VIRTUAL ACOUSTIC RECONSTRUCTION OF TWO ANCIENT SPACES: METROPOLIS ANCIENT THEATRE AND EFLATUN PINAR OPEN AIR WATER SANCTUARY

A Thesis Submitted to
the Graduate School of
İzmir Institute of Technology
in Partial Fulfilment of the Requirements for the Degree of

MASTER OF SCIENCE

in Architecture

by
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June 2022

İZMİR

ACKNOWLEDGMENTS

First and foremost, I would like to express my special thanks to my supervisor Prof. Dr. Mustafa Emre İlal for the guidance and patience throughout the development of this thesis. I also would like to thank to my co-advisor Assoc. Prof. Dr. Elif Ünlü for providing me with every information related to the Hittite culture and the opportunity to work on this special historical site.

I am particularly grateful to Univ. Prof. Dr. Ardeshir Mahdavi who is the Chair of Building Physics and Building Ecology at TU Wien, for his supervision on Metropolis Theatre during my exchange study. I would like to express my thanks to Prof. Dr. Serdar Aybek who is the head in the excavations of Metropolis Ancient Site, for providing me with the chance of doing a research on this historical theatre. I also would like to thank to Res. Asst. Burak Arslan who has provided me with the technical drawings and dimensions of the theatre which I needed them to build the 3D model. I would like to thank Res. Asst. Helene Teufl who has never left my questions unanswered throughout the development of my research on Metropolis Theatre during my exchange study. I would like to express my sincere thanks to audio engineer and musician Alper Türkkan, for his helping hand to reconstruct an old Hittite song for the incantation ritual used in the acoustic simulations.

I dedicate this thesis to my beloved parents Sevgi and Zafer Bolat for encouraging me throughout my education life and bringing me a broad vision to reach out my best during my entire life.

ABSTRACT

VIRTUAL ACOUSTIC RECONSTRUCTION OF TWO ANCIENT SPACES: METROPOLIS ANCIENT THEATRE AND EFLATUN PINAR OPEN AIR WATER SANCTUARY

Physical damage caused by various natural events or incorrect uses causes the original acoustics of historical places to be lost over time. In this context, protecting and maintaining the acoustic heritage of historical places which stand out with their acoustic characteristics becomes a crucial subject. Metropolis Ancient Theatre and Hittite Open Air Water Sanctuary are two historical places where acoustic character is at the forefront. In this study, acoustics of these two spaces in their original state is reconstructed. Firstly, original purpose of use for the Metropolis Ancient Theatre is investigated. In accordance with the original use scenario, a study is conducted in which passive interventions were explored for performances at the orchestra level and on stage in the present state of the theatre. This intervention provides a guidance on how the theatre can be best utilized for the future events suitable to its original use scenario, today. Secondly, acoustics of the Hittite Open Air Water Sanctuary is reconstructed through virtual acoustic simulations. In the Hittite culture, it is well-known that water plays a significant role in everyday life. Through an auralization study, the acoustic environment during religious ceremonies, celebrations and sacrificial rituals is explored. How the constant sounds of flowing water affects perception of musical instruments played around the sanctuary is investigated through the virtual reconstruction of the space. Both of the two case studies are chosen to explore their original acoustics using two different methods which include objective evaluation for Metropolis and subjective evaluation for Eflatun Pınar. Within the scope of virtual acoustic reconstruction studies, the validity of two different methods is aimed to be investigated under a single study. With virtual acoustic reconstructions, experiencing the acoustic memory of historical places becomes possible. With the similar studies in this field, acoustic memory is aimed to be preserved in accordance with its original purpose of use within the scope of acoustic heritage, in a very general sense.

Keywords: Virtual Acoustic Reconstruction; Auralization; Acoustic Heritage

ÖZET

İKİ TARİHİ MEKANIN SANAL ORTAMDA AKUSTİK CANLANDIRILMASI: METROPOLİS ANTİK TİYATROSU VE EFLATUN PINAR AÇIK HAVA SU ANITI

Tarihi mekanlar ve buraların korunması konusu genellikle görsel açıdan değerlendirilen bir konu olmakla birlikte günümüzde soyut değerler kategorisinde tanımlanmış akustik miras başlığı altında da dikkat çekmeye başlamıştır. Çeşitli doğa olayları veya beklenmedik kazaların tarihi mekanlara verdiği fiziksel zararlar buraların akustik ortamının zarar görmesine ve dolayısıyla akustik hafızanın da zaman içinde yok olmasına neden olmaktadır. Bu kapsamda, akustik özelliğiyle ön planda olan tarihi mekanların akustik mirasının korunması ve sürdürülmesi önem kazanmıştır. Metropolis Antik Tiyatrosu ve Hitit Açık Hava Su Anıtı akustik mirasıyla öne çıkan önemli tarihi mekanlardır. Günümüzde sanal ortamlarda elde edilmiş simülasyonlar sayesinde mekanların akustiği canlandırılabilmektedir. Bu çalışmada bahsi geçen iki tarihi açık hava mekanının akustik ortamı sanal ortamda simüle edilerek mekanların özgün halindeki akustik koşulları araştırılmıştır. Veriler ışığında Metropolis Antik Tiyatrosu'nun müzik veya konuşma işlevleri için gösterdiği performansa dayalı olarak özgün kullanım amacı belirlenmiş ve mevcut durumdaki tiyatronun bu amaca akustik olarak ne kadar uygun olduğu değerlendirilmiştir. Mevcut durumdaki sahneye tiyatronun orijinal kullanımına uygun panel tasarımları önerilmiş ve etkinlikleri incelenmiştir. İkinci kısımda ise Hitit Açık Hava Su Anıtı'nın akustik ortamı sanal ortamda canlandırılmıştır. Antik çağda Hititlerin günlük yaşamında suyun önemli olduğu bilinmektedir. Anıtın çevresindeki akustik ortamın sanal olarak canlandırılması ile dini törenlerde, kutlamalarda ve tanrıya adanan kurban ritüelleri esnasında, su sesinin oynadığı rol araştırılmıştır. Akustik canlandırma çalışmalarının tarihi mekanların akustik hafızasının tespitinde kullanılması ile akustik hafızanın akustik miras kapsamında aslına uygun olarak sürdürülmesi amaçlanmaktadır.

Anahtar Kelimeler: Sanal Akustik Canlandırması; İşitselleştirme; Akustik Miras

~To my beloved parents, Sevgi and Zafer Bolat~

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LIST OF ABBREVIATIONS

C50	: Clarity for Speech
C80	: Clarity for Music
D50	: Definition
EDT	: Early Decay Time
GA	: Geometrical Acoustics
HRTFs	: Head-related Transfer Functions
R_{left}	: Receiver point at the left side
R_{mid}	: Receiver point in the middle
R_{right}	: Receiver point at the right side
RIRs	: Room Impulse Responses
RT	: Reverberation Time
SPL	: Speech Pressure Level
STI	: Speech Transmission Index
T30	: Reverberation Time calculated based on the time it takes for a 30 dB drop
VR	: Virtual Reality

CHAPTER 1

INTRODUCTION

1.1. Motivation

At the end of the 20th century the word "heritage" was defined in a very general sense; people started using the word to mean someone else's place like monument and cultural property. This frequent use became a reason for re-defining the meaning of heritage so the significance of the ‘Intangible Heritage’ was realized by the Convention for the Safeguarding of the Intangible Cultural Heritage (Vecco, 2010). Preservation of the historical heritage by considering the visual aspects is generally the most contemplated subject of conservation issues. However, the protection of the acoustic heritage should also be considered within the scope of cultural heritage. Because, as in concert halls, opera halls and religious buildings, there are buildings where acoustic features stand out as much as visual features (Karabiber, 2000). From this point of view, a curiosity aroused for the preservation of the sound field within the framework of heritage buildings and acoustic heritage began to be explored with an inclusive perspective.

Murphy et al. (2016) defines acoustic heritage as a subject of archaeoacoustics, which reveals the aspects that is expressed with mostly quantitative features of buildings, sites and landscapes and as an important part of our intangible cultural heritage. As archaeological heritage, amphitheatres are an advanced representation of social and cultural development related to Greek and Roman societies. Aside from previous usage functions which is sacred ceremonies, events take place at the political context, and performing arts, in its present condition, theatres indicate a specific geographic knowledge at the Mediterranean coasts and other countries having signs from Roman Empire (Bo et al., 2015). Ancient theatres are endangered in modern use due to the high density of touristic activities and sound reinforcement systems. Therefore, preservation of ancient theatres becomes an important issue in modern use. UNESCO and many of the international Charters are involved in several studies and developed rules and regulations for maintaining the heritage for the next generations (Bo et al., 2015). ERATO project also points out the inappropriate use of ancient theatres nowadays. They produced a report for preservation of the sites that need protection from adverse conditions most likely to occur during festivals (Rindel and Nielsen, 2006).

Auralization studies enable us to explore cultural heritage through virtual acoustic reconstructions. Vorländer (2008) states that "Auralization is the technique of creating audible sound files from numerical (simulated, measured, or synthesized) data." In a very basic sense it is an audio rendering similar to 3D rendering used in architectural representations. CAHRISMA 'The Conservation of Acoustical Heritage by the Revival and Identification of Sinan's Mosques' Acoustics' project was a major step in acoustical heritage studies (Karabiber, 2000). Jonathan et al. (2013) conducted a study in Hagia Sophia within the framework of the 'Icons of Sound' project. The main concern of the study was to represents sound characteristics of Hagia Sophia in a Big Concert Hall with a performance 'From Constantinople to California' presented by the famous American vocal chamber ensemble Cappella Romana (Jonathan et al., 2013). Since any musical performance were not allowed to play inside of the Hagia Sophia at that moment, auralization study allows us to experience different sounds as they were performed inside of the Hagia Sophia.

The historical acoustic conservation studies have a variety of research areas which involves enclosed buildings and open-air amphitheaters. In some cases, proposed a plan scheme that provides the necessary acoustic conditions for music concerts organized in a cathedral (Alonso et al., 2014), or some studies enabled us to experience the previous acoustic environment of the monumental building in Islamic era as in the example of Mosque of Cordoba (Suárez, Alonso, and Sendra, 2018). Aside from amphitheaters, many open air ancient sites and other heritage sites have been investigated as in the example of Stonehenge monument in Maryhill, USA (Fazenda and Drumm, 2013) or as in the underground heritage site called Ħal Saflieni Hypogeum in Malta (Debertolis, Coimbra and Eneix, 2015).

Today simulation techniques and virtual reality technologies become reliable tools in recreating the sound fields of historical buildings (Suárez, Alonso, and Sendra, 2018). After two decades of development virtual reality tools enable us to improve guidelines for the preservation of archaeological sites while continuing to use them in social activities (Bruno et al., 2010). Odeon and Catt Acoustics is some useful examples for these simulation tools. Ancient sites subjected to this thesis are open air spaces. Acoustic software is generally preferred for indoor simulations. Nevertheless, it is seen that many studies have been already carried out in open air ancient sites in the literature with these tools.

1.2. Aim and Scope

This thesis presents a study aimed at investigating acoustic heritage in two ancient sites through virtual reconstructions of their original states using two different methods. These two ancient sites are both located in Turkey. The first is the Metropolis Ancient Theatre in Torbalı, İzmir (Figure 1.1). The second is Eflatun Pınar Open Air Water Sanctuary in Konya (Figure 1.2). these two case studies together illustrate how state-of-the-art tools can help in both understanding the past and making decisions for the future.

For Metropolis, first the original acoustics of the theatre is explored through measurements, virtual models and simulations. Then, for future use scenarios of the existing theatre; acoustic performance of three alternatives for reflective panels to be placed behind the stage and orchestra are evaluated.

For Eflatun Pınar Open Air Water Sanctuary, a virtual model is constructed that allows experts to explore, through auralizations, how various scenarios for religious ceremonies accompanied by water sounds would have been experienced. The goal is to understand the original acoustics of the sanctuary.

Figure 1.1. Metropolis Ancient Theatre.

(Source: Arslan, June 2021)

Figure 1.2. Eflatun Pınar Open Air Water Sanctuary.

(Source: Hittite Monuments, accessed: May 2022)

1.3. Research Questions

This study on virtual acoustic reconstructions of two cultural heritage sites mainly focuses on exploring the following research questions:

1. How was the acoustics in the original Metropolis Ancient Theatre? Was it more for speech based events or musical performances?
2. How is the acoustic character of the Metropolis Ancient Theatre in its current state different than its original state?
3. Is it possible to improve the acoustics of the current state of the Metropolis Ancient Theatre with the interventions proposed to the stage? Is this in accordance with the original use scenarios?
4. Is it possible to preserve original acoustics of the heritage sites using the available computer simulation techniques?
5. Is it possible to recreate the original acoustic environment at Eflatun Pınar Water Sanctuary using virtual acoustic reconstruction?
6. How useful is auralization in reaching a better understanding of intangible cultural heritage?
7. How useful are available computer simulation tools in investigating original acoustics of heritage sites?

1.4. Methodology

Investigation of acoustics in the original states of the two ancient spaces within the scope of this study is based on computer simulations. The simulation models are prepared for virtual reconstructions of the original states and for existing states of both the Metropolis ancient theatre and the Eflatun Pınar water sanctuary. On-site measurements have been carried out and the acoustics of the existing states are determined. Measurements allow building a more accurate simulation model. Simulation results of the existing states are compared with actual measurements and the simulation models can be "calibrated" by adjusting material properties used in the models to improve the fit between simulation and measurement results. However, for Metropolis, the simulation results did not require any such adjustments. For Eflatun Pınar, since the space is completely open, reverberation times are already too low and again material properties are not adjusted. After these calibration considerations, using the same unadjusted materials available through the simulation tool database, acoustics of the original states are explored based on simulation results.

For the Metropolis ancient theater, using the simulation model of its existing state, the effect of planned improvements and stage designs are investigated comparatively. Three different shell designs are proposed to be placed on the stage and at the orchestra. For Eflatun Pınar water sanctuary, auralizations are created using on-site recordings of water sounds flowing into and out of the pool. These water sounds are convolved with an anechoic synthesis of music composed specifically for this study.

1.5. Contents

This thesis consists of six chapters. The first chapter, introduction, presents the motivation, goals and an overview of the methodology of the study.

In the second chapter, relevant acoustic evaluation criteria are defined and the basics of auralizations are described. The evaluation criteria consist of some acoustic parameters which is determined in accordance with the research methods used in the case studies that are the subject to this thesis. Some lecture notes are also included related to the principle of virtual acoustic reconstructions and auralizations.

In the third chapter, a detailed literature review is presented organized under three headings that are archaeoacoustics, ancient theatre acoustics and auralization studies.

In the fourth chapter, acoustics of Metropolis Ancient Theatre is evaluated. Firstly, a detailed description of the ancient amphitheater is given. Then, site measurements, 3D modelling and simulations for the present and reconstructed states of the ancient theatre are presented. The results are evaluated to reach out the original use scenarios.

In the fifth chapter, original acoustic field of Eflatun Pınar is recreated. A detailed description of the ancient site is provided. Then, the reconstructed acoustics of the ancient site is investigated through site measurements, 3D modelling, acoustic simulations and auralizations.

In the sixth chapter, the limitations of the study, the findings, and answers to the research questions are discussed, and conclusions are stated. Finally, opportunities for future research related to this study are offered.

CHAPTER 2

BACKGROUND

2.1. Acoustic Evaluation Criteria

There are acoustic parameters that makes the evaluation of acoustics possible for the speech and musical performances in a space. In this chapter performance indicators related to the use scenario of the ancient sites are described. These performance indicators are reverberation time (RT), sound pressure level (SPL), clarity for speech (C50), clarity for music (C80) and speech transmission index (STI). In the fourth chapter the theatre's acoustics are evaluated through these parameters.

2.1.1. Reverberation Time (RT)

In acoustics the significance of decay rate has been already recognized for years. However, Wallace Clement Sabine, who is a professor of physics at Harvard University, had been the first to describe it in numerical form. Sabine directly related the decay rate to the reverberation time and determined it as the time it takes for the sound to drop by 60 dB after the sound source is switched off (Figure 2.1). Sabine acquired a correlation between reverberation time and room parameters via an equation. Figure 2.2. demonstrates the recommended reverberation times at 500 Hz depend on different use scenarios (Mehta, Johnson, and Rocafort, 1999).

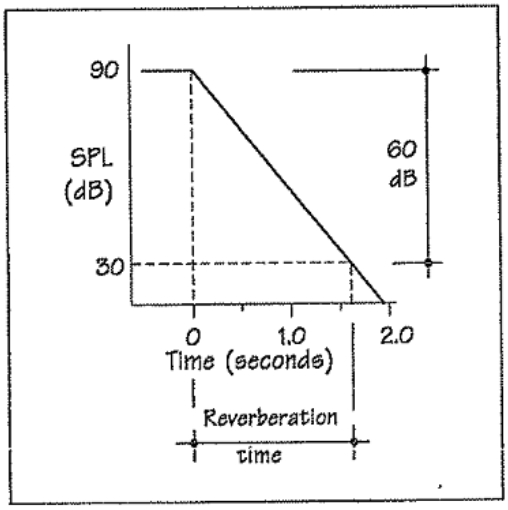


Figure 2.1. Description of Reverberation Time

(Source: Mehta, Johnson, and Rocafort, 1999).

$$RT = 0{,}16\ V / \sum A$$

where:

RT = reverberation time in seconds

V = room volume in m^3

$\sum A$ = room's total absorption in metric sabins

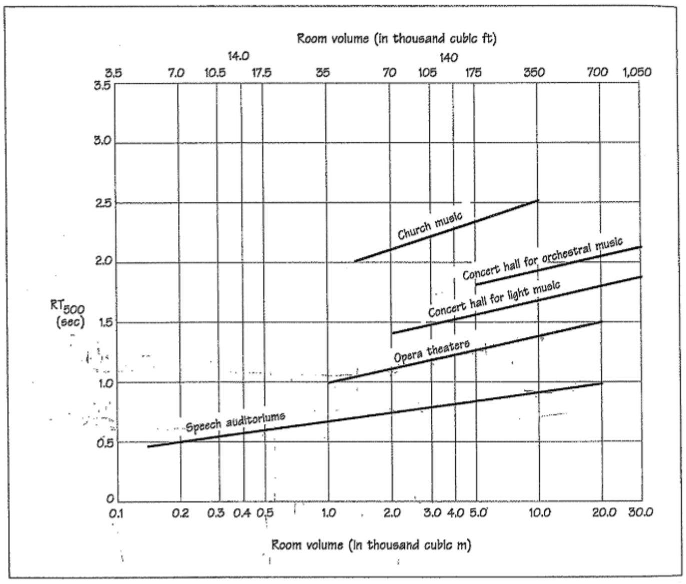


Figure 2.2. Recommended optimum reverberation times for diverse functions at 500 Hz.
(Source: Mehta, Johnson, and Rocafort, 1999).

2.1.2. Sound Pressure Level (SPL)

In architectural acoustics, sound pressure is the change in pressure due to a sound wave. Sound pressure level, in turn, is the sound pressure measured in decibels. Practically sound pressure level is measured by using sound level meters. SPL values are also used to indicate noise levels. All levels are expressed in decibels (Mehta, Johnson, and Rocafort, 1999).

