 647-656.

[13] Brans, J.P., Macharis, C., Kunsch, P.L., Chevalier, A., Schwaninger, M., (1998). Combining multicriteria decision aid and system dynamics for the control of socio-economic processes. An iterative real-time procedure. European Journal of Operational Research 109, 428-441.

[14] Brans, J.P., Vincke, Ph., Mareschal, B., (1986). How to select and how to rank projects: the PROMETHEE method. European Journal of Operational Research, 24, 228-238.

[15] Hwang, C.L.; Yoon, K. (1981). Multiple Attribute Decision Making: Methods and Applications. New York: Springer-Verlag.

[16] Chu, T.C. (2002. Facility location selection using fuzzy TOPSIS under group decisions", International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems, Vol. 10 No. 6, pp. 687-701.

[17] Choudhary, D. and Shankar, R. (2012. A STEEP-fuzzy AHP-TOPSIS framework for evaluation and selection of thermal power plant location: a case study from India", Energy, Vol. 42 No. 1, pp. 510-521.

[18] Zavadskas, E.K., Mardani, A., Turskis, Z., Jusoh, A., Nor, K.M. (2016) Development of TOPSIS method to solve complicated decision-making problems: An overview on developments from 2000 to 2015. International Journal of Information Technology & Decision Making, 15, 645-682.

[19] Roy, B. (1991). The outranking approach and the foundation of ELECTRE methods. Theory and Decision, 31(1), 49–73.

[20] Fei, L., Xia, J., Feng, Y., Liu, L. (2019) An ELECTRE-Based Multiple Criteria Decision Making Method for Supplier Selection Using Dempster-Shafer Theory. IEEE Access, 7, 84701-84716.

[21] Zadeh L.A., (1965). Fuzzy Sets. Information and Control, 8, 338-353.

[22] Bellman, R.E., Zadeh, L.A. (1970). Decision-making in a fuzzy environment. Management Science, 17(4), 141–164.

[23] Fausti, P., Pompoli, R., Prodi, N. (2003). Comparing the acoustics of mosques and Byzantine churches.

[24] Carvalho, A., Monteiro, C. (2009). Comparison of the Acoustics of Mosques and Catholic Shurches. 16th International Congress on Sound and Vibration 2009, ICSV 2009.

[25] Zhonghua, G., Lau, S. (2017). Acoustic Design for an Auditorium Project. 51st International Conference of the Architectural Science Association (ANZAScA)), pp. 167–176.

[26] Jeong, K., Hong, T., Kim, S.H., Kim, J., Lee, S. (2018). Acoustic Design of a Classical Concert Hall and Evaluation of its Acoustic Performance – A Case Study.

[27] Nowicka, E. (2020). The acoustical assessment of the commercial spaces and buildings. Applied Acoustics 169 (2020) 107491. 10.1016/j.apacoust.2020.107491.

[28] Sert, F. Y., Karaman, Ö. Y. (2021). An Investigation on the Effects of Architectural Features on Acoustical Environment of Historical Mosques. Acoustics, 3(3), 559–580. doi:10.3390/acoustics3030036

[29] Üretmen, N. (1991). Selimiye Camii'nin Akustik İncelemesi.Doktora Tezi, Trakya Üniversitesi, Fen Bilimleri Enstitiüsü, Edirne.

[30] Ardil, C. (1991). Üç Şerefeli Camii'nin Ses Basınç Seviyelerinin İncelenmesi. Yüksek Lisans Tezi, Trakya Üniversitesi, Fen Bilimleri Enstitiüsü, Edirne.

[31] Erdem, A. (1992). Muradiye Camii'nin Akustik Karakteristikleri Üzerine Bir Araştırma. Doktora Tezi, Trakya Üniversitesi, Fen Bilimleri Enstitiüsü, Edirne.

[32] ISO 3382-1. Acoustics. Measurement of Room Acoustic Parameters. Part 1: Performance Spaces; ISO: Geneva, Switzerland, 2009.

[33] DIN18041. Acoustics Quality in Rooms—Specification and Instructions for the Room Acoustics Design;DIN:Berlin, Germany, 2016.

[34] Labia, L., Shtrepi, L., Astolfi, A. (2020). Improved Room Acoustics Quality in Meeting Rooms: Investigation on the Optimal Configurations of Sound-Absorptive and Sound-Diffusive Panels. Acoustics, 2(3), 451–473. doi:10.3390/acoustics2030025

[35] UNI 11532-2. Internal Acoustical Characteristics of Confined Spaces—Design Methods and Evaluation Techniques—Part 2: Educational Sector; UNI: Milan, Italy, 2020.

[36] ISO 3382-1. Acoustics. Measurement of Room Acoustic Parameters. Part 1: Performance Spaces; ISO: Geneva, Switzerland, 2009.

[37] ISO 1996-2. Acoustics—Description, Measurement and Assessment of Environmental Noise—Part 2: Determination of Sound Pressure Levels; ISO: Geneva, Switzerland, 2017.

[38] ISO 1996-2. Acoustics—Description, Measurement and Assessment of Environmental Noise—Part 2: Determination of Sound Pressure Levels; ISO: Geneva, Switzerland, 2017.

[39] ISO 17497. Acoustics Sound Scattering Properties of Surfaces—Part 1: Measurement of the Random-Incidence Scattering Coefficient in a Reverberation Room; ISO: Geneva, Switzerland, 2004.

[40] ISO 354. Acoustics. Measurement of Sound Absorption in a Reverberation Room; ISO: Geneva, Switzerland, 2003.

[41] UNI EN ISO 11654. Acoustics—Sound Absorbers for Use in Buildings—Rating of Sound Absorption; UNI: Milan, Italy, 1998.

[42] AES-4id-2001. AES Information Document for Room Acoustics and Sound Reinforcement Systems—Characterization and Measurement of Surface Scattering Uniformity; AES: New York, NY, USA, 2008.

[43] Beranek, L.L. (2016). Concert hall acoustics: Recent findings. The Journal of the Acoustical Society of America 139, 1548 (2016); https://doi.org/10.1121/1.4944787