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Technical note

The effects of stage house coupling on multipurpose auditorium acoustics

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ABSTRACT

The current scientific research on coupled spaces has augmented the design applications of reverberation chambers and stage house-coupling in music venues in the last couple of decades, and vice-versa the halls that incorporate room acoustics coupling has attracted attention of researchers in the field. Most of the cases, depict the room acoustics coupling from a positive perspective, as the non-exponential energy decay aids clarity and reverberance, which are two simultaneous requirements to satisfy in a music hall. However, not many studies discuss the negative effects of a potential non-exponential energy decay in an auditorium, or a multi-function hall, if not intentionally and carefully utilized. This study aims to highlight the importance of stage tower design in an auditorium, which is aimed to be used dominantly for speech-oriented activities and occasionally to host recitals. The paper initially introduces the acoustical design phases of the auditorium that is within the Ted Ankara Foundation College Performance Art Center. Acoustical simulations are utilized during design phase. The selected auditorium has multiple construction phases, including pre and post acoustical treatment within the stage. Accordingly, field tests are held before and after stage tower acoustical interventions. Collected impulse responses are analyzed by Bayesian decay parameter estimations, in both stages of construction. The discomfort caused by the surplus sound energy within the stage tower, specifically the excessive late coming low frequency sound energy -boomy sound-, are validated by the double-slope sound energy decay within the hall. The desired acoustical comfort could only be provided when the multi-slope sound energy decays are overcome by sound absorptive treatment applications in stage tower and its auxiliary side and back spaces.

1. Introduction

Coupled-space concept has long been investigated by researchers in the field of architectural acoustics due to its certain advantages in tuning of the halls. One reason is that by coupling spaces an additional volume is introduced to the main volume. If properly and intentionally treated, this will result in augmented (sur-plus) sound energy. Thus, firstly the original reverberation time of the hall can be adjusted for multi-purpose use [1–3]. Another possible outcome of a coupled space is the peculiar to sound energy decay that is non-exponential. A non-exponential (multiple) sound energy decay incorporates an early and a late energy decay component [4–6], which is very attractive for the design of concert halls [1,7,8], as if properly tuned it proposes a compromise between the competing acoustic conditions for both reverberance and clarity [9].

Studies on the theory, rather than the applications of acoustical coupling on real cases, comprise the major academic research background on this specific field of interest. Architectural parameters such as absorption ratio of materials, volume ratio of sub-rooms, aperture size, door orientation, partition properties, location sensitivity are the basic room acoustics coupling variables [10–17]. Multiple decay formation can also be observed within single volume spaces, especially if the sound field is not diffuse. In that case the virtual separation of energy zones within a single space, can create energy flow from one location to another as in multi-domed superstructures [18–20] or shoe-box shaped concert halls [21]. All these variables and conditions affect the complex sound decay behavior of coupled volumes and necessitate an extensive analytical and experimental research [22].

For the identification and characterization of sound energy decay under different coupling conditions numerous theoretical approaches are developed. Some prominent ones can be summarized as follows; statistical theory [5,23,24], wave theory

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[25–28], statistical energy analysis [29–32], ray-based geometrical acoustics [33–35], diffusion equation model [36–40] and surface coupling approach [41]. On the other hand, there are comparisons of different numerical simulation approaches utilized in coupled space studies [42]. Perceptibility and subjective assessment of non-exponential energy decay have also been studied by some researchers [43–45].

Through all these scientific explorations, the deliberate use of coupled volumes in real practice also has flourished. In practice, there exist mainly-two types of coupled volume applications which are, namely, source-area coupling (stage house coupling) and distributed coupling (reverberation chambers). In source-area coupling, source is in the auxiliary room and auxiliary room is the stage tower above, as in the case of Bass Performance Hall in Fort Worth, TX. Distributed coupling employs volumes above ceiling or side walls; the so-called reverberation chambers. In this case, chambers provide energy feedback to the main hall when the coupling doors or apertures are partially or totally open (Fig. 1). Eugene McDermott Concert Hall in Dallas, TX and KKL Luzern Concert Hall, Switzerland and Heydar Aliyev Center Auditorium in Baku, Azerbaijan are examples to distributed coupling [3,46]. Birmingham Symphony Hall in London, UK is a mixture of stage house (or-back stage) and distributed coupling. The reverberation chambers in this case surround the organ and also are located on the upper side walls. These doors can be opened in any number to create variable reverberation times to match the type of music or other uses of the hall (Beranek, 2002). A very recent and unique example is the application of reverberation chamber in a recital hall up above the entire floor of the room (McPherson Recital Room - Laidlaw Music Center, Scotland) [47].

Case studies that incorporate acoustical coupling as a design aid are very few in academic literature. As Jaffe [1] stated "much of the new technology developed by scientists and academics has been reported and recorded by acoustical societies throughout the world, the practical experience of professional acousticians has not been well documented." This is still the case, especially for stage-house coupling in auditoria. In the literature, most of the cases are selected specifically for understanding the ambiguous sound field due to different energy interactions between subspaces. The discussions are mostly on the positive effects of acoustics coupling, or a secondary reverberation, in concert halls [3,7]. In this study, a reverse experience with the presence of multi-slope sound energy decay is discussed over an auditorium with a stage-house coupling.

The paper initially introduces the acoustical design phases of the auditorium, by acoustical simulations. Partial applications of acoustical treatments proposed for the stage tower in initial construction phase resulted in non-exponential energy decay within the auditorium, which caused acoustical discomfort, specifically due to the excessive late coming low frequency sound energy - boomy sound-. And, this is validated after the first set of field tests. The curing/correction of non-exponential energy decay, through the stage-tower interventions are validated by a second set of field measurements. Room impulse responses collected from the hall, for before-and after-stage-tower intervention, are analyzed by applying a multiple decay rate model selection approach based on Bayesian information criterion to select the most parsimonious model [48], all of which are detailed in the following sections. The systematic of the research steps are summarized in Fig. 2.

2. Description of the auditorium

Ted Ankara Foundation College Performance Art Center, designed by Uygur Architects in Ankara, was opened in 2020 (Fig. 3). The auditorium located in the core of the center, has multiple functions including conferences, school ceremonies, seminars, drama performances, recitals, and small-size band concerts. The auditorium has a fan-shape layout enveloped in a rectangular base structure, coupled to another rectangular prism with the proscenium opening, which accommodates the stage tower and back stage areas. The multi-function hall has necessitated an adjustable audience capacity and variable acoustics. For that reason, retractable curtains are utilized to divide the hall for a smaller audience capacity in the case of drama performances. Stage tower is isolated from the hall by heavy proscenium curtains in seminars, or other similar activities, to minimize the flow of sound energy of the stage tower and side stages, to the main hall. The various types of curtains and their acoustical functions are described in Section 3.1.

The auditorium in full capacity accommodates 1490 seats. Seating capacity decreases to 763 for the drama theater scenario. The overall seating area is approximately 1500 m^2 and the hall has a volume of 13,500 m^3. The stage has three sections; main stage has dimensions of w:14 m $\times$ l:22 m $\times$ h: 22 m; one side stage on the left wing has w: 13 m $\times$ l: 20 m $\times$ h: 8,3 m; back stage has w: 5,5 m $\times$ l: 24 m $\times$ h: 8,3 m. In terms of architectonics, rough concrete base surfaces of the center are in coherence with the other buildings on the whole campus, a noticeable architectural language [49]. The auditorium has mostly cladded with wooden surfaces over the concrete and steel load bearing structure. The wooden reflectors are shaped in convex form to enhance early

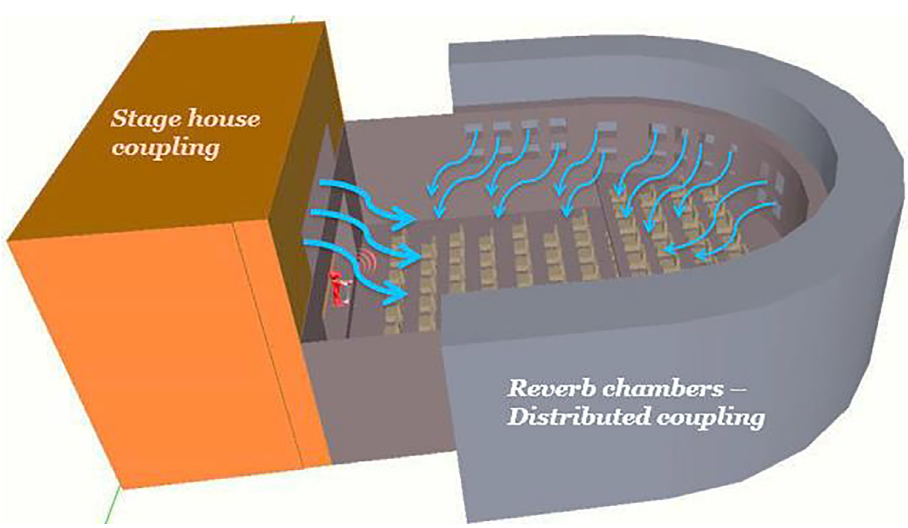


Fig. 1. A schematic drawing for stage house and distributed coupling *(Source: produced by the author)*.