2.1.3. Integration and Precedence Effect

Helmut Haas carried out a study to understand the working principle of the human ear in detecting the intensity and direction of sound from two sources. He placed two loudspeakers to each sides of the ear. Then he switched on the loudspeakers at different sound levels and at different timings. He found out that when the sound levels are the same and the sounds are played simultaneously, human ear perceives a single source positioned in the middle of the two speakers. According to this experiment, the sounds are perceived as a single source if there is no more than 10 dB difference and the lag is no more than 40 milliseconds (Figure 2.3). In this situation, ear integrates the sound signals and perceives it as coming from the source of the first arriving signal. This is called the integration and precedence effect or the Haas effect.

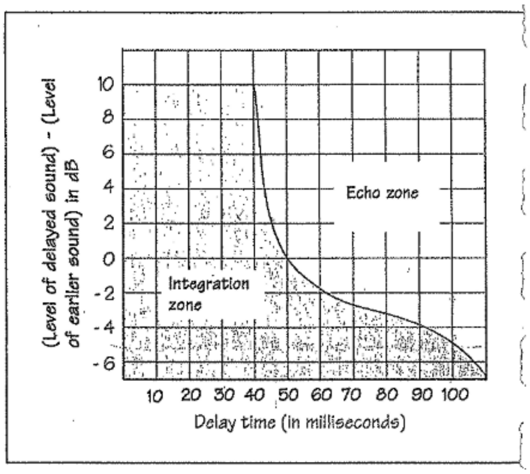


Figure 2.3. Integration and echo zones for the different sound levels at different time lags. (Source: Mehta, Johnson, and Rocafort, 1999)

2.1.4. Clarity for Speech (C50) and Clarity for Music (C80)

Clarity is defined as the ratio of early sound energy to the late (or reverberant) energy. Based on the Haas effect, for speech, early energy is the energy arriving at the receiver in the first 50 ms. For music this time frame extends to 80 ms. Clarity for speech (C50) and clarity for music (C80) are expressed as follows:

$$C50 = [\text{Energy}_{0\text{ to }50} - \text{Energy}_{50\text{ to }\infty}] \text{ (in dB)}$$

$$C80 = [\text{Energy}_{0\text{ to }80} - \text{Energy}_{80\text{ to }\infty}] \text{ (in dB)}$$

Reverberation time plays an inverse effect in the definition of clarity for music as can be seen in the equations. Concert halls were rated according to their C80 values (Figure 2.4). When reverberation time is long, the reverberant energy will increase and clarity will decrease. Recommended values for C80 for concert halls is between -4 dB and 1 dB (Beranek and Martin,1996)

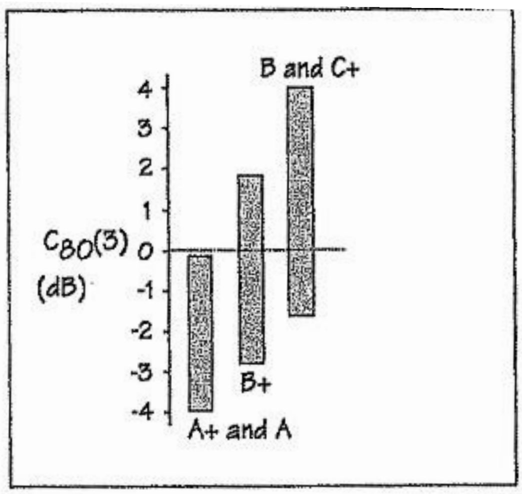


Figure 2.4. Clarity ratings for the music halls.

(Source: Mehta, Johnson, and Rocafort, 1999)

2.1.5. Speech Transmission Index (STI)

Speech transmission index is an objective calculation and evaluation method of speech intelligibility (Rindel, 2014). STI rates range from 0 to 1 where 1 represents an excellent intelligibility and 0 bad intelligibility (Figure 2.5).

Intelligibility rating	STI
Excellent	> 0,75
Good	0,60 to 0,75
Fair	0,45 to 0,60
Poor	0,30 to 0,45
Bad	< 0,30

Figure 2.5. Clarity ratings for the music halls.

(Source: Rindel, 2014)

2.1.6. Early Decay Time (EDT)

Early decay time is a reverberation time calculated by taking the time required for the sound energy to decrease by 10 dB and multiplying by 6. EDT refers to a time representing decays in early sound energy while RT consists of whole sound energy. This allows us to compare the very early reflections to the overall reverberation. In addition, while EDT is affected by changes in room geometry, RT is considered separately from the room geometry as many other factors such as material surfaces are involved in process. Human perception of reverberance is best estimated by EDT. (Mehta, Johnson, and Rocafort, 1999).

2.1.7. Definition (D50)

D50 indicates an energetic part of the sound which is necessary for a clearly understandable speech. This part is represented by 0,50ms so if the measured D50 is under this value it means the place shows suitable definition value for musical plays but if this value is measured above 0,50 then the place is more suitable for speech function so a comprehensible speech can be performed in this place (Manzetti, 2020).

2.2. Auralization

Recently, auralization techniques has progressed a lot in the field of simulation of virtual environments. Simulation methods are basically depending on the basis of Geometrical Acoustics (GA) so developments in Computer Graphics (CG) techniques have caused a speed-up in simulation techniques. As in the same logic used in CG, audio data has been degraded to the inconsistently distributed sound particles with a determined frequency and energy. However, frequency ranges consist of three classifications by size where small and large wavelengths cannot be predicted with the general confirmation techniques. Wave phenomena which is significant in terms of diffraction at low frequencies, scattering in high frequencies and specular reflections have to be taken into consideration so that a physically based sound environment can be achieved in virtual environment. This process clarifies why sound modeling and simulations in virtual environment is more challenging than visual modeling (Schröder, 2011).

While it is still difficult to define the sound environment virtually at indoor spaces, outdoor simulations with low-reflections can yield comparatively fast and precise results, particularly in real-time renderings. As the level of user's integration into the environment increases in indoor simulations, the acoustic environment becomes more complex even if the model is simple. All in all, this virtually created sound output is not aimed to be precisely accurate but it is perceptually reasonable meanwhile capability of computers and simulation precision is still tried to be improved (Schröder, 2011).

In 1929, a 1:10 scale model room has been created in Munich by Spandöck and colleagues in order to test speech and music plays at scaled frequencies. In that model room, they have played scaled frequencies, recorded them and tried to reconstruct the recorded voices in real frequency scales. This experiment was the first attempt for auralization analysis. Nowadays, advanced computer tools enable us to acquire the auralization outputs (Vorländer, 2008). The steps of auralization process consists of three main units which are sound generation, sound propagation and sound reproduction and then representation of this units by using corresponding tools within the system theory. The exemplified source signal should be recorded dry. This dry sound comprises only a single sound signal and no reverberant fields. In general, sound source is recorded at a determined distance and direction in an anechoic chamber. Moreover, the pattern of the source directivity is a factor must be considered. Finally, the complete auralization work consists of spatial data forms obtained from the source through the propagation route to the sound reproduction system. Consequently, the sound after propagation includes the features of the sound source and the transmitting system. Sound propagation brings the factor of reverberation to the source signal, whilst a listening happens by the transmission of sound via walls is qualified according to a low sound pressure level and a dull sound. Impulse responses in a system indicates the performance of sound transmissions in the scope of sound propagation physics. When the original dry sound convolved with the impulse response the resulting sound signal is obtained at the receiver point (Vorländer et al, 2015).

Spatial hearing is a significant factor in human perception and in acoustics it consists of two main head-related factors which are physical sound diffraction at the head and torso of the listener and sound transmitting occurred by wave incidents from multiple directions. In the frequency and time domains head-related transfer functions (HRTFs) represent convolution filters which also characterize this transmitting sound at the listeners' eardrums. HRTFs vary for different angles of sound incidence and they are particular for every person (Vorländer et al, 2015).

To better understand the basis of auralization some terms are clarified below which are room impulse response (RIR), binaural hearing, room and building acoustic simulations, and geometrical acoustics.

2.2.1. Room Impulse Responses (RIRs)

Considering the basis of sound propagation, a sound-transmitting system is qualified by the impulse responses obtained from the system (Vorländer et al., 2015). Impulse responses indicate distinctive qualification of each linear time invariant systems. A room is supposed to be a linear time invariant system and impulse response is measured through sending a Dirac Impulse to the system and receiving the reaction as a data. As a result, this data is expressed as a total time-shifted weighted impulse responses (Alpkocak and Sis, 2010). The dry sound and impulse responses are then convolved in order to obtain the sound signal received at the listener point. Psychoacoustics says the room impulse response (RIR) consists of three components which are the direct sound, the early reflections and the late reverberation. In line of these features, RIR stand for unique sound perception to each person (Vorländer et al., 2015).

2.2.2. Binaural Hearing

As in the architectural visualizations where 3D models apply more than 2D drawings among representation techniques, spatial hearing is a significant factor perceiving the sound. Spatial hearing in acoustics based on two main processes associated to head position which are the physical sound diffraction occurring at the head and torso of the listener and transmitted sound through wave events reaching the listener from various paths. There are convolution filters which is named as head-related transfer functions (HRTFs) in the frequency domain and head-related impulse responses in the time domain. HRTFs differs by the angles of sound incidents and it varies from person to person (Vorländer et al., 2015).

CHAPTER 3

LITERATURE REVIEW

Historical acoustic conservation studies have a variety of research areas which involve enclosed buildings, open-air amphitheaters and ancient spaces. In some cases, a plan scheme is proposed that provides the necessary acoustic conditions for music concerts organized in a cathedral (Alonso et al., 2014), some studies enabled us to experience the previous acoustic environment in monumental buildings as in the example of the Mosque of Cordoba (Suárez, Alonso, and Sendra, 2018). In this chapter, a broad literature review is presented below under the categories of archaeoacoustics, ancient theatre acoustics and auralization.

3.1. Archaeoacoustics

Archaeoacoustics is an evolved perspective on the analysis of ancient sites in terms of exploring the real intention of their designers. By doing this, it is aimed to reveal its natural connection with the specific place it was built and its visitor profile within the context. It is also a significant field of study in terms of showing us the psychological state of mind that corresponds to the activities of a person using that ancient site (Debertolis and Bisconti, 2013). Shedding light on the lifestyles of the people who lived in ancient times is one of the interest of archaeology. To reach out people's spiritual states, visual reconstructions remain inadequate in some cases. Considering the spiritual reflections of auditory stimuli and their undeniable impact during religious ceremonies, it becomes more important to revive the auditory environment in ancient times. Two research areas that are the subject of this thesis were built and used in ancient times. Considering that the Metropolis Theatre is a performance place and the Hittite Water Sanctuary is a place for religious worship or rituals, auditory environment has had a significant impact on daily life. It can be said that sound brings these places a unique character and thus is an integral part of them. From this point of view, studies in the archaeoacoustics at the literature extends to many open-air monuments such as in the case of the Stonehenge replica in Maryhill USA (Fazenda and Drumm, 2013) and Ħal Saflieni Hypogeum in Malta (Debertolis, Coimbra, and Eneix, 2015).

Stonehenge is the oldest and most complicated stone sequence ever recorded in human history. The semi-closed space by the huge stones causes an extraordinary reverberant sound field. The virtual recreation of the sound study was conducted based on the site measurements taken from a real size reproduction of the original monument in Maryhill, USA (Figure 3.1). A hybrid ambisonic and the wave field synthesis (WFS) technology were applied to realize the auralisation study. As a future work, researchers started study on more B-format rendering system which is manipulated by moving sources in a more certain way. The study was considered to involve finite difference time domain models to get clear results at the relevant topic (Fazenda and Drumm, 2013).

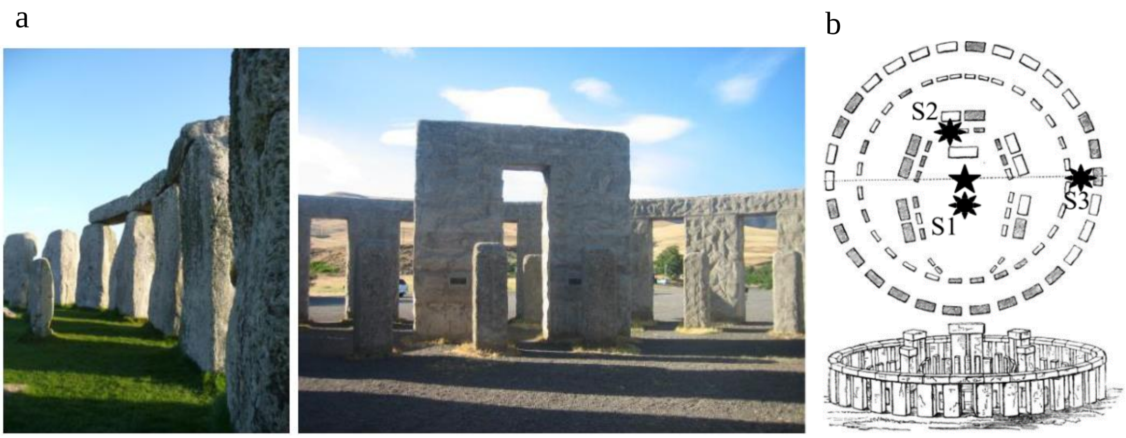


Figure 3.1. (a) Views from StoneHenge; the original at the left, the replica at the right. (b) Positions of the receiver and the sources. (Source: Fazenda and Drumm, 2013)

Ħal Saflieni Hypogeum in Malta (Figure 3.2a), which was carved into a rock as an underground complex around 4,000 B.C. or earlier, was studied to demonstrate how this monumental space resonate the sound specifically produced at 70Hz and 114Hz. These specific frequencies are playing a significant role on human brain during ritual chanting to raise mystic recognition. For this reason, some instruments from ancient ages which are the large Mediterranean marine shell (Charonia Lampas), a bull horn called qrajna and a drum named rabbaba (also known as a shamanic or Irish drum) have been recreated (Figure 3.2b). The researchers have pointed out that the specific ceiling scheme and vertical megalith at the front in ‘Oracle Room’ were not built haphazard. It was planned to serve the resonance, reflection and amplification of sounds at those frequencies known to cause a significant impact on the human brain in rituals (Debertolis, Coimbra, and Eneix, 2015).

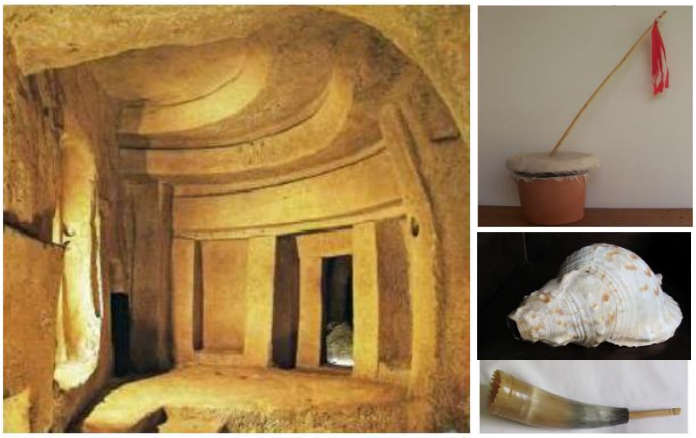


Figure 3.2. (a) A view from Ħal Saflieni Hypogeum; the central hall at the left side, the replica of some musical instruments which is rabbaba, charonia lampas, qrajna (starting from above respectively) at the right. (Source: Debertolis, Coimbra, and Eneix, 2015).

Since the amphitheaters are used during the performances and the acoustic properties is at the forefront, a majority of studies in the field of archaeoacoustics have been conducted on the acoustics of the ancient amphitheaters. Thus, many of the Roman and Greek theatres could be analyzed and their original use intention could be rediscovered through virtual modelling and acoustic simulations.

3.2. Ancient Theatre Acoustics

Open-air theatres and amphitheatres which remained from Roman and Greek ancient societies are significant proofs of social and cultural development of human life in urban scale. Religious ceremonies, theatre performances, and musical events have been the main focuses at these venues (Bo et al., 2015). Acoustic properties and use scenarios of some well-conserved theatres such as Python (Manzetti, 2020), Aspendos, Jerash, Syracuse (Rindel and Nielsen, 2006) and the proven documents from Benevento (Iannace and Trematerra, 2014) have been established in literature.

ERATO project was conducted between the years of 2003 and 2006. The project focused on Roman and Greek theatres which have been constructed for various kinds of acoustic purposes. It demonstrated which of the theatres have been built for which acoustic conditions. Case studies were selected from open air amphitheatres and enclosed theatres covered by a roof, the odea. Virtual 3D models of three theatres, Aspendos, Jerash and Syracuse; and two odea Aosta and Aphrodisias were developed in the study. Existing situations of the theatres have been taken into consideration as acoustic measurements were taken, so the preserved conditions were found valid for a site measurement in Aspendos and Jerash (Figure 3.3) theatres only (Rindel and Nielsen, 2006). The researchers analysed the theatre's acoustics, both in the Roman period and in its current state. They found that the open-air theatres showed good characteristics for the clarity parameter which is required for speech function whilst the odea showed more appropriate features for playing music and concert hall functions due to the suitable amount of T30 (reverberation time) values (Rindel and Nielsen, 2006).

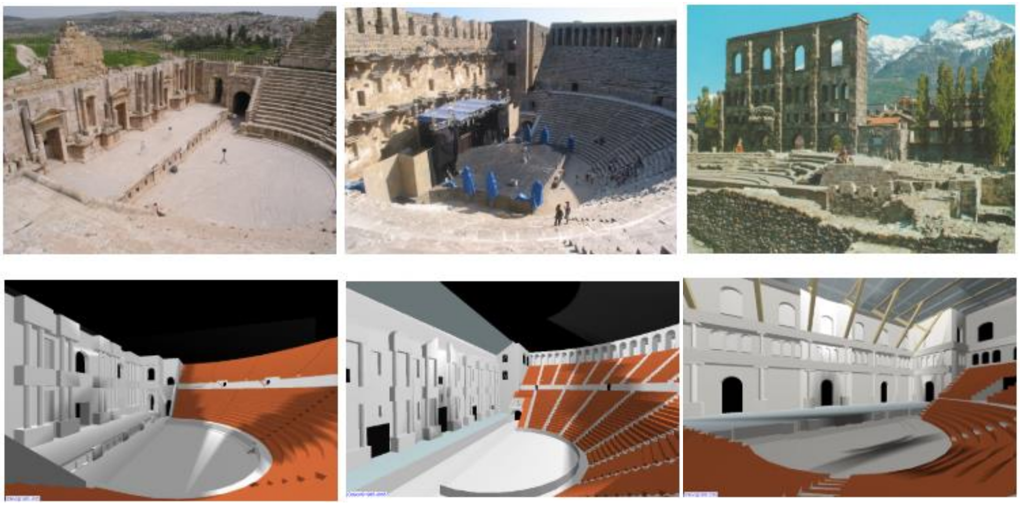


Figure 3.3. Photos showing current states and views representing the reconstructed states of the amphitheaters and odea. Left: Jerash, Middle: Aspendos amphitheaters, Right: Aosta odea. (Source: Rindel and Nielsen, 2006).

Benevento Roman Theatre (Figure 3.4) is a historical amphitheater that is used for various events such as national and international festivals for dancing, music, and drama performances. Researchers demonstrated the acoustics of the theatre during the Imperial period with a computer model using Odeon acoustic simulation software. The comparison was made between different positions of sound sources and receivers at different distances to the sources. The "good acoustics" of the Roman and Greek theatres has been attributed to the scheme of the seating sequence besides the use of reflective materials and absence of background noises (Iannace and Trematerra, 2014).

