ITU A|Z • Vol 22 No 3 • November 2025 • 735-749

Impact of coupled volume feature on reverberation time and acoustical characteristics of Süreyya Opera House

Büşra GÜNAL[1*], Sevtap YILMAZ DEMİRKALE[2]
[1] aktibusra@itu.edu.tr • Department of Architecture, Faculty of Architecture, Istanbul Technical University, Istanbul, Türkiye
ORCID: 0000-0001-9426-1460
[2] demirkale@itu.edu.tr • Department of Architecture, Faculty of Architecture, Istanbul Technical University, Istanbul, Türkiye
ORCID: 0000-0002-6451-1649

** Corresponding author*
Received: March 2024 • Final Acceptance: April 2025

Abstract
The coupled spaces with apertures can manifest distinct acoustic behaviors, giving rise to unique reverberation characteristics. These coupled volumes exchange sound energy through coupling apertures, resembling reverberation chambers, offer a solution for accommodating diverse architectural acoustic requirements. Concurrently, the architectural features of a hall may inherently exhibit coupling. Süreyya Opera House displays the characteristic of coupling with its stage, main hall, and balconies. The primary objective of this study is to examine thoroughly the architectural acoustics of this coupled hall using objective parameters. The methodology employed entails conducting acoustic measurements in the hall utilizing "DIRAC - Room Acoustics Software," adhering to the requirements of the " BS EN ISO 3382-1:2009 Acoustics – Measurement of room acoustic parameters" standard, validating the hall's simulation based on the measurement results in the "ODEON Room Acoustics Software (v14.05)" simulation program, and conducting a detailed analysis of the hall's architectural acoustics based on objective parameter measurement results and the outputs obtained from the simulation. The examined parameters encompass reverberation time (T30), early decay time (EDT), clarity (C80), definition (D50), and center time (Ts). Several key findings of this study can be summarized as follows: Locations near the stage opening, receive higher early energy levels due to internal stage reflections. As sound waves disperse in the air and over the audience area, energy decreases toward the rear hall and upper-level boxes. Balcony parapets and wooden-clad dividers further limit energy distribution to receivers.

Keywords
Acoustical measurement, Architectural acoustics, Coupled volumes, Opera houses, Süreyya Opera House.

doi: 10.58278/0.2025.108

1. Introduction

It is common occurrence for two spaces to be coupled through an opening, creating what is referred to as coupled volumes. The most encountered coupled spaces are a hall connected to a stage through a proscenium opening or a hall connected to a deep balcony. This coupling is frequently observed in large public gathering spaces, as well as in offices, homes, and other smaller volumes. In coupled spaces, sound energy is exchanged between the coupled rooms through the opening. When the sound source is turned off, each room decays its individual decay process. In cases where the reverberation times of the rooms differ, an energy surplus exists in one room compared to the other during the decay process. This leads to an energy transfer from the surplus room to the deficient one, resulting in a modification of the reverberation characteristics of the rooms. Non-linear decays in the reverberation time graph are often attributed to the presence of coupled volumes with different reverberation time characteristics connected through an opening. Individuals near the coupling aperture may experience a double-slope reverberation time. After the sound level in the main volume has dropped to a significantly low level, the reverberation time in the main volume is influenced by the slowly decreasing sound from the adjacent volume that feeds it, and individuals exposed to the sound in the other volume with a different slope may perceive distorted sound (Barron, 2010; Everest & Pohlmann, 2009; Mehta et al., 1999).

The coupled space feature is strategically employed in performance halls, where coupled reverberation rooms can meet diverse reverberation characteristics within the same volume. For example, a steep decay curve provides definition in music, while a slow and heavy decay contributes to the liveliness and richness of tone. The purpose of the empty and reverberant featured reverberation rooms coupled to the main concert hall through an opening is to have the relatively steep decay curved concert hall had its the reverberation graph resulting in a low-slope tail (Mehta et al., 1999). Hereby, such coexistence of divergent reverberation requirements allows for the provision of short and long reverberation characteristics within the same hall. This also contributes to achieving different lengths of reverberation times necessary for the pieces to be performed in a concert hall.

The field of architectural acoustics has witnessed numerous studies on non-exponential decay curves. These studies aim to understand the causes and degrees of non-exponential decay curves, improve analysis and calculation methods, consider the impact of architectural form and surface finishes, evaluate variability based on source-receiver positions in coupled spaces. Additionally, it involves comparing the obtained data with measurement results and investigating the subjective perceptibility of this non-exponential decay characteristic in detail.

Eyring conducted a theoretical study and formulated principles regarding acoustically coupled rooms (Eyring, 1931). Harris and Feshbach (1950) addressed coupled volumes as a boundary problem and adopted the 'wave' approach. Nilsson (2004) investigated the decay process in rooms with non-diffuse sound fields. It was observed that the distribution of absorbers within the room and the placement angles make a difference in the sound decay stages. Bradley and Wang (2005) examined the architecturalparameters affecting the double-sloped decay of a coupled volumecreated in the ODEON Room AcousticsSoftware (ODEON) program. Additionally, psychoacoustic tests were conducted for the subjective analysis of the perception of these energy decay curves. Xiang et al. (2011) have pointed out the challenge of identifying parameters associated with double-slope decay characteristics and detecting more than two decay behaviors in coupled volume systems. Sü Gül et al. (2012, 2014, 2016) examined the sound energy decay and flows in the Süleymaniye Mosque, a structure with multiple domes. The study investigated the non-exponential sound energy decay characteristics caused by different material types and the volume's intrinsic properties using simulations and acoustic measurements in the field. Aspöck and Vorländer (2019) conducted a study on a coupled volume scenario consisting of a laboratory and a reverberation room. They analyzed three data sets and two different apertures, comparing the measured energy decays with simulation models based on geometrical acoustics.

The literature indicates a preference for geometrical acoustic analysis when the wavelength of sound is short compared to the room's surface dimensions, particularly for frequencies above the Schroeder frequency. Geometrical acoustics assumes that sound propagates like a ray, neglecting the wave behaviors of sound. Therefore, wave behaviors such as diffraction and scattering caused by wave propagation are not considered in geometrical acoustics (Vorländer, 2013). The diffusion equation model can be used for calculations in non-diffuse sound fields, it incorporates boundary conditions and still allows for faster computations. (Valeau et al., 2006). Energy flow vectors and energy fluxes, which cannot be obtained through ray analysis, can be obtained using the diffusion equation calculation method. These data are valuable in associating multiple sound decay curves with architectural form and interpreting these curves (Sü Gül, 2019). The wave theory, on the other hand, is used in cases where small-sized rooms are involved. When the wavelengths in the studied frequency range are comparable with the room dimensions, it is employed to investigate acoustic behaviors such as room modes, etc. The lower frequency limit associated with room dimensions can be determined by calculating the Schroeder frequency (Sü Gül, 2019; Vorländer, 2013).

