ACOUSTIC EVALUATION OF THE SURP YERRORTUTYUN CHURCH AND ACOUSTICAL PROPOSALS FOR ITS MULTI-FUNCTIONAL USE

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
BUILDING SCIENCE IN ARCHITECTURE

MAY 2022

Approval of the thesis:

ACOUSTIC EVALUATION OF THE SURP YERRORTUTYUN CHURCH AND ACOUSTICAL PROPOSALS FOR ITS MULTI-FUNCTIONAL USE

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ABSTRACT

ACOUSTIC EVALUATION OF THE SURP YERRORTUTYUN CHURCH AND ACOUSTICAL PROPOSALS FOR ITS MULTI-FUNCTIONAL USE

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May 2022, 148 pages

The main focuses of the study are (i) to define the as-is acoustical features of the Surp Yerrortutyun Church and its current acoustical problems by means of field measurements and acoustical simulation analyses, and (ii) to assess acoustic performances of some scenario-based proposals for the specific musical- and speech-related activities which are the real demands of local authorities. The investigation is composed of acoustic field measurements held in the monument and the acoustic simulation analyses of the monument's computer model, which is calibrated according to the data achieved by field measurements. The acoustic parameters of Reverberation Time (T_{20}, s), Early Decay Time (EDT, s), Clarity (C_{80}, dB), and Speech Transmission Index (STI, unitless) were used for the evaluations of field and simulation data. The field measurements exhibit the existing acoustic environment of the Surp Yerrortutyun Church, which underwent many repairs. All proposals integrate sound absorptive surfaces, made of transparent fabrics (curtains), into the Church space, attached or hung free by mountable-demountable (temporary) encircling systems. The results show that the Surp Yerrortutyun Church in existing conditions suffer from excessive longer reverberation times and low clarity levels. The blurred sound environment and poor speech intelligibility in the Church point out the need for acoustic improvement. When compared to the recommended values in the literature, all acoustical rehabilitation proposals enhance the Church's acoustic environment at medium and high frequencies, specifically for music-related activities. The outcomes of the research conducted on this church museum are expected to be guiding for the identification and rehabilitation of acoustic problems of similar monuments as well as for the development of innovative and portable acoustic control assemblies, which can be temporarily used in monuments.

Keywords: Church-museum, Sivrihisar Surp Yerrortutyun Church (Sivrihisar Armenian Church), field acoustical measurements, acoustical simulation analyses, acoustic rehabilitation proposals

ÖZ

SURP YERRORTYUN KİLİSESİNİN AKUSTİK DEĞERLENDİRMESİ VE ÇOK İŞLEVLİ KULLANIMINA YÖNELİK AKUSTİK ÖNERİLER

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Bu araştırmanın temel hedeflerinden ilki (i) tarihi Surp Yerrortutyun Kilisesi'nin akustik özelliklerini ve mevcut akustik problemlerini saha ölçümleri ve akustik benzetim analizleri ile tanımlamaktır. İkincisi, (ii) yerel yönetimin talepleri doğrultusunda kilisenin müzik ve konuşma etkinliklerine ev sahipliği yapmasına yönelik akustik iyileştirme önerileri geliştirmek ve bu önerilerin akustik performanslarını değerlendirmektir. Çalışmalar, tarihi kilisede yapılan akustik saha ölçümleri ve bu ölçümlerinden elde edilen verilere göre kalibre edilmiş bilgisayar modelinin akustik simülasyon analizlerine dayanmaktadır. Yerinde ölçümler ve benzetim verilerinin değerlendirilmesi için Çınlama Süresi (T_{20}, s), Erken Sönümleme Süresi (EDT, s), Netlik (C_{80}, dB) ve Konuşma İletim İndeksi (STI, birimsiz) akustik parametreleri kullanılmıştır. Bu veriler yapıldığı günden bu yana onarım geçiren Surp Yerrortutyun Kilisesi'nin mevcut akustik ortamını tanımlamaktadır. Buna göre akustik iyileştirme önerileri, sökülüp takılabilir (geçici) çevreleme sistemleri ile tutturulmuş veya serbest halde asılmış yarı saydam ses yutucu kumaşların (perdelerin) kilise hacmine dahil edilmesiyle oluşturulmuştur. Elde edilen veriler, Surp Yerrortutyun Kilisesi'nin mevcut koşullarda aşırı uzun çınlama sürelerine ve düşük netlik düzeyine sahip olduğunu göstermektedir. Kilisedeki bulanık ses ortamı ve zayıf konuşma anlaşılırlığı, akustik iyileştirmenin gerekliliğine işaret etmektedir. Literatürde önerilen değerlerle karşılaştırıldığında, tüm akustik tasarım önerileri, Kilise'nin akustik ortamını özellikle müzikle ilgili faaliyetlere ev sahipliği yaptığı durumda orta ve yüksek frekanslarda iyileştirdiğini ortaya koymuştur. Bu kilise-müze üzerinde yürütülen araştırma sonuçlarının, benzer anıtların akustik sorunlarının tespiti ve rehabilitasyonu ile anıtlarda geçici olarak kullanılabilecek yenilikçi ve taşınabilir akustik kontrol düzeneklerinin geliştirilmesinde yol gösterici olması beklenmektedir.

Anahtar Kelimeler: Kilise-müze, Sivrihisar Surp Yerrortutyun Kilisesi (Sivrihisar Ermeni Kilisesi), yerinde akustik ölçümler, akustik benzetim analizleri, akustik iyileştirme önerileri

To my beloved family

ACKNOWLEDGMENTS

My sincere appreciation is to my guide, Assoc. Prof. Dr. Ayşe Tavukçuoğlu for her endless support and encouragement. Her impressive commentaries have always enlightened my road, aided in overcoming blockages throughout this journey, and guided every study step.

I would also like to express my sincere appreciation to my co-supervisor, Prof. Dr. Mehmet Çalışkan, for his valuable support, crucial guiding commentaries, and sharing his wisdom.

Special thanks to the Ministry of Culture and Tourism (T.C. Kültür ve Turizm Bakanlığı), Ankara Directorate of Surveying and Monuments (Ankara Rölöve ve Anıtlar Müdürlüğü), Eskişehir Regional Board of Protection of Cultural Heritage (Eskişehir Kültür Varlıklarını Koruma Bölge Kurulu Müdürlüğü) and Sivrihisar Municipality (Sivrihisar Belediyesi) for providing measured drawings of Surp Yerrortutyun Armenian Church and for giving permission on field measurements.

I would like to extend my appreciation to Erdal Kara and Karakutu Electroacoustics team for their technical support on field measurements. Also, special thanks to Zühre Sü Gül and Mezzo Stüdyo team members for their technical support on acoustical simulation studies.

Most special thanks are to my precious one Emir Bahadır Ateş for his presence, endless support, trust, and love. In closing, my greatest gratitudes are to my family. My parents, Şeylâ & Abdullah Cangür, Sevilay & Emir Ahmet Ateş, my lovely sister Suendam Cangür-Ezgü, my brother Atakan Ezgü, my beloved nephew Barış Ezgü and my sister Jülide İpek Ateş are gratefully acknowledged for their trust and support.

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LIST OF ABBREVIATIONS

°C	C celsius Degree
Avg	Average
C_{80}	Clarity
dB	decibel
EDT	Early Decay Time
Hz	Hertz
ISO	International Organization for Standardization
JND	Just Noticeable Difference
Leq	Equivalent Continuous Sound Level
NC	Noise Criteria
R	Receiver
RT	Reverberation Time
S	Sound Source
SPL	Sound Pressure Level
SPLA	A Weighted Sound Pressure Level
STI	Speech Transmission Index
T_{20}	Reverberation for the first 30 dB decay
T_{30}	Reverberation for the first 20 dB decay
V	Volume

CHAPTER 1

INTRODUCTION

Many historical church museums in Turkey host cultural, scientific, and social events to contribute to social development activities. This tendency has revealed the need to eliminate acoustic problems or control the indoor acoustical environment. Therefore, this research is conducted on the acoustical improvement of churches for their multi-purpose uses and their performance assessments.

In this chapter, the problem statement, arguments, objectives, and motivation of the study are presented.

1.1 ARGUMENT

There is a necessity to better understand the as-is acoustical features of churches and the changes that occurred in time in their indoor acoustical environment to develop conservation projects by keeping their authentic features, and improving the acoustic environment for speech and music-related activities. In Turkey, many historic church buildings are currently used as a museum, such as Hagia Irene Museum (Istanbul) and Surp Yerrortutyun Church Museum (Eskişehir). Since those monuments in Anatolia are under the auspices of Municipality and/or the Turkish Ministry of Culture and Tourism, those authorities are also being used these monuments to host some events such as conferences, chamber music concerts, and exhibitions (Dedeoğlu, 2019; İnceoğlu, 2013). However, most churches suffer from poor acoustical conditions for hosting these events. Surp Yerrortutyun Church Museum in Sivrihisar (Eskişehir) is one of the historical churches in Anatolia and is currently used as a museum. The Sivrihisar Municipality and Ministry of Culture and Tourism use this monument for cultural activities. Following the activities, many complaints about the acoustical problems have revealed the necessity of acoustic improvement in the church's space.

Therefore, the relevant authorities demand, if possible, is to improve the poor indoor acoustic environment of the church and to develop some suggestions to be guiding for its multi-purpose use.

The Municipality and the people of Sivrihisar put their efforts into their hometown's social and cultural development, thereby for awareness-raising of people in Turkey on the cultural values of Sivrihisar (Bursa Eskişehir Bilecik Kalkınma Ajansı, 2012; Uysal, 2019). Their efforts have focused on the local festival and congress/conference organizations enriched with cultural and touristic activities. The local municipality mentions that Surp Yerrortutyun Church Museum has a crucial role in this regard and has many attempts to host national/international conferences, musical events, sculpture, and painting exhibitions in the Church, even at its peripheral yard (İtez, 2019). However, the attempts in the form of conference and trio concerts till now have failed due to considerably-poor acoustic conditions in the Church. Therefore, developing some proposals to improve the existing acoustic conditions of the Church and producing data to be guiding for improvement of its acoustic features with consciousness on cultural heritage conservation principles are needed.

This study focuses on research:

- forming scientific data to find out solutions for acoustic improvement of the existing church indoors when they are intended to be used for musical and speech activities, and
- using the data achieved by this study for acoustical rehabilitation practices with consciousness on cultural heritage conservation issues.

Considering these focuses, the study is conducted on Surp Yerrortutyun Church Museum as a representative case. This study is shaped to evaluate its existing acoustical features and propose and assess some solutions having the potential to provide an appropriate acoustic environment.

1.2 AIM AND OBJECTIVES

The main purpose of the study is to improve the acoustical performance of the Surp Yerrortutyun Church for musical and speech-related activities by way of developing proposals according to the defined scenarios. The main targets of the study are:

- to examine whether the highly-reverberant sound field of a church can be controlled with demountable and modularly-shaped acoustical panels or fabrics,
- to calibrate the produced simulation model based on the field measurement data to test the adequacy of the suggested improvement studies and to minimize errors,
- to develop a portable encircling system composed of panels and/or fabrics considering the as-is condition of the church and for some specific musical and speech activities.

For achieving those targets, the main objectives of the study are:

- to examine the existing acoustic features of the church museum and its current acoustical problems in terms of basic acoustical parameters.
- to assess the as-is acoustical features of the Surp Yerrortutuyun Church in reference to the recommended/reference values defined in the literature, and to discuss its acoustical performance of as-is case.
- to suggest some proposals based on scenarios in terms of the design of the venue and seating layout for specific activities to control highly-reverberant sound field of the Church.
- to suggest the demountable and modular acoustical panel arrangements or fabric frames encircling the defined space vertically and horizontally.
- to assess their performances to control the reverberant field at various frequencies and use that knowledge for their enhancement.

The outcomes of the research and the analytical methods conducted on the Surp Yerrortutuyun Church are expected to be useful for:

- the acoustical rehabilitation works of the monuments suffer from similar problems.
- the development of demountable encircling systems as innovative and portable acoustical control elements that can be adapted in monuments without giving damage.

1.3 DISPOSITION

This research is presented in six chapters. The first chapter, *'introduction',* covers the argument, aim, objectives and disposition. The second chapter, *'literature review',* comprises church architecture and acoustics, including investigation of recommended values defined in the literature and a comparison with acoustic properties of similar volumed churches in Europa. Also, acoustic data analyzing tools are compiled, and some case studies on church acoustic improvements are mentioned in this chapter. The third chapter is given in the heading *'material and method'*, provides the information about Surp Yerrortutyun Church, including historical background, architectural features, basic interventions. The methodology that followed behind this study and data collection, including field tests and simulations analyses, designed scenarios, review of some acoustical materials, and design criteria for improvement proposals, are also presented in this chapter. The fourth chapter, *'results',* displays the analysis, outcomes, and results of field measurements and proposal simulations based on scenarios. The fifth chapter, *'discussions',* is made of arguments in relation to the field measurements and simulation analyses for the defined scenario to assess the adequacy of the proposals. All the outcomes, arguments, and findings are summarized in the *'conclusion'* in the sixth chapter, the last.

CHAPTER 2

LITERATURE REVIEW

This study examines the as-is acoustic and architectural features of the Surp Yerrortutyun Church. Under this chapter, to provide background information, the architectural features of the churches, recommended acoustic conditions for specific events, and acoustic parameters necessary for data analysis are explained separately.

2.1 ARCHITECTURAL FEATURES OF THE ORTHODOX CHURCH

The design of Orthodox churches may vary by period and region over the world, and the characteristics of the surrounding cultures could have influenced their architectural designs. Although each one is unique, several elements are in common (Hart, 2003).

Basically, church design can be divided into three main groups: centrally oriented, cruciform, and basilica type. Centrally oriented churches can take various forms, such as circular, octagonal, or polygonal. Although centrally oriented churches are considered impractical for the regular Christian liturgy, they are suitable for Martyriums (a church that is built in the memory of a saint or holy site) due to their center-oriented design.

In general, Orthodox churches are designed to allow regular liturgy by integrating the features of the centrally oriented plan type (Elicio & Martellotta, 2015) with those of the basilica, as in Hagia Sophia or designed in a cruciform plan (Hart, 2003). There are also lots of traditional cathedrals and churches designed in cruciform and basilica plan (Kleiner et al., 2010c).

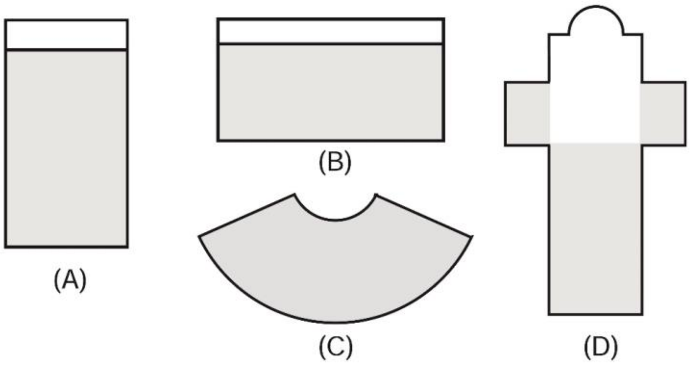


Figure 2.1 Some typical floor plans for worship places, possible seating areas marked as gray A) The Basilica, which is common for synagogues and churches, and (D) Cruciform are mostly common for traditional churches. (B) Plan often used for mosques. (C) Plan often used for evangelical churches *(Kleiner et al., 2010c)*

The basilica type church plan was developed based on an ancient secular type of building with a rectangular form belonging to the Roman period. In general, the rectangular form has a curved apse on the east side, and there may be rows of columns longitudinal arranged in the plan. The cover coat is in the form of a hipped roof, sometimes with barrel vaults but rarely with a dome or domes. The roof above the fields formed by column rows, which are called an aisle, is lower than the main part (nave) of the Church. There are windows located at the top named clerestory.

Cruciform type plan (Figure 2.2) is specially designed for Christian worship places considering the requirements of a Church (Hart, 2003).

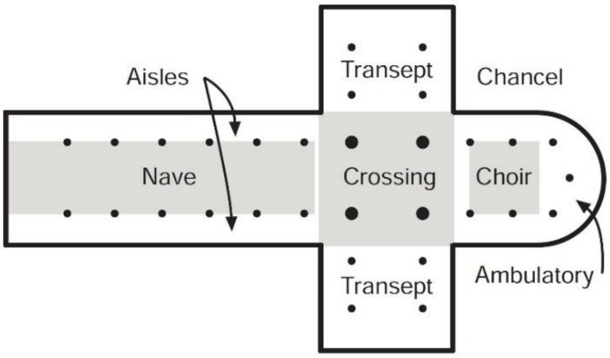


***Figure 2.2* Some terms used in describing cruciform Roman Catholic and Protestant churches *(Kleiner et al., 2010c)*.**

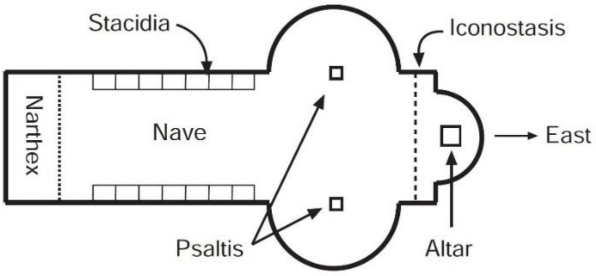


Figure 2.3 Some terms used in describing cruciform Greek Orthodox churches ***(Kleiner et al., 2010c)***

The parts of the church are briefly summarized in Figures 2.2 and 2.3. Accordingly, the naos is the main zone in the church reserved for the congregation (Karabey, 2001), and it is the central part located between the narthex and bema. Elongating from the narthex (entrance) to the crossing, the central nave part (naos) of a Christian Basilica is often separated into side aisles by pillars. The floor of the sanctuary area (the east of a church) may be higher than the naos in some cases and form a stage called a Chancel. This creates highlighted form of the temple as the holiest part of the church named Bema. The apse is a semicircular/polygonal form, topped by a hemispherical vault, located in this sanctuary part. Aisles are the paths flanked into the central nave, and often separated by a colonnade, or arcade (Gáldy, 2016; Marinis, 2013).

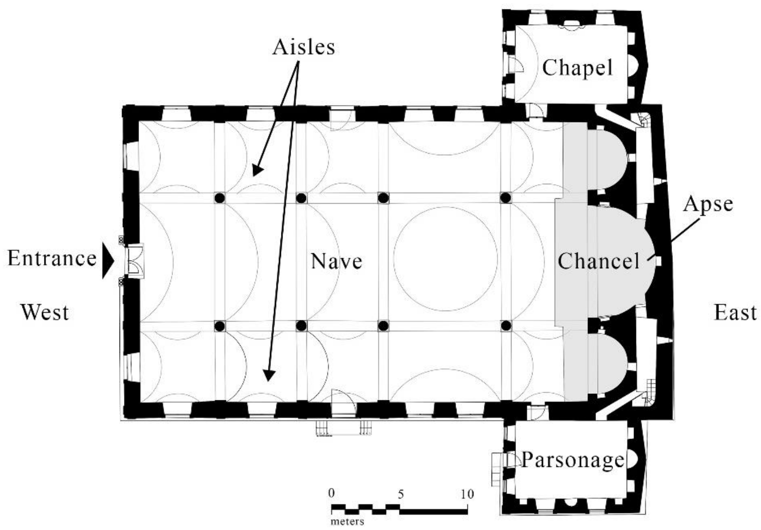


Figure 2.4 Parts of the Surp Yerrortutyun Church ***(Source: Illustrated by the author)***

Considering the information above, Surp Yerrortutyun Church Museum is a medium-sized church without a transept and approximately has 10 000 m^3 volume. As presented in Figure 2.4, the monument was designed based on a three-nave domed basilica plan type, including a Chapel and Parsonage (house of clergy).

2.2 ACOUSTICAL PARAMETERS

The main measurable acoustical parameters which are used to assess the acoustic features of architectural space are Reverberation time (RT, s), Early Decay Time (EDT, s), Clarity (C_{80}, dB), and Speech Transmission Index (STI, unitless) (Barron, 2005). In addition, for the architectural spaces where the silence is crucial, the background noise (L_{eq}, dB) parameter is the other measurable acoustical criterion that should be considered in acoustic features analyses (Sü Gül & Çalışkan, 2013). Here, these parameters' definitions and the relevant numerical ranges recommended for several functions of architectural spaces are summarized in the following subheadings.

2.2.1 REVERBERATION TIME (RT, T_{30}, T_{20})

When the sound energy travels in a volume, it loses some of its energy as it reflects, depending on the sound absorption coefficient of the surface materials. Thus, the reflected sound, which is produced after the direct sound, weakens over time. In order to evaluate this process and its effects on acoustical comfort, some parameters are defined in the literature.

Reverberation time (RT) is the primary acoustic metric for scientific research. It is defined as the time elapsed for sound to decay by 60 dB from the state of equilibrium after the sound source shuts down (Kleiner et al., 2010b). RT is determined separately for each octave band, usually defined by 125, 250, 500, 1000, 2000, and 4000 Hz frequencies (Beranek, 2004). The reverberation time from the energy decay curve is calculated by measuring the T_{30} and/or T_{20} parameters. T_{30} represents the time required for the sound level in the room to decrease by 30 dB, and T_{20} refers to the time it takes for the sound level to decrease by 20 dB.

In this research, RT of the Surp Yerrorutyun Church was calculated as three times the T_{20} value in the field measurements (Cangür et al., 2021).

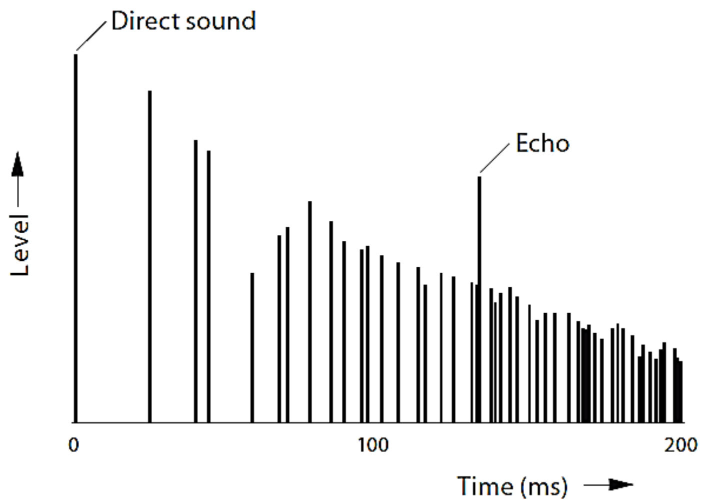


Figure 2.5 Impulse response of a room with an echo *(Barron, 2011)*

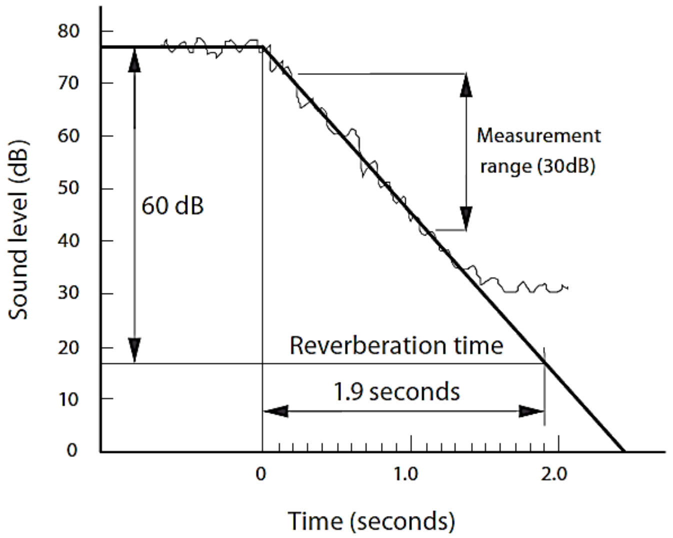


Figure 2.6 Sample of Reverberation Time decay *(Barron, 2011)*

The metric was first developed by W.C Sabine in 1985 (Egan, 1988). As a result of his research, Sabine reached the experimental correlation named Sabine formula. The equation has two quantities: the volume of the room (V) and the total sound absorption area (*A*).

Global Reverberation Time Formula (RT / T_{60})

$$RT = \frac{0.161\ \mathrm{V}}{\Sigma \mathrm{A}}$$

$$\Sigma A = S_1\alpha_1 + S_2\alpha_2 + S_3\alpha_3 \ldots + S_n\alpha_n$$

RT is the reverberation time of the room (seconds)

V is the volume of the space (m^3)

∑A is total absorption in the room (m^2)

α_n is the absorption coefficient value for each material (%)

S_n is the surface area covered by each material (m^2)

This formula is based upon an assumption that the reverberation time should be equal to zero when the whole room is covered with completely sound absorber elements where the α value equals 1. In a room, the audience composes the most sound absorptive area; thus, Sabine has calculated the audience absorption per person according to the number of seats. The measurements should be carried out at any frequencies needed, at least from 125 Hz to 2 kHz. (Barron, 2011).

However, for some frequencies, air absorption in a room affects the reverberation time, especially in high frequencies. So, to calculate the RT more accurately, the air absorption coefficient should also be taken into account. The Sabine formula with air absorption is,

$$RT(s) = \frac{0.161\ V}{\sum S\alpha + 4\mathrm{mV}}$$

The coefficient of air absorption is symbolized with “m” and is affected by humidity and temperature, generally RT at 2 kHz and above (Barron, 2011).

The reverberation time perceived by the listener is also expressed in subjective expressions. Accordingly, the sound in the room is perceived as “live” when the RT values are excellent and “dead” for low or insufficient RT values. However, if there is an excessive reverberation in a room, it may become heard like a discrete sound, which is disruptive. The reflection that comes after 50 ms later than direct sound is perceived as an “echo”, which is an acoustical defect (Barron, 2011; Long, 2006).

Optimum RT varies for rooms with different functions (Barron, 2011; Beranek, 2004; Egan, 1988; Long, 2006). In general, the RT should be kept short for speech activities and long for musical activities. A room's main function is fundamental to achieving optimum RT (Long, 2006). The reverberation times that rooms should provide for music- and speech-related activities are included in many sources. For instance, Berardi et al. (Berardi et al., 2016) state reverberation times of 1.0 s for clearer speech perception and 2.5 s for music concerts are accepted as appropriate. Besides, in church structures, especially where the music is performed with the church organ, 3 s and above reverberation times are common (Berardi et al., 2016). According to Egan's (Egan, 1988) reference reverberation times in the mid-frequencies (500-1000 Hz), the range of 1.2 – 1.9 s for chamber music, 0.6 – 1.3 s for conference rooms, and 0.8 – 2,6 s for churches are appropriate values (Egan, 1988). These reference reverberation times also conform with the recommended values described by Berardi et al. (Berardi et al., 2016).

2.2.2 EARLY DECAY TIME (EDT)

Early reflections are in the initial field of the room impulse response pattern. The metric that calculates the sound decay rate on the first 10 dB of reverberation (T_{10}) is named Early Decay Time (EDT). It is multiplied by 6 to establish a correlation between RT values (T_{60}) (Kleiner et al., 2010b). The EDT will be longer than RT if the sound field is close to diffuse field conditions in a room, and RT and EDT will be equal in fully diffused field conditions. In the evaluations, it is stated that the EDT value better expresses the objective response of the audience to the reverberation (Çalışkan, 2014).

$EDT\ (s) = \mathrm{t} \times 6$ (t is the time first 10 dB decay)

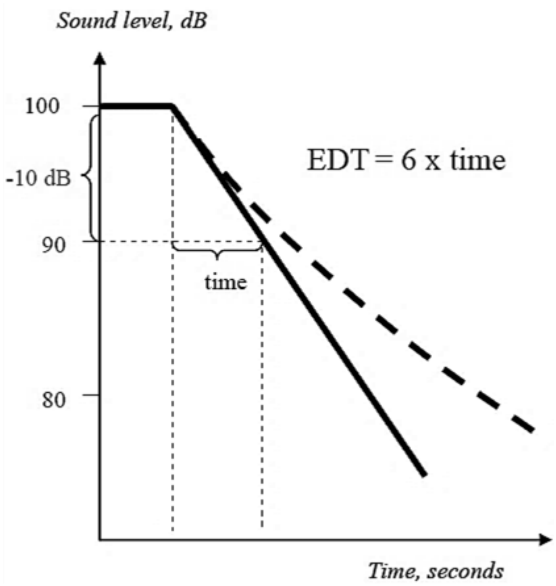


Figure 2.7 Early Decay Time demonstration (*RT 2*, 2018)

According to the data obtained from the literature, the EDT value is expected to be within the range of ± %10 Reverberation Time (RT) for decent acoustic conditions (Odabaş et al., 2011).

2.2.3 CLARITY (C_{80})

The ratio of early sound to late sound energy is defined as Clarity and expressed in the decibel unit. Assessed by octave-band analysis, computer simulation is usually required for accurate results. The clarity (C_{80}) parameter is also closely related to speech intelligibility, the ability to distinguish timbres (tone quality) in musical performances, and is inversely proportional to Reverberation Time.

The sound energy at 50 ms after the direct sound is considered early sound energy for speech activities in the range of 500 Hz to 4 kHz. However, for musical events, the energy arriving at 80 ms after the direct sound is considered as early sound energy in the range of 125 Hz to 4 kHz. The value of the clarity is generally recommended between the range of -5 to 5 dB (Kleiner et al., 2010b; Queiroz de Sant'Ana & Zannin, 2011).

The equation of the Clarity,

$$C50\ (dB) = 10 \log \left(\frac{\int_0^{50} h^2(t)dt}{\int_0^{\infty} h^2\ (t)dt} \right)$$

$$C80\ (dB) = 10 \log \left(\frac{\int_0^{80} h^2(t)dt}{\int_0^{\infty} h^2\ (t)dt} \right)$$

When the reverberation time is excessively long, the sound energy loses its clarity. In this case, the C_{80} value becomes higher and takes a negative value (Beranek, 2004). In short, the longer the reverberation times lead to the lower the clarity (C_{80}) value, which expresses the clarity of the sound. Besides, the geometry of a room is another factor that significantly affects the clarity value of sound, especially at the furthermost points from the source (Queiroz de Sant'Ana & Zannin, 2011).

Many sources have figured adequate Clarity values (C_{80}) for music and speech activities. For example, the recommended C_{80} value for musical concerts, in which perceiving the tones of the music is important, is between -2 dB and +2 dB (Barron, 2011; Berardi et al., 2016) for speech activities where sound intelligibility is crucial, the recommended C_{80} value is expected to be above +2 dB (Barron, 2011; Berardi et al., 2016). It is also mentioned descending to -3 dB is an acceptable level (Kuttruff, 2017). The C_{80} value is considered an effective measure in concert halls as a reliable descriptor of the clarity of music/sound and speech intelligibility (Barron, 2011; Berardi et al., 2016; Kuttruff, 2017).

2.2.4 SPEECH TRANSMISSION INDEX (STI)

The intelligibility of sound is significant for liturgy in worship places such as churches and mosques. One of the most common acoustical defects in these places is decreased intelligibility due to echo or noise problems. Some parameters have been developed to estimate the speech intelligibility level (Kleiner et al., 2010b). One metric that analyzes sound intelligibility is the Speech Transmission Index (STI). When sound comes from the source is modified by the medium as it reaches the receiver, leading to problems such as distortion of sound. Sound Intelligibility is also affected by background noise and reflected sounds in a room. These effects are determined by analyzing the decrease in sound energy signal along the transmission path, from source to receiver. Computer simulations can measure STI values via impulse response and background noise spectrum (Kleiner et al., 2010b; Long, 2006).

Therefore, the sound signal envelope should maintain its characteristics for good speech intelligibility (Kuttruff, 2001). When the sound transmission is excellent, the STI metric takes the value 1. In the opposite case, if the sound signal cannot be recognized, STI takes the value 0.

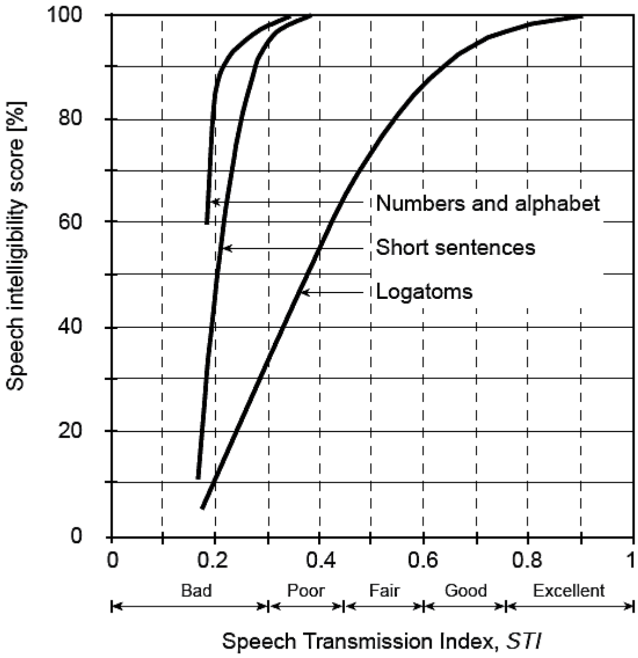


Figure 2.8 The relationship between speech intelligibility and STI *(Kleiner et al., 2010b)*.

The definitions of intelligibility or quality corresponding to the different STI ranges are summarized in Table 2.1 (Brezina, 2015; IEC 60268-16:2011, 2011; Queiroz de Sant'Ana & Zannin, 2011). Briefly, the sound signal should reach the receivers without distortion in speech frequency bands for better understanding and it is critical that the sound must not be affected by highly reverberant sound energy and background noise in spaces (Odabaş et al., 2011). Currently, the STI parameter is accepted as the most functional objective measure for identifying speech intelligibility (Queiroz de Sant'Ana & Zannin, 2011).

Table 2.1 Intelligibility rating scale and STI relation *(IEC 60268-16:2011, 2011)*

Intelligibility Rating	STI value
Bad	0.00 – 0.30
Poor	0.30 – 0.45
Fair	0.45 – 0.60
Good	0.60 – 0.75
Excellent	0.75 – 1.00

2.2.5 BACKGROUND NOISE (L_{eq})

There can be many sources of background noise, such as traffic, ventilation system, etc. However, in buildings like churches or museums, where the silence is crucial, the congregation or people themselves is also the source of background noise. Moments of dramatic silence created by the audience may make the sound experience impressive during the event (Barron, 2011). Recommended ratings for background noise in a church are determined as NC-25 and NC-35 (Moamar et al., 2017)

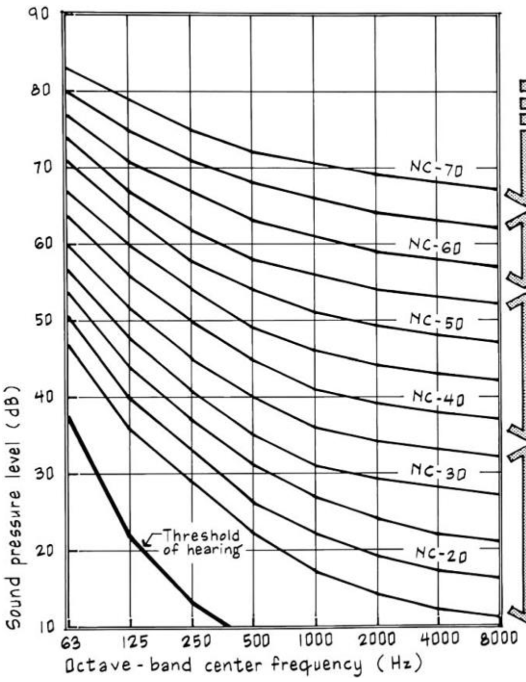


Figure 2.9 Noise Criterion Curves *(Egan, 1988)*

The decay time of the sound energy in a room and the sound power of the source are essential parameters that affect the intelligibility of speech. However, the masking effect of the background noise, which varies depending on the frequency, can noticeably weaken the intelligibility of speech (Sü Gül et al., 2014). The background noise causes can be environmental noises such as traffic, weather conditions, or operating technical equipment in the space. The upper limit of noise criteria (NC curve) and background noise levels (dBA) recommended in the literature are as follows: NC25-NC30 (35-39dBA) for small auditoriums with 500 or less audience capacity, NC20-NC35 (30-44dBA) for churches, NC15-NC20 (25-30dBA) for concert halls (American National Standards Institute / Acoustical Society of America, 2008). Lastly, this value is recommended for museums NC-35 (45dBA) (Carvalho et al., 2013).

2.3 ACOUSTICAL FEATURES OF CHURCHES

Originally, the Surp Yerrortutyun Church Museum is constructed as a worship building, an Orthodox church. Although it is used as a cultural house for secular activities today, evaluating the adequacy of the acoustic qualities in terms of its original function is also significant. Here, some acoustical features, recommended conditions for music and speech-related activities focusing on churches, comparison with similar monuments, and some case studies about the acoustic improvement studies on churches in the literature are presented in the following subheadings.

In this regard, analyzing the acoustical conditions of Christian worship music could be difficult due to its wide range of diversity in the musical aspects. For instance, Eastern Orthodox ritual usually does not include musical instruments but the human voice. Prayers are often chanted by the choir and the priest. Speech intelligibility is required in such churches (Elicio & Martellotta, 2015), which requires lower reverberation times, between 1.0 to 1.3 seconds (Egan, 1988; Kleiner et al., 2010a). However, some Orthodox churches may have large reflective surfaces, resulting in high reverberation time. For instance, in Russian, Greek, or Serbian Orthodox churches, some chants may require a longer reverberation time from a musical point of view, approximately 2 to 3 seconds (Berardi et al., 2016). Sometimes Protestant rituals may start with an organ sound intro, which requires a reverberation time of about 3 to 4 seconds, depending on room size. The liturgy may proceed with spoken or sung congregational or choral hymns; therefore, adequate reverberation time is required between 1 to 2 seconds. On the other hand, unlike other churches, “non-denominational” Evangelical church liturgy may start with a band with an amplified sound system to invite the congregation for worship. This liturgy requires a short reverberation time (Ansay & Zannin, 2016) of about 1 second and needs high sound absorptions in a church (Kleiner et al., 2010a).

In addition to the diversity in music, the geometry and volume of the places of worship can vary considerably (Elicio & Martellotta, 2015; Girón et al., 2017). For instance, some churches have a volume of fewer than 1000 m^3, which may be designed consciously small to maintain a sense of intimacy in the congregation (Kosała & Małecki, 2018). Other ones, for example, may be built to hold thousands of pilgrims in a volume of 400 000 m^3 (Girón et al., 2017; Kleiner et al., 2010a).

On the other hand, the necessities of Christian liturgical music may overlap each other; thus, instead of all rituals, it may be a simplifier to analyze the two different types, acoustically. The interior can be qualified by various acoustic properties such as reverberation or clarity, and these can be explained by multiple room acoustic metrics. Roman Catholic Mass has challenging ceremonies in terms of reverberation times, including both music and speech-related activities (Álvarez-Morales et al., 2014). Generally, the Catholic rituals are conducted in places with high reverberation time desired for instruments such as organs where the speech intelligibility is poor (Kleiner et al., 2010a). However, the participation of the ensemble in chanting is also essential. Therefore, apart from the reverberation time, other acoustic components such as noise control and sound isolation are also significant.