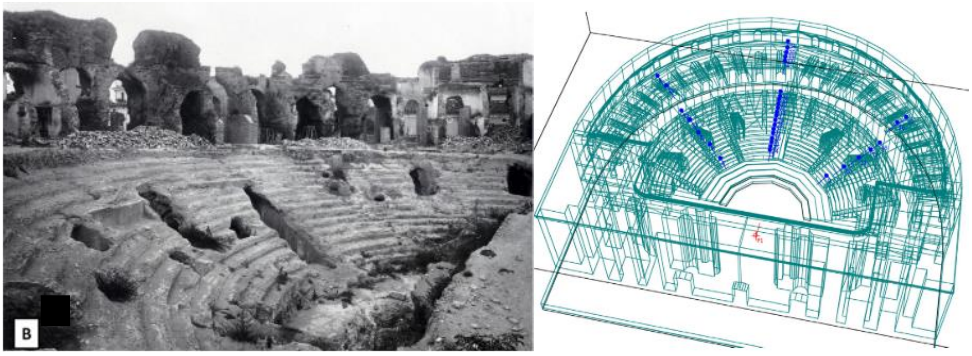


Figure 3.4. Photos showing current state of Benevento Roman Theatre and a view representing the reconstructed 3D model of the theatre. (Source: Iannace and Trematerra, 2014).

Another study was carried out by Manzetti (2020) in which the purpose of the study was to investigate the options for the suitable acoustic conditions of the Theatre of the Pythion among various performances and events held in the venue (Figure 3.5). The researcher aimed to determine the main function of the theatre through the calculated parameters which were RT, EDT, difference between RT and EDT, STI, C80 and D50. These acoustic parameters were calculated using Odeon room acoustic software. As a result, it was found that the theatre of Pythion was designed for the speech based functions like other researched Roman theatres as in Aspendos, Jerash, Ostia and Pompeii. Specifically, it was concluded based on the calculations of clarity, definition and speech transmission index. The findings supported the idea that Roman theatres were designed for speech based functions unlike Greek theatres that were mostly built for musical performances (Manzetti, 2020).

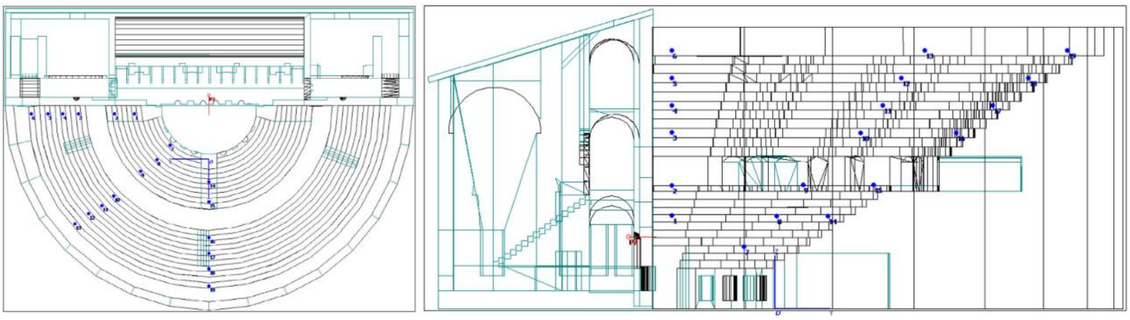


Figure 3.5. Plan and side views of the 3D model taken from Odeon. Theatre of the Pythion. (Source: Manzetti, 2020).

Bo et al. (2015) conducted a study to develop a sustainable and passive approach for present amphitheater acoustics instead of using active sound reinforcement systems during performances. The researchers have simulated the acoustics of the Syracuse

Ancient Theatre proposing five different orchestra shells which is positioned in two different source locations (Figure 3.6). Finally, they compared their performances to reach out the best composition depending on the music or speech functions.

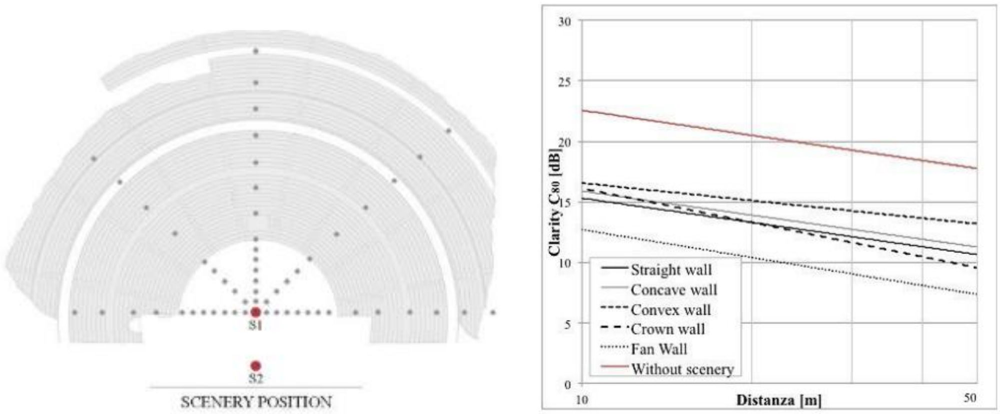


Figure 3.6. Plan layout indicating the source and receiver positions at the 3D model taken from Odeon at the right. Clarity for speech values relative to the increasing distance from the source for different shell designs. Syracuse Ancient Theatre. (Source: Bo et al., 2015).

A comprehensive review of research studies on acoustic evaluation of ancient theaters has been compiled by Giron, Álvarez-Corbacho and Zamarreño (2020).

Pompoli and Gugliermetti (2006) conducted a study called ATLAS which is a project that draws attention to the preservation of the acoustic and visual identity of ancient theatres.

Vassilantonopoulos and Mourjopoulos (2003) studied three ancient theaters (one of them is Epidaurus) with sources placed in two different locations in empty and fully occupied conditions. The theatres have been investigated with low and high ambient noises when they are with audience. The analysis examined the acoustic parameters of SPL, G, Ts, D50, C80, RASTI and JLFC.

Declercq and Dekeyser (2007) have explained the reasons for the good acoustics of Epidaurus as, wind transmitting the sound, rhythm of spoken words in the compositions of Hellenistic period, and the focusing of sound due to the masks worn by actors.

Izenour (1996) states that the remarkable acoustics of the Epidaurus theatre due to the clear way the sound reaches from the source to the listener. However, diffraction on the seating sequence causes more significant effect rather than the clear path effect according to Declercq and Dekeyser (2007). The researchers have simulated the Greek

Theatre of Epidaurus by considering the multiple diffraction orders and found that the sound reaches the listener both from the front and back of the theatre called koilon by scattering effect. Declercq and Dekeyser (2007) have also studied whether the slope of the cavea has impact on the amplifications occurring in some frequency bands. They also found that the sound characteristics of the theatre do not change in summer and winter times.

Lokki et al. (2013) have studied the theatre of Epidaurus through the model of the lower koilon and analyzed using finite-difference time domain (FDTD) which allows the estimation of diffraction and interference. According to the simulations for the low frequencies up to 1kHz, the excellent acoustics of Epidaurus with high sound strength and high speech intelligibility, is the result of high signal-to-noise ratio. Epidaurus is located where the background noise is low so signal-to-noise ratio is high.

Another research has been carried out in Theatre of Syracuse, Sicily. Gullo et al. (2008) present measurements taken from five different locations in the theatre. Bo et al. (2016) also studied the theatre of Tyndaris (Sicily) which calibration of the model was attributed to the evaluation of the objective parameters and to the temporal and energy components of the impulse responses. Bo et al. (2018) have carried out a study on the theatre of Syracuse (Sicily), presenting acoustic measurements and their simulation model estimations. IRs were taken with two different source locations and at different receiver positions, reverberation time (T20), clarity (C80) and sound strength (G) were obtained. The study was conducted using both Odeon and CATT-Acoustic software. Measured and simulated values of each acoustic parameter were investigated according to the Just Noticeable Differences (JNDs) (Bo et al., 2018).

Farnetani, Prodi and Pompoli (2008) has studied five Roman and Greek Theatres. According to the G results, it is found that the sound energy was included in the first part of the impulse responses which consists of direct sound and two remarkable reflections from the floor and the stage.

Within the scope of the Italian research program called PRIN 2005 (Resources for the acoustical and visual fruition, safeguard, and valorization of ancient theatres), Gugliermetti, Bisegna and Monaco (2008) has demonstrated the total acoustic determination of spatially distributed sound of the Roman theatre of ancient Ostia, both in original and current states. A temporary stage was set and carried out a survey on the on-site measurements applying standard specifications. It has also been investigated how the state of the theater is affected by the changing usage scenarios over time. It was found that the theatre performs better for speech based performances in its present condition while original state was more suitable for musical and drama performances.

Iannace and Berardi (2017) published a study investigating the reconstructed and current states of the Roman theatre of Posillipo in Naples while Sato, Sakai and Prodi (2002) investigated the Roman theatre at Taormina in Italy. The impact of the reconstructed stage has been studied and it was concluded that the reconstruction of the stage has impact on the magnitude of the inter-aural cross correlation coefficient (IACC).

'Valeria' is a term, used in early Imperial Age Roman open-air theatres, for a kind of canopy tensed over the cavea. Alfano et al. (2014) have published a study investigating the impact of valeria on the acoustics of two theatres which are Pompeii in southern Italy and the Roman theatre of Benevento. Impulse responses were obtained from on-site measurements using balloon pops. Applying for different surface density values for the used canopy, T30 and EDT were analyzed for the conditions of with and without canopy. The theatre of Pompeii showed the T30 and EDT values similar to the room having thin glass walls. As a result, it is found that the theatres' acoustics was not influenced significantly by usage of valeria considering its supposed structure and weight. However, they stated that with the use of mass-per unit surface material can work good for modern performances played in the theatre.

Iannace, Trematerra and Massimiliano (2013) have published a study representing the development of acoustic environment of the theatre of Pompeii throughout the Greek-Hellenistic and Roman periods and its current state. In the Roman period its stage and cavea has been enlarged but some parts were renovated after being under Vesuvius lava. So, the acoustic condition of the Pompeii was explored simulating the acoustic parameters of T30, EDT, C80 and D50). At the end of the analysis, the theatre was found unsuitable for musical plays due to its high C80 values and low reverberation time.

The preservation of historic buildings and their adaptation to modern use is an area of interest, particularly in southern Spain. An international forum held in Seville (Spain) which is called International Forum of Roman Theatres unify people from various disciplines (including historians, archeologists, architects and technicians, writers, designers, choreographers, producers and particularly public) who are interested in ancient Roman Theatres. Italica theatre (Santiponce, Seville) (Álvarez-Corbacho et al., 2014), theatre of Regina Turdulorum (Casas de Reina, Badajoz) (Álvarez-Corbacho et al., 2015) and the Roman theatre of Cadiz (Álvarez- Corbacho et al., 2018) have been analyzed through their reconstructed models in virtual environment. Álvarez-Corbacho et al., (2017) has also reconstructed the acoustic memory of Roman theatre of Palmyra, Syria. These researchers have contributed to a national project which aims to assess the acoustic characteristics of all Roman theatres over Spain. As a conclusion 198 theatres have been reported with the input of their specific geographical locations, the dimensions of their cavea and added the studies carried on these theatres.

For open-air theater research, questions remain regarding the appropriateness of standard acoustic parameters and methods such as ISO 3382-1 which is intended for indoor spaces. For example, Farnetani, Prodi and Pompoli (2008), has demonstrated that the analyses on EDT parameter are inadequate for the validation of acoustic field of open-air theatres because of the varying source and receiver positions.

3.3. Auralization Studies

Parallel to the development in computer technologies, auralization was evolved by Schroder (1962) in the early 1960s. Krokstad, Strom, and Sørsdal (1968) designed the first room acoustical simulation software in 1968. Auralization was first presented as a word in 1990s (Kleiner, Dalenbäck, and Svensson 1993). Since then, much progress has been made in recreation techniques and model algorithms in the binaural phase (Vorländer, 2008).

Today, many studies have been carried out in the field of auralization. One of them is on the acoustics of Hagia Sophia. Jonathan et al. (2013) conducted a study within the framework of the ‘Icons of Sound’ project to analyze the interior visual and acoustic characteristics of the Hagia Sophia through generating videos, balloon pops, modelling the place, literature research, auralisation and performance simulations. The main concern of the study was to recreate the sound characteristics of Hagia Sophia in a Big Concert Hall with a performance ‘From Constantinople to California’ presented by the famous American vocal chamber ensemble Cappella Romana. Since any musical performance were not allowed to play inside of the Hagia Sophia at that time, auralization study allowed us to experience different sounds at different places as they were performed inside of the Hagia Sophia.

Another study is the CAHRISMA (The Conservation of Acoustical Heritage by the Revival and Identification of Sinan’s Mosques’ Acoustics) project that was a major step in acoustical heritage studies. CAHRISMA was aimed to analyze and preserve the heritage of Sinan's Mosques and Byzantine Churches in terms of the visual and acoustic aspects by recreating them in a virtual environment. The project was conducted by researchers from Yildiz Technical University-YTU (Turkey), Technical University of Denmark-DTU (Denmark), Universita degli Studi di Ferrara-UNIFE (Italy), École Polytechnique Fédérale de Lausanne-EPFL (Switzerland), University of Geneva-UNIGE (Switzerland), AEDIFICE (France) and University of Malta-UOM (Malta). It involved both objective and subjective evaluations of the acoustic features in virtual environment. As one of the results in this study, the sound of Sinan's Mosques could be listened to in its original form recreated in a virtual crowd environment (Karabiber, 2000).

Real-time auralization has been also studied by many researchers. First and striking work was realized by Lauri Savioja (1999) in the TKK Helsinki University, Finland, which is named as Experimental Virtual Environment (EVE) which has a basis of an auralization engine called Digital Interactive Virtual Acoustics (DIVA). In the line with 'REVES', a project at INRIA, France, a conceptual audio rendering was presented by Nicolas Tsingos et al. (2004) for virtually complex spaces. Chandak et al. (2008) in the University of North Carolina, USA, has improved the scope of the simulations as developing an open source project called 'UNI-VERSE' and the scope of auralization by Noisternig et al. (2008). RAVEN has been developed at the RWTH Aachen University on the basis of Geometrical Acoustics (GA) principles (Schröder and Vorländer, 2011), as an open and a flexible real-time simulation content, working in coordination with the available network service called VISTA (Schröder, 2011). RAVEN enable the user to auralize the sound propagation in a space through processing significant waves like sound scattering, airborne sound insulation between rooms and sound diffraction. Besides simulating moving sources and moving receiver points, it allows taking a real-time audio rendering even the scene changes during the audio-visual representation (Schröder and Vorländer, 2011). Therefore, it offers an advanced real-time auralization simulation to the user. EVERTims is another project provided as an open-source room acoustic modeler which uses an 'image-source' technique for the real-time auralizations. It aims to bring the acousticians, researchers and sound designers a trustworthy, straightforward and flexible use experience (Poirier-Quinot, Katz and Noisternig, 2017).

Within the scope of archeology, creating an acoustically vivid reconstruction of archeological sites in a virtual environment has become possible by the latest advancements in computer technologies. The EVAA project (Experimental Virtual Archeological Acoustics) associates archeological sites, that have a sound based functions, with the studies in the field of acoustics within the scope of “historically informed performance” (HIP). Among many other studies on reproducing historical instruments and their sounds, EVAA deals with musical performances played in historical places by carrying real-time auralization studies. In this context, starting from the historically valuable places around Paris (including the Salle de concert du Conservatoire and the Château de Versailles) it revives the dynamic auditory atmosphere when the music of Baroque and Classical music was exhibited. Therefore, Katz, Le Conte and Stitt (2019), conducted a study investigating the simultaneous real-time auralisation of a live performance by musicians in a virtually reconstructed historical venues. Higher Order Ambisonics (HOA) were used to include the directivity data of the moving sources. EVAA initially studied on Hotteterre flutes from 17th. century and Delusse oboes from 18th.century since they were played in the music salon in Versailles at that times. A rendering engine was used to determine the effects of the music, played in acoustically different environments, on the performance. The source directivity and dynamic environment were the main concerns of the rendering.

In another research, a study about the real-time augmented auralization was carried out in the Virtual Reality (VR) environment, empowering the production of immersive auditory experiences with low CGI capabilities and a low-cost architecture. The study was carried out on the historical Théâtre de l’Athénée in Paris (Poirier-Quinot, Postma and Katz, 2016). The auralization process consists of convolution of High Order Ambisonic RIRs via Max/MSP, simulation of the calibrated model was made using CATT-Acoustics which is based on Geometrical Acoustics (GA) and render by using binaural headset or a set of ambisonic loudspeakers. The virtual avatars were created by using point clouds in the VR environment and were represented as a recorded RGB/Depth videos of the sound sources. The 3D model was rendered by using BlenderVR which is an open source service for VR. A sensor called Kinect 2 was used to generate the 3D-AV video to be able to perform the same playing in the environments having different acoustical characteristics with no construction or animation of CGI avatars required. The study encourages the researches related to this field so it was conducted within an open-source framework (Poirier-Quinot, Postma and Katz, 2016).

An investigation has been made in the Royal Chapel of the Gothic Cathedral of Seville about how it is experienced in VR environment by clarifying which of the variables affect immersion, like loudness and the type of sound piece (Álvarez-Morales et al., 2017). The study has a methodology consists of four main stages which are the present acoustical condition analyzed through measured RIRs, acoustical model and simulation to get valid RIR outputs, producing auralizations from both measurements and simulations and finally a physical model to assist the auralization. WinMLS2004 tool was used to take measurements in RIR form. The 3D model was created using AutoCAD 2014 but the surface complexity was reduced using SketchUp. The model was acoustically analyzed utilizing the CATT-Acoustic v9.1a which uses the principles of geometrical acoustics. Then the simulation results were acquired by using the engine tool TUCT v1. Textures were assigned to the surfaces with the specific scattering coefficients depend on the material identity on its present condition. EDT, C80 and Ts were analyzed and demonstrated by point receivers depending on their frequency band. A rendering tool called World Wizard 5 VR software was used to take renders of VR environment consists of the visuals, track of users, and auralizations. The auralizations produced by using RIR were confirmed by doing subjective listening tests by conducting a survey with 27 participants in order to compare the measured and simulated RIR and its reliability and have an idea about the general impact. Perceived reverberation, clarity and feeling of envelopment were represented in graphs in three types of stimuli respectively: cello piece, male speech, and choral singing. The result demonstrated that reverberation time is perceived suitable for music and choral performances while it is high for speech intelligibility. The piece of sound was perceived clearly by the participants in each direction in parallel with the calculation results of the parameters C80, D50 and STI. In terms of future studies, it shows that a psychoacoustic research conducted with this method will yield useful and bring reliable results (Álvarez-Morales et al., 2017).