It has been demonstrated in the literature that coupled volumes interact with each other, there is an energy flow from one volume to another, and this affects the acoustic properties of the volumes (e.g., reverberation time) (Anderson & Bratos-Anderson, 1997; Barron, 2010; Everest & Pohlmann, 2009; Mehta et al., 1999; Sü Gül et al., 2012, 2014, 2016). Similarly, it can be hypothesized that reflections from the stage structure of Süreyya Opera House, which exhibits coupled volume characteristics, feed the hall, affecting the reverberation time. This study aims to investigate the impact of the coupling feature on the reverberation characteristics of Kadıköy Süreyya Opera House and conduct an architectural acoustic assessment through the unique characteristics of the hall and the objective parameters. In this context, acoustic measurements were conducted according to the "BS EN ISO 3382-1: 2009 Acoustics – Measurement of room acoustic parameters" standard (BS EN ISO 3382-1), and the dimensions and the Schroeder frequency of the opera house were analyzed to determine the applicability of the geometric acoustic analysis method. Via the field measurement results, validation of the acoustical simulation was completed. Architectural acoustic analysis of the hall was conducted by the field measurements results and the auxiliary data obtained from the program.

2. Method

The acoustical properties of an actual venue can be effectively analyzed through on-site measurements, which reveal the impact of architectural forms on sound behavior. Süreyya Opera House, a significant cultural venue on Istanbul's Anatolian Side, hosts concerts, operas, theaters, and other events, making its acoustical evaluation essential. Following site measurements, a sufficiently detailed interior geometry imported in ODEON simulation software. In ODEON software, the absorption coefficients of differing surfaces can be assigned with different coefficients and in the light of actual materials in the hall, prior to the simulation studies the model was validated by site measurement results especially taking into account the reverberation time. Afterwards the validation studies, in-depth analysis were conducted, including ray analysis, objective parameters visuals, material properties, and architectural form to assess key acoustical parameters and coupling feature of the hall overall in several aspects.

2.1. Description of the hall: Süreyya Opera House

Süreyya Opera House (Figure 1) is situated on Bahariye Street in the Kadıköy district of İstanbul, Türkiye. Its construction was initiated by Süreyya Paşa (İlmen) in 1924 with a specific focus on accommodating opera performances. However, upon its opening in March 1927, the venue was utilized primarily as a cinema due to incomplete construction of the stage section, which was later completed in 1932-1933, but the technical equipment, dressing rooms, and other necessary facilities for stage arts were not completed. Structurally, the building consists of two main units. The first encompasses the auditorium, an initially unfinished stage, and a two-story foyer at the entrance, serving dual functions as a theater and cinema.

In 2006, survey and restoration projects for the building were finalized by MSc. Architect Cafer Bozkurt and received approval from the Cultural and Natural Heritage Preservation Board. Spaces with identified deficiencies, as noted by Süreyya Paşa, were redesigned by Cafer Bozkurt and Metin Deniz. Enhancements included the expansion of the orchestra pit and the installation of stage equipment, illumination, sound system, and lighting system. Interventions that could alter the overall appearance of the building were carefully avoided, and both exterior facades and interior spaces were preserved. Following the restoration efforts and the rectification of deficiencies to fulfill its intended opera function, Süreyya Opera has been operational, primarily hosting opera performances since October 2007 (Katoğlu et al., 2007).

Süreyya Opera House, encompassing 570 seats, features a rectangular floor plan spanning around 19 m x 36 m. The auditorium boasts an average ceiling height of approximately 11 m, while the stage height extends to 14 m, inclusive of an orchestra pit. The opera hall comprises the main hall, ground floor (main hall) boxes, and boxes on the first and second floors (side and the backmost boxes).

Examining the interior materials, the flooring is constructed with solid wood parquet. Comfortable, well-upholstered seats with wooden backs are distributed throughout the hall. The box partitions are covered in solid wood, and wall surfaces are either painted over plaster or adorned with wallpaper. Circular columns in the hall exhibit painted plaster surfaces. Absorptive elements adorn the solid wood cladded parapets of the main floor boxes, while the upper floor box parapets feature a plaster application. Oil paintings grace the expansive side wall surfaces on these floors, and hall doors are wooden, equipped with upholstered, leather-like absorbers. The ceiling frescoes are executed in paint over plaster. The stage flooring is comprised of wood material over an air void (Figure 2).

2.2. Acoustical examination of the hall by objective parameters, field measurements, simulation

2.2.1. Objective parameters evaluated in the study

The assessment of architectural acoustics and the analysis of acoustic conditions within the hall rely on objective parameters. To conduct the acoustic analysis of Süreyya Opera House, acoustic measurements were

Figure 1. *Süreyya Opera House – general view (photos taken by B.Günal).*

Figure 2. *Süreyya Opera House – main hall, boxes, stage (photos taken by B.Günal).*

systematically performed in accordance with relevant standard. Utilizing the impulse responses of the hall to the generated signal, measurements were undertaken for objective parameters outlined in the standard, encompassing T30 (reverberation time), EDT (early decay time), C80 (clarity), D50 (definition), and Ts (center time). Reverberation time stands out as a fundamental parameter as it's role in many room acoustic theories and regulations governing room acoustic conditions in buildings (Gade, 2007). Wallace Clement Sabine, credited as the first to quantify reverberation time and the formula is expressed as follows (Mehta et al., 1999):

$$RT = \frac{0.16V}{\sum A}$$

Equation 1.

where, RT: reverberation time (s), V: room volume (m3), A: the total absorption in the room (in metric sabins).

For venues that host opera performances, a reverberation time ranging from 1.3 s to 1.8 s is considered appropriate, contingent on preferences (Barron, 2010).

2.2.2. Field measurements

Given that Süreyya Opera House has a volume exceeding 300 m3 (British Standards Institution, 2008) and functions as a performance venue, field measurements were systematically carried out in compliance with the BS EN ISO 3382-1 standard (British Standards Institution, 2009), utilizing "DIRAC - Room Acoustics Software 4.1 Type 7841" (DIRAC) simulation program (Acoustics Engineering, 2007). These measurements were conducted during periods when no rehearsals were taking place, aligning with the established schedule of the hall. The collection of room impulse responses during these measurements was employed to estimate the objective parameters that characterize the architectural acoustics of the hall. The measurements utilized a logarithmic sweep sine signal, chosen for its capability to generate impulse responses characterized by a high dynamic range and reduced harmonic distortion attributable to the loudspeaker (Christensen et al., 2013). The impact of background noise level on parameters extracted from impulse responses is considerable. Therefore, efforts were made to ensure that the impulse responses exceeded the noise floor in the relevant octave band, in accordance with the stipulations of the relevant standard (Hak et al., 2008).