It also contributes to intangible elements such as the dramatic and "awe-inspiring" character of a church, such as hearing the natural reverberant sound field of the monument thanks to the low background noise in the range of NC 15-25 (American National Standards Institute / Acoustical Society of America, 2008; Kleiner et al., 2010a; Moamar et al., 2017). It is also important to ensure privacy for confessional activity.

In brief, churches can host various types of music and worship events. Some requirements of ceremonies may overlap each other such as good speech intelligibility and long reverberation time. Usual Christian ritual music with an organ needs a longer reverberation time for optimized conditions. However, contemporary evangelical music and speech-related rituals are needed shorter reverberation time. The acoustical demands of a church should be adequately determined, and the seating layout and architectural elements should be arranged so that the reverberation time and clarity measures show sufficient conditions.

2.3.1 RECOMMENDED CONDITIONS FOR MUSICAL AND SPEECH ACTIVITIES

In order to evaluate the acoustical performance of the Surp Yerrortutyun Church, some recommended ranges of Reverberation Time (T_{20}, s), Early Decay Time (EDT, s), Clarity (C_{80}, dB), Speech Transmission Index (STI, unitless) and Background Noise (L_{eq}, dB) are examined and complied in Table 2.2 for specific musical and speech activities. These parameters and recommended values are used in the acoustic performance assessment of the as-is case and suggested rehabilitation proposals.

Table 2.2 Recommend values of the acoustic parameters for some activities

Parameter	Recommended Values	Reference
T_{20}, s (500-1000Hz)	2,5 – 3,0s (for musical activities)	(Berardi et al., 2016; Egan, 1988)
	0,6 – 1,3s (for speech activities)	(Egan, 1988)
EDT, s (500-1000Hz)	RT ± 10%	(Odabaş et al., 2011)
C_{80}, dB	-2dB – +2dB (for musical activities)	(Barron, 2011; Egan, 1988)
	C_{80} > +2dB (for speech activities)	(Berardi et al., 2016)
STI, unitless	STI > 0,45	(IEC 60268-16:2011, 2011)
Background Noise (dBA)	25 ± 1 dBA	(American National Standards Institute / Acoustical Society of America, 2008)

Accordingly, the recommended Reverberation Time (T_{20}, s) range is 2,5 – 3,0 s for musical activities and 0,6 – 1,3 s for speech-related activities in a room (Berardi et al., 2016; Egan, 1988). To achieve optimum acoustic conditions the Early Decay Time (EDT, s) should be in a range ±10% of the reverberation time (Odabaş et al., 2011). Another crucial parameter for music and speech activities is Clarity (C_{80}, dB), preferably recommended in the -2dB – +2dB range for the music; and above +2dB for speech-focused activities. Moreover, for all multi-purpose uses, to provide “fair” speech intelligibility, the Speech Transmission Index (STI, unitless) should be above the 0.45 threshold with a 25 dBA background noise level (American National Standards Institute / Acoustical Society of America, 2008; IEC 60268-16:2011, 2011). On the other hand, some graphs obtained from different sources, indicating the optimum reverberation times, which is the basic parameter in evaluating the acoustic performance, are compiled in the following figures (Figure 2.10, Figure 2.11, Figure 2.12).

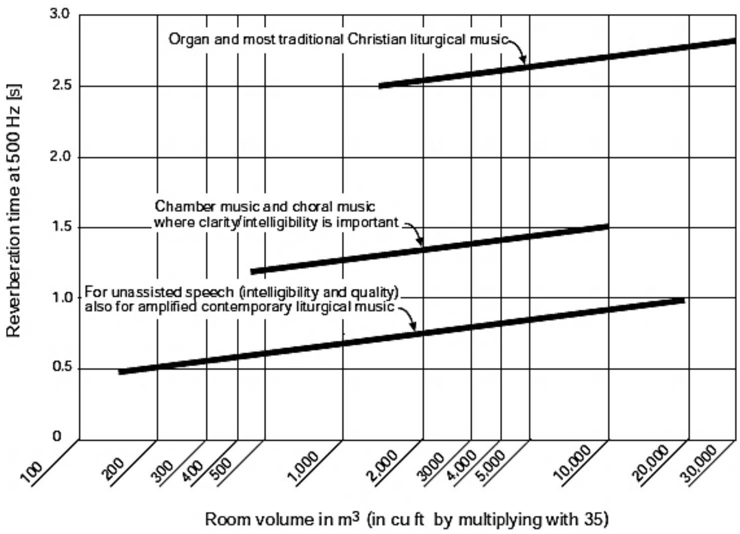


Figure 2.10 Recommended target RT values at 500 Hz *(Kleiner et al., 2010c)*

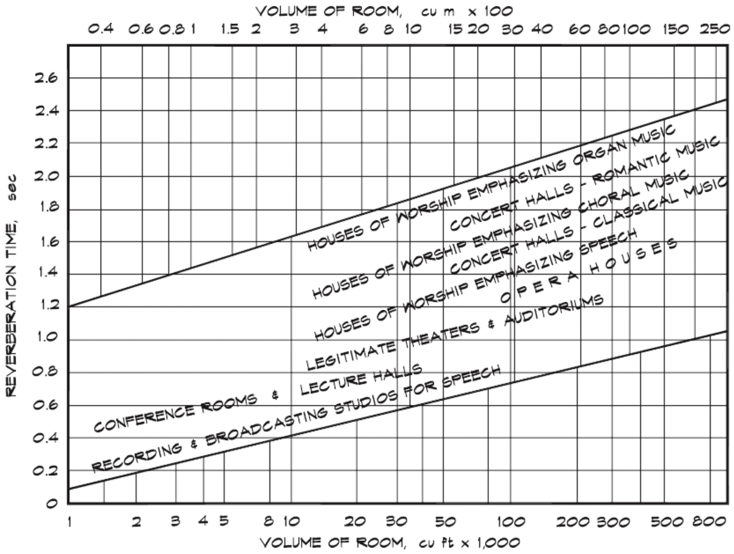


Figure 2.11 Optimum T60 (RT) values for different functions and volumes are stated in the shaded area *(Long, 2006)*

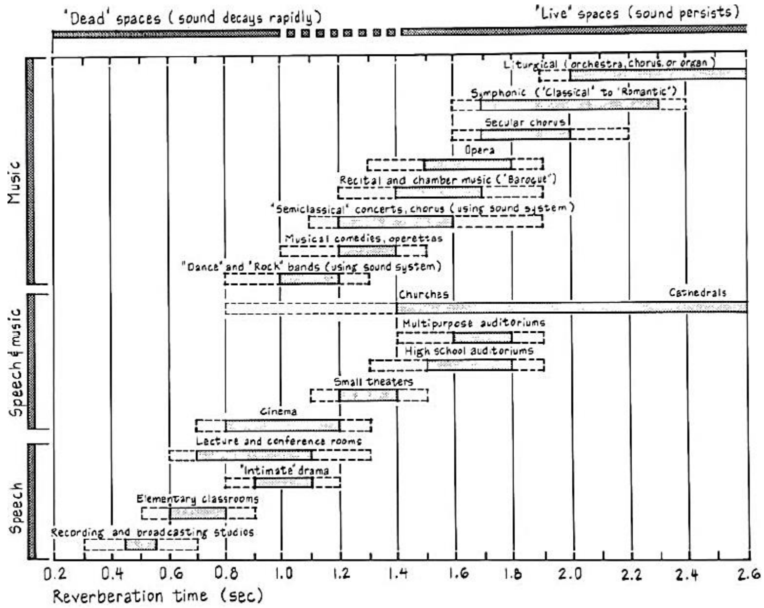


Figure 2.12 Chart of optimum reverberation time *(Egan, 1988)*

Accordingly, the relation between the reverberation time and the function and the volume is shown in the figures. As the volume increases or the music genre becomes liturgical, longer reverberation times become more acceptable. A shorter reverberation time is recommended for small volumes or speech-related activities in all three charts.

2.3.2 ACOUSTICAL EVALUATION AND COMPARISON OF CHURCHES

The churches are particular structures where RT values were examined in many researches and observed that such structures vary slightly from the recommended ranges in given general.

Table 2.3 Acoustical properties of several churches in Europe from different periods ***(Cirillo & Martellotta, 2006; Elicio & Martellotta, 2015; Girón et al., 2017; Kosała & Małecki, 2018)***

Name of the Church	Location	Period / Age	Volume (m^3)	RT_{mid} (s)	C_{80} (dB)
The Holy Spirit Church	Białystok, Poland	na	9500	6.53	1
St. Maxymilian	Włocławek, Poland	na	9600	7.80	na
Abbatiale Payerne	Payerne, Switzerland	RO	10000	5.50	na
Cathedral of Silves	Silves, Portugal	GO	10057	3.93	na
Silvacane Abbey	Provence, France	CI	10100	6.02	na
The Basilica of Santa Croce in Gerusalemme	Rome, Italy	BA	10500	6.10	-9
St. Marina	Seville, Spain	MU GO	10708	3.09	na
St. Martin	Basel, Switzerland	GO	10732	3.95	na
Nossa Senhora da Lapa	Porto, Portugal	NC	11423	5.72	na
Dormition	Moscow, Russia	XV	11500	4.42	na
Serra do Pilar	Gaia, Portugal	RO	11566	7.83	na
La Grande Madre di Dio	Turin, Italy	NC	12000	6.30	na
St. John the Baptist	Krakow, Poland	na	14360	7.40	na
The Basilica of Santa Sabina all'Aventino	Rome, Italy	EC	17500	4.30	-7

Table 2.4 (continued)

BA: Baroque; EC: Early-Christian; GO: Gothic; RO: Romanesque; NC: Neo-Classical; CI: Cistercian; MU: Mudejar; XV: 15. century; na: no data.

Here, to evaluate the as-is acoustic performance of the Surp Yerrortutyun Church (acoustical volume ~ 10 650 m^3), by comparing it to churches with a similar volume, including the acoustic and architectural features for a number of churches from Europe, the data are listed in Table 2.3 (Cirillo & Martellotta, 2006; Elicio & Martellotta, 2015; Girón et al., 2017; Kosała & Małecki, 2018).

The investigated Christian churches in the literature are originally from different time periods and several locations with various dimensions.

In table 2.2, average RT values in mid frequencies (500 – 1000 Hz), average C_{80}, and average STI values are compiled as basic acoustic parameters in the previous section. On the other hand, for comparisons some architectural data of similar-volumed churches, including volume (m^3), name of the monument, the region where it is located, and the era to which it belongs, have also been indicated in Table 2.3 to comprehend better the architectural properties of the monuments to make acoustical comparisons from a broader perspective. All the selected churches have a volume of 9 500 to 17 500 m^3.

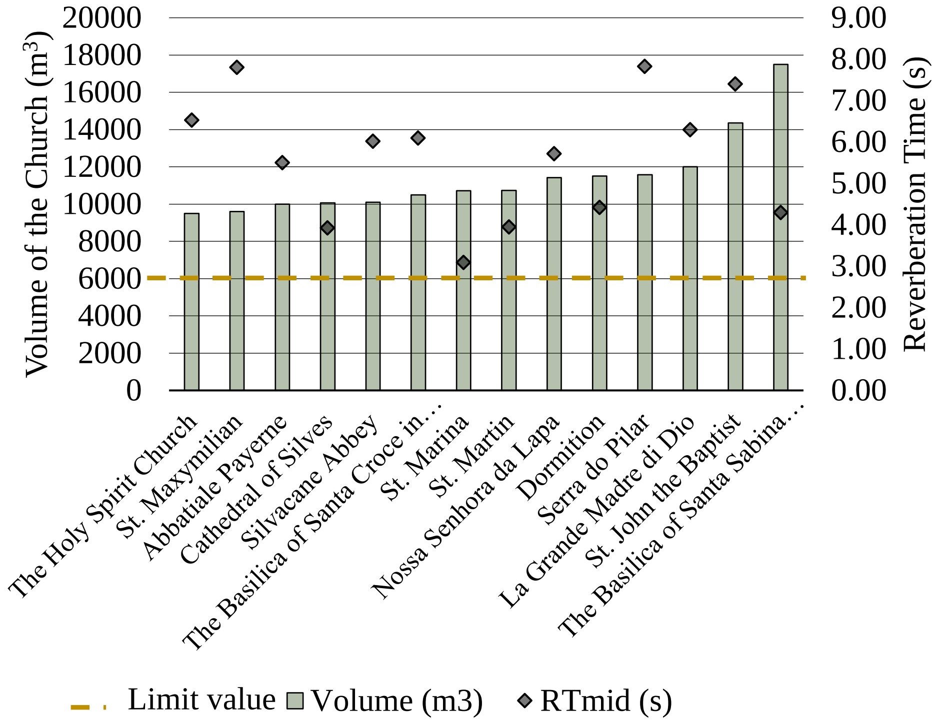


Figure 2.13 Comparison of the relation between reverberation times and volume of some European churches which are similar in size to the Surp Yerrortutyun Church

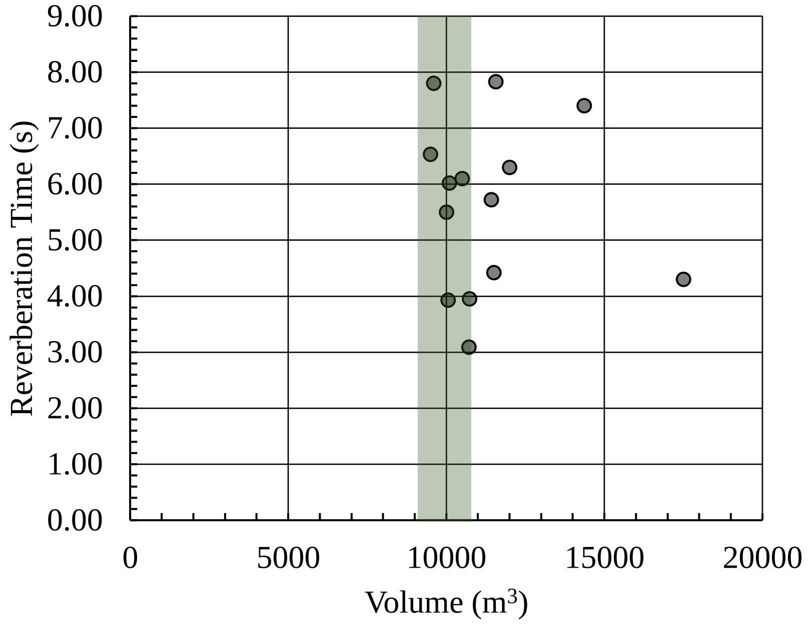


Figure 2.14 Scatter plot graph based on volume and reverberation time data of mentioned European churches which are similar in size to the Surp Yerrortutyun Church

When Table 2.3 is examined, it can be figured that The Holy Spirit Church from Poland has one of the highest RT of around 6.53 s; despite having the smallest volume (9 500m^3) in the table with 1 dB C_{80} value which is as recommended. On the other hand, other cases having a volume of 10 500 m^3 to 17 500 m^3 have reverberation times about 3 s to 8 s; and 1 dB to -9 dB C_{80} value which are out of the recommended values in the literature.

All the RT data is above the 3 s limits mentioned in the literature as acceptable upper limits for churches. In addition, remarkable and unexpected results were observed in the data. In ordinary conditions, based on the RT equation, the reverberation time is expected to become longer as the church volume increases. However, some churches having larger volumes, such as The Basilica of Santa Sabina all'Aventino (Rome, IT), exhibit lower RT when compared to the ones such as The Holy Spirit Church (Białystok, PL) having lower volumes. According to the data taken from the literature, there is no such a tendency observed. It has been noticed reverberation times in the range of 3 and 7 s can be appeared both in larger and smaller venues. In other words, as the volume of the church decreases, the reverberation time may become longer. Obviously, this situation is closely related to the sound absorptive and reflective material's surface area and the distribution in the church venue. The reduced RT values measured in the larger volumes can be attributed to the presence of a higher amount of sound absorptive surfaces in the churches. Thus, this means that the selection of finishing material for the indoor space, which is another main factor affecting the reverberation time apart from the room's volume, is decisive. As the reflective surface area increases, the reverberation time may become longer. As a result, all these values were generally found to be slightly higher than the RT and C_{80} values recommended values for churches in the literature. It is observed that the RT and C_{80} values measured in historic churches may differ from the recommended ranges.

2.3.3 SOME CASE STUDIES ON IMPROVEMENT OF CHURCH ACOUSTICS

This section provides a summary of a few notable studies (Alonso et al., 2014; Bartalucci et al., 2018; Berardi et al., 2015; Buratti et al., 2022; del Solar Dorrego & Gardella, 2016; Eren, 2019; Gagliano et al., 2015; Iannace, 2016; Merli & Bevilacqua, 2020; Suárez et al., 2003; Tămaș-Gavrea et al., 2018; Tronchin & Bevilacqua, 2020) in the literature on acoustic improvement studies for cultural heritage properties and the findings of several pieces of research.

In their research paper, Berardi, Iannace, and Ianniello (2015) focus on the acoustic improvement of the Palatine Chapel in the Royal Palace in Caserta (Italy) for its use in cultural activities. The measured average RT_{mid} is about 5 s in unoccupied conditions, which is inappropriate for the public events hosted in this place. It needs to propose acoustic treatments while respecting its historical value. For that purpose, some proposals were developed and evaluated by using simulations. Field measurement was conducted and used to calibrate the simulation model. Transparent vibrating panels and heavy curtains along the lateral walls were considered options for providing high sound absorption while having a minimal visual impact. The proposal resulted in a 2.5 s reduction of RT value in the mid frequencies, which is acceptable for the demanded functions in the Chapel (Berardi et al., 2015).

In another similar study, Iannace (2016) aims to explore some temporary acoustic treatments for the Cathedral of Benevento in his research. The measured average RT value is about 10 s in an unoccupied state which is unsuitable for speech and musical performances. Using perforated ceramic tiles for low-frequency sound absorption and micro-perforated sheets for the mid frequencies has been mentioned as beneficial for acoustic improvement studies. The impacts were evaluated through the simulations. On the other hand, architectural features were preserved as the side walls remained visibly smooth, and the ceiling was covered with transparent sheets. The RT is around 6 s, which is still above the recommended values even with the suggested improvement. But the C_{80} value was measured as compatible. Therefore, the acoustic environment of this place is considered only suitable for certain types of music and instruments (Iannace, 2016).

In another study, Merli and Bevilacqua (2020) aim to adapt the acoustic conditions of S. Domenico of Imole Church for musical performances, considering the preservation of its architectural elements. For this purpose, reversible and temporary proposals were planned to control the highly reverberant sound fields in hosting temporary venues. Simulation results were used for the comparison of proposals' efficiency. Accordingly, sufficient treatments include curtains, fabric wrap, and wooden panels, which have been observed significantly control the RT and C_{80} values for desired activities (Merli & Bevilacqua, 2020).

In the paper, Buratti et al. (2022) examined and discussed the acoustic performance of the San Francesco al Prato church in Perugia (Italy), which has been refurbished and transformed into an auditorium. Validation of the simulation was conducted by measured data, including RT and C values, for developing experimental attempts. Accordingly, for mid-and low-frequency sound absorption, 20-unit canopies made of perforated resonant systems with rock wool inside hung over the ceiling, working as Helmholtz resonators. Therefore, the RT value gradually reduced from 4.56s to 1.96s, and C_{80} decreased from a 4 dB mean value to 0.5 dB. The as-is values are consistent with the values of similar volume churches stated in the literature; however, after the suggestions, optimal ranges for music listening are achieved (Buratti et al., 2022).

In their study, Tămaș-Gavrea et all. (2018) investigated the acoustic performance of a church in Cluj-Napoca, Romania, and proposed an acoustic rehabilitation solution considering the interior design. It is stated in the paper that the use of acoustic materials with high sound absorption on the periphery reflective surfaces can significantly reduce reverberation time values. Proposed acoustic rehabilitation options include the followings; plating the columns with board panels having perforations, application of panels with plywood and melamine finish with perforations, and perforated gypsum panels on the walls, use of carpet between the rows of benches, use of perforated gypsum boards for the acoustic ceiling in the balconies (Tămaș-Gavrea et al., 2018).

2.4 SOME ACOUSTICAL MATERIALS TO CONTROL HIGH REVERBERANT ENVIRONMENTS

Basically, acoustic materials can be classified as sound absorbers, sound reflectors, sound diffusers, and noise barriers. In this context, some materials, especially sound absorbers for reducing excessive reverberation, and their application techniques suitable for acoustic rehabilitation proposals for Surp Yerrortutyun Church are investigated.

Materials with a high sound absorption coefficient are more porous and less smooth, less weight, and thicker. In other words, the features that affect the sound absorption of materials are briefly thickness, density, porosity, and fiber orientation. Materials are generally accepted as sound-absorbent if the sound absorption coefficients (α value) are greater than 0.50, while if the α value is less than 0.20, they are accepted as sound reflective (Ermann, 2015).

Sound-absorbing acoustic materials can be grouped into four primary types: perforated absorbers, porous materials, membrane (resonant) absorbers, and Helmholtz resonators (Avgın, 2014). The main characteristics are briefly explained in this section.

Perforated absorbers are mostly composed of wood, metal, or gypsum panels. Existing holes on the surface serve as a neck of the Helmholtz resonator. The air gap behind the panel affects the sound absorption performance of the product; for example, as the gap increases, the absorption at low-frequency increases (Figure 2.15). The fabric material can be placed behind the panel to improve the sound absorption at mid frequencies.

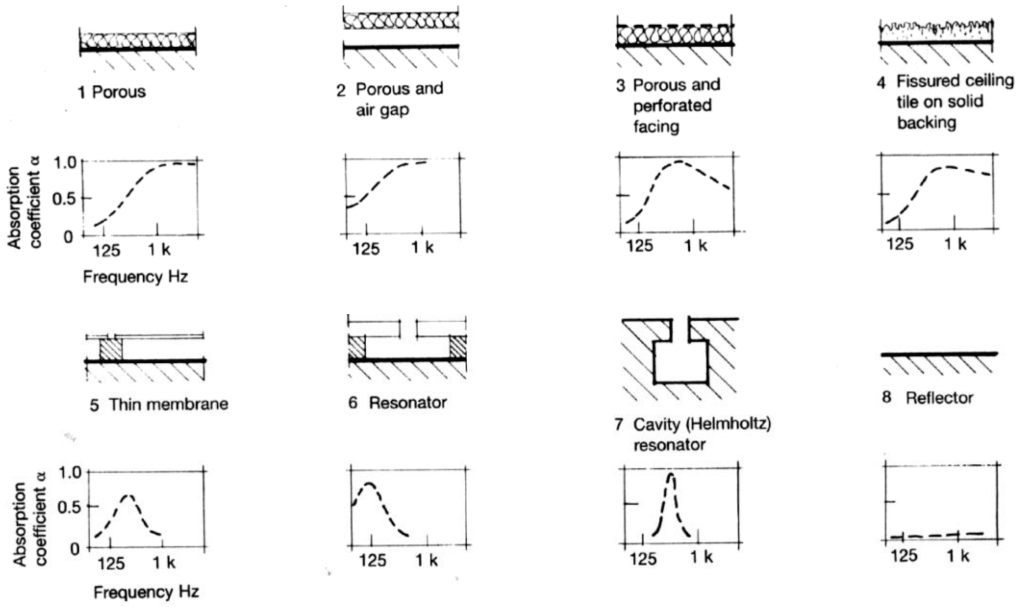


Figure 2.15 Different types of sound absorbers and their acoustical behavior *(Çalışkan, 2004)*

Porous sound absorptive materials are composed of pores and, in this way, absorb the sound energy by converting it into thermal energy. Basic porous materials are porous concrete, sand, foam, polyurethane, some kinds of asphalt, synthetic fibers such as glass wool and rock wool, and natural fibers like cotton (Avgın, 2014; Ermann, 2015; Long, 2006). Resonant (Membrane) absorbers compose non-porous, thin materials covering the opening of a cavity as a dampener. They vibrate by incident sound energy and convert it into thermal energy. Helmholtz resonator is another sound-absorbent that is briefly an air container with one open hole (named the neck). Mostly they are effective at sound absorption at a single frequency, particularly at low frequencies.

2.4.1 TRANSPARENT AND TRANSLUCENT SOUND ABSORPTIVE MATERIALS

There are many ways to reduce excessive reverberation time, including the use of sound absorbers in a room; however, it may be unacceptable from the architectural point of view or possibly expensive in some cases (Kleiner et al., 2010c). Here, sound-absorbing materials that have the potential to be used for the acoustic rehabilitation proposals of the Surp Yerrortutyun Church are presented. In this respect, the use of transparent or translucent perforated panels and/or textile curtains as porous sound absorbers become crucial as an option due to architectural points of view.

In acoustic rehabilitation proposals, it has been decided to use sound-absorbing translucent curtain fabric as the primary material that respects the historic monument's architectural and cultural heritage values while reducing the reverberation time. The main characteristics of the selected sound absorptive polyester-based material are listed in Table 2.4. Properties including physical, mechanic, acoustic, and optic of selected sound-absorbing curtain textile are compiled in Table 2.5.

Table 2.5. Main characteristics of the selected fabric

Characteristics of the Fabric		Reference
Appearance	sheer/transparent	*
Description	linen look, half-transparent acoustic curtain fabric	
Composition	100% flame-retardant polyester	

***** (Vescom Corsica, 2022)

Properties including physical, mechanic, acoustic, and optic of selected sound-absorbing curtain textile are compiled in Table 2.5.

Table 2.6 The material properties of the selected transparent sound absorptive product given by the manufacturer's technical specification (Vescom Corsica, 2022)

Property	Unit / Scale	Data	Standard
Area-related mass (m'')	g/m²	107	-
Thickness (t)	mm	0.35	-
Airflow Resistance (RS)	Pa s/m	255	EN 29053
Sound Absorption	α	0.65	ISO 354
	NRC	0.65	ASTM C423
Flame Retardancy	-	Class 1	EN 13773
		Type C	BS 5867 – 2
		B1	DIN 4102

Table 2.5 (continued)

Colorfastness to Crocking	Scale: 1-5	wet 4-5 dry 4-5	ISO 105 X12
		wet 5 dry 5[c]	AATCC 8
Colorfastness to Light	Scale: 1-8	6[d]	ISO 105 B02
	Scale: 1-5	5[d]	AATCC 16.3: 60 hours
Visual Contact with the Outside	Scale: 0-4	2/3[e]	EN 410/EN 14501 DIN EN 14501:2006-02

[c] No color transfer, [d] No fading or color change, [e] Moderate to high effect (mentions semi-transparent), [f] Very small effect

The sound absorption measurements for the fabric were conducted according to EN ISO 354 standard. Accordingly, the textile was tested as a curtain in both a flat and folded (100 % fabric addition) configuration at a distance of 150 mm gap from the reflective wall. Since the sound transmission coefficients of the hung curtains are not available, only their sound absorption coefficients corresponding to the values when they are positioned 150 mm away from the wall surface are used as inputs in simulation analyses.

As it is shown in Table 2.5, the transparency degree of the fabric is measured as 2/3 on a 0-4 scale, which means the material provides moderate visual contact with the outside, referring to semi-transparency (Figure 2.16). Visual contact with the outside parameters shows that the fabric is semi-transparent. Fire retardancy levels comply with the acceptance criteria. Colorfastness to crocking is noted as "no color transfer in wet and dry condition", and colorfastness to light indicated as "no fading or color change" is observed.

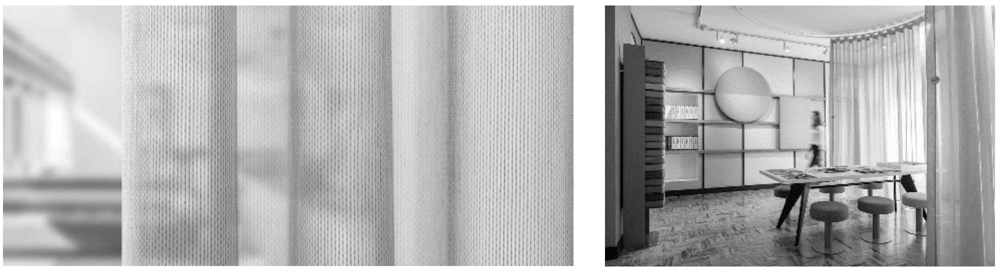


Figure 2.16 Sample texture and application of the fabric

The fabric's sound absorption coefficients are presented in Figure 2.17 for flat and folded arrangements. Detailed sound absorption coefficients are compiled in the Table 2.6.

Table 2.7 Sound absorption coefficient of the selected fabric in flat and folded (100% fabric addition) arrangement

Flat Arrangement			Folded Arrangement		
Frequency [Hz]	α 1/3 octave	α 1/1 octave	Frequency [Hz]	α 1/3 octave	α 1/1 octave
100 125 160	0.01 0.01 0.04	0.00	100 125 160	0.05 0.09 0.17	0.10
200 250 315	0.08 0.11 0.24	0.15	200 250 315	0.29 0.37 0.54	0.40
400 500 630	0.37 0.49 0.56	0.45	400 500 630	0.63 0.68 0.67	0.65
800 1000 1250	0.62 0.50 0.38	0.50	800 1000 1250	0.72 0.71 0.72	0.70
1600 2000 2500	0.46 0.55 0.48	0.50	1600 2000 2500	0.73 0.75 0.76	0.75
3150 4000 5000	0.56 0.55 0.52	0.55	3150 4000 5000	0.78 0.80 0.80	0.80

Note: sound absorption coefficient (α) in 1/3 octave measured according to ISO 354
sound absorption coefficient (α) in 1/1 octave measured according to ISO 11654

In the flat configuration, the results are as follows.

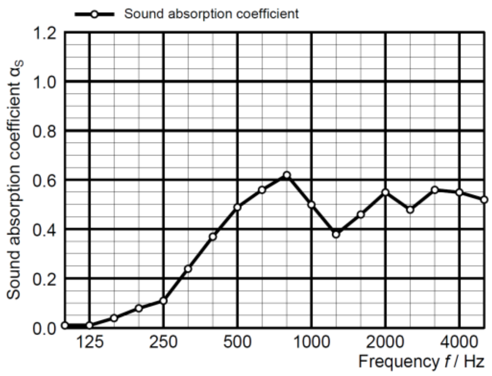
- Rating according to ISO 11654 weighted sound absorption coefficient αw = 0.45 and sound absorption class: D.
- Rating according to ASTM C423 Noise Reduction Coefficient NRC = 0.40 and sound Absorption Average SAA = 0.40.

The results are as follows in folded (100 % fabric addition) configuration.

- Rating according to ISO 11654 weighted sound absorption coefficient αw = 0.65 (H) and Sound absorption class: C.

- Rating according to ASTM C423 Noise Reduction Coefficient NRC = 0.65 and Sound Absorption Average SAA = 0.63.

There is a significant increase in sound absorption in the folded arrangement. Sound absorption predominates at mid (500 – 1000 Hz) and high (2000 – 4000) frequencies in both configurations. Although sound absorption at mid frequencies (0.45 – 0.50 for flat arrangement; 0.65 – 0.70 for folded arrangement), which is crucial in using music and speech-related activities, is quite efficien. The sound absorption at low frequencies becomes weak (0 – 0.15 for flat arrangement; 0.10 – 0.40 for folded arrangement).



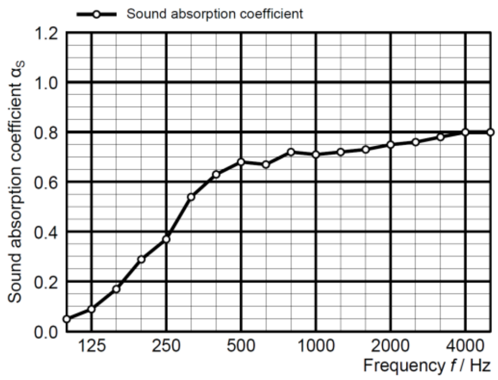


Figure 2.17 Acoustic performance properties of selected curtain fabric. Flat arrangement on the left, folded arrangement on the right.

2.4.2 CURTAIN SOUND ABSORPTION SYSTEMS

The main focus of this section is to investigate sound-absorbing systems to be used in improvement proposals for the variable uses of the Surp Yerrortutyun Church, considering temporary, compatible repeatable criteria for acoustic interventions without causing any damage to the historical monument.

Some commonly preferred variable sound absorption systems are acoustic curtains, banners, rotating acoustic systems, hinged panels, moveable panels, and sliding panels (Adams, 2016; Atelier Crescendo, 2021; Barron, 2011; Cox & D'Antonio, 2017). Possible application methods for the use of acoustic curtains to reduce the reverberation in the Surp Yerrortutyun Church and the points to be considered while generating a computer model to obtain accurate results are mentioned in this section.

Sound levels in a room can be decreased effectively by using sound-absorbing materials such as curtains and carpets (Egan, 1988). Porous sound absorbers in the form of fabrics can be mounted in suspended systems as a curtain panel. For instance, at the ceiling level of the audience zone, the curtains textiles can be used as suspended screens while providing open ceiling perception. Also, these screens are used to define the borders of the audience zone as strips. For this purpose, using sound absorptive curtain systems is found to be feasible.

As shown in Figure 2.18, sound-absorbing curtains are used extended along walls to decrease the reverberation in the venue or; stored to increase the sound reverberation in some cases.

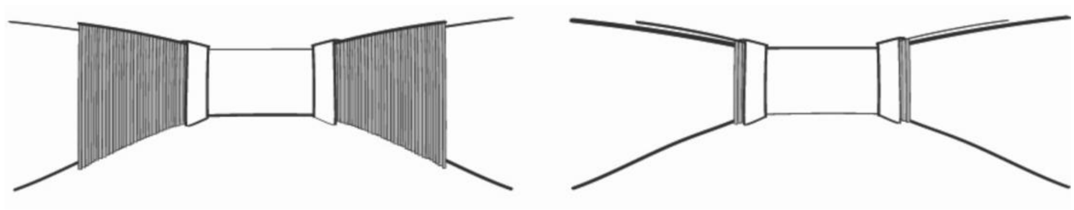


Figure 2.18 Sound absorption curtains. Extended on the left, stored on the right

Using acoustic curtains in the Church has both advantages and disadvantages. Curtain systems made of fabrics with a rail track are relatively moderate cost compared to other solutions. Also, the system can be run manually without the need for a motorized system and is easy and quick to deploy, unlike other systems. However, curtains have some limitations in variable sound absorption. As a porous material, fabrics are effective at mid and high-frequency sound absorption. Hence, to control low-frequency reverberation, sound-absorbing curtains may not be sufficient in some cases.

The sound absorption quality of the fabric curtain systems basically depends on; the weight of the textile, the fullness (such as flat or folded) of the curtain, the air space between the curtain and the backing (if applicable), and the airflow resistance of the textile (Adams, 2016; Atelier Crescendo, 2021; Barron, 2011; Cox & D'Antonio, 2017).

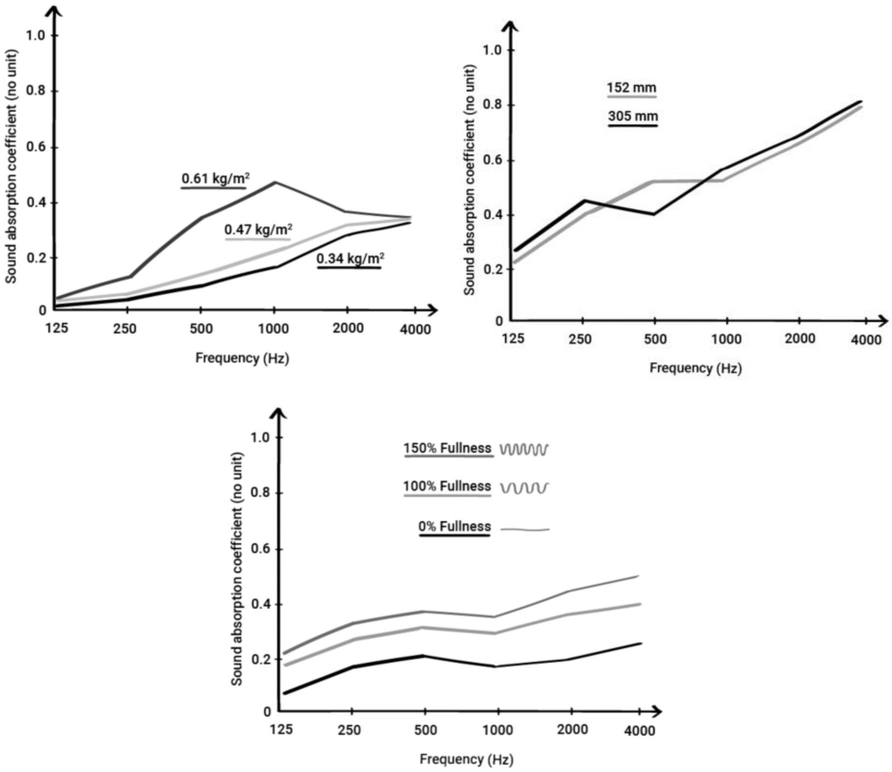


Figure 2.19 Sound absorption coefficient of the curtain fabric depends on the weight, fulness and distance from a hard surface *(Atelier Crescendo, 2021)*

According to Figure 2.19, it is shown that especially for mid frequencies, heavier fabric is more likely to absorb better sound energy. On the other hand, the difference between flat and folded configurations is also presented. Accordingly, if the total length of the curtain fabric corresponds to twice the length of the rail track system, it is mentioned as "folded", and if it is equal, mentioned as "flat", and folded version has better sound absorption capacity. Finally, the gap between the curtain and the hard surface is another criterion that affects sound absorption. If the curtains are located in front of a hard surface or away from (generally 100 – 300 mm) the surface, the sound absorption quality increases (Figure 2.19). In brief, as the fulness of the curtain, the weight of the curtain fabric, and the distance (air space) between the curtain system and the backing increases, the sound absorption quality improves.

The most basic methods involve hanging fabric curtains or banners from tracks that can be stored and lowered into venues by hand or mechanically (Long, 2006). Sufficient treatments can be achieved by hanging sound-absorbing fabric curtains in folded fullness (100 percent) is emphasized in the literature from different sources. Considering low-frequency absorption, providing deep air space (gap/distance) between (Figure 2.20) the sound-absorbing material and the backing surface is crucial (Egan, 1988).

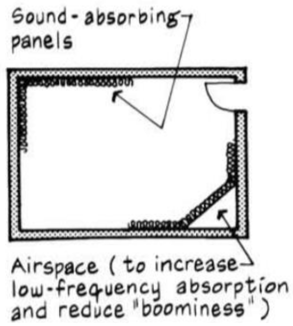


Figure 2.20 Air space for increasing low-frequency sound absorption (Egan, 1988)

Retractable sound-absorbing curtains or banners enable a broader range of reverberation times. Thus a broader range of performance types can be hosted in the hall thanks to the possibility of deploying for reducing RT and retracting to increase RT values (Ermann, 2015).

Suspended acoustical treatments are commonly used systems to reduce reverberation time and echoes in large spaces. These items can be applied in various techniques such as attached to the beams, suspension cable support, or direct attachment to the roof deck. In a place where regular applications cannot be feasible, hung-free usage can be considered.