The Cordoba Aljama Mosque was reconstructed in a virtual environment with the auralizations of its different forms to represent various usage functions between the 8th and 10th centuries (Figure 3.7). This Mosque-Cathedral is known as a mosques of the West and the largest representation of the Muslim culture between the western countries. In 1984, it was proclaimed as Patrimony of Humanity by UNESCO (Suárez, Alonso, and Sendra, 2018). This hypostyle mosque has been enlarged many times for various reasons at different terms. This explains the sequence of columns by a large amount bringing a unique visual and acoustical impact at the space. Thus, four different models were made to represent the four modified typologies of the hypostyle mosque. The model calibration was done, using the on-site RIR measurements taken from its empty present condition, placing the source at the mihrab area with 8 receivers around. The analysis for the reconstructed condition was taken thinking the space occupied with the audiences. Two sources were located at the reconstructed models; one at the mihrab, the other in the minbar. CATT-Acoustic v9 software with the TUCT v1.0 h tool was utilized for the acoustic analysis. The acoustic parameters analyzed related to its use scenario are T30, EDT, D50 and STI. Background noise have been downloaded from the database at the CATT website. The periods from the founding mosque of Abd al-Rahman I, enlargement by Abd al-Rahman II, the expansion by Al-Hakam II and of Al-Mansur has been analyzed acoustically. The results have shown that the enlargement through a change in proportions at the floor layout causes a remarkable difference in the perceived sound. the mean values of the simulated T30, EDT and D50 values are greater in each unit than the whole interior space of the mosque. Therefore, it is clear that each unit's sound field acts as a single unit with homogenous sound field, contrary to the acoustic character seen in the whole area. It has been indicated that the increase in the volume decreases the intelligibility in speech. As a result, enlargements did not improve the acoustic conditions of the mosque, it caused a huge degradation in the acoustic conditions contrarily. The new expansions failed to provide the necessary acoustic environment that coincided with the Islamic usage scenario of the mosque, but gave the space a visual quality (Suárez, Alonso, and Sendra, 2018).

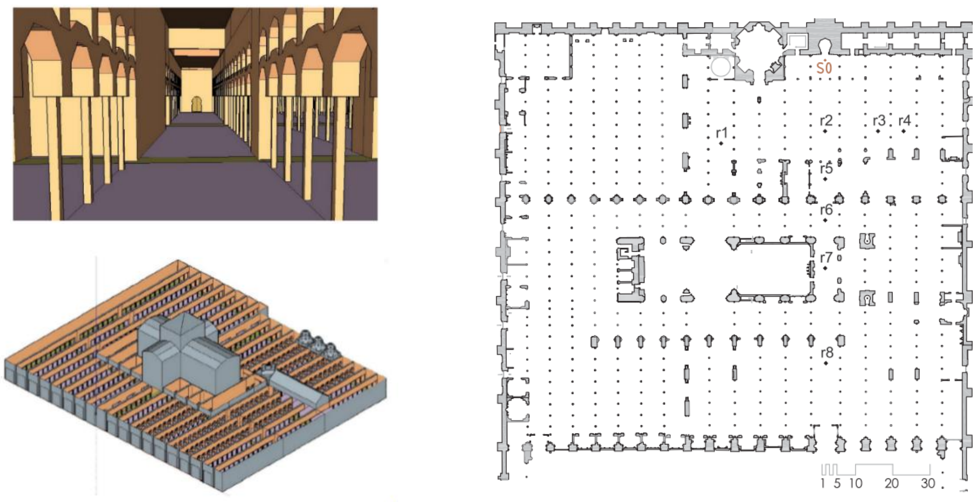


Figure 3.7. Interior and exterior views from the 3D model. A plan view indicates the source and receiver positions at the current state of the Mosque-Cathedral. (Source: Suárez, Alonso, and Sendra, 2018).

Vassilantonopoulos and Mourjopoulos (2001) have carried out a virtual acoustic reconstruction study on three historical Roman and Greek places which plays a significant role in public and sacred ceremonies. These places are the Acheron Necromancy (2nd.

Century B.C. as a necromancy; 8th. Century B.C. constructed for a specific purpose) (Figure 3.8a), the Olympia Echo Hall (4th Century B.C.) (Figure 3.8b), and the Temple of Zeus (450-457 B.C.) (Figure 3.8c). The places are investigated to show whether their functions are suitable with the acoustic characteristics of these places. Reverberation time (T30 and T15), Rapid Speech Transmission Index (RASTI (%)), Early Decay Time (EDT (s)), Speech Pressure Level (SPL (dB)), Definition (D50 (%)), Clarity for music (C80 (dB)) were the estimated acoustical parameters for each case studies. RIR was used as an input to auralization process. As a final output, wav files available for listening via headphones were generated through the binaural post-processing auralization analysis. In terms of the consistency in the relation between the function and acoustical characteristics; the necromancy has shown dry acoustics which means low reverberation time leading a good acoustics for speech function. Visitant of the necromancy were doing a special diet from the beginning of the ritual to be able to get into a special state of soul for the final day of the ceremony. The necromancy was acoustically good isolated so it is considered that its clearance in speech due to the low background noise. It is assumed that, even though people who were meditated, including dieting, spoke very quietly, their voices could be heard from anywhere (Vassilantonopoulos and Mourjopoulos, 2001). The Olympia Echo Hall is a semi-open space provided with 44 doric columns and having two main parts which serve for public activities, reunions and productive environment lead for educative activities while the second part serves for the training activities of the athletes. Echo Hall is assumed to be named so because the voice was echoed at least 7 times at the space. The impact of this feature on speech-based daily life has been investigated through acoustic simulations. According to this, a listener at a distance of up to 5 meters from the speaker can hear the speech clearly. This distance is supposed to get lower in reality due to the background noise. In the absence of background noise, it is estimated that approximately 300 people can hear a speech with a good intelligibility (Vassilantonopoulos and Mourjopoulos, 2001). The Temple of Zeus consists of two main areas: main temple and temple back. According to the analysis results, main temple performs high reverberant field with a high level of diffusion and lateral reflections derives from the doric columns and side walls. Its Definition value and EDT corresponding to the T30 values was found appropriate; however, C80 and STI were not high enough to meet the optimums. As a conclusion the main temple was found appropriate for chants and religious ceremonies. For the temple back, which offers a semi-open area, it was found that speech is clearly understandable even at the distance above

5 meters between the source and receiver. Finally, it has been proven that indoor spaces with high reverberation time increasing with volume are not designed in accordance with the speech function (Vassilantonopoulos and Mourjopoulos, 2001).

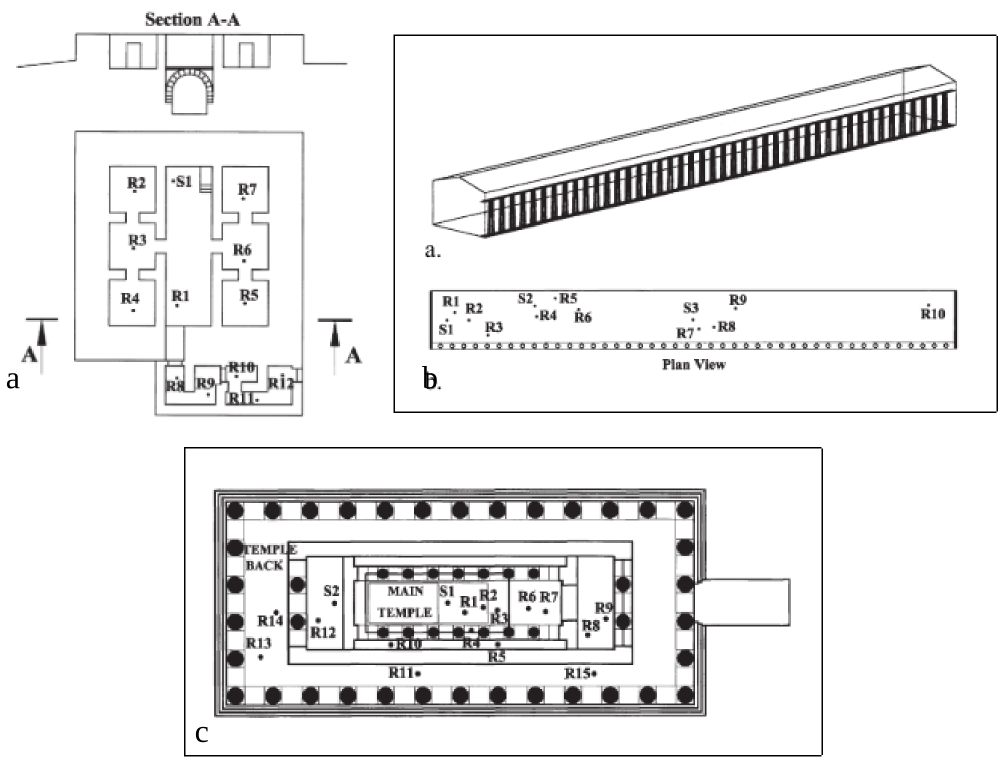


Figure 3.8. a: plan and section of the Acheron Necromancy. b: 3D and plan view of the Olympia Echo Hall. c: Plan view of Temple of Zeus. (Source: Suárez, Alonso, and Sendra, 2018).

The concept of real-time auralization is not a main concern of this thesis study. However, real-time auralization studies lead to a promising future for designing an audibly perceivable architecture through integration of sound to the architectural design process at the early stages of the design. Previous knowledge brings a vision about the future of the auralization studies in terms of creating the sensory-rich environments for architectural representations. Considering today's virtual reality technologies and its intersection with the audibly perceivable architecture, previous studies in this field intended to mention.

CHAPTER 4

METROPOLIS ANCIENT THEATRE

In this chapter measurement and analysis of the acoustics in Metropolis Ancient Theatre (AT) will be discussed. First, the site will be described in detail. Then, the on-site measurements are explained. Then, the simulation model for the existing state is presented and a comparison of simulation and measurements results is given. The simulation model for the original state and related simulations to investigate how far the original theatre was appropriate for speaking performances and/or for musical activities are discussed. Finally, three alternative reflecting panel designs to improve the acoustics in existing conditions are compared.

4.1. Metropolis – Detailed Description of Site

Ionia Metropolis (Figure 4.1) which means the city of Mother Goddess is an antique city located in Torbalı, İzmir (Turkey). The city started to grow in the Hellenistic period, 1st-2nd century BC. It further expanded down to its foothills during the period of the Roman Empire. In the Byzantine period the city was used as a centre of episcopacy. It was destroyed due to the wars and became smaller with the remaining parts which were the castle, the stoa and the acropolis. The ruins of the city were first recognized in 1675. The parts of the city which have reached the present are the Atrium, the Roman House, the Temple of Zeus, the amphitheatre, and the Temple of the twelve gods. All elements of the theatre were made of marble including the parts from the stage, orchestra, seating, and noble seats. In the Metropolis theatre (Figure 4.2) musical activities were played in the orchestra while theatres and speech based activities were performed on the stage.

Figure 4.1. Metropolis city plan.

(Source: Arslan and Aybek, 2022)

Figure 4.2. Metropolis Ancient Theatre top view.

(Source: Res.Assist. Burak Arslan, June,2021)

The theatre was first built during the late Hellenistic period. The stage was enlarged in the Roman period. The cavea is separated in two by a diazoma, and provides a volume for 8-10 thousand people (Izmir Provincial Directorate of Culture and Tourism, n.d.). As identified from the foundation walls, it is estimated that the stage consisted of three rooms in the Hellenistic period. These stage rooms are represented as 03, 04 and 05 in Figure 4.3 below. The stage building of the Metropolis Theater, which has survived to the present day, consists of five rooms. The original plan of the building contains elements of both Hellenic and Roman theater architecture. The most striking point in the new planning in the proskenion is the continuation of the high stage tradition in Hellenic theater architecture with a height of 2.66 m. In this respect, it would be appropriate to count the Metropolis Theater among the Greco-Roman or Anatolian Roman Type theatres (Arslan and Aybek, 2022).

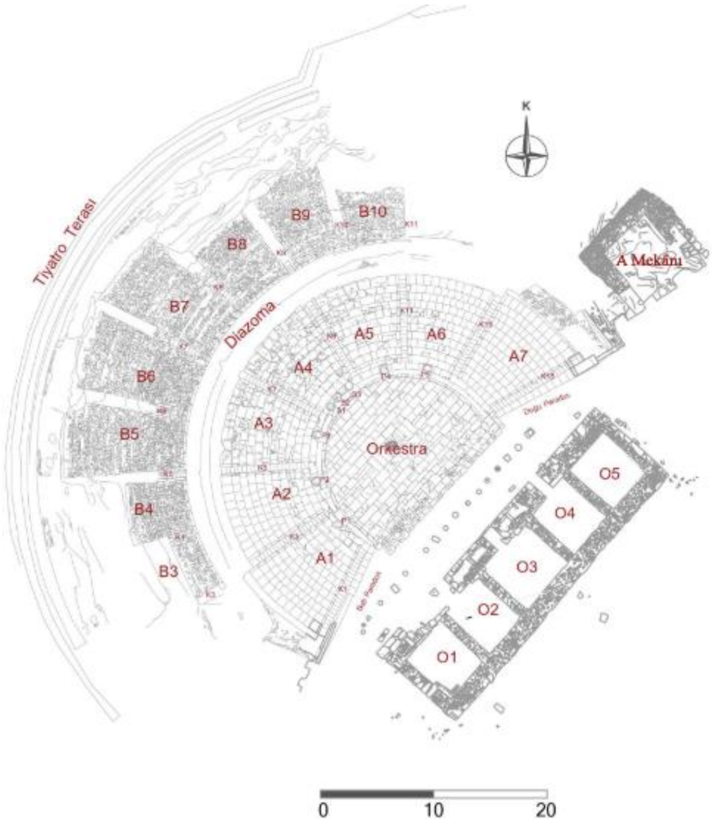


Figure 4.3. Present state of the Metropolis Ancient Theatre plan.

(Source: Arslan and Aybek, 2022)

4.2. Metropolis Theatre Acoustic Analysis

In this part Metropolis ancient theatre is investigated through the measurements taken from the site by modelling the theatre in the virtual environment and taking its simulation results.

4.2.1. Measurements

Measurements were conducted on 29 July 2021 in the theatre using a B+K 2260 Sound Analyzer, a B+K 4292 omnidirectional sound source and a B+K 2716 integrated amplifier. Reverberation time measurements were conducted according to ISO 3382.

RT were measured at the 8 points which are at the receiver points of 5, 7, 9, 11, 13, 15, 17 and 19 shown in Figure 4.10. The measured values for reverberation times are given in Table 4.1 and the average RT are given in Figure 4.8. RT measurements for low frequencies were not reliable at some of the points (R7: 125 and 250 Hz; R13: 125, 250Hz and 4 Hz; R17: 125 Hz; R19: 125 Hz). These points are marked with a '*' in Table 4.1. This is attributed to the high background noise levels at these frequencies during measurements. Measured SPL [dB] values are shown in Table 4.2.

Table 4.1. Measured Reverberation Times [s] at different frequencies.

Measured Reverberation Times [s] at different frequencies						
Receivers	**125 Hz**	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**4 kHz**
R1	0,43	0,63	0,9	0,71	0,55	0,58
R3	0,52	0,73	0,81	0,53	0,67	0,79
R5	0,48	0,57	0,58	0,63	0,52	0,56
R7	*	*	0,84	0,6	0,55	0,62
R9	0,74	0,49	0,63	0,47	0,48	0,54
R11	0,54	0,67	0,46	0,55	0,5	0,61
R13	*	*	0,61	0,7	0,58	*
R15	0,48	0,66	0,67	0,52	0,52	0,49
R17	*	0,51	0,58	0,51	0,45	0,54
R19	*	0,48	0,61	0,63	0,57	0,66

Table 4.2. Measured SPL [dB] at different frequencies.

Measured SPL [dB] at different frequencies							
Receivers	**125 Hz**	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**4 kHz**	**Distance (m)**
R15	-22	-24	-27	-26	-22	-22	8,2
R9	-29	-26	-27	-26,5	-22	-21	8,5
R5	-28	-24	-28	-26	-21	-21	9,3
R1	-21,5	-25,5	-29	-28	-20	-20	10,1
R17	-23	-30,5	-30,5	-28	-24	-25	12,8
R11	-29	-28	-30	-29,5	-24	-25	13,1
R7	-24	-35	-30	-29,5	-28	-26	13,9
R3	-29	-32	-32	-28,5	-24,5	-24	14,7
R19	-33	-34	-35	-36	-31	-31	19,9
R13	-33	-38	-32	-34,5	-31	-29	20,2

Measurements were taken while the theatre was empty. The background noise levels (Leq [dB]) during measurements are given in Figure 4.4 below. Table 4.3 also shows the same values for measured background noises. During measurements, there was significant cicada activity in the surrounding trees. Additionally, although the highway is about one kilometer away, there was noticeable low frequency vehicular noise.

Table 4.3. Measured background noise Leq [dB].

Measured Background Noise								
Frequencies [Hz]	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
Leq [dB]	56,7	48,5	37,4	36,7	36,1	36,4	48,8	40,5

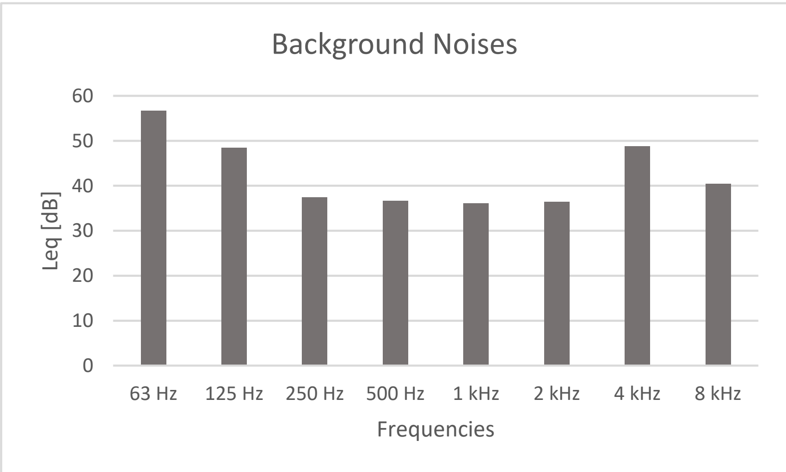


Figure 4.4. Measured background levels (Leq) during measurements.

4.2.2. Modeling

The 3D model of the Metropolis Theatre was created in SketchUp 2017 to represent the theatre's current state. Layers were defined for surfaces in the model to be able to assign required materials during acoustic analysis. The air-tight model was obtained by covering the theatre with an additional air layer at the top. After a careful examination of the model's reliability, using the Su2Odeon plugin, it was imported into Odeon v.14.0 (Figure 4.5) where materials were assigned to surfaces.