The instrumentation utilized for the measurements included the following:

- Brüel & Kjaer Dodecahedral Omni Directional Loudspeaker (Type 4296) with B&K Power amplifier Type 2716 as sound source.
- ½ inch microphone (B&K Type 4165) and sound level meter (B&K Modular Precision Sound Analyzer Type 2260) as receiver to capture the room impulse response.
- DIRAC Room Acoustics Software (DIRAC 4.1 Type 7841) and Roland Quad-Capture Analog 2x2 Digital 2x2 external sound card to generate the noise signals to excite the room.
- Necessary cables to set the connections between the equipments.

Considering both the capacity and the physical conditions of the hall, in accordance with the measurement criteria of BS EN ISO 3382-1 (British Standards Institution, 2009), it was determined to conduct measurements at 15 receiver points, aiming for a uniform distribution within the hall (Figure 3). Seven of these receiver points are evenly spread across the main hall, ranging from the front of the stage to the back of the hall. Three receiver points are situated within the boxes

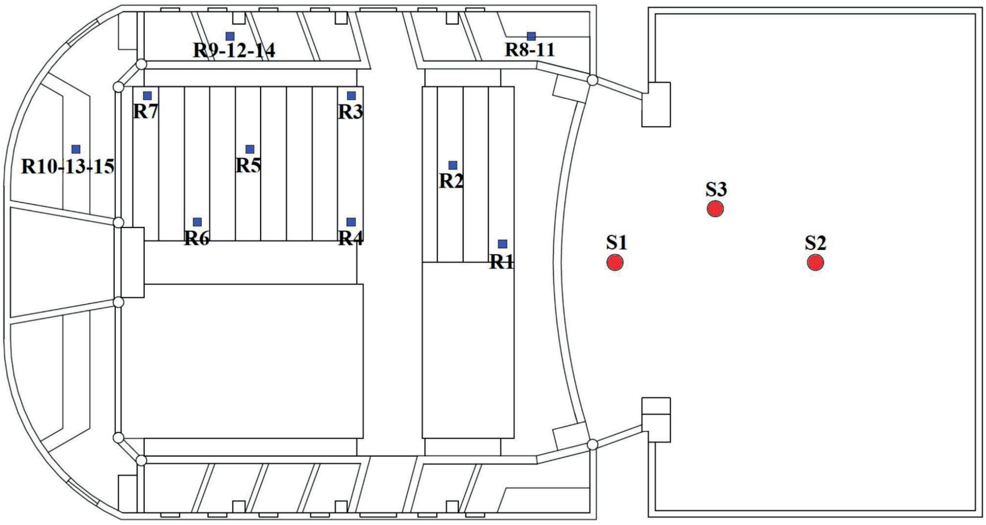

Figure 3. *Süreyya Opera House layout – source and receiver positions.*

of the main hall, considering the local characteristics of these areas. In the first-floor boxes, three receiver points were designated in a manner like the locations in the main hall boxes, and for the second-floor boxes, the receiver points were determined in a manner consistent with the other floor boxes' locations. Additionally, three distinct source positions (British Standards Institution, 2009) were identified for the hall and stage structures, which exhibit coupled volume characteristics (Figure 3).

2.2.3. Simulation

Simulations offer a fast and efficient way to estimate parameters, relying on geometrical acoustic algorithms that simplify wave phenomena (Rindel et al., 2013). The transition from wave-based to ray-based methods depends on the model's size and complexity (Siltanen et al., 2010). Since ray-based methods ignore phase information, results are valid only above the Schroeder limit frequency, where mode overlap is high, minimizing phase-related wave effects. Below this limit, distinct room modes become significant (Rindel et al., 2013).

Where fs: Schroeder frequency (Hz), T60: Reverberation Time (s), V: volume (m³).

$$f_s = 2000\sqrt{\frac{T_{60}}{V}}$$

Equation 2.

The Schroeder frequency of Süreyya Opera House, which is calculated based on the average reverberation time of 1.32 s, is below the investigated frequency range of 125 Hz to 4000 Hz. Therefore, geometric acoustic analysis methods have been employed.

Before running the simulation, specific settings were configured in the program, including the number of rays and maximum reflection order, provided in Table 1, while Table 2 lists the sound absorption coefficients across octave bands for the proposed materials of representative surfaces.

2.2.4. Validation of simulation by field measurements

Simulation studies offer a methodology for investigating real acoustic environments, and simulations that accurately represent actual venues can be achieved by incorporating on-site measurements. In this study, the finishing surface materials of the hall were realistically assigned in the ODEON simulation program. Given that the reverberation time serves as a fundamental objective parameter, and considering its interconnectedness with other parameters (Gade, 2007), and the validation processes conducted in prior research have been anchored in the reverberation time (Bradley & Wang, 2007), a validation study was executed based on the reverberation time data obtained from measurements, specifically focusing on the S1, S2, and S3 sources. The

Table 1. Simulation details.

ODEON	v 14.05 Combined
Number of late rays	250,000
Max. reflection order	10,000
Number of surfaces in the room	8070

results of the simulation-measurement validation at 1000 Hz for the S1-2-3 sources are given in Table 3 via the frequency-dependent standard deviation ratios of the reverberation time for these sources. Analyzing the standard deviation values reveals higher magnitudes at lower frequencies and lower magnitudes at medium and high frequencies, aligning with the literature's indication that geometric acoustic analysis is more effective in the latter frequency ranges (Savioja & Svensson, 2015). It is noteworthy that the simulation outputs and deviation values for the S1, S2, and S3 sources fall within the acceptable tolerance range specified in the literature for the reverberation time (20%) (Ahnert & Tennhardt, 2008; Everest & Pohlmann, 2009). Moreover, in a separate investigation incorporating both measurement and simulation outcomes in the ODEON software, it was observed that the mean deviation of the reverberation time at 1000 Hz fell within the just noticeable difference of 0.16 and it is indicated that the deviation was not larger than 0.7 just noticeable difference for measurements of any of the BS EN ISO 3382-1 parameters tested at 1000 Hz, signifying a favorable concurrence of the results (Christensen et al., 2013). Consequently, it is reasonable to assert that the validation concerning acoustic measurement outcomes and the simulation of the Süreyya Opera House, when juxtaposed with data extracted from the existing literature, has been accomplished at a commendable level.

Absorption coefficient uncertainties, including deviations from laboratory data (Christensen et al., 2013), in ISO 354 can lead to simulations with reverberation times beyond the subjective limen. Additionally, scattering values may produce varying results across different programs (Vorlander, 2013), while ray tracing simulations often overestimate decay curves (Sü Gül et al., 2020).