Today, computer simulations are the most practical way of testing acoustic improvement suggestions. In this regard, there are some critical issues to be considered. Acoustics modeling of textile materials in computer simulations may have some challenges in achieving accurate results, especially if used in a freely hung position, as they both absorb and transmit the sound. In their research, Alonso and Martelotta (2016) investigated how sound-absorbing curtains should be modeled in acoustic computer models. Generally, sound absorption coefficients of the textiles are measured close to reflective surfaces. But, as textiles are porous sound-absorbing materials, their behavior can be challenging to estimate when they hung-free in the space. However, there is not enough research conducted on this issue.

In the experiments mentioned in the paper, absorption coefficients and transmission coefficients were considered for the tests. For samples that were hung free in the center of the hall, no notable variation was observed in the measurements with or without including transmission factor. But if the curtain material is placed in a way to create sub-volumes in a space, some remarkable differences were observed in the experiments in the case of taking into account the transmission factor. In this case, if the transmission is neglected, the absorption coefficients in the simulation model get higher values than the real data, which may be misleading. This means that not only sound absorption is sufficient in the acoustic modeling of freely hung textiles, but also sound transmission through the curtain screens may also play a significant role, particularly when the textile divides the space into sub-volumes. In short, it is explained that transmission has an essential role in defining the sound absorption coefficients used in acoustic simulations when the freely hung textile material subdivides the space into parts (Alonso & Martellotta, 2016).

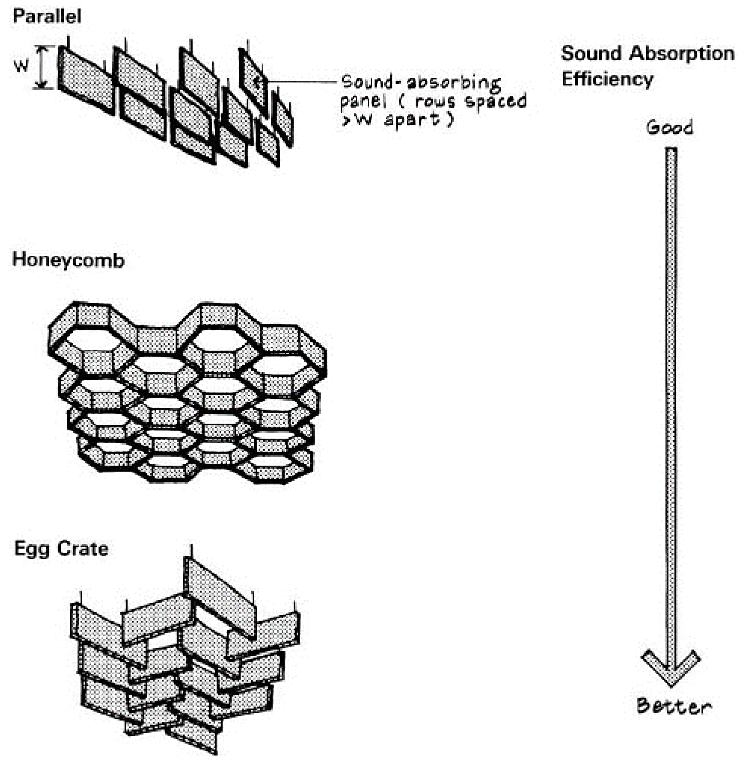


Figure 2.21 Suspended baffle panel systems (on the left) ***(Egan, 1988)***

There is a relationship between the placement of acoustic products and sound absorption. As shown in Figure 2.21, the farther the arrays from parallelism, the closer they are to the eggshell, and the higher the sound absorption capacity is achieved for reducing long reverberation.

In brief, as the fulness of the curtain, the weight of the curtain fabric, and the air space between the curtain system and the backing increase, the sound absorption capacity is enhanced. Apart from these, the placement of the items in the acoustic design affects the sound absorption performance of the acoustic treatment.

CHAPTER 3

MATERIAL AND METHOD

In the scope of this study, the sound field of the Surp Yerrortutyun Church is examined by field measurements and room acoustics simulations based on the ray-tracing method.

3.1 SURP YERRORTUTYUN ARMENIAN CHURCH

Among the historical churches in Anatolia, the 19th century Orthodox Church, namely "Surp Yerrortutyun (Holy Trinity) Armenian Church" in Sivrihisar (Eskişehir), which is already in use as a museum, was selected as a case study due to the availabilities in access, permission given by authorities for in-situ measurements, as well as due to the complaints about the poor acoustic environment in the church when used for various purposes, and the demands of those authorities for eliminating those problems.

Surp Yerrortutyun Church Museum was announced as a cultural center by the authorities (Sivrihisar Municipality and Ministry of Culture and Tourism) in 2009 (İnceoğlu, 2013) and underwent extensive repair works until 2013.

In this study, the Surp Yerrortutun Church (Figure 3.1) was examined in terms of its architectural and acoustical characteristics, considering its religious, political, and historical emphasis, including the repair works. The monument is located on Santral Street in the northwest of the Sivrihisar district center and in the south of Yazıcıoğlu Castle. It is also in the southeast of the Gavur Bath, which is located further outside the district settlement. There is a rocky hill to the east of the church, in which the clock tower is also found (Kaya, 2013). The monument is in possession of the Sivrihisar Municipality (ÇE-MİM, 2001).

Figure 3.1 Exterior and interior view of Surp Yerrortutyun Church in 2019 ***(Source: photographed by the author)***

3.1.1 HISTORICAL BACKGROUND

The historical and cultural accumulation of the Sivrihisar region dates to historical times and hosts many civilizations. The Surp Yerrortutyun church, built in such a precious area, has been one of the region's most important landmarks since its construction. In this regard, this monument plays a vital role in ensuring the continuity of cultural activities in the region. The social and political developments reveal the importance of preserving this monument. Here the history of the Sivrihisar and the Surp Yerrortutyun Church by pointing out its significance is compiled.

In the 6th century, during the Justinian I (527-565) period, who was the emperor of the East-Roma (Byzantine) Empire, Sivrihisar (in Galatia) was renamed Justinianopolis. This new town displaced the Pessinius Ancient city, which was located in the southeastern town of the Sivrihisar, so-called Ballıhisar, and has one of the important cultural heritages of Anatolian history, the Temple of Kybele (Bursa Eskişehir Bilecik Kalkınma Ajansı, 2012; ÇE-MİM, 2001). Justinianopolis (Sivrihisar), known as

"Spaleia" in ancient times, was developed in the empery of Justinianus. It first became the archbishopric and then became the metropolitan center in those days (Kaya, 2013).

As mentioned, the region has hosted many civilizations. However, the information accessed in this context dates back to the Ottoman Empire period in the recent past. Accordingly, the 19^{th} century is a period of crucial changes for non-muslim citizens in the Ottoman Empire. Associated with the Edict of Gulhane (Ottoman Tanzimat Edict) in 1839, which was declared during the westernization movements, some rights were granted to non-muslims, such as building many new churches. After the Edict of Gülhane (Tanzimat Edict), the cities were enriched with new worship places; for instance, 130 churches were built in Kayseri at the end of the 19th century. These churches, which are generally built with vernacular construction practices and local materials, have adopted the architectural style in Europe and Istanbul (Ahunbay & Açıkgöz, 2008).

After all, political and social developments resulted in the population exchange between Muslims in Greece and Greeks in Anatolia and the deportation of Armenians in those days. Therefore, these political developments have caused the abandonment of churches, and some of them were damaged by vandalism or urbanization. The remaining churches have been used for other functions that may injure their architectural identity regardless of their cultural heritage value (Ahunbay & Açıkgöz, 2008).

The worship places of the Armenians living under the auspices of the Ottoman Empire were built by specific rules, as mentioned. Surp Yerrortutyun Church, which will be examined within the scope of the thesis, was also built after the declaration of Ottoman Reform Edict (1856). The monument was constructed near Eskişehir, by the side of Kütahya sub-district, which is located in the town called Sivrihisar today (Kaya, 2013).

The first author who mentioned Eskişehir Armenians was Paul Lucas, the traveler. He came to Eskişehir in 1705 during his travel by command of French King Louis XIV and stated that the Armenians dwelled near the lower part of a hill in a village, which is located 2 kilometers away from Eskişehir. The Scottish diplomat and traveler John Macdonald Kinneir, who came to Eskişehir in the 19th century, states that 1 500 people, 400 of whom were Christians, lived in Sivrihisar, which is a district of Eskişehir today (Alkaya, 2006; Kaya, 2013). French archaeologist Georges Perrot, who came to Eskişehir in the second half of the 19th century, mentioned that the Armenians were living in Sivrihisar and there was an Armenian church (Alkaya, 2006). However, no information has been found as to whether this church is the Surp Yerrortutyun Church surviving today (Figure 3.2). Other travelers coming to Eskişehir and its surroundings in 1882 were German engineer, architect, and archaeologist Carl Humann and the German classical archaeologist Otto Puchstein. For them, the population of Eskişehir counted as 10 000, and some of them were Armenians. The population of the Sivrihisar is reported as there are 2000 Turkish houses, and an Armenian settlement composed of 800 houses in the northwest of Sivrihisar. Based on this information, it can be inferred that the population of Armenians living in Sivrihisar increased in the second half of the 19th century, and an Armenian settlement was established (Alkaya, 2006). As a result, it may be indicated that Armenians had a crucial role in the social and ethnic structure of the region in the 19th century (Kaya, 2013).

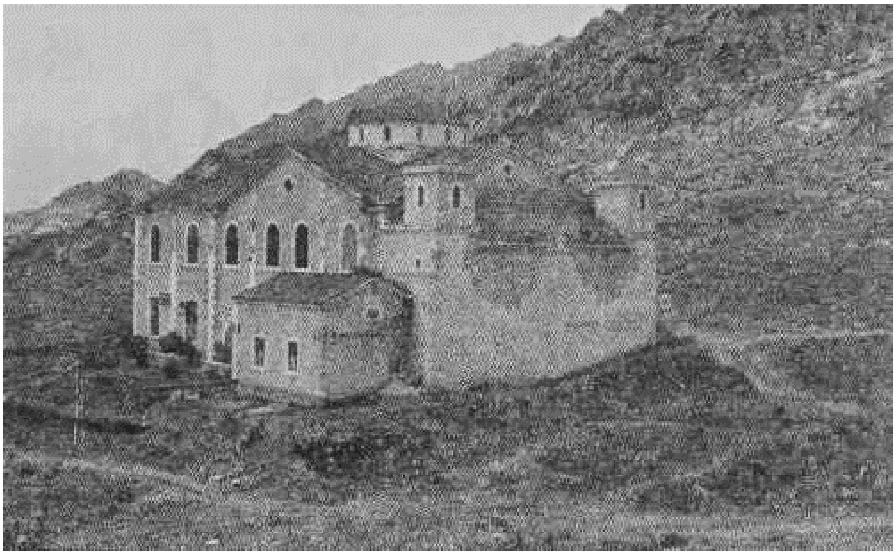


Figure 3.2 Surp Yerrortutyun Armenian Church in 1965 *(Source: anonymous)*

The first certain information about the Eskişehir Armenians is in the book called "La Turquie d'Asie" (1890-95) written by French geographer Vital Cuinet. The book was prepared upon request by the Düyun-ı Umumiye (Ottoman Public Debt Administration) to reveal the socio-economic status of the Ottoman Empire (Alkaya, 2006). The population distribution of the district is given in Table 3.1 based on "La Turquie d'Asie" by Vital Cuinet (Alkaya, 2006).

Table 3.1 Distribution of Population, Eskişehir (Alkaya, 2006)

Population	Distribution of Population
Muslim	48200
Greek Orthodox	12700
Gregorian Armenian	6074
Jew	100
Total	**67074**

It can be inferred from these population data that by the beginning of the 20th century, the Armenian population in Eskişehir and its surroundings corresponds to 10% of the total population (Alkaya, 2006). In that period, Vital Cuinet also mentions the existence of an Armenian Church in this region (Kaya, 2013). On the other hand, Ottoman-Albanian writer and philosopher Şemsettin Sami (Sami Frashëri) indicates the total population of Sivrihisar is counted as 34 902, including 4000 Armenians in his book Kamusu'l-A'lam (Alkaya, 2006). Surp Yerortutyun Church, located in Sivrihisar, which was built in 1881, attracts attention in the region where the Armenian population has increased (Kaya, 2013).

All these political developments, including the dissolution of the Ottoman Empire and the foundation of the Republic of Turkey, caused the Surp Yerrortutyun Church to lose its function as a result of the relocation of the Armenian congregation. Today, it has remained a treasured cultural heritage. Providing the continuity of cultural activities in Surp Yerrortutyun Church, which has a critical and authentic cultural value in this region, is expected to contribute to the cultural sustainability of the Sivrihisar region and its public.

3.1.2 SUMMARY OF INTERVENTIONS AND RESTORATION WORKS

Over centuries of its existence, Surp Yerrortutyun Church has suffered damages from using out of original function. The monument has also undergone some interventions due to changes in its usage. This section focuses on crucial changes in the interior of Surp Yerrortutyun Church that may affect its acoustic environment.

In the building survey report prepared in 2001, the church was out of use in the first half of the 1900s and was used as a power plant (Figure 3.3) in the 1960s, based on the information received from oral sources.

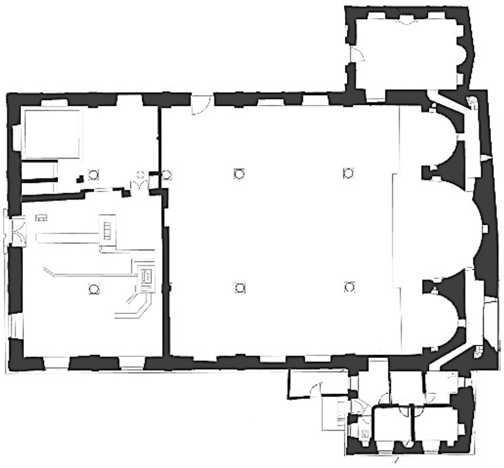


Figure 3.3 *Rölöve* plan of the Surp Yerrortutyun Church, view of additional walls and installed the central unit on the West part *(Source: reconfigured by the author)*

It is stated that additional walls were included in the original state of the main hall (Figure 3.4), and a central unit was installed on the west side of the interior (Figure 3.3); therefore, the floor covering was changed. Partitions walls were added, some windows and bell towers, and the mezzanine floor (known to be in its original state) were removed during alterations (Figure 3.6). In the current state, the traces of the mezzanine floor beams can be perceived. However, the original structure of the mezzanine floor and how to go upstairs are not known. Likewise, the original form of the semi-demolished bell towers is undetermined.

Figure 3.4 Additional walls included in the original state of the main hall, before the restoration works, (ÇE-MİM, 2001)

Clarifying the information about the period when the monument was built, the materials and architectural restitution studies of its original state are a particular research topic. However, in its original form, the structural and finishing materials of the Church are briefly mentioned as rubble stone, cut stone, plaster, mortars, paint layers, glass, wood, and iron. In the as-is case, most of the stone surfaces in the monument are covered with paint on plaster, and the ground surfaces are covered with natural stone. There is information that the columns, capitals, pedestals, and iron ropes in the main hall were also repaired in this context.

The General Directorate of Cultural Heritage and Museums issued a notice for the conservation of the Church in 1975. The registration certificate of the building was prepared in 1987 (ÇE-MİM, 2001). It is understood that the church became its current state after the repair works were completed in 2013.

In the main structural system of the church, exterior load-bearing wall thickness varies between 90 cm and 150 cm. The inner top point of the dome, which is made of ashlar stone mesh, and the highest point of the main hall, is at 20.76 m level from the ground and has a 58 cm wall thickness. All the walls and roof covers of the monument were made of rubble stone. The secondary materials supporting the stone masonry system are iron and wood. The arches that carry the roof cover are fastened to each other by iron cables (Figure 3.4) at the level of the arch ring (at about 9m level). In the arches bearing the dome, there are also other iron cables on the top level (at about 10.80m level). The arches on both sides of the main entrance, which carries the mezzanine floor, and the floor beams that do not exist today, are consist of wooden elements. The yellowish-brown rubble stone walls, white ashlar stones, and red roof tiles were used in the bare form (unplastered) from the exterior. All the surfaces were plastered with lime plaster and painted gray in the interior. The door and window frames, made of ashlar stone, were also plastered from the interior. The natural-stone floor covering was used in both the main hall, chapel, priest house, and the galleries, except for the stairs. Other authentic materials and elements of the church consist of iron window lattices, wooden window frames, door leaves, and glass windows.

It is mentioned in the survey report that the soil where the church was built is classified as hard rock soil, no ground subsidence was detected due to the earthquake movements, and the main structure is completely sound. Except for the upper parts of the bell towers (Figure 3.5), no structural losses were observed. Also, there was no structural cracks, detachments or deformation in the walls, columns, vaults, arches, and dome.

Figure 3.5 View of semi-demolished bell towers (ÇE-MİM, 2001)

However, many detachments and plant formations were observed on the dome pendentives and tile roof coverings. In the upper cornice of the façade, detachments and discolorations were found intensively. The major problem with the facades is the deterioration of the mortar joints between the rubble stones. Also, rising dampness in the eastern and northern façades in lower parts is observed in rubble stonewalls. Similarly, these problems are also observed in the chapel and priest house facades. The roof coverings, broken tiles and plant formations, separations and dark staining on the roof cornices, material loss on the mortar joints of the rubble masonry wall, and the rising dampness were stated. Other material-originated problems are corrosion on iron window lattices, decay and fiberisation on wooden joinery, and discoloration (dark staining) problems on window and door frames made of ashlar stone. The absence of a drainage system on the ground, and the accumulation of soil, especially on the east and north facades, caused the rising damp problem. Likewise, the absence of roof drainage has caused a rainwater penetration problem. For these reasons, some of the building components and joineries were deformed, and some of them suffered from poor environmental conditions, which may accelerate the degradation process. Also, the use of new cement-type material, incompatible with the authentic materials, may cause damage to the monument.

The many problems detected on the exterior have not been observed in the interior. The most intense concern in the interior is the plaster flaking on the top cover, including the upper parts of the dome and vaults. Also, a smoke stain was observed on the apse wall.

As mentioned in the conservation and restoration report prepared in 2001 by ÇE-MİM, the Church was found structurally sound, preserving its main volumetric characteristics. The most critical interventions were made in the plan layout by dividing the Church into parts. Also, bell towers and galleries were closed throughout the alterations.

In the report, it is stated that the main hall had divided into two places by a high brick wall, and the western part had divided into more areas (Figure 3.3 and Figure 3.4) Besides, the one-room south chapel was also sectioned into six roomed by additional walls to be used as the priest's house. Furthermore, the kitchen counter and chimney were also constructed, which makes this place the most modified place in the monument.

It is possible to determine the original condition of the walls, window, and door openings. The significant problem encountered is the inability to the determination of the original form of the mezzanine floor, even though beam traces can be observed on the wall (Figure 3.6). In addition, it is assumed that due to the existence of large window voids on the walls, the staircase may be made of a lightweight structure enveloping the pillar. Another critical problem is the unknowing original form of the bell towers, which have no traces today. However, according to the ÇE-MİM, the architectural office preparing the conservation project, the simplicity and symmetrical design of the single-room plan of the Church ensures most of these interventions can be reversible except for the unknown lost parts.

Figure 3.6 View of beam traces of the mezzanine floor and canceled window openings (ÇE-MİM, 2001)

3.1.3 ARCHITECTURAL PROPERTIES AS OF TODAY

Here, the architectural and spatial features of Surp Yerrortutyun Church which might affect its acoustic properties, are explained in this section.

Figure 3.7 Exterior view of Surp Yerrortutyun Church from the western entrance in 2020 ***(Source: photographed by the author)***

The monument (Figure 3.7) was constructed in 1881 in the name of the Holy Trinity and designed by the architect Mintesh Panoyat under patriarch Nerses II. Varjapetian (1874-1884) (Kaya, 2013).

The following information is included in the marble inscription placed by the Sivrihisar Municipality in the garden of the monument's western entrance; the building was originally built in 1650, exposed to a fire in 1876, and rebuilt in 1881 by the Armenian community which will become the current state as of today. The stonemasonry monument is made of local building materials. Since it was constructed, it has been one of the largest churches in Anatolia (Sivrihisar Belediyesi, 2020).

The interior plan of the Surp Yerrortutyun Church was organized in a three-nave, domed basilica plan without a transept (Figure 3.8). On the east wall, three apses are in each aisle. The central apse faces through the main aisle (nave) and is the largest one of the three.

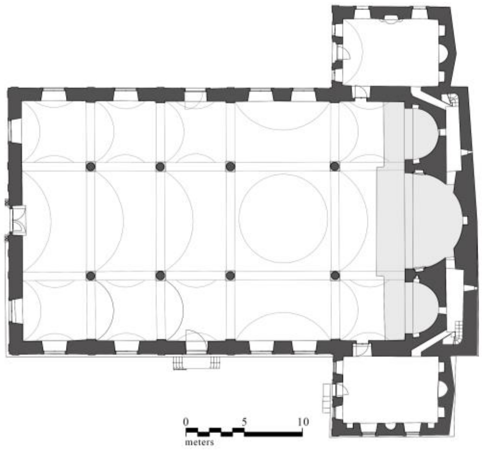


Figure 3.8 Plan view displays the as-is condition of Surp Yerrortutyun Church *(Source: reconfigured by the author)*

The three-nave interior was sectioned as the central nave in the middle and aisles on both sides (Figure 3.9). The central nave is separated from each aisle by four pillars (with plaster-finished ionic capital) from the north and south and supported by the arcades. These four columns, lined in two rows in the north-south direction, are attached to each other by drop arches (Figure 3.9).

Figure 3.9 Section views of Surp Yerrortutyun Church from the central axis *(Source: reconfigured by the author)*

The structure is classified as a rectangular domed basilica with three naves. The roof cover emphasizes the Latin crucifix from the top with a central dome and the crossing barrel vaults (Figure 3.10) (Kaya, 2013).

Figure 3.10 Emphasized Latin crucifix form seen from the top of the Church in 2019 *(Source: photographed by the author)*

The east-west axis divides the monument into two identical sections through the center of the nave. The church's main entrance, which faces eastward, receives the congregation from the monumental portal. The Bema is slightly raised (about 1m) above the floor and centered in the large apse, which is in the middle. The side aisles of the Surp Yerrortutyun Church are lighted by windows on both the north and south sides, and the central nave is enlightened with twelve windows ringed in the dome drum.

The monument consists of three parts: the main hall (the Church) in the middle, the parsonage (house of clergy) in the south, and the chapel in the north. All three are attached to the same load-bearing structural system. However, the places are connected via openings; the circulation system allows the transition (ÇE-MİM, 2001).

The monument, made of rubble stone, has a total of three entrances on the north and south sides, including the main gate on the westward. The double row of windows arrangement is seen on all facades excluded the east. The windows in the bottom row are rectangular-shaped and have a triangular pediment with a crucifix ornament embossed on the keystones. The windows in the upper row formed in a semicircular arch surrounded by bricks. All the windows are surrounded by white stones, and iron window lattices were used identically. But, the windows on the eastern facade are smaller than the others and can be counted as embrasure.

The west façade is divided into three sections by four marble pilasters, while the north and south facades are divided into five sections vertically. The entrance to the chapel and the side aisles are accessed by exterior stairs from the southern side.

Naos is enlightened by six windows from the west, including two rectangular-shaped in the lower row and four semicircular shaped in the upper row, while a four-leaf clover-shaped window at the top point of the middle of the nave. On the north and south facades, the interior is lightened with a total of ten windows consisting of four at the bottom and six at the top row. Additionally, four-leaf clover-shaped windows are placed at the top point corresponding to the dome level on both sides too. The chapel and the clergy house have single-row rectangular-shaped windows with triangular pediments.

The main portal in the middle of the western facade can be considered the most decorated part of the monument. It has a semicircular arched frame carried by capitals with acanthus leaves and a crucifix ornament embossed on the keystone. The arches fitting on the four pilasters located on the north and south sides of the main portal are partly demolished. The remaining pointed-arch envelopes the outside area of the gate, point outs there may be a porch in the past. From the exterior, there are embossed figures above the western gate entrance. At the bottom, these figures consist of the angels who open the inscription in the form of scroll paper. In the upper part, a pigeon representing the Holy Spirit and two bearded human figures on a sphere are embossed, depicted in a circular area carried by two winged heads.

The total floor area of the church is stated as 1067 m^2 in the building survey report prepared by the ÇE-MİM (2001), which is the latest one obtained from The Turkish Republic Ministry of Culture and Tourism Ankara Directorate of Surveying and Monuments Archive (2019). Based on these drawings, the floor area of the central main hall is calculated as 735 m^2 by means of computer software, SketchUp Pro v.2015. The maximum dimensions of the whole monument, including the chapel and priest's house, measured approximately 41m x 23m x 21m. The maximum dimensions of the main hall from the interior are measured at about 38.6 m x 20.6 m and 20 m (the inner height of the dome). The estimated acoustic volume of the interior is calculated at approximately 10 650 m^3 using ODEON v.16 software based on the drawings.

The main hall is defined by eight columns placed at the intersection points of the three longitudinal and five latitudinal axes (Figure 3.11). The central nave is broader and higher in the naos, which means the vaults covering the side aisles are lower in height than the central nave to emphasize the cruciform shape. The expanding parts create a T-shaped form in the plan and the roof covering, highlighting the Latin cross. The width of the central nave and T-shaped arms are approximately 8.65 m, with a 15.90 m height. The approximate width of the side aisles is 5.25 m, with a height of 12.40 m. Therefore, the side arms and the tail elongated through the east-west axis of the T-shaped region are broader and higher than the other parts.

The intersection of the T-shaped region with the central nave creates a square section, which is topped with an 8 m diameter central dome that is supported on the pendentives and finished in plaster. The inner height of the central dome is about 20.76 m (ÇE-

MİM, 2001). The columns are attached with pointed /drop arches and then fit into the pilasters through profiled capitals. These freestanding circular cross-sectioned columns consist of cube-shaped pedestals and ionic capitals. The composition of pointed arches is projected as a cross-gabled roof from the exterior.

Figure 3.11 Interior view of Surp Yerrortutyun Church from the western entrance during field measurements in 2020 ***(Source: photographed by the author)***

There are triple apses on the eastward, one is the apse, and two are absidiole. Two doors are open to the apse, and there are three niches in the north, south, and east directions. The apsidioles facing the side naves have a door connecting them to a common area from behind the bema. Also, there are semi-demolished staircases to non-exist bell towers in that field.

The frescoes were observed in some parts and dome pendentives. But today, it is stated that there are only a few pieces left, and the other parts are completely flaked off. Many of them and inscriptions were covered with plaster. There is also an inscription on the northern apsidiole. The text, similar to Latin number forms and written in black paint, was covered with plaster. There are semicircular-shaped vegetative decorations on the upper part of the two symmetrical niches in the central apse. These blue-colored decorations are composed of ornaments with symmetrically curved vegetal decorations. The decoration on the southwards of the apse wall was better preserved, while the north wall was more damaged. Besides, different cross figures are engraved on the surface of the niche in the north of the apse, including the Maltese and the Greek cross. There are also various letters around the apse arches; however, only a few have been preserved.

In brief, the Surp Yerrortutyun Church, built in the 19th century, has a three-nave domed basilica plan oriented in the east-west direction. The roofing cover consists of a dome in the center and the crossing semi groin vaults through the west, north, and south axis, which express the Latin crucifix from the top view. The structures with a similar plan typology date back to the 5th century.

The examples of the Early Christian period, The Church of Saint Sarkis also known as The Tekor Basilica (Kars, Turkey) from the 480s, and the Odzun Church (Lori, Armenia) dated to the 5th-7th centuries have similar architectural characteristics to the Surp Yerrortutyun Church (Sivrihisar). However, there is no triple apse in Odzun Church and Tekor Basilica dissimilarly; only all three have a three-nave basilica plan with an emphasis on the Latin crucifix. The highlighting of the dome with crossing groin vaults, which is projected as a cross-gabled roof from the exterior in the Surp Yerortutyun Church, is similar to the Tekor Basilica in the same way.

Similar Armenian churches built during the same period as the Surp Yerortutyun Church are seen mostly in Kayseri (Turkey) in the 18th-19th centuries in terms of plan orientation. Germir Agia Panagia Greek Church (1837), Balagesi Surp Haç Armenian Church (1842), Efkere Surp Stepanos Armenian Church (1871), Everek Surp Toros Armenian Church (19^{th}-c) in Kayseri, have similar plan orientation with the Surp Yerrortutyun Church by having three-nave basilica plan with three apses.

3.2 ACOUSTICAL FIELD MEASUREMENTS

Surp Yerrortutyun Church field tests are held on 20th October 2020 within the context of thesis research, hours between 12.00 – 16.30 as permitted, when the Church is unoccupied. The impulse responses are captured from different sound sources and receiver positions to measure the sound field properties of the Church in accordance with the ISO-3382-1:2009 and IEC 60268-16:2011 standards.

B&K Type 4292-L standard dodecahedron sound source and B&K Type 2734 power amplifier were used for acoustic signal generation in the measurements. Impulse responses are collected by the NTI Audio M2230 Type 1 microphone using the NTI Audio Type XL-2-TA handheld acoustic analyzer for the diverse measuring points. The microphones at the receiver points are positioned 1.20 m above the ground to represent the audience, and the source points are placed 1.50 m above the ground to represent the performer. Background noise is measured at the R_{01} receiver position (Figure 3.12).

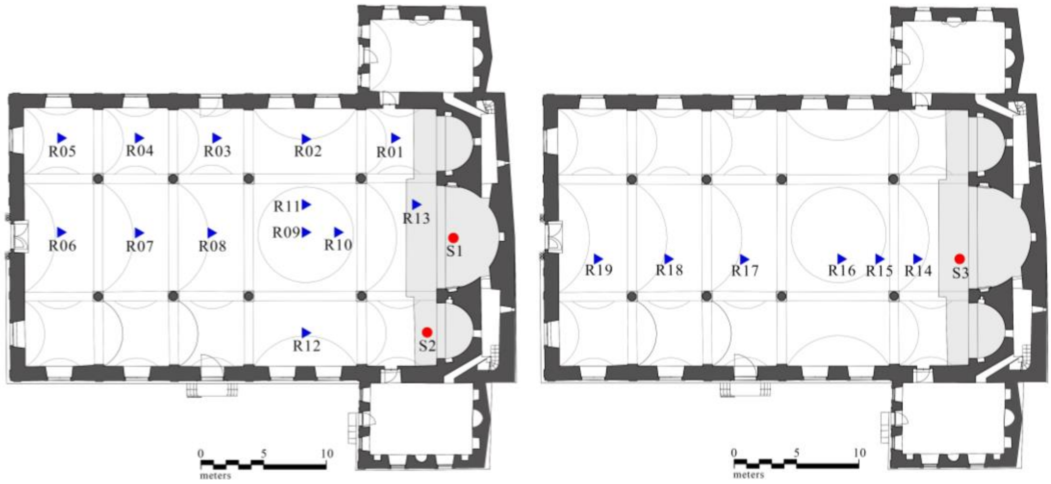


Figure 3.12 Surp Yerrortutyun Church field measurement source (S) and receiver (R) locations in plan view

Three measurements were conducted in the field tests in the defining room acoustic parameters of Surp Yerrortutyun Church.

The first measurement obtained the data directly by producing a pink noise signal using an electro-acoustic source with the interrupted noise method. Two sources (S_1-S_2) and thirteen receiver positions (R_{01}-R_{13}) are tested in different configurations (Figure 3.12). In these measurements, the reverberation time that accounts for the first 20 dB decay (T_{20}, s) was captured in the frequency range of 50-10000 Hz.

Figure 3.13 Surp Yerrortutyun Church field measurement photographs, 10th October 2020

In the second measurement, for defining the basic properties of the sound field, the impulse responses are gathered in the 125 - 8000 Hz frequency range for the same source-receiver configurations as the first measurement. The test signal is set to sine sweep signal, and the sampling frequency of the impulse response is 44.1 kHz, 16 bits. Each source-receiver configuration is run multiple times to obtain accurate data with minimum distortion. For signal-producing and post-processing, Easera Measurement Analysis software is used. Data including Reverberation Time (T_{20} T_{30}, s), Early Decay

Time (EDT, s), and Clarity (C_{80}, dB) parameters were derived from the collected impulse responses.

Figure 3.14 Surp Yerrortutyun Church field measurement photographs, 10th October 2020

The third measurement aims to observe the distance-dependent decrease of the speech transmission index (STI). Thus, the configuration consists of one source point (S_3) shown in Figure 3.12, and six receiver points (R_{14}-R_{19}) positioned at approximately 3m or 6m increments on the same axis (Figure 3.12, on the right). The nearest receiving point to the source (R_{14}) is about 3m, and the most distant receiving point (R_{19}) is about 29m distance from the sound source. "NTI Audio Talkbox" (Figure 3.14, on the right) is used as a sound source for acoustic signal generation, and an STI-PA signal is produced for the STI test.

The calibration of the devices used in the measurements was made with the Norsonic Type 1251 sound adjuster.

3.3 Acoustical Modelling and Simulation Analyses

The geometric acoustic model of the Surp Yerrortutyun Church is produced to represent its as-is condition and calibrated according to the field test data. This acoustic model is named Scenario I and examined for unoccupied states. This model is used as a base to develop and assess some acoustic solutions proposed for acoustic improvement studies in the Church. Acoustical simulation analyses are conducted to simulate and define the acoustic problems in terms of measurable acoustic parameters and to examine the proposals' acoustic performances for the activities (defined in Scenario II and Scenario III) intended to be held in the Church. In addition, simulation analyses allowed estimating the changes in acoustic performances when the Church is occupied with the 80% audience and in rehabilitated states.

For these purposes, The 3D computer acoustical model of Surp Yerrortutyun Church that represents its current state is produced by using AutoCAD 2013 and SketchUp Pro 2015 software, following the latest measured data drawings obtained from the Ankara Directorate of Surveying and Monuments (2019). In the accurate assessment of acoustic modeling, the computer model is calibrated based on field measurement data in unoccupied conditions, as mentioned.

In the process of generating the graphical model, simplicity is substantial in the point of computational load, as mentioned in the ODEON manual (ODEON, 2018). The produced computer acoustical model keeps its original volumetric details to reflect the maximum effects of the architectural properties while considering the limits of the room acoustics software. Therefore, the simplified model of Surp Yerrortutyun Church made up 3D face elements consisting of 24 793 planes and imported into ODEON Combined v.16 to run the acoustic calculations.

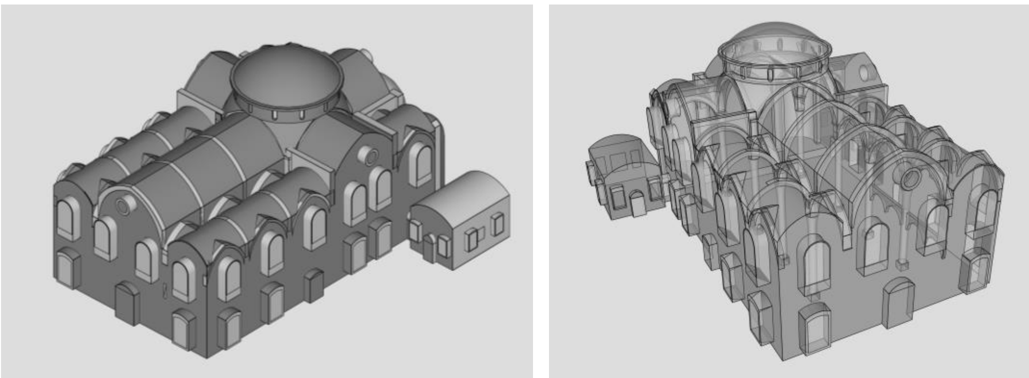


Figure 3.15 Surp Yerrortutyun Church, computer model view

In evaluating the room acoustics parameters, the reliability of the computer model is crucial. For this reason, the waterproofness of the model is checked by visualized raytracing (Figure 3.16).

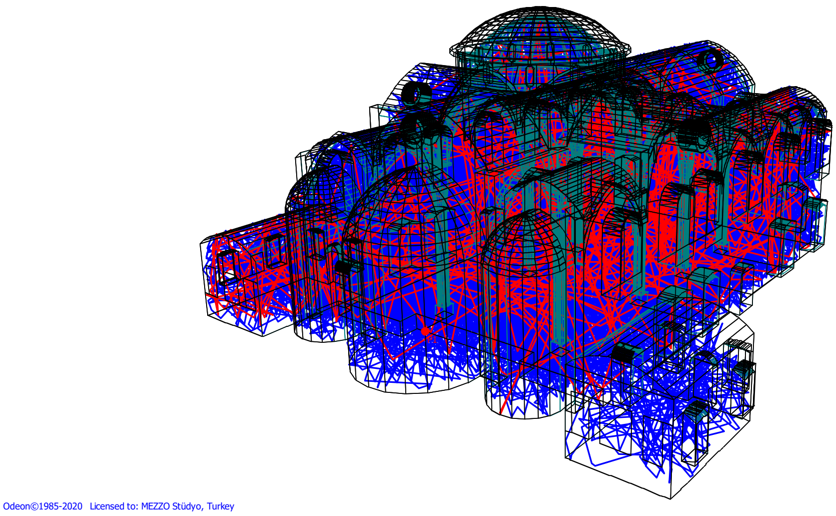


Figure 3.16 Surp Yerrortutyun Church, ODEON raytracing view

As recommended values by the ODEON software, the impulse response length is set to 20 000 ms, and the number of late rays is determined to be 19 896 ms in ODEON calculations. The estimated acoustical volume of the Church is about 10 650 m^3.

In the calibration process, first, the computer acoustical model is imported into the ODEON in an unoccupied state. Then, surface material properties, including sound absorption coefficient and scattering, are adjusted by a heuristic approach in accordance with the field test results held in 2020 within the context of this thesis research. The field measurements' room conditions are also defined in the acoustic model to obtain the proximate results. The value for temperature is 26.5 °C, relative humidity is 60%, and the measured background noise level is NC15. Accordingly, the sound reflective surfaces are depicted in light colors, while the absorptive materials are illustrated in dark colors in the 3D OpenGL view (Figure 3.17).