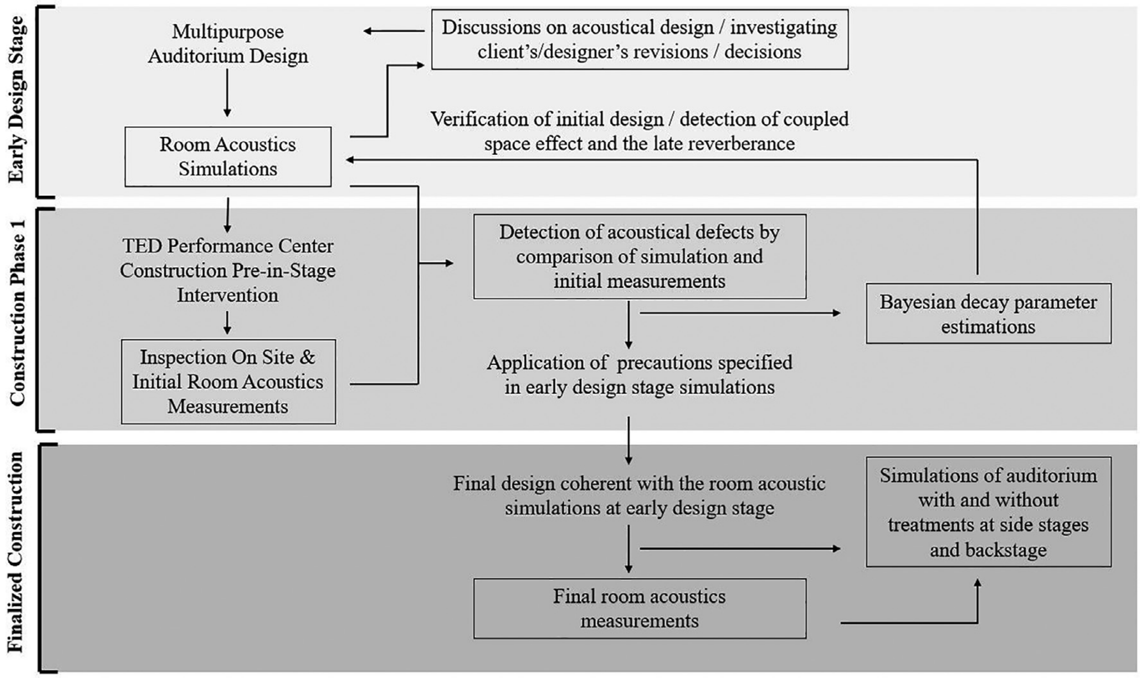


Fig. 2. Research diagram.

Fig. 3. On the left; an exterior view of the Ted Ankara College Performance Center (photo by, Cemal Emden, Deniz Uygur), on the right; an interior view of the auditorium, conference scenario, during field tests (photo by the authors).

reflections towards the audience, and to provide an even distribution of sound (Fig. 3).

The back of the hall is enveloped by large glass panels that provide natural light from either directly outside or from the foyer area. Curtains are proposed by the designers to control the daylight during the drama performances held in the daytime. These black-out curtains are also aimed to attenuate the strong late-coming sound reflections that may be caused by the glass partition walls separating the hall from its foyer. Seats of the hall are selected to provide compatible acoustical conditions when the hall is empty and occupied. Floor surface of the seating area is wooden parquet over platform. The plenum space underneath seating platform provides natural flow of air with minimum velocity and noise. HVAC diffusers are placed beneath each seat distributed throughout the hall.

3. Methods

3.1. Acoustical simulations

The acoustical design steps are guided through room acoustics simulations for the two activity patterns within the hall including conference use and drama theater. A simplified graphical model comprising of 3,486 plane surfaces is generated to be imported in ODEON Room Acoustics Software, an energy-based room acoustic modeler. Single model is utilized for both conference and drama theater scenarios. The house dividing curtains and proscenium curtain split the model into portions; former applied in drama scenario, latter used in close position for conference use. Ray tracing models of the auditorium for different scenarios are presented in Fig. 4. Detailed information on simulation setup is presented in Table 1.

Sound absorption coefficients over octave bands for proposed materials are listed in Table 2. Scattering coefficients to different surfaces are also listed in the same table, where the major sound diffusive surface is the audience area. One key point of these simulations is attaining proper transmission loss values to the divider curtains; as the sound passes from curtain to rear side spaces and later feeds back into the hall (Table 3).

3.2. Field tests

This section introduces the detailed methodology of in-situ field tests. The details of design steps are given in Section 4. Field tests

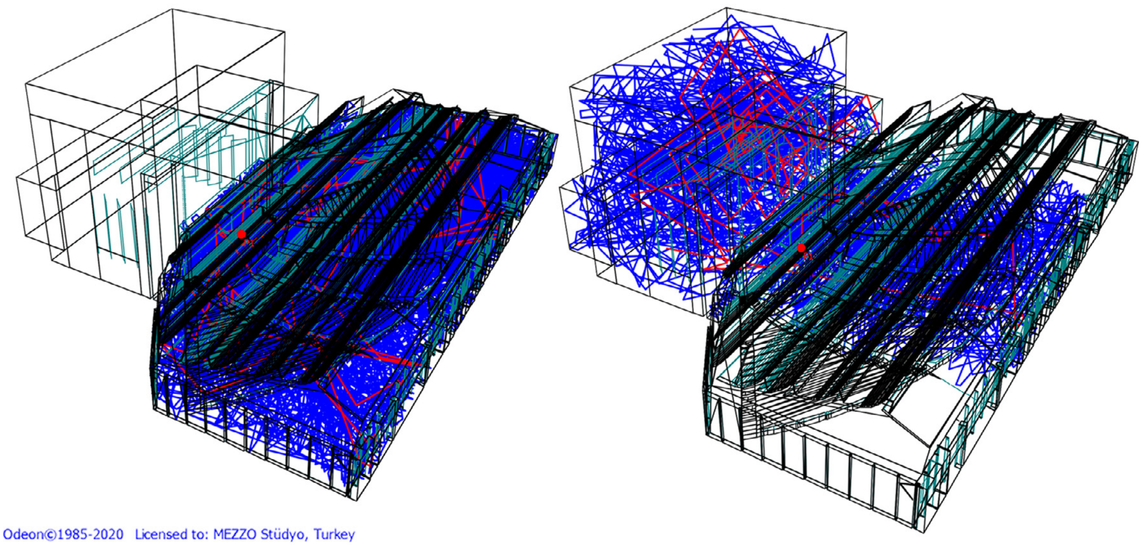


Fig. 4. Ray tracing model of the auditorium for conference (on the left) and drama theater (on the right) uses.

Table 1
Detailed information on computer simulations.

Program Version	v. 16.01
Number of late rays	106,384
Max. reflection order	10,000
Number of surfaces in the room	3579

are held twice for the auditorium in the unoccupied halls, in accordance with ISO 3382–1. Initial set of measurements were outsourced to be held on 21th of March 2020, after partial implementation of stage houses' acoustical design. Nor276 Norsonic dodecahedron omni-directional sound source and Nor280 Power amplifier are used together in signal generation. Impulse responses of the hall are collected by Type 1 Nor140 sound Analyzer and Behringer ECM 8000 measurement microphone above 1,25 m from floor. Furthermore, collected impulse responses are analyzed in ARTA Audio Measurement and Analysis Software [53]. Second set of field tests were held by the Mezzo Stüdyo team on 12th of February 2021, after full acoustical precautions are applied in the stage house. The room impulse responses are collected by B&K-Type2250-A hand-held analyzer. Acoustic signal excitation is provided by B&K-Type4292-L standard dodecahedron omni-directional sound source and B&K-Type2734-A power amplifier. Two different types of signals are used for room excitation: exponential sine sweep (ESS), maximum length sequence (MLS). The impulse responses with higher peak signal-to-noise ratios are utilized in analysis of room acoustic parameters at each source-receiver configuration. The source and receiver configurations are same to those used in the first set of measurements, in order to be able to make a proper comparison for before and after acoustical interventions. Collected impulse responses are analyzed by DIRAC room acoustics software v6.0.6470. Receiver points are distributed in the hall along with the audience seats. In total four source (S) and nineteen receiver positions (R) are tested in different configurations (Fig. 5). The source and receiver configurations are kept similar to those used in the first set of measurements, for ease of a proper comparison for before and after acoustical interventions. During measurements background noise levels in the unoccupied hall were measured below 35 dBA in the hall. The average temperature was 20.4° (Celsius) and the relative humidity was 20 % during the measurements. The impulse to noise ratio is higher than the 50 dB (INR > 50 dB) in the hall for each scenario during the field tests in mid frequencies (250 Hz, 500 Hz, 1000 Hz, and 2000 Hz).

