

**ACOUSTICAL ASSESSMENT OF MUSIC HALLS
WITH VARIABLE SYSTEMS THROUGH OBJECTIVE
AND SUBJECTIVE METHODS: THE CASE OF
BILKENT MUSIC HALL**

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By

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ACOUSTICAL ASSESSMENT OF MUSIC HALLS WITH VARIABLE SYSTEMS
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MUSIC HALL

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ABSTRACT

ACOUSTICAL ASSESSMENT OF MUSIC HALLS WITH VARIABLE SYSTEMS

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M.S. in Architecture

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In concert halls, the need for variable acoustics elements arises from the diverse demands posed by different types of musical performances. Previous research suggests that incorporating passive variable acoustic solutions can effectively adapt acoustical conditions to suit various musical performance needs. This research explores the challenges and potentials associated with passive variable acoustic techniques in symphonic music venues, with a focus on Bilkent Music Hall in Ankara, Türkiye. This venue serves as the main performance space for the Bilkent Symphony Orchestra (BSO) and is one of the earliest examples of variable acoustic systems. Over this case, the impact of the existing variable acoustic system for diverse musical performances such as chamber music, orchestral music, orchestral music with choir and vocal accompaniment, solo recitals, and occasional speech-oriented activities is investigated. The methodology begins with acoustical field measurements to evaluate the existing variable acoustic system at Bilkent Music Hall, which consists of operable wooden doors with fabric backing. This analysis highlights the need to investigate the contribution of interior finishing materials

to excessive sound absorption at low frequencies, as one major problem of the hall. As a second step of the methodology, subjective data is collected through questionnaire and online surveys that are administered to BSO members and Bilkent Music Conservatory faculty and students. The analysis offers insights into the musicians' acoustical experiences and acoustical preferences in relation to the venue. Later, the findings are compared with precedent cases worldwide. The final step of the study is acoustical simulations that is applied first to assess the occupied state of the hall then to evaluate the proposed design intervention for improving the acoustical comfort within the hall for different music performances.

Keywords: Room acoustics, variable acoustics, Reverberation Time, Clarity, Bilkent Music Hall

ÖZET

DEĞİŞKEN SİSTEMLERE SAHİP MÜZİK SALONLARININ AKUSTİK ÖZELLİKLERİNİN OBJEKTİF VE SUBJEKTİF YÖNTEMLERLE DEĞERLENDİRİLMESİ: BİLKENT KONSER SALONU VAKASI

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Konser salonlarında değişken akustik unsurlara duyulan ihtiyaç, farklı türde müzikal performansların gerektirdiği akustik koşullardan kaynaklanmaktadır. Önceki araştırmalar, pasif değişken akustik çözümler ile akustik koşulların çeşitli performans ihtiyaçlarına uygun şekilde adapte edilebileceğini öne sürmektedir. Bu çalışma, Ankara’ da yer alan Bilkent Müzik Salonu'na odaklanarak senfonik müzik salonlarında pasif değişken akustik yöntemlerin sorunlarını ve potansiyellerini araştırmaktadır. Bu müzik salonu, Bilkent Senfoni Orkestrası'nın (BSO) ana performans alanı olarak hizmet vermekte olup, Türkiye'deki en erken değişken akustik örneklerinden biridir. Çalışmanın temel amacı, mevcut değişken akustik sistemin, orkestra müziği, oda müziği, koro ve vokal eşlikli orkestra performansları, solo resitaller ve ara sıra yapılan konuşma ağırlıklı etkinlikler gibi çeşitli

performanslar üzerindeki etkisini deęerlendirmektir. Metodoloji, Bilkent Mzik Salonunun mevcut deęişken akustik sistemini (kumaş kaplı açılabilir ahşap kapılar) deęerlendirmek için akustik saha ölçmleri ile başlamaktadır. Ölçmler sonucunda salonda düşük frekanslarda olddukça düşük ınlama sreleri tespit edilmiştir. Bunu takiben, BSO yelerine ve Bilkent Mzik Konservatuvarı öğretim yelerine ve öğrencilerine uygulanan yüz yüze ve çevrimiçi anketler yoluyla öznel testler yapılmıştır. Bu analizler, saha testi bulgularını desteklemekte ve müzisyenlerin mekandaki akustik deneyimleri hakkında öngörler sunmaktadır. Daha sonra bulgular dünya çapındaki emsal vakalarla karşılaştırılmıştır. Salondaki ana sorun olarak belirlenen düşük frekanslardaki aşırı ses yutumuna iç mekan kaplama malzemelerinin katkısının araştırılmasının gereklilięi ortaya çıkmıştır. Son aşamada, akustik benzetimler ile öncelikle salonun dolu kullanım halinde objektif akustik metrikler hesaplanmış, sonrasında mevcut akustik koşulları salonun farklı mzik performanslarına uygun hale getirecek şekilde tasarım önerileri akustik simlasyon yöntemi ile deęerlendirilmiştir.

Anahtar kelimeler : Oda akustięi, deęişken hacim akustięi, ınlama Sresi, Netlik, Bilkent Mzik Salonu

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LIST OF ABBREVIATIONS

C80	Clarity
EDT	Early decay time
JND	Just noticeable difference
RIR	Room impulse response
RT	Reverberation time
RT _{mid}	Reverberation time at mid-frequencies
T30	Decay time, based on the impulse decay curve, -5 dB to -35 dB
T20	Decay time, based on the impulse decay curve, -5 dB to -25 dB
V	Room volume in m ³
α	Sound absorption coefficient

CHAPTER 1

INTRODUCTION

The effectiveness of concert halls in accommodating various musical performances relies heavily on their acoustical flexibility. Different music types require different acoustical conditions for optimal sound quality and audience experience. To address these needs, variable acoustic solutions have been introduced to adjust and customize concert hall acoustics according to the requirements of different performances. This study focuses on evaluating the effectiveness of these solutions in optimizing acoustical environments across a diverse spectrum of musical genres over the case of Bilkent Music Hall in Ankara, Türkiye. In this chapter, problem statement, research problems and the objectives aimed at investigating the effectiveness and application of variable acoustic techniques in concert halls are discussed.

1.1. Problem Statement

Concert halls need to be designed with acoustical conditions suitable for specific types of musical performances. However, due to spatial limitations and operational costs, the need for performance venues that can be tuned for various functions have been increased. This new challenge for flexible room acoustics creates the approach of variable acoustics. Variable acoustic systems are commonly employed to adapt music halls for different types of music performances such as chamber music, orchestral music, orchestral music with choir and vocal accompaniment and solo recitals. They aim to tune concert halls by modifying the physical parameters that determine the acoustical performance of the sound field, some of which include Reverberation Time (T_{20} , T_{30} , RT), Clarity (C_{80}) and Early Decay Time (EDT). Even though these systems offer the opportunities for a wide range

of performances, variable installations are often avoided due to additional costs, regular maintenance requirements and the potential for incorrect operation (Kuttruff, 2017).

Depending on the concert hall volume and shape, different variable solutions may be needed to accommodate different performances. In smaller halls, retractable curtains (Aretz and Orłowski, 2009; Komoda et. al, 2010) can be an effective solution for creating a perceptible impact on reverberation. In other cases, the utilization of movable panel systems (Cairolì, 2018; Pereira et al., 2021; Adelman-Larsen, 2019) is a widely adopted solution. However, it should be noted that this approach may require a considerably large area to be treated in order to achieve a noticeable impact on the reverberation time. This can potentially lead to limitations on the interior design. The primary concerns related to these systems involve their impact on sound levels and the potential dampening of early reflections (Makrinenko, 1994; Barron, 2009). Additionally, due to characteristics of porous materials, variable sound absorption systems often fail to provide significant acoustic alteration across the entire frequency spectrum. The effective implementation of variable systems requires a clear understanding of the range of activities that might take place in the venue, along with a clear understanding of the specific design considerations that are required for each performance, within the defined acoustical limits. The effectiveness of variable applications is also influenced by factors such as the appropriate quantity of sound absorptive material, the properties of the material, and the method of installation. For optimal acoustical performance in concert halls, wooden surfaces should be heavy and supported by solid structures to prevent low-frequency energy loss (Long, 2014). In concert halls with thin wooden surfaces, bass sounds can diminish significantly in intensity.

In summary, the implementation of variable acoustic systems in music halls, aimed at

achieving optimal acoustical conditions tailored to specific performances, serve as both a valuable tool and a significant challenge. If variable systems are not properly developed and effectively used by trained operators/users, their implementation can lead to poor acoustical outcomes. This specific condition constitutes the central focus of the primary research problem addressed in this study. The case study, Bilkent Music Hall in Ankara, Türkiye, which belongs to the Faculty of Music and Performing Arts Department, is mainly used by Bilkent Symphony Orchestra (BSO) and conservatory students. The hall was designed and built in 1994 by Şahinbaş Architecture. It is one of the early examples of passive variable acoustics systems and first to be built in Türkiye. In relation to the variable acoustics, there are three rows of operable wooden doors with fabric backing installed on the side walls. The quality of sound at low frequencies is reported as problematic in the previous study conducted by Şahin (1995) and by BSO musicians who perform regularly in the concert hall, noting the need to tune their instruments when transitioning between venues. Based on current complaints, this study investigates the underlying causes of the acoustical issues in Bilkent Music Hall and their potential link to the variable acoustic system.

1.2. Aim and Scope of the Thesis

One of the objectives of this research is to explore the potential of variable acoustic systems in modifying the acoustical environment for various music performances.

The capabilities of these systems are investigated through a specific case study; Bilkent Music Hall in Ankara. While numerous studies delve into the practical benefits of variable acoustic systems, a notable gap remains in the academic field regarding experimental

studies that assess both subjective and objective data for different configurations of passive variable systems in actual concert halls, covering various music performance types.

Bilkent Music Hall holds a distinct position as being one of earliest music venues in Türkiye, particularly featuring variable acoustics. The venue serves for Bilkent Symphony Orchestra (BSO), Türkiye's pioneering private and academic ensemble, and it occupies a distinctive position in the cultural landscape of the country. Moreover, the hall elevates its prominence by hosting a wide array of distinguished international musicians and orchestras from numerous countries. In order to address the existing acoustical issues, this study aims to investigate the main causes and provide potential solutions tailored to accommodate different types of musical performances.

This study begins with an outline of the research problem, its significance, hypotheses, and objectives related to passive variable acoustic methods in symphonic music halls. Then, it is segmented into sections that cover acoustical assessment tools, the acoustical needs of different music styles, reviews of variable acoustic solutions, and analyses of notable concert halls worldwide. In the light of findings, the study details the architectural and acoustical characteristics of Bilkent Music Hall, which is main case study of this research. The thesis research utilizes both objective methods such as field tests and simulations, as well as subjective methods involving questionnaires and surveys. Combining both objective and subjective assessments allows for a comprehensive understanding of a music venue's acoustics. Objective measurements provide the data needed to identify and address technical problems, while subjective feedback ensures that the venue meets the practical needs and preferences of its users. This integrated approach is essential for designing and maintaining concert halls that provide outstanding acoustical

experiences for both performers and audiences.

For objective assessment of the current acoustical conditions of Bilkent Music Hall, a series of acoustical field measurements are conducted. These measurements provide critical insights into the hall's acoustical performance and highlight the need for acoustical simulations. Acoustical models representing both the retracted and closed states of the hall are developed and tuned based on the field test data. These simulations evaluate the impact of interior finishes and the variable acoustic system under typical occupied conditions. Additionally, acoustical simulations test the effectiveness of proposed design interventions aimed at improving the acoustic characteristics of the hall for various types of musical performances.

In parallel, a questionnaire is administered to musicians to gather subjective feedback on their acoustical experiences within the hall. This subjective data is crucial for understanding perceptible acoustical issues that field measurements alone might not reveal. The musicians' insights, derived from extended musical experience, offer a valuable perspective that complements the objective data collected from field tests. This dual approach - integrating both objective measurements and subjective evaluations - forms a core component of this study, facilitating a comprehensive analysis of the hall's acoustical performance. The methodology and acoustical parameters employed in this study is summarized in the flowchart presented in Figure 1. Subsequently, the acoustical characteristics of the passive variable system in Bilkent Music Hall are compared with its precedents, which is crucial for understanding its relative performance, identifying areas for improvement, and contributing to the broader knowledge of effective acoustical design in music venues.

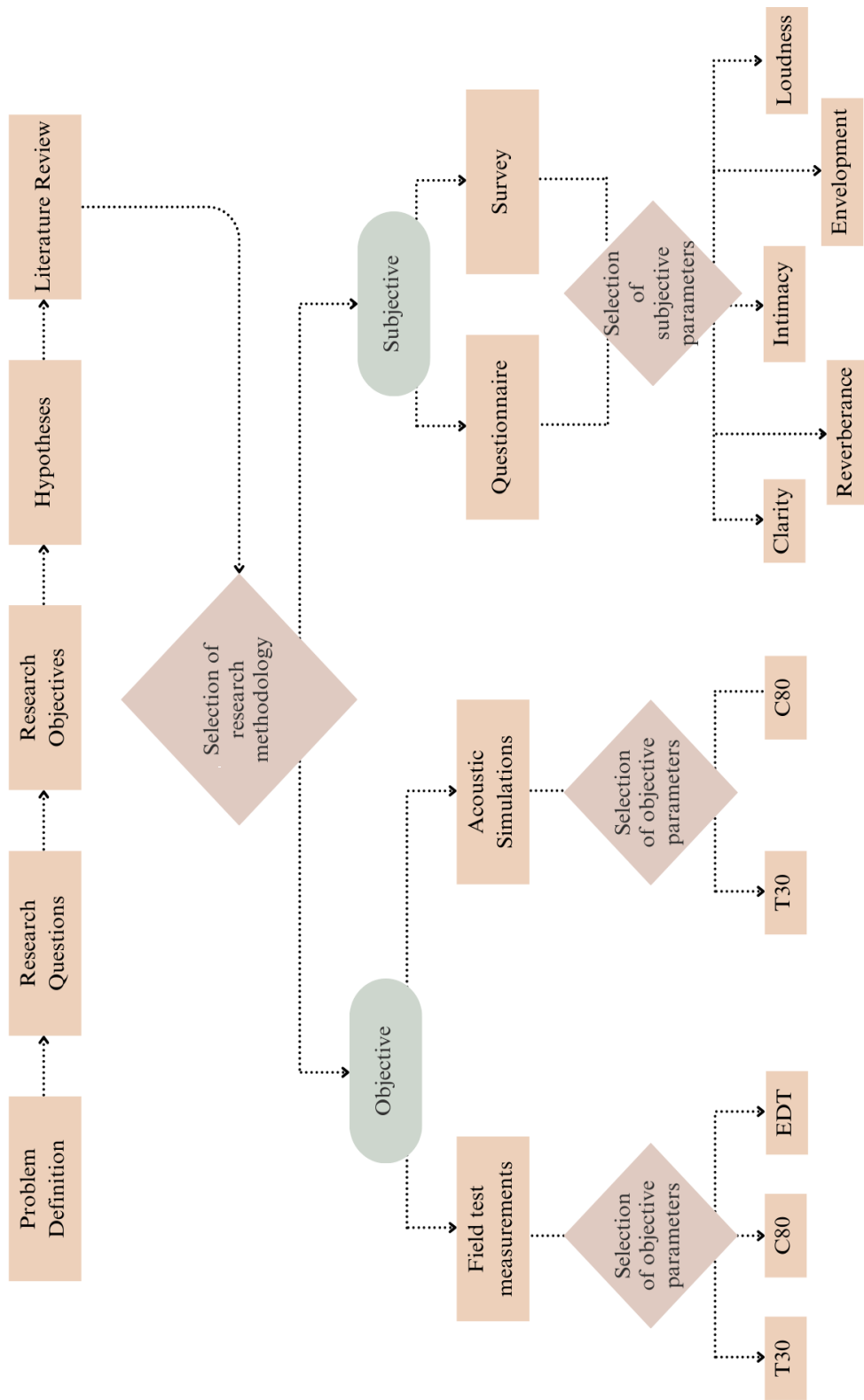


Figure 1. The methodology and acoustical parameters employed in this study

1.2.1. Research Questions

This study answers this primary research question:

- How do passive variable systems contribute to acoustical tuning of concert halls for various music performances?

In order to answer the primary research question, a number of sub - questions are required to be answered as well, which are as follows:

- How do the acoustical criteria range of objective metrics vary depending on different music performances?
- What is the current state of the room acoustics conditions of Bilkent Music Hall when compared to its precedent cases?
- How effective are the current retractable acoustic panel systems in controlling the objective acoustic metrics of the hall (RT, C80)?
- How do musicians' acoustic preferences differ, and how can this be supported by the current retractable panel system or other design solutions?

1.2.2. Hypotheses

- The criteria range of acoustic metrics varies significantly in relation to the specific characteristics of the musical performance, such as ensemble size and the instrument types involved.
- The existing retractable panel system in Bilkent Music Hall causes excessive absorption, resulting in poor performance at low frequencies compared to precedent cases.
- The current retractable panel system as well as the upper wall and ceiling cladding materials in Bilkent Music Hall needs improvement to address

excessive low-frequency sound absorption. Solutions can include increasing the thickness of wooden panels (doors and side walls) and increasing the number of gypsum board panel layers on upper wall and ceiling surfaces.

- Musicians have varying preferences for suitable reverberation times in Bilkent Music Hall depending on their played instruments. This can be supported by the current retractable panel system or through other design solutions to meet these specific needs.

1.2.3. Objectives

The objectives of the study can be summarized as follows:

1. Objective assessment of the existing variable absorption system in different states and measurement of its effect on the acoustic field. By;
 - Comparing the objective parameters of the concert hall for retracted and closed states of the music hall.
 - Evaluating the performance of the variable system for various music performance types.
 - Evaluating the performance of the variable system compared to precedent cases.
2. Subjective assessment of the variable system for different states of the panel system. By;
 - Administering questionnaire/surveys to gain insight into the experiences of musicians who regularly play in the music hall.
3. Assessing the effect of interior finishing materials on the sound energy decay for

retracted and closed states. By;

- Measuring the effects of the current state for occupied state of the hall through room acoustic simulations for retracted and closed states
- Proposing an acoustical design solution for identified problems.
- Evaluating the acoustic conditions after interventions, through objective data obtained in simulations, by comparisons to the precedent cases worldwide.

1.3. Structure of the Thesis

This study includes 6 chapters; Chapter 1 consists of three sections which introduces the problem and highlights the gap in the academic field on objective and subjective testing of variable systems for various music types. This chapter also emphasizes the significance of Bilkent Music Hall in the cultural landscape of Türkiye.

Chapter 2 provides an in-depth review of the current knowledge and research related to variable acoustics in concert halls. It consists of 5 sections; the first and second sections cover the room acoustics assessment tools and introduce the objective and subjective acoustical parameters utilized for the assessment of concert hall acoustics. The parameters are explained and their significance in the study is highlighted. The third section presents the acoustic requirements for different music styles. The fourth section reviews variable acoustics solutions and their applications in various concert halls. By examining diverse venues around the world, this section aims to identify common challenges and innovative solutions in concert hall acoustics. The findings from this section inform the proposed recommendations for improving the acoustic environment at Bilkent Music Hall, ensuring it meets the varied demands of different musical genres and performance styles. Fifth section presents the acoustical characteristics of precedent cases in the world.

Chapter 3 introduces the main case study and outlines the methodologies employed. It consists of two sections. First section introduces the architectural and acoustical characteristics of Bilkent Music Hall, providing a detailed analysis of its design features and their impact on the hall's acoustical performance. It examines the hall's architectural elements, including materials, layout, and design configurations, and how these factors contribute to the overall sound field. This thorough understanding of Bilkent Music Hall's specific attributes allows for a better evaluation of its current performance.

The second section of this chapter outlines the methodologies used in this study, detailing the procedures for field test measurements and questionnaires carried out in accordance with established standards (ISO 3382) and relevant literature. It also details the acoustic simulations performed to determine the sound absorption coefficients of interior finish materials.

Chapter 4 presents the findings of the study, offering a comprehensive analysis of the data collected from field test measurements, questionnaires, and room acoustics simulations. This chapter provides detailed insights into the acoustical performance of Bilkent Music Hall, examining key metrics such as RT, C80 and EDT. The results from the questionnaires shed light on the subjective experiences and preferences of the musicians, while the simulations help to pinpoint the effectiveness of the interior finish materials in sound absorption.

Chapter 5 interprets the data discussed in the previous chapter, highlighting the impact of various factors on the acoustical issues identified. This chapter delves into the implications of the results, explaining the relationships between architectural features, material properties, and acoustic outcomes. It provides a nuanced understanding of how each element contributes to the overall sound field.

Chapter 6 concludes the study by summarizing the key findings and implications of the research. It highlights the effectiveness of passive variable acoustic systems in optimizing concert hall acoustics for diverse musical performances. Overall, the thesis contributes valuable insights into the practical applications and challenges of implementing variable acoustic systems in performance spaces. This chapter suggests potential areas for future research, offering practical recommendations for improving the acoustical quality of similar music halls.



CHAPTER 2

STATE OF THE ART

The objective of this chapter is to present information on two noteworthy topics: the acoustic requirements for diverse musical styles and the implementation of variable acoustic systems. In the first section, objective and subjective testing methods and room acoustics parameters that are used to evaluate concert hall acoustics are briefly explained. The first group comprises objective parameters, namely RT, C80 and EDT. The second group incorporates subjective parameters, including reverberance, clarity, envelopment, intimacy and loudness. Moreover, the optimal ranges for diverse musical performance types are provided. In the second section, variable acoustic solutions are explained in detail for various musical performance types. Then, the chapter provides research on existing concert halls with variable acoustics.

2.1. Objective Acoustical Assessment and Parameters

For objective assessment of concert halls, different techniques including scale models, computational models, field measurements in existing halls and acoustical simulations (ray-tracing, image-source method, geometrical acoustics modeling, scale model testing, time-frequency analysis, and spatiotemporal visualizations etc.) are employed (Kuttruff, 2007; Bradley and Wang, 2007). Acoustical field tests are held in compliance with ISO 3382 standard to estimate objective measures (RT, EDT, C80, LF, and G).

In this study, acoustical field tests and room acoustics simulations are utilized to obtain acoustical parameter values of Bilkent Music Hall. Main objective parameters that are assessed throughout this study are presented under this chapter.

Reverberation Time (RT)

Reverberation time is a key parameter in room acoustics. According to Sabine, it is defined as the duration required for sound to diminish by 60 dB from its original level (Egan, 2007). However, in practice, due to the background noise, it is often impossible to measure the full 60 dB decay therefore, reverberation time is often determined by other parameters that measure the partial decays. The parameter measuring the sound level decay in range from -5 to -25 dB from the initial sound level is defined as T20 and the parameter measuring the sound level decay in range from -5 dB to -35 dB from the initial sound level is defined as T30 (Gade, 2007). Figure 2 presents a sample sound energy decay curve.

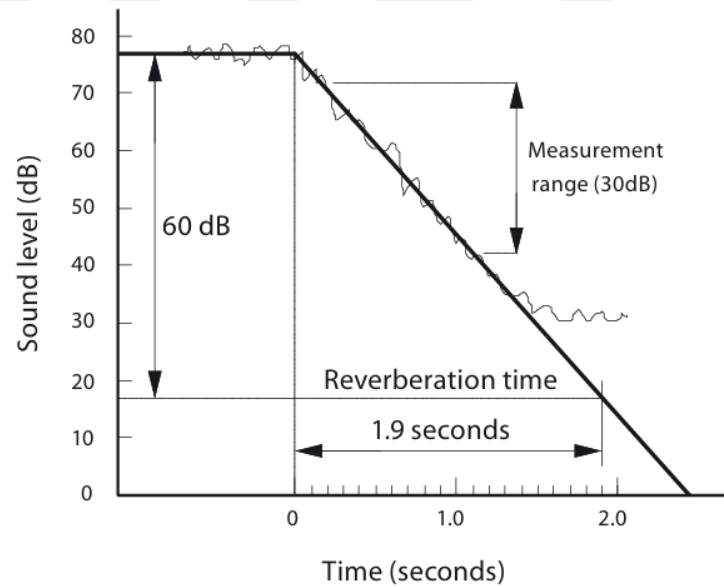


Figure 2. A sample decay for reverberation time, T60 and T30 presented (Barron, 2009)

The equation which is defined and proved by Sabine is:

$$T = 0.161 \frac{V}{A}$$

Where,

T = Reverberation time, or time required for sound to decay 60 dB after the source has stopped (s)

V= Room volume (m^3)

A = Total area of room absorption (m^2) ($= \sum S a_{av.}$) (Egan, 2007)

Beranek (2008) measures the reverberation time at mid-frequencies for 40 concert halls and juxtaposes these measurements with subjective ratings. In higher-rated halls, reverberation time typically ranges between 1.7 and 2.0 s, while lower-rated halls exhibit reverberation time ranging from 1.5 to 1.7 s. These ratings are based on standard symphonic repertoire.

Early Decay Time (EDT)

Early decay time (EDT) is defined as “the time for the initial 10 dB decay, multiplied by 6 (Jordan, 1970, as cited in Del Solar Dorrego and Vigeant, 2022)”. EDT is influenced by the position at which measurements are taken within a hall, due to its dependency on the strength of the early reflections (Del Solar Dorrego and Vigeant, 2022). In the context of continuous music, the early part of the reverberant decay is audible, whereas the late reverberance is perceptible during silent intervals (Poletti, 2011). This illustrates the importance of EDT as a criterion in such musical contexts. Previous research indicates that EDT is more critical than RT in evaluating a hall's acoustical quality for music, providing strong correlation with the perception of reverberation than T30. (Barron, 1995; Beranek, 2004). In highly rated halls, $\text{EDT}_{\text{M(unoccupied)}}$ is typically 0.5 s longer than $\text{RT}_{\text{M(occupied)}}$. Additionally, EDT exhibits a substantial correlation with RT across all halls, with the exception of those with unconventional shapes or adjustable volumes (Hidaka et

al., 2000).

Clarity (C80)

Clarity in room acoustics refers to the perceived precision of musical detail. Beranek (2004) defines this criterion as “the degree to which a listener can distinguish sounds in a musical performance.” The clarity value is predicted from the clarity index, C80, which is determined by the logarithmic ratio of early sound energy to late or reverberant sound energy. Early sound is the direct and reflected sound arriving within the first 80 milliseconds, while the late sound is the energy after 80 milliseconds, presented in decibels (Beranek, 2004, as cited in Miskiewicz et. al. 2012).

Clarity index, C80, is calculated according to the following formula (Reichardt et al., 1975, as cited in Miśkiewicz et al., 2012):

$$C80 = \frac{10 \log \log \left(\int_0^T h^2(t) dt \right)}{\int_T^\infty h^2(t) dt}$$

According to Beranek (1996), in best concert halls, the average of $C80_{(3)}$, averaged over the three octave bands; 500, 1000, and 2000 Hz, value is between -1.0 and -4.0 (as cited in Hidaka et. al., 2000). According to Meyer (2009), the clarity factor should ideally fall within the range of -2 to +4 dB, although a value of -5 dB can still be justified for distant seats. More detailed range of criteria is presented in Table 3 in the following section.

Bass Ratio (BR)

The bass ratio (BR) is calculated by dividing RT_{low} to RT_{mid} ; the average of RT_{125-Hz} and RT_{250-Hz} divided by the average of RT_{500-Hz} and $RT_{1000-Hz}$ (Beranek, 2004). Hidaka and

Nishihara (2004) calculate that traditional halls have BRs between 1.07 and 1.24, with a median of 1.15 for occupied conditions. Modern halls, on the other hand, have BRs ranging from 0.90 to 1.12, with a median of 1.01. Studies have shown that BR is a better predictor of bass perception than level (Bradley and Soulodre, 1997; Beranek, 2004).

Heavy materials, such as 50 mm thick wood backed by concrete or plaster, effectively amplify bass frequencies. For instance, McDermott Hall in Dallas, USA utilizes concrete reverberation chambers to enhance the room's natural reverberation. Conversely, thin materials like wood, drywall, and glass tend to absorb low-frequency sound energy and should be avoided unless firmly attached to a heavy backing of concrete or plaster (Long, 2014). Table 1 presents the $T_{30\text{mid}}$ and BR values of highly rated concert halls.