Hence, the disparities identified in the measurement and simulation validation study can be primarily ascribed to uncertainties in the absorption coefficients of materials and, contingent on the computational approach, potential overestimation of the simulation results regarding reverberation time. Upon examining the validation values presented in Table 3, the validation ratios are acceptable for all three

Table 2. Material list of the surfaces.

Material Location	Material	Frequency (Hz)					
		125	250	500	1000	2000	4000
Audience floor	Wooden floor on joists	0.15	0.11	0.10	0.07	0.06	0.07
Balcony/box parapets	Wood panelling, 5-10 cm airspace behind, thickness [cm] = 9-12 mm, cavity = 5-10 mm	0.30	0.25	0.20	0.17	0.15	0.10
Ceiling of the main hall	Plasters, plaster on lath, deep airspace	0.20	0.15	0.10	0.05	0.05	0.05
Seating area	Areas with audience, orchestra, or seats, including narrow aisles	0.60	0.74	0.88	0.96	0.93	0.85
Stage floor	Wood platform, large airspace below						
Walls	Plaster on solid wall	0.04	0.05	0.06	0.08	0.04	0.06
	Plaster with wallpaper on backing paper	0.02	0.03	0.04	0.05	0.07	0.08

Table 3. Reverberation time measurement results as per BS EN ISO 3382-1 for three sources.

	125 Hz	Std.dev.	250 Hz	Std.dev.	500 Hz	Std.dev.	1 kHz	Std.dev.	2 kHz	Std.dev.	4 kHz	Std.dev.
S1	1.66	0.1305	1.38	0.0582	1.32	0.0350	1.28	0.0273	1.30	0.0292	1.20	0.0275
S2	1.79	0.1056	1.47	0.0562	1.35	0.0424	1.32	0.0319	1.32	0.0288	1.22	0.0234
S3	1.74	0.1428	1.43	0.0628	1.34	0.0643	1.30	0.0428	1.31	0.0346	1.22	0.0309

sources, yet it is evident that the measurement and simulation values for the S1 source exhibit greater proximity in the mid frequency range (500 Hz, 1000 Hz) in comparison to the other two sources. Consequently, the analyses phase of the investigation proceeded based on the S1 source. Commencing from the reverberation times for the three sources (Table 3), a single-digit T30,mid value (average of 500 and 1000 Hz) calculation and the mean of each reverberation time for all independent source and microphone positions were derived, as specified in the BS EN ISO 3382-1 standard (British Standards Institution, 2009). The mean reverberation time for the hall was determined to be 1.32 s, aligning with the specified reverberation time values in the literature.

3. Field measurement and simulation results

Field measurements were conducted to assess objective parameters specified in the BS EN ISO 3382-1 standard (British Standards Institution, 2009), encompassing T30 (reverberation time), EDT (early decay time), C80 (clarity), D50 (definition), Ts (center time), and were derived from the impulse responses (IRs) measured at each receiver position. The results of objective parameter measurements for frequency of 1000 Hz and the associated deviation values are presented in Table 4. Just noticeable differences can be utilized for each parameter to detect variations in architectural acoustics (Bradley, 2010). These values guide the accuracy of measuring the objective parameter, the precision of computer models in calculating the parameters, and whether listeners can perceive differences in interior changes (Cox et al., 1993). Upon examination of standard deviation values, it is evident that the deviation in reverberation time is less than the deviation in early decay time among the receivers. While the reverberation time exhibits less variability throughout the hall, the early decay time is more variable depending on the location (Gade, 2007). EDT, associated with the early part of the decay curve, is influenced by early reflections, which originate from the defining surfaces of the room, and is impacted by the geometry of the hall (Mehta et al., 1999). The level and distribution of early reflections change over time based on the positions of the sources and receivers, as early reflections are influenced by the geometry of the room (Gade, 2007). In the literature, it is indicated that in a highly diffuse hall, early decay time and reverberation time ratio (EDT/RT) tends to have a value close to 1. In a directed design in which early sound is reflected onto the absorptive audience area, the ratio tends to be lower; to compensate for, it may be necessary to have a longer reverberation time to give an acceptable EDT. In particular, if the reverberation time is already short, one does not want an even shorter early decay time (Barron, 2010). Upon reviewing the results in Table 4, it is observed that the EDT values in the Süreyya Opera House (average 1.24 s) fall within the reference range specified in the BS EN ISO 3382-1 standard (1.0 s – 3.0 s) (British Standards Institution, 2009) and are generally shorter than T30. Early reflections, constituting early energy, are rapidly absorbed by the surfaces in the hall and inside the boxes and by the audience. Additionally, in the boxes, the view of the stage is restricted by dividing elements and parapets. The restricted view causes the boxes to be fed with direct energy less than the hall section (Mehta et al., 1999), and the decrease in sound access in the boxes due to the inherent enclosure of the boxes (Barron, 2010) also results in a shorter EDT duration.

The parameters that signify the proportions between early and late energy include clarity (C80), definition (D50), and center time (Ts). The clarity parameter (C80), reflecting the perception of clarity in music (Mehta et al., 1999), falls in positive values within the standard's reference range (-5 to +5, just noticeable difference 1 dB) (British Standards Institution, 2009), with an average value of 2.46. The higher the value of C80, the more pronounced presence of early sound and enhances the perception of clarity (Gade, 2007). Therefore, it can be asserted that there is a heightened sense of clarity in the

Table 4. *Objective parameters (1kHz) measured as per BS EN ISO 3382-1 at each receiver position in Süreyya Opera House.*

S1 - 1kHz - Objective Parameters

Rec.	T30 (s)	Dev.	EDT (s)	Dev.	C80 (dB)	Dev.	D50	Dev.	Ts (ms)	Dev.
R1	1.303	0.019	1.293	0.056	5.420	2.956	0.680	0.190	56.200	29.887
R2	1.298	0.014	1.302	0.065	4.350	1.886	0.650	0.160	85.200	0.887
R3	1.299	0.015	1.170	0.067	2.210	0.254	0.450	0.040	94.700	8.613
R4	1.268	0.016	1.204	0.033	2.450	0.014	0.490	0.000	83.700	2.387
R5	1.286	0.002	1.051	0.186	3.300	0.836	0.530	0.040	76.600	9.487
R6	1.243	0.041	1.229	0.008	0.650	1.814	0.340	0.150	100.900	14.813
R7	1.275	0.009	1.200	0.037	1.800	0.664	0.440	0.050	86.200	0.113
R8	1.317	0.033	1.472	0.235	4.440	1.976	0.660	0.170	62.400	23.687
R9	1.268	0.016	1.207	0.030	1.150	1.314	0.440	0.050	95.000	8.913
R10	1.279	0.005	1.097	0.140	3.000	0.536	0.520	0.030	79.400	6.687
R11	1.296	0.012	1.555	0.318	0.520	1.944	0.440	0.050	104.200	18.113
R12	1.320	0.036	1.122	0.115	1.120	1.344	0.330	0.160	100.300	14.213
R13	1.337	0.053	1.106	0.131	3.530	1.066	0.540	0.050	78.200	7.887
R14	1.242	0.042	1.374	0.137	0.310	2.154	0.360	0.130	106.400	20.313
R15	1.232	0.052	1.166	0.071	2.710	0.246	0.480	0.010	81.900	4.187