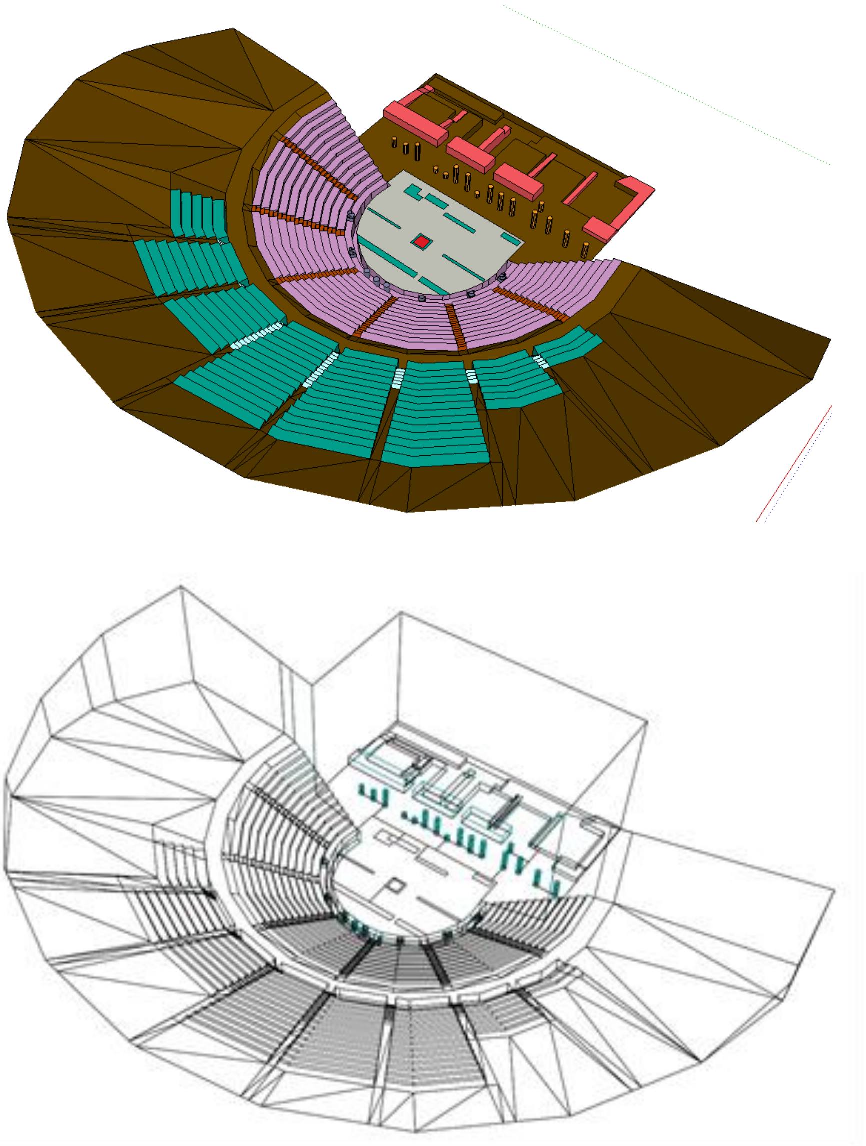


Figure 4.5. Metropolis Theatre's 3D model at the top, the model imported into Odeon at the bottom.

The reconstructed 3D model has been also created in SketchUp and imported into Odeon. The models are shown in Figure 4.6 below.

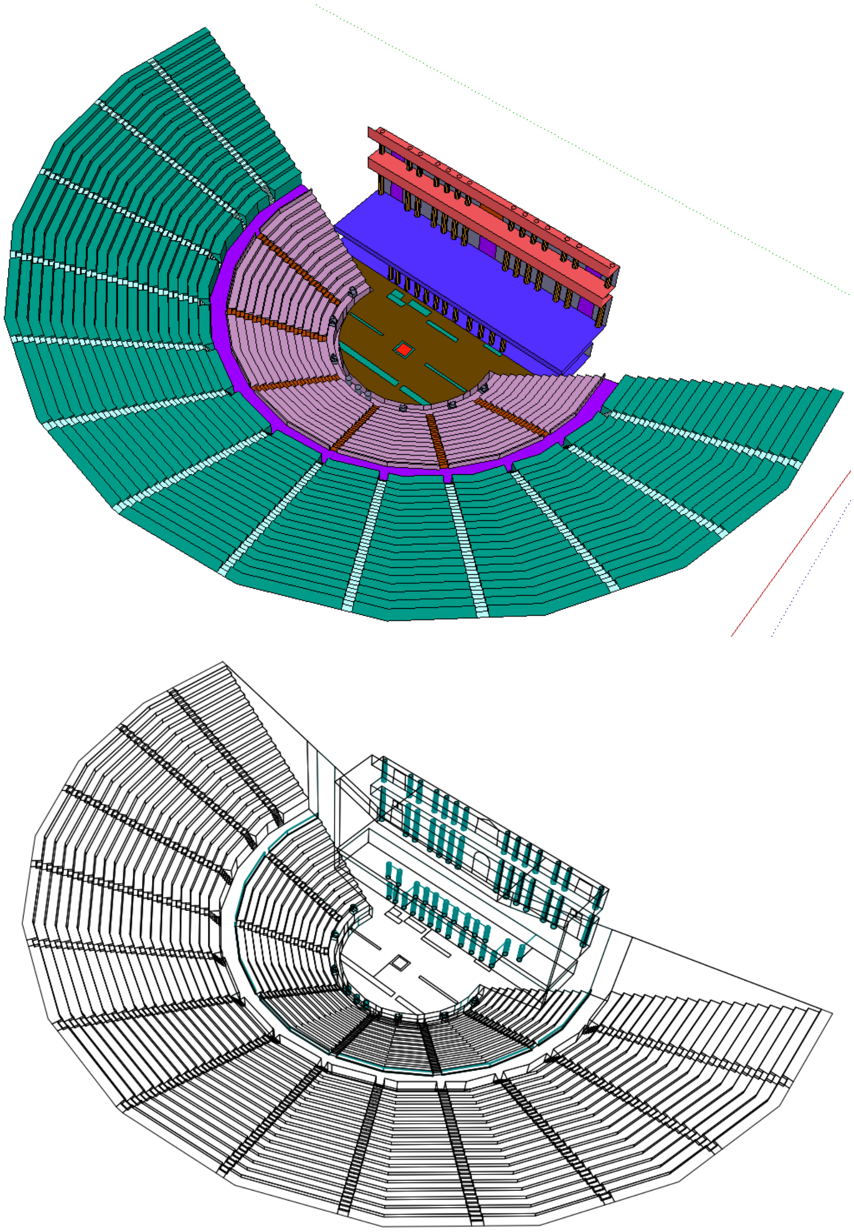


Figure 4.6. Metropolis Theatre’s 3D model at the top, the model imported into Odeon at the bottom.

The reconstructed scene of the theatre was modelled using estimated dimensions received from the excavation team at the site. Figure 4.7 shows the dimensions of the reconstructed scene.

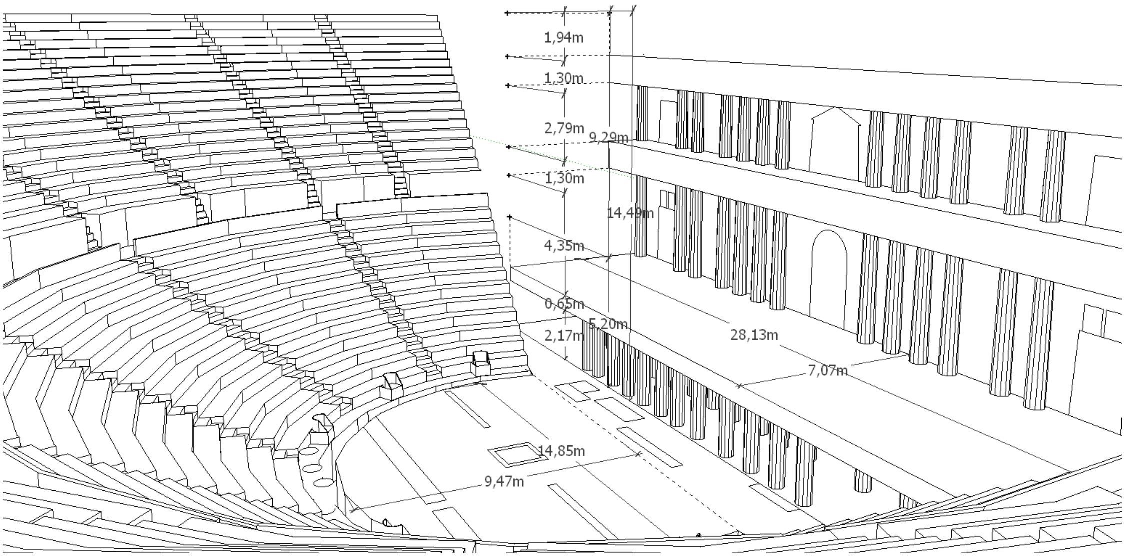


Figure 4.7. Dimensions of the reconstructed scene. 3D model of Metropolis Ancient Theatre.

4.2.3. Simulations

Simulations were carried out using Odeon Combined Version 14. The model was imported into Odeon using the Su2Odeon plugin in SketchUp.

Model check process was realized in Odeon by using 3D geometry debugger tool which detects the model errors caused by overlapping surfaces. Also, free run ray tracing process was done to check the model's airtightness.

Table 4.4 below shows the material variety in the model. New materials were created in Odeon library for the surfaces which are earth covered with grass (m. code: 14301 (Kim et al., 2011)) for the disappearing part of the cavea and the soil (m. code: 14302 (Kim et al., 2011)) for the ground material remained from the scene.

Table 4.4. The materials assigned to the surfaces in the present condition of the theatre.

<table>
<tr><th rowspan="2">Layer name</th><th rowspan="2">Material</th><th rowspan="2">Scattering Coef.</th><th colspan="6">Absorption Coefficients</th></tr>
<tr><th>125 Hz</th><th>250 Hz</th><th>500 Hz</th><th>1 kHz</th><th>2 kHz</th><th>4kHz</th></tr>
<tr><td>Air</td><td>100% absorbent</td><td>0.01</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>Audience area</td><td>Audience</td><td>0,01</td><td>0,16</td><td>0,24</td><td>0,56</td><td>0,69</td><td>0,81</td><td>0,78</td></tr>
<tr><td>Earth</td><td>Grass, marion grass (Kim, 2011)</td><td>0.01</td><td>0,11</td><td>0,26</td><td>0,6</td><td>0,69</td><td>0,92</td><td>0,99</td></tr>
<tr><td>Ground scene</td><td>Top soil 200T (Kim, 2011)</td><td>0.01</td><td>0,33</td><td>0,58</td><td>0,76</td><td>0,88</td><td>0,9</td><td>0,7</td></tr>
<tr><td>Breccia corellina</td><td rowspan="10">Marble/glazed tile (Harris,1991)</td><td rowspan="9">0.01</td><td rowspan="9">0,01</td><td rowspan="9">0,01</td><td rowspan="9">0,01</td><td rowspan="9">0,01</td><td rowspan="9">0,02</td><td rowspan="9">0,02</td></tr>
<tr><td>Ground theatre</td></tr>
<tr><td>Ground stone type 1</td></tr>
<tr><td>Imma cavea</td></tr>
<tr><td>Monumental seatings</td></tr>
<tr><td>Stage columns</td></tr>
<tr><td>Stair imma</td></tr>
<tr><td>Stair summa</td></tr>
<tr><td>Summa cavea</td></tr>
<tr><td>Stage walls</td><td>0.3</td><td>0,01</td><td>0,01</td><td>0,01</td><td>0,01</td><td>0,02</td><td>0,02</td></tr>
</table>

Simulation results were compared to measured actual RT values. The comparison of average RT is shown in Figure 4.8. Relative error across all measured points can be seen in Figure 4.9. It can be observed that simulation results remained within an acceptable range and it was decided that there was no need to adjust absorption coefficients of assigned materials. “Calibration” of the virtual model was not required. Reverberation time was analyzed using point response analyses in the computer simulation. It should also be noted that for this model a high number of rays (900000) was necessary for reliable simulation results.

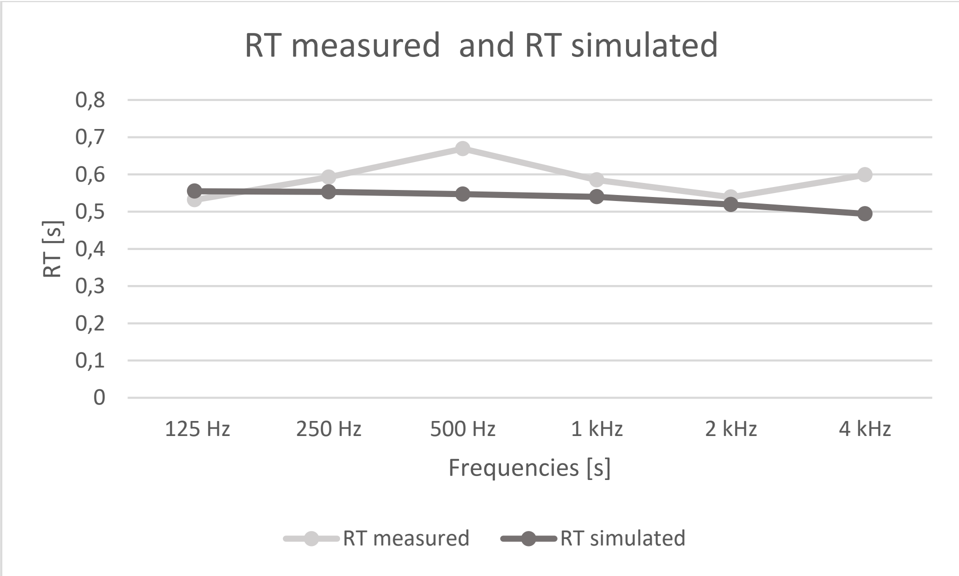


Figure 4.8. Measured and Simulated Reverberation Times [s]. Present Theatre.

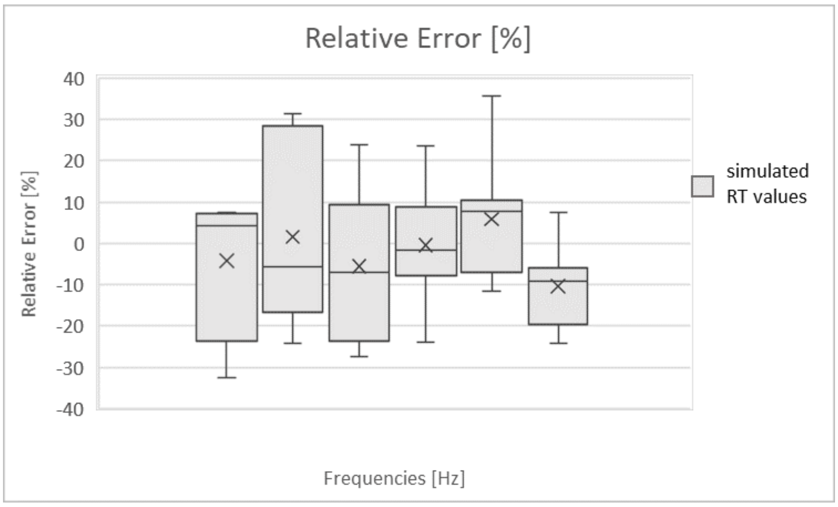
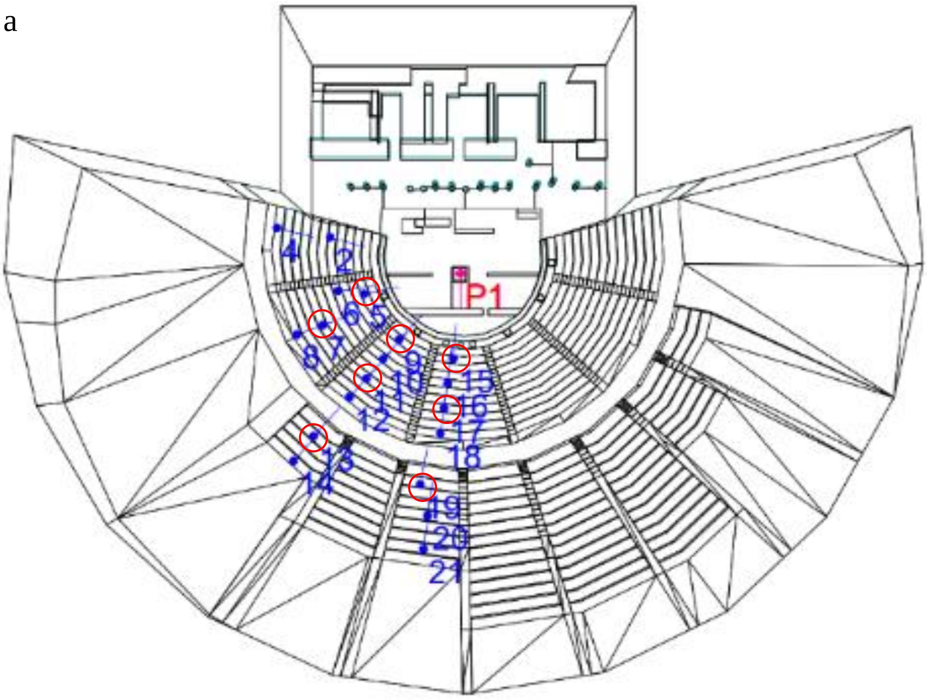


Figure 4.9. The graph represents relative error of all simulated receiver points for the different frequencies.

The type of the source used for simulations is omnidirectional sound source. In the reconstructed model 40 point receivers were placed at equal intervals of 10 receivers in separate directions. The symmetrical geometry was taken into consideration so the placement was on the single side and the results assumed to be similar for the other half of the theatre plan. In the layout of theatre in its current state analysis there are 19 receiver points due to the absence of some parts. Figure 4.10 below shows the placement of the source and the receivers in the present and reconstructed condition of the theatre. Analysis was conducted by using high number of late rays (900000) to increase precision. Calculated parameters to identify the acoustic characteristics of the theatre were reverberation time (T30(s)), sound distribution (SPL (dB)), clarity for speech (C50(dB)), clarity for music (C80(dB)), and speech transmission index (STI) for the theatres' empty and fully occupied conditions in all frequencies.

a



b

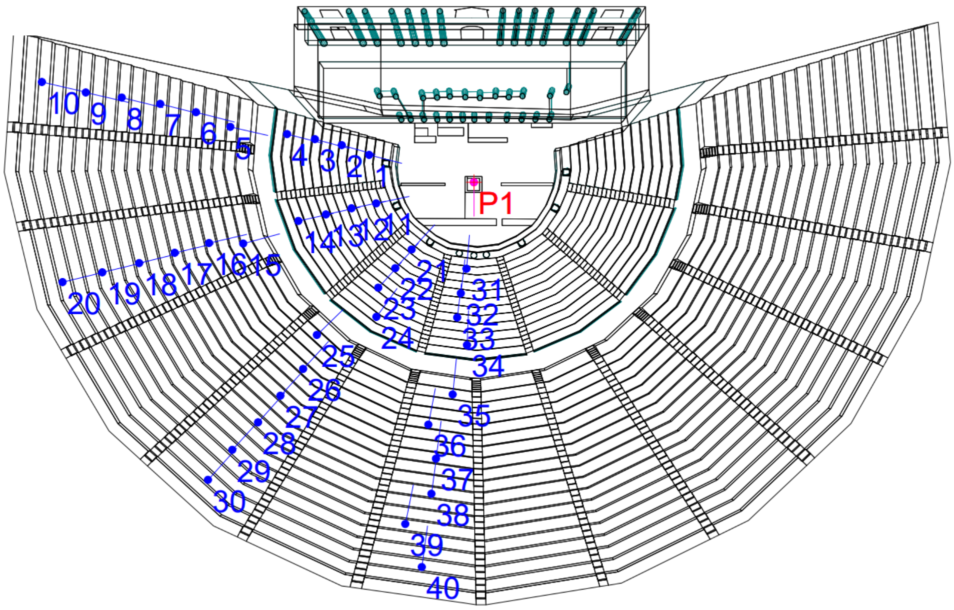


Figure 4.10. The placement of the source (red point on the orchestra) and the receivers (blue points) in the plan. a: theatre in the present condition, b: reconstructed theatre.

4.2.3.1. Simulations of Present Theatre

First, Metropolis Ancient Theater's acoustics in its present state is analyzed through simulations. This analysis is used for improving the accuracy of the models through comparisons with actual measurements. Also, it serves as a base case for evaluating improvement scenarios.