3.3. Bayesian decay parameter estimations

In this section, the methodology for analyzing the multi-slope energy decay that is observed within the hall in the absence of sound absorptive treatment application in stage is presented briefly. The computational analysis procedure of this study employs Bayesian probabilistic inference. Bayesian analysis has long been applied by researchers [48,54,55] and reliable methods in characterizing sound energy decays consisting of one or two slopes has been presented. Bayesian model-based parameter estimation, relies on the model approximation of real-data out of Schroeder curve, to produce an algorithm for the evaluation of multi-rate decay functions. It allows for the estimation of the number of decay rates without requiring an initial guess on the number of slopes inherent in the decay. This analysis method is used to determine the parameters of the decay profile, namely, the slopes of the decays and ordinate intercepts of those slopes. The generalized linear model consists of linear combinations of a number of nonlinear terms or exponential terms. Schroeder decay functions are obtained through Schroeder backward integration. Parametric model describing Schroeder decay function is as follows;

$$H_s(\mathrm{A}\,,\,\mathrm{T},\,t_\mathrm{i}) = A_0(t_\mathrm{K} - t_\mathrm{i}) + \sum_{\mathrm{j}=1}^{\mathrm{S}} \mathrm{A_j}\left(\mathrm{e}^{\frac{-13.8\times t_\mathrm{i}}{Tj}} - \mathrm{e}^{\frac{-13.8\times t_\mathrm{K}}{Tj}}\right) \tag{1}$$

Where index $0 \leq i \leq K - 1$

Parametric model (1) contains decay parameters of A_j and T_j, where A_j is the linear amplitude parameter and related to the level of individual exponential decay terms, T_j is the decay time associated with the logarithmic decay slope of individual exponential decay terms, with j = 1, 2, ..., S, and S is the maximum number of exponential decay terms, also termed as the decay order, $A_0(t_K - t_i)$ is the noise term, and t_k is the upper limit of integration [48]. The multi-slope energy decay analysis results of the auditorium for its different phases are presented under Section 5.1.

Table 2
Specifications of different materials applied within the auditorium and sound absorption coefficients over 1/1 octave bands used in simulations.

Material Location	Material	Frequency (Hz)						Scattering coefficient
		125	250	500	1000	2000	4000	
Wooden ceiling and wall surfaces	600 kg/m^3 18 mm thick plywood (flexible beech tree, 1 mm natural wood veneer on both sides), 50 mm, 90–110 kg/m3 mineral wool covered with Soundtex or air permeable fireproof nonvowen fabric / fleece) behind (under roof decking)	0.20	0.18	0.15	0.12	0.10	0.10	0.05
Stage Floor	Solid wood flooring (pine tree / 45/80/1000–3000 mm) on counter floor, with 50 mm, 70 kg/m3 mineral wool behind	0.25	0.15	0.10	0.09	0.08	0.07	0.05
Audience floor surfaces	16 mm solid wood flooring (beech tree) on counter floor (80 + 40 = 120 mm concrete)	0.04	0.04	0.07	0.06	0.06	0.07	0.05
Glazing surfaces	Min. 5 mm + 0,76 PVB + 5 mm laminated glass	0.10	0.06	0.04	0.03	0.02	0.02	0.05
Doors	Solid timber door	0.14	0.10	0.06	0.08	0.10	0.10	0.05
Seating area	Figueras Lyon −1310, medium-density upholstery (seating; 65 kg/m^3, backrest; 57 kg/m^3)	0.27	0.30	0.49	0.55	0.51	0.51	0.60
Back stage wall surfaces	Concrete, with colorless surface protector	0.01	0.01	0.02	0.02	0.02	0.05	0.01
Last three rows of ceiling panels	18 mm thick perforated wood panels (flexible beech tree, 1 mm natural wood veneer on both sides), circular perforation, 8 mm perforation diameter, 15–30 mm center-to-center distance with 50 mm 90–110 kg/m^3 mineral wool covered with Soundtex or air permeable fireproof nonvowen fabric / fleece) behind (NRC 0.82)	0.60	0.95	0.95	0.80	0.60	0.35	0.10
Back wall surfaces	18 mm thick perforated wood panels (flexible beech tree, 1 mm natural wood veneer on both sides), circular perforation, 8 mm perforation diameter, 15–30 mm center-to-center distance with 50 mm 90–110 kg/m^3 mineral wool covered with Soundtex or air permeable fireproof nonvowen fabric / fleece) behind (NRC 0.82)	0.60	0.95	0.95	0.80	0.60	0.35	0.10
Main stage tower, back and side stage ceilings, upper wall surfaces	100 mm 110 kg/m^3 mineral/stone-wool covered with air permeable fireproof nonvowen fabric / fleece	0.45	0.86	0.95	0.92	1.00	0.93	0.05
In front of the façade glazing above + 2.75 m on rear side of the hall	Single layer of 1 mm microperforated foil with 100 mm air gap behind, ~ 0.2 mm perforation diameter, 2 mm center-to-center distance	0.05	0.10	0.45	0.60	0.40	0.50	0.05
Curtains								
Retractable house dividing curtains	750 g/m^2 Showtex Soundvelor curtain	0.12	0.14	0.06	0.02	0.03	0.05	0.15
Façade blackout curtains	300 g/m^2 Molton curtain*	0.03	0.22	0.74	0.74	0.75	0.76	0.15
Borders (5 pieces)								
Legs (5 on each side. total of 10 pieces)								
Proscenium curtain	400 g/m^2 velvet curtain	0.07	0.14	0.27	0.32	0.36	0.40	0.20
Rear backdrop curtain	450 g/m^2 velvet curtain	0.15	0.47	0.87	0.89	0.89	0.94	0.15

*Sound absorptive materials including perforated wood with mineral wool backing, seats and stage curtains are attained from the manufacturers test reports. In addition to that previous experience with curtains freely hung in space is also applied in tuning simulations. The sound reflective materials are generic, similar in different sources and can be find in many textbooks or software libraries [50,51].

Table 3
TL values over 1/1 octave bands attained to curtains in simulations.

Curtain Type	Material	Transmission Loss (dB) [52]					
		125	250	500	1000	2000	4000
Proscenium and rear backdrop curtain	400–450 g/m^2 velvet curtain	3	3	4	4	5	5

4. Acoustical design

4.1. Concept design

Acoustical design of the auditorium has been handled for two major activity layouts; conference and drama theatre functions. For testing the acoustical requirements in different scenarios of use, initially, the design criteria are set for relevant acoustical parameters (Table 4). For the drama scheme stage tower is acoustically included into the hall as the proscenium curtains are rolled up. Two house divider retractable curtains are used on both sides of the center sitting area in order to adjust the volume, to accommodate an optimized number of audience and to increase the side reflections with comparatively heavy and close-by side surfaces (Fig. 6, Table 4). In conference, school ceremony or seminar uses the retractable curtains are rolled up, making all seats available for audience, whereas the stage is excluded by the proscenium curtain that is kept in open position (Table 4). By the help of that, the stage tower, and side stage zones are acoustically detached from the hall, as much as possible. These are the basic interventions that are taken not only for acoustical purposes but also for the functional needs.

In order to fulfill acoustical design criteria, the proposed key acoustical design treatments can be summarized in four steps. First one is the application of "perforated wood panels with fleece/nonwoven fabric and 50 mm 110 kg/m^3 mineral wool behind" on rear wall surfaces, where there are solid surfaces, and for the last three rows of ceiling panels. Apart from that the rest of the ceiling panels are kept as solid convex shaped 18 mm thick wood, for providing a useful broadband early sound reflections towards the audience area and for increasing the loudness of natural sound. As well known, ceiling reflections in an auditorium are significant for perception of sound. Human hearing system is weaker in localization in the vertical plane. Reflections coming from overhead surfaces