music within the hall. The definition parameter (D50), representing clarity in speech (average 0.49), falls within the standard's reference range (0.3 - 0.7, just noticeable difference 0.05) (British Standards Institution, 2009), signifying favorable speech conditions throughout the hall. The center time parameter (Ts), delineating the balance between early and late sound and the center of gravity of the squared impulse response, is within the standard's reference range (60 ms - 260 ms, just noticeable difference 10 ms) (British Standards Institution, 2009). A lower Ts value corresponds to a clear sound, while higher values suggest a dominance of late, reverberant energy (Gade, 2007). The Ts parameter maintains a low value throughout the hall (average 86.09 ms), indicating a prevalence of early energy. Upon examining standard deviation values for these parameters, variations are noted based on the location. A detailed examination in terms of location is conducted in the subsequent section.

4. Discussion

Considering the coupling feature in all aspects, this study examines the interaction between the stage house, main hall, and balcony boxes, as observed in theater, concert, recital, and similar events. This investigation serves as a foundation for future studies on the effect of the orchestra pit and its associated outcomes, allowing for comparisons with the results of this study. Various geometric attributes within a hall (such as coupled volume characteristics, the listener's location in the main hall or balcony, proximity or distance to side walls, etc.), and diversity in surface finishing materials, the positioning along with the sources and their relative locations, can result in architectural acoustics variations. Detailed examinations are undertaken within these contexts to comprehend, interpret, and compare architectural acoustics. Assessing the values for sources S1 located in the main hall and S2, S3 situated on the stage in Süreyya Opera House, which exhibits coupled volume features (Table 1), reveals that reverberation time durations are longer when the sources on the stage are active. In coupled rooms, halls exhibit sound decay in specific proportions, followed by the transfer of energy from a room with excess energy to a room with energy deficiency, leading to changes in the reverberation characteristics of the rooms (Mehta et al., 1999). It can be asserted that the sources on the stage structure, which is coupled to the main hall, initially fill the stage and then, through stage reflections, extend the reverberation time by feeding the receivers in the hall.

Reverberation times belonging to the receivers located in front of the main hall (R1-R2), the main hall-box front (R8) and first-floor box front (R11) are the highest in the hall. By examining the reflections of these receivers (Figure 4), it is observed that they are fed from the stage volume due to their proximity to the coupling aperture and receive reflections from the rear of the hall. These findings suggest that the reflections received from the rear surfaces and the stage contribute to the elongation of T30 by increasing the amount of late energy with a long reflection path. As expected, the reverberation curve of the receivers near the aperture creating coupling resembles the reverberation time of the coupling volume (Everest & Pohlmann, 2009), causing those receivers' T30 values to be higher than the ones at the rear of the hall. Consistent with the studies by Sü Gül et al. (2012, 2014, 2016), the energy flow between coupled volumes is observed in this study through reflections reaching the main hall from the stage and can be identified by ray analyses (Figure 4).

In the middle section of the hall, near the front of the box parapets, the receivers R3-R5 exhibit longer reverberation times than the R4 receiver positioned geometrically in the middle of the hall. Ray analyses indicate that R3-R5 receivers receive reflections from the stage, ceiling, and side surfaces of the hall, while the R4 receiver primarily captures reflections from the ceiling. Examining the ray analyses/reflections (Figure 4) and energy diagrams (Figure 5), it is inferred that ceiling reflections contribute to the increased early energy of R4. Consequently, the reverberation time for R4 is shorter than that of R3-R5 due to the lower late energy content.

The reverberation time for first-floor box receivers (R11-R12-R13) is observed to be similar to the front of the main hall, the main hall-box front, and the middle hall receivers but longer than that of the rear section receivers (rear of the main hall R6-R7, the main hall-box rear R9, the main hall-box backmost R10), with a noticeable mean value difference. Positioned at a distance from the stage and within the box, the 1st-floor receivers collect late energy, limiting their direct energy supply compared to hall receivers. Under a balcony, the vertical angle through which sound reaches a seat significantly decreases (Barron, 2010). The side box receivers obtain reflections that take longer to arrive compared to the backmost boxes. On the contrary of the backmost box receiver R13, the side box receivers R11 and R12 do not receive direct reflections from the source. Analyzing the energy diagram suggests that the backmost box receiver (R13) collects more early energy than the side box receivers (R11-R12). The side boxes are fed by late energy reflections off the opposite surfaces of the hall.

Examining the ray analysis/reflections (Figure 4) and energy diagrams (Figure 5) of the second-floor box receivers (R14-R15), it is noted that these receivers, being the furthest from the source, receive late-natured energy due to sound wave dispersion over longer distances, causing this energy not to be as pronounced as that received by receivers closer to the source (Barron, 2010), resulting in shorter reverberation. In terms of the just noticeable difference (JND) for reverberation time, they exhibit noticeably shorter durations compared to the front (R1-R2-R8), middle (R3-R4-R5), and first-floor boxes (R11-R12-R13), like the receivers in the rear section of the hall (R6-R7-R9-R10).

The early decay time is observed to be longer in receivers (R1, R2, R8, R11) situated closest to the source and the stage opening, which constitutes the coupling (Table 2). This phenomenon is attributed to the higher influx of early energy from the source and the distance of these receivers from absorptive surfaces in their vicinity (Mehta et al., 1999). Receivers R1-R2, positioned with the shortest distance to the source and away from absorptive surfaces in front of the stage, receive the most pronounced early energy (Figure 5). Although the energy supply for receivers numbered R8-R11 is constrained due to their location (box front) (Figure 4), their proximity to the source allows them to receive early energy (Figure 5) and early reflections from the reflective side walls (Mehta et al., 1999). Reflections from the side walls constitute early reflections, and the reflection path between direct sound and reflected sound from the side wall is short (Mehta et al., 1999). Considering that the boxes of these receivers are larger and less absorbent in terms of the ratio between seat density and box size compared to other boxes, hence the absorption within these boxes is also lower. This contributes to the prolonged decay time of the energy. The comparatively longer early decay time (EDT) of R11 in comparison to R8 can be ascribed to the absence of a balcony above R11 and the surrounding of R11 by a lesser number of surfaces creating an absorptive effect (Long, 2006).