Table 1. $T_{30\text{mid}}$ (s) and BR for highly rated concert halls around the world (Ahnert and Tennhardt, 2008)

Venue	$T_{30\text{mid}}$ (s)	Bass Ratio (BR)	Brilliance Ratio (TR1)	Shape
Amsterdam, Concertgebouw	2,0	1.09	0.77	Rectangle
Basel, Stadt-Casino	1,8	1.18	0.74	Rectangle
Berlin, Konzerthaus	2,05	1.08	0.79	Rectangle
Boston Symphony Hall	1,85	1.03	0.78	Rectangle
Cardiff, David's Hall	1,95	0.98	0.87	Polygon
New York, Carnegie Hall	1,80	1.14	0.78	Rectangle
Tokyo, Hamarikyu Asahi	1,70	0.93	1.04	Rectangle
Vienna, Musikvereinssaal	2,0	1.11	0.77	Rectangle
Zürich, Tonhallensaal	2,05	1.32	0.58	Rectangle

2.2. Subjective Acoustical Assessment and Metrics

Several studies in the literature focus on subjective testing with musicians to analyze ideal acoustic conditions for ensembles (Marshall et al., 1978; Gimenez et al., 2011). Subjective assessment methods can be based on laboratory experiments with simulated acoustic fields, field studies such as questionnaires during concert performances and auralization for reproducing musical performances for subjective judgments and listening tests (Gimenez et. al., 2011; Hawkes and Douglas, 1971; Gade, 1989). Lachenmayr et al. (2023) conduct objective and subjective evaluations on seven chamber music halls using occupancy simulation and two music excerpts. In the study, listeners fall into two groups: one preferring enveloping warmth, the other clarity, similar to previous findings in the literature in symphony halls. According to the results, none of the evaluated halls is universally preferred, however, a fan-shaped hall consistently ranks lowest for chamber music. Conversely, a non-shoebox hall receives medium to high ratings across attributes, likely due to strong early reflections and enveloping late reverberation. Pätynen and Lokki (2016) use listening tests to examine the relationship between acoustics and emotional response where the participants listen reproductions of an orchestral music excerpt in six different halls. The study reveals that concert hall design significantly influences listeners' emotional responses to orchestral music. Rectangular halls evoke stronger emotional impact compared to other hall types, aligning with previous hypotheses. Physical proximity also affects emotional response, with some halls providing strong experiences even from seats further back. Jeon et al. (2015) explore musicians' subjective impressions of acoustic conditions during live performances of solo, duet, and quartet pieces at six various stage positions, evaluating the overall quality of these performances.

Even though objective parameters are widely used in practice to evaluate acoustics,

acoustical impression of these parameters can be different for audience and performers. Barron (1988) evaluates the acoustics of 11 British concert halls through questionnaires administered to sound experts. In order to evaluate the acoustical experience in concert halls by impression, subjective parameters are developed, which are as follows:

2. **Reverberance** (or liveness) is defined as “the sense of reverberation (Barron, 2013)”.

3. **Clarity** refers to “the ability to hear the musical detail and distinguish sounds in a musical performance (Barron, 2009)”.

4. **Envelopment** depends on “the spatial aspect of the perceived sound and refers to the degree to which the reverberant sound seems to surround the listener (Beranek, 2004)”.

5. **Intimacy** refers to “one’s degree of identification with the performance, whether one felt acoustically involved or detached from it (Barron, 2009)”. It depends on how quickly the first reflected sound reaches the listener's ears after the direct sound. In halls with proper early reflections, acoustic intimacy would be high. (Hidaka et. al., 2000).

6. **Loudness** refers to the relative sense of the orchestral forces involved. Different from the precise measurement of sound in decibels, subjective loudness refers to the strength of sound at one’s ears (Hawkes and Douglas, 1988; Barron, 2009).

2.3. Acoustic Requirements for Different Music Styles

Variations in acoustical demands across different music styles arise from differences in instrumental arrangements and the size of performing ensembles typical of each musical era. Raichel (2006) defines an orchestra as a trained ensemble of musicians who perform on string, wind, and percussion instruments, under the guidance of a conductor. Unlike bands, which predominantly feature wind and percussion instruments, orchestras emphasize string instruments for the main musical content. Orchestras adapt to various musical demands, such as symphonies, operas, or theatrical performances, requiring different instrumentation. Figure 3 presents the typical configuration of instruments for a symphony orchestra, a small orchestra and a small dance band.

Large orchestras with 80 - 120 players are common to achieve desired sound effects in sizable venues, occasionally incorporating organs into performances as necessary. A symphony orchestra generally comprises four main sections: strings, woodwinds, brass, and percussion. String instruments produce sound through strings that are struck, bowed, or plucked. The strings section includes violins, violas, cellos, double basses, harps, and often a piano. The woodwinds section features bassoons, bass clarinets, clarinets, contrabassoons, English horns, flutes, oboes and piccolos. The brass section comprises French horns, trumpets, tubas, and trombones. Percussion instruments are classified based on their pitch, either definite or indefinite. The percussion section may include bass drums, castanets, celestas, glockenspiels, gongs, drums, tambourines, timpani, tubular chimes, xylophones, and triangles (Raichel, 2006; Pagliaro 2012). Further details regarding the classification of instruments can be found in Table 2.

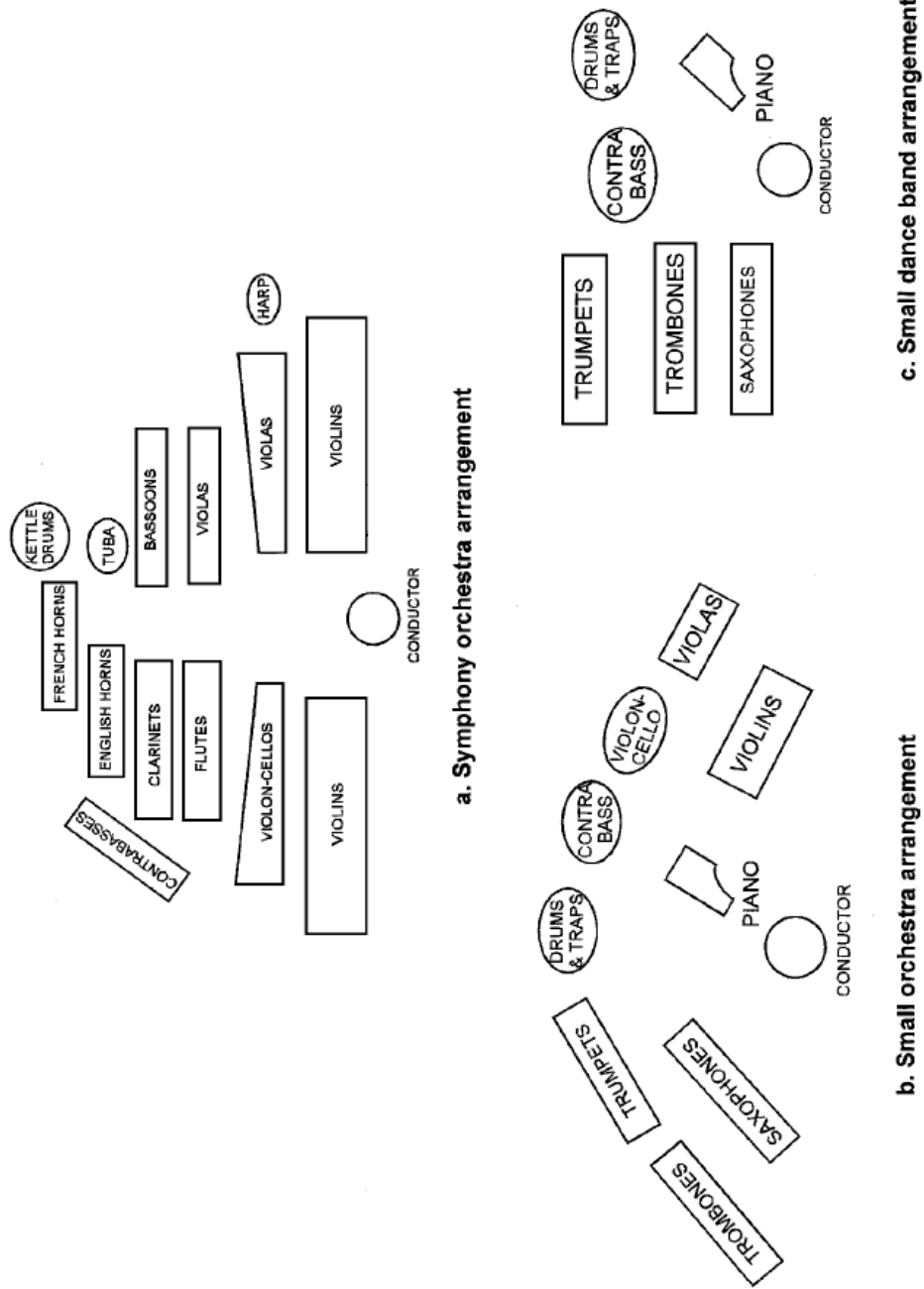


Figure 3. Typical instrumental arrangements for different ensemble types; Symphonic (a) and small (b) orchestra, and small dance band (c) (Raichel, 2006)

Table 2. Classification of Musical Instruments; String, Wind, Percussion (Raichel, 2006)

String Instruments			
Plucked Strings		Bowed Strings	Struck Strings
Lyre		Harp	Ukulele
Violin		Violoncello	Mandolin
Piano		Zither	Banjo
Lute		Double Bass	Sitar
Viola		Guitar	Harpsichord
Dulcimer			
Wind Instruments			
Air Reed	Single-Mechanical Reed	Double-Mechanical Reed	Lip Reed
Whistle	Free-reed organ	Oboe	Bugle
Flue Organ Pipe	Reed organ pipe	English horn	Trumpet
Recorder	Accordion	Oboe d'amore	Cornet
Flageolet	Harmonica	Bassoon	French horn
Ocarina	Clarinet	Contra bassoon	Trombone
Flute	Bass clarinet	Sarrusophone	Bass trombone
	Saxophone		
Piccolo	(soprano, alto, tenor, and bass)		Tuba
Fife	Bagpipe		
	Organ (combination air reed and mechanical reed)		
Percussion Instruments			
Definite Pitch		Indefinite Pitch	
Tuning fork		Castenets	
Snare or side drum		Bell	
Celesta		Triangle	
Military drum		Chimes	
Xylophone		Steel drum	
Bass drum		Carillon	
Kettledrums (tympani)		Cymbals	
Gong		Glockenspiel	
Marimba		Tambourine	

Previous research on the acoustic requirements for different music types are diverse. Ueno et. al.'s (2005) study aims to identify the ideal acoustical conditions for chamber music. The study involves eight string instrument players and six wind instrument players, who are asked to perform in various simulated stage conditions and subsequently to rank their auditory impressions. The results indicate that musicians are adversely affected by the extreme conditions of early reflections and reverberation time, and highly aware of the degree of the reverberation. Another study on musicians' preferences for acoustical reflections is conducted by Marshall et. al. (1978). In the experiment, a musician is seated in an anechoic room where recordings of the Beethoven Opus 3 are played in different settings. The study concludes that the reflections of high frequencies are preferred by musicians for ease of ensemble. Gade's (1989) study is on flute and string players. The findings highlight that flute players perceive the influence of the reflection more precisely compared to string players.

Others study the influence of acoustic factors on trumpet players (Gari et. al, 2019), piano players (Bolzinger et. al., 1992), and bowed string instruments (Grillo et. al., 2018). Many studies in the literature explore how the physical characteristics and directivity of musical instruments impact acoustic performance, which falls under the realm of musical acoustics rather than architectural acoustics. These studies examine how these factors impact sound propagation and quality in performance spaces, contributing to a deeper understanding of acoustical optimization for diverse musical performances (Pätynen and Lokki, 2010; Meyer, 2009; Rossing et. al., 2002; Benade, 1990; Ackermann et. al., 2024; Gough, 2014). Nagata (1989) studies the preferred reverberation times for different music types, such as solo piano, chamber music, orchestral organ music and oratorio. Figure 4 illustrates the preferred reverberation times for such events. In addition, his study discusses the

reverberation over frequency spectrum which had not received much attention before. The study concludes that classical music spans a broad frequency range, and the frequency characteristics of reverberation affect tonal quality and orchestra balance (Nagata, 1989).

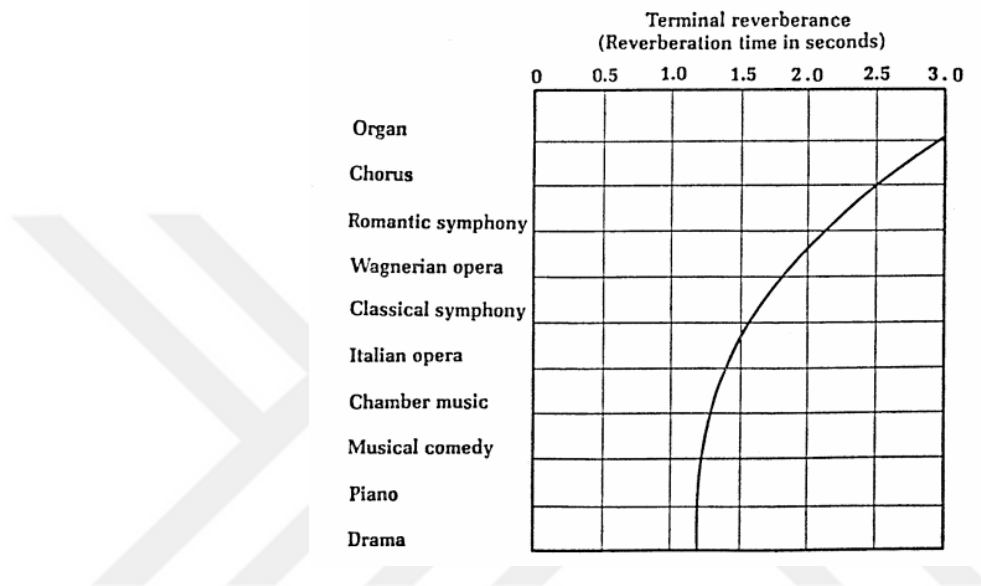


Figure 4. Optimum reverberation times in relation to music types (Nagata, 1989)

Figure 5 shows the frequency characteristics of various Japanese concert halls. Each hall has a distinct reverberation sensation, and the desired characteristics depend on the music repertoire and the ensemble size. For organ, religious, and orchestral music, halls should avoid frequency pattern (d), while piano, vocal, and chamber music venues should avoid pattern (b). Most modern large concert halls have either flat reverberation frequency characteristics or slightly longer reverberation times at lower frequencies (Nagata, 1989).

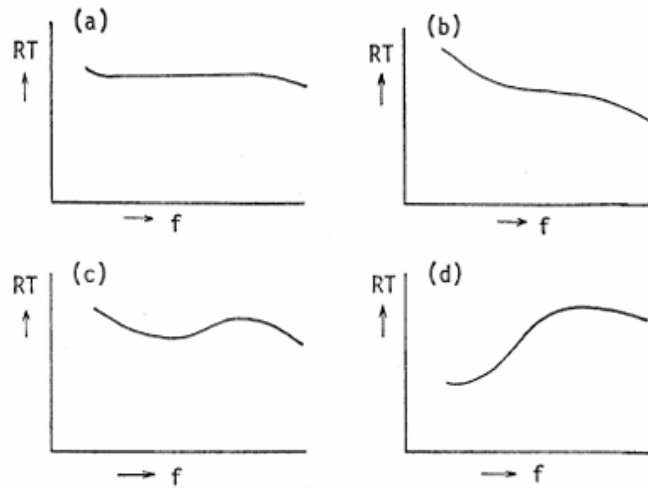


Figure 5. Reverberation frequency characteristics of Japanese halls, low to high frequency ranges (left to right) (Nagata, 1989)

The piano pedal allows the performer to extend the duration of notes as desired; thus, in solo piano performances, a shorter reverberation may be acceptable. However, some pianists prefer longer reverberation for solo recordings in order to enhance the sound quality of their performance. In contrast, woodwinds and brass instruments suffer from short reverberation (Cairolì and Agostinelli, 2024; Nagata, 1989). Instruments such as pipe organ and violin benefit from a longer reverberation time that allows the previous notes to resonate, creating a dramatic transition between notes (Hidaka and Nishihara, 2022; Beranek, 2004). The study by Hidaka and Nishihara (2022) employs a combination of field tests and subjective experiments with music experts to investigate the optimal reverberation time for violin and piano solo performances. The findings indicate that the optimal T30 value for violin solo performances is between 1.8 and 2.4 s, while for piano solo performances, it is between 1.2 and 2.0 s. In order to ensure the success of a variety

of performances, it is essential that acousticians design a well-balanced and adaptable acoustical environment. In addition to music types, the acoustic requirements for different musical periods are also commonly studied in the literature.

Reverberation time is often used as the criterion for determining the optimum range. Optimum objective acoustical criteria range for different performance types is presented in Table 3 (Altun and Sü Gül, 2023). For the Baroque period, musical pieces typically involve a single instrument and are ideally performed in rooms with high intimacy. Therefore, the optimum reverberation time for Baroque music is around 1.6 s (Beranek, 1992). Classical style music (i.e. Bach, Mozart and Haydn) was originally performed in smaller rooms by quartets and symphony orchestras. The ideal reverberation time for classical style is between 1.6 s - 1.8 s (Long, 2009). Romantic style music emphasizes personal expression, emotion, and poeticism, diverging from Classical formalities. Composers of this era aim to convey inner thoughts and feelings, often using symphonic poems or programmatic compositions to tell stories. In this period, the increased loudness of instruments and the adoption of full orchestras led to construction of larger concert halls. Longer reverberation times are preferred for romantic style music (i.e. Schubert, Mendelssohn, and Brahms), between 1.9 s - 2.1 s, since these pieces include complex harmonies and instrument organizations (Beranek, 2004; Long, 2009).

For twentieth century music, characterized by smaller instrument combinations, a reverberation time of 1.4 s is considered ideal however, there is a lot of variety in terms of performance types which reinforces the need for variable acoustics (Beranek, 2004).

Grosser Musikvereinssaal in Vienna, Austria is acclaimed for its exceptional rendering of both romantic and classical compositions, boasting a RT_{mid} of 2.05 s (Meyers, 2009).

Kuhl (1954) reveals that the suitable reverberation time for early classical compositions

(such as Mozart's Symphony No. 41 Jupiter) is 1.54 s, for romantic classical pieces (like Brahms' Symphony No. 4) is 2.07 s, and for modern music (such as Stravinsky's Le Sacre du Printemps) is 1.48 s (as cited in Long, 2014).

Table 3. Optimum objective acoustical criteria range for different performance types
(Altun and Sü Gül, 2023)

Design Parameter	Criteria
Reverberation Time, T30 (s)	1.4 s – 1.7 chamber music (Barron, 2009; Egan, 2007) 1.7 s – 2.3 s symphonic music (Egan, 2007; Hidaka and Nishihara, 2022) 1.2 s to 2.0 s (for piano) (Hidaka and Nishihara, 2022) 1.8 s to 2.4 s (for violin) (Hidaka and Nishihara, 2022)
<i>Musical Periods,</i> Baroque Classical Romantic Twentieth Century	1.6 s (Beranek, 1992) 1.6 s – 1.8 s (Beranek, 2004) 1.9 s – 2.1 s (Beranek, 2004) 1.4 s (at mid-frequencies, occupied) (Beranek, 2004)
Early Decay Time, EDT (s)	1.8 s – 2.2 s (Barron, 2013)
Clarity, C80 (dB)	-2 dB to 2 dB (for music) (Barron, 2009) 0 – +2.4 dB (for piano) (Hidaka and Nishihara, 2022) -1,6 – 0.7 dB (for violin) (Hidaka and Nishihara, 2022)
Bass Ratio	1.1 – 1.25, for halls with RT > 1.8 s 1.1 – 1.45, for halls with RT < 1.8 s (Beranek, 2004)

2.4. Variable Acoustics in Concert Halls

Concert halls have specific acoustical design requirements, however, owing to spatial and financial limitations, these venues are frequently repurposed to host a diverse range of events. This challenge is particularly pronounced in concert halls located within university campuses or smaller cities, where such venues may find themselves hosting a variety of events, spanning from lectures to symphonic music performances. Additionally, as discussed in the previous section, the distinctive acoustic requirements associated with different musical periods also contribute to the necessity of designing multipurpose venues. Consequently, ‘variable acoustics’ are employed in concert halls to achieve flexibility, allowing for modifications to the acoustic characteristics of the rooms for different performances.

In the field of room acoustics, variable acoustic systems can be implemented, initially to adjust reverberation time, which serves as a primary acoustic metric. Music halls need special attention for tuning the length of the sound energy decay, according to the size and the type of the hall. When reverberation is excessively long, a single note may become inaudible due to the masking effect of an earlier sound. Conversely, when reverberation is insufficient, the sound may lose its richness, resulting in a dull sound field.

Variable acoustic systems are categorized into two main groups: active systems that alter the acoustical environment through electronic solutions and passive systems that rely on architectural modifications. According to Sabine equation, there are two factors that affect the reverberation time, which are the volume and the quantity of the sound absorbing materials (Barron, 2009). Therefore, the principle of passive variable systems depends on temporary adjustment of either of these two factors, each with own advantages and

disadvantages.

In the following section, different variable system solutions are presented.

2.4.1. Active Variable Systems

Active variable systems in concert halls are advanced audio technologies that enable real-time adjustments to the acoustical properties of the performance space. They achieve this by employing electronic processors, loudspeakers and microphones to introduce artificial reverberation to the sound field. This capability allows for immediate changes to acoustical qualities, often offering a wider range of adjustments compared to passive methods, especially when also accompanied by architectural modifications.

It is possible to vary the reverberation time of a venue by electronic means in a range of approximately 0.5 s without adversely affecting the spatial impression and timbre (Ahnert and Tennhardt, 2008). There are two different approaches for active acoustical design. The initial approach involves in-line systems, which excel in controlling early energy and enhancing reverberation for onstage sound sources. However, unlike natural reverberation that fills the room uniformly, in-line systems are unable to globally enhance reverberation. While suitable for events not dependent on this feature, they prove inadequate for situations requiring audience participation, where global reverberation enhancement is essential. An alternative to in-line systems is the non-in-line, or regenerative systems. In this approach, microphones are distributed throughout the room with the intention of artificially prolonging the reverberation time (Poletti, 2011). Some of the active variable systems and their acoustical characteristics are summarized by Nagata (1989), which is presented in Table 4.

Table 4. Electroacoustic systems and their acoustic features (Nagata,1989)

	Assisted resonance (AR)	Multi-channel reverberation system (MCR)	Reverberation on demand systems (RODS)	Electronic reflected energy system (ERES)	Asisted acoustics (AA)
Acoustic Feedback	✓	✓			
Increase in reverberation	✓		✓	✓	✓
Addition of reflections				✓	✓
Reinforcement of low frequency sound				✓	

Artificial reverberation devices commonly include, tape delays, spring reverbs, plate reverbs, and echo chambers. These devices operate by converting sound energy into mechanical vibrations, which are then transmitted to a medium such as a chamber, plate, or spring. Within this medium, the vibrations are blended with the original sound to create a reverberating effect. However, the initial versions of these devices have shortcomings in replicating a genuine reverberation experience due to their inability to adjust time delay and reverberation density (Hyon and Jeong, 2021).

Active variable acoustic systems are implemented in many performance venues. In Cornerstone Arts Center, in Colorado, USA and Nokia Concert Hall, in Tallinn, Estonia, “Constellation” that utilizes VRAS algorithms is installed. In the Royal Festival Hall in London, UK, an assisted resonance (AR) system has been installed, comprising 172 channels and designed to extend the reverberation time within a frequency range from 58 Hz to 700 Hz (Poletti, 2010). Eugene Performing Arts Center in Oregon, USA features an

installation of ERES, an electronic reflected energy system. The LARES system is widely installed in Europe and the USA, including notable venues such as Staatsoper in Berlin, Germany Staatsschauspiel in Dresden, Germany and the Seebühne (floating stage) in Mörbisch, Austria (Ellison and Schwenke, 2010; Ahnert and Tennhardt, 2008; Parkin and Morgan, 1965).

In the Congress Hall of the Prague Congress Centre in Prague, Czech Republic, VRAS is installed. The hall is a large venue with a volume of 41,000 m³ and 2,766 seating capacity. Before installment of any electroacoustic systems, the hall has a RT of 1.74 s at mid-frequencies and a BR of 0.95. The system includes 24 microphones; eight hypercardioid microphones placed above the stage to assist with early reflections and sixteen ceiling-mounted microphones to extend reverberation. 64 loudspeakers are distributed throughout the hall. In Figure 6, the performance of the VRAS is demonstrated for chamber, symphony and off settings, comparing EDT and RT values.

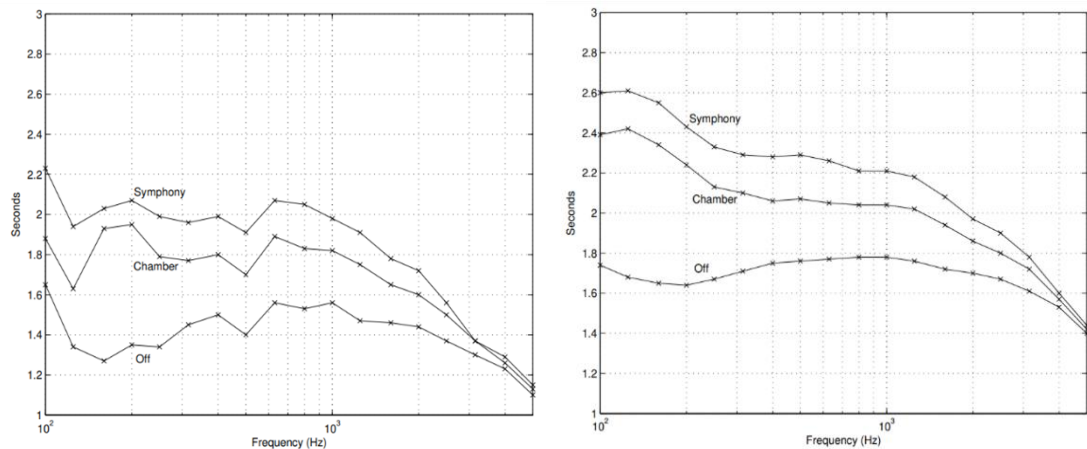


Figure 6. EDT (left) and RT (right) values for Prague Congress Hall, VRAS in symphony, chamber and off settings (Poletti, 2006)

In addition to early reflection and reverberation processing, digital signal processors are implemented for time alignment, ensuring direct sound reaches all seats before any electroacoustic signals.

In Table 5, off, chamber and symphony settings of VRAS in Congress Hall of the Prague Congress Centre is presented. When the electroacoustic system is off, the EDT at mid-frequencies in the venue is 1.48 s. In the chamber hall setting, the EDT value increases to 1.73 s and in the symphony hall setting, it rises to 1.89 s. Meanwhile, the RT at mid-frequencies is 1.74 s when the VRAS is off, extending to 1.99 s in the chamber hall setting and 2.15 s in the symphony hall setting. The C80 value is 2 dB when VRAS is off. In the chamber hall setting, this value decreases to 0.9 and 0.4 dB in the symphony setting. These findings highlight the VRAS's effective enhancement of early reflections and overall reverberation while maintaining satisfactory clarity (Poletti, 2006).

Table 5. Comparison of EDT, RT, C80 values for Congress Hall in Prague Congress Centre for VRAS off, chamber, and symphony settings, at mid frequencies (Poletti, 2006)

System setting	EDT (s)	RT (s)	C80 (dB)
VRAS off	1,48	1,74	2.0
Chamber	1,73	1,99	0.9
Symphony	1,89	2,15	0.4

2.4.2. Passive Variable Systems

Passive variable acoustic systems transform the physical attributes of a performance venue

to achieve an acoustical atmosphere that aligns with its intended use. By modifying surface geometries, spatial volumes and sound absorption capabilities of finishing materials, it is possible to alter the critical acoustical factors of a given space in order to enhance its functionality (Chiang et. al. 2009; Ortiz 2016; Pereira et. al., 2021). In comparison to previously mentioned systems, in a passive hall, where acoustical adjustments aren't actively made, musicians can vary their playing intensity throughout a concert without altering the consistent reverberation time which is not possible in concert halls with electroacoustics (Cairolì and Agostinelli, 2024). There are two different approaches in passive variable acoustics which are altering the volume or altering the absorption in the space.

Variable Volume

The acoustical characteristics of concert halls can be tailored through temporary adjustments in volume. A method commonly employed to prolong the reverberation time is coupled volume which increases the volume located adjacent to the main space through doors or movable wall sections. Two distinct methodologies exist for the coupling of room acoustics: source-area coupling, also known as stage house coupling, and distributed coupling utilizing reverberation chambers (Sü Gül et al., 2022). In stage house coupling, the stage shell, particularly in conjunction with a proscenium stage, serves as a multifunctional component that alters absorption, volume, and reflection patterns (Cremer and Müller, 1982, as cited in Chiang et. al., 2009).

In Kung Hsue She (KHS) Concert Hall, a 403-seat venue in Taipei, Taiwan, the proscenium stage is installed to couple stage space for music programs requiring a longer reverberation time. Moveable curtains are also installed for variable absorption. Results

show that incorporating large apertures around the proscenium enable stage reverberation to affect both early and late decay. Triangular lateral reflectors mitigate unbalanced absorption and direct reflections to remote seats. The unoccupied mid-frequency T30 ranges from 1.2 to 1.7 s, confirming variable reverberation time for music performances (Chiang et. al., 2009). In Figure 7, T30 and EDT are presented for different variable volume configurations.