Figure 4.11 shows the simulated T30 values for three receiver points representing seats in the front, the middle and the back of the cavea under empty and fully occupied conditions along with the overall average. The selected points are R15, R17 and R19 (Figure 4.10a). At these points, the empty theatre performs average reverberation times in between 0,54-0,57 s while the fully occupied theatre performs reverberation time in the range between 0,41 and 0,54 s.

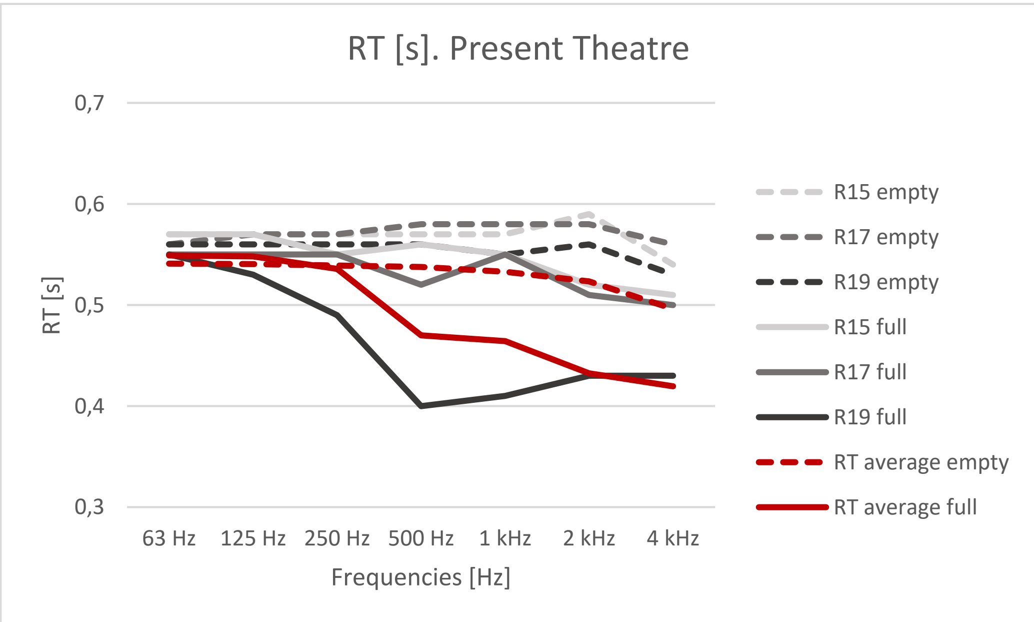


Figure 4.11. RT[s] of the selected receiver points for the empty and fully occupied condition in all frequencies. Present theatre.

In order to evaluate the distribution of T30 values across all receiver points in the space, the performance indicator values are plotted as box-and-whisker plots indicating the spread of the data. Figure 4.12 compares the spread of simulated T30 values for the empty and fully occupied theatre in its present condition. As expected the T30 values decrease significantly in higher frequencies.

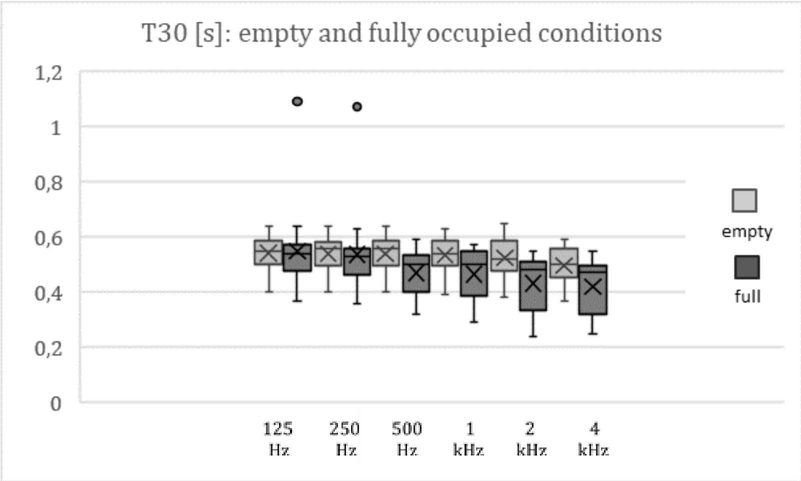


Figure 4.12. T30(s) for the empty and fully occupied condition in all frequencies. Present theatre.

SPL distribution throughout the cavea is also analyzed. SPL values for all receiver points are plotted against their distance from the source. In the empty theatre the front row SPL values vary between -29 and -23,6 dB, and the back row SPL values vary between -37,3 and -28,7 dB. Under fully occupied conditions, front row SPL values range between -30,6 and -23,9 dB, and back row SPL values are between -35,1 and -29 dB (Figure 4.130).

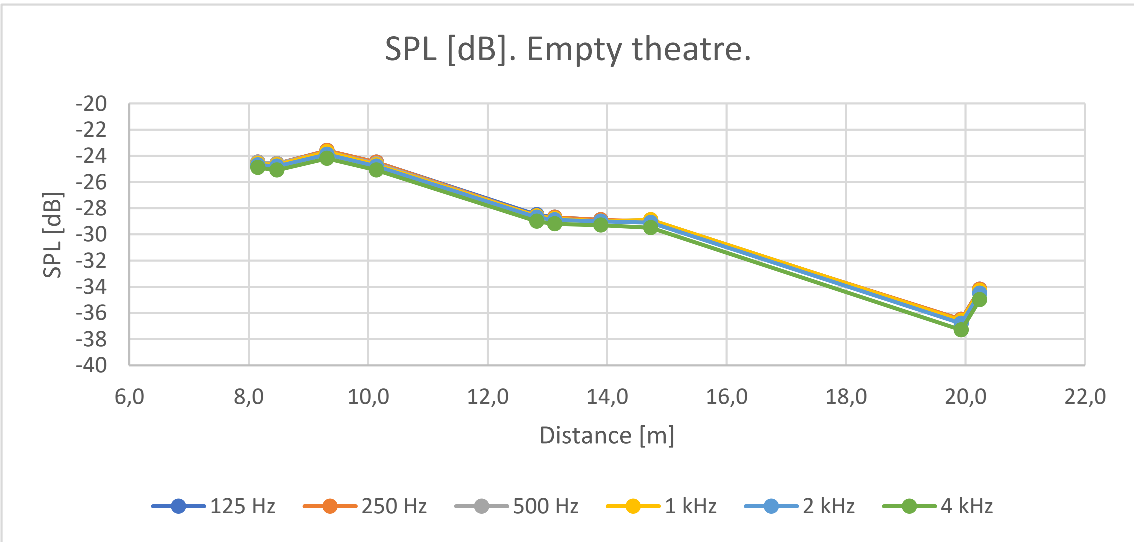


Figure 4.13. SPL [dB] for the empty and fully occupied condition in all frequencies. Present theatre.

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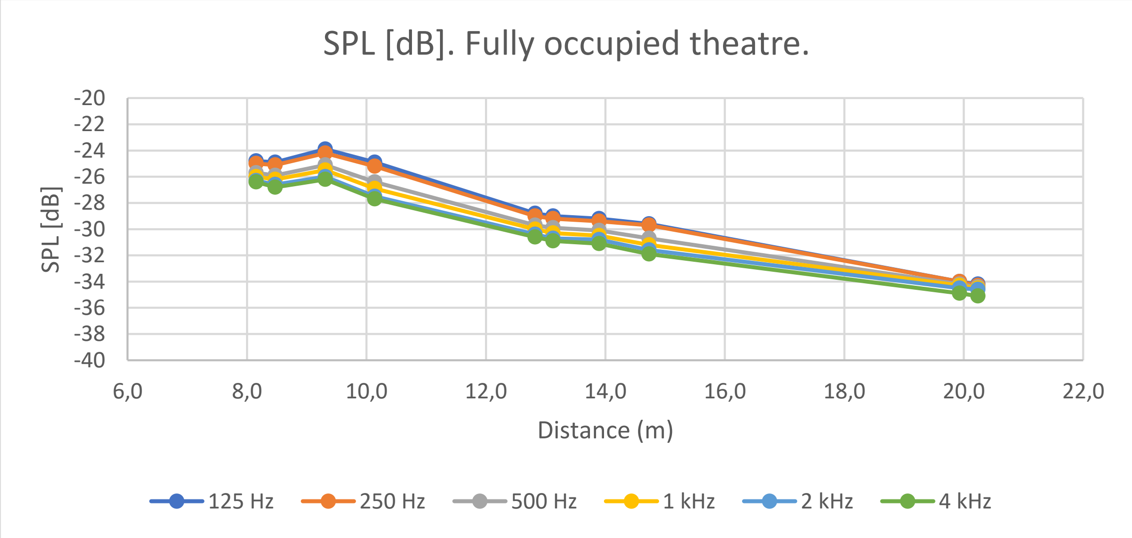


Figure 4.13. (cont.)

For STI analysis, the measured background noise levels are used although they were high. This resulted in low STI values. The STI values according to the increasing distance of the receiver points is given in Figure 4.14 below. The average STI value of the theatre is 0,34 which known as poor in terms of speech intelligibility.

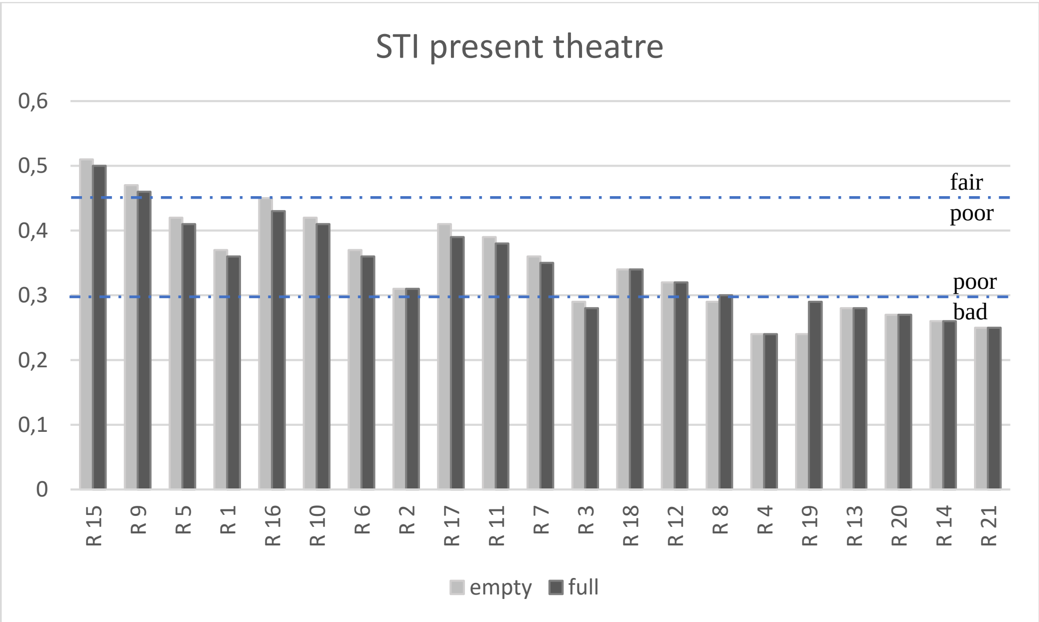


Figure 4.14. STI according to the increased distance of receivers. Empty and fully occupied conditions. Present theatre.

The existing state of the theater is also analyzed in terms of Clarity – both for speech and for music. Figure 4.15 and 4.16 show simulated C50 and C80 values respectively. The figures compare empty and fully occupied conditions. As expected clarity values are high. C50(3) is 12 dB for the empty and 19,6 for fully occupied conditions. C80(3) values are 15,2 dB and 23,4 dB for empty and fully occupied conditions, respectively.

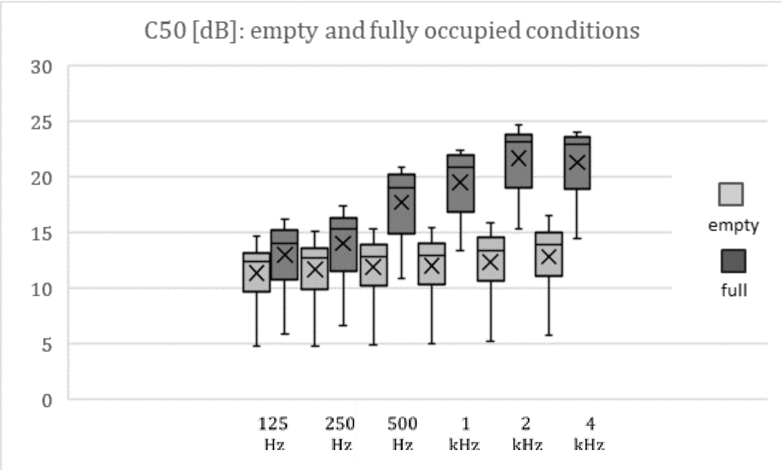


Figure 4.15. C50 [dB] for the empty and fully occupied condition in all frequencies. Present theatre.

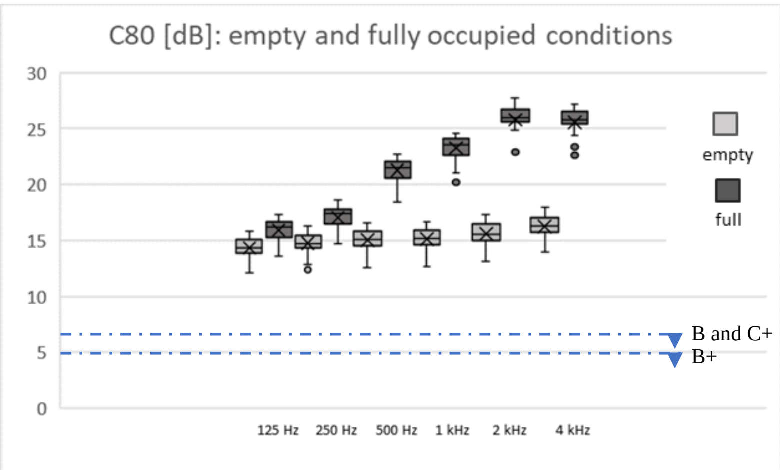


Figure 4.16. C80 [dB] for the empty and fully occupied condition in all frequencies. Present theatre.

4.2.3.2. Simulations of Reconstructed Theatre

After the existing state of the Metropolis Ancient Theater is analyzed, the same approach is repeated using the virtual reconstruction of the theater's original state. The goal is to reach a better understanding of how ancient theaters were used.

Figure 4.17 reports simulated T30 values of the reconstructed theatre for three receiver points representing the front, middle and back rows in the cavea under empty and fully occupied conditions. These selected receiver points R31, R33, and R35 – although numbered differently - refer to the exactly same locations used for the analysis of the current state of the theatre (R-15, 17, and 19) in the previous section.

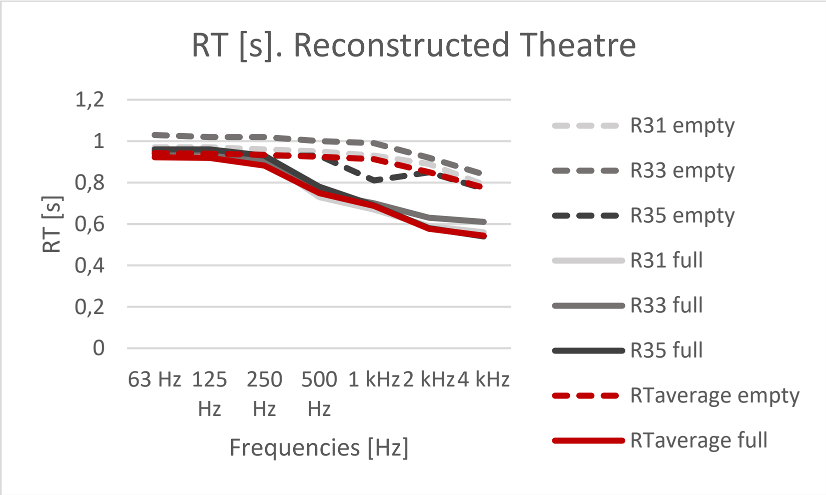


Figure 4.17. RT[s] of the selected receiver points for the empty and fully occupied condition in all frequencies. Reconstructed theatre.

In order to evaluate the distribution of values across all receiver points in the space, the performance indicator values are plotted as box-and-whisker plots indicating the spread of the data. Figure 4.18 shows simulated T30(s) values for the reconstructed theatre's empty and the fully occupied conditions in all frequencies.

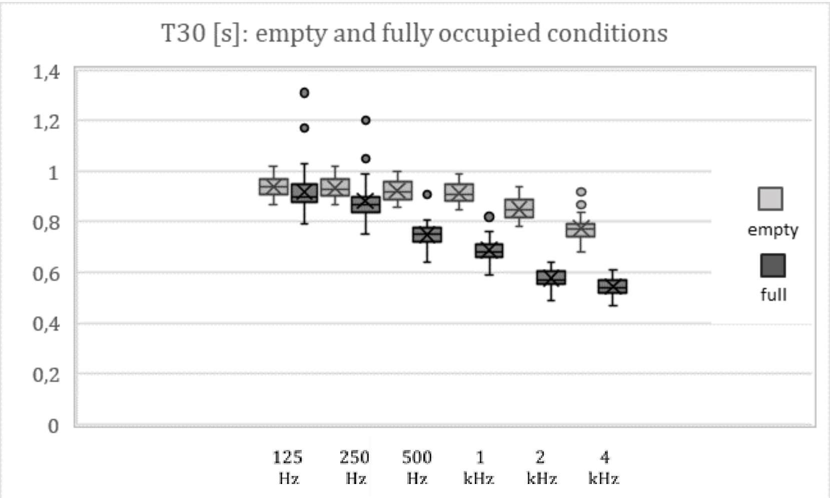
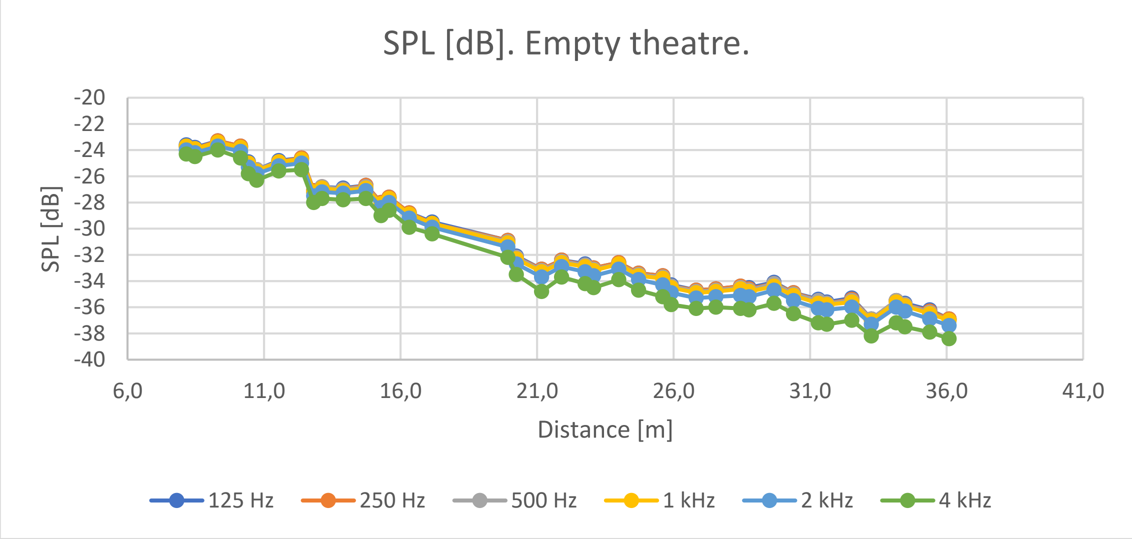


Figure 4.18. T30(s) for the empty and fully occupied condition in all frequencies. Reconstructed theatre.