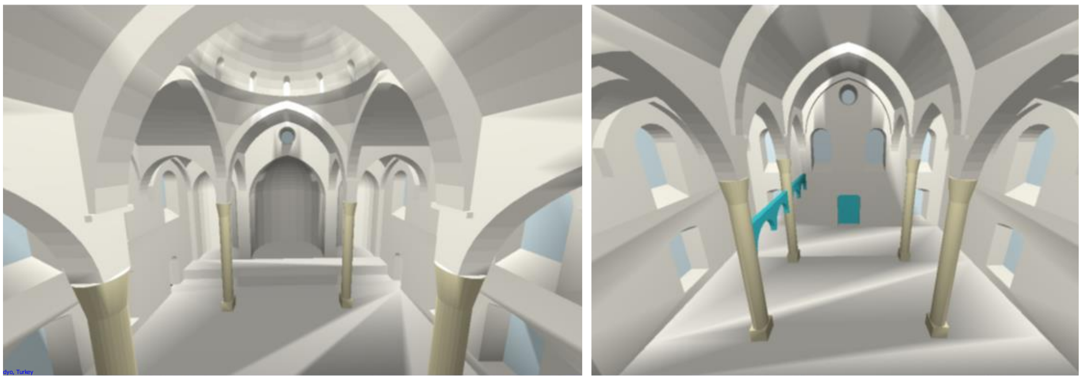


Figure 3.17 3D-OpenGL view of modeled Surp Yerrortutyun Church

The source-receiver points in the computer simulation are duplicated as in the field tests (Figure 3.18). The receivers are distributed throughout the main listening area from the symmetry axis of the zone. As in standard reverberation calculations, an omnidirectional sound source is placed in the middle of the scene at 1.50 m representing the performer.

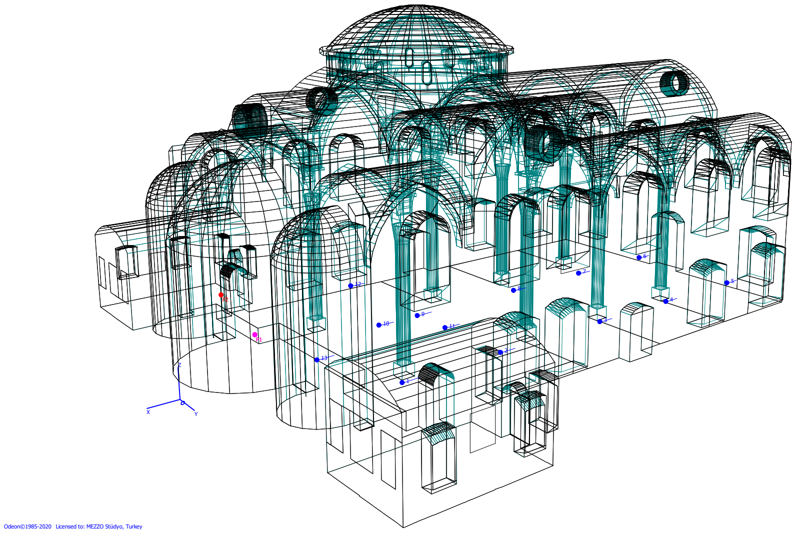


Figure 3.18 Surp Yerrortutyun Church, ODEON acoustical model with source (pink) and receiver (blue) points

Additionally, to analyze the acoustic performance of the Surp Yerrortutyun Church in the simulations reflecting the occupied state, the grid audience zone is defined in the computer model consisting of 120x120 cm squares.

In brief, the generated 3D acoustic model of the Church is calibrated according to the field measurement data. This model is used as a base to examine the acoustic performances of the developed acoustic rehabilitation proposals (Proposal I, II, and III) for speech (Scenario II) and musical (Scenario III) activities. Acoustic simulation analyses are conducted on Proposal I, Proposal II, and Proposal III to assess their acoustic performances for speech and music-related activities. The relevant scenarios and proposals mentioned here are explained in detail under the following headings.

3.4 DESCRIPTION OF THE SCENARIOS

The acoustic simulation analyses are conducted on mainly three scenarios: Scenario I, Scenario II, and Scenario III. Scenario I represent the existing situation of the church, which is calibrated according to the acoustic data obtained from the field measurements. Scenario II represents the seating layout for speech-related activities, while Scenario III represents the seating layout for music-related activities. In these three scenarios, the behavior of sound energy in the church volume, and speech intelligibility quality are the two crucial acoustic criteria for the evaluations. For this reason, the assessments focus on the parameters of reverberation time (RT), clarity (C_{80}), and speech transmission index (STI). The use of amplification systems, including loudspeakers, sound boosters, etc., are not included in these scenarios.

The definitions of these three scenarios, including the acceptances and assumptions, are explained in the following subheadings.

3.4.1 SCENARIO I: CALIBRATED AS-IS CASE

Scenario I represents the as-is condition of the Church in an unoccupied state. Its acoustic environment was simulated by a computer model where materials assigned to the Church's surfaces were selected to achieve the closest values of “Reverberation Time, (RT, s)”, “Early Decay Time (EDT, s)” and "Clarity (C_{80}, dB)" obtained from the field measurements. The sound absorption and scattering coefficients of the materials assigned to the Church's surfaces for the calibration process are summarized in Table 3.2. The database existing in ODEON software and the literature were used during the surface materials' properties setting process, while some new data were assigned as input to enhance the proximity between the in-situ and simulated RT and C_{80} data.

Table 3.2 Absorption and scattering coefficients of the materials assigned to the surfaces for the calibration

Existing Surface Description	Sound Absorption Coefficients in terms of 1/1 Octave Band Frequency (Hz)						Scattering Coefficient
	125	250	500	1000	2000	4000	
Natural Stone Tile floor	0.01	0.01	0.02	0.02	0.02	0.05	0.20
Natural Stone Pillars	0.02	0.03	0.03	0.03	0.04	0.07	0.25
Plastered and satin paint (semigloss) coated wall surfaces*	0.02	0.03	0.03	0.03	0.03	0.04	0.20
Plastered and satin paint (semigloss) coated superstructure surfaces (vault and dome surfaces)*	0.02	0.03	0.03	0.03	0.03	0.04	0.25
Glass windows	0.10	0.06	0.04	0.03	0.02	0.02	0.20
Wooden Portals (Gates)	0.60	0.30	0.09	0.09	0.09	0.09	0.20
Smooth Wood Surface	0.60	0.30	0.09	0.09	0.09	0.09	0.20

(*) assigned by author and added to ODEON databank

The confirmation of the calibrated simulation model, in other words, the verification of the proximity between the in-situ and simulated acoustic performance results, is done in reference to the Just Noticeable Difference (JND) criteria defined in terms of RT and C_{80} parameters in ISO 3382-1:2009 Standard (ISO 3382-1, 2009; Katz et al., 2018). A 3D computer model is accepted as "well-calibrated", in other words, "perceptually equivalent", when the difference between real data and simulated data is less than JND values (Vorländer, 2010).

The JND criteria defined as the acceptable ranges in terms of RT and C_{80} are summarized in Table 3.3. According to ISO 3382-1:2009 standard, JND is set to be

±5% of actual RT and EDT values and ±1 dB of the actual C_{80} value. During the calibration process, priority is given to RT. First, the simulated RT value is calibrated to achieve ±%5 of real RT by adjusting the sound absorption coefficients of surface materials (Table 3.2). The simulated C_{80} is then calibrated to obtain an actual C_{80} of ±1 dB by adjusting the scattering coefficients of the surfaces, including ornament surfaces and irregular geometries in the Church (Table 3.2).

Table 3.3 The JND criteria of RT, EDT, and C_{80} parameters defined in ISO 3382-1:2009 standard *(ISO 3382-1, 2009)*

Subjective listener aspect	Acoustic Parameter	Single number frequency averaging *	Just Noticeable Difference (JND)	Typical range**
Perceived reverberance	Early Decay Time (EDT) in seconds	500 to 1000 Hz	Rel. 5%	1.0; 3.0 s
Perceived clarity of the sound	Clarity (C_{80}) in decibels	500 to 1000 Hz	1 dB	-5; +5 dB

(*) the arithmetic average of the octave bands.
(**) frequency-averaged values in single positions in non-occupied concert and multi-purpose halls up to 25000 m^3.

3.4.2 SCENARIO II AND SCENARIO III

Both scenarios have the same seat layout, which is shown in Figure 3.19. The acoustical simulations of Scenario I and Scenario II are modeled according to the arrangement presented in Figure 3.19. The seat layout is planned considering the audience comfort requirements defined in the literature (Neufert et al., 2012) and the restrictions of the church space. Based on criteria related to the room volume, aural, and sightline comfort requirements, the seating area model, is proposed to have 112 audience capacity. The seat layout is composed of 14 rows with 8 seats in total, separated into 2 sections with a circulation aisle in between. In addition to the central aisle, there are circulation aisles on both sides of the rows. The width of the central aisle is 1.5 m, and 0.90 cm for the ones on both sides. As recommended, the chair unit dimensions are 580 x 590 mm, and the seating density per spectator is 0,34 m^2. The seating layout is determined considering the recommended sightline angle, which is

30° for a good view with a slight eye movement (Neufert et al., 2012). This capacity may be reduced in pandemic conditions. The space area required for each listener in theatres is 4-5 m^2. Accordingly, in this scenario, 7 m^2 space is served per spectator.

Hosting speech-related activities such as conferences, lectures, and seminars at the Surp Yerrortutyun Church organized by state and private foundations is one of the primary uses of the monument. The use of the monument for speech-related activities is mentioned as “Scenario I: Speech Activities” in the text. Controlling the *humming* sounds due to the highly reverberant acoustical environment enhances the audience and speaker's comfort and allows a better understanding of the speaker’s speech during the occasion. In Scenario I, the sound source is the speaker in a conference or lecturer in a seminar positioned on stage, specifically located at the center of the stage in the acoustical model (Figure 3.18).

Hosting music-related activities such as trio and chamber music concerts or recitals in the Surp Yerrortutyun Church organized by state and private foundations is one of the other primary use of the monument. The use of the monument for music-related activities is mentioned as “Scenario II: Music Activities” in the text. Controlling the highly reverberating sound field while providing reverberation at a certain extent enhances the comfort of the audience and performers on the stage during the musical activities. In this case, a longer reverberation time can be acceptable. In Scenario II, the sound source, specifically located at the center of the stage in the acoustical model, represents the recital performer or chamber music performer (Figure 3.18).

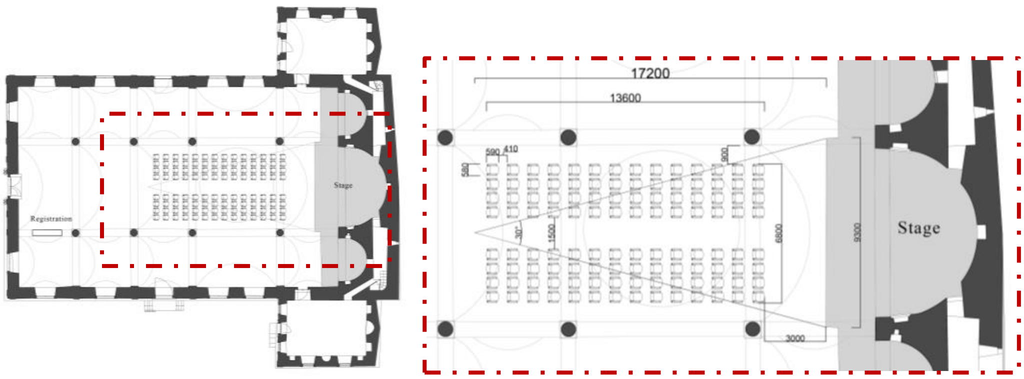


Figure 3.19 Audience seating layout for the Scenario II and III

3.5 DESIGN CRITERIA OF ACOUSTICAL IMPROVEMENT PROPOSALS

The considered design criteria for the acoustic rehabilitation work are compiled in this section. Surp Yerrortutyun Church is a historic monument, and special care is needed for developing acoustic improvement proposals. None of the elements can be fixed permanently in a way that damages the original conditions. All the interventions should be decided with minimal impact on the monument. On the other hand, the audience expected to feel the visual integrity of the Church as well as acoustic comfort. Therefore, developed solutions should include a temporary structure with movable, demountable, and adjustable properties appropriate for historical buildings as in this case. Besides, an approach that will not negatively influence the visual perception of the whole monument and not overshadow the architecture of the Church should be provided. A material/product survey is made for the proper selections that control the Surp Yerrortyun Church's highly reverberant sound field. Using transparent materials can be a suitable selection that minimizes the visual barriers in the monument.

Design criteria to be guiding for material selection and demountable assembly design are summarized in Table 3.4. The proposals for the acoustic rehabilitation of the Surp Yerrortutyun Church should be based on some major design criteria. For instance, keeping the visual integrity, architectural features, and authentic values are the primary design criterion that should be concerned in the proposed designs. On the other hand, the proposals for acoustical improvement should have a not-permanent manner designed as minimum intervention. In addition to the conservation principles/concerns related to the design of acoustic interventions, interior design criteria concerning restrictions of the existing church space should be considered. For instance, entrance to the semi-open encircled environment and integration of this environment within the overall church volume are some interior design criteria that should be considered together with the scenarios defining the needs of the musical- or speech-related activities and seat layout. Here, three proposals are designed in the form of a temporary encircled system composed of movable/portable, demountable, and adjustable assemblies that can be easily mounted and demounted without damaging the historic church's existing surfaces. By means of simulation analyses, their acoustic performances were assessed.

Table 3.4 The summary of the design criteria to be guiding for material selection and demountable assembly design

Proposal Design Criteria	
Material Selection	**Keeping Visual Integrity**
	Preferably use of transparent or translucent sound absorptive materials
	Preferably semi-open periphery design – solid-void periphery design
	Use of compatible, re-treatable, repeatable materials or construction techniques without giving any damage to the cultural property, its surfaces, and spatial integrity
Assembly Selection	**Minimum Intervention, If Necessary**
	dry and lightweight construction techniques without using any wet material
	Not permanent, demountable attachments without giving any damage to the existing surfaces of the cultural property
	Preferably portable or moveable assemblies/panel systems or suspended systems that can be easily placed, mounted, and demounted
	Panels, screens, and curtains in intervals allow the audience to feel the architectural geometry and to contact visually and auditory

Table 3.4 (continued)

Acoustical Needs	**Increasing Sound Absorption**
	Providing sound absorptive periphery to control highly reverberant sound field
	Preferably increase the sound absorptive surface as much as possible
Restrictions of the Church Space	**Seat Layout**
	Considering the audience comfort requirements; room volume, aural, and sightline comfort requirements

The material "sound absorptive polyester-based acoustic curtain fabric" is selected to be used in the acoustic rehabilitation proposals since the material fulfills the design criteria of "keeping visual integrity" and "increasing sound absorption". The suspension systems and vertical separation assemblies, which can be manually or mechanically folded with a sliding mechanism and portable screens, can be placed in the Church through mountable-demountable attachment. Such demountable and portable suspension curtain screens can be installed by forming a cable grid system above the audience and scene zone. These systems are preferred to be used in the acoustic rehabilitation proposals since they fulfill the design criteria of the church space as portable.

3.6 PROPOSALS FOR THE ACOUSTIC IMPROVEMENT

By means of acoustic simulation analyses, the performance of acoustic rehabilitation proposals, both when the church is unoccupied and when it is 80% full of spectators, were examined. These analyses were conducted on mainly three proposals: Proposal I, Proposal II, and Proposal III for acoustic performance evaluations.

The proposals are based on the seating and scene layout suggested for the musical and speech-related activities (Figure 3.19: Scenario II and Scenario III). The performance zone is defined by the selected material which is defined as “sound absorptive polyester-based acoustic curtain fabric”. The material properties of this selected enclosing material are presented in detail in Section 2.4.1.

By using semi-transparent sound absorptive curtain fabric, three design concepts are proposed; these are Proposal I: Closed Periphery System, Proposal II: Opened Encircling System, and the last Proposal III: Combined Design in the Church venue. Proposal I provide a partially isolated acoustic zone surrounded by curtain fabrics at the ceiling level and the vertical sides, in the form of a “closed-box” and creates sub-volume in the Church. On the contrary, Proposal II provides an open acoustic controlled zone with a holistic approach, including architectural and spatial points of view in the Church. Accordingly, it allows visual contact between the activity zone and the Church venue. Proposal III is the combination of Proposal I's the closed and surrounding features with the open plan concept of Proposal II. In three proposals, the acoustic properties of the selected fabric are used as inputs for the acoustic simulation analyses in different configurations.

Historical monuments such as the Surp Yerrortutyun Church are cultural heritages where invasive interventions are not allowed. The proposed project, which aims to adapt the acoustic environment of the monument to musical and speech performances, considers the preservation of the architectonic elements of the historic church as completely reversible. When the Church venue hosts the musical activities, the temporary and reversible intervention for performance space has been designed to have a capacity of 112 seats in the central nave, as shown in Figure 3.19 in Section 3.4.2.

According to the existing demand for specific flexibility in the use of historic Church venue, it was supposed to allow host public events, including speech comprehension and chamber music listenings. These varied two requests for the acoustic environment need some compromises in acoustical targets (Berardi et al., 2015). Among the various acoustic rehabilitation alternatives, using a semi-transparent fabric curtain rail track system and the sound absorptive carpet was considered a solution to increase absorptive surface area with a minimum visual presence.

Accordingly adding fabrics in the form of a curtain frame next to the lateral walls are provide high sound absorption at high frequencies, but also mounted curtains at a certain distance from the wall are absorptive at low frequencies (Berardi et al., 2015).

Through the improvement proposals, the sound absorption coefficients of the components are presented in Table 3.5. Besides, in each scenario, a one piece of sound absorbing carpet was laid on the floor between the sitting areas and remained during analyses. The width of the sound absorptive carpet is 0.9m, and the length is 13.6 m, as shown in the plans (Figure 3.20, Figure 3.23, Figure 3.26). The sound-absorbing carpet and audience chair were selected from the ODEON material library.

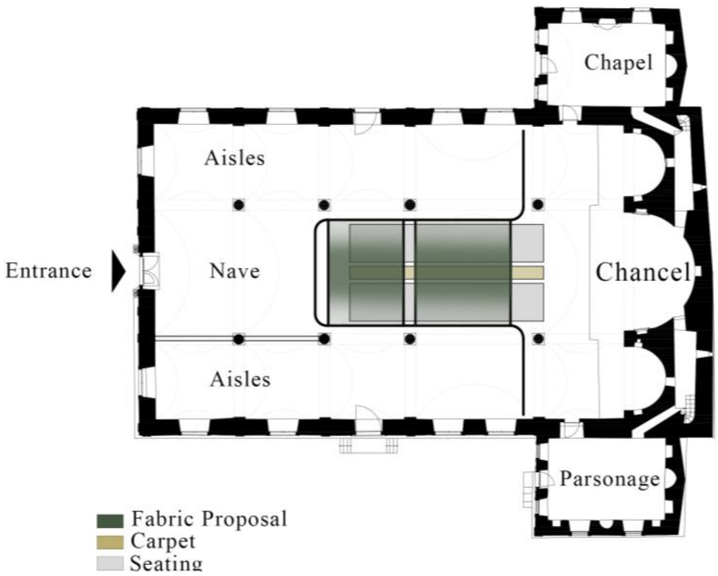
Table 3.5 The absorption and scattering coefficients of the materials used in the proposal models

Surface	Product	Absorption Coefficient						Scattering
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	
Curtain System (folded)	Fabric	0.10	0.35	0.65	0.70	0.75	0.80	0.10
Carpet	Carpet*	0.20	0.06	0.14	0.37	0.60	0.65	0.05
Seating 80% occupancy	Steel pipe, fabric upholstery chair*	0.32	0.46	0.52	0.53	0.56	0.53	0.70

**taken from ODEON data bank*

3.6.1 PROPOSAL I: CLOSED PERIPHERY SYSTEM

Depending on the architectural features, the main approach is to cover the surfaces with sound absorptive materials to increase the surface area in the Church. For this purpose, some demountable-mountable systems are adapted to wall and ceiling surfaces. In Proposal I, the acoustic rehabilitation application was mainly designed along the defined audience zone in the scenarios, enclosure of the seating area which separates the middle nave from the side naves with a top cover by creating a sub-volume in the venue. Proposal I have 473 m^2 sound absorbing surface area consisting of 947 m^2 sound absorptive fabric in the folded arrangement. Proposed curtain fabrics are used in the form of a rail system as a closed periphery in the dimension of approximately 13.7 x 7.4 x 8.5 m. The designed "acoustic closed-box" height is 8.5 m from the ground floor level, where authentic tie bars are positioned between the columns. In addition to these, the surface area of the sound-absorbing carpet laid on the floor is 14 m^2 (Figure 3.20). The focus is to reduce the excessive reverberation times in the 500 – 1000 Hz frequencies recommended in the literature.



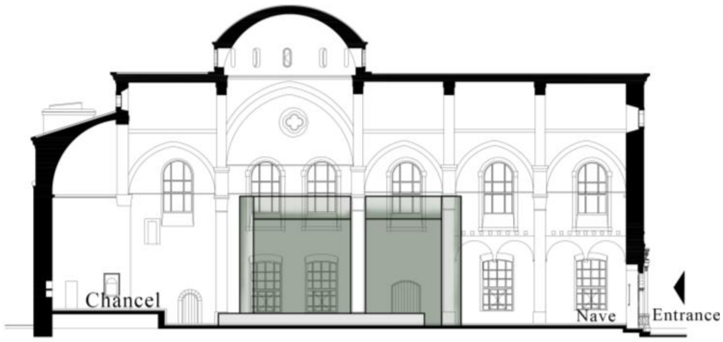


Figure 3.20 Proposal I in the Surp Yerrortutyun Church, plan and longitudinal section view

The potential of flexibility is the determinant factor in this design made of translucent fabric and a portable rail system. The acoustically treated zone covered by the periphery system was defined with a focus on the main audience zone based on real demand in use. The height and design of the curtain system are formed considering the positions of the existing chandeliers hanging from the center of each vault, which is a notable architectural element in the monument, and the iron cables connecting the pillars since the monument's original state. The horizontal banner-like curtain on the top cover is suspended in two separate parts, aligned with the pillars, and curved downwards to increase the surface area. (Figure 3.21).

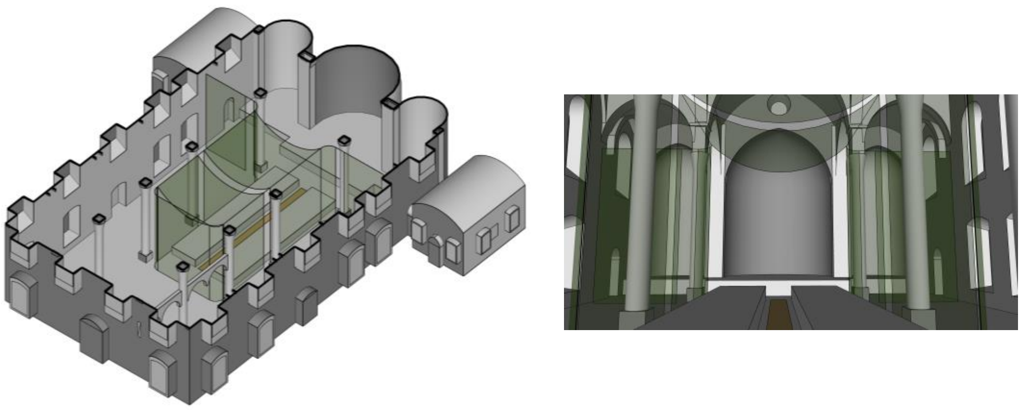


Figure 3.21 Perspectives of Proposal I from the Audience area to the stage

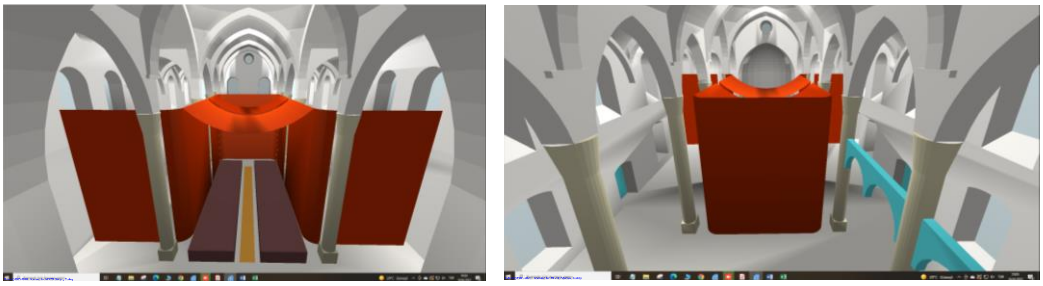


Figure 3.22 3D OpenGL view of the acoustic model of Proposal I in Odeon, which displays the material distribution

Accordingly, generated architectural model is given in Figure 3.21, and the geometric acoustic model is illustrated in Figure 3.22 for Proposal I.

3.6.2 PROPOSAL II: OPEN-PLAN ENCIRCLING SYSTEM

Proposal II aims to provide an open-plan controlled acoustic zone considering the holistic approach of architectural and spatial points. The main components of this proposal are sound absorptive curtain screens and carpets.

Semi-transparent sound absorptive curtains (Figure 3.23 and Figure 3.24, illustrated in green) aim to shield some reflective surfaces such as semi-gloss painted walls in an elegant way to reduce the high reverberant sound by allowing the interaction between the whole venue. Accordingly, Proposal II provides an audial and visual contact between the performance zone and the Church volume with a holistic view apart from Proposal I's isolated design. For this purpose, some lightweight and demountable systems are adapted to the Church's interior to control the excessive RT in the mid-frequencies. The acoustic modular curtain track systems were placed, allowing transition throughout the venue and including suspended ceiling components as if freely hung flags (Figure 3.23 and Figure 3.24).

The curtain screens were placed on the lateral walls in the venue with a 150 mm gap as suggested in the literature to control reverberant sounds at low frequencies. Thanks to the impedance between the wall and the curtain, it is aimed to reduce the high reverberant sounds at low frequencies. Similarly, in order to control the excessive reverberation on the stage, a semicircular curtain system was placed inside the apses of the stage. The width of curtain screens varies between 2.7 m – 4.7m, with a height of 5 or 7 meters depending on their location in the church. Those around the audience zone suspended curtain flags are suggested in the dimensions of 0.9 x 2m and 5m offset from the ground level. The curtain fabrics are used in the form of suspended screens providing an open-ceiling arrangement that defines the audience zone in this proposal. A total of 83 pieces of suspended curtain flag hung on the ceiling in 15 rows with a shifted arrangement.

The total proposed sound absorption area for Proposal II is calculated as approximately 506 m^2 consisting of 1012 m^2 of sound absorptive fabric in the folded arrangement. The surface area of the sound-absorbing carpet laid on the floor is 14 m^2, the same size as Proposal I. Finally, the total value noted in Proposal II provides more sound absorption surface area with an open-plan encircling system than Proposal I's isolated periphery.

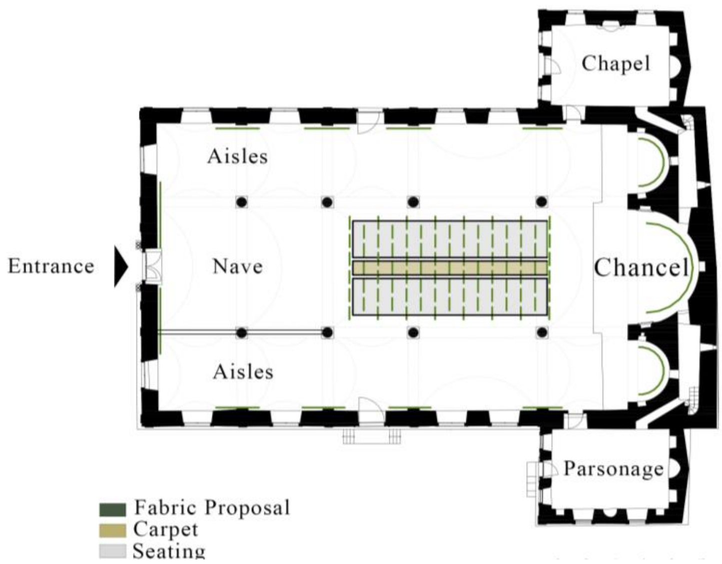


Figure 3.23 Proposal II in the Surp Yerrortutyun Church, plan and longitudinal section view

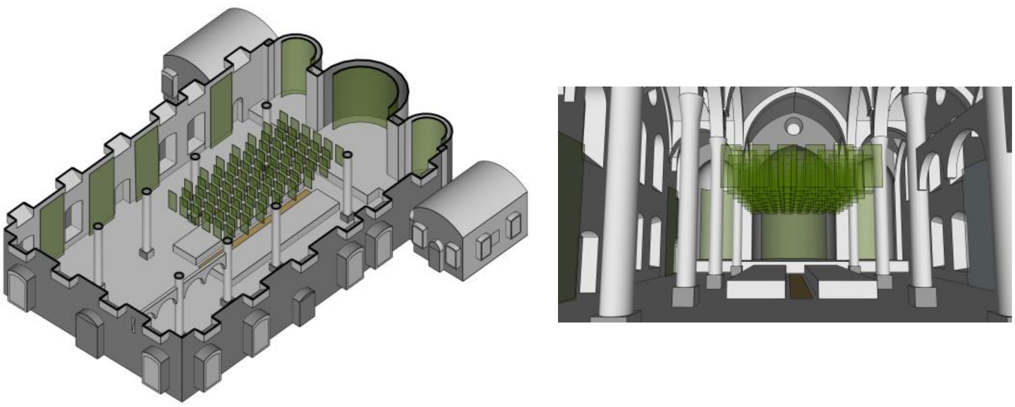


Figure 3.24 Perspectives of Proposal II from the Audience area to the stage

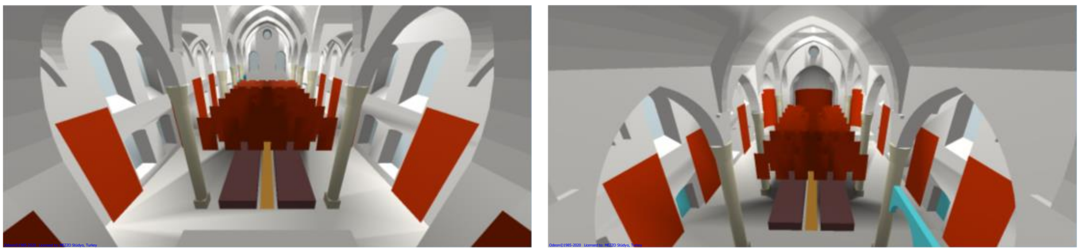


Figure 3.25 3D-OpenGL view of the acoustic model of Proposal II in Odeon, which displays the material distribution

Accordingly, the plan and section demonstration is presented in Figure 3.23, the generated architectural model is given in Figure 3.24, and the geometric acoustic model is illustrated in Figure 3.22 for Proposal II.

3.6.3 Proposal III: Combined Design

Proposal III aims to combine the encircling feature of Proposal I with the open plan concept of Proposal II by providing the highest sound absorption. Accordingly, the main design is based on a Proposal II layout. All proposals mentioned in Proposal II are also included in this design. An additional curtain was hung between the pillars at 2.5m level with an approximate dimension of 4.2 x 2m (4 pieces, separated aisles) and 7.1 x 2m (2 pieces, encircling the crossing zone) which surrounds the audience zone as in Proposal I, but in an open-plan concept approach (Figure 3.26). Also, two additional sound absorptive carpets were laid, one for each side aisle, to increase sound absorption surface area (Figure 3.26). In this way, the total carpet area is 71 m^2 in Proposal III, almost five times larger than Proposal I and Proposal II's carpet area.

In addition, the total proposed sound absorption area for Proposal III is calculated as approximately 569 m^2 consisting of 1138 m^2 of sound absorptive fabric in the folded arrangement. Proposal III provides the highest sound absorption surface area with its combined design when all three proposals are compared.

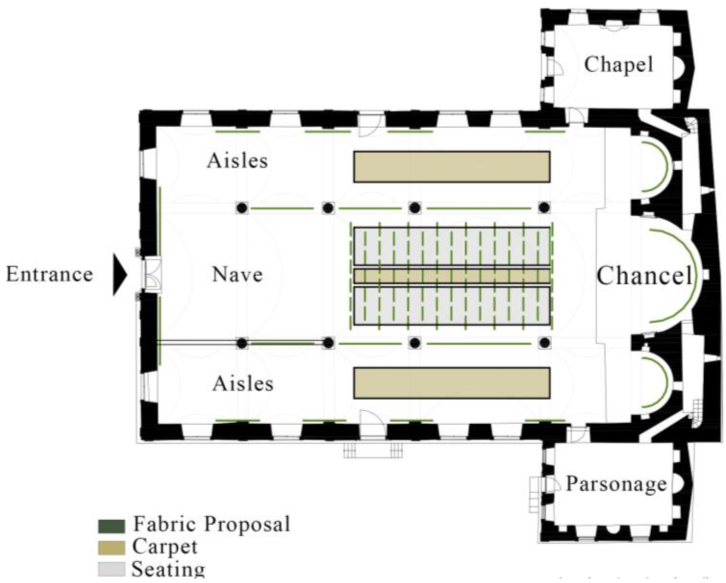


Figure 3.26 Proposal III in the Surp Yerrortutyun Church, plan and longitudinal section view

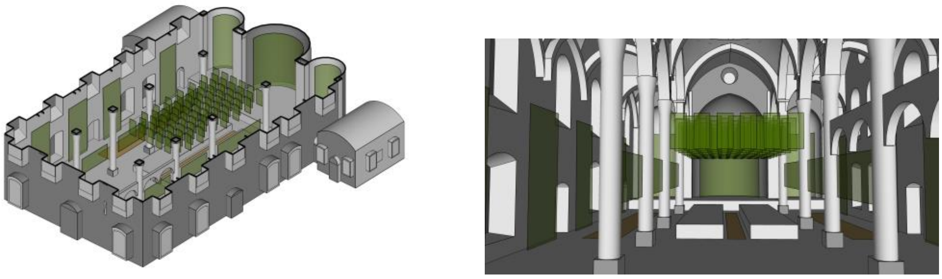


Figure 3.27 Perspectives of Proposal III from the Audience area to the stage

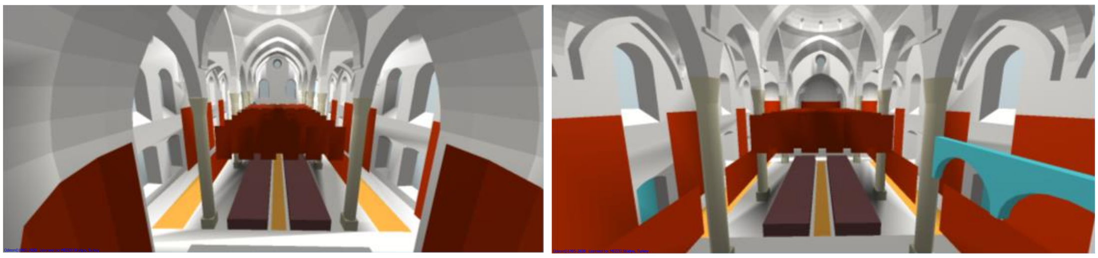


Figure 3.28 3D-OpenGL view of the acoustic model of Proposal III in Odeon, which displays the material distribution

Accordingly, the plan and section demonstration is presented in Figure 3.26, the generated architectural model is given in Figure 3.27, and the geometric acoustic model is illustrated in Figure 3.28 for Proposal III.

CHAPTER 4

RESULTS

This chapter displays the data obtained from field measurements and room acoustic simulations. Measured parameters and sound energy distributions are examined.

Acoustic assessment of the current state developed proposals and comparisons for the acoustical improvement of Surp Yerrortutyun Church and detailed analyses of results are presented under the Discussion section.

4.1 FIELD MEASUREMENT DATA OF THE AS-IS CASE

Surp Yerrortutyun Church field measurement's room acoustics parameters results, including T_{20}, EDT, C_{80}, STI, and L_{eq}, are presented. Data derived from three different measurements are included in the analysis for each source-receiver configuration in the unoccupied state.

Previously, source and receiver positions are demonstrated in Figure 3.12 in the 3rd chapter. T_{20} reverberation time results of Surp Yerrortutyun Church in 1/1 octave bands are given in Table 4.1 for 26 source-receiver configurations.

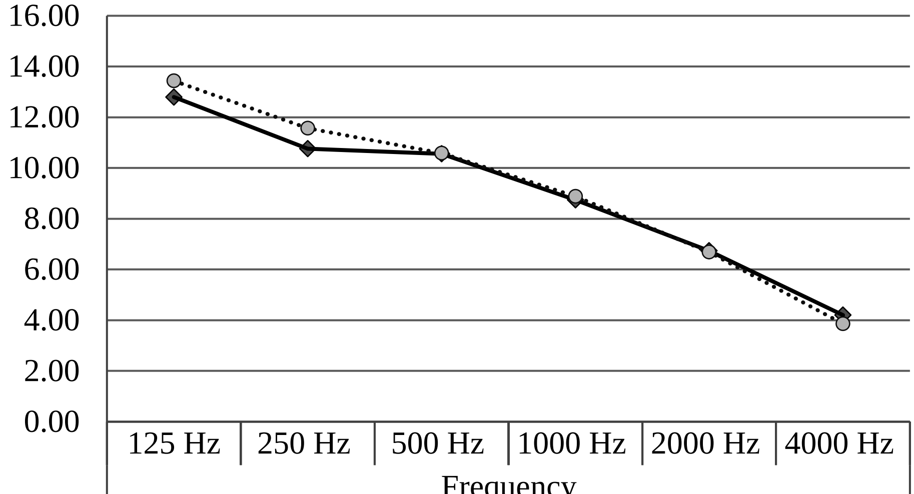
In the field measurements made after the last repair work, it has been observed Reverberation Time (T_{20}, s) is in the range of 11 – 13 s at low frequencies (125-250 Hz), in the range of 9 – 11 s at medium frequencies (500-1000 Hz), and in the range of 4 – 7 s at high frequencies (2000-4000 Hz) (Figure 4.2, and Table 4.1). Measured values are considerably above the recommended levels for music and speech-related activities and reduce the speech's intelligibility. The EDT values are proximate with the T_{20} values. In other words, the similar behavior of the sound energy at the first 10 dB and 20 dB decays in the room indicates the sound energy is uniformly diffused in the Church venue (Figure 4.1).