In both the main hall and the boxes, there is a noticeable reduction in early decay time towards the rear of the hall (R1-2-3-4-5-6-7, R8-9-10, R11-12-13, R14-15). Progressing away from the source toward the rear of the box leads to early energy experiencing absorption through both air and seating (grazing incidence) (Barron, 2010), resulting in a decrease in energy. The side boxes receive limited energy compared to other hall sections due to their location, the parapets in front of them, and the wooden-clad elements that separate the boxes from each other (Figure 5). The stage view of the boxes is also constrained by these elements. With restricted visi-

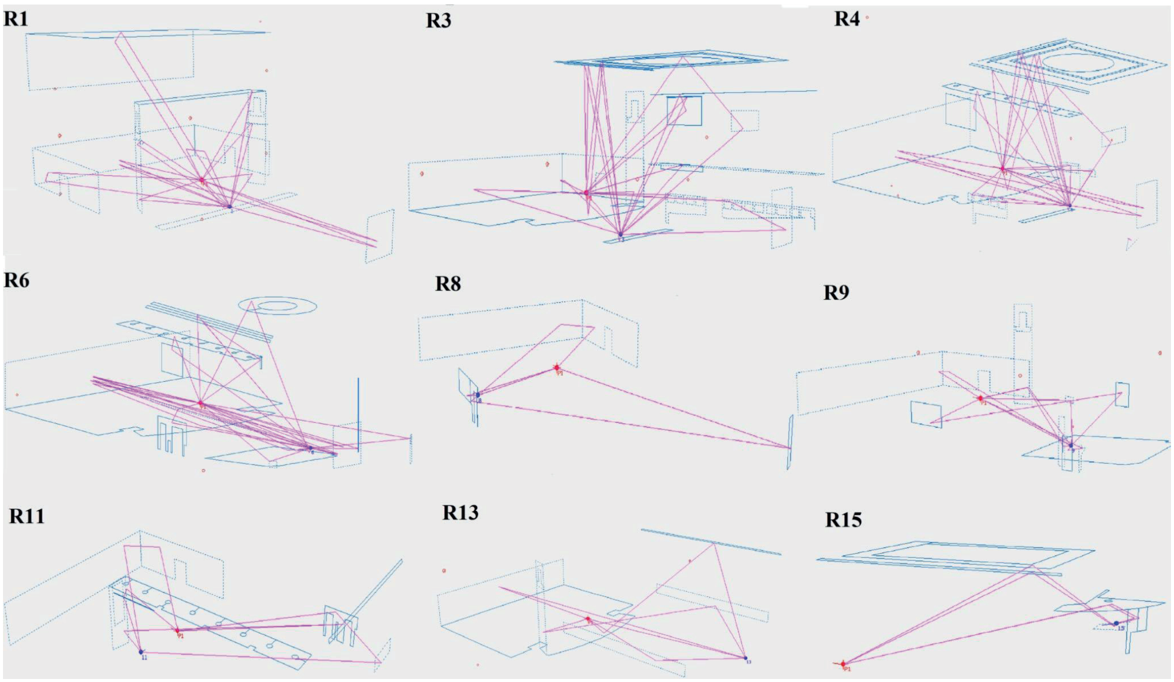

Figure 4. *Sample receivers' reaching rays through the hall.*

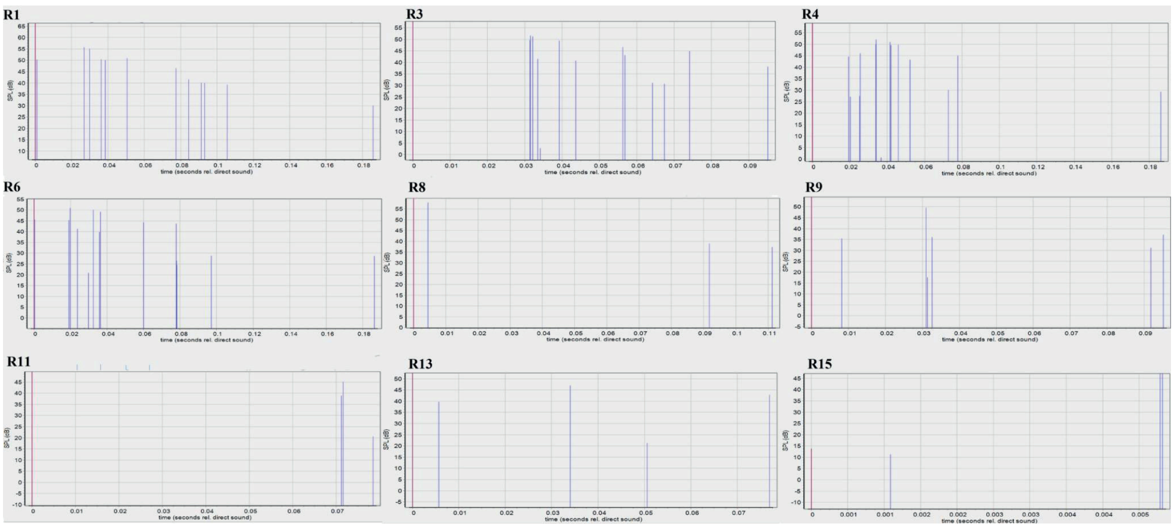

Figure 5. *Sample receivers' energy diagrams through the hall.*

bility, the boxes cannot receive direct energy as much as the hall section (Mehta et al., 1999), and the reduction in sound access in the box, due to its inherent enclosure, along with the decrease in energy, contributes to the shortened early decay time (Barron, 2010). Comparatively, the EDT values in the backmost boxes are shorter than those in the side boxes, given the larger seating area of the backmost boxes. This observation suggests that increased absorptivity in the backmost boxes shortens the decay time of early energy. Simultaneously, a comparison between the front and rear of the hall indicates a shorter EDT at the rear section of the hall. This can be attributed to the increased distance from the source and exposure to air and seat absorption (grazing incidence) (Barron, 2010).

According to the measurement results, the clarity values in the receivers exhibit a positive trend, indicating a high ratio of energy reaching the receivers in the first 80 ms compared to the energy received after 80 ms. Notably, the values for the front of the hall (R1-R2) and the front main hall-box (R8) are the highest. A higher C80 value signifies a more pronounced early sound, leading to a heightened impression of clarity (Gade, 2007). Upon examining the energy diagrams, it becomes evident that the quantity of early energy, especially for the receivers positioned in front of the stage, surpasses that of late energy. Furthermore, the level of early energy reaching these receivers is notably elevated (the highest). In comparison to the rest of the hall, air and seat absorption, influenced by distance (Barron, 2010), is minimized due to their proximity to the stage. Additionally, R1-R2 are distanced from surfaces that could cause energy loss through reflection (Long, 2006). In the location of R8, the lower seat density in the box, attributed to its larger size, coupled with reflective wallpaper on the walls, results in less absorption and, consequently, a higher energy level. Therefore, in these receivers, the values for the 'definition' parameter (D50), which, alongside clarity, signifies speech intelligibility, are the highest. Moreover, the parameter for center time (Ts), demonstrating the balance between early and late sound, is also low, further supporting the notion of clear sound formation in these receivers (Gade, 2007).