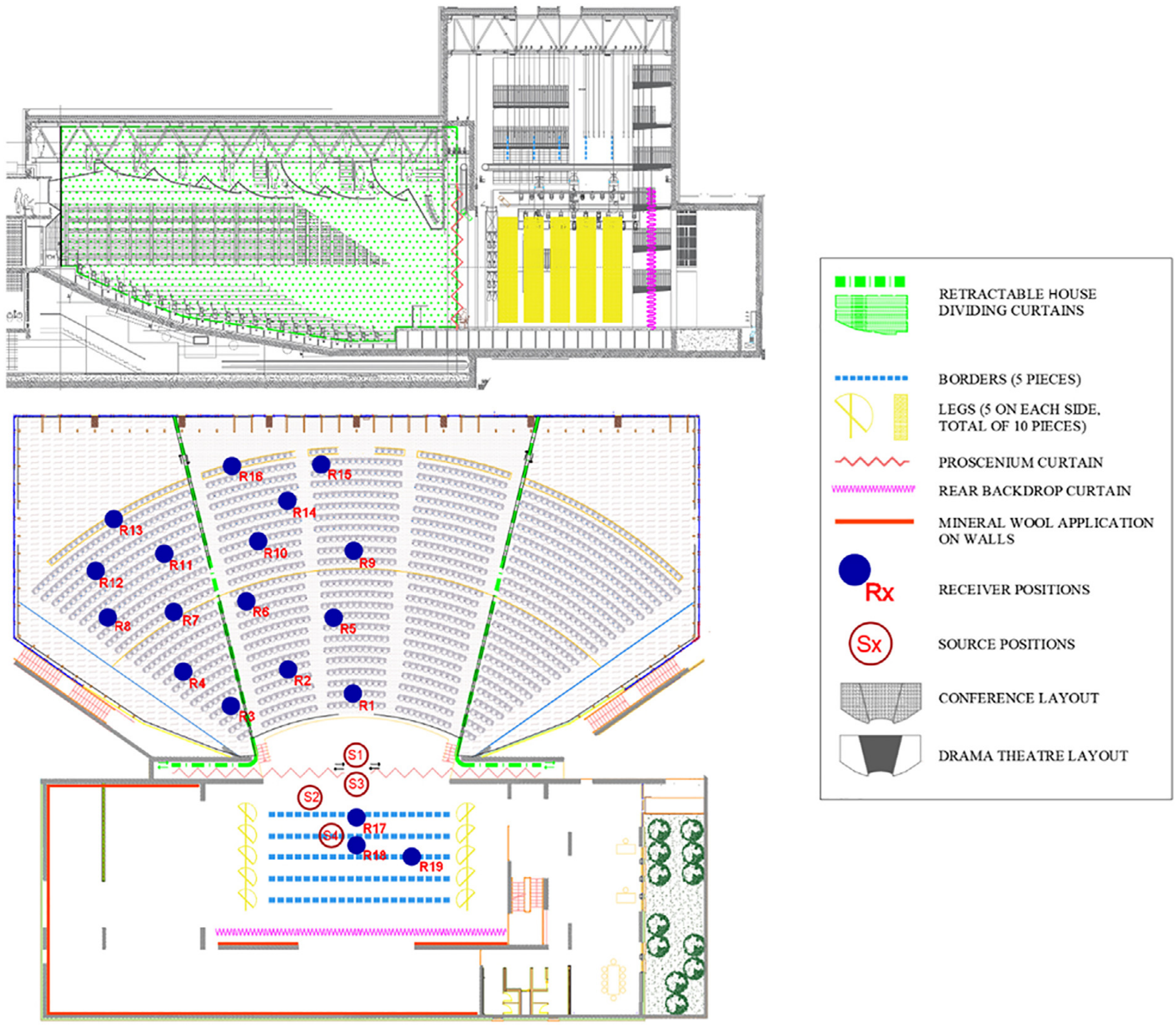


Fig. 5. Source and receiver positions in the hall, acoustical treatment applications, and curtain types and their locations shown on the section (above) and plan (below) drawings.

Table 4
Acoustical Parameters and Recommended Ranges [56–58].

Acoustical design parameter	Criteria	Just Noticeable Difference
Reverberation time, T30 (s) (500 Hz and1000 Hz average)	Conference Scenario; 1,0 s – 1,2 s Theatre Scenario; 0,9s – 1,1s	%5 (0,1 s)
Early Decay Time, EDT (s)	Not to differ>10 % from T30 values	
Clarity, C80 (dB)	> 0, <+9,0 dB	1 dB
Definition, D50	> 0,50	0,05
Speech Transmission Index, STI	> 0,60	0,05
A- Weighted Sound Pressure Level, SPL-A (dBA)	Minimum variations in SPL < 10 dBA	1–3 dB

are perceived as coming from the speaker, which is a useful illusion [9].

Second acoustical treatment, that one specifically to control late coming reflections on the stage and in the front tiers, is the application of "single layer of 1 mm microperforated foil with 100 mm air gap behind" in front of the glass above + 2.75 m on glazed back and back side walls of the hall. Third intervention is the application of "100 mm 110 kg/m^3 mineral wool covered with fleece" on the ceilings of main stage tower and side stage. Lastly, various types of curtains within the stage and the hall are incorporated into acoustical design process.

In both scenarios, all curtains play an active role in acoustic design process. In conference layout, house dividing retractable curtains and facade blackout curtains are collected (rolled up). Front curtain (proscenium curtain) is open, so separates the stage volume from the audience area (Fig. 3). In drama theatre layout, facade blackout curtains are fully open (in use). House dividing retractable curtains are also fully open (in use). Front curtain (proscenium curtain) is rolled up and stage curtains have become in active use. Rear backdrop curtain, 5 borders and total 10 legs (5 on each side) are used in tuning the stage acoustics (Fig. 6). A summary of applied treatments in different scenarios are given in Table 5. The proper assignment of sound absorption coefficients and transmission loss values are highly critical for proper interpretation of the acoustical parameter results, which are discussed in detail under Section 5.

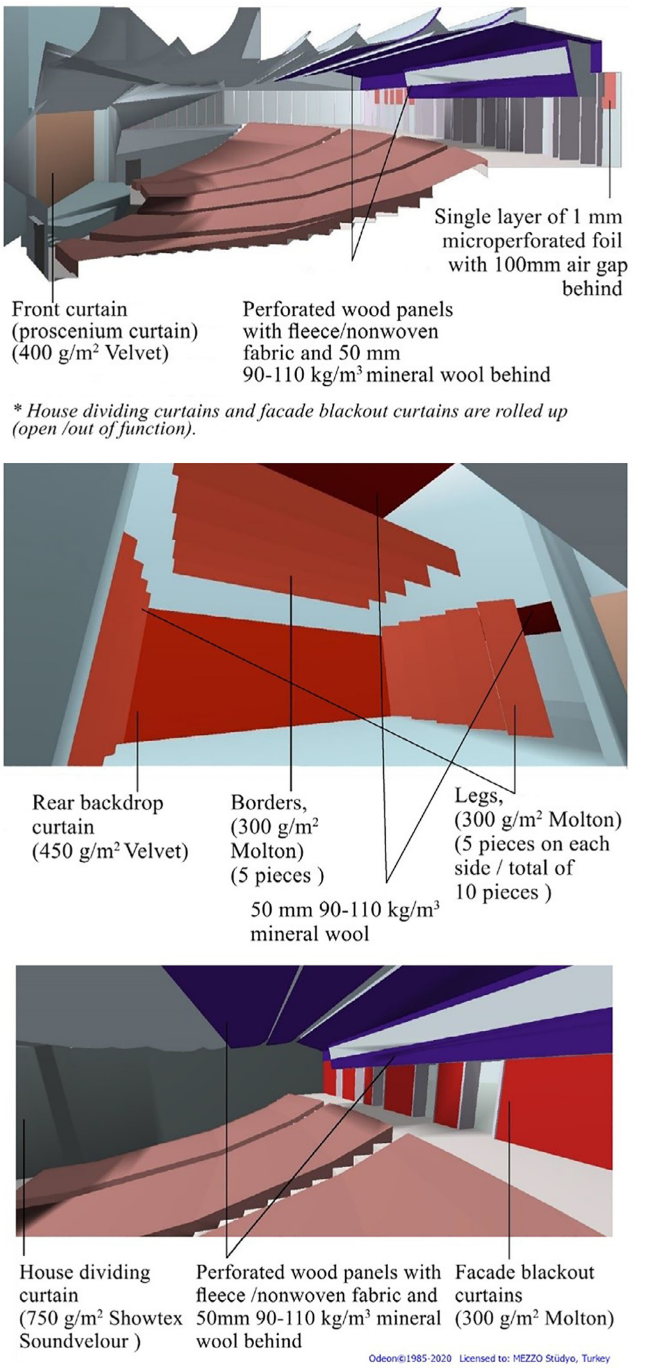


Fig. 6. 3D OpenGL view of the hall from acoustical simulations, acoustical design solutions for conference layout (above) and drama theatre layout (below).

4.2. Design progress and validation

The construction of the auditorium is completed in two phases. In the first phase the acoustical treatments summarized in Table 5 are applied partially; including items 1–4, 7, 9, 10–11. Basically, the microperforated film application on glazed surfaces (item 5) and mineral wool applications over main and side stage ceilings (items 6 and 7) are not applied in the first phase, in order to observe their real contribution to the interior sound field. Clients' perspective is that if not necessary, these materials should not be applied.