Table 4.1 Surp Yerrortutyun Church overall T_{20} (s) field test results in 1/1 octaves

Reverberation Time (T_{20}, s)								
Location	**63 Hz**	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**	**8000 Hz**
S1R1	12.72	13.71	11.98	10.88	8.69	6.67	3.88	1.48
S1R2	13.36	13.57	11.87	10.43	8.81	6.65	3.91	1.54
S1R3	11.80	13.38	11.85	10.40	8.88	6.61	3.89	1.54
S1R4	12.45	13.61	10.86	10.80	8.79	6.68	3.86	1.83
S1R5	13.81	13.66	11.73	10.52	8.96	6.76	3.79	1.58
S1R6	14.50	13.57	11.36	10.44	8.92	6.72	3.85	1.61
S1R7	13.41	12.78	11.33	10.21	9.01	6.58	3.91	1.54
S1R8	12.62	14.03	11.33	10.42	9.01	6.63	3.81	1.59
S1R9	12.99	13.49	11.39	10.83	8.65	6.46	3.92	1.57
S1R10	14.74	13.31	12.19	10.30	8.84	6.71	3.88	1.47
S1R11	12.39	12.69	11.49	10.95	9.15	6.78	3.78	1.52
S1R12	13.63	13.27	11.74	10.58	8.77	6.83	3.93	1.50
S1R13	12.95	13.57	11.20	10.83	8.90	6.84	3.77	1.36
S2R1	11.83	13.45	10.98	10.15	8.72	6.77	3.79	1.47
S2R2	15.17	13.51	11.77	10.18	8.58	6.54	3.92	1.62
S2R3	11.54	13.38	11.90	10.96	8.90	6.65	3.84	1.63
S2R4	12.80	13.13	11.63	10.67	9.03	6.77	3.93	1.56
S2R5	11.89	13.30	11.56	10.59	8.68	6.80	3.91	1.63
S2R6	11.87	13.37	11.43	10.30	8.98	6.81	3.90	1.51
S2R7	12.08	13.35	11.59	11.04	8.96	6.69	3.91	1.66
S2R8	12.45	13.93	11.89	10.73	8.67	6.50	3.93	1.57
S2R9	12.96	13.26	12.26	11.10	8.77	6.64	3.95	1.51
S2R10	12.24	14.15	11.94	11.03	8.50	6.60	3.88	1.45
S2R10*	11.72	13.11	11.73	10.60	8.64	6.58	3.86	1.57
S2R11	11.72	13.11	11.73	10.60	8.64	6.58	3.86	1.57
S2R12	12.79	12.35	11.66	10.65	8.85	6.65	3.85	1.50
S2R13	13.94	13.28	11.78	10.55	8.91	6.62	3.90	1.48
S1-R_{AVG}	13.18	13.43	11.56	10.58	8.88	6.69	3.86	1.55
S2-R_{AVG}	12.50	13.33	11.70	10.65	8.77	6.66	3.89	1.55
$T_{20(AVERAGE)}$	**12.84**	**13.38**	**11.63**	**10.62**	**8.83**	**6.68**	**3.88**	**1.55**

Table 4.2 Surp Yerrortutyun Church EDT field test results in 1/1 octaves

Early Decay Time (EDT, s)						
Location	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
S1R1	13.69	10.00	9.69	8.85	6.39	4.05
S1R2	12.74	10.71	10.60	8.60	6.72	4.21
S1R3	12.84	10.23	11.07	8.95	6.94	4.26
S1R4	13.12	11.69	11.03	9.08	6.81	4.45
S1R5	12.87	11.17	10.44	8.58	7.00	4.43
S1R6	13.45	11.12	10.25	8.55	6.81	4.71
S1R7	14.63	11.35	10.49	9.02	7.01	4.60
S1R8	12.34	10.77	10.77	9.12	6.84	4.50
S1R9	12.39	11.15	10.81	8.74	6.41	4.08
S1R10	12.20	9.99	10.49	8.80	6.81	3.89
S1R11	11.80	10.37	10.80	8.94	6.88	4.08
S1R12	11.98	9.60	10.24	8.39	6.83	4.07
S1R13	12.31	11.69	10.56	7.99	6.13	3.29
$EDT_{AVERAGE}$	12.80	10.76	10.56	8.74	6.74	4.20



	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
EDT (s)	12.80	10.76	10.56	8.74	6.74	4.20
T20 (s)	13.43	11.56	10.58	8.88	6.69	3.86

Figure 4.1 Surp Yerrortutyun Church EDT field test results in 1/1 octaves

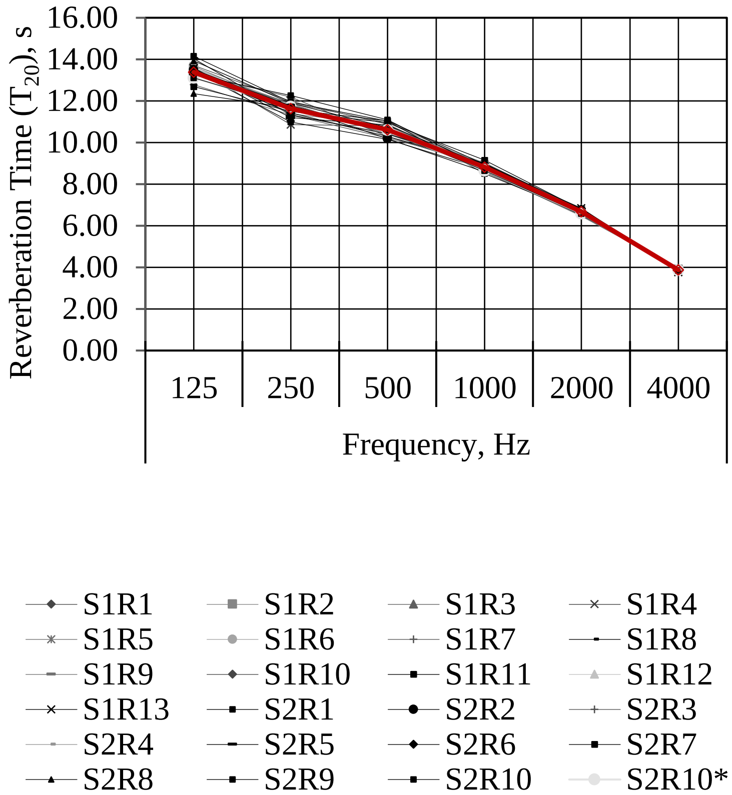


Figure 4.2 Surp Yerrortutyun Church EDT field test results in 1/1 octaves

The dome, which is the dominative architectural element of Surp Yerrortutyun Church, has a reflective finishing material on its concave surface. In such cases, the acoustical focusing effect may be observed negatively derived from dome geometry. However, in comparison with this phenomenon, the sound focusing effect has not been remarked as a crucial problem in Surp Yerrortutyun Church.

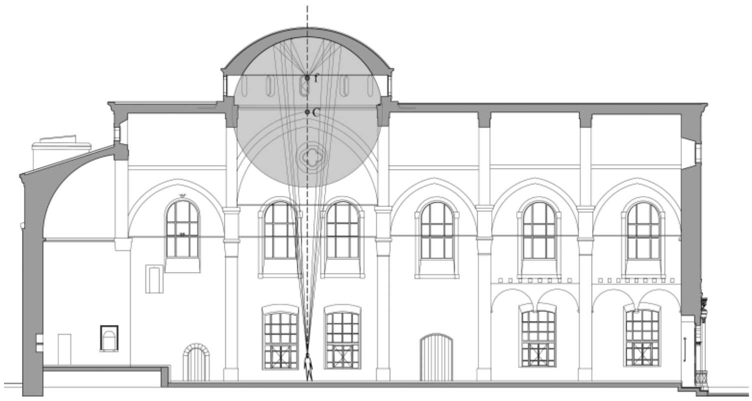


Figure 4.3 Demonstration of the effective acoustical zone of the dome in shaded *(C: center, f: sample focal point)*

Consequently, the 8.70 m diameter of the dome and the 20.40 m inner height allow the focal zone to occur higher than the audience's ear height at seated or standing ear level (Figure 4.3). Thus, it should be bear in mind the central dome is disabled the negatively focusing effect, but its focal zone can still negatively operate the sound scattering.

Table 4.3 Surp Yerrortutyun Church EDT field test results in 1/1 octaves

Clarity (C80, dB)						
Location	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
S1R1	-9.5	-7.4	-6.8	-7.0	-7.8	-4.0
S1R2	-10.5	-8.7	-10	-9.3	-7.4	-4.9
S1R3	-10.0	-10.2	-12.4	-8.6	-9.5	-7.5
S1R4	-13.3	-12.7	-13.4	-11.7	-10.3	-6.9
S1R5	-13.5	-10.8	-14.4	-11.8	-11.0	-9.6
S1R6	-12.9	-12.4	-11.8	-10.9	-9.9	-7.6
S1R7	-11.6	-12.8	-14.0	-11.3	-10.0	-7.2
S1R8	-13.3	-13.5	-13.4	-10.3	-7.9	-5.6
S1R9	-10.3	-13.6	-8.0	-5.8	-4.3	-1.6
S1R10	-6.9	-8.5	-7.4	-4.7	-2.7	0.1
S1R11	-9.4	-10.0	-8.6	-7.9	-7.5	-4.7
S1R12	-9.5	-9.8	-7.6	-8.2	-7.6	-4.4
S1R13	-6.0	-2.6	-2.8	-1.0	-0.6	1.7
$C_{80(AVERAGE)}$	-10	-7.5	-8.6	-7	-5.2	-3.6

The averages of the C_{80} values are calculated with the data obtained from the field measurements and summarized in Figure 4.4.

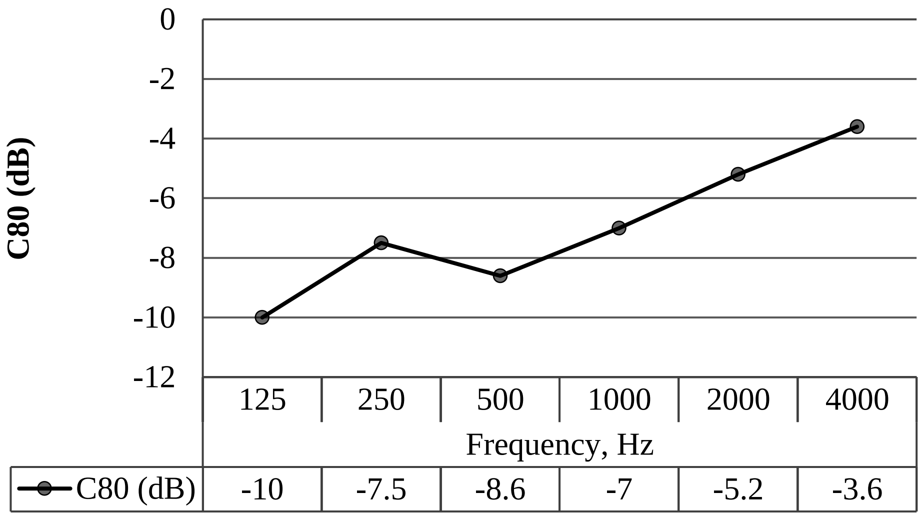


Figure 4.4 Surp Yerrortutyun Church EDT field test results in 1/1 octaves

Accordingly, average C_{80} values in the 1/1 octave band range from -10 dB to -3.6dB, which are notably below the recommended -2 dB threshold for musical and speech-related activities. It points out potential speech intelligibility problems during events. The geometry of the monument with a three-nave domed shell and mostly reflective surfaces increase the existing time of the sound energy in the air and causes strong late reflections in the Church, which is perceived as *"sound-blurring"* or less clear.

Table 4.4 Surp Yerrortutyun Church STI field test results for R14-R19 receivers

Speech Transmission Index (STI)		
Location	**Value**	**Distance from Source (m)**
R14	0.63	3.0
R15	0.50	6.4
R16	0.42	9.1
R17	0.33	17.0
R18	0.26	22.7
R19	0.28	28.9
Average	0.40	
Standard Deviation	0.14	
$STI_{AVERAGE}$	0.26	

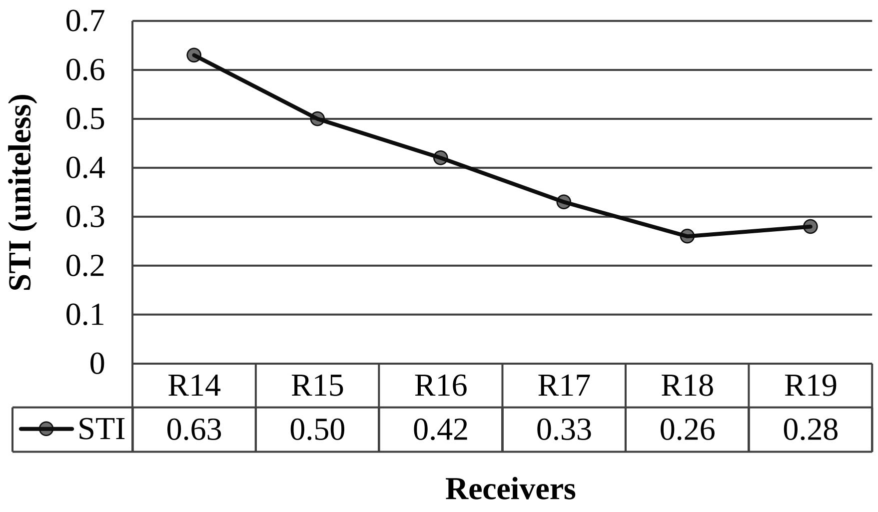


Figure 4.5 Surp Yerrortutyun Church STI test results by receivers

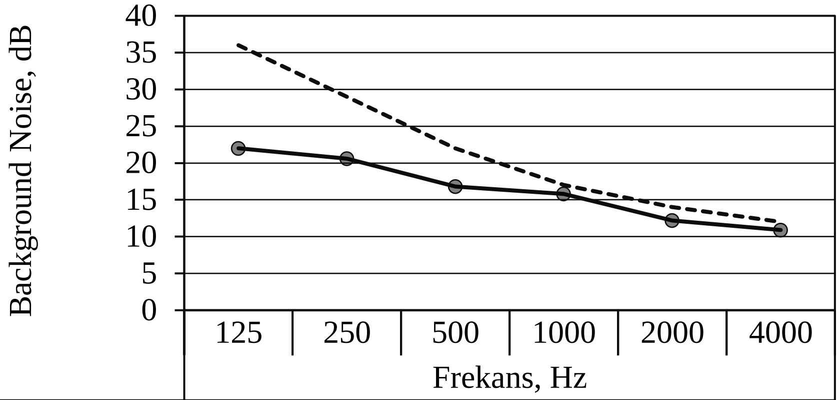
The STI measurements are held according to the IEC 60268-16:2011 standard in field tests, and the results are summarized in Figure 4.5 and Table 4.4. Intelligibility levels are assessed within the scope of definitions given in Table 4.5.

Table 4.5 Intelligibility rating scale and STI relation (IEC 60268-16:2011, 2011)

Intelligibility Rating	STI value
Bad	0.00 – 0.30
Poor	0.30 – 0.45
Fair	0.45 – 0.60
Good	0.60 – 0.75
Excellent	0.75 – 1.00

At the first 3m distance from the source (R14), speech intelligibility was measured as "good" and decreased to "fair" at a 6 m distance, then weakened between 9 m-17 m, and after 17 m, STI was evaluated as "poor". The points closest to the source are less affected by reflections. Therefore, it is an anticipated case the STI value at the R14 receiver position is measured as "good". However, the intelligibility rate declines rapidly at short intervals. STI average values are recommended to be at or above the "fair" level in rooms where speech activities are planned to be held. But, average STI was found to be 0.26, which corresponds to a "bad" level in the Surp Yerrortutyun Church.

The background noise is measured during field tests to understand the effects on intelligibility. In the as-is case, there is no mechanical system installed in the Church that may cause continuous noise. In this regard, background noise measurement is held without mechanical equipment operating in the structure. The evaluation is carried out based on the NC15 curve, which corresponds to the lowest background noise among the noise criteria recommended for the small auditorium, concert halls, churches, conferences, and museum events (Egan, 1988). In Figure 4.6, background noise data obtained from field measurements compared to the NC15 curve, which is referenced as the upper-limit noise, is demonstrated. The frequency-varying background noise data ranges from 36 dB to 12 dB below the NC15 curve.



	125	250	500	1000	2000	4000
Surp Yerrortutyun Church	22	20.6	16.8	15.8	12.2	10.9
NC-15	36	29	22	17	14	12

Figure 4.6 Measured background noise levels (dB) in octave bands concerning the NC15 noise criterion curve

The A-weighted average of the background noise is measured as 26.2 dBA in the field measurements. This value is very proximate to the recommended 25 dBA background noise value at the NC15 level. These data show that the Church meets the noise criteria of NC15, has an eligible indoor noise level for multi-functional use such as worship places and museums where music and speech events are held, and briefly displays that the background noise is within acceptable limits. Moreover, it also he background noise level in the Church is at a convenient level for performing in-situ acoustic measurements.

4.2 SIMULATED DATA REPRESENTING AS-IS CASE

To achieve the closest values representing the actual acoustic environment in the Church by simulation analyses requires calibrating the acoustic model of the Surp Yerrortutyun Church in reference to the acoustic field measurement results.

Accordingly, the calibrated acoustic model representing the as-is case of the church, acoustic field measurement data, and the differences between those values are summarized in Tables 4.7, 4.8, and 4.9 with mentioned Just Noticeable Difference (JND) value.

Table 4.6 Average Reverberation time (T_{20}) data achieved by in-situ measurements and Odeon model simulation analyses, showing that simulation analyses are calibrated in reference to in-situ results, and the calibrated model is achieved with a high accuracy

RT, s	Frequency (Hz)					
	125	**250**	**500**	**1000**	**2000**	**4000**
$T_{20(IN-SITU)}$	13.33	11.70	10.65	8.77	6.66	3.89
$T_{20(MODEL)}$	13.41	11.73	10.62	8.74	6.78	3.79
ΔT_{20}*	-0.08	-0.03	0.03	0.03	-0.12	0.10
JND_{RT}**	$\Delta T_{20}<0.67$	$\Delta T_{20}<0.59$	$\Delta T_{20}<0.53$	$\Delta T_{20}<0.44$	$\Delta T_{20}<0.33$	$\Delta T_{20}<0.20$

(*) ΔT_{20} means $T_{20(IN-SITU)} - T_{20(MODEL)}$
*(**) JND_{RT} means **J**ust **N**oticeable **D**ifference which is of ±%5 in RT*

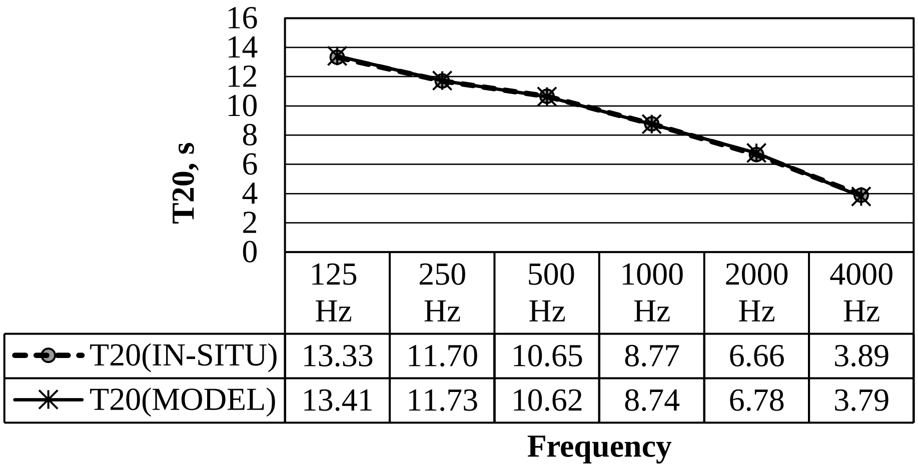


Figure 4.7 Relation between average reverberation time values in field measurements and calibrated simulation data

Acoustic simulation model analyses highly correspond to data obtained from in-situ measurements, and the differences between those values are in the mentioned JND limits. As shown in Figures 4.7 and Table 4.6, the RT value in the simulation model is calibrated with high accuracy.

Table 4.7 Average Early Decay Time (EDT) measurement and modeling results by frequency

EDT, s	Frequency (Hz)					
	125	250	500	1000	2000	4000
$EDT_{(IN\text{-}SITU)}$	12.80	10.76	10.56	8.74	6.74	4.20
$EDT_{(MODEL)}$	13.31	11.65	10.56	8.68	6.74	3.72
ΔEDT*	-0.51	-0.89	0.00	0.06	0.00	0.48
JND_{EDT} **	ΔEDT <0.64	ΔEDT <0.54	ΔEDT <0.51	ΔEDT <0.44	ΔEDT <0.33	ΔEDT <0.21

(*) ΔEDT means $EDT_{(IN\text{-}SITU)} - EDT_{(MODEL)}$
*(**) JND_{EDT} means **J**ust **N**oticeable **D**ifference, which is ±%5 in EDT*

The accuracy in the calibration of the RT value is verified by the compatibility of the EDT values which are also within the mentioned JND limits in the ISO 3382-1 standard.

Table 4.8 Average Clarity (C_{80}) data achieved by in-situ measurements and Odeon simulation analyses, showing that the calibrated model is acceptable for simulation analyses

C_{80}, dB	Frequency (Hz)					
	125	250	500	1000	2000	4000
$C_{80(IN\text{-}SITU)}$	-10.0	-7.5	-8.6	-7.0	-5.2	-3.6
$C_{80(MODEL)}$	-10.6	-9.9	-9.4	-8.6	-7.4	-4.5
ΔC_{80}*	0.6	2.5	0.8	1.6	2.2	0.9
JND_{C80}**	$\Delta C_{80}<1$	$\Delta C_{80}>1$	$\Delta C_{80}<1$	$\Delta C_{80}>1$	$\Delta C_{80}>1$	$\Delta C_{80}<1$

(*) ΔC_{80} means $C_{80\,(IN\text{-}SITU)} - C_{80\,(MODEL)}$
*(**) JND_{C80} means **J**ust **N**oticeable **D**ifference, which is ±1dB in C_{80}*

RT data is the major and determinative acoustical parameter for forming a calibrated model. Here, RT data in the calibrated model are in the acceptable ranges representing the actual RT data with high accuracy. Some C_{80} data is below the JND_{C80}, while some are above with a slight difference. C_{80} data in calibrated data is also acceptable since slight differences compared to the $C_{80(IN\text{-}SITU)}$ are in negligible ranges, and RT values of the calibrated model are highly accurate.

Accordingly, the analysis results of the calibrated acoustic model are compiled. These simulation results are also employed in assessing the acoustical performances of the developed proposals to rehabilitate the acoustical conditions in the church. Considering the volume and desired functions of the Surp Yerrortutyun Church, the values of the recommended reverberation time for music and speech activities are reviewed from the literature. Accordingly, the comparison of recommended limit values for music and speech activities, the field measurements, and simulation model results is shown in Table 4.9 and Figure 4.8.

Table 4.9 Average T_{20} values by frequencies, including field measurement, simulation, and recommended values

RT, s	Frequency (Hz)					
	125	250	500	1000	2000	4000
$T_{20(IN\text{-}SITU)}$	13.33	11.70	10.65	8.77	6.66	3.89
$T_{20(MODEL\text{-}UN)}$*	13.41	11.73	10.62	8.74	6.78	3.79
$T_{20(MUSIC\text{-}MAX)}$	2.6	2.6	2.6	2.6	2.6	2.6
$T_{20(MUSIC\text{-}MIN)}$	1.2	1.2	1.2	1.2	1.2	1.2
$T_{20(SPEECH\text{-}MAX)}$	1.3	1.3	1.3	1.3	1.3	1.3
$T_{20(SPEECH\text{-}MIN)}$	0.6	0.6	0.6	0.6	0.6	0.6

(*) $T_{20(MODEL\text{-}UN)}$ means T_{20} for simulation model in an unoccupied state

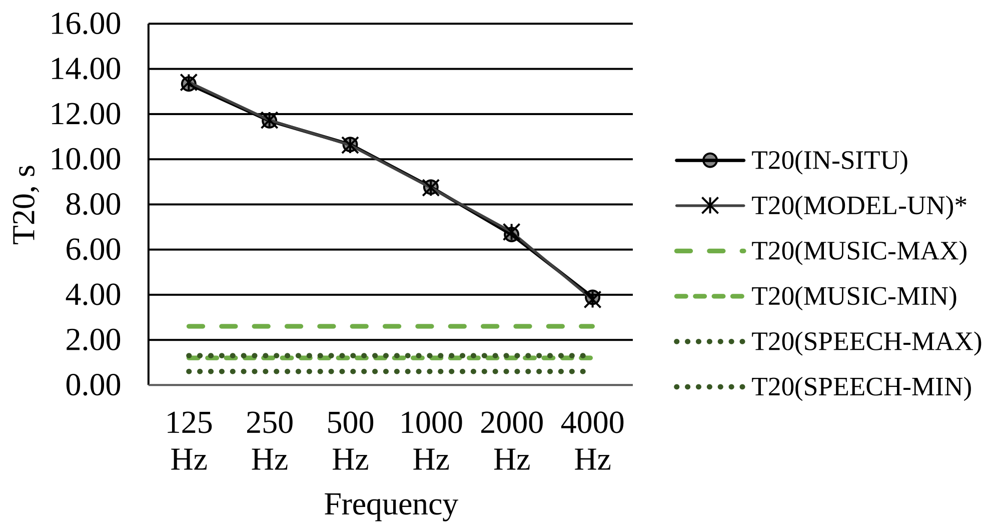


Figure 4.8 The graph showing T_{20} values by frequencies including field measurement, simulation, and recommended values

According to the graph in Figure 4.8, reverberation time (T_{20}, s) exceeds recommended limits at all frequencies for music and speech-related activities in an unoccupied state. The longer reverberation times in the structure are observed intensely at low frequencies (125 Hz - 250 Hz). As the frequency rises, the reverberation time is relatively close to the maximum limit of the recommended values, e.g., at 4000 Hz.

The values of the recommended Clarity level for music and speech activities are reviewed from the literature considering the volume and desired functions for the Church. The comparison of recommended limit values for music and speech activities, the field measurements, and simulation model results is given in Table 4.10 and Figure 4.9.

Table 4.10Average C_{80} values by frequencies including field measurement, simulation, and recommended values

C_{80}, dB	Frequency (Hz)					
	125	250	500	1000	2000	4000
$C_{80(IN-SITU)}$	-10.0	-7.5	-8.6	-7.0	-5.2	-3.6
$C_{80(MODEL-UN)}$	-10.6	-9.9	-9.4	-8.6	-7.4	-4.5
$C_{80(MUSIC-MAX)}$	2	2	2	2	2	2
$C_{80(MUSIC-MIN)}$	-3	-3	-3	-3	-3	-3
$C_{80(SPEECH-MIN)}$	0	0	0	0	0	0

(*) $C_{80(MODEL-UN)}$ means C_{80} for simulation model in unoccupied state

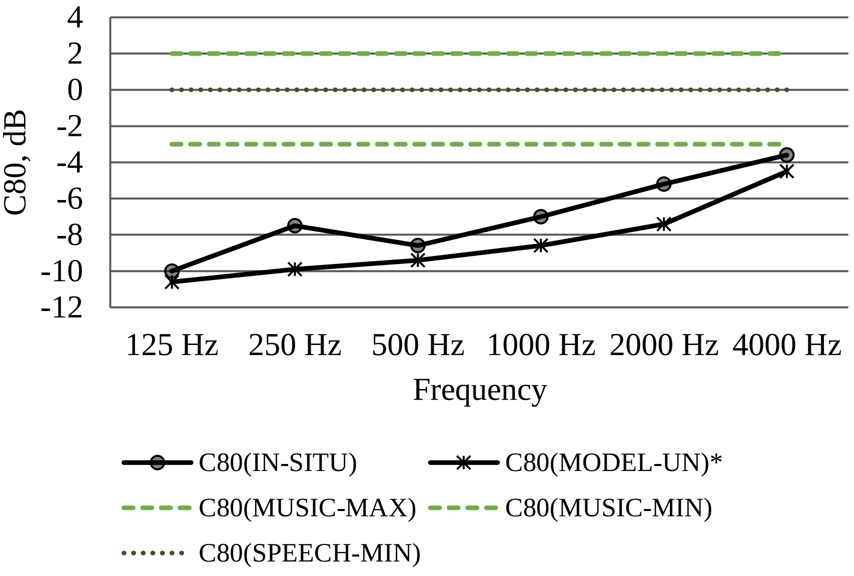


Figure 4.9 The graph showing C_{80} values by frequencies including field measurement, simulation, and recommended values

According to the graph in Figure 4.9, the Clarity level is below the recommended values for music and speech-related activities in an unoccupied state. This is an expected state in such an environment with excessive long reverberation time. The lower clarity levels are recognized substantially at low frequencies (125 Hz - 250 Hz). As the frequency rises, the clarity is relatively close to the minimum limit of the recommended values, e.g., at 4000 Hz.

4.3 ACOUSTIC IMPROVEMENT PROPOSAL RESULTS FOR THE SCENARIO II-III

The acoustic analyses of developed proposals for the acoustic improvement of Surp Yerrortutyun Church are presented in this section. Accordingly, three main approaches are examined: one of closed periphery Proposal I, one of open-plan encircling system Proposal II, and the last one Proposal III, which is mentioned as the combined design. Detailed acoustic simulation results are presented in the following subheadings for unoccupied and occupied states of the Church.

In the previous sections, the as-is state of the church is evaluated by the data obtained from in-situ measurements and an acoustic simulation model for 13 receiver points. This part compiles the evaluations of the developed acoustic improvement proposals for the defined audience zone in an unoccupied and 80% occupancy state by comparing it with the as-is case. Due to occupied state measurements referring to more realistic conditions for use, more detailed evaluations, including grid distribution maps for defined audience zone, are presented. The average values derived from acoustical simulations, including EDT, T_{20}, T_{30}, C_{80} and STI parameters, are summarized in tables for both unoccupied and occupied states for proposals. In the tables, “(UN)” means simulations in an unoccupied state, and “(OC)” means simulations in an 80% occupied state. The grid maps of mentioned parameters are obtained and evaluated for 500 and 1000 Hz ranges. The overall distribution representations for the defined audience zone in the Church venue and the whole church are listed in the Appendix.

4.3.1 ASSESSMENT OF PROPOSAL I: CLOSED PERIPHERY SYSTEM

Under this part, the acoustic performance assessments for Proposal I, described in Section 3.6.1 in detail, are presented. It is observed that the occupancy affects reverberation times most at low frequencies, and the difference was more negligible at medium to high frequencies, such as in T_{20} values, which remain stable at medium frequencies in occupied and unoccupied states. However, in all parameters, occupancy has a positive effect on controlling the reverberation at low frequencies as an expected situation due to the potential sound absorption capacity of the audience. This also increases the level of clarity which is inversely proportional to reverberation.

Table 4.11 Early decay time (EDT) data based on Proposal I's acoustic simulation results for the overall case

EDT, s	Frequency (Hz)							
	63	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
$EDT_{(UN)}$	7.31	7.23	3.56	2.40	2.22	2.02	1.62	1.09
$EDT_{(OC)}$	6.52	6.46	3.49	2.41	2.02	2.22	1.62	1.07

Coming to the EDT distribution, as shown in Figure A.1 and Figure A.2 in Appendix A, the overall range in the defined audience zone is decreased to 1.50 to 2.0 s from 9.6 to 11.69 s, which is as-is measured values for 500 Hz and that corresponding to 83.6% decrease. This case indicates the mid-frequency EDT time is below the 3s upper limits. The distribution maps noted that the EDT values become longer at 500 Hz under some points of the central dome and mid-backward of the seating zone. These values were found to be more homogeneous at 1000 Hz.

Table 4.12 Reverberation Time (T_{20}) data based on Proposal I's acoustic simulation results for the overall case

T_{20}, s	Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
$T_{20(UN)}$	7.57	7.48	3.75	2.48	2.25	2.02	1.55	0.99
$T_{20(OC)}$	6.91	6.84	3.73	2.48	2.25	2.01	1.54	1.00

Table 4.13 Reverberation Time (T_{30}) data based on Proposal I's acoustic simulation results for the overall case

T_{30}, s	Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
$T_{30(UN)}$	7.61	7.53	3.85	2.57	2.34	2.10	1.59	1.01
$T_{30(OC)}$	6.89	6.82	3.79	2.65	2.38	2.11	1.58	1.00

From the grid maps, two problematic spots are observed in the T_{20} value at 500 Hz (Figure A.3). Accordingly, two excessive spots, one of the lowest (1.7 s) and one of the highest (2.5 s) in the audience zone, under the south side of the central dome, are observed very close to each other. This situation is similar at 1000 Hz but generally more homogeneous. Looking at the T_{30} distribution in the audience zone at 1000 Hz, Figure A.5 and Figure A.6 show that the sound field becomes much even. At 500 Hz, some spots are found with longer reverberation times under the dome and the southern sitting area backward. In the overall case, as compiled in the Table 4.12 and Table 4.13 and demonstrated in Appendix D, the T_{20} average at mid-frequency (2.48 s – 2.25 s, occupied) and T_{30} average at mid-frequency the results are below (2.65 s – 2.38 s, occupied) the 3 s upper limits defined in the literature for a church or performance space in the occupied and unoccupied state.

Table 4.14 Clarity (C_{80}) data based on Proposal I's acoustic simulation results for the overall case

C_{80}, dB	Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
$C_{80(UN)}$	-11.4	-11.4	-7.4	-4.8	-4.3	-3.7	-2.1	0.7
$C_{80(OC)}$	-10.3	-10.2	-6.7	-4.4	-4.0	-3.4	-1.9	-1.0

Coming to the Clarity parameter, distribution maps are shown in Figure A.7 and Figure A.8. It is observed that the values are varied from 0 to 3 dB both for 500 Hz and 1000 Hz in the audience zone. However, in terms of overall values in the venue, the average is calculated as -4.4 to -4.0 dB, as compiled in Table 4.4 and shown in Appendix D, which is out of recommended range. In general, analyzing the clarity distribution maps in the audience zone for an occupied state, most of the seating area is found in desired range as above the 0 thresholds. In addition, maps indicated homogeneous values noted in the defined sitting area at 500 Hz and 1000 Hz. Towards the back rows, where the absorber curtains are placed, the clarity values become higher.

Table 4.15 Speech Transmission Index (STI) data based on Proposal I's acoustic simulation results for the overall case

Value	**STI_{UN}**	**STI_{OC}**
Minimum	0.29	0.29
Maximum	0.60	0.60
Average	0.41	0.42
Std. dev.	0.10	0.10

Another critical parameter is STI for speech-related activities. According to the distribution maps of the audience zone in the occupied state, there is no problematic spot observed. In the audience zone (Appendix A), homogenous sound field are ranged from 0.45 – 0.55 for the sitting area; however, 0.29 – 0.60 for the overall venue (Appendix D). The STI value is at the recommended values in the controlled acoustic environment created by Proposal I.

Acoustic field measurement results describing the as-is state of the Church and acoustic simulation results of Proposal I are compared in tables and graphics to indicate the progress of the overall church venue. Accordingly, the reverberation time and clarity values are presented by comparing with the recommended ranges.

Table 4.16 Comparison of T_{20} results for the real data in the unoccupied state of the Church ($T_{20(IN\text{-}SITU)}$) and the acoustic simulation results of Proposal I in the occupied ($T_{20(PI\text{-}OC)}$) and unoccupied state ($T_{20(PI\text{-}UN)}$) in 1/1 octave bands

RT, s	**Frequency (Hz)**					
	125	**250**	**500**	**1000**	**2000**	**4000**
$T_{20(IN\text{-}SITU)}$	13.33	11.70	10.65	8.77	6.66	3.89
$T_{20(PI\text{-}UN)}$	7.48	3.75	2.48	2.25	2.02	1.55
$T_{20(PI\text{-}OC)}$	6.84	3.73	2.48	2.25	2.01	1.54

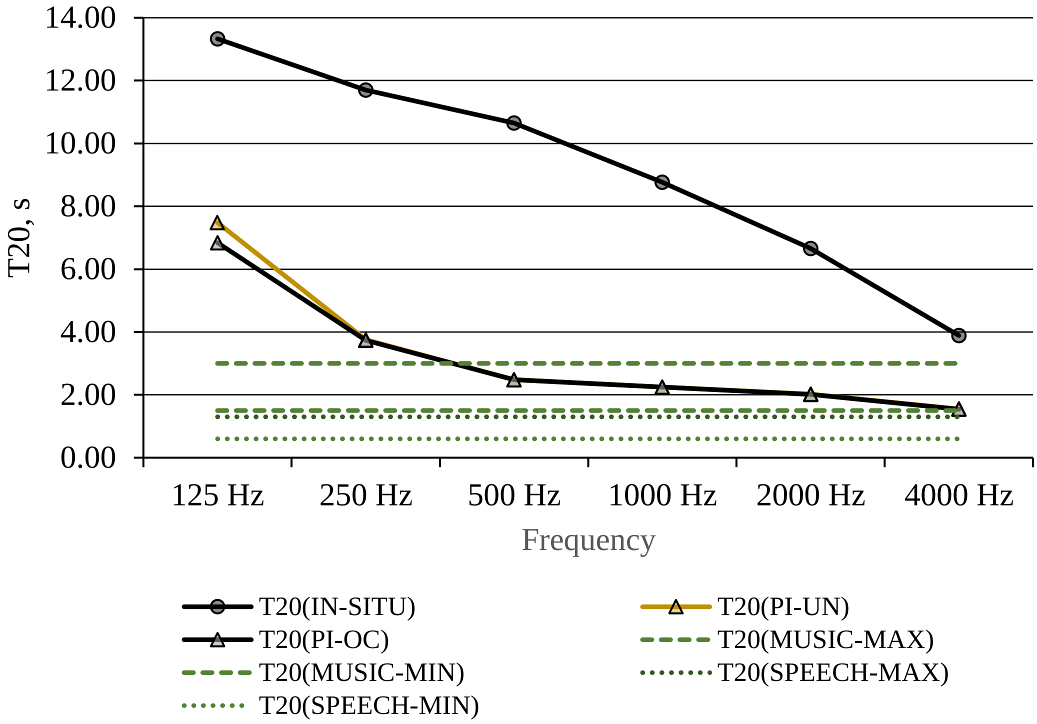


Figure 4.10 Comparison of T_{20} results for the Surp Yerrortutyun Church in 1/1 octave bands including Proposal I data and their comparison with limits of criteria as recommended in the literature

The graph in Figure 4.10 implies that the average reverberation time values exceed the acceptable limits at all frequencies for speech activities in the as-is state. The developed model Proposal I provided that the values are in the range of acceptable limits, especially at medium and high frequencies. However, it displayed that although a very effective reduction is achieved at low frequencies (around 7 s), it is still above the recommended value of 3 s.

The proposed model is quite effective in using music-related activities, but the problem is not fully resolved in the case of speech function. Long reverberation times at low frequencies may cause disturbance in the Church.