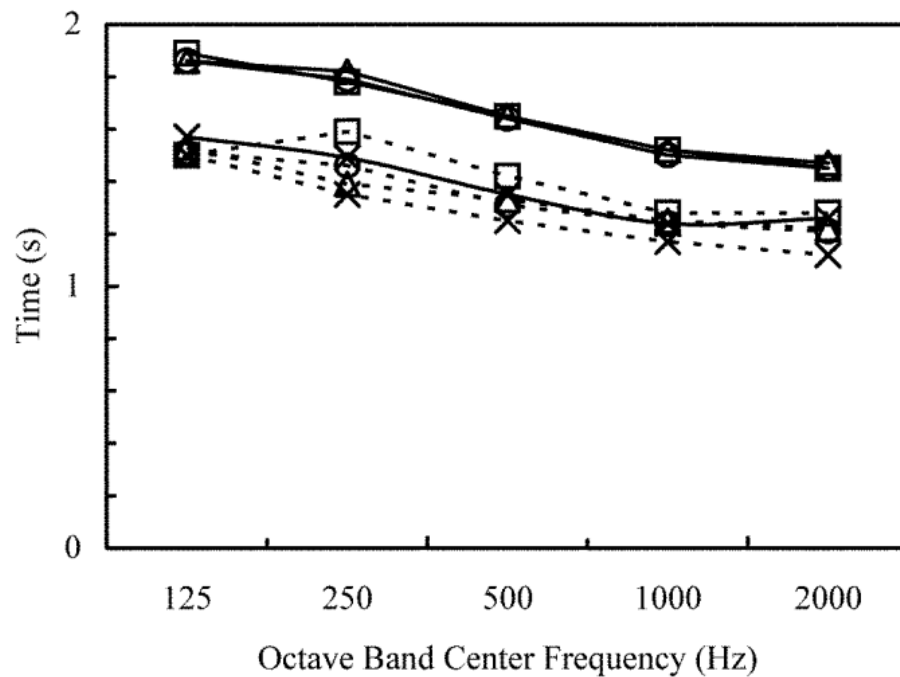


Figure 7. Comparison of T30 (solid line) and EDT (dotted line) of the sealed orchestra shell (X) to three configurations with the coupled stage in KHS Hall, data obtained through scale model testing (Chiang et al., 2009)

The effect of the distributed coupling volume method differs from previous approaches. These volumes extract energy from the main hall and reintroduce it later at reduced intensity, creating a segmented energy decay curve (multi-exponential sound energy

decay) (Long, 2014). In most cases, distributed coupling is achieved through the use of reverberation chambers that enclose the side and back walls of the main seating area. Variable volume systems are often favored in concert halls due to their ability to minimize sound level loss, making them a preferred choice despite the cost and complexity of implementation. Examples of the distributed coupling method include the Eugene McDermott Concert Hall in Dallas, USA, the KKL Luzern Concert Hall in Lucerne, Switzerland, Heydar Aliyev Center Auditorium in Baku, Azerbaijan, Morton H. Meyerson Symphony Center in Dallas, USA, the Sibelius Hall in Lahti, Finland (Beranek, 2004; Hyon and Jeong, 2021; Sü Gül et. al., 2022; Sü Gül and Çalışkan, 2010; Möller, 2017). The Symphony Hall in Birmingham, UK, utilizes both stage house and distributed coupling methods. The acoustic flexibility is designed to support a variety of performances, from chamber music to pipe organ concerts. The hall features a 12,700 m³ U-shaped reverberation chamber behind the stage (see Figure 8), accounting for 50% of the hall's volume, with remotely controlled doors for acoustical adjustment.

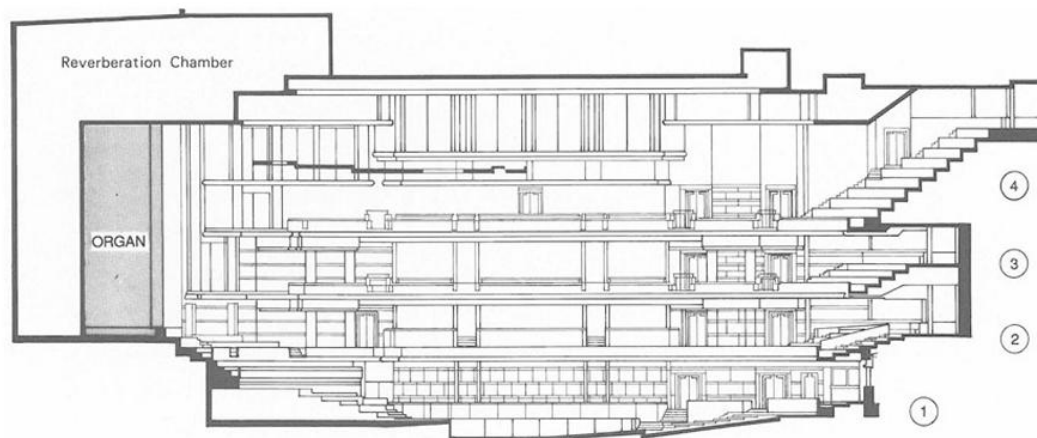


Figure 8. Cross section view of Birmingham Symphony Hall (Beranek, 2004)

An adjustable acoustical canopy above the stage and extendable or retractable dampening panels further enhances the hall's ability to match its acoustics to different musical styles (Beranek, 2004).

In Heydar Aliyev Cultural Center Auditorium, a coupled volume solution is implemented to facilitate a multifunction use for the hall; that is used for conference, concert, and opera. The spatial configurations for different purposes are presented in Table 6. In order to provide sufficient speech intelligibility for conference use, a stage tower is designed with removable ceiling panels. By opening these panels, the stage shell allows the stage tower to connect with the main hall. To reduce the excessive reverberation within the hall, the walls and ceiling are covered with materials composed of rock wool with a geotextile facing that exhibit high absorption properties.

Table 6. Acoustical configurations of coupled volume system in Heydar Aliyev Auditorium for different performance types (Sü Gül and Çalışkan, 2010)

Type of Use	Stage Shell position	Orchestra pit status	Coupled room apertures	Orchestra Location
Conference	Lifted and stored in the stage tower	Closed	Closed	Absent
Concert	In place	Closed	Open	On the stage
Opera	Lifted and stored in the stage tower	Open	Partially open	In the pit

A volume behind the initial row of ceiling panels is enclosed to provide energy feedback in the case of concert use (see Figure 9). The variable doors of the coupled volume are open in half for opera and totally closed in the case of speech related activities. The

coupled room has RT of 3.71 s at mid frequencies. The implementation of coupled volume results in an increase in reverberation time to a value exceeding 2.0 s at mid frequencies, optimal for classical music performances. This setup improves low-frequency warmth with a bass ratio of 1.30, which is ideal for a hall of its size.

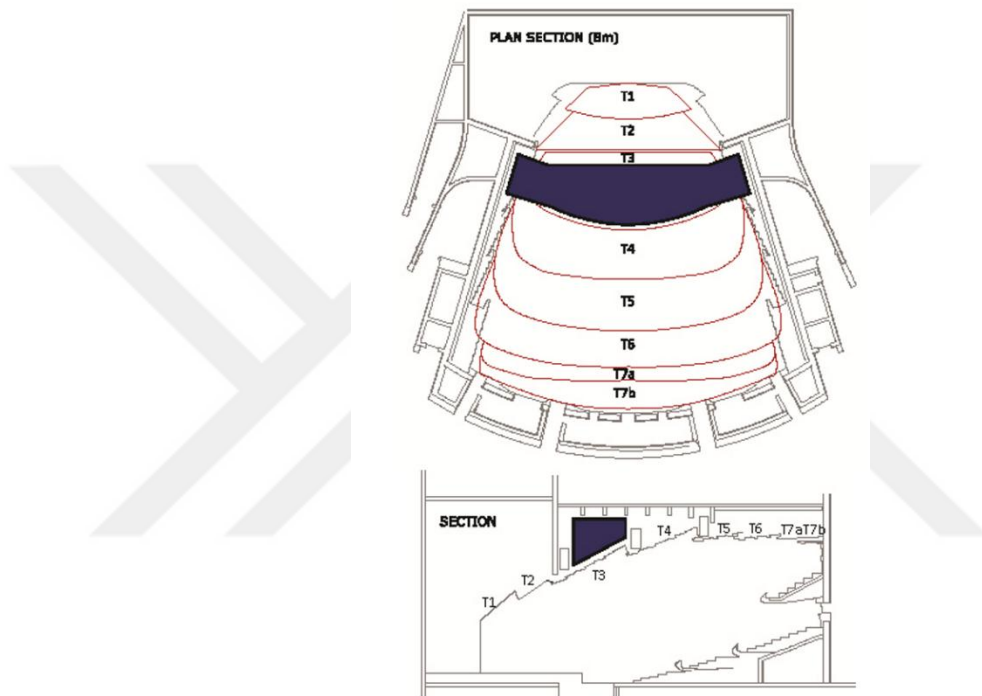


Figure 9. The location of the coupled volume system in Heydar Aliyev Auditorium (Sü Gül and Çalışkan, 2010)

Ermann (2007) studies the differences between a double-sloped decay and a single decay in room acoustics through listening tests. While the respondents can recognize the recordings as having a double slope when there is a substantial diversion from a typical single decay, the study does not confirm that participants prefer recordings with a double-sloped decay. On the other hand, Luizard and Katz (2015) conduct a listening test with

trained listeners to evaluate reverberation changes of coupled spaces for different musical excerpts. According to the study, respondents prefer simple exponential decay for the symphony orchestra, while they prefer double-slope decay for the choir and solo performances.

The implementation of coupled volume techniques require ingenuity and can be costly, so they are often paired with variable absorption solutions. Jesse Jones Performing Arts Hall in Houston, TX employs a combination of variable volume and variable room absorption systems to alter the acoustics of the hall (Hyon and Jeong, 2021). The variable volume system implemented in Jesse Jones Performing Arts Hall is presented in Figure 10.

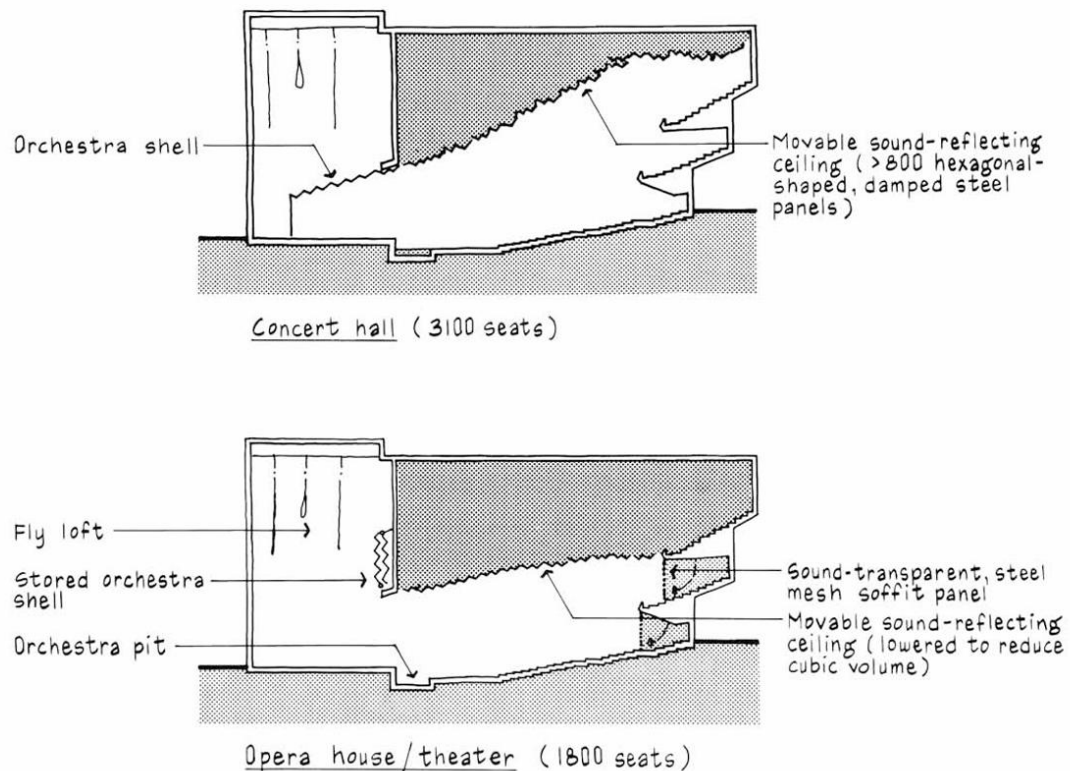


Figure 10. Concert and opera settings of Jesse Jones Hall (Egan, 2007)

Another widely adopted method for adjusting reverberation in venues is the use of a vertically movable ceiling. This approach allows for flexibility during events requiring longer reverberation times, such as performances of Romantic period compositions, by raising the ceiling to its maximum position. Conversely, for chamber music performances, the ceiling can be lowered to maintain a shorter reverberation time. Additionally, adaptable seating systems are employed to convert venues into flat-floor configurations suitable for events like dances and banquets. For example, in a shoebox-shaped hall measuring 20 meters by 40 meters, changing the ceiling height by 3.5 to 4 meters can result in a 20% alteration in reverberation time (Hyon and Jeong, 2021). Milton Keynes Theatre in Buckinghamshire, UK, accommodates a diverse range of performances by utilizing a movable ceiling and adjustable sidewall drapes to modify acoustic conditions. The ceiling features three height configurations (see Figure 11) tailored for different types of performances: the highest level is used for orchestral music. This setting provides a RT of 1.60 s. The medium height setting is used for drama and musicals and provides a RT of 1.25 s. In this ceiling configuration, retractable drapes are implemented to increase speech intelligibility for drama performances, RT ranging between 1.10 s - 1.50 s. In the lowest ceiling height configuration, the upper balcony is covered, decreasing seating to 850 people. This ceiling height setting is used for drama and provides a RT of 1.0 s with extended drapes. The ceiling height varies by 10 meters to suit each performance type

(Barron, 2009; Orlowski, 1999).

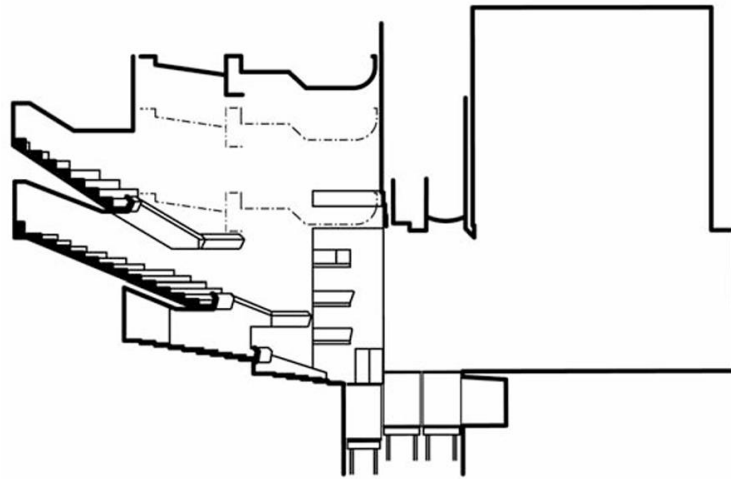


Figure 11. Cross section of Milton Keynes Theater; showing low, medium and high ceiling configurations for drama, lyric and chamber music, respectively (Barron, 2009)

Variable Absorption

The properties of interior finishing materials play a crucial role in determining the reverberation time. Variable absorption systems involve the integration of temporary sound reflective and absorptive surfaces to adjust the acoustical properties of the venue in accordance with the performance being conducted. These components mostly consist of panels that can be operated to alternate between sound reflective and absorptive surfaces. Another approach involves covering reflective wall sections with sound absorbing curtains, or hiding absorptive wall sections with thick, impermeable curtains to produce reflective surfaces (Kuttruff 2017). The sound absorptive surfaces mostly employ porous or fibrous materials and can be optimized for absorption enhancement in higher frequencies depending on various material characteristics such as fiber length, porosity,

thickness, or density (Pereira et. al., 2021). Most of the existing systems that are used for variable absorption are manually controlled, rendering active utilization challenging and often resulting in neglect. Depending on the concert hall's volume and the location of the variable systems, the variable surfaces can be in different shapes. In small venues, the use of retractable curtains can noticeably affect the acoustic environment across various performances. The folds in curtains improve sound absorption performance at low frequencies by increasing the thickness of the material. The degree of gather is calculated by dividing the curtain's total length by its final length, represented as a percentage. The effectiveness of curtain absorption is highly dependent on the percentage of gather (Long, 2014). Figure 12 illustrates the influence of drapery on the sound absorption coefficients of curtains across 1/1 octave bands.

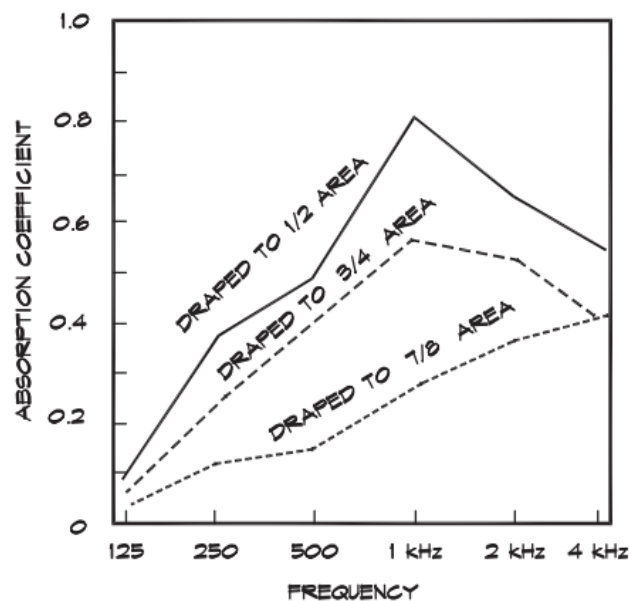


Figure 12. The impact of draping on sound absorption coefficient of curtains, 1/1 octave bands (Mankovsky, 1971, as cited in Long, 2014)

In larger halls, the utilization of only curtains can be costly, therefore, curtains are used as additional sound control equipment or can be positioned strategically to solve certain acoustical issues (Barron, 2009). Long's (2014) study reveals that in order to decrease reverberation time from 2.0 s to 1.5 s, it is necessary to cover approximately one third of the audience area with sound absorbing material. In a 2000 seat hall, this could entail around 370 m² of highly sound absorptive material - a substantial quantity, particularly considering the need for storage when not in use.

Curtains can be employed to dampen loud instruments positioned near walls and to obstruct late reflections, depending on the source placement. Since curtains are commonly implemented as additional systems, they are commonly used in concert halls. Some examples are Chicago Symphony Center in Chicago, USA, New Danish Radio Concert Hall in Copenhagen, Denmark, Long Center's Dell Hall in Austin, TX, Walt Disney Concert Hall in Los Angeles, USA, Helsinki Music Centre Concert Hall in Helsinki, Finland, Soka University Concert Hall in California, USA (Komoda et. al., 2010; Holden, 2016; Toyota et al., 2020).

In the Vanaja Hall in Verkatehdas Cultural Center in Hämeenlinna, Finland, the four double layered curtains extend from the ceiling across the hall's width and serve as the primary tool for adjusting the hall's acoustical environment for different performances as well as rehearsals. Side wall curtains are also utilized and can be individually operated to cover most of the side walls, allowing for precise adjustments. Additionally, the stage features a reflector cloud and areas with variable absorption, while side wall elements can be moved to provide more absorption on the stage when required. Different configurations of the variable system are presented in Figure 13. The variation in reverberation time reaches approximately 40% for mid and high frequencies, and between 15% and 20% for

low frequencies (Möller et. al., 2008).

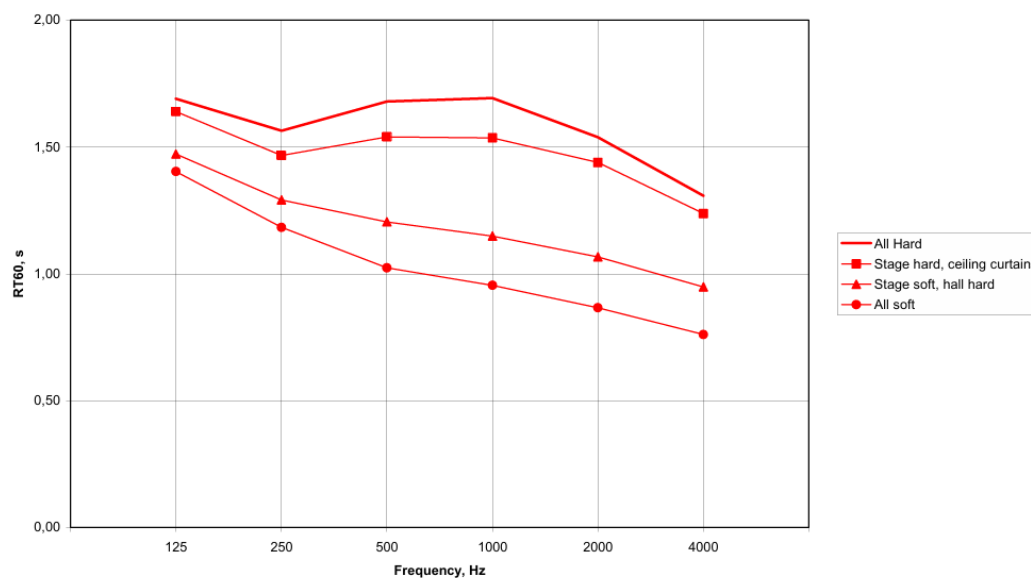


Figure 13. Measured RT of Vanaja Hall with four different configurations of the variable absorption system (Möller et. al., 2008)

Acoustic banners and curtains are typically more effective at absorbing high frequencies compared to low frequencies. To enhance low-frequency sound absorption, it is essential to leave airspace behind the curtains (Long, 2014). Figure 14 illustrates the absorption performance of 600 g/m² wool curtains at varying distances from the wall. While increasing the distance from the wall improves sound absorption, the increase is not linear (Möller, 2017).

Acoustic banners are surfaces designed to serve as reflectors and/or absorbers. They are typically suspended from the ceiling and can be retracted through openings or folded into acoustically sealed boxes when not in use (Barron, 2009).

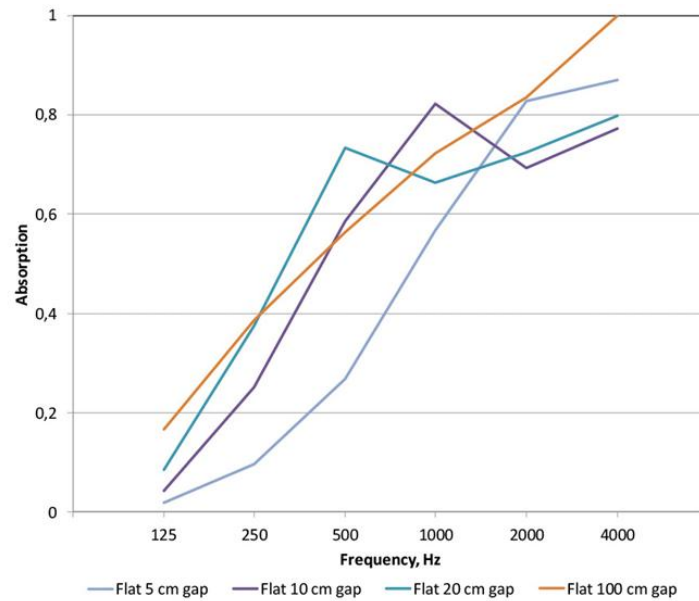


Figure 14. Wool curtain (600 g/m²) application at different distances from wall (Möller, 2017)

As shown in Table 7, double-layered acoustic banners made of wool, placed approximately 15 cm apart and positioned about 38 cm from the wall, have high low-frequency sound absorption coefficients.

Table 7. Sound absorption coefficients for some acoustic drapes and banners effective at low frequencies (Holden, 2016).

Adjustable Acoustic Materials	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
acouStac 3W11, (375 mm from wall)	0.45	0.70	0.90	1.00	1.00	1.00
acouRoll RW12, (375 mm from wall)	0.60	0.80	0.85	0.95	1.00	1.00
Velour, 25 oz., Single 100% gathered, (375 mm from wall)	0.52	0.75	0.79	0.90	0.93	0.93
Velour, 25 os, Single 100% gathered, (125 mm from wall)	0.34	0.73	0.94	0.83	0.90	0.87
Wenger Transform, Velour 22 oz., (101.6 mm Air Space)	0.36	0.79	0.90	1.03	1.05	1.07

Additionally, 10 cm thick glass fiber panels that can move on tracks along the walls or within the reverberant volume can effectively absorb more reverberant energy below 200 Hz (Holden, 2016).

For broadband absorption, specifically designed systems that are effective at managing low frequencies should be implemented. In Oosterpoort in Groningen, Netherlands, 15 cm thick rotating panels with reflective and absorptive sides are installed on the stage walls and the lower side walls of the flat floor area for low frequency absorption. In addition, thick, flexible sound absorbing mats, composed of multiple layers of 10 cm thick sheep wool, which is wrapped in acoustically open fabric, are installed on the ceiling. These mats enhance mid- and high-frequency absorption but reduce low-frequency absorption when placed in an open setting, as observed in reverberation chamber tests. To prevent sound waves from bypassing the material and equalize pressure disparities, it's crucial to close any air gaps. At Oosterpoort, a roll-up system is used for the mats above the ceiling, allowing them to be lowered along the walls through gaps between the ceiling and walls.

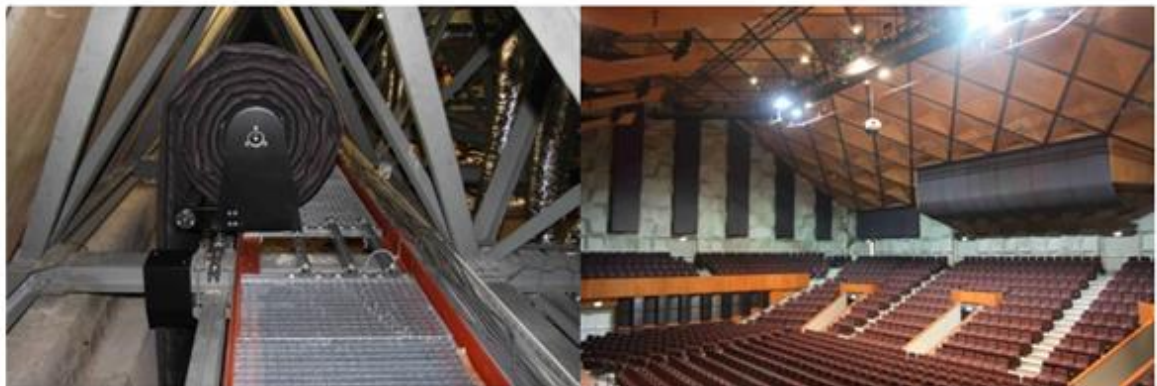


Figure 15. The roll-up sheep wool mats in Oosterpoort Groningen (Vercammen and Lautenbach, 2020)

For the large control room, additional coverage is provided by extending the mats toward the walls. These mats are positioned approximately 2 meters above the floor, allowing reflections from the walls above the audience area (Vercammen and Lautenbach, 2020). Membrane absorbers present specialized solutions for absorbing low frequencies, as highlighted by Larsen et al. (2005). Hoffman (2004) studies the implementation of storage pockets and acoustical banners that act as Helmholtz resonators in Lowe San Nam Hall at the LG Arts Center in Seoul, Korea (as cited in Chiang et al., 2009). These innovative approaches provide tailored solutions for addressing low-frequency challenges in acoustical design.

Another common variable absorption method is installing operable mineral wool-filled variable elements on the side walls. When closed, these elements act as scattering/diffusing elements, and when opened, they function as absorbers. Mineral wool typically exhibits almost full absorption at high frequencies however, if the thickness of the material is increased, absorption performance at lower frequencies can be increased while the absorption at high frequencies remains constant. For example, by doubling the material thickness, the lower limit frequency decreases from approximately 1000 Hz for 30 mm thick mineral wool, to 500 Hz for 50 mm thick mineral wool, and roughly to 250 Hz for 100 mm thick mineral wool (Möller, 2017).

The Fitzwilliam College Auditorium, in Cambridge, UK has a volume of 2047 m³ and seats 250 people. As located in a college campus, the shoe-box shaped venue is designed to accommodate a diverse range of events, including concerts, drama and dance performances, conferences, and exhibitions. To successfully host such diverse performances, the concert hall is equipped with operable sound absorptive panels on the upper side walls.



Figure 16. Fitzwilliam College Auditorium, music configuration; panels opened (Aretz and Orlowski, 2009)

When these panels are arranged for musical events, they expose interior surfaces composed of hard and reflective materials such as concrete and brickwork (Figure 16), for enhancing the acoustic quality for a wide range of musical performances. In speech configuration (Figure 17), panels are closed which increases the sound absorption, decreasing the reverberation time (Aretz and Orlowski, 2009).



Figure 17. Fitzwilliam College Auditorium, speech configuration; panels closed

In Figure 18, the average RT and G values over 1/1 octave bands are presented for open and closed states of the variable panel system in Fitzwilliam College Auditorium. The difference in RT values at 500 Hz between open and closed states is approximately 0.2 s, which is sufficient for speech to chamber music performances. However, the RT values at 65 Hz and 125 Hz are not affected by the panels due to the limited thickness of the sound absorbing material.