Comparing the front and the back of the hall, a reduction in early energy occurs due to increase in air and seat absorption (Barron, 2010). Consequently, clarity and definition values decrease, and center time values increase as the received energy takes on the characteristics of late energy owing to extended reflection paths. The clarity (C80) and definition (D50) values of the backmost box receivers (R10-R13-R15) surpass those of the side boxes, and their center time values are lower. Analysis of the rays (Figure 4) reveals that more rays reach the backmost box receivers, while the side boxes receive fewer. Despite the lower energy amounts of the backmost receivers due to increased distance from the source (Barron, 2010), their early energies exceed those of the side receivers. As a result, this situation enhances clarity and definition while reducing center time values, indicating a balance between early and late sound. Additionally, the higher seat density of the backmost boxes accelerates energy absorption within the box, further enhancing clarity and definition. The shorter EDT values of the backmost box receivers compared to the side box receivers support the conclusion that more absorption occurs in this area. In receivers at the back of the hall, side boxes, and upper-level boxes, the decrease in early energy due to distance and location (Barron, 2010) and the receipt of reflections characterized as late energy led to a decline in clarity (C80) and definition (D50) values, while center time (Ts) values increase. The findings suggest that in the middle sections farther from the edges of the hall, more ceiling reflections are observed, contributing to early energy at the receivers. These ceiling reflections are acceptable in opera halls as they support the singer's voice (Barron, 2010).

The architectural acoustic assessment of Süreyya Opera House and the impact of the coupled volume feature on reverberation time were determined using objective parameter outputs obtained from acoustic measurements and the simulation. It is observed that the objective parameter results are comparable to the reference values specified in the standard. Detailed analysis was conducted with simulation outputs validated by acoustic measurements and compared with findings from previous studies. The following conclusions were drawn from the study. The energy flow between the main hall and the stage volume, as indicated by stage reflections, is detected, and the results are consistent with the findings of studies on energy flow between coupled volumes by Sü Gül et al. (2012, 2014, 2016).

Variability in reverberation time is identified through the results of S1-S2-S3 sources, with longer reverberation times observed when sources on the stage are active. According to the reverberation time formula, an increase in reverberation time is associated with a decrease in absorption (Mehta et al., 1999). The surface finishing material inside the stage (paint over plaster) is less absorptive than that in the hall (absorptivity of audience, wallpaper on walls, absorptive parapets finishing materials, etc.), contributing to the increase in reverberation time (S1 T30: 1.30 s, S2 T30: 1.33 s, S3 T30: 1.32 s). Consistent with literature, receivers in proximity to the aperture forming coupling (receivers near the stage) exhibit reverberation times with characteristics similar to longer reverberation behavior of the coupled volume (Everest & Pohlmann, 2009), and their values are higher compared to the receivers in other positions.

Objective parameter outputs for receivers are examined in the context of location, surrounding surfaces of the receiver, and the architectural features, leading to specific conclusions. The indication in architectural acoustics regarding the limited energy access in the boxes is deduced by energy diagrams, ray analyses, and parameter values (T30, EDT, C80, D50, Ts) of receivers. This is consistent with the information that restricted views provide limited energy and that the boxes are not acoustically efficient (Barron, 2010; Mehta et al., 1999).

The average reverberation time of 1.32 s in the hall is within the optimal reverberation time range (1.3 s - 1.8 s) stated by Barron (2010) for opera functions. The architectural feature of the box layout and high absorptive seat coverings, increases overall absorption, accelerating the early decay time associated with the decay of the early part of the energy. Especially in the boxes, this time is shorter, and the impact of limited energy intake on that matter is observed in energy diagrams. Clarity (C80) and definition (D50) values are high, and center time (Ts) values are low overall in the hall in the light of the reference values deducted from the literature. As energy absorption increases with distance from front to back in the hall, clarity and definition values decrease. Receivers at the stage front, closest to the source, have the highest values for these parameters, as well as the highest early energy amounts.

In summary, the study provides valuable insights into the architectural acoustics of Süreyya Opera House, highlighting the impact of the coupled volume feature on reverberation time. The results are in line with established literature and contribute to the understanding of acoustic characteristics in different areas of the opera house. In this study, examinations were conducted based on the results obtained from acoustic measurements, and simulation outputs were utilized to elucidate architectural relationships.

5. Conclusion

This study aims to investigate the impact of the coupled volume feature on the reverberation time in the Süreyya Opera House and to conduct a detailed analysis of the architectural acoustics of the venue, correlating it with its form. To ensure the comprehensive investigation of the venue, on-site acoustic measurements were conducted in accordance with the BS EN ISO 3382-1 measurement standard, and the simulation program was validated through obtained results. It was determined that there is a high degree of correlation between the measurements and simulations. The analysis of measurement results related to objective parameters was associated with the position of receivers, the surrounding surfaces, and specific architectural features of the venue using auxiliary outputs obtained from the simulation program. Evaluations were performed based on standard and literature reference values. The reverberation time of the venue was found to be suitable for opera functions. It was observed that receivers near the stage opening, which ensures coupling between the main hall and the stage, have longer reverberation times compared to other receivers. It was concluded that the stage, coupled to the main hall, feeds the hall with reflections, affecting and extending the reverberation time. The distribution of energy within the venue was analyzed, revealing that early energy decreases towards the back of the hall based on grazing incidence over seatings and air absorption by distance, and the energy supply to the boxes is limited due to their inherent enclosure. Higher values of parameters related to clarity of music and definition of speech in the front parts of the hall, influenced by higher energy, and lower values in the boxes due to limited energy were observed.

In the context of examining the coupled volume feature deeper, a further study of a model-based parameter estimation method can be employed to decompose the decay curves, revealing the degree of decay. This constitutes the next step in the research to further elaborate the analysis and investigation of the coupled volume feature of Süreyya Opera House.

Acknowledgement

The authors would like to thank and acknowledge that MSc. Architect Cafer BOZKURT, Architect Sibel ÖZKARS, MSc. Architect Hasan YİRMİBEŞOĞLU provided their support, the necessary information, and drawings regarding the restoration and design process. The authors would like to thank to Murat KATOĞLU, Ph.D. and Aslı AYHAN in charge of the management and the staff of Süreyya Opera House that have cooperated in the various studies. The authors would also like to thank to Dilara DEMİR TUNCA for her support during the field studies. This research did not receive any funding or grants.