SPL values for all receiver points are plotted against their distance from the source in the reconstructed state also (Figure 4.19). In the empty theatre the front row SPL values vary between -34,8 and -23,3 dB, and the back row SPL values vary between -38,4 and -32,6 dB. Under fully occupied conditions, front row SPL values range between -37,6 and -22,5 dB, and back row SPL values are between -40,3 and -32,9 dB.



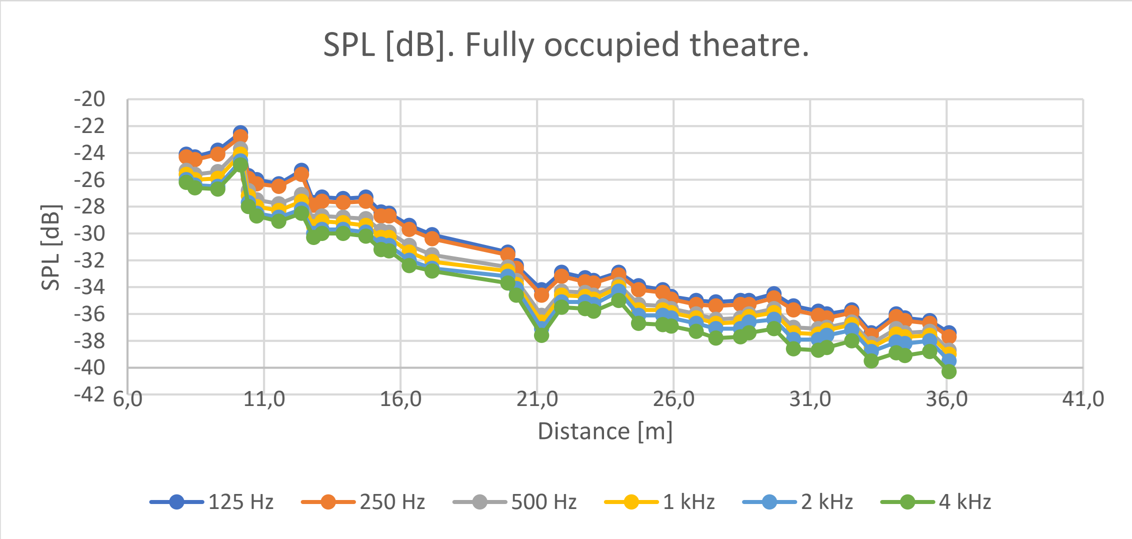


Figure 4.19. SPL [dB] for the empty and fully occupied condition in all frequencies. Reconstructed theatre.

For the virtual reconstruction model, measured background noise levels are used in STI analysis. The STI values according to the increasing distance of the receiver points is given in Figure 4.20 below. Regarding these results average STI value of the theatre is around 0.25 which is rated as “bad” in terms of speech intelligibility. While the average

STI in the front two rows is 0.38, average STI in the back two rows drops to 0.17 when the theatre is empty. In the fully occupied theatre the STI averages for two front and two back rows are 0.39 and 0.17, respectively.

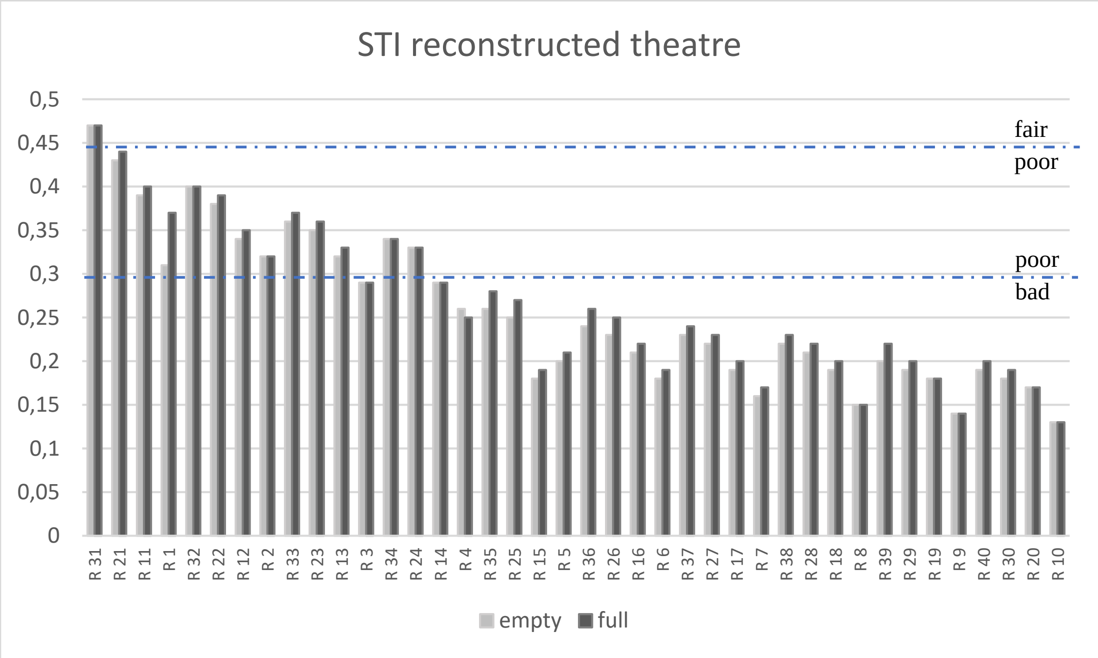


Figure 4.20. STI according to the increased distance of receivers. Empty and fully occupied conditions. Reconstructed theatre.

C50 and C80 values have been investigated in order to identify the most suitable function for Metropolis Ancient Theatre (Figure 4.21 and 4.22). As expected, the higher reverberation times in the virtual reconstruction of the theater decreases clarity values. While C50 values are acceptable for speech oriented use, C80 values are still high for music. C50(3) is 3,03 dB for the empty and 8,79 dB for fully occupied conditions. C80(3) values are 4,64 dB and 10,83 dB for empty and fully occupied conditions, respectively.

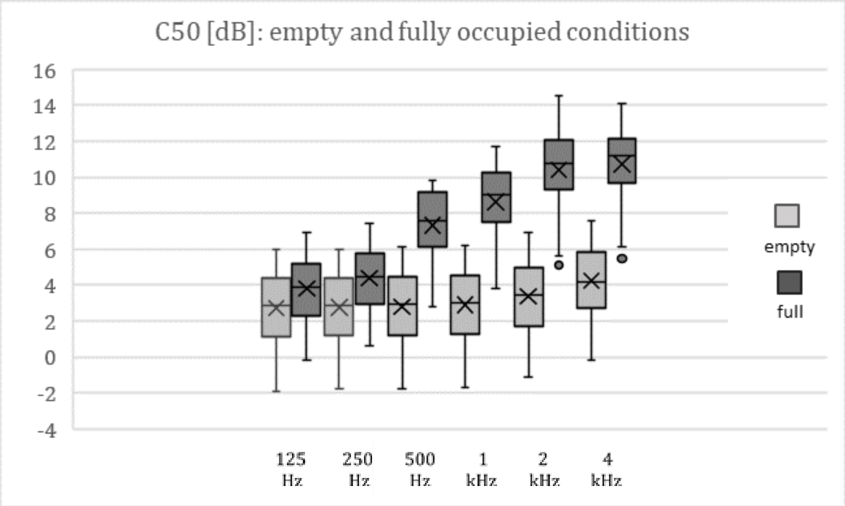


Figure 4.21. C50 [dB] for the empty and fully occupied condition in all frequencies. Reconstructed theatre.

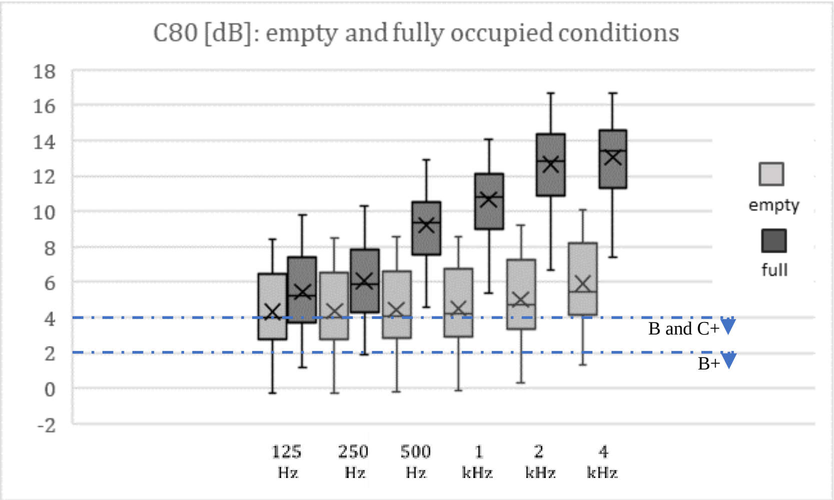


Figure 4.22. C80 [dB] for the empty and fully occupied condition in all frequencies. Reconstructed theatre.

Based on simulation results it can be seen that the original Metropolis Ancient Theatre had a more reverberant field compared to the existing conditions. Average reverberation time for the original theatre is expected to be 0.89 s while average measured reverberation time in the existing theatre is 0.53 s when it is empty; the values are 0.75 s and 0.48 s in the fully occupied theatre, respectively. Seeing the SPL values, it can be said that the theatre provides a homogenously distributed sound field along the receiver points that are increasingly distant from the source. C50 values indicate that the theatre has high speech clarity characteristics while C80 values remain out of recommended range for concert halls. Nevertheless, increased reverberant field causes an improvement at the musical clarity values in the reconstructed state of the theatre. STI values has revealed that theatre performs poor speech intelligibility in both of the conditions.

In the continuation of the study, the effectiveness of reflective panels to be placed on the stage and in the orchestra area was investigated. The goal is to improve the acoustics for activities held in the venue today. Accordingly, three alternative shell designs to provide support for the acoustic environment of the theatre during speech-based performances were investigated.

4.2.4. Passive Acoustic Interventions to the Scene

In order to prevent the misuse of the Metropolis theatre, a study was conducted in which passive interventions were proposed for the performances played in the orchestra and on the stage. Orchestra shells were designed to be able to compare the results and reach out to the best version of a shell providing the theatre with the best acoustic condition depend on the performance playing at that moment. The investigation was done through computer simulations of three alternative shell designs which are concave, convex and fan wall.

Previous research showed that the most suitable function to the theatre is for theatrical events and speech-based performances. Metropolis Theatre was analyzed in its present condition fully occupied with audiences. For scenarios with an orchestra, an omnidirectional sound source (S1) was positioned on the center stone with red marble at the height of 1.6 m (Figure 4.23). For scenarios where the stage is used, an omnidirectional source (S2) was placed on a reconstructed stage (Figure 4.24). The source (S2) is positioned at 1,6 m above the stage floor and it has a total height of 2.86 m from the orchestra floor. Receiver locations were the same as in the previous simulations. Since the seated person is 70 cm tall, the receivers are adjusted to this height on the stairs of the cavea. A platform was set on the top of ruins to provide a smooth floor for performances played on the stage. Table 4.5 represents the materials assigned to the audience area, platform and the shells. The remaining materials are kept the same used in previous simulations.

Table 4.5. Materials assigned to the surfaces to analyse the retrofit options. Present Theatre.

Layer name	Material	Scattering Coef.	Absorption Coefficients					
			125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4kHz
A platform for the scene floor	Floating wooden floor (Ref. Dalenback, CATT)	0,01	0,1	0,07	0,05	0,06	0,06	0,06
Audience area	Audience	0,01	0,16	0,24	0,56	0,69	0,81	0,78
Shell	Plasterboard on frame, 9.5 mm boards, 100 mm empty cavity	0,01	0,11	0,13	0,05	0,03	0,02	0,03

Figure 4.23 shows the three designed shells which are concave, convex, and fan wall, and presents their positions for the performances in the orchestra. Figure 4.24 shows the same shell designs and their placements for performances on the stage.

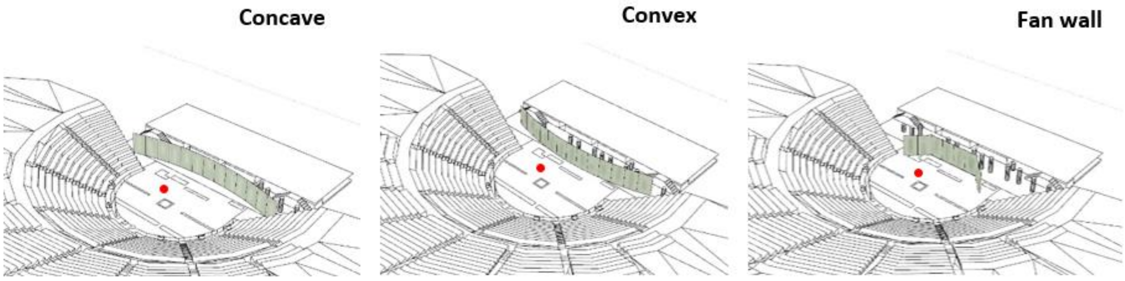


Figure 4.23. Designed shells and their position for the performances taken place in the orchestra. S1 source.

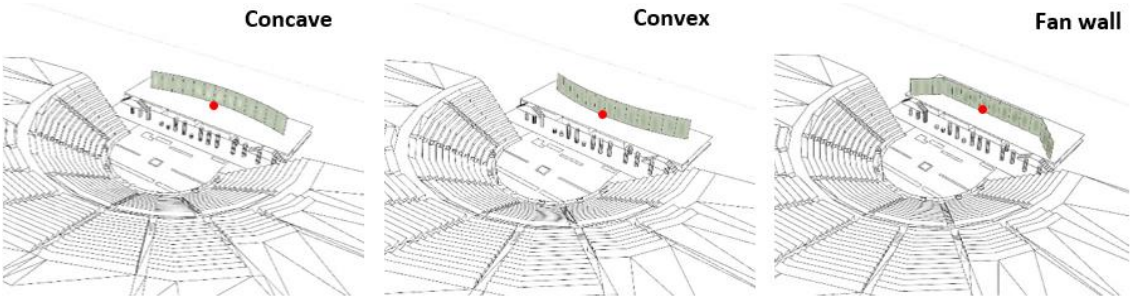


Figure 4.24. Designed shells and their position for the performances taken place on the stage. S2 source.

Simulations for the Retrofit Options

Calculated parameters were reverberation time (T30 (s)), sound distribution, clarity for speech (C50 (dB)), clarity for music (C80 (dB)) and speech transmission index (STI) for the theatres' fully occupied conditions at all frequencies.

In the first situation where the source (S1) is in the orchestra proposed shell designs reduced the T30 values as it is seen in Figure 4.25. This can be explained as the reflections which derives from the stage ruins at the back were blocked by the designed shells. Since the designed shells were closer to the source than the stage ruins, they reflect the sound from the source to the cavea in a shorter time effectively reducing the volume. Therefore, the designed shells in the orchestra area caused a shorter reverberation field in the retrofit scenario.

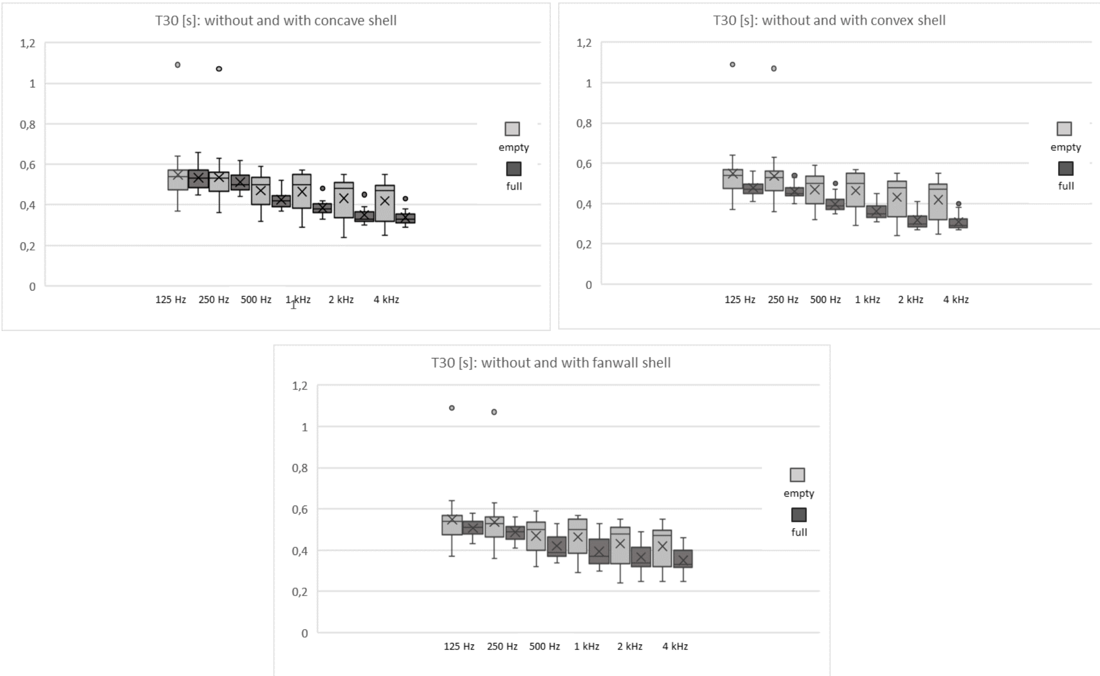


Figure 4.25. Simulated T30 values with and without shells. Source (S1) in the orchestra.

In the second situation where the source (S2) is on the stage, the change in T30 values which the proposed shell designs caused can be seen in Figure 4.26. In these alternatives, the shell on the stage prevents the loss of sound energy and allows more reflections towards the cavea. This increases the reverberation times.

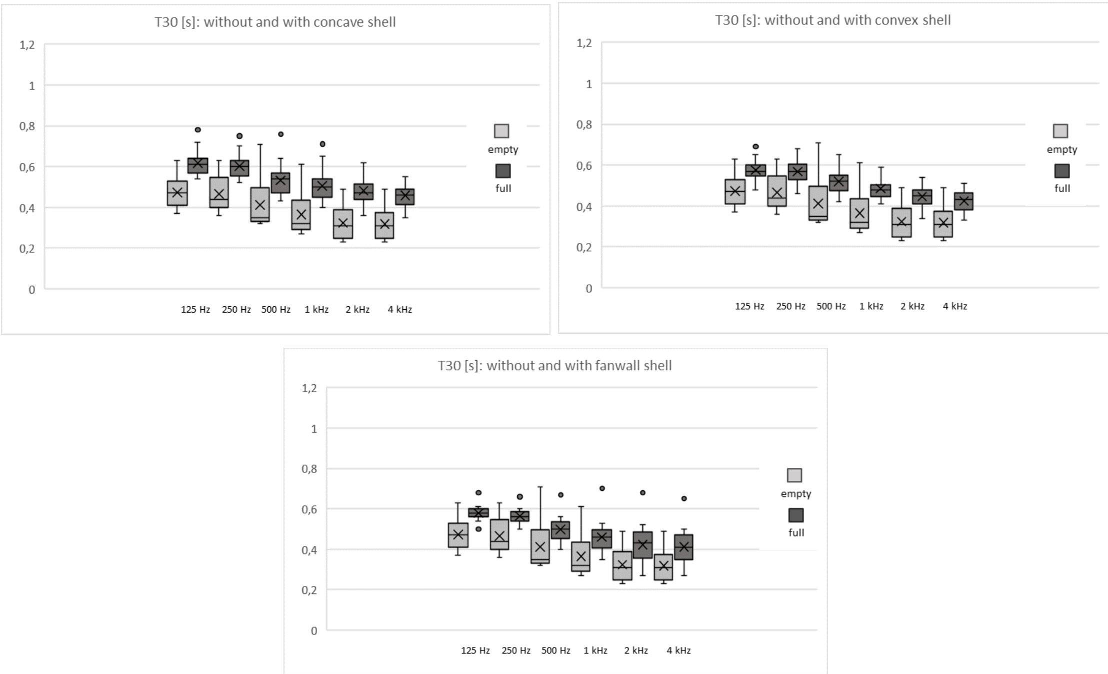


Figure 4.26. Simulated T30 values with and without shells. Source (S2) on the stage.