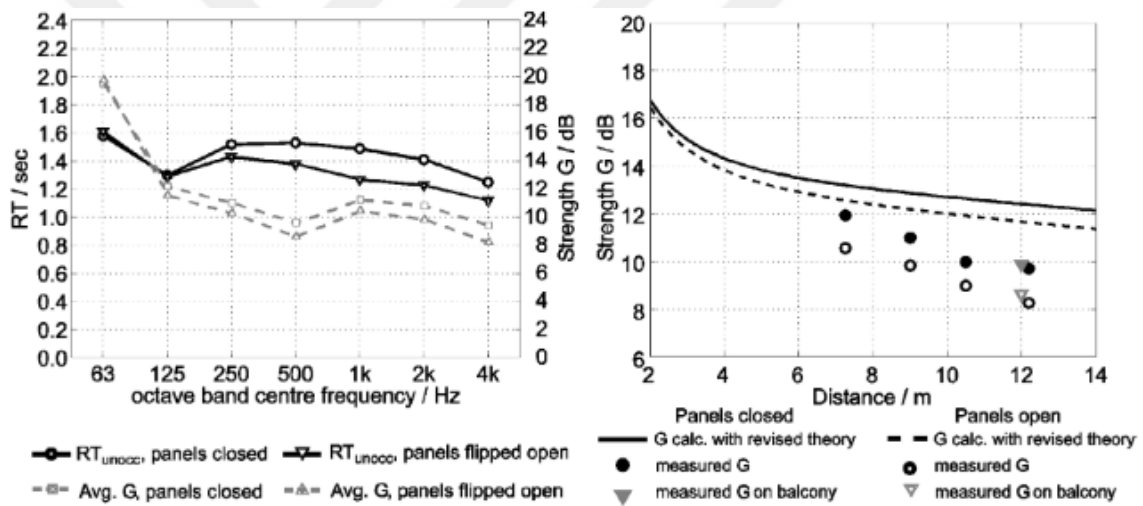


Figure 18. Average unoccupied octave band RT and strength for the panel system in Fitzwilliam College Auditorium; open and closed states (left) and comparison between calculated and measured mid-frequency strength with distance (right)

Ortiz (2016) studies the acoustics of Auditorio 400, located at the ‘Museo Reina Sofia’ in Madrid. The venue is utilized for a wide range of performances, spanning from avant-garde and contemporary music to electronic and computer-based music. Additionally, the hall hosts lectures, conferences, and awards ceremonies, necessitating clarity and speech

intelligibility to accommodate various events. To improve speech intelligibility and reduce high reverberation in the hall, half of the existing reflective panels are replaced with sound absorbing panels, measuring 1 meter by 0.6 meters (See Figure 19). The panels feature multiple cavity resonators filled with sound absorptive material, effective on wide range of frequencies. The panels are equipped with movable poly-cylinder diffusers on rails, allowing for flexible adjustments in absorption levels of maximum, medium, or minimum absorption rates. To ensure uniform sound distribution across the hall, elliptically shaped acoustic reflectors are installed on the ceiling. RT differences for different panel arrangements for the panel system is presented in Figure 19. These reflectors come in two sizes: larger ellipses measuring 14.5 meters by 2 meters and smaller ones measuring 7.5 meters by 2 meters, both suspended from the ceiling to optimize acoustic conditions.

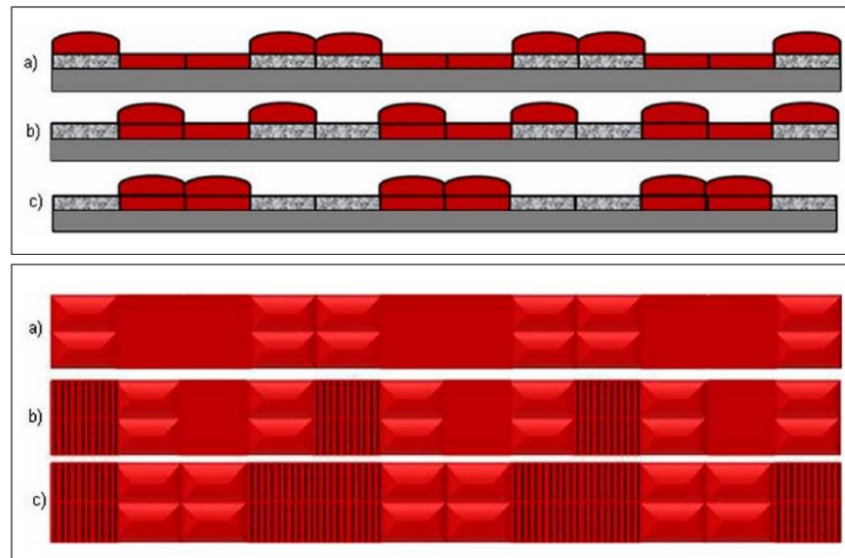


Figure 19. Section and front views for the panel system in Museo Reina Sophia, in Madrid, Spain; (a) Minimum absorption setting, (b) Medium absorption setting, (c)

Maximum absorption setting (Ortiz, 2016)

Five different arrangement settings are included in the study which are minimal absorption with reflectors placed at the highest position (Arrangement 1), moderate absorption with reflectors placed at the highest position (Arrangement 2), moderate absorption with reflectors placed at the lowest position (Arrangement 3), maximum absorption with reflectors placed at the highest position (Arrangement 4) and Maximum absorption with reflectors placed at the lowest position (Arrangement 5) (Ortiz, 2016).

Arrangement 1 offers T30 value of 1.86 s at mid frequencies which is suitable for music performances and Arrangement 5 offers T30 value of 1.12 s, which would be the best for speech (Ortiz, 2016).

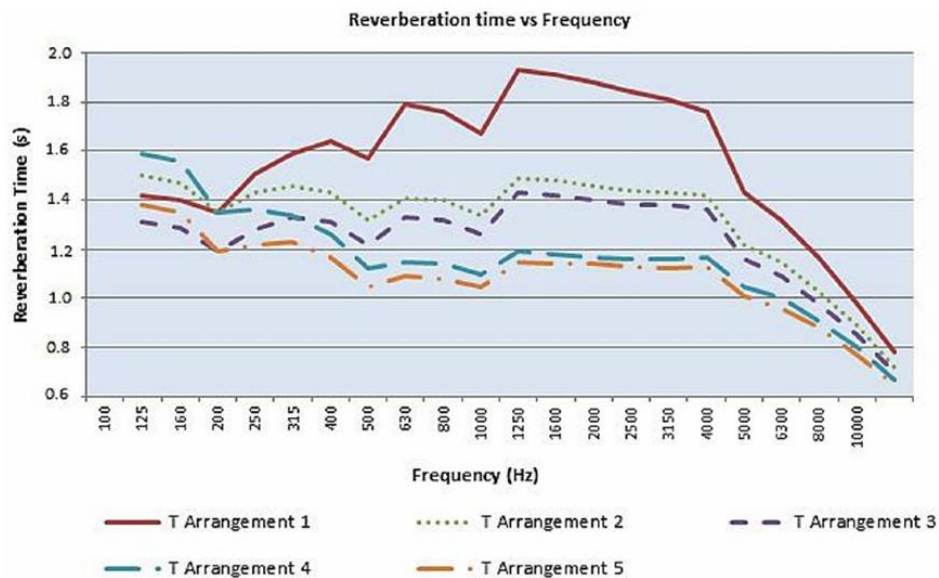


Figure 20. RT differences for different panel arrangements (1-5) for the panel system Museo Reina Sophia, in Madrid, Spain (Ortiz, 2016)

Some other concert halls with variable panel systems include the Calzedonia Auditorium,

Espace de Projection in IRCAM in Paris, France, Le Serre Hall in Villa Erba Convention Center in Como, Italy, and Symphony Hall in Birmingham, UK (Cairoli 2018; Shtrepi et al., 2016; Cairoli, 2021). These systems are particularly common in venues hosting both speech and music events. For instance, Dronningesalen Hall at the Royal Library in Copenhagen, Denmark (Figure 21), uses movable panels on side walls and folded curtains and roller blinds on end walls to adjust sound absorption levels. This allows for varying the reverberation time from 1.1 s for speech events up to 1.8 s for music performances (Figure 22) (Gade, 2014).

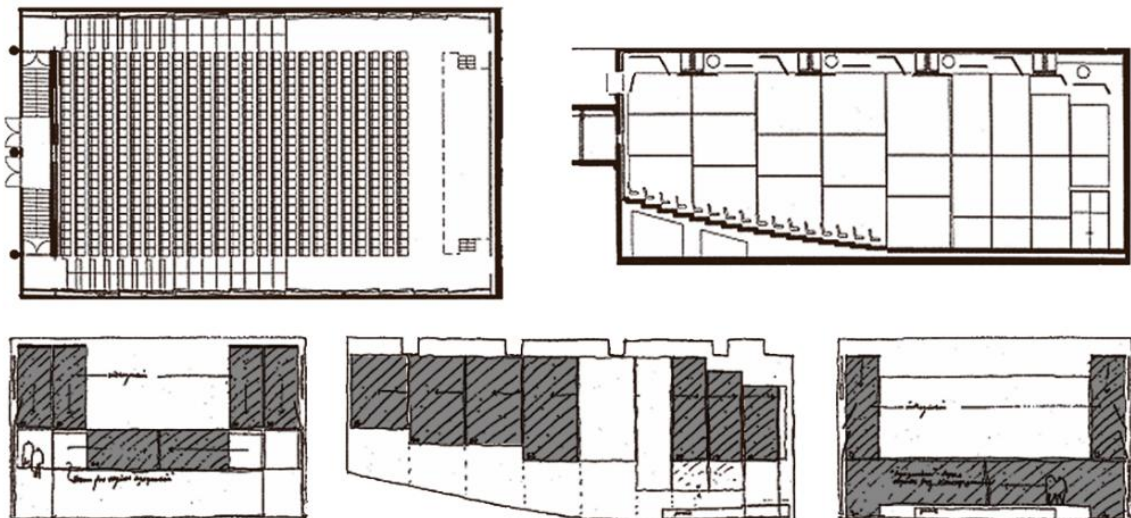


Figure 21. Plan, section view and wall elevations with variable panel system of Dronningesalen Hall at the Royal Library in Copenhagen, Denmark (Gade, 2014)

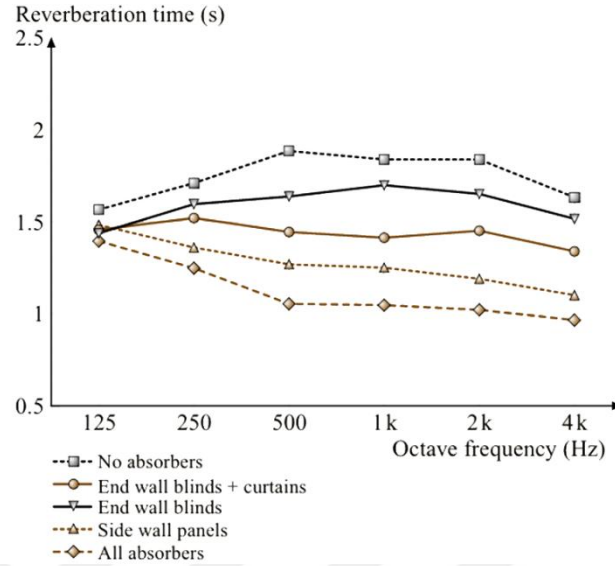


Figure 22. RT values for different configurations of the panel system in Dronningesalen in The Royal Library, Copenhagen, Denmark (Gade, 2014)

Variable panel systems can also feature rotatable surfaces that alternate between reflective and sound-absorptive materials. However, these systems require additional space where the panels can be operated (Figure 23).

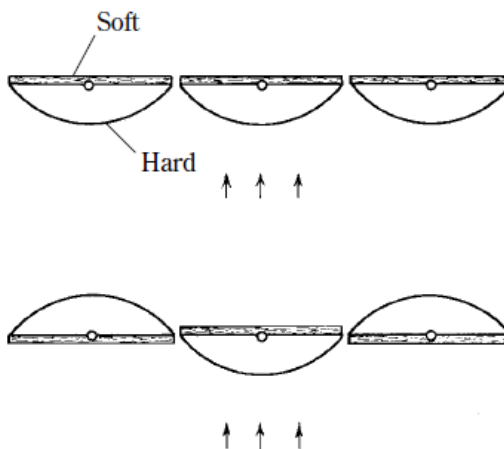


Figure 23. Rotatable panels with reflective (hard) and sound absorptive properties (soft) (Everest and Pohlmann, 2009)

Shtrepi et al. (2016) conduct a study that evaluates objective and subjective data of a variable concert hall, the Espace de Projection, at the Institut de Recherche et Coordination Acoustique/Musique (IRCAM). The acoustical design of the hall includes an adjustable ceiling with height configurations from 2,2 m to 12 m, and 172 adjustable panels, with reflective, diffusive, and absorptive acoustic properties, which allow for the adjustment of six distinct acoustic conditions. This versatility enables modification of RT across a spectrum ranging from 0.4 s to 4 s at 1000 Hz. For the study, the acoustical effect of one wall on the sound field is investigated. The wall is configured with two main setups: one featuring a reflective setting and the other a reflective/diffusive setting. The study reveals that the parameters such as EDT and T30 are highly affected by the changes in acoustic scattering. Additionally, listeners can perceive the impact of these surfaces on the sound field from distances as far as 2.15 meters from the wall.

In conclusion, variable acoustic systems significantly enhance the versatility and functionality of concert halls. By adjustable elements such as panels, curtains, and banners, the acoustic environment can be tuned to match the specific requirements of different musical genres and events. This adaptability ensures that the acoustics are optimal for each performance, improving sound clarity, balance, and overall listener and musician acoustical experience. Despite their advantages, implementing variable acoustic systems presents certain challenges. The design and installation require an in-depth understanding of acoustic requirements for the performance types hosted in the venue to ensure that adjustments do not introduce unwanted acoustical conditions. Furthermore, the operational complexity necessitates trained personnel to manage the variable system effectively. However, these challenges are outweighed by the benefits, as evidenced by the successful application of such systems in prominent venues like Dewan Philharmonic

Petronas and the Hong Kong Academy for Performing Arts. As technology continues to advance, variable acoustic systems will play an increasingly vital role in concert hall design, offering unparalleled adaptability and acoustic excellence.

2.5. Precedent Cases: Concert Halls with Variable Systems

As revealed by the conducted literature review, passive variable implementations showcase two distinct types of applications. The preceding application of passive variable systems has been oriented towards repurposing venues from speech to musical functions. However, recently, the focus of variable acoustics is on establishing adaptable musical environments for various types of musical performances (Beranek, 2004). The architectural attributes of selected exemplary venues worldwide, along with details of the installed variable systems, are summarized in Table 9 at the end of this section.

One successful example of halls that adapts variable absorption for speech-music configurations, is Aula Magna Hall in Caracas, Venezuela (Beranek, 2004). Within this hall, reflective panels are suspended from the ceiling with detachable glass fiber blankets to adjust the reverberation time for speech and music events (see Figure 24). Also, another purpose of the system is to solve the non-uniform sound energy distribution caused by the fan shape floor plan and the domed ceiling. When glass fiber blankets are attached to reflective panels (257 m² of coverage area), the RT_{mid} is 1.35 s which is more suitable for speech, and when the sound absorber blankets are detached, the hall has a RT_{mid} of 1.70 s which is suitable for music performances that require high clarity such as piano, modern music and chamber music (Beranek, 2004).



Figure 24. The variable absorption system in Aula Magna, Caracas, Venezuela
(Villanueva, 2001)

In Dewan Filharmonik Petronas Hall in Kuala Lumpur, Malaysia (Figure 25), a motor operated acoustical ceiling is installed. Different performance settings of the concert hall are presented in Table 8 with different RT_{mid} values. In the lowest setting, the ceiling height is 17 m with the volume of $15,386 \text{ m}^3$, the venue is more suitable for chamber music. In the highest setting, the ceiling height is 23 m with the volume of $20,792 \text{ m}^3$, it is possible to achieve longer reverberation time suitable for Romantic music. In addition, the concert hall incorporates operable sound absorber panels on the side walls (Husin, Mustapa, & Kamal, 2004), which can further lower the reverberation time for speech activities (Beranek, 2004). The RT values for different settings of the motorized ceiling system in Dewan Filharmonik Petronas Hall in Kuala Lumpur, Malaysia are presented in Table 8.

Table 8. Suitable performances for different settings of the motorized ceiling system in Dewan Filharmonik Petronas Hall in Kuala Lumpur, Malaysia; low, half and high

Performance Type	Ceiling height	Absorption	RT _{mid}
Romantic music	23 m	Min. absorption	2,40 s
Chamber music	20 m	Max. absorption	1,65 s
Symphonic music	20 m	Min. absorption	1,96 s
Speech, modern music	17 m	Max. absorption	1,46 s

In highest ceiling setting without absorption, the hall exhibits a reverberation time of 2.40 s at mid-frequencies. In the half ceiling height setting with maximum absorption, the reverberation time at mid-frequencies is adjusted to 1.65 s for chamber music, and without absorption, it is 1.96 s which is suitable for symphonic music. Conversely, when the ceiling is in the lowest setting with maximum sound absorption, the reverberation time can be further adjusted to 1.46 s, rendering it suitable for speech and modern music.



Figure 25. Symphonic music setting, Dewan Philharmonic Petronas (photo by The City

List)

Orchard Hall in Dartford, UK (see Figure 26) functions as a versatile venue, accommodating conferences, trade shows, dance performances, sporting events and music performances (Lord and Templeton, 1986). Given its diverse usage, the hall incorporates a motorized floor system that adjusts volume and absorption with removable seating. By raising and lowering floor sections, a 'flat floor' setup is provided for dance events and the slotted ceiling can be opened / closed to specific needs (Figure 27). The ceiling disperses sound laterally, enhancing spatial impression and overall acoustics. During music performances, ceiling panels are opened which merge the roof void with the auditorium, creating acoustic transparency. In this setting, RT_{mid} of 1.50 s is achieved. For speech and drama events, the reflective ceiling is provided by closing the ceiling panels for a RT_{mid} of 1.20 s. (Lord and Templeton, 1986).



Figure 26. View from the stage in Orchard Hall (Lord and Templeton, 1986)

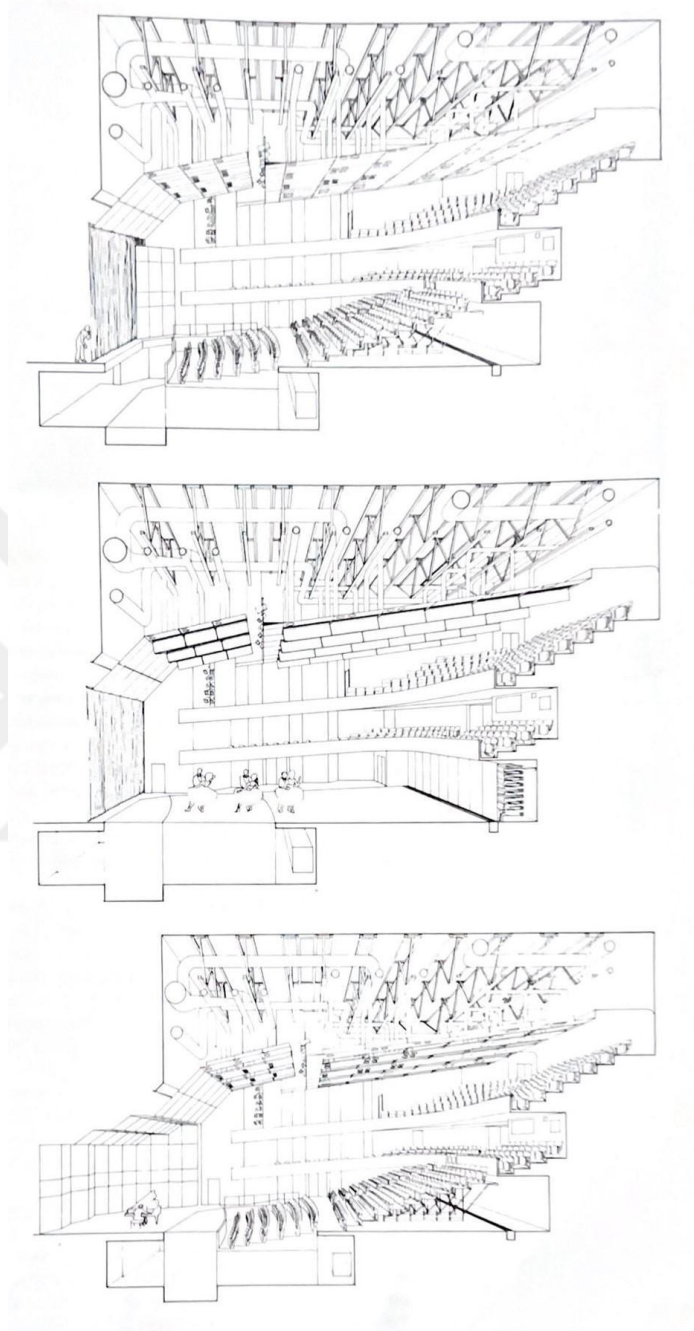


Figure 27. Different ceiling configurations for various performance types in Orchard Hall; drama, dance and music (top to bottom) (Lord and Templeton, 1986)

When it comes to applications of passive absorption systems for various musical performance types, volume plays a crucial role in determining the optimal placement of such systems and their quantity. In large concert halls with volume over 20,000 m³, such as Roy Thompson in London, UK and Louise M. Davies Hall in San Francisco, USA, the substantial distance of the side walls from the stage poses a challenge, resulting in a loss of acoustical intimacy. The volume of 24,070 m³ of Louise M. Davies Hall provides a long RT of 2.20 s, which makes the venue suitable for organ music. For performances that require shorter reverberation, reflective suspended banners are strategically installed above the woodwind and string sections (Figure 28). By raising or lowering these banners, different quantities of absorptive material is exposed, thereby adjusting the acoustic properties of the hall to achieve different reverberation times, ranging between 1.50 s to 2.20 s. The hall accommodates large choral and orchestral performances like Romantic period requiring longer reverberation times to smaller-scale compositions that benefit from shorter reverberation (Lord and Templeton, 1986; Beranek, 2004).

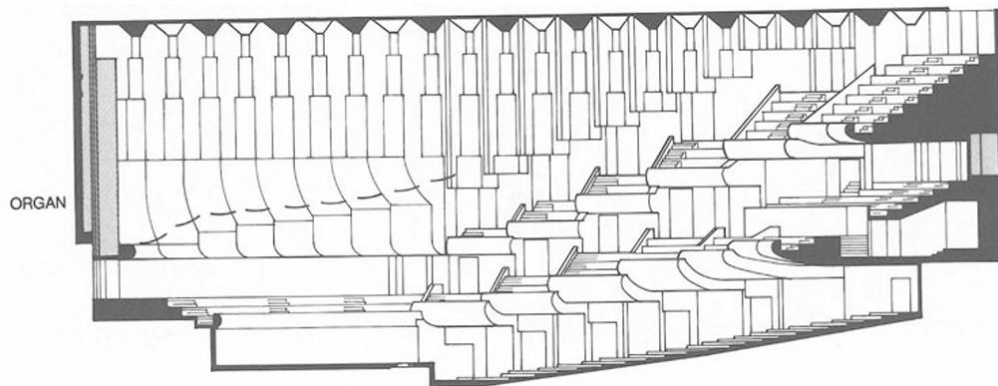


Figure 28. Longitudinal section view of Louise M. Davies Symphony Hall (Beranek, 2004)

In Roy Thomson Hall (Figure 29), fire-treated wool banners with coverage area of 1200 m² are lowered from slots in the ceiling to reduce the reverberation time from 2.0 s to 1.5 s at mid-frequencies for Baroque and modern performances (Lord and Templeton, 1986).



Figure 29. The interior of Roy Thomson Hall, suspended ceiling discs (photo by Peter Sellar)

In other halls, mostly smaller in size, operable panels are sufficient to adjust the reverberation time for various performances.

The hall for the Hong Kong Academy for Performing Arts in Hong Kong serves as a notable case of successful variable absorption implementation in a smaller hall with volume lower than 10,000 m³. Thin and porous material in the lower regions of the side walls, extending up to 3 m high, controls flutter echoes. Above this height, a system of rotatable panels is mounted, offering open, half-open, and open configurations (Figure

30). The fully open state represents the most sound-absorbing state. The RT is adjusted to 1.70 s during rehearsals for a chamber orchestra and is adjusted to 2.20 s for recording sessions involving a large orchestra (Figure 31) (Lord and Templeton, 1986).

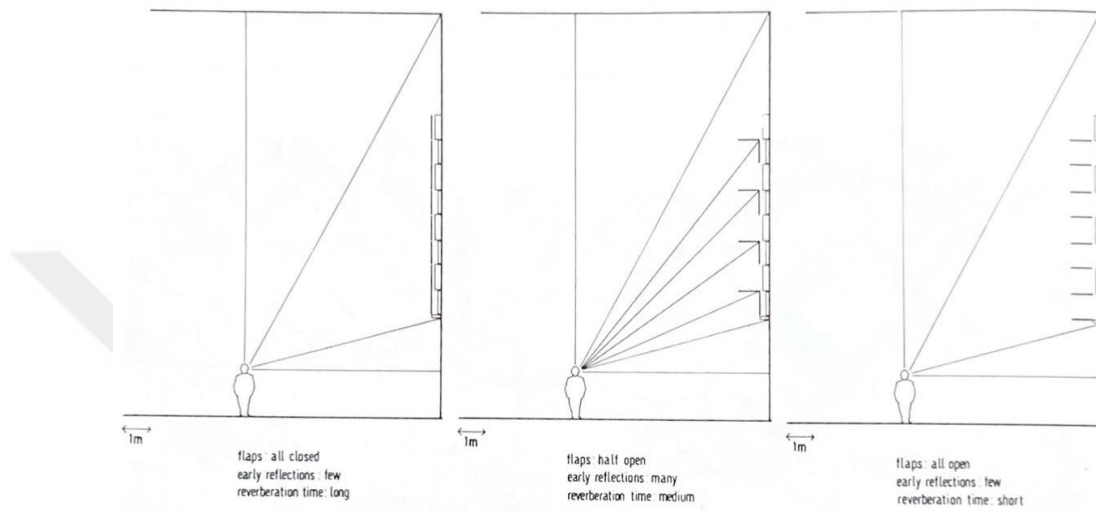


Figure 30. The variable absorption system in Hong Kong Academy (Lord and Templeton, 1986)



Figure 31. Large orchestra setting of the hall for the Hong Kong Academy for Performing Arts

Table 9. Acoustical and architectural features of well-known concert halls with variable systems in the world; reverberation times (s), volume and number of seats

Concert Halls	Variable Elements	RT _{mid} (s)	Volume (m ³)	Seat
The Orchard Hall (RT _{mid})	Operable reflective panels on ceiling, closed	1,20	-	1025
The Orchard Hall (RT _{mid})	Operable reflective panels on ceiling, folded	1,50		
Aula Magna	Panels (without glass fiber blankets, occupied)	1,70	24,920	2660
Aula Magna	Panels (with glass fiber blankets, occupied)	1,35		
Dewan Filharmonik Petronas	Panels (Half volume; No absorption)	1,96	17,860	850
Dewan Filharmonik Petronas	Panels (Half volume; 100% absorption)	1,65		
Hong Kong Academy for Performance Arts (RT _{mid})	Rotating flap system	1,70	7,056	100
Hong Kong Academy for Performance Arts (RT _{mid})	Rotating flap system	2,20		
Louise M. Davies Symphony Hall (%100 absorption)	Ceiling banners and draperies	1,50	24,070	2739
Louise M. Davies Symphony Hall (no absorption)	Ceiling banners and draperies	2,20		
Roy Thompson Hall (RT _{mid})	Adjustable, fire-treated felted wool banners on ceiling, lowered	1,50	24,500	2613
Roy Thompson Hall (RT _{mid})	Ceiling banners	2,00		
Bilkent Concert Hall (retracted)	Manually operated wooden doors on side walls	1,66	10,982	707
Bilkent Concert Hall (closed)	Manually operated wooden doors on side walls	1,90		

CHAPTER 3

MATERIALS AND METHODOLOGY

This chapter comprises two main sections. The first section provides a detailed overview of the architectural and the acoustical features of Bilkent Music Hall, selected main case study of this research. The second section elaborates on the methodologies employed to assess and analyze the acoustical performance of the hall. This section is further divided into two sub-sections: objective and subjective acoustical assessment methods. The objective assessment methods include field measurements and acoustical simulations, while the subjective assessment methods include the questionnaire and online survey.

3. 1. Bilkent Music Hall

Bilkent Music Hall in Ankara, Türkiye is selected as the case study of this study. One of the objectives of this study is to examine and address the acoustical concerns related to the existing variable absorption system in the venue.

Bilkent Music Hall was designed in 1994, by Erkut Sahinbas for Faculty of Music and Performing Arts and Bilkent Symphony Orchestra (BSO). Situated within the Faculty of Music and Performing Arts at Bilkent University, the music hall primarily hosts solo performances, symphonic concerts, and rehearsals, along with occasional speech events such as seminars and conferences. It serves as the main venue for special university events and regularly accommodates touring orchestras, as well as music conservatory students and the Bilkent Symphony Orchestra (BSO) (Altun and Sü Gül, 2023).