Table 4.17 Comparison of C_{80} results for the real data in the unoccupied state of the Church ($C_{80(IN\text{-}SITU)}$) and the acoustic simulation results of Proposal I in the occupied ($C_{80(PI\text{-}OC)}$) and unoccupied state ($C_{80(PI\text{-}UN)}$) in 1/1 octave bands

C_{80}, dB	Frequency (Hz)					
	125	250	500	1000	2000	4000
$C_{80(IN\text{-}SITU)}$	-10.0	-7.5	-8.6	-7.0	-5.2	-3.6
$C_{80(PI\text{-}UN)}$	-11.4	-7.4	-4.8	-4.3	-3.7	-2.1
$C_{80(PI\text{-}OC)}$	-10.2	-6.7	-4.4	-4.0	-3.4	-1.9

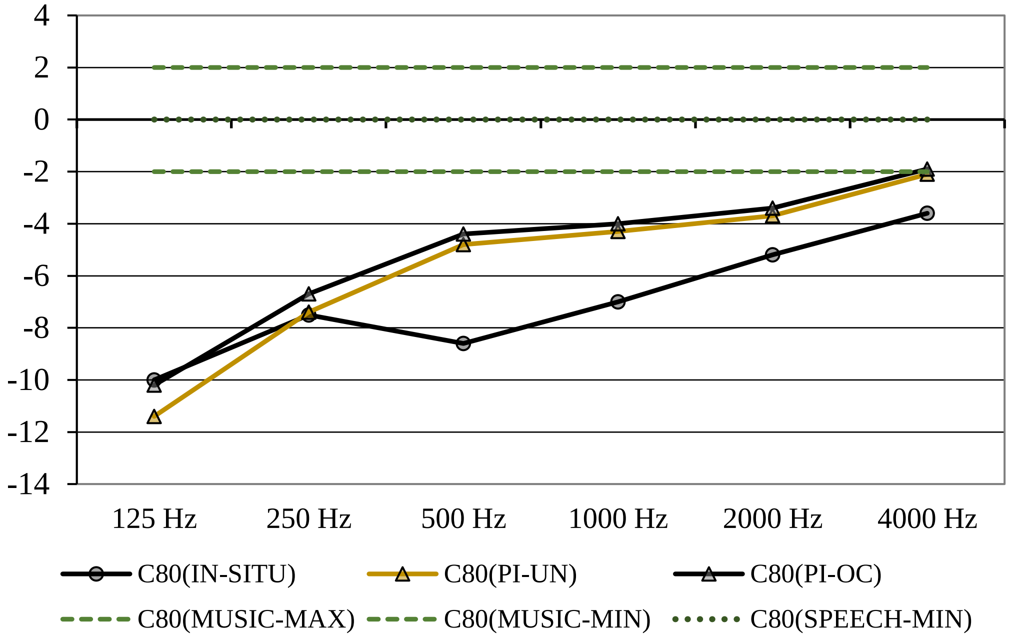


Figure 4.11 Comparison of C_{80} results for the Surp Yerrortutyun Church in 1/1 octave bands including Proposal I data and their comparison with limits of criteria as recommended in the literature

The acceptable clarity limits for use in speech and music-related activities and the as-is state and Proposal I for the Surp Yerrortutyun Church are given in Table 4.17 and Figure 4.11. As seen in the graph in Figure 4.11, the C_{80} data confirm the results of the reverberation times, which are inversely proportional to each other. However, in Proposal I, the overall clarity value calculated in the church satisfied neither music nor speech function requirements.

4.3.2 ASSESSMENT OF PROPOSAL II: OPEN-PLAN ENCIRCLING SYSTEM

The simulation analysis results of Proposal II, which was developed differently from the closed periphery idea by allowing a holistic design approach considering the architectural points of view, which is explained in detail in the 3.6.2 Section, are presented. The average values derived from acoustical simulations, including EDT, T_{20}, T_{30}, C_{80}, and STI parameters, are compiled in tables for unoccupied, and 80% occupied states.

Table 4.18 Early decay time (EDT) data based on Proposal II's acoustic simulation results for the overall case

EDT, s	Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
$EDT_{(UN)}$	7.15	7.07	3.82	2.63	2.43	2.21	1.73	1.19
$EDT_{(OC)}$	6.11	6.07	3.37	2.40	2.23	2.06	1.65	1.18

For the EDT distribution, as shown in Figure B.1 and Figure B.2 in Appendix B, the overall range in the defined audience zone is decreased to 1.80 to 3.2 s from 9.6 to 11.69 s, at 500 Hz that corresponding to a 76.5% decrease. In the overall results for the venue, EDT time at mid-frequency is below the 3 s upper limits as indicated in Table 4.18. The distribution maps (Appendix B and D) noted that the EDT values become shorter at 500 Hz and 1000 Hz under some points of the central dome and front tiers of the seating zone.

Table 4.19 Reverberation time (T_{20}) data based on Proposal II's acoustic simulation results for the overall case

T_{20}, s	Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
$T_{20(UN)}$	7.22	7.14	3.97	2.80	2.57	2.32	1.76	1.07
$T_{20(OC)}$	6.17	6.13	3.54	2.52	2.33	2.13	1.64	1.03

Table 4.20 Reverberation time (T_{30}) data based on Proposal II's acoustic simulation results for the overall case

T_{30}, s	Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
$T_{30(UN)}$	7.24	7.16	3.98	2.85	2.63	2.35	1.78	1.09
$T_{30(OC)}$	6.17	6.13	3.56	2.59	2.38	2.15	1.66	1.05

No problematic spots in the T20 value are observed at 500 Hz and 1000 Hz from the grid responses (Figure B.3 and Figure B.4). Accordingly, values varying between 2.50 and 2.75 s show that homogeneity is provided for the audience area. At 1000 Hz, the T_{20} value observed becomes shorter at the front tiers. For T_{30} values at 500 Hz, through the southern back rows, the reverberation time rises to 3.5 s, which is a notable spot. Except for this case, T_{30} distribution is generally uniform in the audience zone. In the general case, as compiled in the Table 4.19 and Table 4.20, T_{20} average at mid-frequency (2.52 s – 2.33 s, occupied) and T_{30} average at mid-frequency, the results are below (2.59 s – 2.38 s, occupied) the 3 s upper limits defined in the literature in occupied and unoccupied state.

Table 4.21 Clarity (C_{80}) data based on Proposal II's acoustic simulation results for the overall case

C_{80}, dB	Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
$C_{80(UN)}$	-7.4	-7.2	-4.1	-2.0	-1.6	-1.0	0.5	3.6
$C_{80(OC)}$	-6.6	-6.5	-3.3	-1.4	-1.1	-0.7	0.9	3.8

For the Clarity parameter, grid maps are shown in Figure B.7 and Figure B.8. It is observed that the values vary from 0 to 2 dB both for 500 Hz and 1000 Hz at the front rows in the audience zone. However, it decreases to -4.5 dB at the backward in some parts of the zone. Decreasing the clarity level towards the backward in the audience zone indicates no homogeneous distribution. Nevertheless, in terms of overall values in the church venue (Appendix D), the C_{80} average at mid-frequency is measured as -1.4 to -1.1 dB for the occupied state, as presented in Table 4.21, which is found in the -2 dB to 2 dB desired range.

Table 4.22 Speech Transmission Index (STI) data based on Proposal II's acoustic simulation results for the overall case

Value	**STI_{UN}**	**STI_{OC}**
Minimum	0.33	0.32
Maximum	0.66	0.69
Average	0.42	0.44
Std.dev.	0.09	0.09

According to the STI distribution maps (Figure B.9) for the audience zone in the occupied state, it is observed that the STI value, which was “fair” (0.45 – 0.55) in the front rows, decreased in the middle and back rows to “poor” (0.30 – 0.45) indicating not homogenous. In general (Table 4.22) average value is calculated as 0.42 – 0.44, which corresponds to the upper limits of the “poor” level. The STI value is slightly under the recommended values.

The as-is condition and acoustic simulation results for Proposal II and the acceptable limits recommended for use in speech and music-related activities are given in the following tables (Table 4.23 and Table 4.24).

Table 4.23 Comparison of T_{20} results for the real data in the unoccupied state of the Church ($T_{20(IN\text{-}SITU)}$) and the acoustic simulation results of Proposal II in the occupied ($T_{20(PII\text{-}OC)}$) and unoccupied state ($T_{20(PII\text{-}UN)}$) in 1/1 octave bands

RT, s	**Frequency (Hz)**					
	125	**250**	**500**	**1000**	**2000**	**4000**
$T_{20(IN\text{-}SITU)}$	13.33	11.70	10.65	8.77	6.66	3.89
$T_{20(PII\text{-}UN)}$	7.14	3.97	2.80	2.57	2.32	1.76
$T_{20(PII\text{-}OC)}$	6.13	3.54	2.52	2.33	2.13	1.64

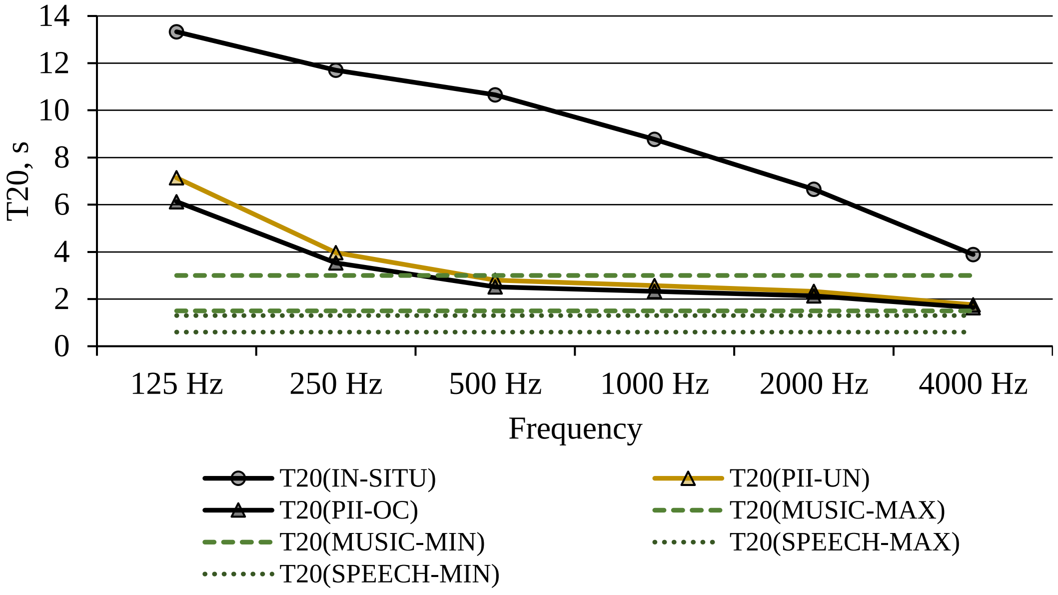


Figure 4.12 Comparison of T_{20} results for the Surp Yerrortutyun Church in 1/1 octave bands, including Proposal II data and their comparison with limits of criteria as recommended in the literature

The graph in Figure 4.12 shows that the average reverberation time values exceed the acceptable limits at all frequencies for speech activities in the as-is state, as mentioned before. The developed model Proposal II provided that the values are in the range of acceptable limits, except at the low frequencies. Although a very effective reduction is achieved at 125 Hz and 250 Hz (around 6s), it is still accepted above the recommended limits. The proposed model is also quite effective in using music-related activities, but the problem is not fully resolved in the case of speech function.

Table 4.24 Comparison of C_{80} results for the real data in the unoccupied state of the Church ($C_{80(IN\text{-}SITU)}$) and the acoustic simulation results of Proposal II in the occupied ($C_{80(PII\text{-}OC)}$) and unoccupied state ($C_{80(PII\text{-}UN)}$) in 1/1 octave bands

C_{80}, dB	Frequency (Hz)					
	125	250	500	1000	2000	4000
$C_{80(IN\text{-}SITU)}$	-10.0	-7.5	-8.6	-7.0	-5.2	-3.6
$C_{80(PII\text{-}UN)}$	-7.2	-4.1	-2.0	-1.6	-1.0	0.5
$C_{80(PII\text{-}OC)}$	-6.5	-3.3	-1.4	-1.1	-0.7	0.9

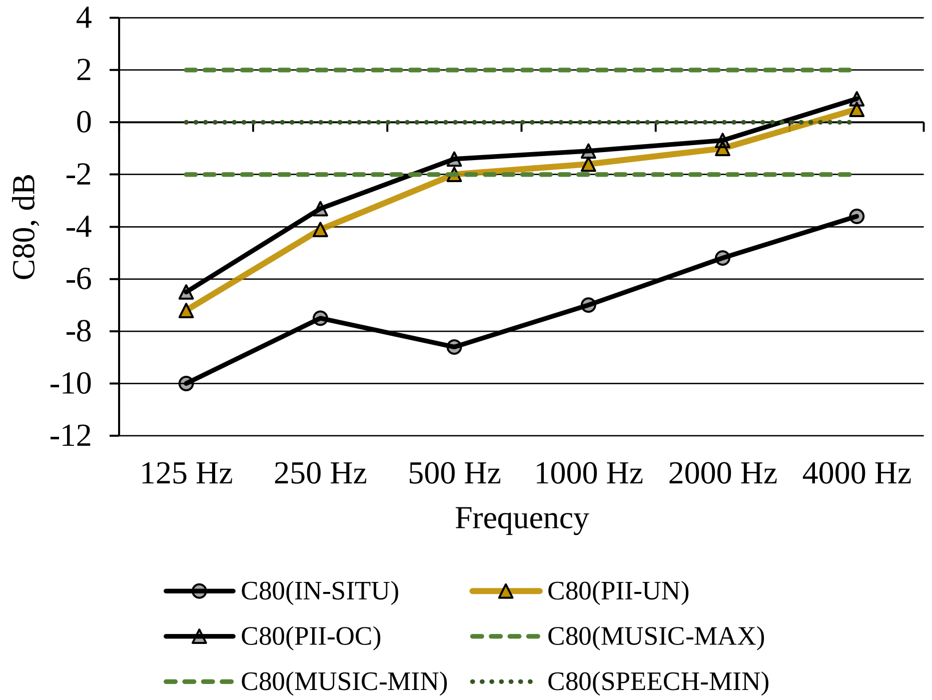


Figure 4.13 Comparison of C_{80} results for the Surp Yerrortutyun Church in 1/1 octave bands including Proposal II data and their comparison with limits of criteria as recommended in the literature

The recommended clarity ranges for speech and music-related activities, the results of the as-is state and Proposal II are given in Table 4.24 and Figure 4.13. As seen in the graph in Figure 4.13, in addition to the improvement in reverberation time for the overall church venue, the increase in the level of clarity is remarkable. Accordingly, for the overall evaluation (Table 4.24 and Appendix D), the clarity value satisfied the requirements for music function, except for the low frequencies.

4.3.3 Assessment of Proposal III: Combined Design

The simulation analysis results of Proposal III, which was developed as a combined design of Proposal I and Proposal II, which are explained detail in the 3.6.3 Section, are compiled. The average values derived from acoustical simulations, including EDT, T_{20}, T_{30}, C_{80} and STI parameters, are compiled in tables for unoccupied and occupied states.

Table 4.25 Early decay time (EDT) data based on Proposal III's acoustic simulation results for the overall case

EDT(s)	Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
EDT_{UN}	6.66	6.59	3.37	2.31	2.12	1.92	1.59	1.15
EDT_{OC}	5.78	5.74	3.04	2.16	2.00	1.83	1.51	1.13

As shown in Figure C.1 and Figure C.2, EDT distribution in the defined audience zone decreases to 1.81 to 2.75 s from 9.6 to 11.69 s at 500 Hz and corresponds to a 78.6% decrease. In overall venue, EDT time (2.16 s – 2.00 s, occupied) at mid-frequency is below the 3 s upper limits as indicated in Table 4.25. The distribution maps noted that the EDT values become shorter at 500 Hz and 1000 Hz under the central dome.

Table 4.26 Reverberation time (T_{20}) data based on Proposal III's acoustic simulation results for the overall case

T_{20}, s	Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
$T_{20(UN)}$	6.78	6.72	3.50	2.41	2.20	1.95	1.52	0.99
$T_{20(OC)}$	5.91	5.87	3.23	2.25	2.05	1.85	1.46	0.95

Table 4.27 Reverberation time (T_{30}) data based on Proposal III's acoustic simulation results for the overall case

T_{30}, s	Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
$T_{30(UN)}$	6.80	6.73	3.54	2.46	2.24	2.00	1.56	1.00
$T_{30(OC)}$	5.93	5.89	3.28	2.36	2.13	1.91	1.49	0.97

No major problematic spots are observed in the T_{20} and T_{30} distribution maps at 500 Hz and 1000 Hz from the grid responses (Figure C.3, Figure C.4, Figure C.5, Figure C.6). Accordingly, slight increments exist under the central dome. Uniform distribution is observed in the audience zone, varying between 1.9 s – 2.5 s in the T_{30}

value. In overall evaluation, as compiled in the Table 4.26 and Table 4.27, the T_{20} average at mid-frequency (2.25 s – 2.05 s, occupied) and T_{30} average at mid-frequency results are below (2.36 s – 2.13 s, occupied), the 3s upper limits defined in the literature in occupied and unoccupied state.

Table 4.28 Clarity (C_{80}) data based on Proposal III's acoustic simulation results for the overall case

C_{80}, dB	Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
$C_{80(UN)}$	-7.1	-7.0	-3.5	-1.2	-0.8	-0.1	1.4	4.3
$C_{80(OC)}$	-6.3	-6.2	-2.8	-0.8	-0.4	01	1.6	4.5

For the Clarity parameter, grid maps are shown in Figure C.7 and Figure C.8. The values vary from -2.0 to 2.5 dB for 500 Hz and 1000 Hz in the audience zone. The clarity decreases slightly from front rows to back rows, indicating smooth heterogeneous distribution. Nevertheless, in terms of overall values in the church venue (shown in Appendix D), the C_{80} average at mid-frequency is calculated as -0.8 to -0.4 dB for the occupied state as presented in Table 4.28, which is succeeded to be in the -2dB to 2dB recommended range both for in audience zone and overall church venue.

Table 4.29 Speech Transmission Index (STI) data based on Proposal III's acoustic simulation results for the overall case

Value	**STI_{UN}**	**STI_{OC}**
Minimum	0.35	0.34
Maximum	0.69	0.68
Average	0.44	0.46
Std.dev.	0.09	0.08

According to the STI grid distribution maps (Figure C.9) for the audience zone in the occupied state, it is observed that the STI value, which was “fair” (0.45 – 0.55) in the front rows and middle rows, decreased to “poor” (0.30 – 0.45) at backward which is indicating the not homogenous state. In overall (Table 4.29) average value is calculated as 0.44 – 0.46, which corresponds “fair” level. The STI value is measured at target limits. The as-is condition and acoustic simulation results for Proposal III and the acceptable limits recommended for use in speech and music-related activities are given in the following tables (Table 4.30 and Table 4.31).

Table 4.30 Comparison of T_{20} results for the real data in the unoccupied state of the Church ($T_{20(IN\text{-}SITU)}$) and the acoustic simulation results of Proposal III in the occupied ($T_{20(PIII\text{-}OC)}$) and unoccupied state ($T_{20(PIII\text{-}UN)}$) in 1/1 octave bands

RT, s	Frequency (Hz)					
	125	250	500	1000	2000	4000
$T_{20(IN\text{-}SITU)}$	13.33	11.70	10.65	8.77	6.66	3.89
$T_{20(PIII\text{-}UN)}$	6.72	3.50	2.41	2.20	1.95	1.52
$T_{20(PIII\text{-}OC)}$	5.87	3.23	2.25	2.05	1.85	1.46

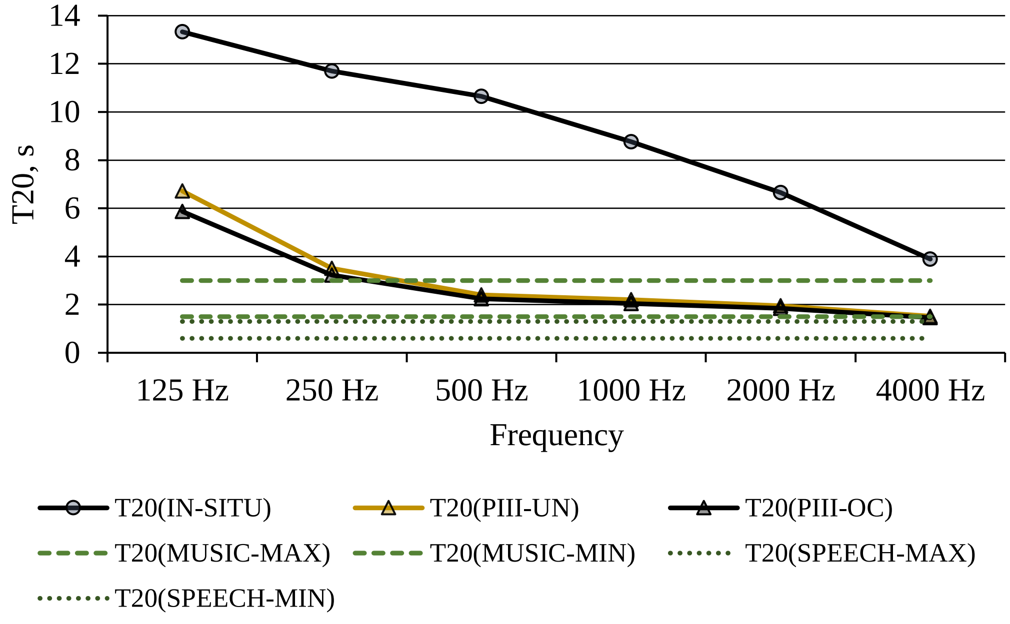


Figure 4.14 Comparison of T_{20} results for the Surp Yerrortutyun Church in 1/1 octave bands, including Proposal III data and their comparison with limits of criteria as recommended in the literature

The graph in Figure 4.14 displays that the average reverberation time values exceed the acceptable limits at all frequencies for speech activities in the as-is state. Proposal III provided that the values are in the range of acceptable limits, except at 125 Hz. The proposed model is found quite effective for music-related activities, but the problem is not totally resolved in the case of speech function as in other proposals.

Table 4.31 Comparison of C_{80} results for the real data in the unoccupied state of the Church ($C_{80(IN\text{-}SITU)}$) and the acoustic simulation results of Proposal III in the occupied ($C_{00(PIII\text{-}OC)}$) and unoccupied state ($C_{80(PIII\text{-}UN)}$) in 1/1 octave bands

C_{80}, dB	Frequency (Hz)					
	125	**250**	**500**	**1000**	**2000**	**4000**
$C_{80(IN\text{-}SITU)}$	-10.0	-7.5	-8.6	-7.0	-5.2	-3.6
$C_{80(PIII\text{-}UN)}$	-7.0	-3.5	-1.2	-0.8	-0.1	1.4
$C_{80(PIII\text{-}OC)}$	-6.2	-2.8	-0.8	-0.4	0.1	1.6

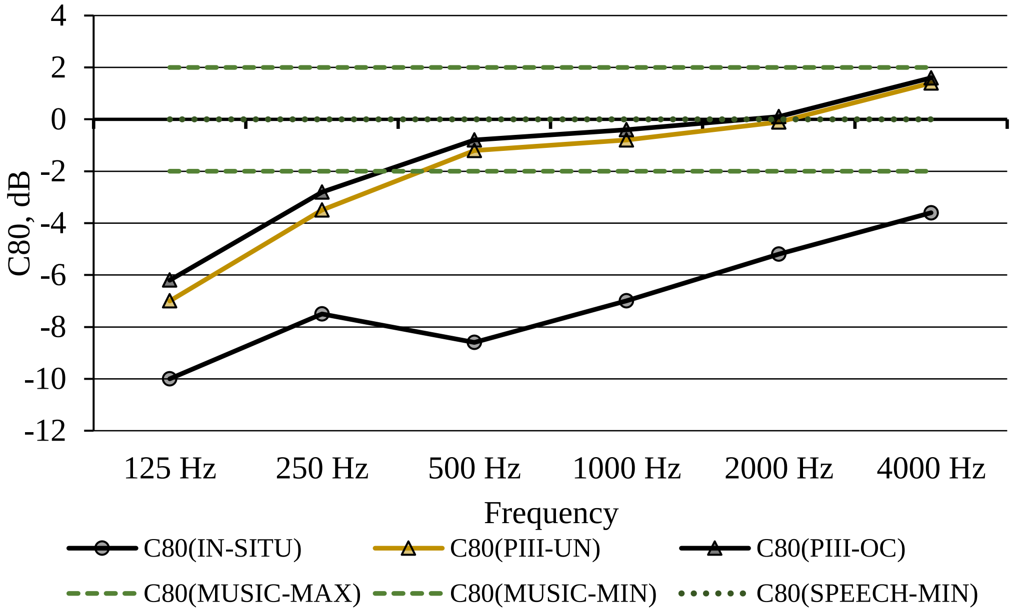


Figure 4.15 Comparison of C_{80} results for the Surp Yerrortutyun Church in 1/1 octave bands, including Proposal III data and their comparison with limits of criteria as recommended in the literature

The recommended clarity values for speech and music-related activities and the as-is state results and Proposal I results are given in Table 4.31 and Figure 4.15. As noted in the graph in Figure 4.15, the overall clarity value calculated in the church improved to a significant extent when hosting music and speech-related activities.

CHAPTER 5

DISCUSSION

In this chapter, the outputs obtained from the in-situ measurements and simulation analyses are summarized to assess the acoustic performance of the Surp Yerrortutyun Church's as-is condition and proposed acoustic rehabilitations. The knowledge acquired from this thesis research is also briefly summarized in the last.

5.1 EVALUATION OF THE AS-IS ACOUSTIC CONDITION

Based on field measurements, the as-is acoustic environment of the Surp Yerrortutyun Church was defined in terms of Reverberation Time (T_{20}), Early Decay Time (EDT), Clarity (C_{80}), Speech Transmission Index (STI), and background noise (L_{eq}) parameters. The field data confirms the highly-reverberant acoustic environment in the Church, therefore, supports the complaints of the users and audience during activities.

The data obtained by field measurements and the recommended ranges for musical and speech activities are compiled in Table 5.1 for the evaluations. That data defining the as-is state of the Church indicates that the venue has an insufficient acoustical environment for speech or music-related actions.

All the field measurements point to long reverberation times within the Church in its unoccupied condition (10.58s – 8.88s at 500 and 1000 Hz, respectively). The 3 s upper limit for churches with similar volumes is not provided for musical activities. In the same way, for speech activities, the recommended limit of 1.3 s for mid-frequencies (500Hz – 1000Hz) is also not satisfied. Besides, reverberation times measured in the structure, especially in low frequencies (125 Hz – 250 Hz) are inconvenient in terms of speech intelligibility factor ($T_{20(125\text{-}250Hz)}$ 13.18s – 13.43s). On the other hand, no notable deviations are observed at different receiver points for the reverberation time. It means diffused sound field conditions are satisfied in the Church. Clarity (C_{80}) is another parameter affecting the intelligibility of sound. For clarity levels by all frequencies indicate lower/insufficient values within the Church in its unoccupied condition as measured in the range -10 dB – -3.6 dB, which are highly below the –2 dB acceptable limit. Likewise, the average STI value measured in the main hall is around 0.26, corresponding to the "bad" intelligibility class. However, the A-weighted equivalent sound level (LA_{eq}) used for background noise determination is measured at 26.2 dBA corresponds to the NC15 curve, a highly satisfying level recommended for speech and music-related activities.

Table 5.1 Field data defining the as-is acoustic environment of the Surp Yerrortutyun Church and the recommended ranges for musical and speech activities used as reference values for the evaluations

Acoustical Parameter	Value	Recommended Limits
T_{20}, s (500 Hz – 1000Hz)	10.58 – 8.88	2.5 – 3.0s for musical activities (Berardi et al., 2016; Egan, 1988)
		0.6 – 1.3s for speech activities (Egan, 1988)
EDT, s (500 Hz – 1000Hz)	10.56 – 8.74	RT ± 10% (Odabaş et al., 2011)
C_{80}, dB (500 Hz – 1000Hz)	(-8.6) – (-7.0)	(-2dB) – (+2dB) for musical activities (Barron, 2011; Egan, 1988)
		C_{80} > (+2dB) for speech activities (Berardi et al., 2016)
STI	0.26	STI > 0.45 (IEC 60268-16:2011, 2011)
Background Noise (dBA)	26.2	25 ± 1 dBA (American National Standards Institute / Acoustical Society of America, 2008)

The results indicate that excessive long reverberation times and lower clarity levels in the Surp Yerrortutyun Church lead to poor speech intelligibility perceived as a "muddy" or "sound-blurring" sound field in terms of acoustical comfort. Even with the longer reverberation times, the sound energy is evenly distributed in the room, and the background noise is determined at acceptable levels.

After the recent repair works, the application of mostly sound-reflecting surfaces in the interior and the mezzanine floor, which is known to exist in its original form, not being in the as-is state, are the factors that caused the alterations in the Church's original acoustic features. As mentioned, there is a demand for multi-functional use of the monument, which was originally built as a church. In this case, the acoustic environment needs to be rehabilitated.

5.2 ACOUSTIC PERFORMANCE ASSESSMENT OF THE PROPOSALS

The acoustic performance of the design proposals comprised of sound absorptive curtains was compared with each other to determine the optimum solutions by acoustical parameters and literature data under this section. The table (Table 5.2) is compiled in regard to the Reverberation Time (T_{20}, s), Early Decay Time (EDT, s), and Clarity (C_{80}, dB) parameters at 500 and 1000 Hz frequency range, including Speech Transmission Index (STI) parameters. Accordingly, in-situ measurements representing the current state of the church are given under “As-Is Case”. The recommended values defined in the literature stated under “Limits”, the results indicating the performance of the Proposal I given in the “P-I”, Proposal II given in the “P-II” and Proposal III is given in the “P-III” column both for unoccupied states and occupied states.

The comparisons were conducted among;

- the different types of design approaches by using the same sound absorptive curtain (all the proposals)
- the same type of curtain system is made of approximate surface area while changing the design approach, including orientation and unit size in the venue (Proposal I and Proposal II)

- the same type of curtain system is made of different surface areas by keeping the major design approaches (Proposal II and Proposal III)

Accordingly, comparisons are made both for the entire church volume (for overall grid responses, Appendix D) with the data obtained from certain 13 receiver points (Figure 3.12) and for the defined audience zone (Figure 3.19) by analyzing the grid distributions (Appendix A, B, and C).

Table 5.2 Comparison chart for the cases according to mid-frequency results (500 Hz – 1 kHz) for all receivers from the overall Church venue

Param.	**As-Is Case**	**P-I**		**P-II**		**P-III**		**Limits**
		UN	**OC**	**UN**	**OC**	**UN**	**OC**	
T_{20}, s (500 Hz)	10.58	2.48	2.48	2.80	2.52	2.41	2.25	3 s* 1.3 s**
T_{20}, s (1 kHz)	8.88	2.25	2.25	2.57	2.33	2.20	2.05	
EDT, s (500 Hz)	10.56	2.40	2.41	2.63	2.40	2.31	2.16	RT ± 10%
EDT, s (1 kHz)	8.74	2.22	2.02	2.43	2.23	2.12	2.00	
C_{80}, dB (500 Hz)	-8.6	-4.8	-4.4	-2.0	-1.4	-1.2	-0.8	(-2dB) to (+2dB)
C_{80}, dB (1 kHz)	-7.0	-4.3	-4.0	-1.6	-1.1	-0.8	-0.4	
STI	0.26	0.41	0.42	0.42	0.44	0.44	0.46	> 0.45

** 3s upper limit for the musical activities, ** 1.3 s upper limits for the speech activities, UN means unoccupied state, OC means occupied state*

Table 5.3 Used sound absorptive material area per Proposals

Material Area (m^2)	Proposal I	Proposal II	Proposal III
Curtain Fabric	947 m^2	1012 m^2	1138 m^2
Carpet	14 m^2	14 m^2	71 m^2
Total sound-absorptive surface area	961 m^2	1026 m^2	1209 m^2

In the overall evaluation, as shown from Table 5.2 and Appendix D, the best acoustic conditions were provided in Proposal III for the music and speech-related activities in terms of acoustical requirements. It is observed that using approximate sound-absorbing surface areas (including curtain and carpet) used in PI and PII brings about slightly similar reverberation times regardless of the design approach and provides the recommended 3 s limits (Table 5.2 and Table 5.3). However, changing the materials' orientation and the design approach from the isolated periphery (Proposal I) to the open-plan design (Proposal II) significantly affects the Clarity (C_{80}, dB), as seen in Table 5.2. The value of -4.4 dB – -4.0 dB in Proposal I in the occupied state increased to -1.4 dB – -1.1 dB, indicating that it succeeded in ascending within the recommended limits (-2dB to +2dB). Proposal III, which has the highest additional sound absorptive area, has the best results among these three proposals in terms of controlling the excessive reverberant and sound blurred acoustic environment in the Surp Yerrortutyun Church. The values provide recommended conditions to a significant extent, especially for music-related activities. The closest values for the speech function are also provided in this proposal. Accordingly, from evaluating the overall condition of the church venue (Appendix D), Proposal III is remarked as the best possible solution, among others.

In the defined audience zone evaluation, grid distribution maps are examined. Firstly, the reverberation time (T_{20}, s) measured in Proposal I shows a few problematic spots under the central dome. The values are homogenously distributed around 2.25 s at 500 Hz and vary from 1.50 s – 2.00 s at 1000 Hz. Clarity value is observed in the range of 0 dB to 3 dB for the defined audience zone. The clarity increases through the back rows where the curtain encircles the audience zone, and the STI value is calculated at 0.45 – 0.55 in Proposal I for this zone. Secondly, the reverberation time (T_{20}, s) measured in Proposal II displays no problematic spots at 500 Hz and 1000 Hz. The values are homogenously distributed around 2.50 s – 2.75 s. Clarity value is measured in the 0 dB to 2 dB range in the defined audience zone at mid-frequencies. The clarity decreases through the back rows. STI value changed from 0.45 – 0.55 in the front rows and decreased to 0.30 – 0.45 in the middle and back rows. And the last, the reverberation time (T_{20}, s) measured in Proposal III states no major problematic spots and displays uniform distribution at 500 Hz and 1000 Hz. The values are distributed around 2.15 s – 2.75 s at 500 Hz and 1.9 s – 2.20 s at 1000 Hz. Clarity value is mainly measured in the -2.0 dB to 2.5 dB range in the defined audience zone at mid-frequencies. The clarity decreases through the back rows, which is slightly heterogenous. STI value changed from 0.45 – 0.55 in the front and middle rows and decreased to 0.30 – 0.45 in the back rows.

Since all three proposals have close reverberation time values, clarity and STI parameters were evaluated as determinant factors. Therefore, Proposal I is considered to be the best solution for acoustic comfort with a focus on a defined audience zone as it homogeneously varies within the recommended level ranges. Also, the STI value is uniformly distributed at a “fair” level in the defined audience zone. Although general problems remain for acoustic comfort throughout the church, the acoustic control in the audience zone has been achieved in Proposal I. However, it is not a preferable approach due to its isolated design in terms of an architectural point of view. In Proposal III, the average value of the overall church venue results indicates that the recommended values are achieved. However, while Proposal III is not the best option for the audience zone, it has adequate distribution. Therefore, considering all the outputs, Proposal I is accepted as the best solution with a focus on the audience zone but not for the overall church. Proposal III is accepted as the best proposal for the acoustic comfort of the overall church venue, not only for the audience zone but also for the entire church. In this case, Proposal III is suggested to provide all conditions at the optimum level and provide a more flexible and integrated design in terms of architectural aspects and by a holistic approach.

In order to evaluate the effects of the proposals, a comparison was made with the reverberation time data of European churches with similar volumes mentioned in the literature review chapter. The graph shows the relationships are given in Figure 5.1 and Figure 5.2.

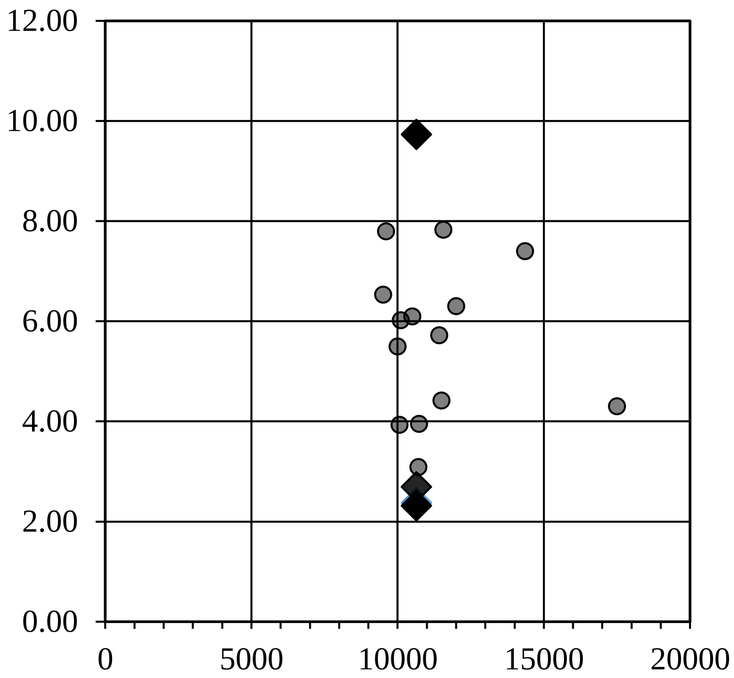


Figure 5.1 Comparison of European churches (grey points) and Surp Yerrortutyun Church (as-is case in black diamond, proposals in green points) according to reverberation time and volume parameters

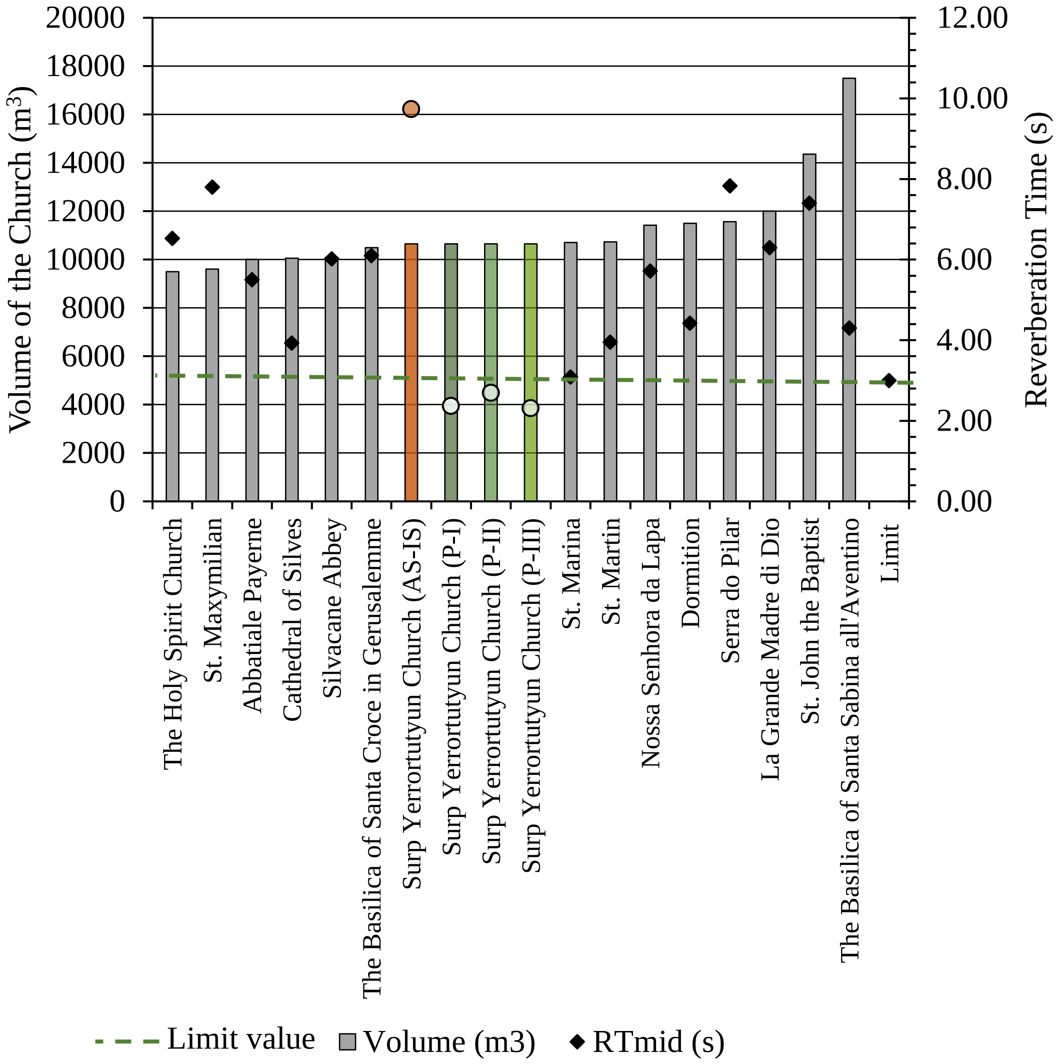


Figure 5.2 Acoustical performance comparison of the as-is state Surp Yerrortutyun Church (AS-IS) and developed proposals (PI, PII, and PIII) with the European churches with similar volume

As can be seen from the graph (Figure 5.2), the Surp Yerrortutyun church in its current state has a remarkably long reverberation time (9.73 s, average RT of the mid-frequencies) among churches of similar volume. In this case, all the developed acoustic rehabilitation proposals succeeded in getting below the upper limit of 3 s as recommended in the literature. It also reached the reverberation time values of St. Marina Church (Seville, Spain) with 3.09 s reverberation time which has the very similar volume.