The avoidance of sound absorptive treatment application within the stage (main stage and side stages) caused excessive low frequency sound energy build up, the field test results of which are presented in detail under Section 5. This surplus energy has then flown from the stage to the audience area, even if the proscenium curtains are in use (open position). The phenomena showed itself in the form of a double-slope sound energy decay (Fig. 10). Due to the speech related activity patterns within the auditorium, this later-secondary and very high reverberance, caused by the stage tower and side and back stages, was distractive. For that reason, the previously recommended mineral wool applications proved their benefit and the client has approved their application. In addition, the rear backdrop curtain, although quite highly dense, has observed to be not sufficient to acoustically isolate the back stage from the main stage. Additional precautions at this point are proposed and not only the stage tower and side stage ceilings, but also back stage ceiling, main stage, side stage and back stage upper wall surfaces are covered with 100 mm thick, 110 kg/m^3 density, mineral wool. The mineral wool panels are applied fully over ceiling surfaces, whereas for upper wall surfaces of the stages a checkboard pattern is utilized (Fig. 7). On the other hand, due to the project budget limitations, item 5, microperforated film application over glazed back-wall surfaces, have not been applied at the final state of the auditorium.

5. Results and discussion

5.1. Comparison of the results for pre and post in-stage acoustical treatments

In this section initially the different design construction phases are compared by the analysis of two sets of acoustical field tests; before and after stage tower, side stage and back stage acoustical panel applications. Initial design targets obtained by acoustical simulations and post simulations are also included in the comparative graphs. The primary difference between acoustical simulations and second set of field tests is that microperforated panels are not applied in the final design while additionally side stage wall surfaces are treated with acoustical panels as detailed in previous sections. Moreover, in second phase back stage is also acoustically treated, in order to attenuate the sound energy that leaks from the main stage to the back stage through the rear backdrop curtains, as well as through the side stage connection corridor.

Fig. 8 compares T30 values for conference and drama theater scenarios for two sets of field tests and acoustical simulations. The first set of measurements (12.02.2020) indicates very high reverberation times within the hall especially in low-to-mid frequency range, reaching maximum 3.25 s at 125 Hz for both conference and drama use. For that reason, the absence of acoustical treatments inside the stage is compared for pre and after treatment by in stage field tests when the proscenium curtain is in use and separates the stage zones from the audience area of the hall (Fig. 9). According to that, a stage tower and side stages with all its curtains applied as listed in Table 5, but without any intervention on the reflective (concrete) walls and ceiling surfaces cause T30 of average 3.42 s at mid frequencies and 3.50 s at low frequencies in stage. This is almost three times higher than the T30 values aimed for the audience area for both conference and drama use, meaning that there will be a sound energy surplus within the stage. In Fig. 8, the error bars indicate the minimum and maximum values. As can be observed, the deviations are much greater in the pre-treatment condition throughout difference receiver positions inside the hall. This eventually proved to be a double sound energy decay curve, which is discussed further in this section. The reason for all the second phase applications in stage (post-in-stage treatment) and validation with post-treatment measurements is to avoid (or cure) such high deviations, uneven distribution of sound

Table 5
Applied acoustical treatments in simulations for different scenarios of use.

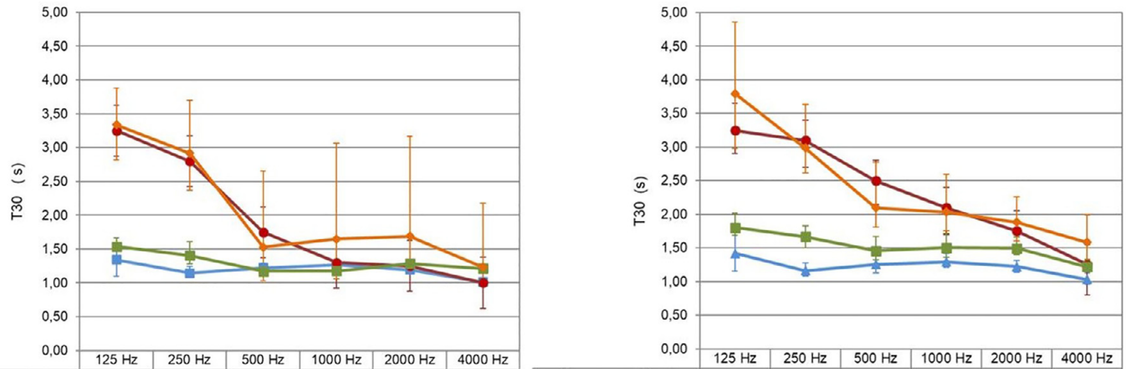
	Application Area	Material	Conference Layout	Theatre Layout
	Acoustical Treatments within Hall			
1	Back wall surfaces	18 mm thick perforated wood panels (flexible beech tree, 1 mm natural wood veneer on both sides), circular perforation, 8 mm perforation diameter, 15–30 mm center-to-center distance with 50 mm 110 kg/m3 mineral wool covered with Soundtex or air permeable fireproof nonvowen fabric / fleece) behind (NRC 0.82) (or equivalent)	√	√
2	Last three rows of ceiling panels		√	√
3	House dividing retractable curtains	750 g/m^2 Showtex Soundvelor curtain	Rolled up	√
4	Façade blackout curtains	300 g/m^2 Molton curtain	Rolled up	√
5	In front of the glass, above + 2.75 m, at back and side glazed walls of the hall	Single layer of 1 mm microperforated foil with 100 mm air gap behind, ~ 0.2 mm perforation diameter, 2 mm center-to-center distance	√	Inactive. Obscured by blackout curtains.
	Acoustical Treatments within the Stage			
6	Main stage tower ceiling	100 mm 110 kg/m^3 mineral wool covered with fleece	√ Behind proscenium curtain.	√
7	Side stage ceiling		√ Behind proscenium curtain.	√
8	Proscenium curtain	400 g/m^2 velvet curtain	√	Rolled up
9	Rear backdrop curtain	450 g/m^2 velvet curtain	√ Behind proscenium curtain.	√
10	Borders (5 pieces)	300 g/m^2 Molton curtain	√ Behind proscenium curtain.	√
11	Legs (5 on each side, total of 10 pieces)		√ Behind proscenium curtain.	√

Fig. 7. (On the left) back stage with checkboard pattern mineral wool panel application on upper walls and over ceiling, (on the right) drama theater house dividing curtains in use, in stage field test configuration, side stage walls with checkboard pattern mineral wool panel application.

and control very high late reverberation especially in the low frequency range.

In coupled-volume systems two or more spaces are joined by a common acoustically transparent surface, known as a coupling aperture. In this case the aperture is the proscenium curtain (in both its open position and rolled-up conditions). This study has proved that such curtains especially in mid to low frequency spectrum are not effective enough to provide sufficient transmission loss. Eventually, in this stage-hall coupled system as the times required for sound decay in each space are unequal, there is an excess energy in one space (stage tower) during the decay process, when compared to the other one (audience zone). This leads to energy transfer from the energy surplus room to the energy deficient room, which causes the non-exponential sound energy decay. This hypothesis is initially visually inspected, then validated through Bayesian analysis. From the analyzed data four typical non-exponential energy decay curves are presented in Fig. 10, for a selected source-receiver configuration, S_1R_2, for conference and drama uses, impulse responses of which are filtered for 250 Hz and 1000 Hz. Table 6 tabulates results of the decay parameters obtained from the Bayesian analysis of sound energy decays presented in Fig. 10. Accordingly, in both conference and drama uses the untreated stage causes double sound energy decay within the auditorium.

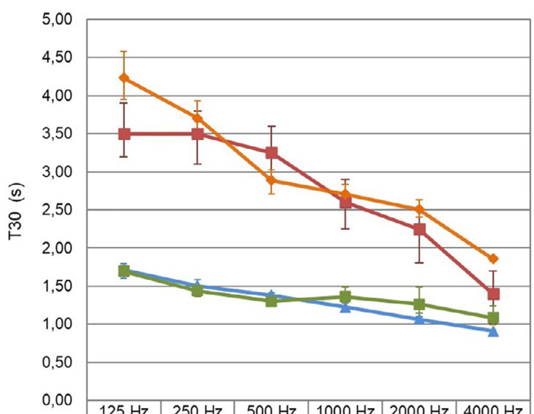
This condition maybe preferable for a symphonic music function, as it helps to provide two conflicting requirements; high clarity and sufficient reverberance. However, in the case of dominantly speech-oriented activities within the TED Foundation College auditorium, the double-decay causes a very high reverberation especially by the addition of the secondary decay. In other words, the 2nd decay slope indicates a decay rate of 3.30 s to 2.30 s, in the frequency range between 250 Hz and 1 kHz, which is much higher



	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Conference, post-in-stage treatment, field	1,34	1,14	1,22	1,27	1,19	1,01
Conference, pre-in-stage treatment, field	3,25	2,8	1,75	1,30	1,25	1,00
Conference, post-in-stage treatment, simulation	1,54	1,41	1,17	1,18	1,29	1,21
Conference, pre-in-stage treatment, simulation	3,34	2,92	1,53	1,65	1,69	1,23

	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Drama, post-in-stage treatment, field	1,42	1,16	1,26	1,29	1,22	1,03
Drama, pre-in-stage treatment, field	3,25	3,1	2,5	2,10	1,75	1,25
Drama, post-in-stage treatment, simulation	1,80	1,67	1,46	1,50	1,49	1,22
Drama, pre-in-stage-treatment , simulation	3,80	2,99	2,10	2,03	1,88	1,58

Fig. 8. Conference use (on the left), Drama theatre use (on the right) comparison of field tests and acoustical simulation, T30 results, unoccupied; the average values (solid line), max. and min. values (error bars) are indicated.