The hall is trapezoidal in shape, with the side walls angling slightly (2.69°) towards the rear, measuring 34 m in length, 19 m in width, and 17 m in height. It has a seating capacity

of 707, distributed as 447 seats on the ground floor, and 212 and 48 seats on two balcony levels. The total volume of the hall is 10,982 m³. The stage platform, which is 0.9 m above the main floor, has a surface area of 127 m² and can accommodate up to 50 orchestra members. The interior photos of the music hall taken during field tests are presented in Figure 32 (Altun and Sü Gül, 2023).



Figure 32. The acoustical field test setup, view from balconies to the stage (photos by the authors)

The predominant materials employed on the interior consist of plasterboard and wood cladding. On lower elevations and sections of the walls, wooden finishes are used in the form of boards on battens. According to the architectural drawings obtained from the Construction Works Department of Bilkent University (see Appendix C), the ground floor rear wall is composed of several layers, from the inside to the outside: wood-veneered board panels, a 2 cm gypsum board, a 10 cm of rock wool, and an 8.5 cm brick wall. The concert hall is separated by a 50 cm air gap from the building's inner wall (Şahin, 1995). The side walls on the ground floor, from the inside to the outside, consist of a 3 cm thick travertine veneer finish, a 3 cm plaster layer, a 13.5 cm brick layer, a 10 cm of rock wool, and a 19 cm brick wall. The floor is constructed with, from the inside to the outside, wooden parquet finishing, a 10 cm floating screed strip, a bitumen felt, a 10 cm of rock wool, and a 40 cm hollow core slab.

On the second floor, from the inside to the outside, adjustable wooden panels are mounted on 3 cm wooden laths, followed by a 2.5 cm air space, a 10 cm of rock wool, and a 19 cm brick wall. The initial design includes three rows of operable/retractable wooden doors on the side walls, backed with fabric, to create a flexible acoustic environment. These wooden doors are 2 cm thick and are manually operated, as there is no automated mechanical system for opening and closing them. Consequently, it is not very practical to frequently adjust the doors, so they are generally kept in one position. They are usually maintained in either their fully retracted (100% sound absorbing) or half-retracted (50% sound absorbing) states. The different states of the panels - retracted, half-retracted, and closed - are illustrated in Figure 33.

Preliminary discussions with BSO members have highlighted a lack of awareness regarding the optimal utilization of the panel system for different performance types. They

have also indicated their dissatisfaction with the current panel system, noting the need to retune their instruments when transitioning to different venues. Additionally, the manual operation of the system poses practical challenges, preventing its proper integration between performances. Consequently, the acoustical benefits of the system remain largely overlooked. Thus, this study aims to unveil the acoustical issues associated with the wooden doors, and possible other acoustical issues in relation to the materials and address the gap concerning the intended purpose of the wooden doors for different musical ensembles.



Figure 33. Retracted, half-retracted and closed states of the variable absorption system in Bilkent Music Hall, respectively (photos by the authors)

Following sections present the methodological approach employed throughout the acoustical analysis of Bilkent Music Hall. Firstly, the procedures for evaluating objective parameters, including acoustical field measurements and acoustical simulations, are detailed. The setup and equipment used for the field tests are described. Then, acoustical simulations that determine the acoustical coefficients of the interior materials are presented. Subsequently, the methods for assessing subjective parameters, namely questionnaires and online surveys, are outlined. The design and implementation of the questionnaire survey, which gathers qualitative insights from musicians regarding their acoustical experiences in the hall is described. Each method is discussed in the context of relevant standards and previous studies, providing a comprehensive framework for the research. This structured approach ensures that the findings are robust, reliable, and comparable to other studies in the field.

3.2. Objective Acoustical Assessment of Bilkent Music Hall

3.2.1. Field Tests

Acoustical field tests of Bilkent Music Hall were carried out in accordance with ISO 3382-1 standards on August 3, 2022. These tests, conducted in the unoccupied hall, aimed to assess the hall's acoustical properties by examining two conditions of the side doors: retracted and closed. A series of room impulse responses (RIR) are collected for two separate sound sources (S1 and S2 positioned on stage) and 14 receiver locations (R) spread across the hall, including the stage, main parterre, and first balcony (see Figure 34). The equipment used for these measurements include:

- B&K-Type2250-A hand-held analyser,
- B&K-Type4292-L standard dodecahedron omni-directional sound source and,
- B&K-Type2734-A power amplifier
- DIRAC software

Figures 35 and 36 illustrate the measurement setup and provide photos taken during the measurements from two receiver positions, respectively (Altun and Sü Gül, 2023). Room impulse responses (RIR) are collected for both states of the side doors and are analysed by DIRAC room acoustics software v6.0.6470. Background noise levels during the measurements were maintained below 20 dBA in the unoccupied hall. The tests are conducted under specific room conditions, with an average indoor temperature of 30°C and humidity at 21%. In order to simulate a typical indoor environment that reflects the hall's usual occupied state under HVAC systems, the collected measurements are converted to room conditions of 22°C and 60% humidity using the DIRAC 1:1 scale model conversion. This adjustment is crucial for creating a realistic scenario for the study. After the post-processing of RIRs, reverberation time (RT), early decay time (EDT) and clarity (C80) metrics are assessed in 1/1 octave bands for open and closed states of side doors. The results are discussed in the Results section.

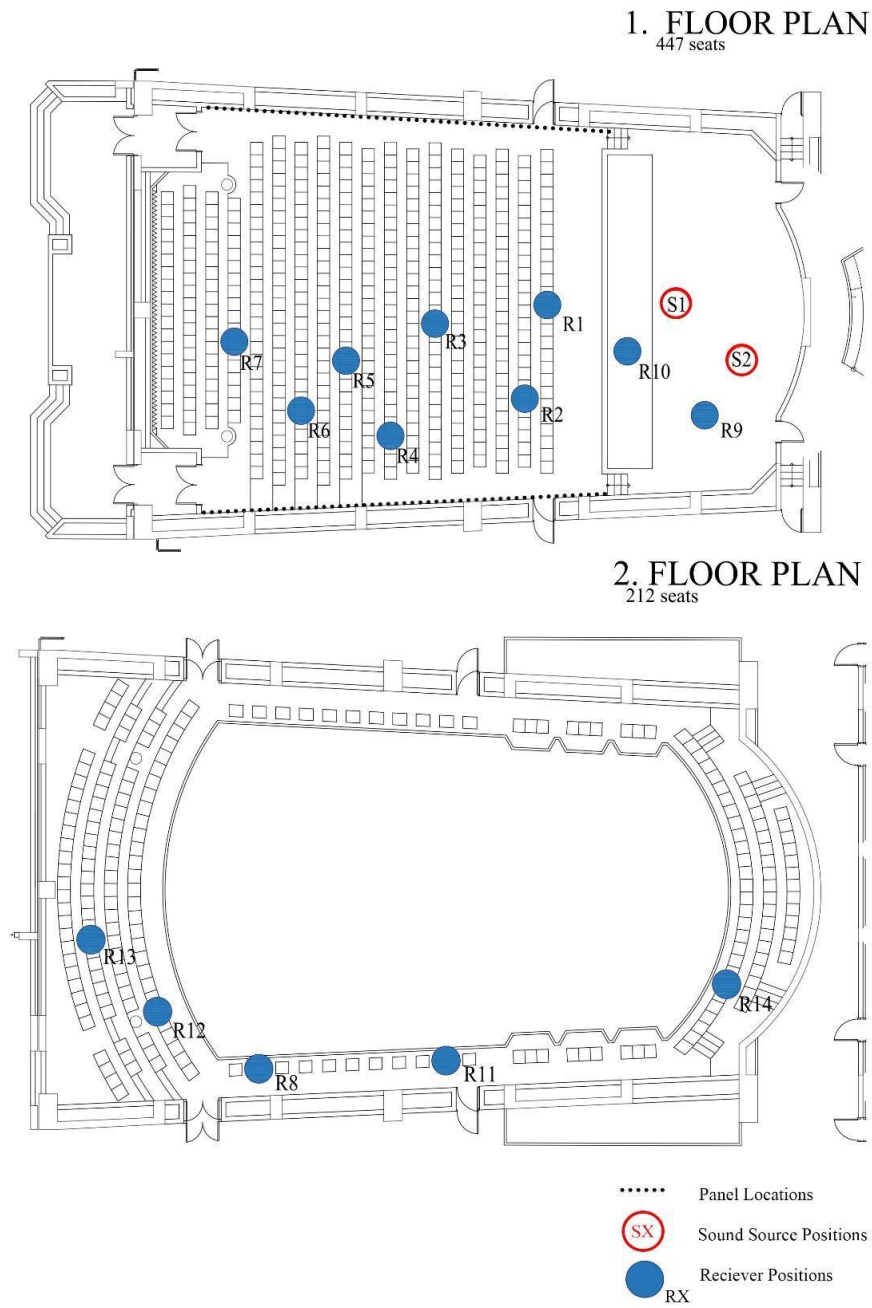


Figure 34. Sound source (S1-S2) and receiver positions (R1-R14) used at in-situ measurements



(a)



(b)



(c)

Figure 35. The acoustical measurement devices, (a) sound level meter, (b) omnidirectional sound source, (c) thermometer



Figure 36. The acoustical field measurement setup

3.2.2. Acoustical Simulations

The acoustical simulations are performed to identify the cause of the excessive low-frequency absorption issue in the hall. Additionally, these simulations aim to assess the impact of existing panel configurations on the acoustic conditions in the presence of an audience and under appropriate environmental conditions, such as the correct humidity level. Another purpose is to develop alternative design proposals to address and solve the identified problem.

Simplified graphical model of Bilkent Music Hall is generated for both retracted and closed states of the doors (variable absorption) and imported into ODEON 17.2 Room Acoustics Software (see Figure 37).

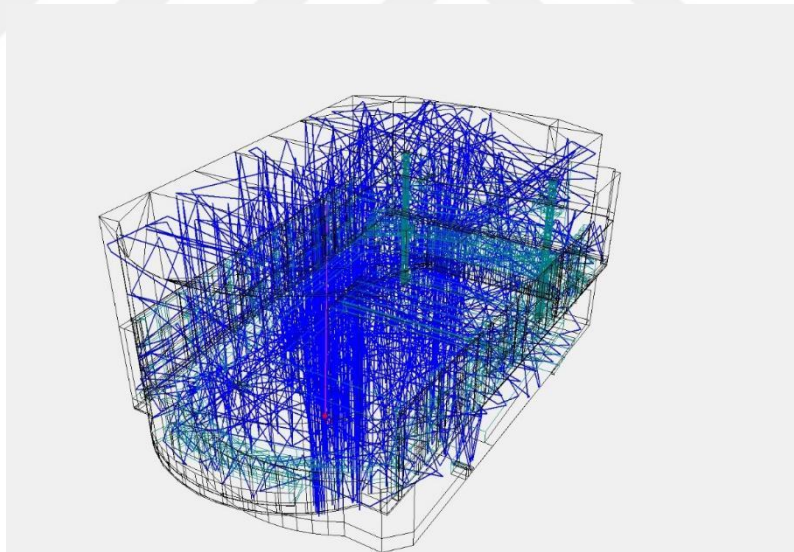


Figure 37. Ray tracing model for Bilkent Music Hall

Initially, the model is tuned for its unoccupied condition by the aid of field test results. The tuning process has continued until the recommended JNDs of 5% (0,1 s) for EDT and T30 are satisfied for optimal alignment with real measurements. The measured and

simulated average T30 values are presented in Figure 38. 3D OpenGL view of the hall from acoustical simulations is presented in Figure 39. The acoustical versatility between the two states has resulted from the modification of the materials exposed on the side walls. Consequently, in the model representing the retracted state, the most influential material is the mineral wool exposed when the panels are folded. On the other hand, in the closed state, it becomes the wooden doors on the side walls. After setting up the model for the current unoccupied state of the hall, occupied conditions are also tested through simulations. Finally, an effective acoustical design intervention is tested through simulations and discussed under Chapter 5.

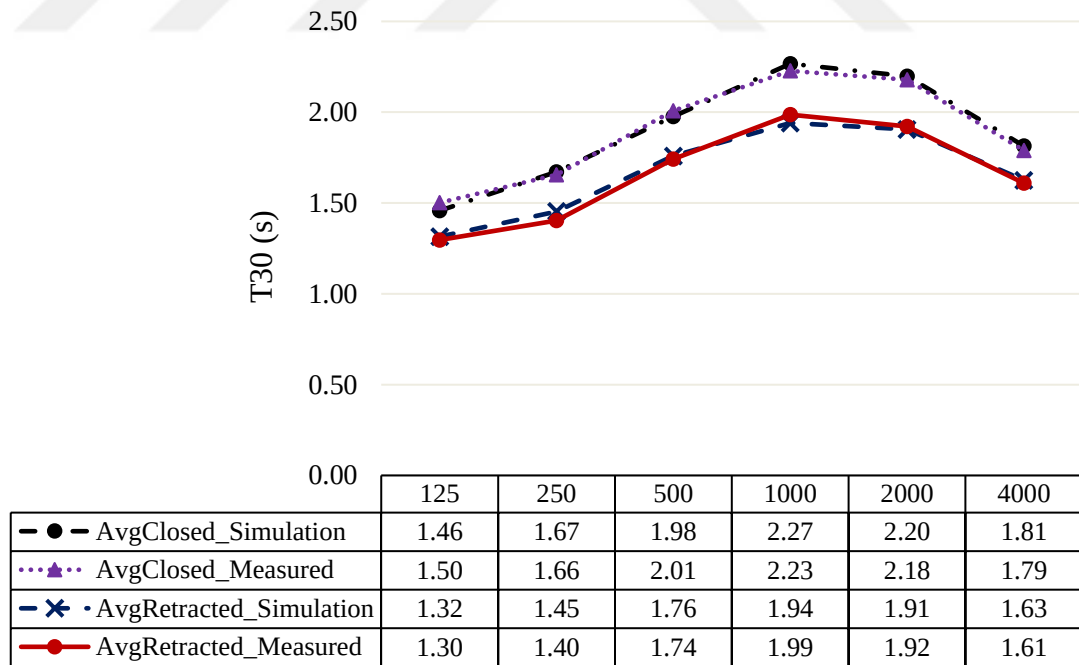


Figure 38. Average T30 (s) values for simulated and measured values for 1/1 octave bands, Source S1, retracted and closed state

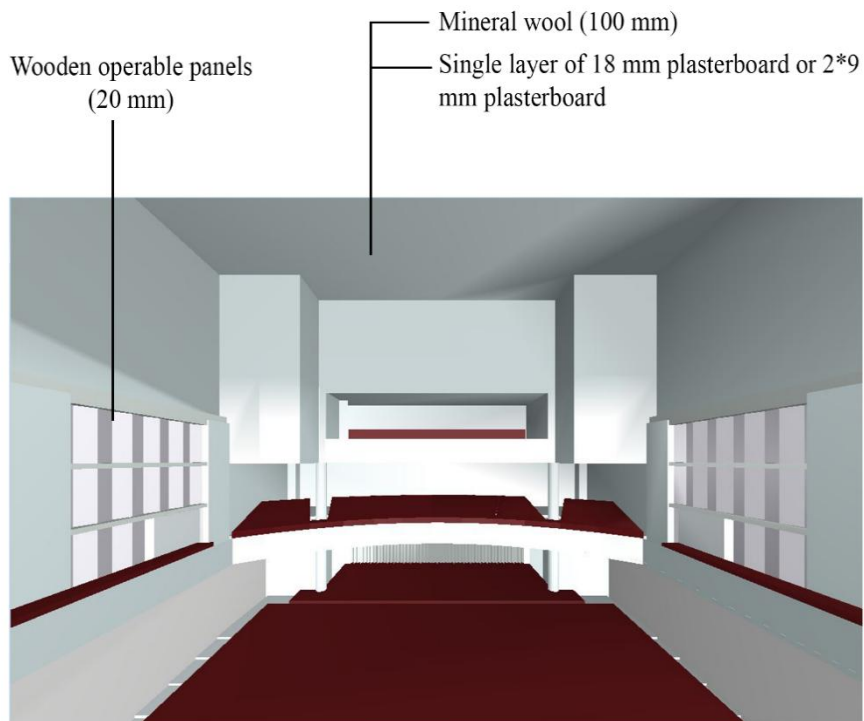
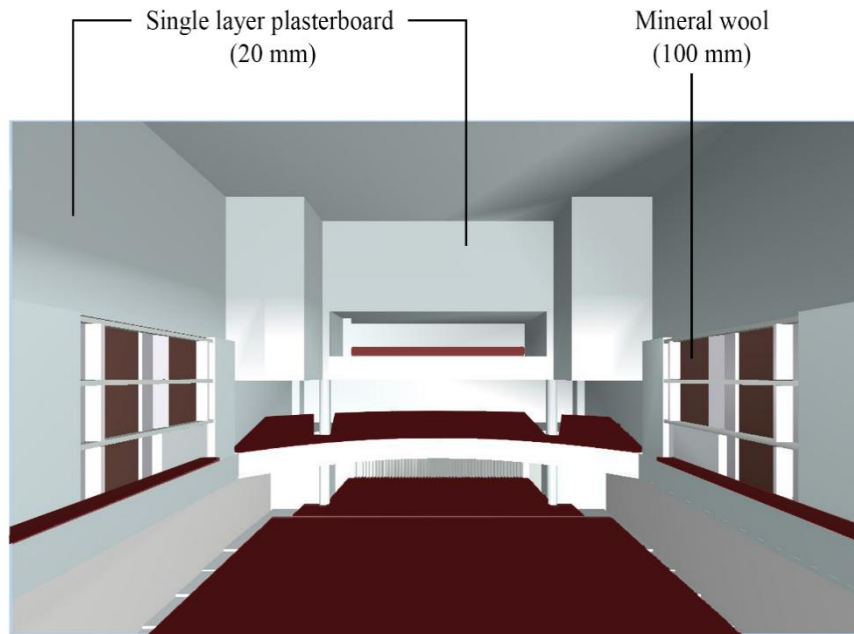


Figure 39. 3D OpenGL- ODEON Room Acoustics simulations view of the hall, retracted (top) and closed (bottom) states of variable doors

3.3. Subjective Acoustical Assessment of Bilkent Music Hall: Questionnaires and Online Survey

After concluding the field test measurements, a questionnaire was administered to musicians to explore the acoustical difficulties encountered by musicians during music performances. The questionnaire was conducted after the rehearsal with 50 members of the Bilkent Symphony Orchestra, all of whom have regular musical experience in the music hall. Subsequently, the same questionnaire was distributed via online survey to 23 students and faculty members of Bilkent University Music Department.

The questionnaire is based on the subjective study carried out by Barron for concert halls (Barron, 1988). The objective is to benefit from the musical expertise of musicians and students with musical training and evaluate the performance of the variable panel system for different instrument and musical piece variations. In the questionnaire, musicians were asked to provide responses to Likert-type questions, incorporating their musical experiences at Bilkent Music Hall after receiving explanations of the necessary terminology.

The questionnaire consists of five sections. The first section gathers data about background information about participants (age, gender, played instrument and musical experience). The second section evaluates the participants' impression of five primary scales which are 'Clarity', 'Reverberance', 'Envelopment', 'Intimacy' and 'Loudness' which are evaluated by a 5-point scale. In the next section, three scales evaluate the acoustical balance between 'treble and mid-frequencies (B_TrebletoMid)', 'bass and mid-frequencies (B_BasstoMid)' and 'singers/soloists and orchestra (B_SingertoOrch)', along with one scale addressing 'background noise (Back_Noise)'. Overall acoustic impression is assessed for 'chamber music (O_Chamber)', 'orchestral music (O_Orchestra)' and

‘orchestral music with choir and vocal accompaniment (O_OrchWithVocal)’ and only these three criteria for the overall acoustic quality are evaluated by using a 7-point scale ranging from ‘Very Poor’ to ‘Excellent’. The final two open-ended questions sought musicians' impressions of the various states of the panel system and asked them to share any additional thoughts.

The responses are analysed using descriptive statistics and t-tests in SPSS (Statistical Package for Social Sciences) and the results are summarized in Chapter 4.

CHAPTER 4

RESULTS

The results section of this study presents a comprehensive analysis of the acoustical performance of Bilkent Music Hall, incorporating both objective measurements and subjective evaluations. Objective field tests are conducted to quantify key acoustical parameters such as T30, EDT, and C80, providing a detailed acoustic profile of the hall. In addition to these measurements, feedback is gathered from musicians, faculty, and students through structured questionnaires and surveys to gain insights into the subjective acoustical experience. This combination of quantitative data and qualitative feedback offer a holistic view of the hall's acoustical characteristics, identifying strengths and areas for improvement. The findings from these assessments are discussed in detail, followed by simulation results aimed at proposing potential solutions to enhance the acoustical environment.

4.1. Field Test Results

Field tests are designed to objectively measure key acoustical parameters that are critical in assessing the overall performance of the concert hall. By systematically evaluating metrics such as T30, EDT and C80, a comprehensive understanding of the hall's acoustics is developed. The data collected provides a foundation for analysing how the hall's design influences sound quality and aids in identifying any acoustical deficiencies. This analysis is crucial for informing any necessary modifications to optimize the acoustic environment for both performers and audiences.

The field measurements are held in reference to ISO 3382-1 standard (ISO, 2009). Measurements are taken using an omni-directional sound source and microphones placed

at various audience positions to capture a comprehensive acoustic profile. The results indicate that T30 values vary across different frequencies, with lower frequencies exhibiting shorter T30 values than mid frequencies, inconsistent with typical results observed in most concert halls worldwide. The EDT measurements, which are crucial for understanding the initial perception of sound decay, show a slightly faster decay rate compared to T30. This discrepancy is primarily due to the short reverberation time at low frequencies. However, in highly rated concert halls, EDT values are generally longer than T30, indicating a more gradual decay of sound. This difference highlights a potential area for improvement in the acoustical design of the hall to better align with the standards of highly rated venues. The C80 values, indicative of the clarity of sound, is within the optimal range for a hall of this size, ensuring that musical detail is preserved. These findings highlight the hall's acoustic shortcomings in providing a satisfactory musical experience, indicating need for improvement at certain frequency range.

In this section, a comprehensive and detailed analysis of the acoustical field tests is presented, comparing the retracted and closed states of the panel system. Figures 40, 41 and 42 present the average values of T30, C80, and EDT, along with their respective minimum and maximum values. The shortest T30 value measured is at 125 Hz with 1.29 s in the retracted state and 1.50 s in the closed state. Conversely, the longest T30 value is measured at 1000 Hz, with 1.97 s in the retracted state and 2.23 s in the closed state.

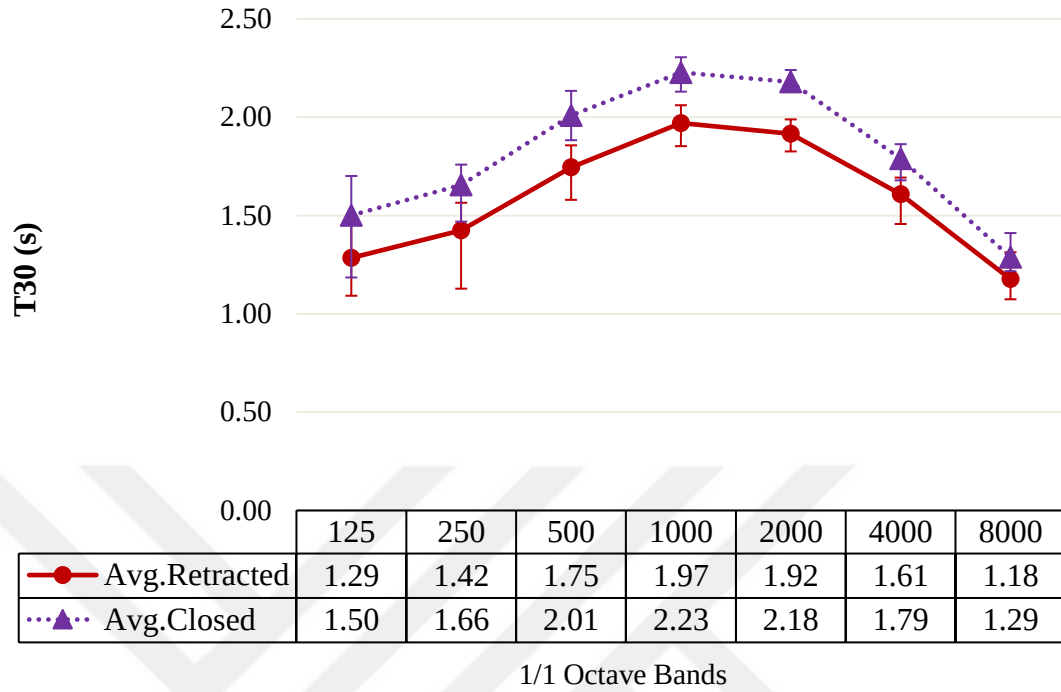


Figure 40. T30 values over octave bands of Bilkent Music Hall for doors retracted and closed states

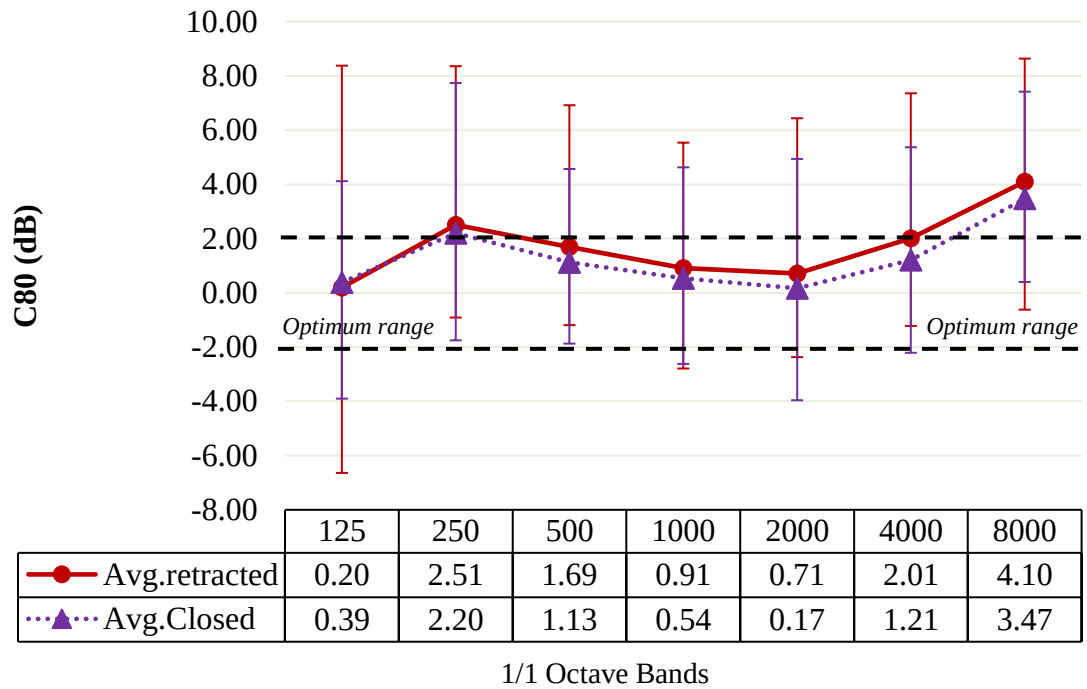


Figure 41. Clarity (C80) values of Bilkent Music Hall for retracted and closed states

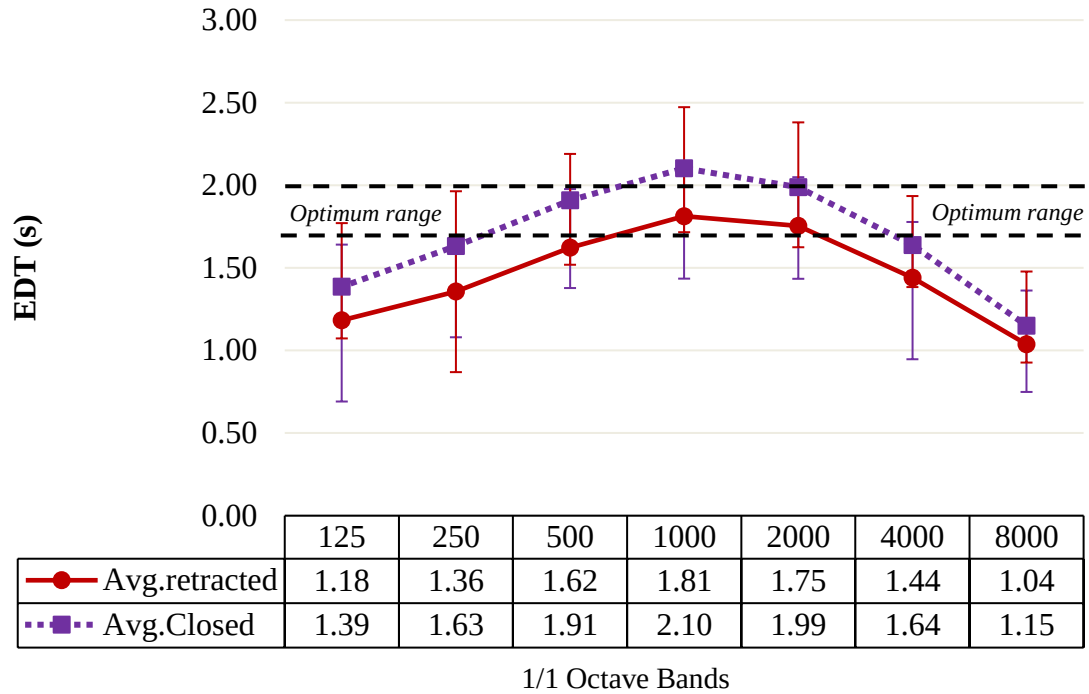


Figure 42. EDT values of Bilkent Music Hall for retracted and closed states

At mid-frequencies, the average T30 value is 1.86 s in the retracted state and 2.12 s in the closed state. At high frequencies, the average T30 value is 1.76 s in the retracted state and 1.98 s in the closed state of the doors. According to the criteria stated in Table 3, the RT in the closed state of doors at mid to high frequencies are in the optimal range specified for a music hall.