References

Acoustics Engineering. (2007). *Measuring impulse responses using Dirac.* [Technical Note TN001]. https://www.acoustics-engineering.com/files/TN001.pdf

Ahnert, W., & Tennhardt, H.-P. (2008). Acoustics for auditoriums and concert halls, In G. M. Ballou (Ed.), *Handbook for sound engineers* (4th ed., pp. 145-200). Elsevier Inc.

Anderson, J. S., & Bratos-Anderson, M. (1997). The acoustics of a large space with a repetitive pattern of coupled rooms. *Journal of Sound and Vibration*, *208*(2), 313-329.

Aspöck, L., & Vorländer, M. (2019). Simulation of a coupled room scenario based on geometrical acoustics simulation models. *Proceedings of Meetings on Acoustics,* 36, 015002. https://doi.org/10.1121/2.0001041

Barron, M. (2010). *Auditorium acoustics and architectural design* (2nd Ed.). Spon Press.

Bradley, D.T., & Wang, L.M. (2005). The effects of simple coupled volume geometry on the objective and subjective results from nonexponential decay. *Journal of the Acoustical Society of America*, *118*(3), 1480-1490). https://doi.org/10.1121/1.1984892

Bradley, D. T., & Wang, L. M. (2007). Comparison of measured and computer-modeled objective parameters for an existing coupled volume concert hall. *Building Acoustics*, *14*(2), 79-90.

Bradley, J. S. (2010, August 29-31). *Review of objective room acoustics measures and future needs.* Proceedings of the International Symposium on Room Acoustics, ISRA 2010, Melbourne, Australia.

British Standards Institution. (2008). *BS EN ISO 3382-2:2008: Acoustics — Measurement of room acoustic parameters. Part 2: Reverberation time in ordinary rooms*. London, BSI.

British Standards Institution. (2009). *BS EN ISO 3382-1:2009: Acoustics — Measurement of room acoustic parameters. Part 1: Performance spaces*. London, BSI.

Christensen, C. L., Koutsouris, G., & Rindel J. H. (2013, June 9-11). *The ISO 3382 parameters: Can we simulate them? Can we measure them?* International Symposium on Room Acoustics, Toronto.

Cox, T. J., Davies, W. J., & Lam, Y. W. (1993). The sensitivity of listeners to early sound field changes in auditoria. *Acta Acustica united with Acustica*, *79*(1), 27-41.

Everest, F.A., & Pohlmann, K.C. (2009). *Master handbook of acoustics* (5th ed., pp. 378-379). McGraw Hill, Inc.

Eyring, C. F. (1931). Reverberation time measurements in coupled rooms. *Journal of the Acoustical Society of America*, *3*(2A), 181–206. https://doi.org/10.1121/1.1915555

Gade, A. C. (2007). Acoustics in halls for speech. In T. D. Rossing (Ed.), *Springer handbook of acoustics* (pp. 301-350). Springer Science Business Media.

Hak, C., Hak, J., & Wenmaekers, R. (2008, May 17-20). INR as an estimator for the decay range of room acoustic impulse responses. *Audio Engineering Society 124th Convention*. Amsterdam, Netherlands.

Harris, C.M., & Feshbach, H. (1950). On the acoustics of coupled rooms. *Journal of the Acoustical Society of America*, *22*(5), 572-578. https://doi.org/10.1121/1.1906653

Katoğlu, M., Gürsel, E., & Aydemir, I. (2007). *Kadıköy Belediyesi Süreyya Opera Binası*. Ofset Yapımevi.

Long, M. (2006). *Architectural acoustics*. Elsevier Academic Press.

Mehta, M., Johnson, J., & Rocafort, J. (1999). *Architectural acoustics: Principles and design*. Prentice Hall, Inc.

Nilsson, E. (2004). Decay processes in rooms with non-diffuse sound fields part ı: ceiling treatment with absorbing material. *Building Acoustics*, *11*(1), 39–60. https://doi.org/10.1260/1351010041217220

Rindel, J. H., Christensen, C. L., & Koutsouris, G. (2013, November 10-15). *Simulations, measurements and auralisations in architectural acoustics.* Acoustics 2013, New Delhi, India.

Savioja, L., & Svensson, U. P. (2015). Overview of geometrical room acoustic modeling techniques. *Journal of Acoustical Society of America*, *138*(2), 708-730. http://dx.doi.org/10.1121/1.4926438

Siltanen, S., Lokki, T., & Savioja, L. (2010, August 29-31). *Rays or waves? Understanding the strengths and weaknesses of computational room acoustics modeling techniques*. Proceedings of the International Symposium on Room Acoustics, ISRA 2010, Melbourne, Australia.

Sü Gül, Z., Xiang, N., & Çalışkan, M. (2012, August 19-22). *Investigations on multi-slope sound energy decays in domed structures.* Inter-Noise 2012, New York City, USA.

Sü Gül, Z., Xiang, N., & Çalışkan, M. (2014). *Sound field analysis of monumental structures by the application of diffusion equation model.* Proceedings of the 2014 COMSOL Conference in Cambridge, UK.

Sü Gül, Z., Xiang, N., & Çalışkan, M. (2016) Investigations on sound energy decays and flows in a monumental mosque. *Journal of the Acoustical Society of America*, *140*(1), 344-355. http://dx.doi.org/10.1121/1.4953691

Sü Gül, Z. (2019, Ekim 17-18). Bağlaşık ses alanlarında çoklu sönümleme eğrileri analiz yöntemleri. *13.Ulusal Akustik Kongresi Ve Sergisi*. Dicle Üniversitesi, Diyarbakır, Türkiye.

Sü Gül, Z., Odabaş, E., & Çalışkan, M. (2020). Comparative evaluation of ray tracing and diffusion equation modeling in room acoustics design of subway stations. *Acoustics Australia*, *48*, 93-105. https://doi.org/10.1007/s40857-020-00179-1

Valeau, V., Picaut, J., & Hodgson, M. (2006). On the use of a diffusion equation for room-acoustic prediction. *Journal of the Acoustical Society of America*, *119*(3), 1504-1513. https://doi.org/10.1121/1.2161433

Vorländer, M. (2013). Computer simulations in room acoustics: Concepts and uncertainties. *Journal of the Acoustical Society of America*, *133*(3), 1203-1213. http://dx.doi.org/10.1121/1.4788978

Xiang, N., Goggans, P., Jasa, T., & Robinson, P. (2011). Bayesian characterization of multiple-slope sound energy decays in coupled-volume systems. *Journal of the Acoustical Society of America*, *129*(2), 741-752. https://doi.org/10.1121/1.3518773