	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Stage, post-in-stage treatment, field	1,71	1,50	1,38	1,22	1,07	0,91
Stage, pre-in-stage treatment, field	3,5	3,5	3,25	2,60	2,25	1,40
Stage,post-in-stage treatment, simulation	1,70	1,44	1,30	1,36	1,26	1,09
Stage, pre-in-stage treatment, simulation	4,23	3,70	2,89	2,71	2,51	1,86

Fig. 9. In-stage field tests with (12.02.2021) and without (21.03.2020) sound absorptive treatments at stage tower ceiling and upper walls, side and back stage ceilings and upper walls, unoccupied; the average values (solid line), max. and min. values (error bars) are indicated.

than the single slope metric T30, estimated from the measured data for the same condition. In any case this late reverberance is not useful for the activity patterns in this auditorium, rather detrimental for speech intelligibility. The secondary reverberation due to the stage house coupling may become even a greater problem in the case of opera houses, where the volumes are much greater [59]. A similar problem may arise in those opera halls that are used for symphonic music as well, if not properly treated by either introducing absorption to the stage tower or addition of overhead reflectors [60]. In another study, the stage house coupling effect to the measurement consistency are discussed and guidelines are set for opera house field tests [61].

In this study, application of in-stage acoustical treatments aid to drop T30 values in stage to 1.3 s in mid-frequencies and 1.61 s in low frequencies (Fig. 9). Moreover, there is no more multi-slope sound energy decay formation within the audience zone, which is tested through Bayesian analysis (Fig. 10). Next chapter presents the final status of the hall by discussing the overall acoustical metric results, obtained at second set of field tests obtained after the post-in-stage treatment applications.

5.2. Acoustical parameter results for the final state of the auditorium

In this section the final field test results are presented. As noted, second set of measurements are held after the previously recommended sound absorptive panel applications within the stage. Additionally, stage tower upper wall surfaces and back and side-stage upper wall surfaces are also treated with mineral wool panels in a checkboard pattern in order to cure the negative effect sound energy built up within the stage. One missing treatment from the initial acoustical design proposal are the micro-perforated film applications on glazed back and side wall surfaces. These only affect the interior sound field, when façade blackout curtains are not in use (rolled up).

In Fig. 11 decay rates including T30 and EDT are presented over octave bands together with recommended ranges for the conference set-up. A- ten percent range over the optimum values is applied considering the number of audience as well as the multi-function use of the hall, where dominantly speech will be practiced, whereas there will be seldom cases in a year when recitals, school graduation ceremonies and small-size band concerts will also be performed. Accordingly, for conference use, except for the 1000 Hz, which is slightly higher than the recommended range with 1.27 s, the rest ofT30 values satisfy the criteria. Drama theater use is still a little higher than recommended at mid-range with an average T30 of 1.25 s. But, this shift from the T30 optimum does not negatively affect speech metrics as of D50 and STI, which are both proper with definition satisfying the minimum limit and STI indicating "*Good*" intelligibility rating (Figs. 12 and 13). EDT values for both conference and drama are in line with T30 results (Fig. 11), indicating a proper distribution of sound and sufficient early reflections, mostly provided by the convex shaped reflector design, that continues throughout the longitudinal section of the hall (Figs. 3 and 5). The evenly distributed early reflection pattern, provided by the overhead reflectors, also contributes to the Clarity (C80) metric, with values ranging in between 2 dB and 6 dB. The overall assessment of acoustical metrics indicates that the auditorium, in its final shape, is satisfactory for a multi-function hall. The distribution of T30 values for mid and low frequency averages over

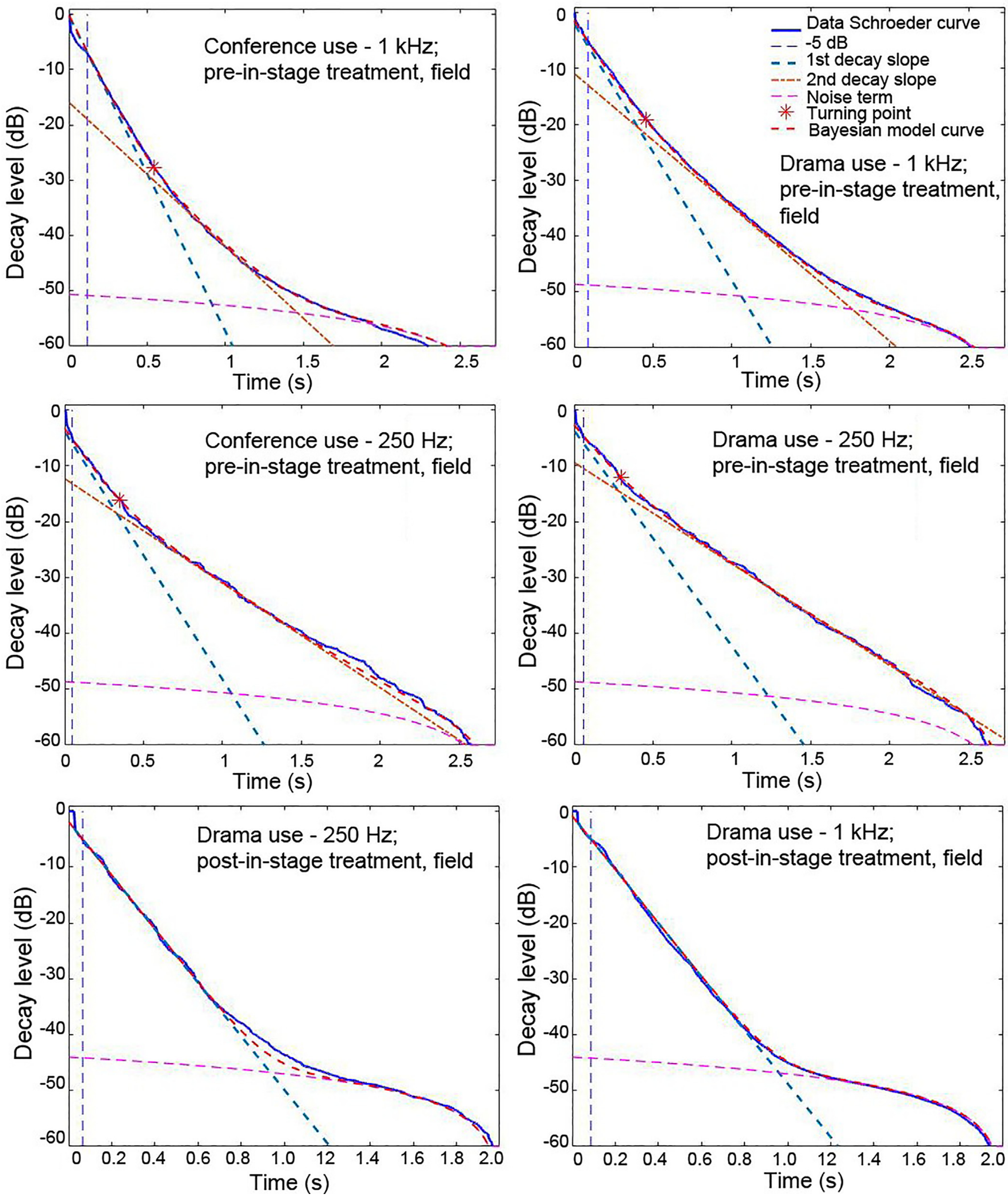


Fig. 10. Sound energy decays, decomposed decay slope lines and turning points are shown for source-receiver configuration, S_1R_2, first set of measurements, pre-in-stage acoustical intervention filtered RIR for; conference use, 1 kHz (on the top-left), for conference use, 250 Hz (at the center-left), drama use, 1 kHz (at the top-right), for drama use, 250 Hz (at the center-right); for second set of measurements, post-in-stage acoustical intervention for drama use, 250 Hz (at the bottom-left), 1 kHz (at the bottom-right).

receiver positions for source position #1 for both conference and drama theater set-up are given in Fig. 14, in order to highlight the location dependency of the reverberation times for the most final measurements. Accordingly, it can be stated that the distribution is fairly even among the seating positions. This may be attributed to the fact that the maximum distance between the stage and

Table 6
Decay parameters (decay levels and decay times) for impulse responses collected at S_1R_2 filtered for 250 Hz and 1 kHz in field tests for conference and drama theater uses, where T_1 is the first decay rate, T_2 is the second decay rate, A_0 is the noise term, A_1 is the first decay level and A_2 is the second decay level, pre-in-stage treatments.