The primary acoustical issue identified is excessive bass absorption within the hall. The average T30 at low frequencies measures 1.58 s in the closed state when the hall is unoccupied. Although this is longer than the RT of 1.29 s measured in the retracted state, it is still arguably too short for optimal music conditions. Even with the doors are in the closed state, when the 10 cm thick mineral wool on the side walls is not introduced to the sound field, T30 values remain relatively short for music. It is anticipated that these values

will decrease further when the hall is occupied with musicians and audience during performances.

This inadequacy of the hall's acoustics can be attributed to several factors, notably the insufficient thickness of the wood panels used as interior finish surfaces, the variable doors, which act as bass traps by absorbing low-frequency sounds. However, the observed differences in T30 values between the retracted and closed states demonstrate that the positioning of the panels primarily influence the overall absorption although it does not appear to significantly affect absorption at low frequencies. This conclusion is supported by the nature of the curves presented in Figure 39, which maintain similar trends across different states. Additionally, the contribution of the single layer of plasterboard applied on the upper parts of the interior walls and ceiling should be investigated. Consequently, the study extends to explore other potential factors through acoustical simulations.

The bass ratio (BR), which is the ratio of reverberation times at low frequencies to mid frequencies, is calculated for both retracted and closed state of the doors. The BR for the retracted state is 0.72 while it marginally increases to 0.74 in the closed state. In both configuration of the doors, it is below the ideal range stated in Table 3, which should be above 1.1, therefore, unfavourable for orchestral music.

For different musical performance types, the optimal reverberation time varies and should be specifically analysed for each musical scenario to ensure the best acoustic experience. For classical musical performances, a longer reverberation time at low frequencies is preferred, as it allows the notes to reach their fullness when they are initially produced by the instruments. At mid frequencies, the reverberation time typically decreases but must still stay within an optimal range to ensure clarity and balance.

According to the optimum acoustical criteria for various performance types, Bilkent Music Hall's acoustics at mid frequencies are well-suited for Baroque and Classical Period pieces, which benefit from moderate reverberation times. However, the hall's reverberation time is insufficiently short for Romantic Period music, which typically requires a more extended reverberation to achieve its characteristic richness and depth. Conversely, the Twentieth Century repertoire, often favouring shorter reverberation times to maintain clarity and precision, finds an ideal setting in this music hall.

For chamber music, the hall's reverberation times at mid frequencies (1.86 s in the retracted state and 2.12 s in the closed state) and at low frequencies (1.58 s in the closed state) are generally within the optimal range of 1.4 s to 1.7 s, providing clarity and intimacy essential for smaller ensembles. However, for symphonic music, which requires longer reverberation times of 1.7 s to 2.3 s, the hall's current acoustics are inadequate. The low-frequency reverberation time, even at closed door scenario where its longest value is measured, remains too short. Consequently, while Bilkent Music Hall offers suitable conditions for chamber music, it does not meet the optimal acoustical requirements for symphonic performances.

In closed doors scenarios, the mid frequency T30 values fall within the acceptable range for piano recitals, providing the necessary acoustic support for this instrument. However, these conditions are less favourable for violin performances, where a longer reverberation time would be necessary to fully support the instrument's tonal qualities.

The Clarity (C80) values presented in Figure 40 indicate that C80 is between -2 to +2 for all octave bands, which is the optimal range for music performances (as presented in Table 3). According to ISO-3382 standards, the typical range of C80 for multipurpose halls is -5 dB; +5 dB (JND is 1 dB). The proper values of clarity relate to both short reverberation

time, but as well as the proper early reflections provided by the compact shape of the hall that is almost a shoebox, in width-length-height proportions. Nonetheless, it is worth emphasizing that for a music hall's acoustical quality and overall impression, it is essential to strike a balance between both clarity and reverberation time, ensuring they both align with acceptable standards. More specifically, C80 values at 500 Hz for both states are within the optimum range for piano performances. Therefore, it exceeds the upper limit recommended for violin performances with 1,69 dB in the retracted state and 1,13 dB in the closed state of the doors.

The initial portion of the sound energy decay process relates more to the subjective assessment. Thus, EDT is highly correlated with the quality of the perceived reverberance. As it is presented in Figure 41, the measurement results for EDT indicate that the average mid frequencies are 1.71 s in the retracted state and 2.0 s in the closed state. According to Beranek (2004), the ideal EDT values for concert halls should be in the range of 1.8 - 2.2 s. Therefore, EDT values are in the acceptable range at mid frequencies in the closed state of doors and measured almost the same as the T30 values. At low frequencies, the average EDT value is 1.50 s, which acts parallel to the T30 value in this frequency range. At mid and high frequencies in the closed state, the EDT value increases to 2.0 s and 1.81 s respectively which creates a suitable auditory environment for symphonic music. However, in this case, the difference between two states is only slightly perceivable therefore, considering only mid to high frequency range, the effectiveness of the system for different music types is found to be low.

4.2. Acoustical Simulation Results

In this section, the findings from the room acoustical simulations conducted in ODEON v17.2 is presented. The acoustic simulations aim to evaluate key acoustic parameters, such as RT, EDT and C80, which are critical for assessing the hall's suitability for musical performances. By comparing the simulation data with established acoustic standards, a comprehensive analysis of the impact of the existing materials on the sound field is aimed. The underlying cause of excessive absorption at low frequencies is determined and areas for potential improvement are investigated. The results are discussed in detail, highlighting significant trends observed during the simulation process.

Table 10 presents the sound absorption coefficients of the existing materials, along with the corresponding coverage areas. The panel doors exhibit a noticeable sound absorption, particularly at lower frequencies, registering absorption coefficients of 0.25 at 125 Hz and 0.18 at 250 Hz, which underscores their substantial role in increasing the overall absorption within this specific frequency range. However, it is evident that despite the expectedly high absorption characteristics of the wooden panels, their influence fails to surpass that of the plasterboard employed on the walls and ceiling. The single-layer plasterboard, with thickness of 18 mm, employed throughout the hall (see Figure 38), exhibits absorption values of 0.24 at 125 Hz and 0.19 at 250 Hz, respectively. Moreover, it covers an area of 1972 m² which makes its impact on the acoustical environment pivotal and indispensable.

Table 10. Specifications of the materials assigned in acoustical model of Bilkent Music Hall and sound absorption coefficients over 1/1 octave bands used in simulations

Surface	Material Name	Octave Band Frequency (Hz)					
		125	250	500	1000	2000	4000
Operable wooden panels	995707/ Operable wooden panels, 2 cm thick wooden panels (158 m ²)	0,25	0,18	0,11	0,08	0,07	0,06
Wall	995698/Gypsum, Plasterboard (1972 m ²)	0,24	0,19	0,15	0,11	0,07	0,06
Wall	7508/Non-operable wooden walls (420 m ²)	0,14	0,10	0,06	0,08	0,1	0,1
Wall	995706/Mineral Wool (235 m ²)	0,75	1,0	1,0	1,0	1,0	1,0
Wall	4012/Travertine (211 m ²)	0,01	0,01	0,01	0,01	0,02	0,02
Ceiling	995698/Plasterboard (45 m ²)	0,24	0,19	0,15	0,11	0,07	0,06
Seat	995705/Seats (688 m ²)	0,50	0,53	0,49	0,47	0,58	0,53
Floor / Stage	4555/Wood floors on joists (1330 / 127 m ²)	0,15	0,11	0,10	0,07	0,06	0,07
Doors	7522/ Door (34,6 m ²)	0,1	0,07	0,05	0,04	0,04	0,04

Global estimate results at 500 Hz are presented for retracted and closed states in Figure 43. In this regard, as it is presented in Table 11, with the implementation of 5 cm thick wooden operable panels that incorporate a comparatively reflective material with 0.08 at 125 Hz and 0.13 at 250 Hz, appropriate reverberation times can be achieved. Furthermore, to address the primary problem, installation of a double-layer plasterboard with the alpha of 0.15 at 125 Hz and 0.10 at 250 Hz is recommended. Another set of simulation study has been run with suggested materials and results for T30 and C80 values are presented in Figure 44 and Figure 45, respectively.

The proposed materials in the retracted state provide T30 value of 1.73 s at low frequencies and 1.85 s at mid frequencies, rendering it suitable for chamber music performances whereas in the closed state, it attains approximately 1.96 s at low frequencies and 2.12 s at mid frequencies which is appropriate for symphonic music with variety of instruments. Furthermore, when considering both T30 and C80 parameters in both retracted and closed states of the wooden doors, they fall in the ideal range with the application of acoustical design proposal, as presented in Table 3. In the retracted state with the proposed materials, the venue accommodates Baroque and Classical Music successfully. In the closed state with proposed materials, Romantic period music can also be successfully accommodated.

While T30 values are increased, C80 values are in the optimal range for music performances which is $-2 \text{ dB} < \text{C80} < 2 \text{ dB}$.

Consequently, the music hall, enhanced with the applied materials, offers an acoustical environment suitable to accommodate a wide variety of musical performances.

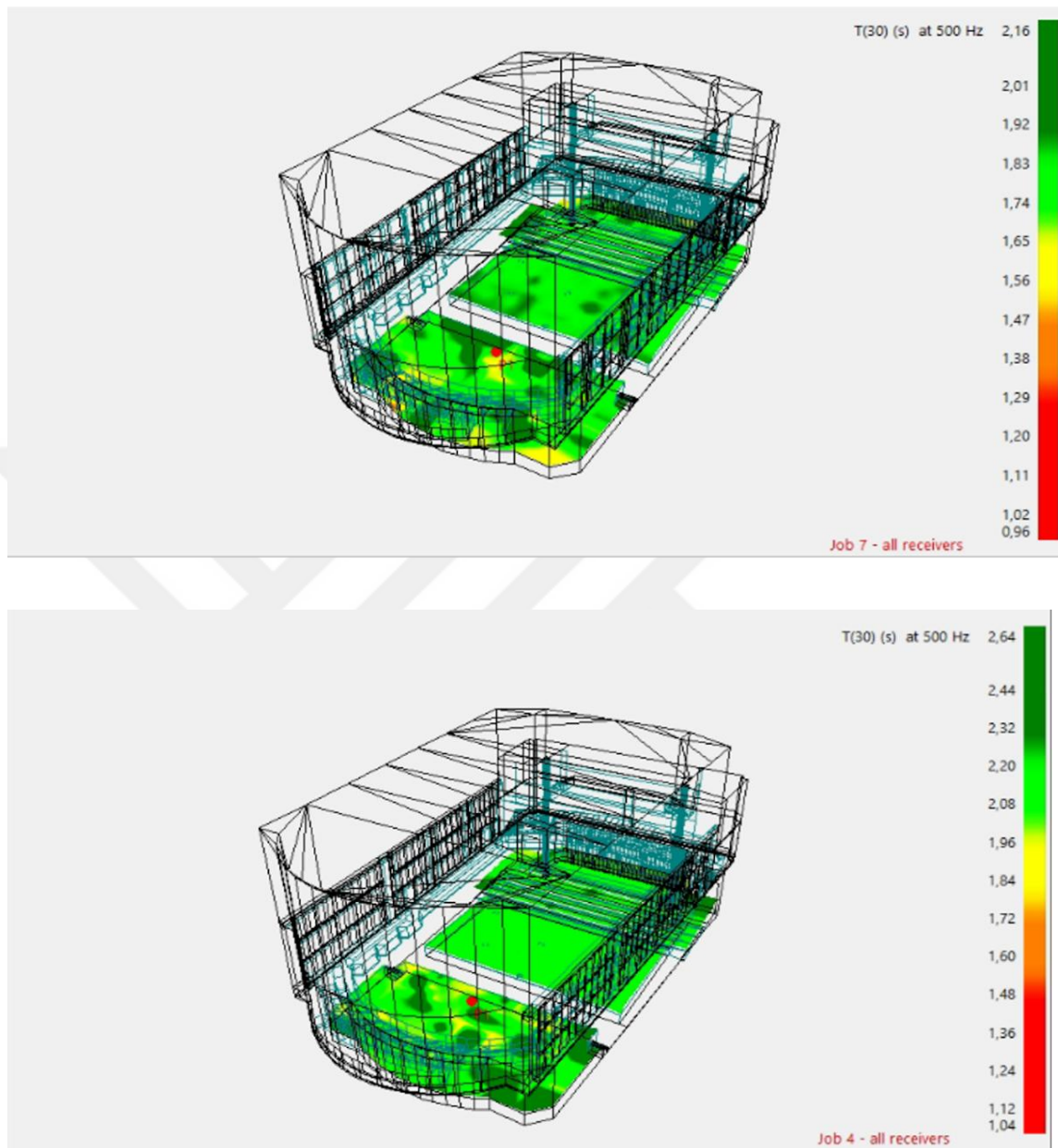


Figure 43. Global estimate results of acoustical interventions at 500 Hz; retracted state(top), closed state (bottom)

Table 11. Assigned acoustical treatments in simulations for better tuning the hall for various performance types

Surface	Material Name	Octave Band Frequency (Hz)					
		125	250	500	1000	2000	4000
Operable wooden panels	4576 / Operable wooden doors, 5 cm thick (158 m ²)	0,08	0,13	0,12	0,09	0,06	0,06
Wall	5013/ Gypsum 2*13 mm plasterboard on frame (1972 m ²)	0,15	0,10	0,06	0,04	0,05	0,05
Wall	7508/Non-operable wooden walls (420 m ²)	0,14	0,10	0,06	0,08	0,10	0,10
Wall	995706/Mineral Wool (235 m ²)	0,75	1,00	1,00	1,00	1,00	1,00
Wall	4012/Travertine (211 m ²)	0,01	0,01	0,01	0,01	0,02	0,02
Ceiling	5013/ Gypsum 2*13 mm plasterboard on frame (45 m ²)	0,15	0,10	0,06	0,04	0,05	0,05
Seat	8008/ Occupied seats, upholstered (688 m ²)	0,52	0,68	0,85	0,97	0,93	0,85
Floor / Stage	4555/Wood floors on joists (1330 m ²)	0,15	0,11	0,10	0,07	0,06	0,07
Doors	7522/ Door (34,6 m ²)	0,10	0,07	0,05	0,04	0,04	0,04

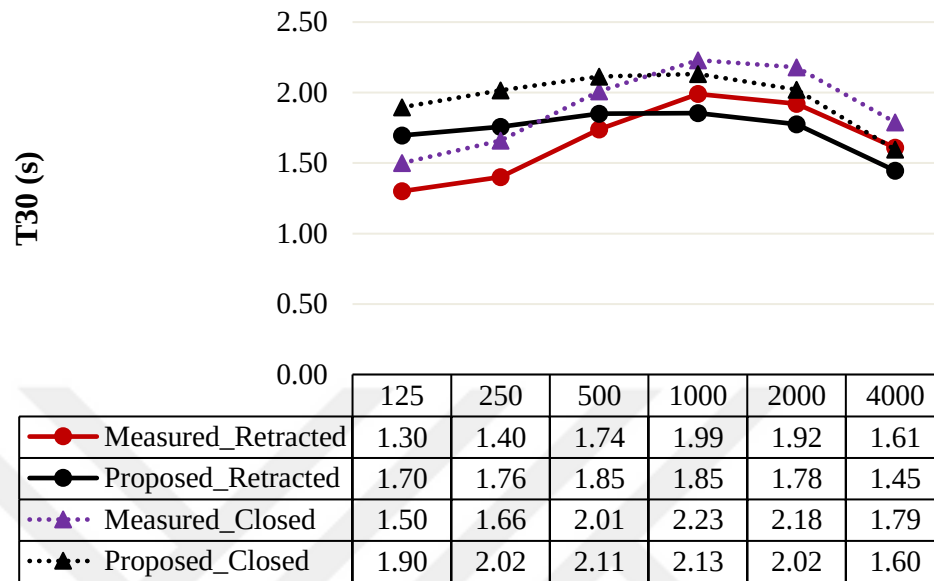


Figure 44. Comparison of measured and proposed T30 values for retracted (solid line) and closed (dotted line) states.

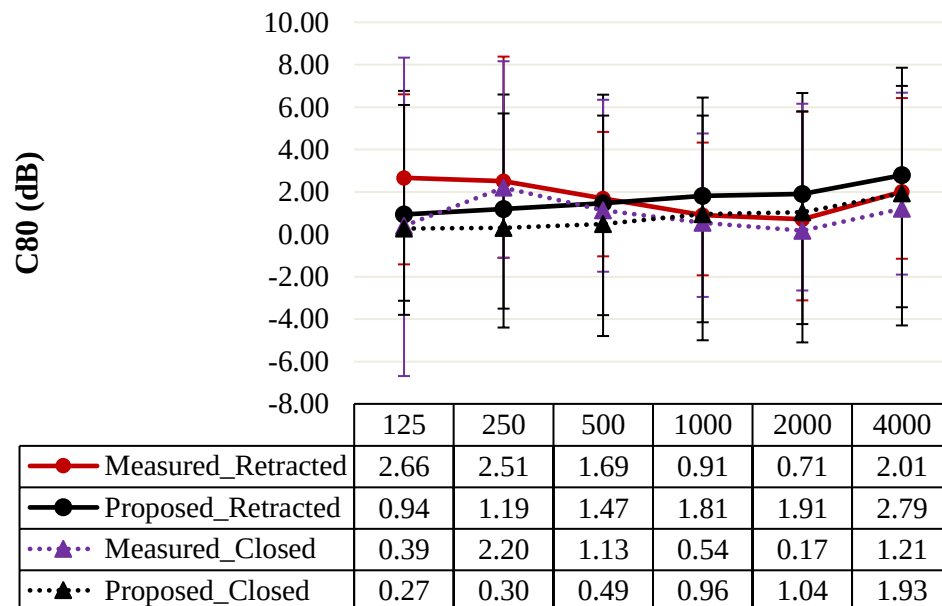


Figure 45. Comparison of measured and proposed C80 values in retracted (solid line) and closed (dotted line) states.

4.3. Questionnaire and Online Survey Results

The following section presents the findings from the questionnaire survey conducted to gather musicians' perspectives on the acoustic environment of Bilkent Music Hall. The questionnaire aims to gather qualitative data on the effectiveness of the hall's variable panel system and its impact on musicians' musical experiences. Musicians who regularly perform in the venue are selected for the questionnaire and are asked to rate the venue's acoustics based on their personal experiences. The insights obtained from these ratings are crucial for identifying the strengths and areas for improvement in the hall's acoustics. Data analysis method entails descriptive statistics that summarize the data, offering a clear overview of the central tendencies and dispersions in the musicians' responses. Further analysis is conducted through t-tests using IBM SPSS Statistics 26. Independent samples t-test is utilized to compare the means of different groups, providing insights into whether there are statistically significant differences between responses from certain groups of musicians. This test is particularly effective in identifying different preferences regarding the acoustical environment based on musicians' experiences or roles within the orchestra. Correlation analyses are conducted to explore the relationships between various acoustical factors. The scale is evaluated for its reliability and consistency using the Cronbach's alpha coefficient, which yields a coefficient alpha value of $\alpha = 0.83$, indicating a high degree of internal reliability among the items. For the correlations, musicians' ratings of 'Clarity', 'Reverberance', 'Envelopment', 'Intimacy' and 'Loudness' are used. Subsequently, ratings related to sound balance are analysed, followed by assessments of overall satisfaction with the acoustical environment.

This combination of statistical methods ensures a comprehensive and robust analysis of the qualitative data, highlighting significant patterns and relationships that inform the

study's conclusions by analysing relationships between subjective scales across different groupings.

The initial study sample includes 50 BSO musicians, ranging from 23 to 65 years old, with 15 females (30%) and 35 males (70%). Then, an online survey is administered to students and faculty, with participation from 11 female students and 7 male students between the ages of 18 and 26, and 5 male faculty members between the ages of 28 and 55.

The questionnaire includes open-ended questions that sought participants' opinions on whether there is a discernible difference between the retracted and closed states of the wooden doors, along with asking for additional comments. This question has a high rate of non-response, with only 47 out of 73 participants providing answers. Only 14 participants state a noticeable difference between different wooden door states. 9 of the BSO members express a preference for the retracted state, citing that the reverberation becomes too long when the wooden doors are in the closed state. At the same time, a significant percentage indicate that they either have not performed in different states of the doors or fail to discern any notable difference between retracted and closed configurations. These observations underline the hypothesis that the wooden door system lacks efficiency in tuning the acoustic environment for various performances and is not used properly and actively for different musical performances since it is manually operated.

Some of the additional comments address acoustical concerns. Notably, there are remarks about the flatness of low frequencies and challenges in achieving a balanced sound between string and wind instruments. Another issue highlighted is the imbalance

involving brass instruments, which tend to either overpower the orchestra or fail to be heard distinctly within the musical composition depending on their position on stage.

In addition, vocalists highlight issues regarding an imbalance between the chorus and orchestra, as well as challenges in achieving even sound distribution throughout the hall during solo vocal performances which contradicts with optimal clarity values measured in the field tests. In chamber music ensembles, vocalists often face difficulties in hearing the instruments and their fellow musicians due to their placement on stage. Vocalists are typically positioned in front of the ensemble, with instrumentalists behind them. This arrangement can cause acoustic shadows, where sound from the instruments cannot reach the vocalists effectively. Therefore, these issues can either be caused by the high absorption of materials or poor sound reflections.

Overall mean comparisons between Orchestra and Faculty/Students for subjective acoustic parameters are presented in Figure 46. The results reveal that orchestra members have a higher preference for all ratings compared to faculty and students.

According to the criteria presented in Table 3, objective clarity is suitable for musical performances while reverberation is too short for symphonic music at low frequencies, however, musicians demonstrate strong preference for 'Reverberance' ($\mu > 4$), making it the most favoured out of major five parameters, over 'Clarity' ($\mu > 3.6$). This contradiction between objective and subjective parameters may be attributed to musicians' limited experience in assessing room acoustics or their inherent preferences as professionals.

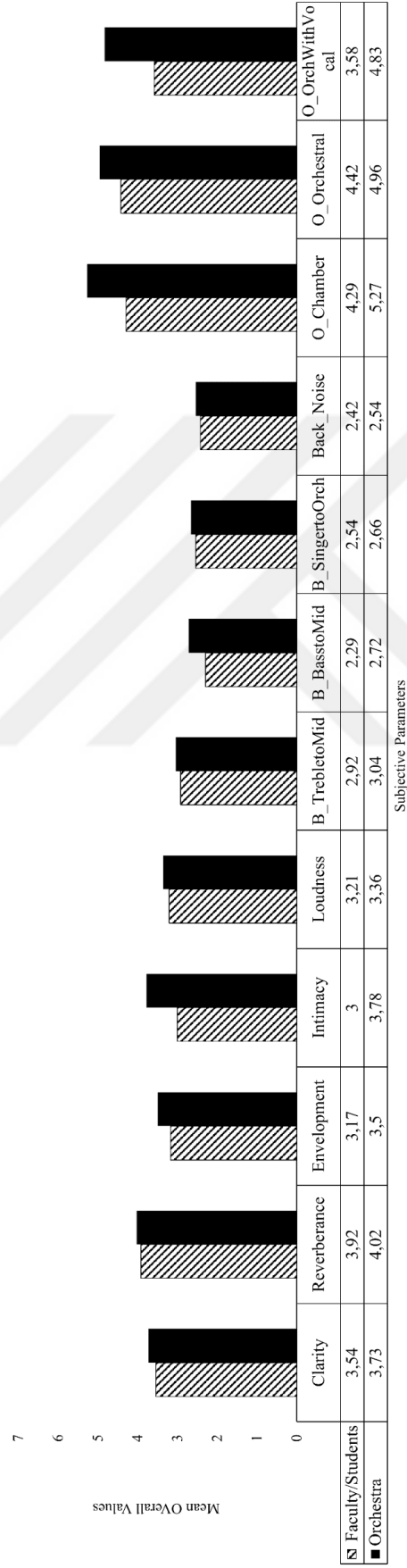


Figure 46. Mean overall rating scores for each subjective acoustic parameters; Orchestra (solid), Faculty/Students (hatched)

The remaining parameters, namely 'Intimacy,' 'Envelopment,' and 'Loudness,' receive ratings around 3.5 and below, signifying them unsatisfactory for musical purposes. 'Intimacy' is mostly related with a subjective impression of the size of the hall, therefore, is expected to be higher for a smaller music hall such as Bilkent Music Hall. 'Envelopment' mostly relates with the reverberation characteristics and lateral reflections of the hall, also rated poorly, indicating that the users do not feel adequately surrounded by sound. 'Loudness' is mostly related with preference in orchestral force, indicating that users find the loudness inadequate.

The low ratings for 'Intimacy,' 'Envelopment,' and 'Loudness' underscore the acoustical issues related to low frequencies, supporting the results of field measurements. However, discrepancies are noted in the subjective and objective assessment of reverberation. Despite musicians expressing a strong preference for 'Reverberance' ($\mu > 4$), objective data indicate that reverberation time is insufficient for symphonic music at low frequencies. These findings highlight the necessity for targeted acoustic design improvements, such as enhancing lateral reflections, increasing reverberation time at low frequencies, and reevaluating the variable system's design and placement to better align objective measurements with subjective auditory experiences.

When orchestra members' (n=50) responses are compared with the academicians/students (n=24), statistically significant results are recorded for scales 'Intimacy', 'O_Chamber' and 'O_OrchWithVocal'. However, the number of samples in each group is unequal, which may influence the interpretation of these findings. 'Intimacy' receives a rating of 4 (over 5) and above from 68% of the orchestra members and 37% of the faculty and students. 70% of the orchestra members and 45% of the faculty and students have preferences of 'Good' and above for chamber music, while 52% of the orchestra members

and 14% of the faculty members/students have preferences of 'Good' and above for orchestral music with vocal accompaniment. This analysis suggests that orchestra members rate the concert hall more successful across these scales compared to faculty members/students.

In the next step, a statistical analysis is performed to further assess the dataset. Given that BSO members have expertise in wind or string instruments, independent samples t-test is conducted to investigate whether there is a statistically significant mean difference between the acoustical preferences of wind instrument players (n=24) and string instrument players (n=36). The result of the independent samples t-test is presented in Table 12. The rejection of the null hypothesis is contingent upon statistical evidence which demonstrates that the p-value (the significance value) is less than 0.05. The analysis reveals that there is no statistically significant difference ($p > 0.05$) between wind and string players in their preference of the five major scales ('Clarity,' 'Reverberance,' 'Intimacy,' 'Loudness,' and 'Envelopment'). These findings align with Barron's (1988) study on British concert halls for the major parameters. On the other hand, statistically significant results are recorded for 'O_Orchestral', 'O_OrchwithVocal' and 'B_TrebletoMid', indicating notable distinctions in preference between wind and string instrument players in these aspects.

String instrument players rate the balance between treble to mid frequencies higher than the wind instrument players. Specifically, 58% of string instrument players rate the Bilkent Music Hall as well-balanced, while only 29% of wind instrument players give ratings of well-balanced.

Table 12. The results of Independent Sample Test conducted between preferences of wind and string instrument players; significant results marked (*)

Independent Samples Test					
	Levene's Sig.	Sig. (2-tailed)		Levene's Sig.	Sig. (2-tailed)
Clarity	0,038*	0,191	B_BasstoMid	0,620	0,536
		0,215			0,543
Reverberance	0,099	0,720	B_SingertoOrch	0,243	0,085
		0,735			0,091
Envelopment	0,589	0,820	Back_Noise	0,680	0,030*
		0,823			0,032
Intimacy	0,215	0,070	O_Chamber	0,470	0,461
		0,082			0,478
Loudness	0,731	0,228	O_Orchestral	0,109	0,000*
		0,229			0,001
B_TrebletoMid	0,009*	0,018	O_OrchWithVocal	0,425	0,013*
		0,031*			0,013

The ratings for overall acoustical quality for orchestral music, orchestral music with vocal accompaniment and chamber music are presented in Figure 47. Further information regarding musicians' ratings based on their instruments is detailed in Table 13. Ratings of 'Good' and above' are considered as indicators of satisfactory, and 'Mediocre and below' ratings are considered as unsatisfactory conditions for the musical performances within the hall.

For chamber music, 46 participants rate the concert hall as satisfactory, 15 of them being wind players and 26 of them being string players. (The 'Others' category includes participants such as composers and piano players who do not belong to the primary groups of wind and string instrument players.)