5.3 GUIDING REMARKS FOR ACOUSTICAL IMPROVEMENT OF HISTORIC CHURCHES

Increasing the sound absorptive surface areas in the Church volume is beneficial in transforming the muddy and echo-rich acoustic environment of the volume to make it a less reverberant space. Here, adaptable and portable dry construction systems enveloping space with transparent/translucent and sound-absorbing materials are recommended because of some potentials mentioned below:

- Interior designs using such systems have the potential to define an acoustically-controlled sub-volume in the Church's space which is one of the solutions for providing an appropriate acoustical environment for demanded activities.
- Any mountable-demountable, moveable, and/or suspended systems are the portable systems that can be beneficial in providing additional sound absorptive surfaces needed for acoustic rehabilitation works in the Church. Considering the architectural and historic/authentic values of the Church, such portable systems have the potential to fulfill the major approaches of cultural heritage conservation (Australia ICOMOS, 2000; ICOMOS, 1964, 1999, 2003), such as:
  - "minimum intervention, if necessary",
  - "compatible, re-treatable, repeatable interventions without giving any damage to the cultural property".
- Fully-enclosing and semi-enclosing peripheral applications with transparent/translucent and sound-absorbing surfaces are the approaches that provide visual contact between the surrounding activity area and the church space itself and contribute to the acoustic comfort in the Church.
- The proposed acoustic rehabilitation designs can be advanced to be more flexible and adaptable according to the Church's needs and other churches planned to be used for many cultural activities.

It is observed that the acoustic data obtained from the acoustic simulation analyses of the Church's 3D computer model, which is produced by assigning the sound absorption properties of the building materials forming the existing surfaces, do not represent the Church's actual/as-is acoustic features properly. The calibration of the acoustic simulation model is necessary and should be conducted by tuning the simulation data according to the measured real acoustic features of the Church. In short, field measurements are necessary to establish acoustic data exhibiting the actual conditions, and this field data should be used to calibrate the acoustic simulation model of the Church. Any acoustic design proposal should be built on the calibrated model; in other words, it should be developed by using the calibrated model as a base.

The impressions concluded from the joint interpretation of simulation analyses are summarized below:

- In the Surp Yerrortutyun Church, adding the sound-absorptive surface area of 960 m^2 – 1030 m^2 with an average of 0.65 sound absorption coefficient at the mid-frequency range provided considerable progress in the audial environment for musical activities, while the added total surface area is not still enough to achieve the recommended values of RT for speech activities. On the other hand, the RT and C_{80} values of 2.25 s – 2.05 s and -0.8 dB – -0.4 dB ranges, respectively, achieved by the Proposal III, are close to the acoustic features measured in many churches still in function, such as St. Marina Church in Seville, Spain. This means that the acoustic features provided by the proposals are similar to some active churches in Europe. Further revisions in the proposals of this study are needed to advance their acoustic performances by providing more sound-absorptive surface area.
- The proposals (Proposal II and Proposal III) that provide open-plan layout have some advantages. It contributes to auditory control in the overall interior of the church, while allowing visual integrity between the audience zone and the rest of the venue, which is valuable when working on historical monuments.

- Proposal I provides a fully-enclosing space by increasing the sound absorption while limiting the visual integrity of the enclosed space with the Church interior.
- Same sound absorber elements in different design approaches/orientations affect the Clarity remarkably. It has been beneficial to place vertical sound absorbers at the back of the audience zone to make clarity value uniformly distributed and increase the level in the audience zone (as in Proposal I). It also shortens reverberation time, significantly increasing the STI value and speech articulation.

CHAPTER 6

CONCLUSION

A lot of historical churches serve as museum in Turkey. Local municipalities and the Ministry of Culture and Tourism tend to host cultural, scientific, and social events in these buildings. Surp Yerrortutyun Church (19th-century Ottoman period) in the Sivrihisar district of Eskişehir is one of our historical monuments desired to be used within the scope of such social development projects by the authorities. However, it was stated by the participants and officials that the acoustical environment of the Church is insufficient, and the sound is perceived as blurred or muddy during the occasions. In particular, throughout speech-related activities such as symposiums, the intelligibility of speeches is notably low in the Church.

This research focuses on the acoustic assessment of the historical Surp Yerrortutyun Church, one of our precious cultural heritage whose basic form and geometry have been preserved until today. The principal analytical studies conducted in the study are the acoustical field measurements held in the monument and the simulation analyses of the acoustic computer model of the monument, which is calibrated by the obtained real data. The field measurements exhibited the existing acoustic environment of the Surp Yerrortutyun Church, which underwent many repairs.

According to the field measurement results, the existing acoustic environment is defined in terms of Reverberation Time (T_{20}, s), Early Decay Time (EDT, s), Clarity (C_{80}, dB), Speech Transmission Index (STI, unitless), and background noise (LA_{eq}, dB).

The results representing the existing acoustic environment in the Surp Yerrortutyun Church show that all the measured acoustic data are out of recommended values given in the literature. This means that the as-is state of the Church has an insufficient acoustic environment for speech or music-related activities. The reverberation time is 10.6 s and 8.9 s at 500 and 1000Hz, respectively. These values are excessively longer than the 3 s upper limit of T_{20} given in the literature (Berardi et al., 2016; Egan, 1988). The Clarity value is determined to be between -10 dB and -3.6 dB in the as-is case. These C_{80} values are highly below the –2 dB acceptable limit given in the literature (Barron, 2011; Berardi et al., 2016; Egan, 1988). The average STI value of the Church is found to be 0.26 in the existing state, which corresponds to a "bad" level, specifically for speech-related activities (IEC 60268-16:2011, 2011). The results indicate that excessive longer reverberation times and lower clarity levels cause the blurred sound environment and poor speech intelligibility. Therefore, the measured acoustic data signals that Surp Yerrortutyun Church needs acoustical improvement.

An acoustic improvement can be achieved by integrating sound absorptive surfaces, preferably attached or hung free by mountable-demountable (temporary) encircling systems and made of transparent fabrics (curtains). Here, some alternative designs of encircling systems were suggested considering the design criteria of “minimum intervention, if necessary”, “keeping visual integrity”, and “increasing sound absorption” and the restrictions of the church space, such as “seat layout”.

The acoustic effectiveness of the proposed acoustic improvement designs was assessed by simulation analyses conducted on the calibrated geometric acoustic model of the Church. The calibration of the geometric acoustic model process is based on the field measurements data. The confirmation of the model as perceptually equivalent to the real acoustic conditions was done by achieving Just Noticeable Difference (JND) values in acceptable ranges.

All acoustic improvement proposals use the ceiling area above the seating layout positioned along the nave aisle to increase the sound absorptive surfaces. In this regard, to keep the visual integrity of the Church, the transparent sound absorptive curtains were hung free at a certain height and intervals. In the Proposal I, the sides of the seating area is fully-covered by the transparent sound absorptive curtains in a way that totally separates the seating area visually from the church volume by creating sub-volume. In the Proposal II and the Proposal III, the sides of the seating area are gradually-covered by hanging the transparent sound absorptive curtains freely in a way that they do not disturb the audience's visual perception of the church. In addition, sound absorptive curtains are also placed in a way to partially screen the fronts of the exterior walls 15 cm away from their interior surfaces. The acoustic performances of the Proposals' unoccupied and occupied states were assessed by their simulation analyses. Here, the sound absorption coefficient values of the curtain fabrics at various frequencies are given as the input for the simulation analyses, and their sound transmission coefficients are not concerned due to the lack of data in the literature.

The results showed that all the proposals provide adequate acoustical conditions as recommended in the literature for music-related and speech-related activities in particular at medium and high frequencies. For instance, by the Proposal III in the occupied state, the reverberation time reduces from the range of 10.7 s – 8.8 s to the range of 2.3 s – 2.1 s at mid frequencies, corresponding to an effective decrease of around 76%. Besides, the Clarity value falls from the range of -8.6 dB – -7.0 dB to the range of -0.8 dB – -0.4 dB at mid frequencies in the occupied state, which indicates a significant improvement, specifically for the speech activities. In addition, the average STI value is improved from 0.26, corresponding to the "bad" level, to 0.46, corresponding to the "fair" level in the occupied state.

However, the excessive long reverberance and lower speech articulation problems persist at low frequencies. This shows that the Proposals cannot provide acoustic improvement enough at low frequencies. Further analyses can develop alternative solutions focusing on solving that problem.

In addition, for the parts in the Church where the sound absorptive curtains are hung free, the area of absorptive surfaces seems to double in amount and may be thought to be more effective. However, the sound transmission coefficient of the suspended curtains dividing the same space into parts may reduce their sound absorption performances in the space. Since the data on sound transmission coefficients of the fabrics are not available, their acoustic impact cannot be integrated into the simulation analyses. To enhance the accuracy of simulation analyses, it is necessary to consider the sound transmission and absorption coefficients of the freely hung curtains, which create sub-volumes in the venue.

In short, when compared to the recommended values in the literature, all acoustical rehabilitation proposals are observed to enhance the acoustic environment in the Church at medium and high frequencies, specifically for music-related activities. Among all, Proposal III provides sufficient acoustic conditions in the Church both for music-related and speech-related activities at medium and high frequencies. On the other hand, it is worth saying that Proposal II has a design that keeps the visual integrity in the Church at most while enhancing the acoustic environment to a sufficient level for musical activities. Proposal I is not a preferable approach due to its isolated chamber-like design; however, the acoustic data achieved by this proposal established reference data for the audience zone and showed the extent of acoustic enhancement that can be provided by the minimum sound absorptive surface area.

Obviously, the major surfaces in the Church have an important role on acoustic performance. To control potential acoustic problems, precautions have to be taken in the development of the conservation projects by keeping their authentic features. As the elimination of the problems in an existing structure is challenging and, in some cases, can be impossible to control due to the conservation criteria. In the case of Surp Yerrortutyun Church Museum, acoustic improvement is achieved by the proposals; however, the ideal solution with logical and economic approaches is facing difficulties considering the conservation criteria. It is expected the data obtained in the study will be guiding for acoustic improvement and repair works in the church museums, which are intended to be used for music-related and speech-related activities in the future.

Considering the multifunctional usage demands of the Surp Yerrortutyun Church, special acoustic designs are developed to improve this problematic and muddy acoustic environment. There is no adequate information about the materials, such as historical plasters, wall paintings, and floor coverings of the church. In addition, the form and materials of the non-existed mezzanine floor today are also unknown. Before conservation or repair work, extensive material conservation studies are required to determine the properties of the original materials. In the current situation, temporary acoustical solutions are planned that will not cause any damage to the original and as-is state of the monument to host events such as conferences and music concerts. The proposals developed within this study have mainly controlled the excessively long reverberation time. Consequently, future studies could investigate the original acoustic conditions of the monument by researching the unknown architectural features and authentic materials by comparing them with the data obtained from this study. Moreover, the construction practices and the cost calculations for the proposals while developing new solutions could be studied.

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APPENDICES

A. SIMULATION RESULTS: PROPOSAL I

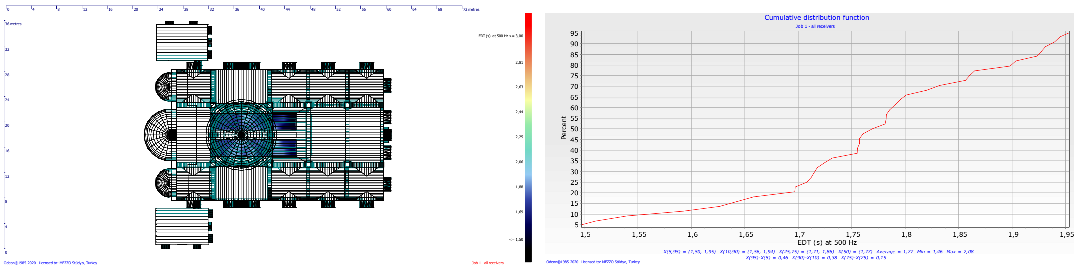

Figure A. 1 EDT grid map and cumulative distribution graph of defined audience zone at 500 Hz and for Proposal I in the occupied state

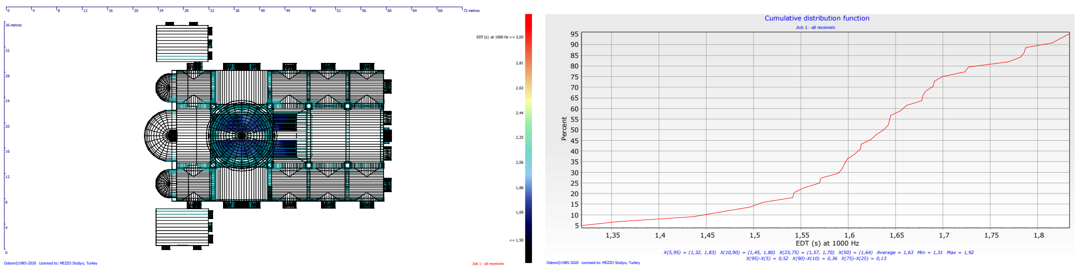

Figure A. 2 EDT grid map and cumulative distribution graph of defined audience zone at 1000 Hz for Proposal I in the occupied state

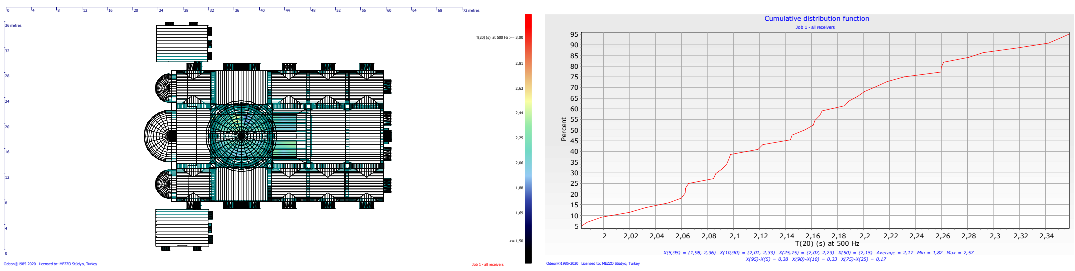

Figure A. 3 T_{20} grid map and cumulative distribution graph of defined audience zone at 500 Hz for Proposal I in the occupied state

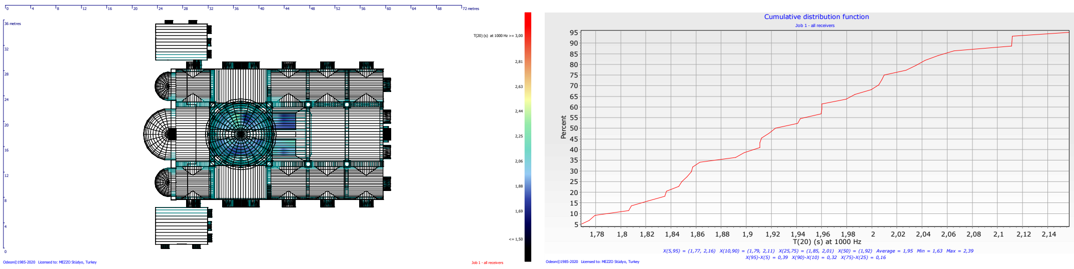

Figure A. 4 T_{20} grid map and cumulative distribution graph of defined audience zone at 1000 Hz for Proposal I in the occupied state

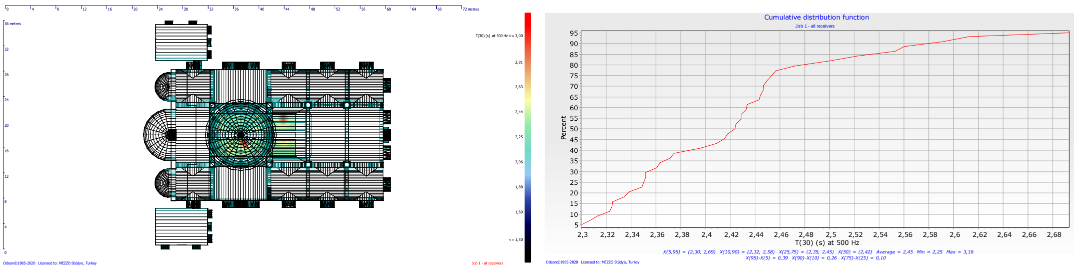

Figure A. 5 T_{30} grid map and cumulative distribution graph of defined audience zone at 500 Hz for Proposal I in the occupied state

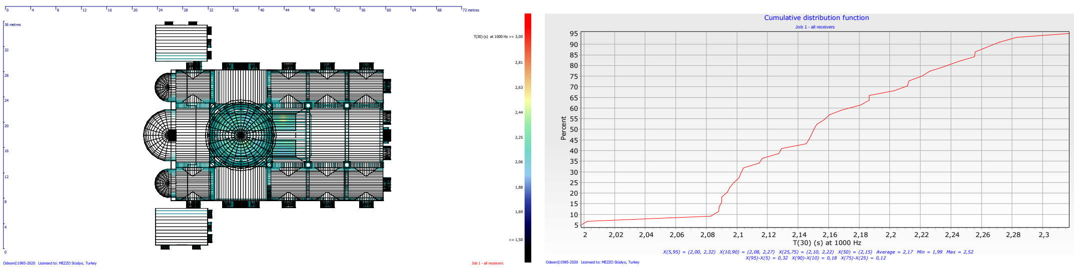

Figure A. 6 T_{30} grid map and cumulative distribution graph of defined audience zone at 1000 Hz for Proposal I in the occupied state

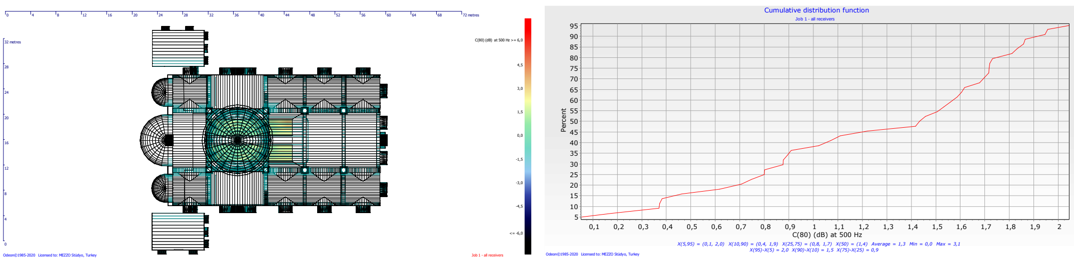

Figure A. 7 C_{80} grid map and cumulative distribution graph of defined audience zone at 500 Hz for Proposal I in the occupied state

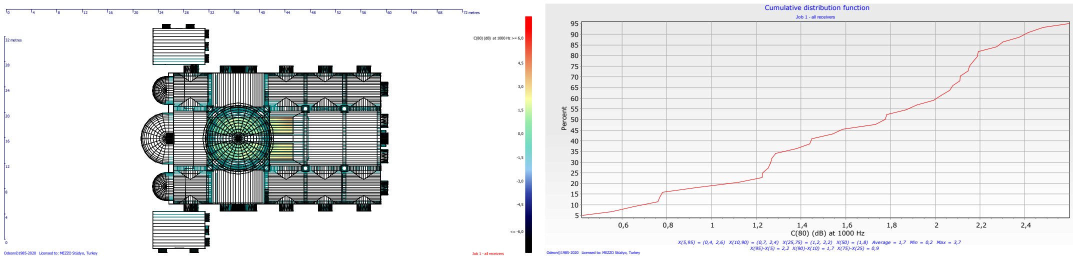

Figure A. 8 C_{80} grid map and cumulative distribution graph of defined audience zone at 1000 Hz for Proposal I in the occupied state

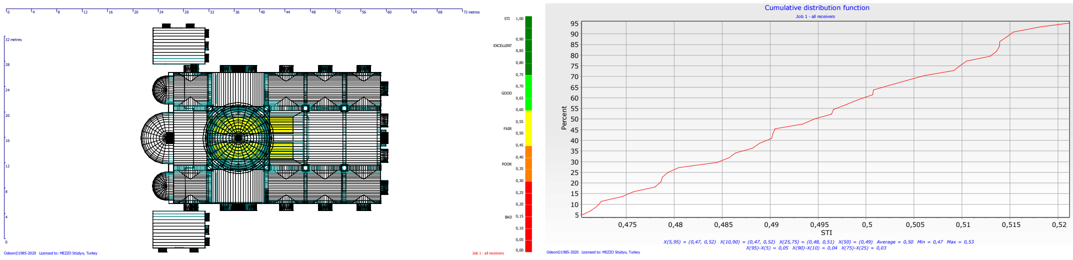

Figure A. 9 STI grid map and cumulative distribution graph of defined audience zone for Proposal I in the occupied state

B. SIMULATION RESULTS: PROPOSAL II

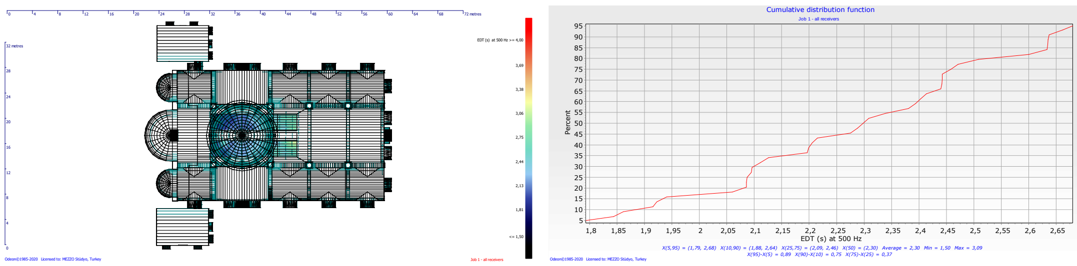

Figure B. 1 EDT grid map and cumulative distribution graph of defined audience zone at 500 Hz and for Proposal II in the occupied state

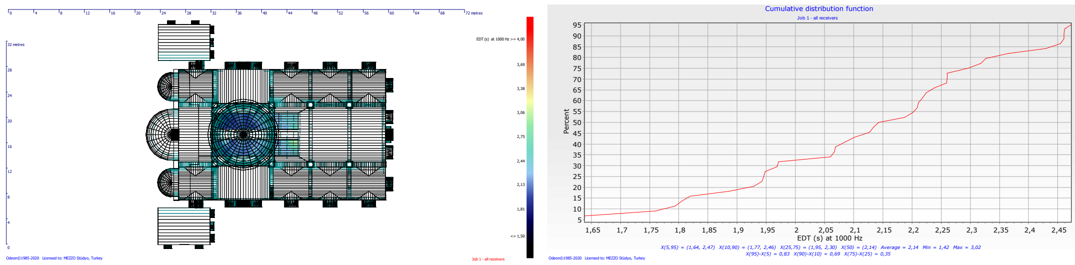

Figure B. 2 EDT grid map and cumulative distribution graph of defined audience zone at 1000 Hz for Proposal II in the occupied state

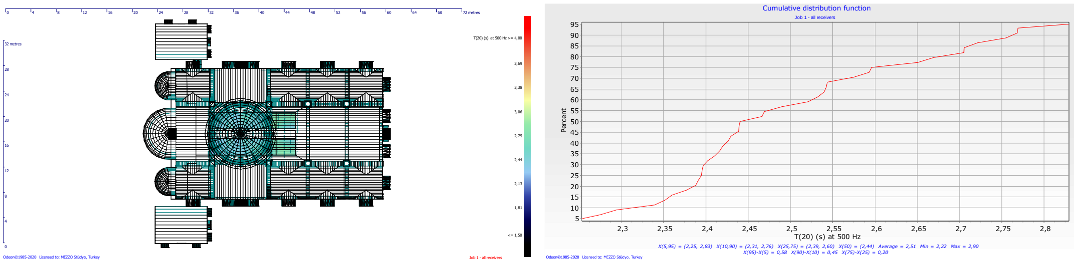

Figure B. 3 T_{20} grid map and cumulative distribution graph of defined audience zone at 500 Hz for Proposal II in the occupied state

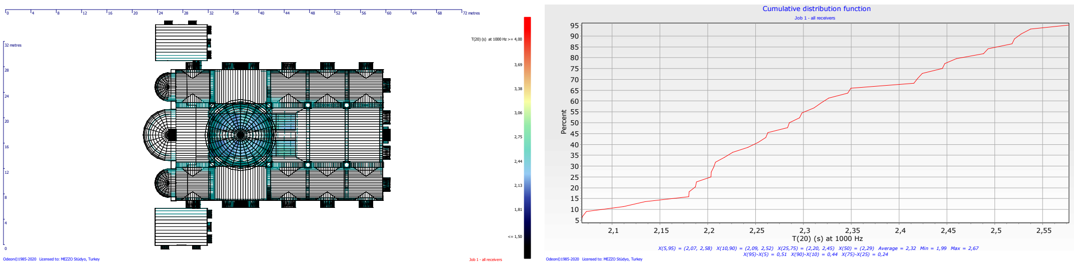

Figure B. 4 T_{20} grid map and cumulative distribution graph of defined audience zone at 1000 Hz for Proposal II in the occupied state

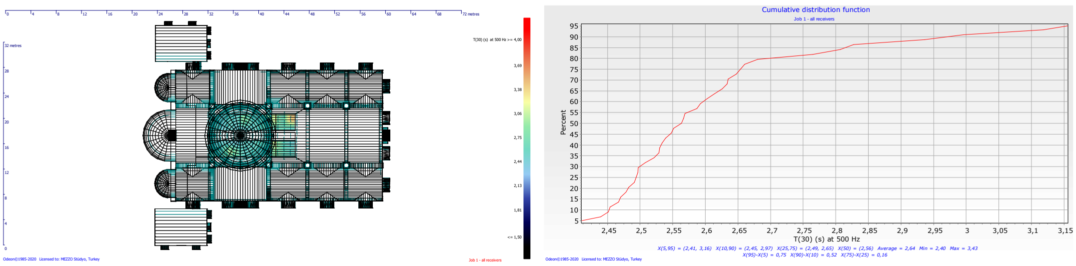

Figure B. 5 T_{30} grid map and cumulative distribution graph of defined audience zone at 500 Hz for Proposal II in the occupied state

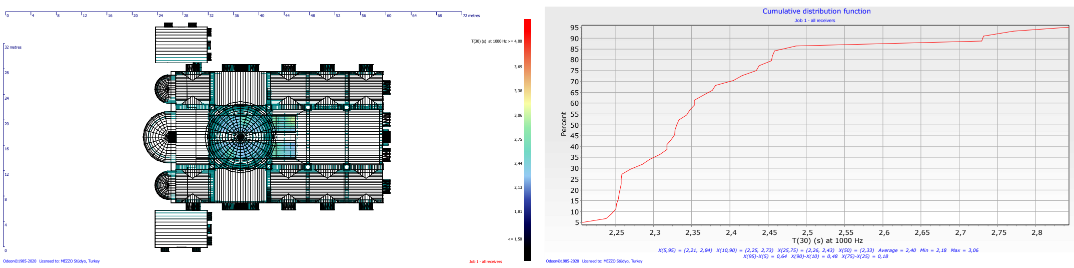

Figure B. 6 T_{30} grid map and cumulative distribution graph of defined audience zone at 1000 Hz for Proposal II in the occupied state

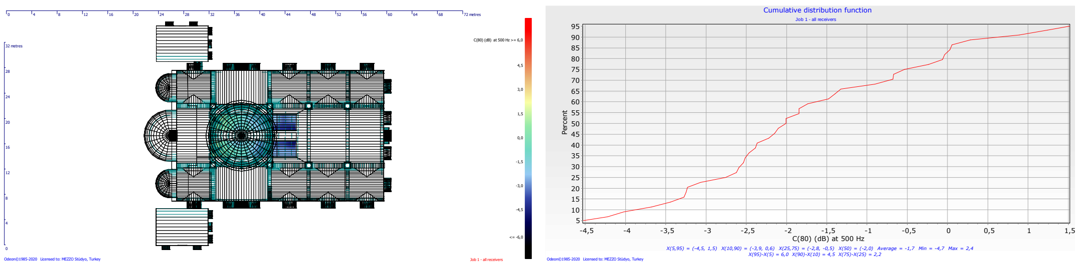

Figure B. 7 C_{80} grid map and cumulative distribution graph of defined audience zone at 500 Hz for Proposal II in the occupied state

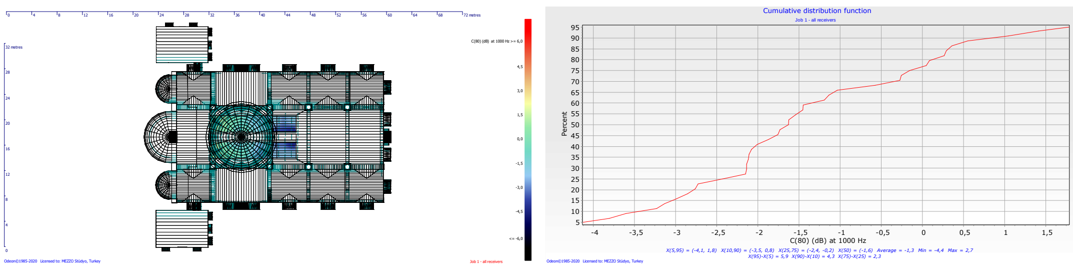

Figure B. 8 C_{80} grid map and cumulative distribution graph of defined audience zone at 1000 Hz for Proposal II in the occupied state

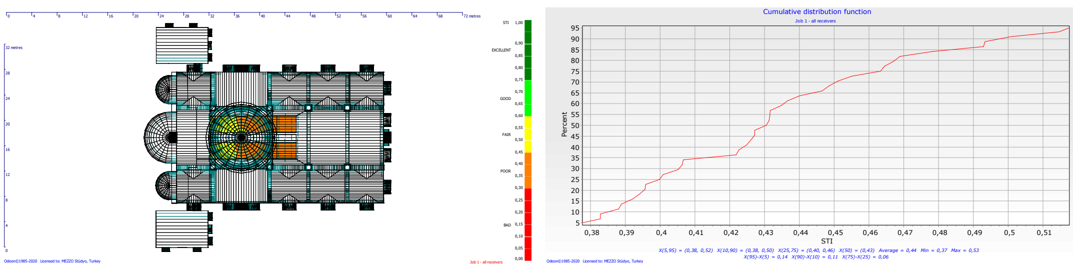

Figure B. 9 STI grid map and cumulative distribution graph of defined audience zone for Proposal II in the occupied state

C. SIMULATION RESULTS: PROPOSAL III

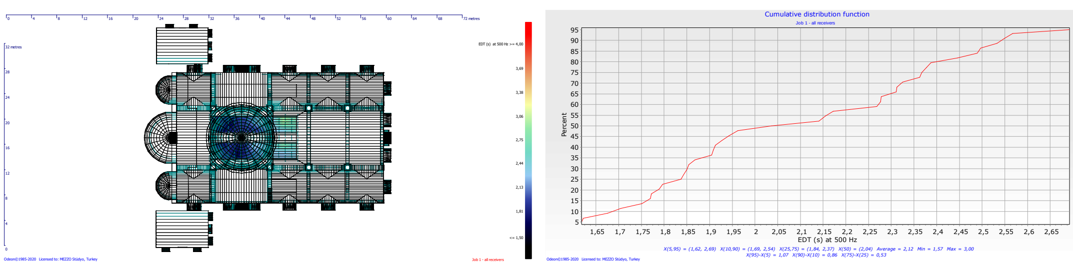

Figure C. 1 EDT grid map and cumulative distribution graph of defined audience zone at 500 Hz and for Proposal III in the occupied state

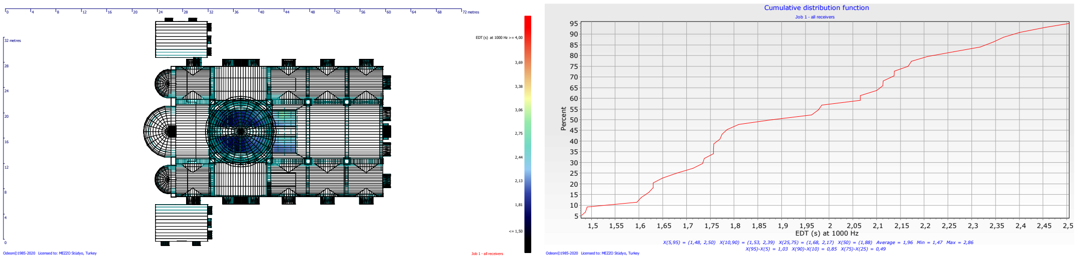

Figure C. 2 EDT grid map and cumulative distribution graph of defined audience zone at 1000 Hz for Proposal III in the occupied state

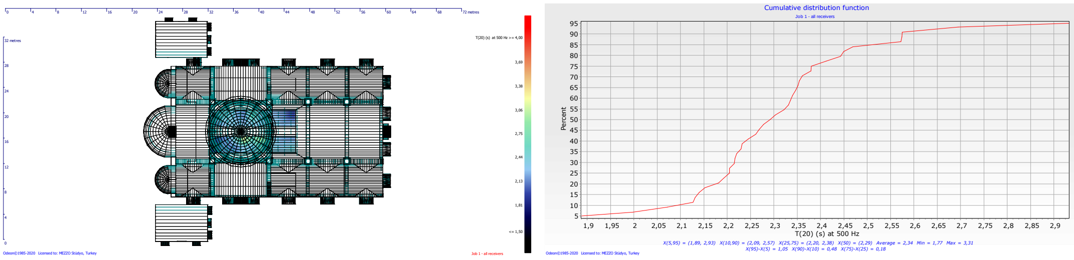

Figure C. 3 T_{20} grid map and cumulative distribution graph of defined audience zone at 500 Hz for Proposal III in the occupied state

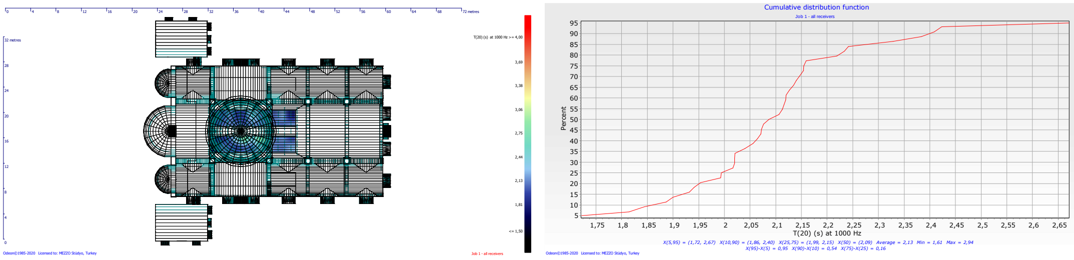

Figure C. 4 T_{20} grid map and cumulative distribution graph of defined audience zone at 1000 Hz for Proposal III in the occupied state

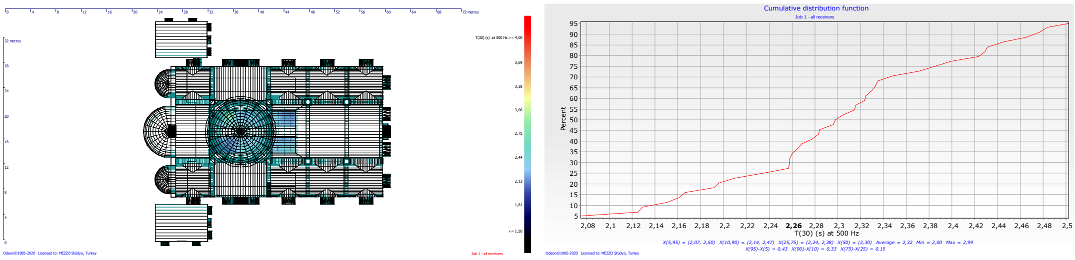

Figure C. 5 T_{30} grid map and cumulative distribution graph of defined audience zone at 500 Hz for Proposal III in the occupied state

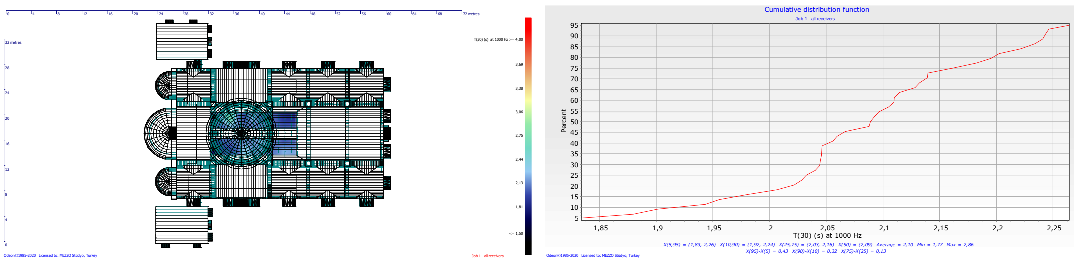

Figure C. 6 T_{30} grid map and cumulative distribution graph of defined audience zone at 1000 Hz for Proposal III in the occupied state

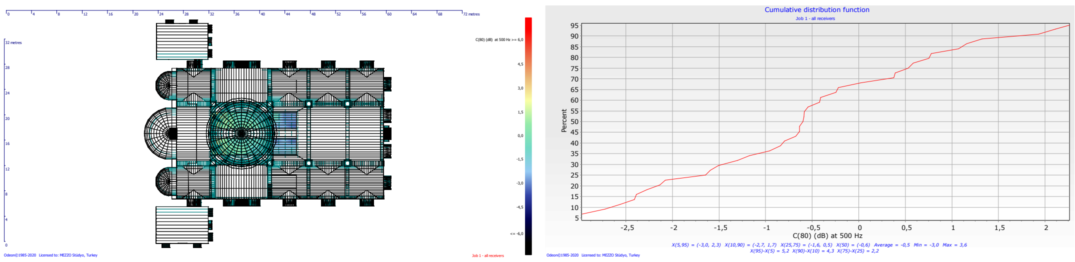

Figure C. 7 C_{80} grid map and cumulative distribution graph of defined audience zone at 500 Hz for Proposal III in the occupied state