Decay parameters	S_1R_2 1 kHz, conference	S_1R_2 250 Hz, conference	S_1R_2 1 kHz, drama	S_1R_2 250 Hz, drama
A_0 (dB)	−85	−83	−83	−83
A_1 (dB)	−7	−6	−6	−6
T_1 (s)	1.05	1.35	1.30	1.55
A_2 (dB)	−19	−13	−13	−11
T_2 (s)	2.30	3.20	2.50	3.30

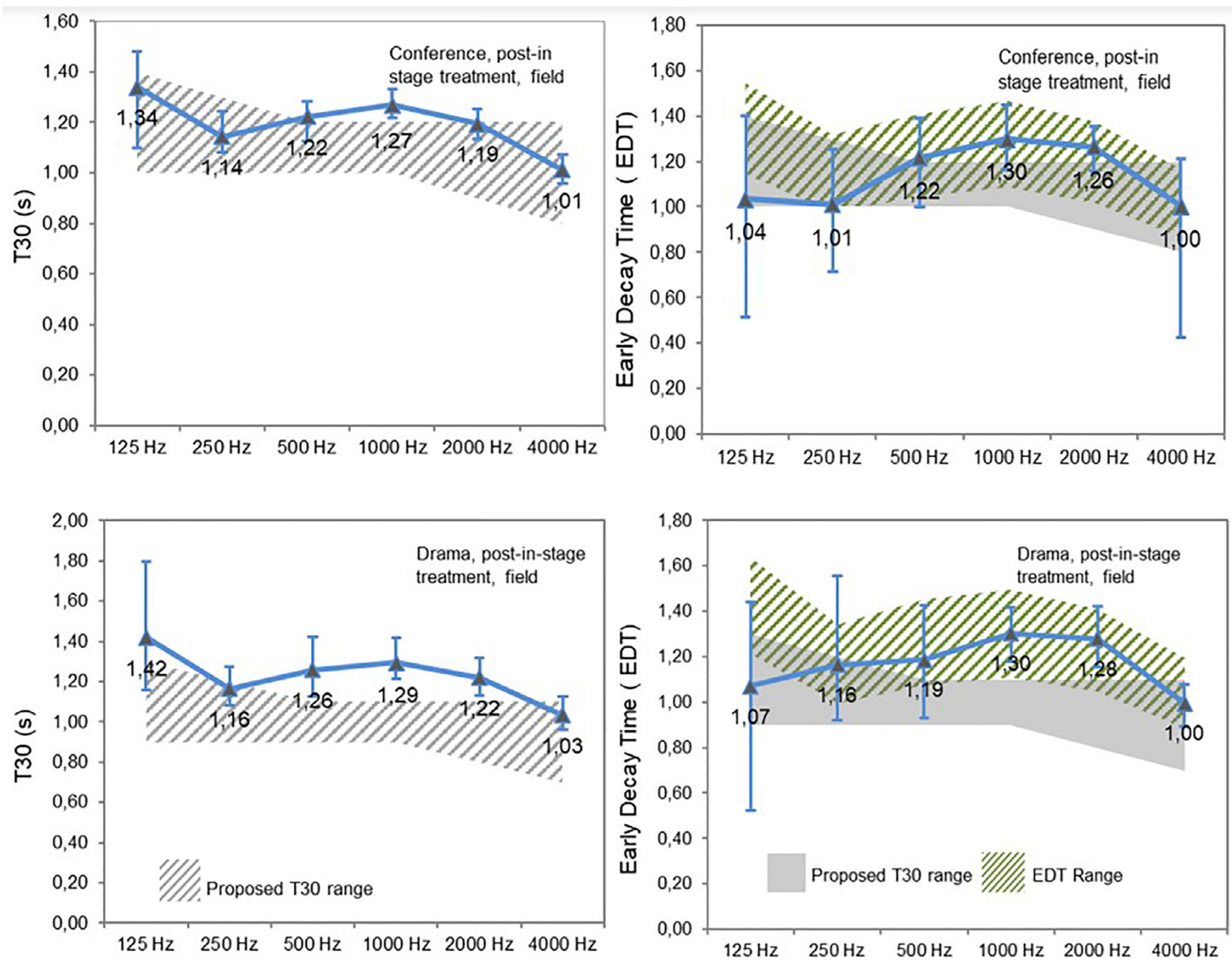


Fig. 11. Field measurements (12.02.2021), conference set-up average values of T30 (on the top-left) and EDT (on the top-right) and recommended ranges; drama theater set-up average values of T30 (on the bottom-left) and EDT (on the bottom-right) and recommended ranges, unoccupied; the average values (solid line), max. and min. values (error bars) are indicated.

the most rear aisle is 23 m, which is very proper both acoustically as well as visually for a conference hall as well as a drama theater.

5.3. Discussion on stage house coupling and the impact of architectural parameters

This short section aims to assess the occurrence of multiple sound energy decay due to the stage house and specific architectural parameters effecting room acoustics coupling. In the case of TED Performance Hall (recently named as TED Ata Stage) it was significant to observe the double sound energy decay when the acoustical precautions are not fully applied to the stage house tower and back stage areas. With full application of acoustical blankets, the details of which are given in Table 2, the reverberation times are lowered and the non-exponential sound energy decay is prevented. It should be noted that, this phenomenon is useful if intentionally used in music halls to provide both clarity and reverberance. However, in our case the hall mostly functions for speech related activities and rarely for solo recitals. And, at pre-in-stage intervention phase excessive uncontrolled late decay had caused acoustical discomfort. The question here is how much additional absorption within the stage tower would solve the problem of non-exponential sound energy decay.

Quantifying the degree of acoustical coupling or at least identifying this specific decay pattern has always been a challenging task. One approach is using the mean coupling factor, as an indicator of the strength of acoustical coupling. As previously discussed by Billon et al. [36] mean coupling factor (κ) takes into account the aperture size and absorption areas of individual volumes coupled to each other (Eq. (2)).

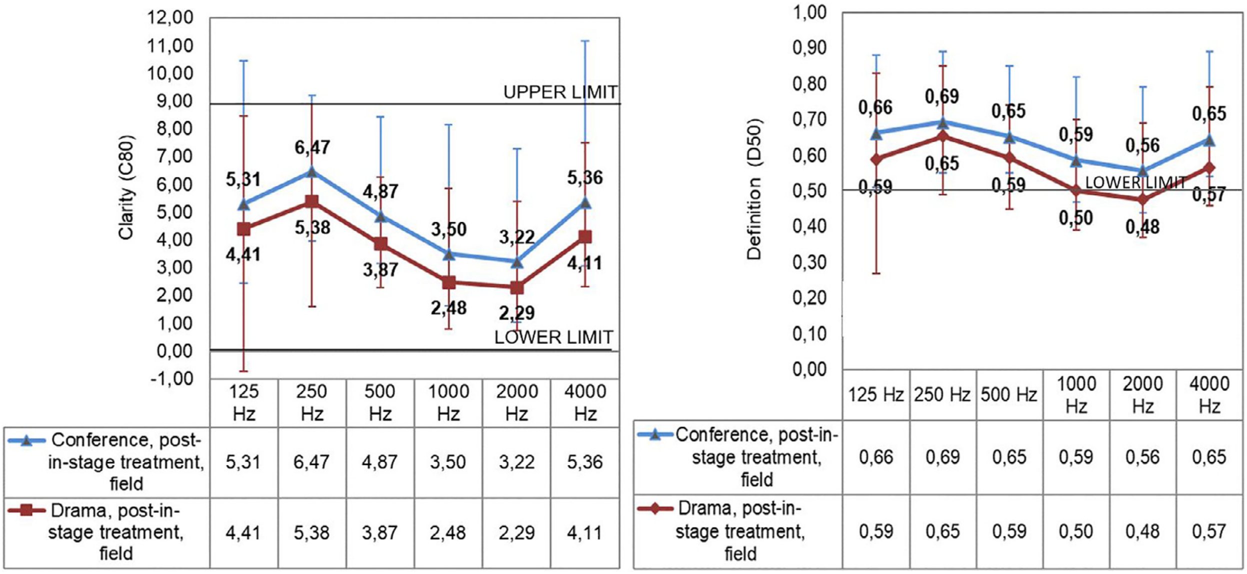


Fig. 12. Field measurements (12.02.2021), conference set-up average values of C80 (on the top-left) and D50 (on the top-right) and recommended ranges; drama theater set-up average values of C80 (on the bottom-left) and D50 (on the bottom-right) and recommended ranges, unoccupied; the average values (solid line), max. and min. values (error bars) are indicated.