For orchestral music, 44 participants rate the concert hall as satisfactory, 11 of them being wind players and 28 of them being string players.

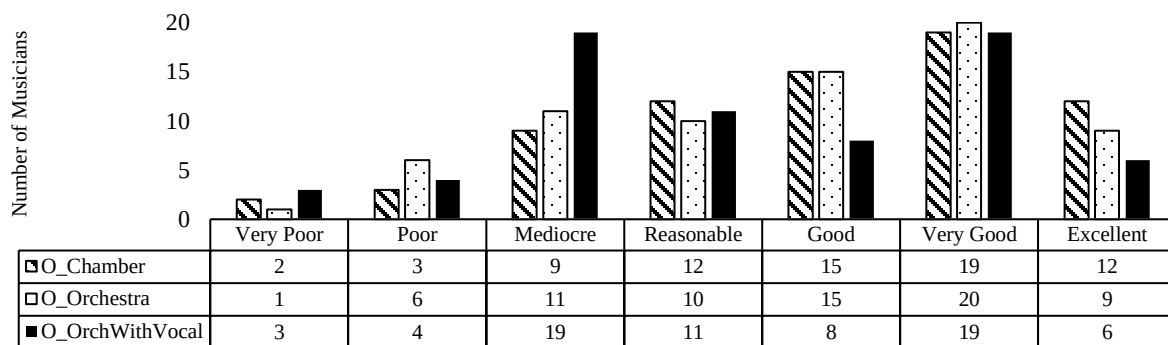


Figure 47. Musicians' overall impressions for different performance types; chamber, orchestral and orchestral music with vocal accompaniment

Table 13. The number of musicians' ratings for different performance types based on their instruments: Wind, string, and others (including percussion, composers, and vocalists).

Parameters	Instruments	Ratings of number of musicians						
		Very Poor	Poor	Mediocre	Reasonable	Good	Very Good	Excellent
O_Chamber	Wind	1	0	4	3	7	2	6
	String	1	1	1	6	7	14	5
	Others	1	2	4	4	1	3	1
O_Orchestra	Wind	1	5	3	3	8	1	2
	String	0	0	5	2	5	16	7
	Others	1	1	3	5	3	3	0
O_OrchWith Vocal	Wind	1	1	9	3	5	0	2
	String	1	1	6	5	3	16	3
	Others	2	2	4	3	1	3	1

For orchestral music with vocal accompaniment, 37 participants rate the concert hall as satisfactory, 5 of them being wind players and 22 of them being string players.

In conclusion, a comparative analysis of the ratings given for various types of music performed in the music hall reveal the music hall more favourable for musicians who play

string instruments compared to musicians who play wind instruments. On the other hand, 14 participants rate the concert hall as unsatisfactory for chamber music, 18 participants for orchestral music, and 26 participants for orchestral music with vocal accompaniment. While the majority of the participants rate the venue favourable for the acoustic quality for various performance types, it is important to acknowledge the concerns of those who rate the acoustics as 'Mediocre' or below.

Additional statistical analyses are performed to delve deeper into the relationships between scales. Two distinct correlation analyses are carried out: the first one is to explore the comprehensive relationships between variables, and the second one is to specifically analyse relationships among variables within string and wind players' groups. The Pearson correlation coefficient is used as a statistical tool to analyse the relationships between variables. According to the correlation test for subjective parameters, as presented in Figure 48, the strongest positive correlation is recorded between variable 'O_Orchestral' and 'O_OrchWithVocal' ($r=0,702$, $p=0.01$). In contrast, the weakest significant correlation is observed between the variables 'Reverberance' and 'Clarity' ($r = 0.253$, $p = 0.05$). The correlation analysis for wind and string instrument players reveals a strong positive correlation between variables 'O_Orchestral' and 'O_OrchWithVocal' ($r=0,740$, $p=0.01$). Conversely, the analysis reveals a weak but statistically significant correlation between 'O_Orchestral' and 'B_BassToMid' ($r=0,273$, $p=0.05$). The detailed data regarding the correlations between major parameters are presented in Table 14. The strongest positive correlation is for string players is between 'Clarity' and 'Intimacy' ($r=0,712$, $p=0.01$). For wind players, the strongest positive correlation is between 'Loudness' and 'Envelopment' ($r=0,553$, $p=0.05$).

Pearson Correlations												
	Clarity	Reverberance	Envelopment	Intimacy	Loudness	B_TrebletoMid	B_BasstoMid	B_SingertoOrch	Back_Noise	O_Chamber	O_Orchestral	O_OrchWithVocal
Clarity	1	,253*	,221	,664**	,263*	,325**	,347**	,290*	-,379**	,487**	,567**	,509**
Reverberance	,253*	1	,255*	,201	-,087	,149	,292*	,181	-,020	,097	,161	,247*
Intimacy	,664**	,201	,374**	1	,258*	,395**	,296*	,366**	-,359**	,584**	,556**	,506**
Loudness	,263*	-,087	,300*	,258*	1	,206	,246*	,147	-,051	,281*	,165	,189
B_TrebletoMid	,325**	,149	,233	,395**	,206	1	,272*	,381**	-,170	,495**	,459**	,340**
B_BasstoMid	,347**	,292*	,082	,296*	,246*	,272*	1	,427**	-,141	,241*	,287*	,228
B_SingertoOrch	,290*	,181	,040	,366**	,147	,381**	,427**	1	-,053	,296*	,416**	,464**
Back_Noise	-,379**	-,020	,020	-,359**	-,051	-,170	-,141	-,053	1	-,257*	-,286*	-,155
O_Chamber	,487**	,097	,302*	,584**	,281*	,495**	,241*	,296*	-,257*	1	,617**	,624**
O_Orchestral	,567**	,161	,002	,556**	,165	,459**	,287*	,416**	-,286*	,617**	1	,702**
O_OrchWithVocal	,509**	,247*	,202	,506**	,189	,340**	,228	,464**	-,155	,624**	,702**	1

*. Correlation is significant at the 0.05 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Figure 48. Pearson Correlation Analysis for subjective parameters

Table 14. Pearson Correlation analysis for major subjective scales

Groups	Subjective Scales	Clarity	Reverberance	Envelopment	Intimacy	Loudness
1 (Wind)	Clarity	1	,173	,414	,477*	,381
2 (String)		1	,519**	,165	,712**	,321
1 (Wind)	Reverberance	,173	1	,010	-,112	-,077
2 (String)		,519**	1	,347	,588**	-,096
1 (Wind)	Envelopment	,414	,010	1	,454*	,553*
2 (String)		,165	,347	1	,435*	,114
1 (Wind)	Intimacy	,477*	-,112	,454*	1	,319
2 (String)		,712**	,588**	,435*	1	,188
1 (Wind)	Loudness	,381	-,077	,553*	,319	1
2 (String)		,321	-,096	,114	,188	1
*. Correlation is significant at the 0.05 level (2-tailed).						
**. Correlation is significant at the 0.01 level (2-tailed).						

These findings highlight valuable insights into musicians' preferences and support the identified shortcomings in the acoustical performance of Bilkent Music Hall across various musical performance types, particularly at low frequencies as noted in field tests. The questionnaire reveals statistically significant mean differences between string and wind instrument players, with string players consistently rating the concert hall more favorably. An intriguing contradiction emerged regarding reverberance preferences: While most musicians find the reverberation suitable for different performance types, issues with reverberation at low frequencies are consistently evaluated in both objective measurements and subjective evaluations. Addressing these discrepancies is crucial for enhancing the overall acoustical experience and effectiveness of the concert hall for diverse musical performances.

CHAPTER 5

DISCUSSION

5.1. The Impact of Interior Finishes

Field tests and questionnaires are conducted in response to concerns about the music hall's acoustics. The analysis determines that the current acoustics fail to establish a suitable acoustical environment across all frequency ranges. The T30 at mid frequencies is suitable for symphonic music when the wooden doors are closed and is suitable for chamber music when they are retracted, indicating that the variable system successfully achieves a noticeable difference between states. However, RT at low frequencies is unsatisfactory for musical performances due to excessive absorption caused by interior finishing materials. The absorption coefficients of interior finishes are calculated in sabins at each octave band frequency to determine their impact on absorption area. The sabin formula is;

$$A_{material} = \sum (S \cdot \alpha)$$

Where:

S = The area of the material in square meters

α = The absorption coefficient at a specific frequency

The overall absorption at octave bands is presented in Table 15. The data reveal that the highest absorption occurs at 125 Hz. The contribution of each material to the overall acoustical performance of the concert hall is presented in Table 16.

Table 15. The overall absorption at all frequencies, in sabins

Frequency (Hz)	Sabins
125	1327
250	1218
500	1067
1000	932
2000	922
4000	880

The major contributors to low frequency sound absorption include gypsum board utilized in ceiling and wall applications, seats and mineral wool. Gypsum board on walls exhibits the highest absorption at 125 Hz with 473 sabins and maintain a significant absorption capacity across all frequencies. The seating area also plays a significant role in sound absorption, with high values at both low and high frequencies (344 sabins at 125 Hz and 400 sabins at 2000 Hz). This indicates that the audience area significantly influences the overall acoustical condition of the hall. The non-operable wooden walls provide moderate sound absorption across frequency spectrum, especially at 125 Hz with 59 sabins and 42 sabins at high frequencies. The operable wooden doors show high sound absorption at 125 Hz with 40 sabins, acting as a bass trap. Mineral wool is highly effective across all frequencies, particularly at mid and high frequencies, absorbing sound energy across the entire frequency spectrum in the retracted state. This is further evidenced by the bass ratio of 0.72 in the retracted state and 0.74 in the closed state of the doors, both of which are significantly lower than in precedent cases.

Travertine is used on the upper parts of the walls near the stage. This material exhibits

very low sound absorption at most frequencies, with slightly higher values at high frequencies (4 sabins at 2000 Hz and 4000 Hz). Its contribution to the acoustic environment is minimal, indicating that it is not effective for sound absorption and may serve more as a reflective surface.

The detailed analysis of each material's sound absorption properties highlights the strengths and weaknesses in the concert hall's current acoustical design. By implementing targeted improvements, the hall can achieve a balanced and high-quality acoustical environment that can enhance the experience for both performers and audiences. This assessment explains the critical role played by these materials and emphasize the importance of both material composition and coverage area in optimizing the acoustical environment.

Excessive bass absorption should be addressed by appropriate door detailing and interior wood finishes to improve the acoustical performance of this hall. The high bass absorption caused by the single layer plasterboard should also be addressed.

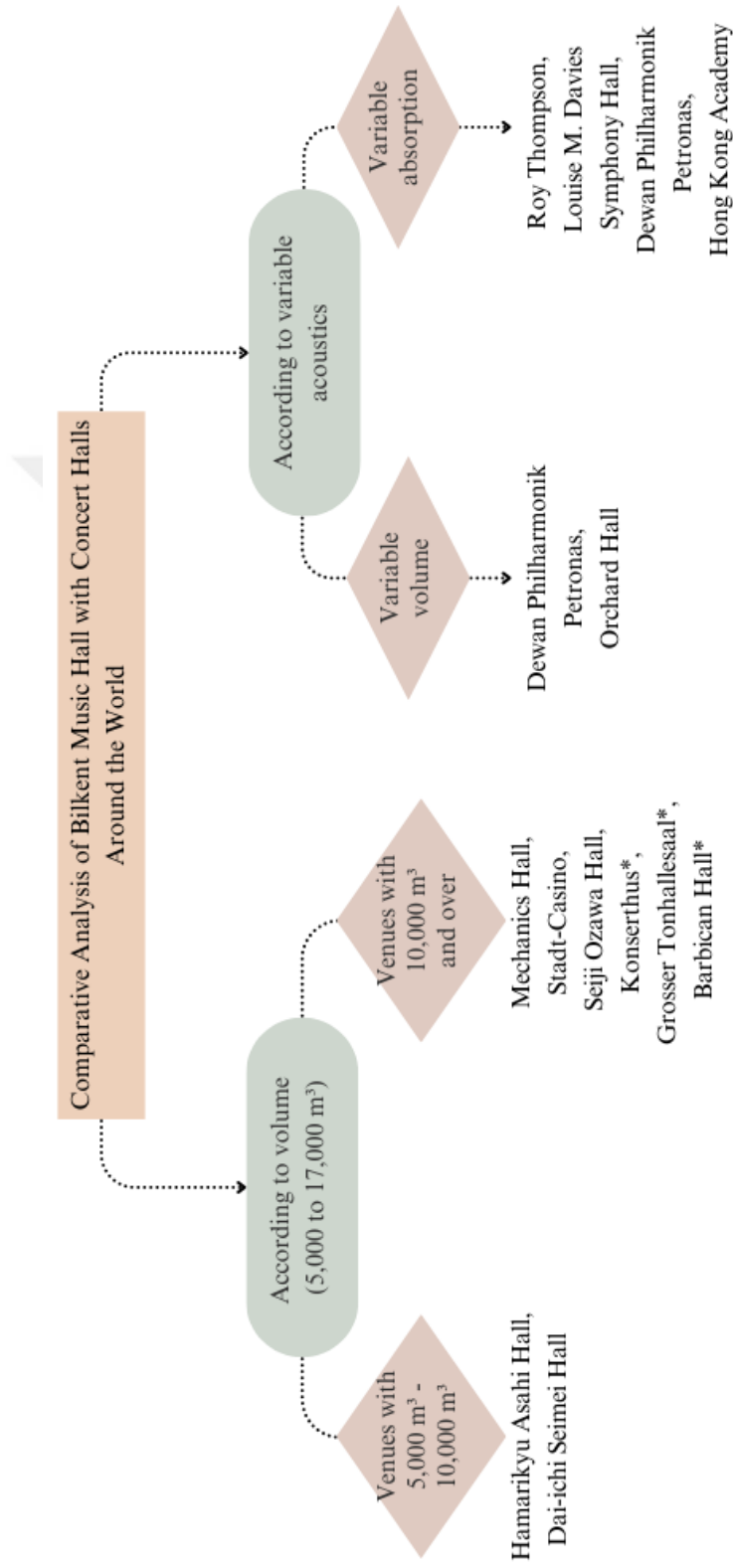
To prevent bass absorption in concert halls caused by wooden doors, thick panels should be used. The acoustical simulation results indicate that utilizing a double-layer gypsum board and wooden door with 50 mm thickness effectively prevent low frequency absorption, thereby ensuring acoustical brilliance and proper bass ration for a wide array of musical performances.

Table 16. The absorption area in sabins of interior finishes at octave bands

Material	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Wooden operable panels	40	28	17	13	11	10
Wall / Gypsum board	473	375	296	217	138	118
Non-operable wooden walls	59	42	25	34	42	42
Wall / Mineral Wool	176	235	235	235	235	235
Wall / Travertine	2	2	2	2	4	4
Ceiling / Gypsum board	11	9	7	5	3	3
Seat	344	365	337	324	400	365
Floor / /Wood floors on joists	200	147	133	93	80	93
Stage /Wood floors on joists	19	14	13	9	8	9
Doors	4	3	2	2	2	2

5.2. Comparison of Bilkent Music Hall's Acoustics with Concert Halls Around the World

In this section, objective acoustic parameters of Bilkent Music Hall are compared with well-known concert halls around the world. The selected concert halls are inspected under two groupings, which are similar volume and seating with Bilkent Music Hall, and the availability of variable absorption systems. For comparisons, average T30 values are used as the main criterion, as it is the only parameter commonly available for all concert halls in Beranek's (2004) study. The initial comparison is conducted on concert halls with a seating capacity of 500 to 1,500 and a volume of 5,000 to 17,000 m³, including the following venues: Hamarikyu Asahi Hall, Dai-ichi Seimei Hall, Mechanics Hall, Stadt-Casino, Konserthus, Grosser Tonhalleaal, Seiji Ozawa Hall, and Barbican Hall. T30, C80 and EDT values of concert halls selected for the first comparison are presented in Table 17. For the second comparison, concert halls with variable absorption elements are selected, which are Orchard Hall, Roy Thompson, Louise M. Davies Symphony Hall, Dewan Philharmonik Petronas and Hong Kong Academy (Altun and Sü Gül, 2023) (see Figure 49).



* These concert halls are also compared with Bilkent Music Hall based on their wooden interior finishes.

49. Acoustical comparison of Bilkent Music Hall and precedent cases: according to similar volume and variable systems

Table 17. RT, C80 and EDT values for concert halls in the first comparison

Concert Hall	Volume (m ³)	Seating	m ³ /person	RT (s)			C80 (dB)	EDT (s)
				125-250 Hz	500 – 1000 Hz	2000- 4000 Hz		
Hamarikyu Asahi Hall	5800	552	10,51	1,66	1,88	1,81	-0,42	1,70
Dai-ichi Seimei Hall	6800	767	8,87	1,95	1,84	1,80	-0,92	1,81
Stadt-Casino	10500	1448	7,25	2,26	2,31	2,07	-2,7	2,24
Mechanics Hall	10760	1343	8,01	2,25	2,15	1,50	-0,83	1,96
Grosser Tonhalleaal	11400	1546	7,37	2,45	2,05	1,69	-4,15	3,02
Seiji Ozawa Hall	11610	1180	9,84	2,35	2,25	1,95	-	-
Konserthus	11900	1286	9,25	2,12	1,81	1,57	-0,47	1,81
The Barbican Hall	17000	1924	8,83	1,67	1,74	1,50	0,94	1,43
Bilkent Concert Hall (retracted)	10982	707	15,53	1,35	1,86	1,76	1,34	1,53
Bilkent Concert Hall (closed)	10982	707	15,53	1,58	2,12	1,98	0,94	1,77

5.2.1 Comparisons Based on Similar Volume and Seating Capacity

Among the concert halls selected for first comparison, Stadt Casino in Basel, Switzerland has the longest RT with 2.35 s at mid-frequencies, and Barbican Hall in London, UK has the shortest RT with 1.74 s. In the case of low frequencies, the shortest RT is observed at Bilkent Music Hall, where the doors are in their retracted state, with a value of 1.35 s. In contrast, Grosser Tonhalle in Zurich, Switzerland, exhibits the longest RT, with a value of 2.45 s. In all the venues, C80 and EDT values are in the recommended range for music performances except average C80 of -4,15 dB and EDT of 3,02 observed in Grosser Tonhalle.

When Bilkent Music Hall is compared with the precedent cases, it has the shortest RT in both retracted and closed states at low frequencies. Hamarikyū Asahi Hall in Tokyo, Japan and Dai-ichi Seimei Hall in Tokyo, Japan are the smallest concert hall in terms of seating capacity and volume, however, despite their smaller sizes, both venues demonstrate longer RT at low frequencies compared to Bilkent Music Hall (Figure 50). In the retracted state of the doors, Bilkent Music Hall demonstrates an RT of 1.35 s at low frequencies which increases to 1,58 s in the closed state of doors. In comparison, Hamarikyū Asahi Hall demonstrates an RT of 1.66 s and Dai-ichi Seimei Hall demonstrates an RT of 1.95 s. According to Beranek (2004), the poor performance of bass sounds in Hamarikyū Asahi Hall is caused by the seating material which has a high coverage area. This discrepancy, when compared to smaller-volume concert halls, reveals the problematic bass performance in Bilkent Music Hall. Also, all the other concert halls demonstrate peak values within the low-frequency range, with exceptions in Hamarikyū Asahi Hall, Barbican Hall and Bilkent Music Hall, where the peak occurs at mid frequency range.

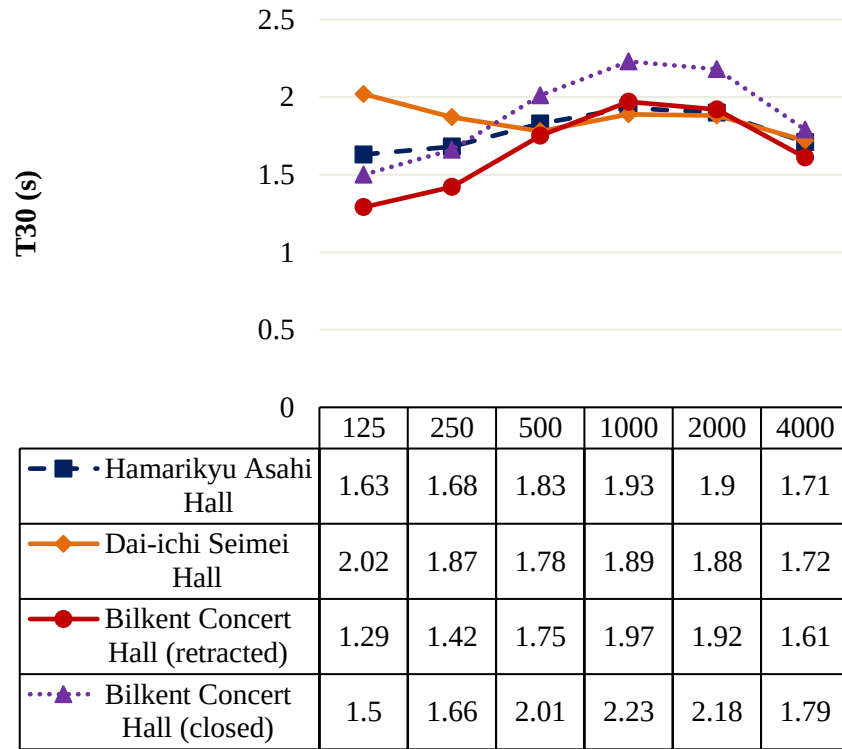


Figure 50. Comparison of T30 values; Bilkent Music Hall, Dai-ichi Seimei Hall and Hamarikyu Asahi Hall

Barbican Concert Hall includes thin wooden interior finishing materials like Bilkent Music Hall which causes bass absorption. In order to solve the issue, thin wooden elements are removed from the available areas and an acoustical canopy over the enlarged stage and audience are installed. Also, the reflective panels with adjustable heights and angles are suspended from ceiling to distribute the sound evenly throughout the hall. These modifications increase the RT_{mid} to 1,74 s (Beranek, 2004) (Figure 51).

In terms of volume-to-seat ratio, Bilkent Music Hall exhibits a larger ratio compared to other selected concert halls.

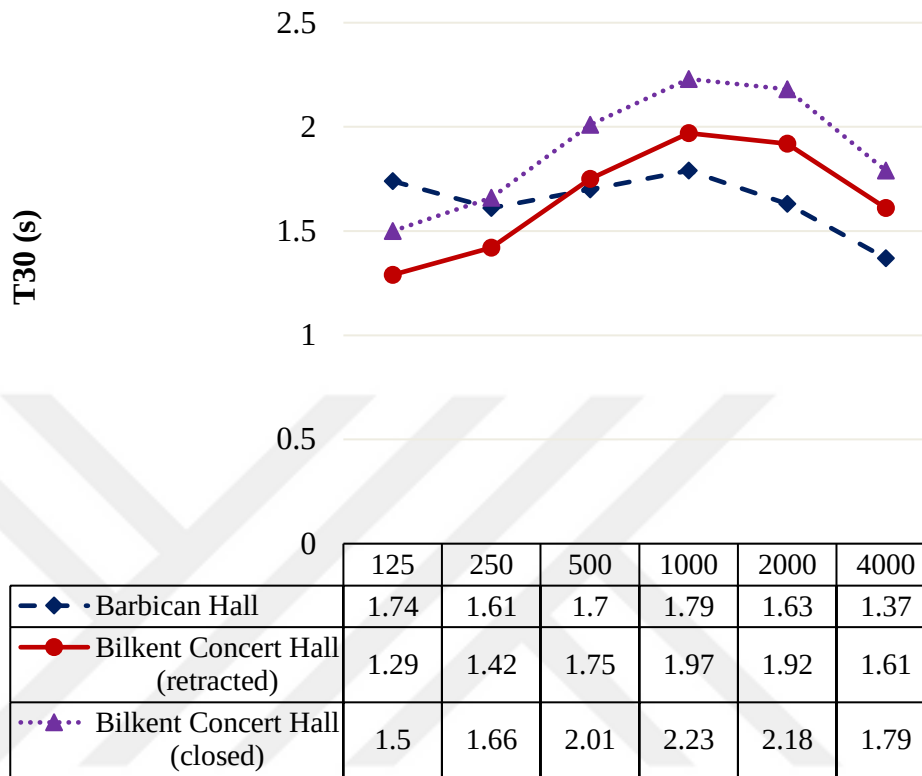


Figure 51. Comparison of T30 values; Bilkent Music Hall and Barbican Hall

With a seating capacity of 707, this ratio suggests potential advantage for sound propagation and reverberation characteristics, however, due to the existence of materials that absorb early sounds, the concert hall becomes dull.

Concert halls with a volume of around 11,000 m³ are presented in Figure 51, which are Konserthus, Mechanics Hall, Seiji Ozawa Hall, Stadt-Casino, Grosser Tonhalleaal and Bilkent Music Hall. Another concert hall that has poor bass performance is Grosser Tonhalleaal in Zurich, Switzerland. The venue receives mixed reviews from conductors. The hall is praised for long mid- frequency RT of 2.0 s however, the bass sounds are not as strong which is traced back to the thin wood panelling applied on the lower side walls.

The interior of the Konserthus Hall in Gothenburg, Sweden, is clad in wooden panels measuring 2.5 cm in thickness, which are securely fixed to a layer of 18 cm thick concrete. This heavy backing prevents the resonance that causes bass absorption. On the contrary, Bilkent Music Hall includes a thin wood panelling (both on walls and wooden doors) with gap which is causing undesired bass absorption. Konserthus has T30 value of 1.81 s at mid frequencies and 2.12 s at low frequencies which make the hall suitable for symphonic and chamber music.

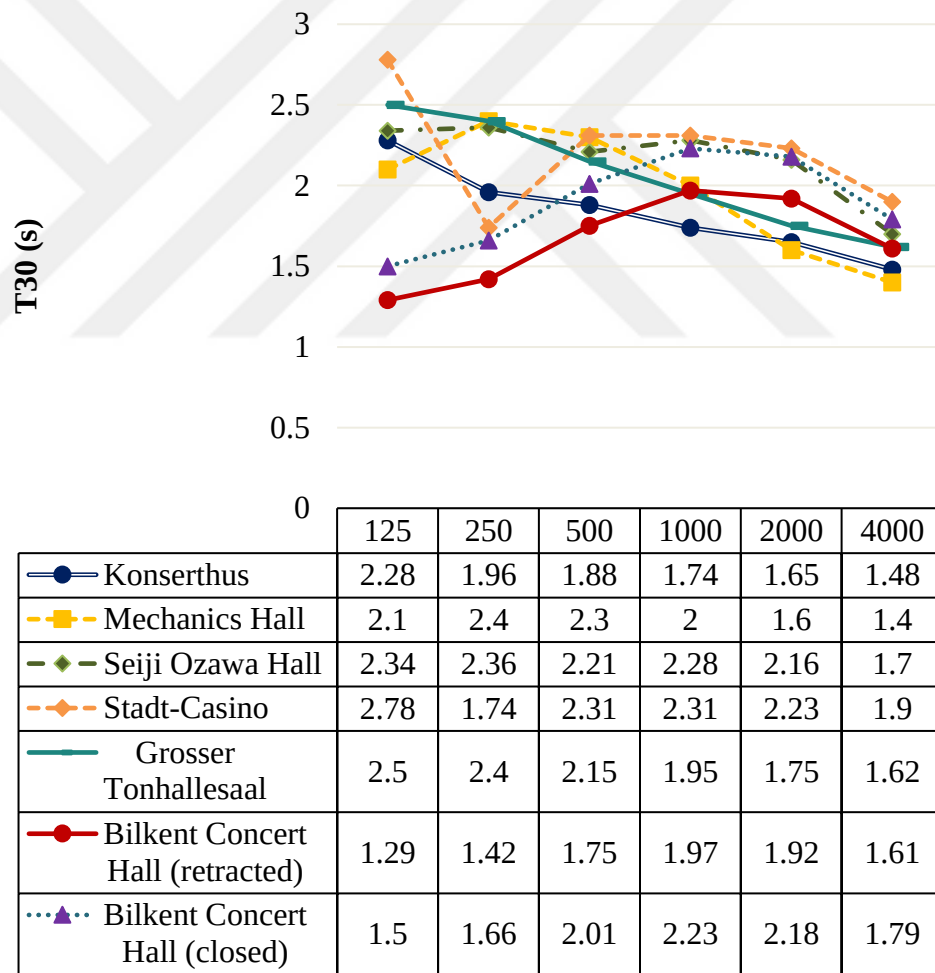


Figure 52. Comparison of T30 values; Bilkent Music Hall with selected precedent cases

Similar to Konserthus, Seiji Ozawa Hall incorporates thick concrete materials that preserve the bass sounds. The hall has the RT of 2.2 s at low frequencies and BR equals to 1.32 which showcase the strength of bass sounds.

Among these halls, Stadt-Casino and Mechanics Hall have the longest RT of 2.30 s at mid frequencies. Stadt-Casino exhibits an even longer RT of 2.76 s at low frequencies, and its C80 values are not within the optimal range, making clarity problematic for large orchestras and organ recitals (Beranek, 2004). Conversely, Mechanics Hall is highly rated as a multipurpose venue for speech and smaller orchestras, as its C80 values range in between -1 and 1.