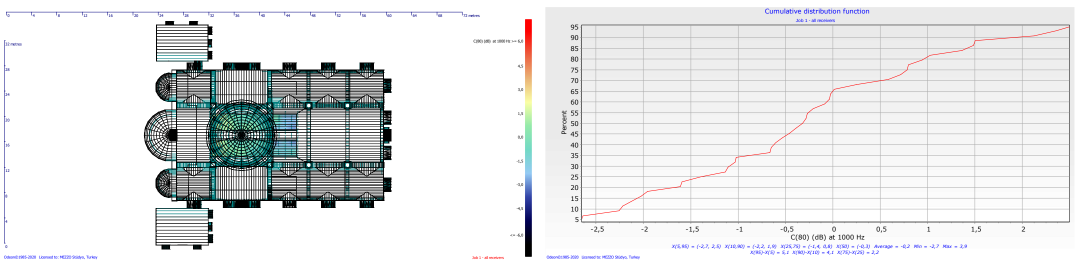

Figure C. 8 C_{80} grid map and cumulative distribution graph of defined audience zone at 1000 Hz for Proposal III in the occupied state

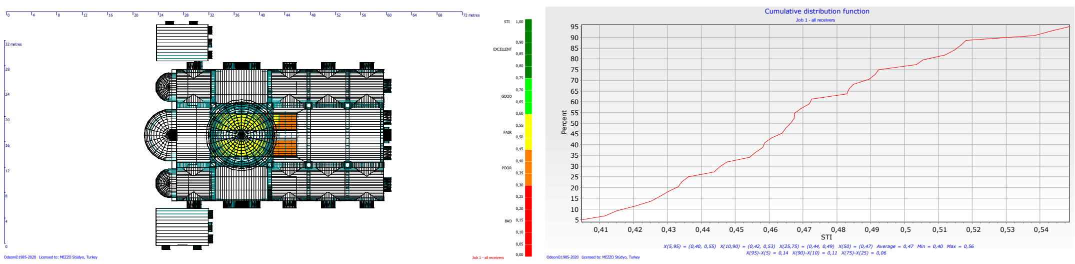

Figure C. 9 STI grid map and cumulative distribution graph of defined audience zone for Proposal III in the occupied state

D. SIMULATION RESULTS: OVERALL

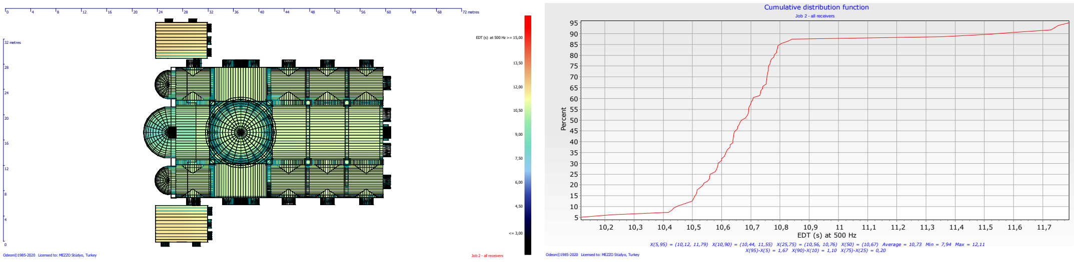

Figure D. 1 EDT distribution map (on the left) and cumulative graph (on the right), 500 Hz, Surp Yerrortutyun Church, as-is case, unoccupied

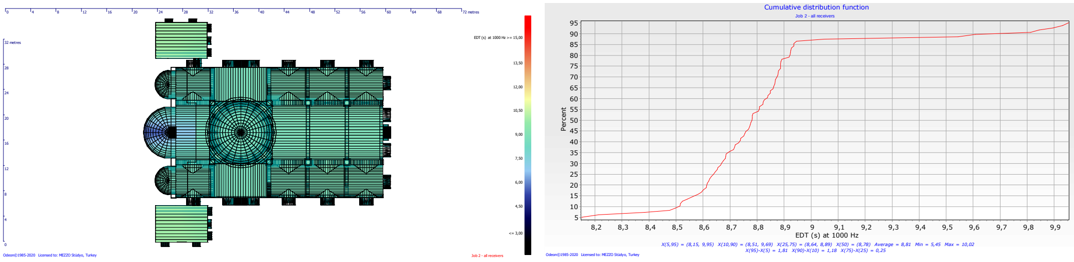

Figure D. 2 EDT distribution map (on the left) and cumulative graph (on the right), 1000 Hz, Surp Yerrortutyun Church, as-is case, unoccupied

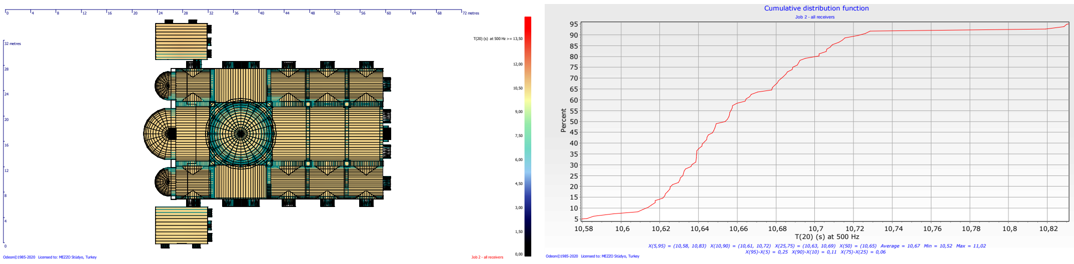

Figure D. 3 T_{20} distribution map (on the left) and cumulative graph (on the right), 500 Hz, Surp Yerrortutyun Church, as-is case, unoccupied

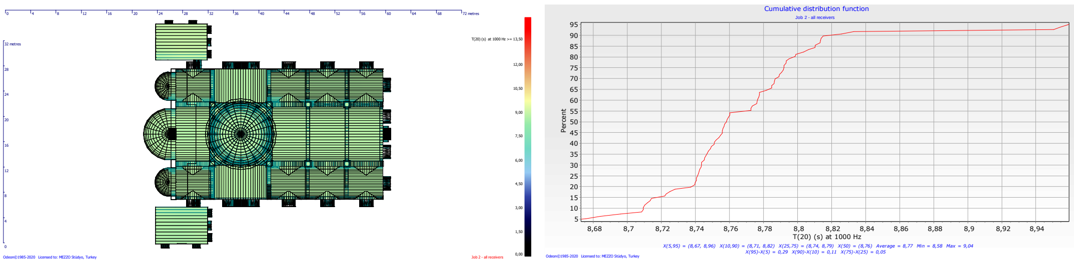

Figure D. 4 T_{20} distribution map (on the left) and cumulative graph (on the right), 1000 Hz, Surp Yerrortutyun Church, as-is case, unoccupied

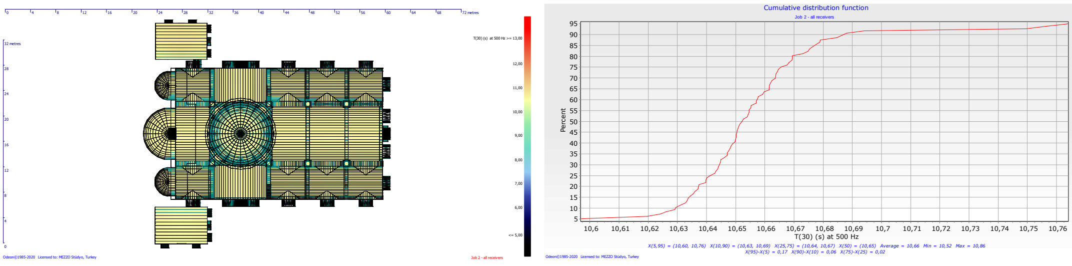

Figure D. 5 T_{30} distribution map (on the left) and cumulative graph (on the right), 500 Hz, Surp Yerrortutyun Church, as-is case, unoccupied

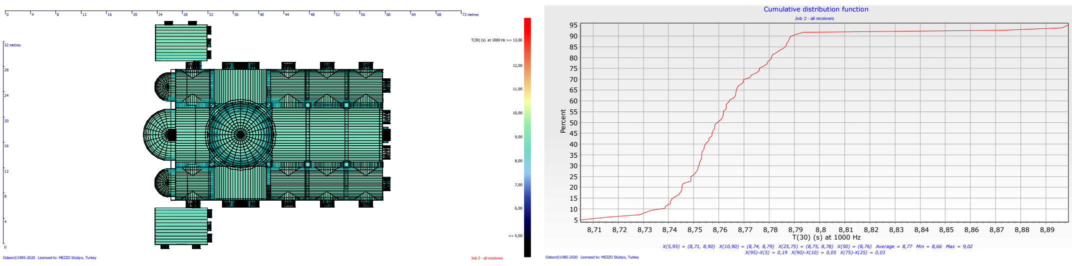

Figure D. 6 T_{30} distribution map (on the left) and cumulative graph (on the right), 1000 Hz, Surp Yerrortutyun Church, as-is case, unoccupied

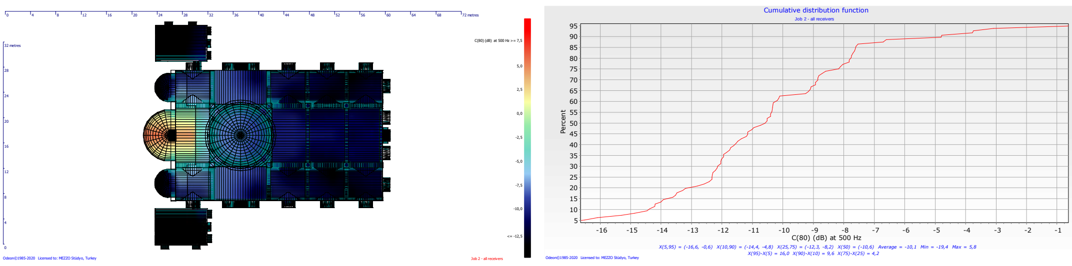

Figure D. 7 C_{80} distribution map (on the left) and cumulative graph (on the right), 500 Hz, Surp Yerrortutyun Church, as-is case, unoccupied

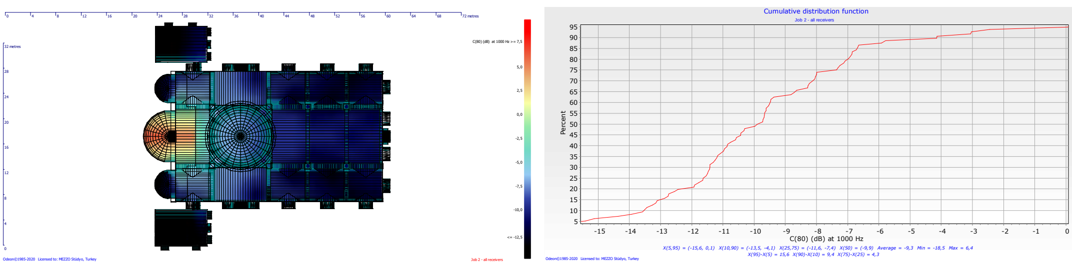

Figure D. 8 C_{80} distribution map (on the left) and cumulative graph (on the right), 1000 Hz, Surp Yerrortutyun Church, as-is case, unoccupied

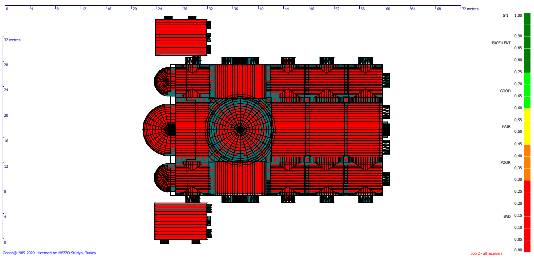

Figure D. 9 STI distribution map, Surp Yerrortutyun Church, as-is case, unoccupied

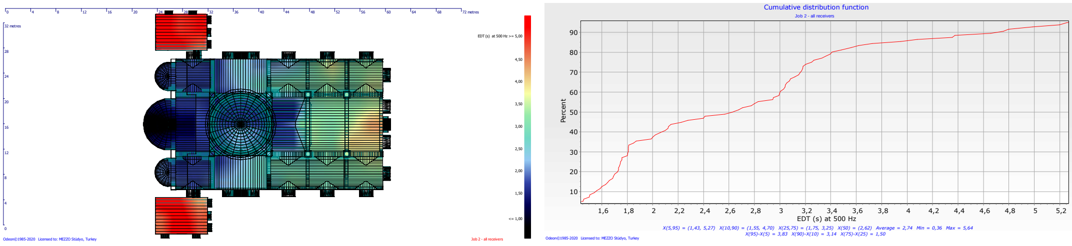

Figure D. 10 EDT distribution map (on the left) and cumulative graph (on the right), 500 Hz, Surp Yerrortutyun Church, Proposal I, unoccupied

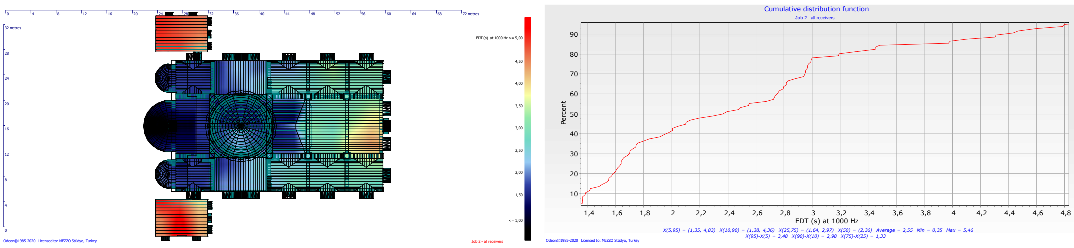

Figure D. 11 EDT distribution map (on the left) and cumulative graph (on the right), 1000 Hz, Surp Yerrortutyun Church, Proposal I, unoccupied

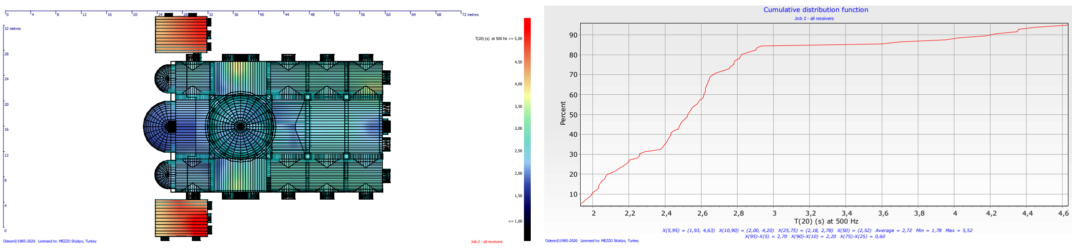

Figure D. 12 T_{20} distribution map (on the left) and cumulative graph (on the right), 500 Hz, Surp Yerrortutyun Church, Proposal I, unoccupied

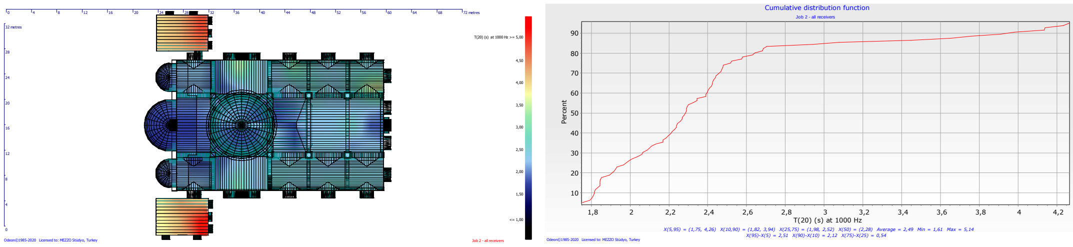

Figure D. 13 T_{20} distribution map (on the left) and cumulative graph (on the right), 1000 Hz, Surp Yerrortutyun Church, Proposal I, unoccupied

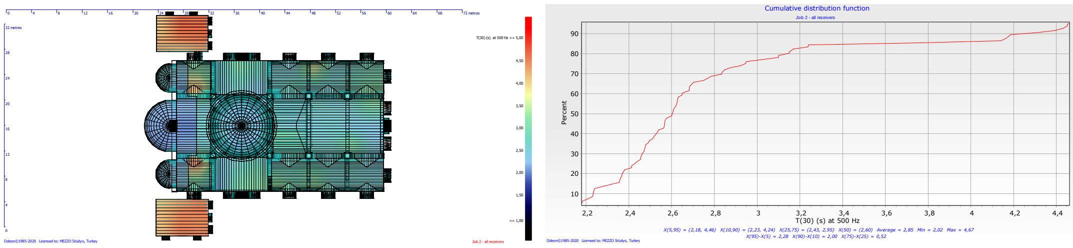

Figure D. 14 T_{30} distribution map (on the left) and cumulative graph (on the right), 500 Hz, Surp Yerrortutyun Church, Proposal I, unoccupied

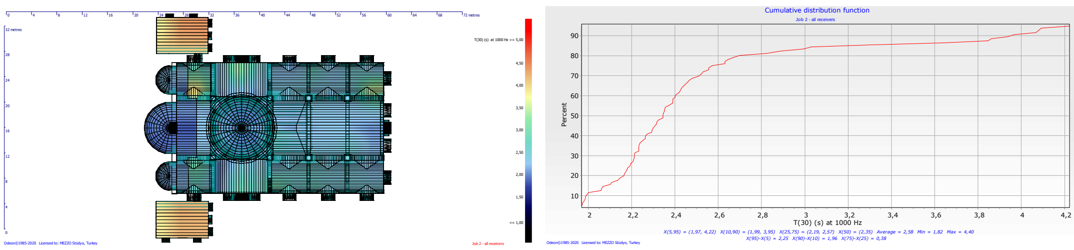

Figure D. 15 T_{30} distribution map (on the left) and cumulative graph (on the right), 1000 Hz, Surp Yerrortutyun Church, Proposal I, unoccupied

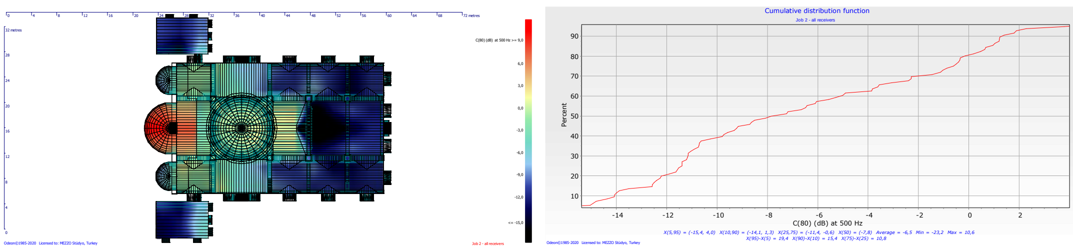

Figure D. 16 C_{80} distribution map (on the left) and cumulative graph (on the right), 500 Hz, Surp Yerrortutyun Church, Proposal I, unoccupied

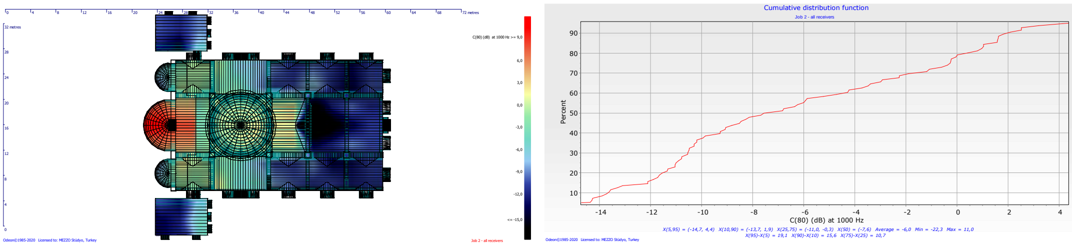

Figure D. 17 C_{80} distribution map (on the left) and cumulative graph (on the right), 1000 Hz, Surp Yerrortutyun Church, Proposal I, unoccupied

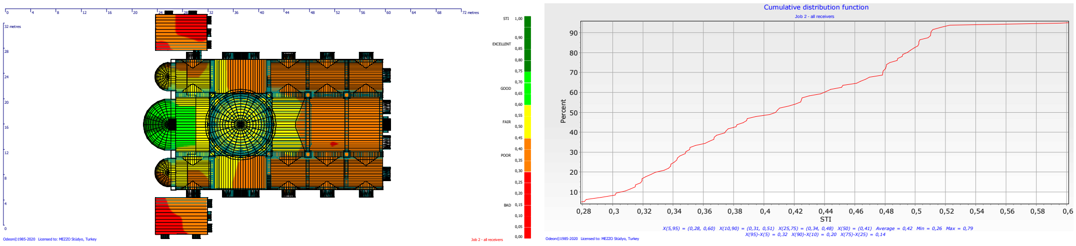

Figure D. 18 STI distribution map, Surp Yerrortutyun Church, Proposal I, unoccupied

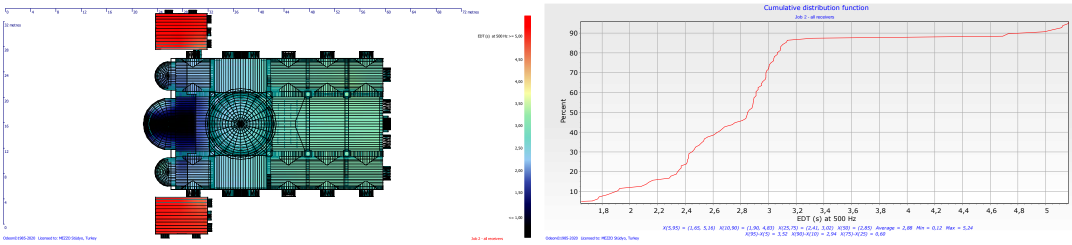

Figure D. 19 EDT distribution map (on the left) and cumulative graph (on the right), 500 Hz, Surp Yerrortutyun Church, Proposal II, unoccupied

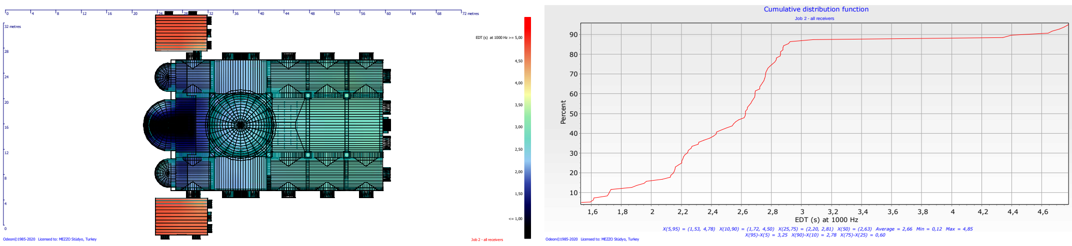

Figure D. 20 EDT distribution map (on the left) and cumulative graph (on the right), 1000 Hz, Surp Yerrortutyun Church, Proposal II, unoccupied

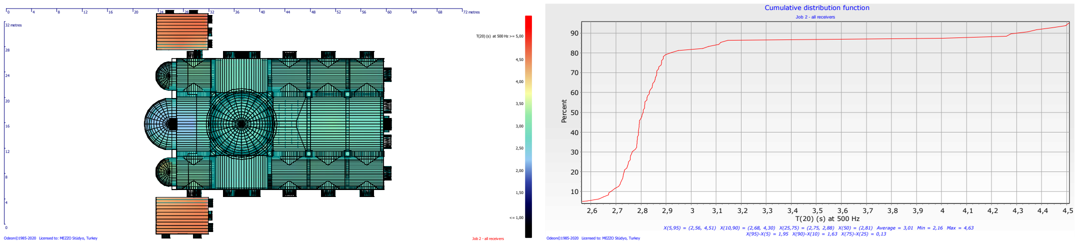

Figure D. 21 T_{20} distribution map (on the left) and cumulative graph (on the right), 500 Hz, Surp Yerrortutyun Church, Proposal II, unoccupied

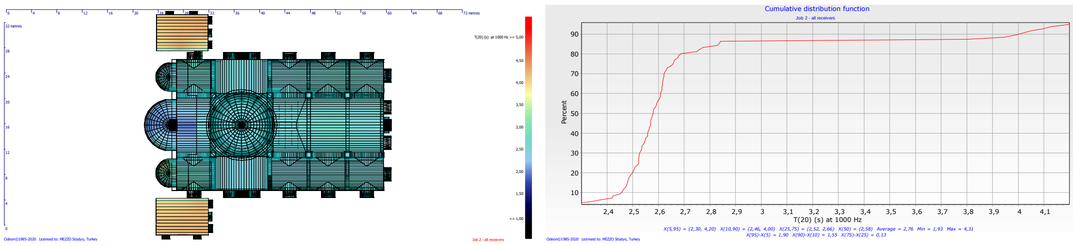

Figure D. 22 T_{20} distribution map (on the left) and cumulative graph (on the right), 1000 Hz, Surp Yerrortutyun Church, Proposal II, unoccupied

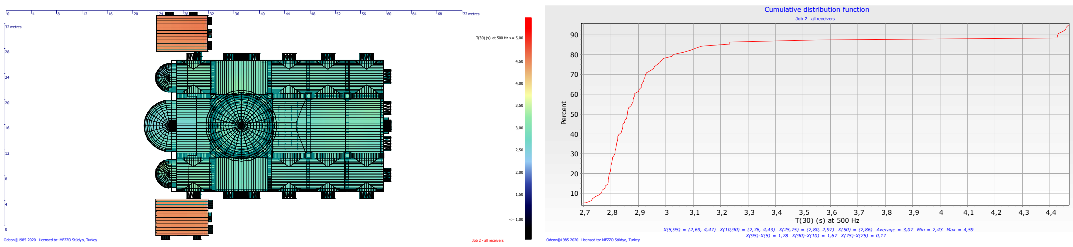

Figure D. 23 T_{30} distribution map (on the left) and cumulative graph (on the right), 500 Hz, Surp Yerrortutyun Church, Proposal II, unoccupied

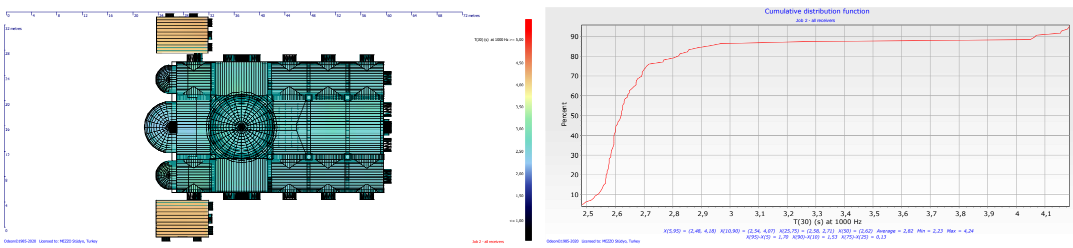

Figure D. 24 T_{30} distribution map (on the left) and cumulative graph (on the right), 1000 Hz, Surp Yerrortutyun Church, Proposal II, unoccupied

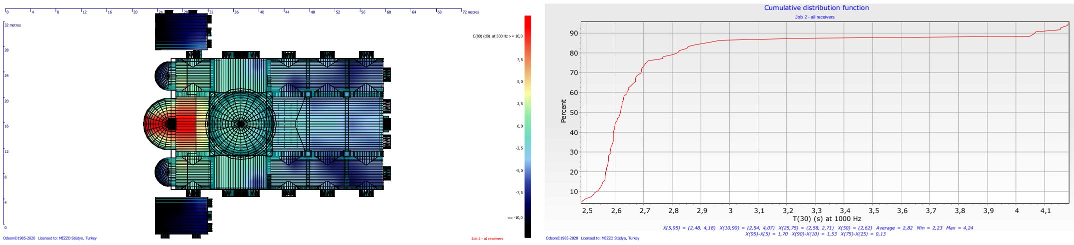

Figure D. 25 C_{80} distribution map (on the left) and cumulative graph (on the right), 500 Hz, Surp Yerrortutyun Church, Proposal II, unoccupied

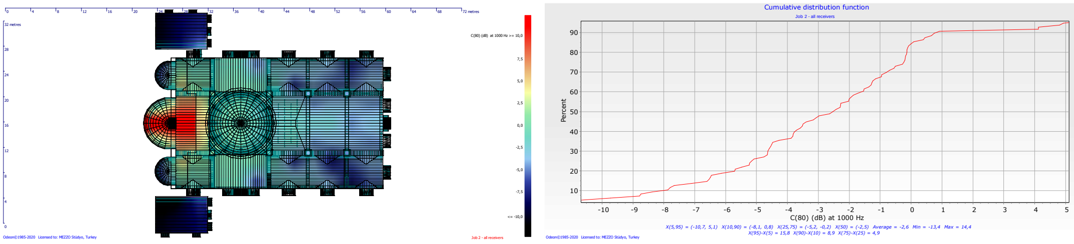

Figure D. 26 C_{80} distribution map (on the left) and cumulative graph (on the right), 1000 Hz, Surp Yerrortutyun Church, Proposal II, unoccupied

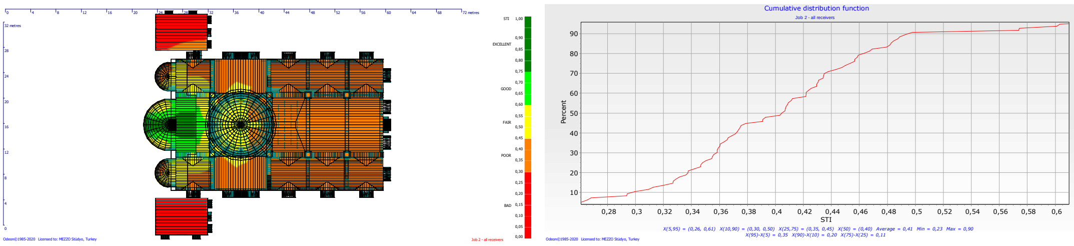

Figure D. 27 STI distribution map, Surp Yerrortutyun Church, Proposal II, unoccupied

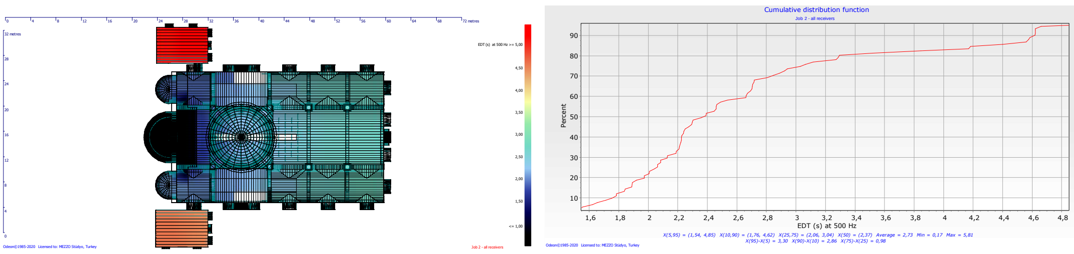

Figure D. 28 EDT distribution map (on the left) and cumulative graph (on the right), 500 Hz, Surp Yerrortutyun Church, Proposal III, unoccupied

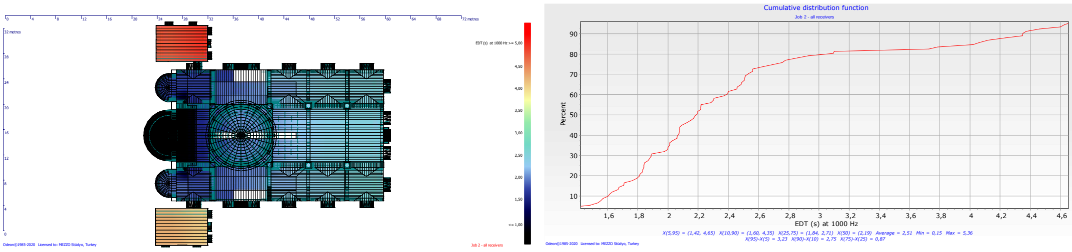

Figure D. 29 EDT distribution map (on the left) and cumulative graph (on the right), 1000 Hz, Surp Yerrortutyun Church, Proposal III, unoccupied

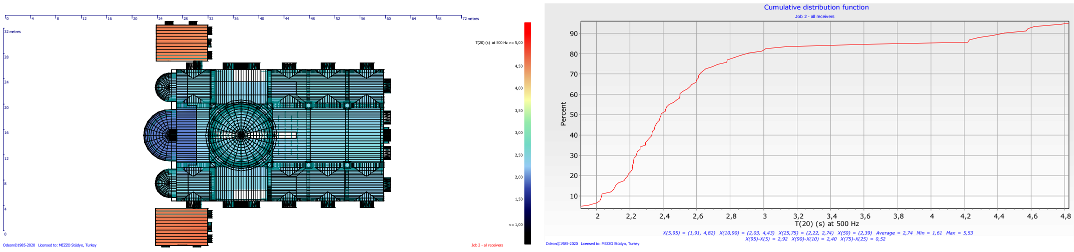

Figure D. 30 T_{20} distribution map (on the left) and cumulative graph (on the right), 500 Hz, Surp Yerrortutyun Church, Proposal III, unoccupied

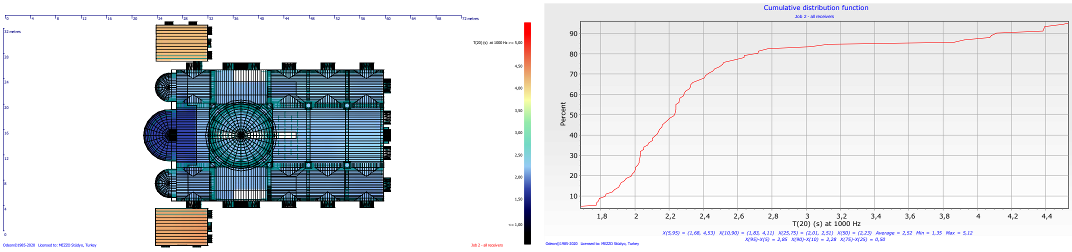

Figure D. 31 T_{20} distribution map (on the left) and cumulative graph (on the right), 1000 Hz, Surp Yerrortutyun Church, Proposal III, unoccupied

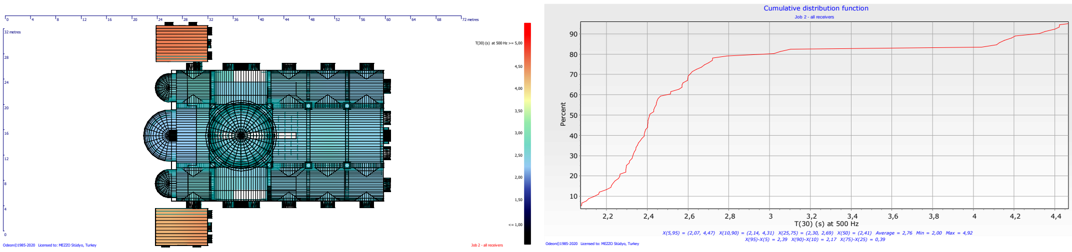

Figure D. 32 T_{30} distribution map (on the left) and cumulative graph (on the right), 500 Hz, Surp Yerrortutyun Church, Proposal III, unoccupied

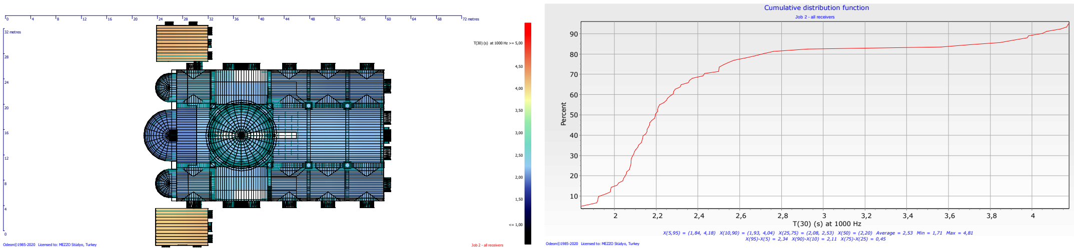

Figure D. 33 T_{30} distribution map (on the left) and cumulative graph (on the right), 1000 Hz, Surp Yerrortutyun Church, Proposal III, unoccupied

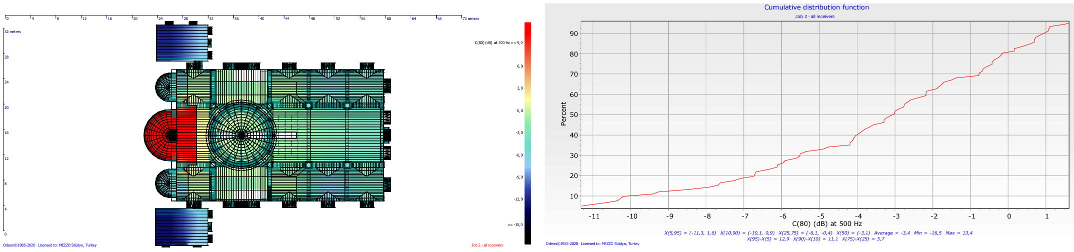

Figure D. 34 C_{80} distribution map (on the left) and cumulative graph (on the right), 500 Hz, Surp Yerrortutyun Church, Proposal III, unoccupied

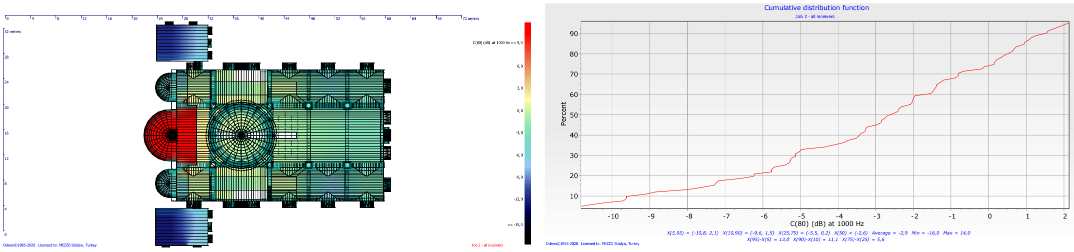

Figure D. 35 C_{80} distribution map (on the left) and cumulative graph (on the right), 1000 Hz, Surp Yerrortutyun Church, Proposal III, unoccupied

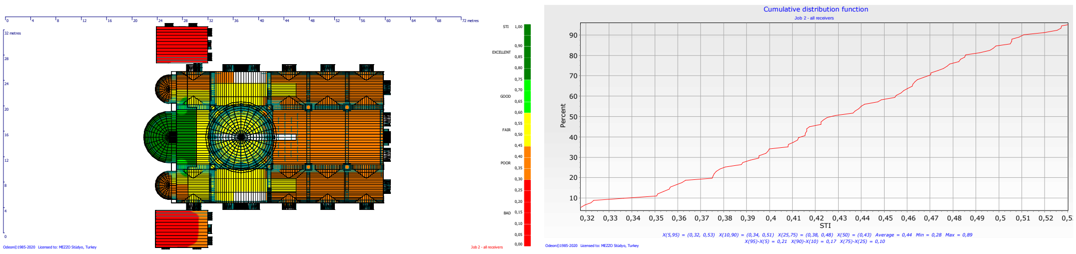

Figure D. 36 STI distribution map, Surp Yerrortutyun Church, Proposal III, unoccupied