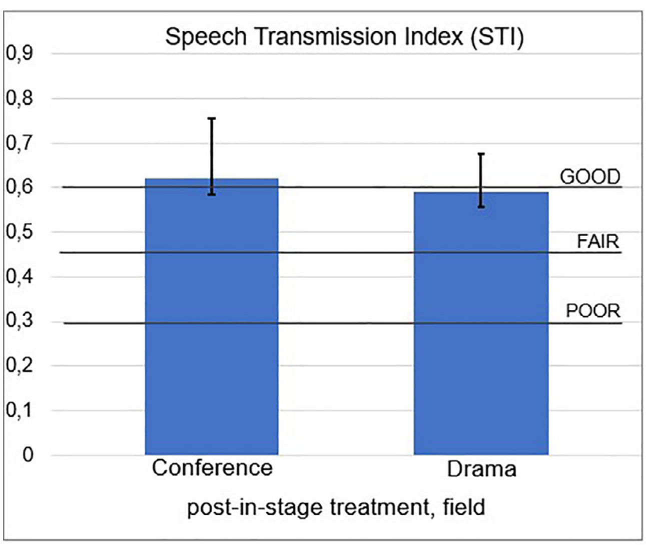


Fig. 13. Field measurements (12.02.2021), average STI results for conference and drama use.

$$\kappa = \sqrt{\frac{S_c^2}{(S_c + A_R) * (S_c + A_S)}} \quad (2)$$

where Sc is the coupling area (proscenium opening), A_R is the absorption area of receiving room (audience hall) and A_S is the absorption area of source room (stage house), in our case. On the contrary of classical distributed reverberation chamber aperture doors, the opening of the stage house is the proscenium opening in the case of TED auditorium. This is quite a large of an opening with an area of 110 m^2. Normally, higher the coupling coefficient higher the degree of coupling, which is a constant from 0 to 1.

For this study, the mean coupling factors are estimated as given in Table 6, for both pre and post in-stage interventions. As can be observed, the variation of coupling factor is not drastic with only 0.02 change from the most reflective condition (pre-stage-interventions) to the most absorptive condition (post-stage-interventions) of the stage. This is due to the fact that the aperture area is dominating the resultant value. On the other hand, the difference between absorption areas and natural reverberation times of the stage house and the audience zone in their decoupled condition is quite high (Table 7). For this reason, it may be more rational

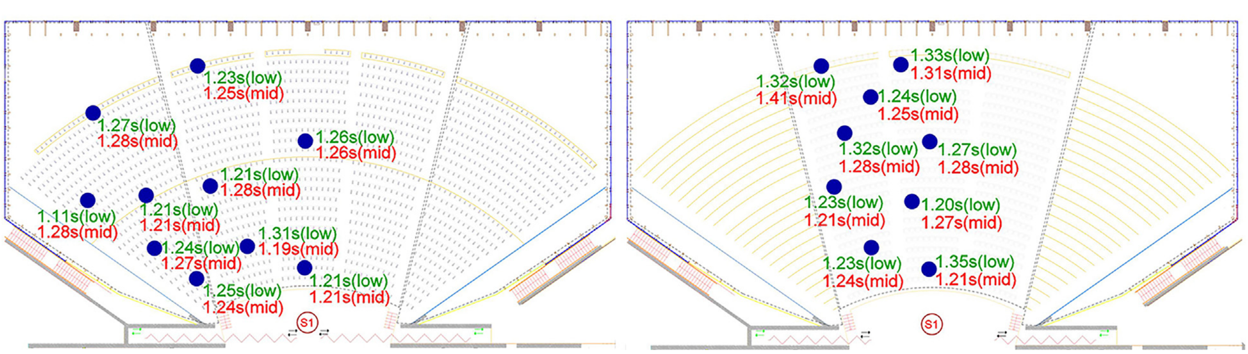


Fig. 14. Mid and low frequency averages of T30 values over receiver positions, for Source #1, for conference (on the left) and drama theater (on the right) set-up, final field tests.

Table 7
∑Si - absorption areas of decoupled conditions of hall versus stage, κ - coupling factor, absorption area ratio of hall over-stage, T30 ratio of stage over hall, and corresponding number of decay slope comparisons for different application percentages of acoustical blankets within the stage house for 250 Hz and 1 kHz.

Hall (R)/Stage (S)		∑Si – Absorption Area		κ – Coupling Factor		A_R/A_S		$T30_S/T30_R$		# of decay slopes	
		250 Hz	1000 Hz	250 Hz	1000 Hz	250 Hz	1000 Hz	250 Hz	1000 Hz	250 Hz	1000 Hz
0 %	(S)	777	955	0,09	0,08	1,9	1,6	1,9	2,0	2	2
	(R)	1513	1516								
25 %	(S)	1034	1388	0,08	0,07	1,5	1,1	1,4	1,5	2	2
	(R)	1513	1516								
50 %	(S)	1163	1521	0,08	0,07	1,3	1,0	1,2	1,3	1	1
	(R)	1513	1516								
75 %	(S)	1293	1655	0,07	0,06	1,2	0,9	1,1	1,1	1	1
	(R)	1513	1516								
100 %	(S)	1422	1789	0,07	0,06	1,1	0,8	0,9	1,0	1	1
	(R)	1513	1516								

to compare the absorption areas and T30 values for different states of the stage, for experimenting with the stage house coupling in the cases that the coupling aperture is the proscenium opening. The audience zone (main hall area) absorption area, which has not changed during phase two of the construction, and the aperture size are kept constant to seek after the effects of changing absorption area of the stage tower. The areas of acoustical blankets that are applied in post-in-stage intervention (100 %) are varied as 25 %, 50 % and 75 % to change the absorption area variance accordingly the reverberation times of individual rooms (stage versus main hall). While in Table 6, 0 % indicates no blanket in the stage house, corresponding to the pre-in-stage-intervention state.

According to Table 7, in overall receiver positions there is a potential of double decay formation when the absorption area of one zone is 1.5 times greater than the other zone. In this case 0 % application of acoustical blankets within the stage house and 25 % of application has caused double decay in 250 Hz. For 1000 Hz the result is still similar for 0 % absorption state. For 25 %, the absorption ratios for 1 kHz are getting closer to 1, while the T30 of the decoupled stage is 1.5 higher than the main hall. As the application percentage of acoustical blankets are increased (including %50, %75 and 100 % of current situation) both the absorption area ratios and the T30 ratios have become closer to 1. Thus, it may be deduced that, 1.5 times greater difference either in absorption area or T30 ratio has caused double decay sound energy formation in the case of TED Performance Hall, which has an aperture area of 110 m^2. For a risk-free choice, or for intentionally not causing such a non-exponential sound energy decay in a multipurpose venue, which is dominantly acting for speech related activities, aiming for comparable T30 values (ratios approaching to 1) for decoupled condition of stage house volume and main audience volume will be a reasonable design guide.

6. Conclusion

Room acoustics coupling has long been investigated in academia and utilized as a design tool by professional acousticians. This is specifically because the non-exponential energy-decay contributes to early and late sound energy in a hall, especially for music halls both of which are very critical. However, the same phenomena may become an acoustical defect if not controlled properly in an auditorium that is dominantly used for speech-oriented activities. In this study the specific cause of the non-exponential, or the double slope sound energy decay is the stage tower, which is not treated acoustically in the first step of construction phase. The early decay (1st slope) in the multi-slope sound energy decay belongs to the main audience zone, whereas the late decay (2nd slope) belongs to the surplus sound energy of the stage tower. The highly reflective stage tower amplified the sound energy, and almost three times of a reverberance within the stage in comparison to the main audience zone caused an energy imbalance within two volumes. As a result, the sound energy has been exchanged in between two rooms through the coupling aperture, which is the proscenium opening in drama theater set-up. And this condition also applies to the conference use when the proscenium curtain is open (in use), due to the back-and-forth sound transmission over the curtain especially at the low frequency range.

In this study acoustical simulation is utilized as a tool for the design progress steps, whereas the validations and design development are held by the aid of acoustical field tests. The impulse responses obtained through field tests are further analyzed for multi-slope formation by Bayesian decay parameter estimations, which support the multi-slope formation in the first stage of construction when no acoustical treatment is applied over the ceiling or wall surfaces of the stage, apart from the absorption area benefited from various stage curtains. The acoustical discomfort due to the non-exponential energy decay, is later tuned by the addition of 100 mm, 110 kg/m^3 mineral wool over main, side and backstage ceilings as well as upper walls as detailed in this study. A proper acoustical environment within the auditorium could only be obtained after the stage is properly treated. It should also be noted that, the tuning of the stage that is competing in volume with the main hall, is as critical as tuning the hall itself. In that respect, during the design phase through acoustical simulations correct assignment of sound absorption coefficients and transmission loss values to multiple types of stage curtains has a key role in reliable assessment of the halls.

CRediT authorship contribution statement

Zühre Sü Gül: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision. **Merve Eşmebaşı:** Data curation, Visualization, Investigation, Writing – review & editing. **Zeynep Bora Özyurt:** Visualization, Investigation, Software, Validation, Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of Competing Interest

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

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