5.2.2. Comparisons Based on Passive Variable Systems

The second comparison focuses on concert halls with variable systems. Among the selected venues, Dewan Philharmonic Petronas has the closest seating capacity to Bilkent Music Hall, with 850 seats. In its lowest ceiling setting, Dewan Philharmonic Petronas possesses a volume of 15,368 m³, which surpasses the 10,000 m³ volume of Bilkent Music Hall. In this volume setting with panel absorption, the RT is 1.83 s at low frequencies and 1.46 s at mid frequencies. Without panel absorption, the RT is 1.98 s at low frequencies and 1.64 s at mid frequencies. The venue is thus successful for chamber and symphonic music in these respective settings. This demonstrates a greater versatility in accommodating different music genres compared to Bilkent Music Hall.

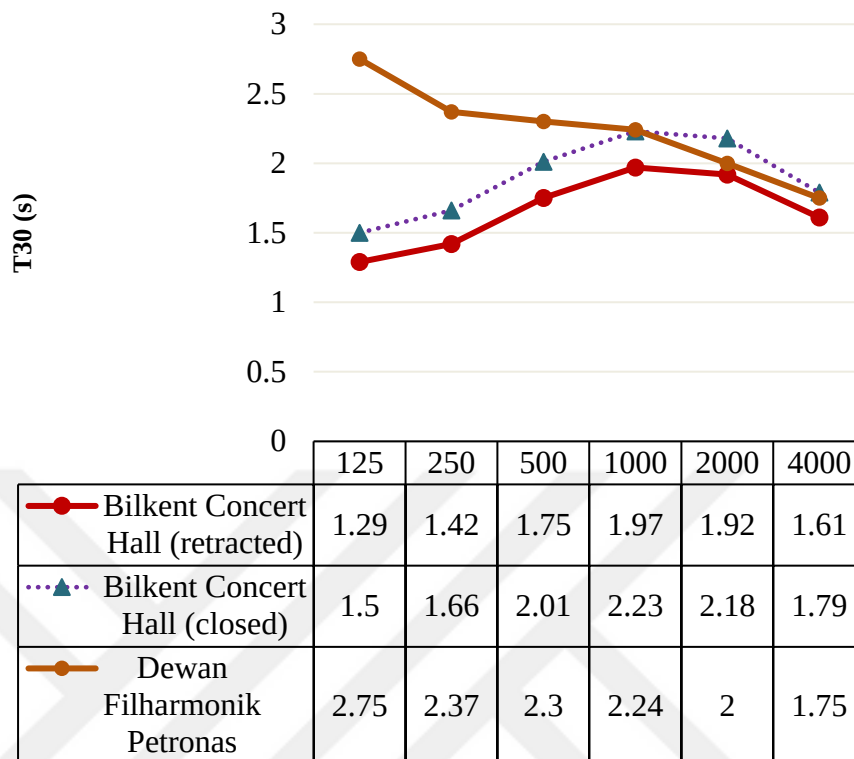


Figure 53. Comparison of T30 values; Bilkent Music Hall and Dewan Filharmonik Petronas

Aula Magna's RT of 1.7 s in the occupied state is suitable for chamber music but insufficient for symphonic music in a venue this size. In contrast to the acoustic properties of Bilkent Music Hall, the reverberation times achievable in Aula Magna are less favourable to accommodating a diverse range of musical performances that require a longer reverberation. Similarly, the Orchard Hall's variable ceiling panels in vertical configuration offers to achieve an RT_{mid} of 1.5 s for music purposes, while for dance functions, the panels are lowered to expose broadband absorption. Compared to Bilkent Music Hall, Orchard Hall has a shorter reverberation time, making it less suitable for music performances.

The Hong Kong Academy for Performing Arts' variable panel system installed on the side walls offers the potential for a variable sound field, which can be adapted to suit the specific acoustic requirements of different performance types. The RT in this hall can be adjusted to 1.7 s for rehearsals with a chamber orchestra. For recordings with a full orchestra, the rotating variable panel system on side walls can lengthen the RT to 2.2 s, making this configuration more suitable for symphonic music compared to Bilkent Music Hall. In large venues, as of Roy Thompson Hall and Davies Hall, the passive variable system can adjust the RT from 1.5 s to approximately 2.0 s, making the halls suitable for a diverse spectrum of performances. The relatively short RT is more appropriate for Baroque and Classical music, whereas the longer RT is more suitable for Romantic period music, helping to achieve the desired acoustical effect.

To conclude, these comparisons with concert halls worldwide, featuring similar volumes and variable elements, reveal an unusual trend in Bilkent Music Hall's acoustics. At low frequencies, bass sounds present a notable problem. However, at mid to high frequencies, the reverberation time values are within acceptable ranges, rendering the hall suitable for chamber music in the retracted state and symphonic music in the closed state. In overall, it is apparent that the low frequency absorption should be minimized for a balanced distribution of acoustical parameters over frequency spectrum and to minimize the sound coloration.

CHAPTER 6

CONCLUSION

In this study, the potentials and shortcomings of variable acoustics systems in music halls for modifying the acoustical environment for various music performances are investigated. The capabilities of these systems are investigated through a comprehensive review of precedent cases worldwide and a focused case study of Bilkent Music Hall in Ankara, Türkiye. The research aims to explore the following question: How do passive variable systems enhance the acoustic tuning of concert halls for different musical performances? In order to address this issue, a number of sub-questions have been formulated, with the Bilkent Music Hall serving as the primary focus of the study. The study utilizes both objective and subjective evaluation methods to identify the underlying causes of the acoustical issues in Bilkent Music Hall, as it is previously reported by musicians and music conservatory faculty. Throughout the study, optimum criteria for variable acoustics are established for different music performance types. The results align with the first hypothesis and indicate that there are significant variations in acoustic metrics based on the type of musical performances.

In the scope of this study, acoustical field measurements are carried out at Bilkent Music Hall in compliance with ISO 3382-1 standards. In the field measurements, room impulse responses are collected to estimate T30, C80 and EDT for two configurations provided by the variable absorption system, which are: retracted and closed states of the wooden doors. The measurement results are analysed according to the optimum range established by previous literature (as presented in Table 3).

In the majority of concert venues, the reverberation time is longer at lower frequencies, which results in a warmer quality of sound. However, the measurements of Bilkent Music Hall indicate excessive absorption at low frequencies in both retracted and closed states of the wooden doors, with a slight increase in RT when the doors are closed. The investigation into the possible causes of the acoustical deficiency identified thin wooden paneling as a potential problem. The findings of the field tests demonstrate that the existing retractable wooden door system as well as the original single layer gypsum board applications on upper side walls and ceiling indeed contribute to excessive low-frequency absorption, which results in poor acoustical performance in certain musical performance scenarios. This finding confirms the second hypothesis, thereby underscoring the necessity for modifications to the panel system as well as the gypsum cladding. However, the parallel trend of T30 values in both retracted and closed states reveals that the only cause of the bass absorption cannot be the wooden doors, as well as the wooden wall surfaces apart from the doors.

Further analysis on the contribution of interior finishes is investigated through acoustical simulations. A 3D model of the music hall is generated and tuned in accordance with the measured values of T30 and C80 in ODEON. The gypsum board walls emerge as the most effective absorber at 125 Hz, demonstrating substantial absorption area of 473 sabins. Non-operable wooden walls offer moderate absorption throughout the frequency spectrum, with notable impact at 125 Hz of 59 sabins and at high frequencies of 42 sabins. Operable wooden doors primarily absorb lower frequencies, particularly at 125 Hz 40 sabins. Mineral wool stands out as highly effective across all frequencies, with high absorption at mid and high frequency spectrum. These findings underscore the importance of selecting appropriate materials based on specific acoustic requirements, considering

their different sound absorption characteristics across the whole frequency spectrum.

The analysis of the sound absorption values across octave bands indicates that the concert hall exhibits a high absorption capacity for low-frequency sounds, with absorption gradually decreasing as the frequency increases. This acoustic profile leads to an imbalance in the acoustic environment, resulting in excessively dry sound at bass frequencies, which is particularly unfavourable for orchestral music performances. The relatively lower sound absorption at higher frequencies suggests room for improvement to ensure a more evenly balanced acoustical environment. To achieve optimal acoustical conditions for a variety of musical performances, it is essential to modify the acoustical characteristics of plasterboard and wooden panels. These adjustments can help to tune the hall's acoustics for various music types, enhancing the overall auditory experience for performers and audiences. To address the detected acoustical issue, acoustical simulations are utilized to evaluate acoustical design solutions. The proposed interventions are increasing the thickness and/or number of layers of currently single-layer plasterboard and thin wooden surfaces. The recommended interior finishing materials, which exhibit lower sound absorption coefficients at low frequencies, include double-layer gypsum board and wood panelling with a thickness of 50 mm. The application of design proposal results in a T30 value of 1.73 s at low frequencies in the retracted state and 1.85 s at mid frequencies, suitable for chamber music performances. In the closed state, average T30 becomes 1.96 s at low frequencies and 2.12 s at mid frequencies, rendering the hall suitable for symphonic music performances featuring a variety of instruments. Acoustical simulations suggest that increasing the wooden door thickness and increasing the number of gypsum board layer can mitigate the acoustical issues associated with the excessive low-frequency sound absorption. This supports the third hypothesis and provides a clear direction for

potential acoustical improvements. The results of the acoustical simulations demonstrate that optimising concert halls based on objective acoustic metrics enhances their adaptability to a range of musical performances. Furthermore, the specific acoustical interventions at Bilkent Music Hall can improve overall acoustical performance.

The preferences of BSO members and Bilkent Conservatory faculty and students are investigated through a questionnaire. This method is a crucial step of the investigation, as the participants regularly perform in the venue, providing valuable subjective evaluations on the acoustical conditions of the hall. The collected data is evaluated through statistical tests utilizing independent samples t-tests and Pearson correlations. The analysis focused on two groups: string and wind instrument players. The t-test reveals significant differences in musicians' perceptions of the acoustical environment. String instrument players consistently provide higher ratings for the acoustical quality of Bilkent Music Hall, which may be attributed to the distinct acoustic requirements and sound production characteristics of the instruments played by each group.

Descriptive statistics highlight a statistically significant mean difference between BSO members and conservatory faculty and students considering intimacy, overall impression for orchestral performances and orchestral performances for vocal accompaniment. Also, there is statistically significant mean difference between preferences of string and wind players for sound balance between treble to mid frequencies, overall impression for orchestral performances and orchestral performances for vocal accompaniment:

- ☐ Low frequencies are perceived as flat, causing imbalance between string and wind instruments, particularly bass instruments.
- ☐ Brass instruments either overpower the orchestra or fail to be heard distinctly, depending on stage position.

□ 58% of string instrument players rate the Bilkent Music Hall as well-balanced while, only 29% of wind instrument players rate the hall as well-balanced.

□ Musicians prefer 'Reverberance' ($\mu > 4$) over 'Clarity' ($\mu > 3.6$), indicating a contradiction between objective measurements and subjective preferences.

□ Vocalists report imbalances between the chorus and orchestra and uneven sound distribution during solo performances.

□ Chamber music vocalists struggle to hear instruments and other musicians due to stage positioning, causing acoustic shadows.

Survey responses indicate that musicians' preferences for reverberance vary based on their instruments. This aligns with the fourth hypothesis, emphasizing the need for adjustable acoustics to cater to diverse musical requirements. In conclusion, this research contributes valuable insights into the practical applications and challenges of passive variable acoustic systems in concert halls. The integration of both objective and subjective assessment methods proved to be essential in understanding and optimizing the acoustical environment of Bilkent Music Hall. In addition to confirming the hypotheses, the study offers practical recommendations to enhance the acoustical performance of Bilkent Music Hall and aims that the hall meets the requirements of a diverse array of musical performances.

As a next step, auralization can be used to reproduce musical excerpts using the proposed acoustical solutions, allowing for testing of the revised acoustical conditions across various performances. Subsequently, paired comparison tests can be conducted with same participants from this study to compare the recommended conditions with those from the earlier phase. Another future step can be the inclusion of objective parameters such as strength (G), lateral fraction (LF), and interaural cross correlation (IACC). Including these

additional metrics can provide the medium for discussion on the effects of room/hall geometry, in comparison to other precedent concert halls worldwide that are discussed within this study.



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APPENDICES

Appendix A- Field Measurements

Table A 1. T30 at Bilkent Music Hall over 1/1 octave bands in seconds, retracted state

Bilkent Music Hall, retracted state (T30)						
S/R	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
S1R1	1,18	1,13	1,77	1,93	1,84	1,54
S1R2	1,28	1,36	1,67	1,92	1,89	1,63
S1R3	1,20	1,47	1,69	1,92	1,85	1,51
S1R4	1,35	1,45	1,66	2,06	1,92	1,61
S1R5	1,43	1,34	1,76	1,99	1,95	1,61
S1R6	1,32	1,56	1,75	2,02	1,96	1,61
S1R7	1,31	1,39	1,72	1,97	1,91	1,61
S1R8	1,45	1,55	1,81	2,05	1,99	1,69
S1R9	1,14	1,31	1,63	2,01	1,92	1,63
S1R10	1,38	1,28	1,71	1,90	1,83	1,46
S1R11	1,27	1,53	1,82	2,02	1,95	1,66
S1R12	1,33	1,51	1,83	2,05	1,98	1,65
S1R13	1,32	1,32	1,82	2,00	1,97	1,68
S1R14	1,19	1,45	1,75	1,99	1,95	1,66
S2R1	1,34	1,57	1,86	1,88	1,88	1,63
S2R2	1,35	1,53	1,86	1,95	1,95	1,61
S2R5	1,09	1,50	1,68	2,00	1,94	1,61
S2R7	1,17	1,34	1,81	1,94	1,91	1,62
S2R10	1,31	1,48	1,58	1,85	1,83	1,55

Table A 2. T30 at Bilkent Music Hall over 1/1 octave bands in seconds, closed state

Bilkent Music Hall, closed state (T30)						
S/R	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
S1R1	1,46	1,60	1,95	2,22	2,15	1,76
S1R2	1,52	1,75	1,99	2,31	2,20	1,81
S1R3	1,57	1,61	2,06	2,17	2,14	1,79
S1R4	1,61	1,74	2,01	2,18	2,16	1,77
S1R5	1,60	1,63	1,91	2,20	2,22	1,75
S1R6	1,43	1,71	2,10	2,26	2,20	1,76
S1R7	1,70	1,56	1,99	2,20	2,17	1,79
S1R8	1,57	1,71	2,02	2,30	2,18	1,83
S1R9	1,19	1,59	1,98	2,28	2,13	1,79
S1R10	1,40	1,75	2,02	2,19	2,16	1,68

S1R11	1,60	1,71	2,04	2,30	2,24	1,84
S1R12	1,33	1,76	2,13	2,13	2,19	1,86
S1R14	1,49	1,60	2,05	2,24	2,22	1,85
S2R10	1,56	1,47	1,88	2,21	2,15	1,77

Table A 3. EDT at Bilkent Music Hall over 1/1 octave bands in seconds, retracted state

Bilkent Music Hall, retracted state (EDT)						
S/R	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
S1R1	1,64	1,34	1,79	1,44	1,46	1,08
S1R2	1,35	1,55	1,58	1,92	1,89	1,54
S1R3	1,18	1,14	1,38	1,60	1,57	1,33
S1R4	1,41	1,30	1,65	2,04	1,86	1,41
S1R5	1,20	1,45	1,54	1,86	1,83	1,49
S1R6	1,25	1,28	1,72	1,71	1,70	1,47
S1R7	1,35	1,37	1,59	1,57	1,63	1,29
S1R8	1,35	1,45	1,78	2,06	2,05	1,75
S1R9	0,98	1,08	1,44	1,69	1,61	1,26
S1R10	0,69	1,39	1,58	1,71	1,43	1,31
S1R11	1,38	1,44	1,69	1,90	2,03	1,78
S1R12	0,94	1,16	1,98	1,98	1,98	1,71
S1R13	0,86	1,45	1,64	1,94	2,03	1,70
S1R14	1,64	1,67	1,75	2,00	1,87	1,54
S2R1	1,08	1,43	1,79	1,91	1,76	1,46
S2R2	1,26	1,24	1,51	1,86	1,92	1,56
S2R5	1,13	1,30	1,60	1,83	1,65	1,46
S2R7	0,89	1,57	1,40	1,71	1,47	0,95
S2R10	0,88	1,19	1,42	1,75	1,60	1,31

Table A 4. EDT at Bilkent Music Hall over 1/1 octave bands in seconds, closed state

Bilkent Music Hall, closed state (EDT)						
S/R	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
S1R1	1,54	0,87	1,70	1,80	1,63	1,38
S1R2	1,46	1,79	2,03	2,09	2,08	1,67
S1R3	1,26	1,54	1,81	1,72	1,81	1,44
S1R4	1,51	1,66	2,07	2,30	1,99	1,59
S1R5	1,07	1,50	2,07	2,02	1,89	1,63
S1R6	1,26	1,48	1,80	1,99	1,95	1,65
S1R7	1,10	1,77	1,52	2,00	2,03	1,54
S1R8	1,62	1,67	2,16	2,47	2,38	1,92
S1R9	1,34	1,89	2,09	2,24	1,90	1,67
S1R10	1,45	1,62	1,68	2,02	1,84	1,48
S1R11	1,23	1,76	2,07	2,23	2,24	1,82

S1R12	1,41	1,66	1,81	2,43	2,23	1,94
S1R13	1,77	1,96	2,19	2,39	2,12	1,71
S1R14	1,37	1,68	1,72	1,76	1,75	1,49
S2R1	1,54	0,87	1,70	1,80	1,63	1,38
S2R2	1,46	1,79	2,03	2,09	2,08	1,67
S2R5	1,26	1,54	1,81	1,72	1,81	1,44
S2R7	1,51	1,66	2,07	2,30	1,99	1,59
S2R10	1,07	1,50	2,07	2,02	1,89	1,63

Table A 5. C80 at Bilkent Music Hall over 1/1 octave bands in dB, retracted state

Bilkent Music Hall, retracted state (C80)						
S/R	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
S1R1	1,94	4,18	3,81	3,05	4,69	7,36
S1R2	-3,63	1,65	1,87	0,34	0,02	1,23
S1R3	-6,64	1,2	-1,19	-1,38	-1,96	-1,22
S1R4	0,72	-0,91	-0,39	0,59	-0,86	1,13
S1R5	2,82	2,65	1,89	-0,44	-2,12	-0,41
S1R6	-5,02	0,57	1,74	-0,25	-0,79	0,39
S1R7	-3,87	0,88	3,31	2,75	-0,07	0,82
S1R8	-0,07	1,55	-0,21	-2,79	-1,82	-0,81
S1R9	4,47	7,42	4,56	4,24	3,91	4,3
S1R10	8,38	8,36	6,92	4,92	6,44	7,08
S1R11	1,4	2,13	0,47	-0,06	-0,46	1,68
S1R12	1,28	0,69	-0,47	-1,45	-2,37	-0,08
S1R13	-0,54	2,25	1	-0,71	-1,08	-0,44
S1R14	4,88	0,95	0,56	1,05	2,79	5,45
S2R1	2,22	2,62	2,91	-0,96	-1,56	0,57
S2R2	-3,67	1,7	-0,76	0,83	1,35	1,52
S2R5	-3,84	0,94	0,09	-0,05	0,06	-0,19
S2R7	-0,26	0,9	1,37	2,12	2,05	4,12
S2R10	3,19	8,01	4,67	5,54	5,34	5,78

Table A 6. C80 at Bilkent Music Hall over 1/1 octave bands in dB, closed state

Bilkent Music Hall, closed state (C80)						
S/R	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
S1R1	0,54	5,12	3,33	0,61	3,22	3,04
S1R2	-3,9	2,74	0,36	0,21	-1,28	0,19
S1R3	-2,3	1,74	0,1	1,35	0,13	0,9
S1R4	1,15	-1,75	-0,37	-0,02	-0,73	0,79

S1R5	3,07	0,51	0,06	-0,57	-0,7	-0,21
S1R6	-2,74	2,44	1,68	-0,67	-1,35	-0,3
S1R7	-2,98	0	1,98	0,36	-0,12	0,77
S1R8	0,25	-0,86	-1,87	-2,62	-3,96	-2,21
S1R9	2,36	3,73	3,42	2,44	0,49	2,63
S1R10	2,14	7,74	4	3,64	4,94	5,37
S1R11	1,06	0,68	-1,55	-0,35	-1,1	-0,2
S1R12	-0,4	1,15	-0,69	-1,97	-3,1	-1,99
S1R13	-0,54	2,25	1	-0,71	-1,08	-0,44
S1R14	4,88	0,95	0,56	1,05	2,79	5,45
S2R1	2,22	2,62	2,91	-0,96	-1,56	0,57
S2R2	-3,67	1,7	-0,76	0,83	1,35	1,52
S2R5	-3,84	0,94	0,09	-0,05	0,06	-0,19
S2R7	-0,26	0,9	1,37	2,12	2,05	4,12
S2R10	3,19	8,01	4,67	5,54	5,34	5,78

Appendix B - Questionnaire

B. 1. The questionnaire used for subjective evaluation of Bilkent Music Hall.

Bilkent University | Faculty of Art, Design and Architecture | Department of Architecture
Master of Architecture – Questionnaire Study for Bilkent Music Hall

Age:

Gender:

Which instrument do you play? How long have you playing that instrument?

How long have you been playing with Bilkent Symphony Orchestra?

How would you rate the acoustical quality of Bilkent Concert Hall as to the following criteria?

1. Clarity

	1	2	3	4	5	
Muddy	☐	☐	☐	☐	☐	Clear

2. Reverberance

	1	2	3	4	5	
Dead	☐	☐	☐	☐	☐	Live

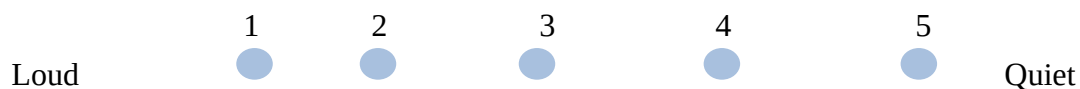
3. Envelopment

	1	2	3	4	5	
Expansive	☐	☐	☐	☐	☐	Constricted

4. Intimacy

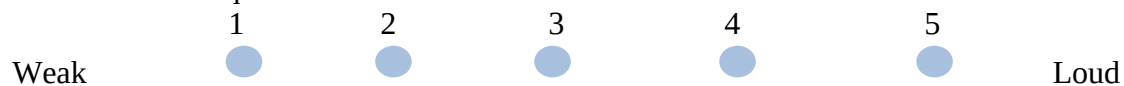
	1	2	3	4	5	
Remote	☐	☐	☐	☐	☐	Intimate

5. Loudness



6. Balance

Treble re. mid-frequencies



Bass re. mid-frequencies



Singers/Soloists re. orchestra



7. Background Noise

Inaudible	Acceptable	Tolerable	Intolerable
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8. Overall Impression

For Chamber Music

Very Poor	Poor		Mediocre	Reasonable	Good	Very good	Excellent
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For Orchestral Music

Very Poor	Poor	Mediocre	Reasonable	Good	Very good	Excellent
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9. Have you noticed much difference when you play in different states of the doors of the hall (semi-closed and/or full open etc.)?

10. Additional comments

Appendix C – Original Architectural Drawings of Bilkent

Music Hall

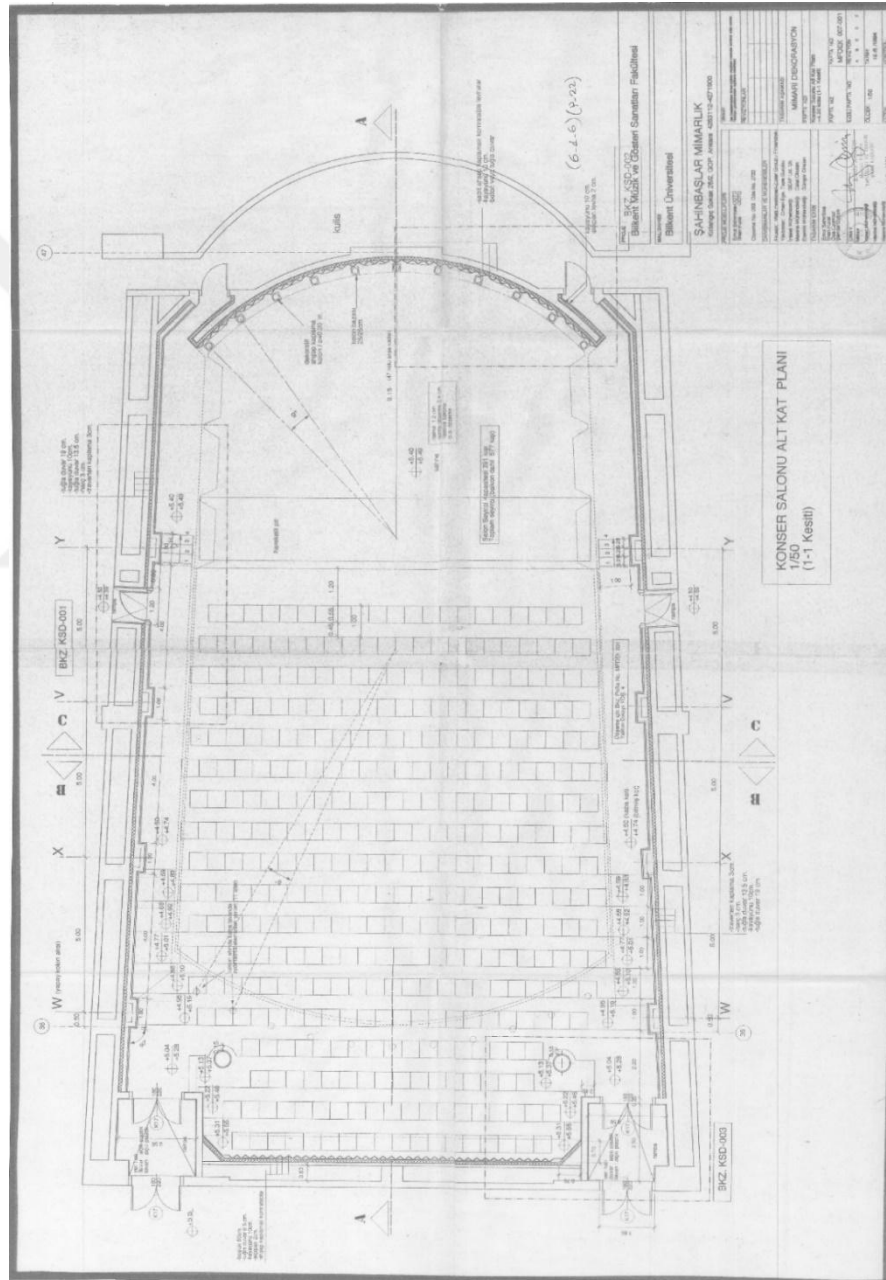


Figure C 1. Ground floor plan of Bilkent Music Hall

Appendix D - Ethics Committee Approval



Bilkent Üniversitesi
Akademik İşler Rektör Yardımcılığı

Tarih : 15 Nisan 2023

Gönderilen : Aslı Altun

Danışman : Zühre Sü Gül

Gönderen : H. Altay Güvenir
İnsan Araştırmaları Etik Kurulu Başkanı

Konu : "An investigation ..." çalışması etik kurul onayı

Üniversitemiz İnsan Araştırmaları Etik Kurulu, 15 Nisan 2023 tarihli görüşme sonucu, "*An investigation on the effects of variable sound absorption systems on the acoustic performance in concert halls for various music types: The case of Bilkent Music Hall*" isimli çalışmanız kapsamında yapmayı önerdiğiniz etkinlik için etik onay vermiş bulunmaktadır. Onay, ekte verilmiş olan çalışma önerisi, çalışma yürütücüleri ve bilgilendirme formu için geçerlidir.

Bu onay, yapmayı önerdiğiniz çalışmanın genel bilim etiği açısından bir değerlendirmedir. Çalışmanızda, kurumumuzun değerlendirmesi dışında kalabilen özel etik ve yasal sınırlamalara uymakla ayrıca yükümlüsünüz.

Kovid-19 salgını nedeniyle konulmuş olan kısıtlamaların yürürlükte olduğu süre içinde, tüm komite toplantıları elektronik ortamda yapılmaktadır; aşağıda isimleri bulunan Bilkent Üniversitesi Etik Kurulu Üyeleri adına bu yazıyı imzalama yetkisi kurul başkanındadır.

Etik Kurul Üyeleri:

Ünvan / İsim	Bölüm / Uzmanlık	
Prof.Dr. H. Altay Güvenir	Bilgisayar Mühendisliği	Başkan
Prof.Dr. Erdal Onar	Hukuk	Üye
Prof.Dr. Haldun Özaktaş	Elektrik ve Elektronik Müh.	Üye
Doç.Dr. Işık Yuluğ	Moleküler Biyoloji ve Genetik	Üye
Dr. Öğr. Üyesi Burcu Ayşen Örgen	Psikoloji	Üye
Dr. Öğr. Üyesi Didem Özkul McGeoch	İletişim ve Tasarım	Yedek Üye
Dr. Öğr. Üyesi A.Barış Özbilen	Hukuk	Yedek Üye

Kurul karar/toplantı No: 2023_04_15_01

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