Simulated SPL values have been demonstrated in Figure 4.27 which is the results showing when the source locating in the orchestra and when the source locating on the stage.

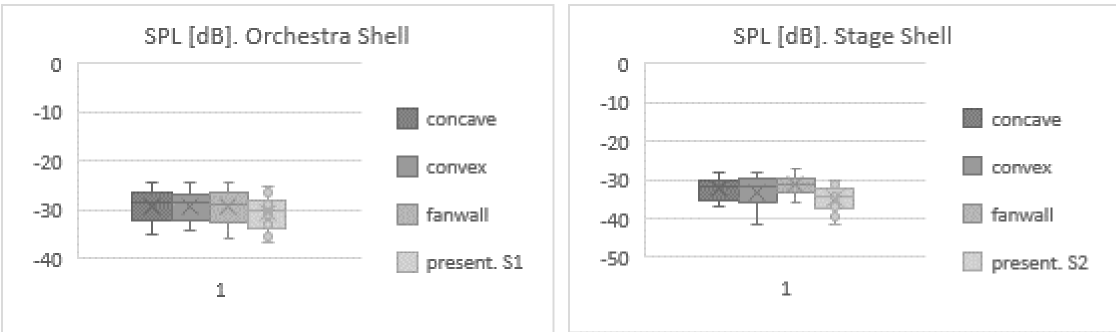


Figure 4.27. Simulated SPL values source (S1) in the orchestra (left) and source (S2) on the stage (right).

Acoustic parameters (C50, C80 and STI) of the theater in its current state have been showed as follows (Figure 4.28) in order to observe the benefits provided by the shell designs clearly and to be able to compare these results with the results of the proposed shell designs.

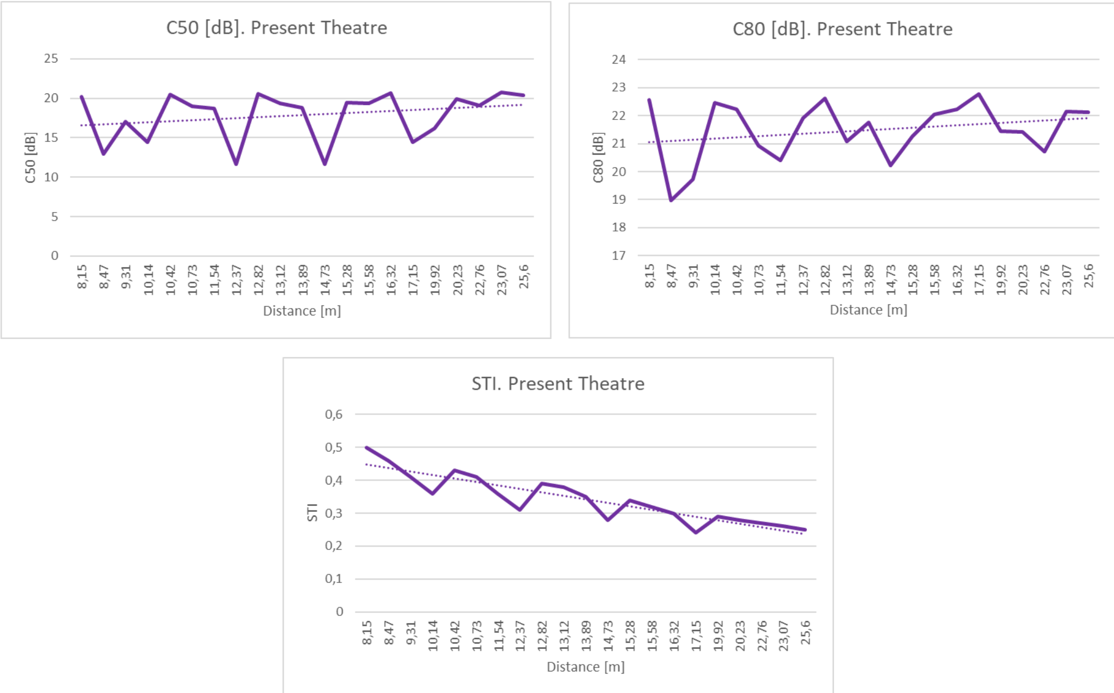


Figure 4.28. Simulated C50, C80 and STI values for the Present Theatre without shells.

In terms of C50 values, convex Shell shows better results to the receiver positions starting from 12 meters distance. We can arrange the performances of the different shells as Convex Shell>Fan Wall>Concave Shell basically (Figure 4.29). Since the higher the C50 the more desired clarity for speech, the best condition can be experienced for the receivers (R) are R14, R37 and R35 when the convex shell is used.

Figure 4.30 shows the simulated C50 values for the performances held on the stage with S2. It is seen that shell which has convex geometry performs better C50. Convex shell shows better results at the closer receiver positions than the fan wall shaped shell. Fan wall indicates lower C50 values when the source is on the stage.

Figure 4.31 and 4.32 shows that the better clarity for music (C80) is experienced with the concave shell when S1 is simulated; it is better experienced with fan wall when S2 is simulated; however, the theatre still does not perform good clarity of sound for music performances. C80 values should be decreased to the range of -1,5 and 4 dB intervals to achieve at least third-party acoustic requirements. It can be clearly seen that they are too high in accordance with this information. Therefore, the designed shells could not achieve better results for the musical performances in Metropolis Theatre.

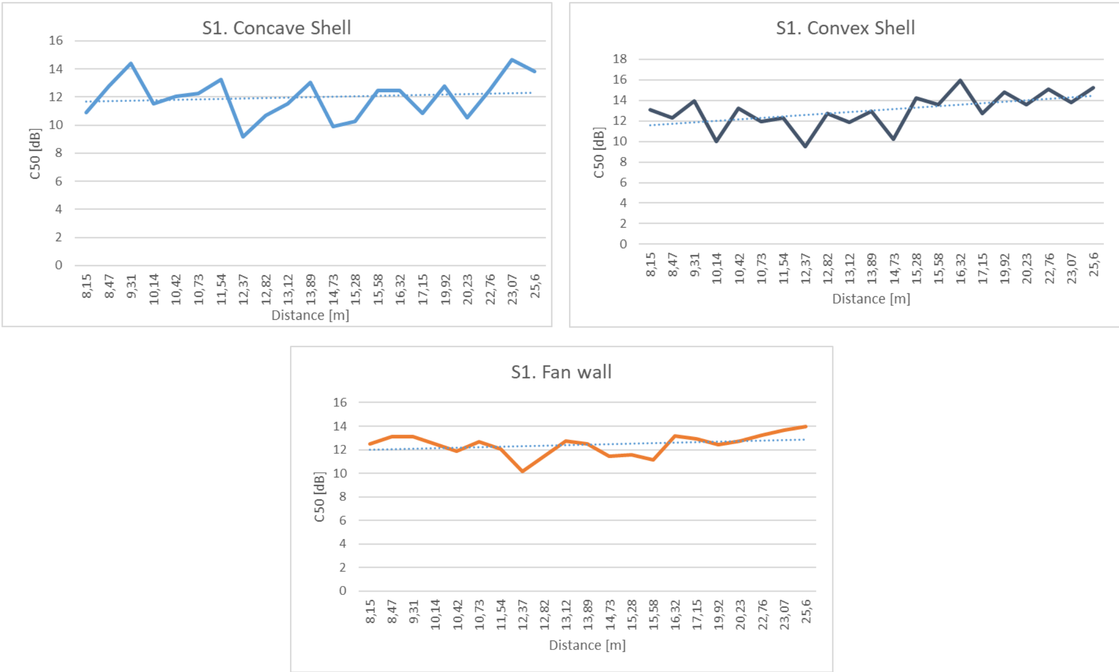


Figure 4.29. Simulated C50 values when the source (S1) is in the orchestra. The charts represent the results of concave, convex and fan wall respectively.

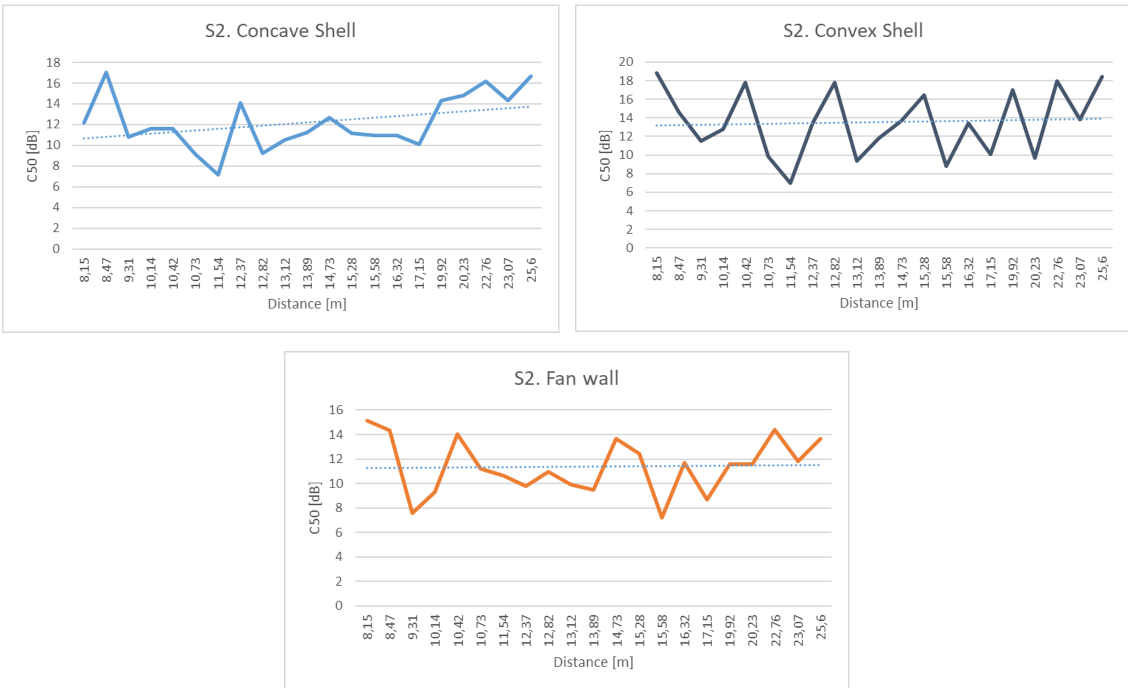


Figure 4.30. Simulated C50 values when the source (S2) is on the stage. The charts represent the results of concave, convex and fan wall respectively.

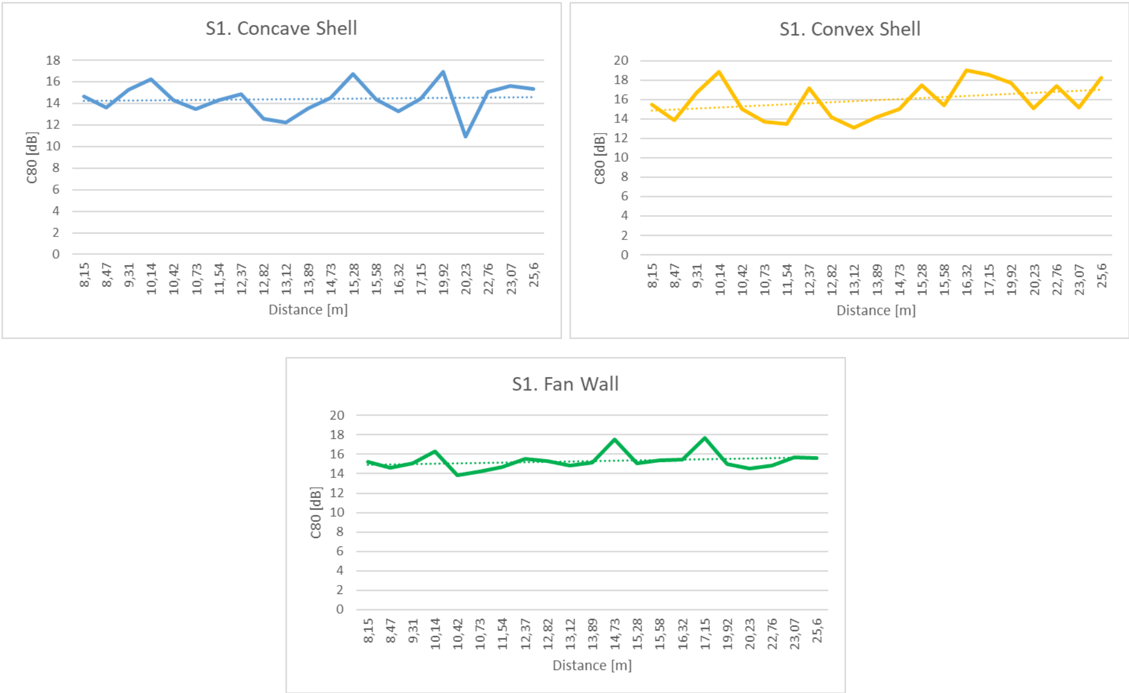


Figure 4.31. Simulated C80 values when the source (S1) is in the orchestra. The charts represent the results of concave, convex and fan wall respectively.

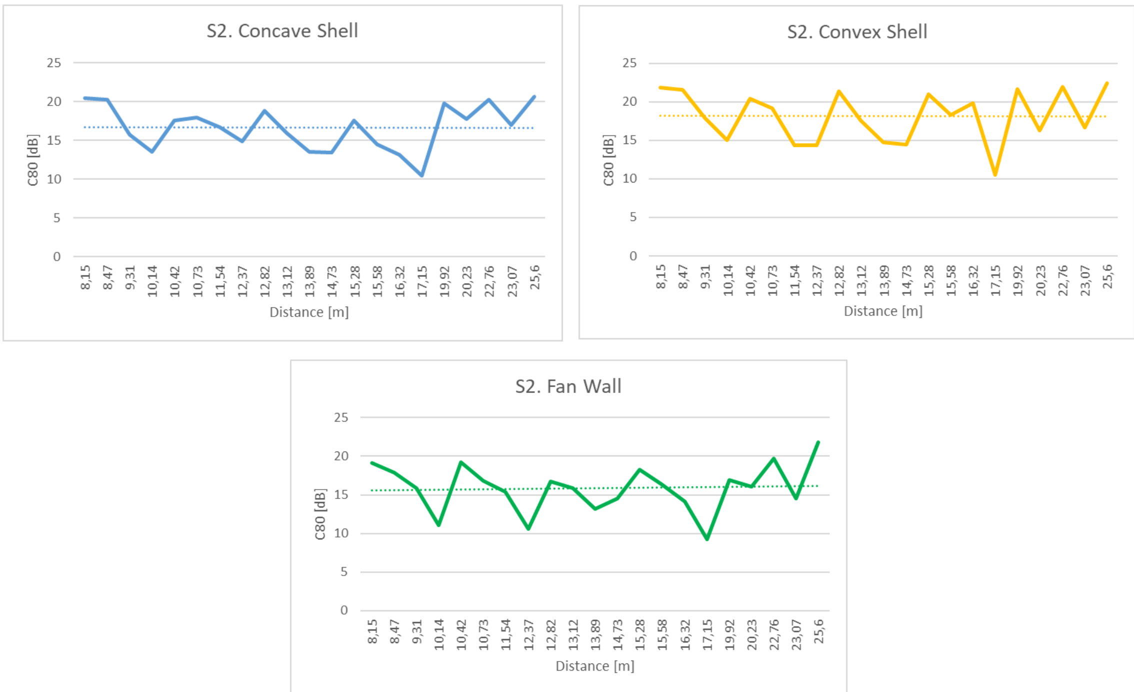


Figure 4.32. Simulated C80 values when the source (S2) is on the stage. The charts represent the results of concave, convex and fan wall respectively.

Different shell designs have not caused a significant improvement in STI values as it is seen in the Figure 4.33 and 4.34 below. The theatre still performs a poor speech intelligibility values for both of the source placements.

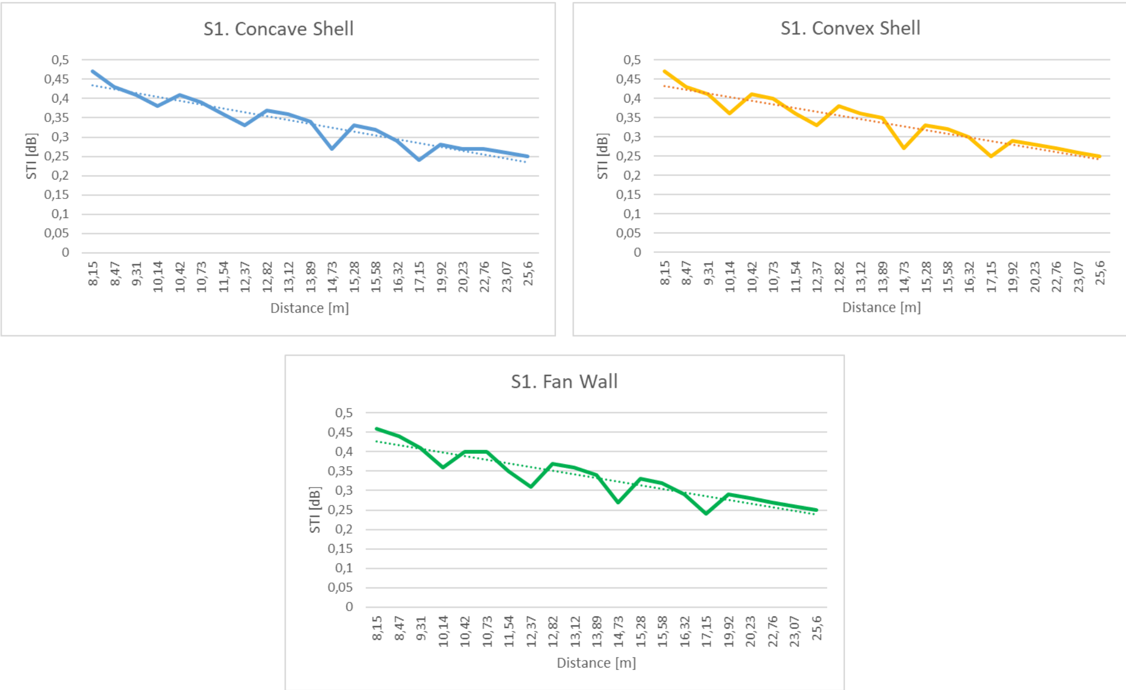


Figure 4.33. Simulated STI values when the source (S1) is in the orchestra.

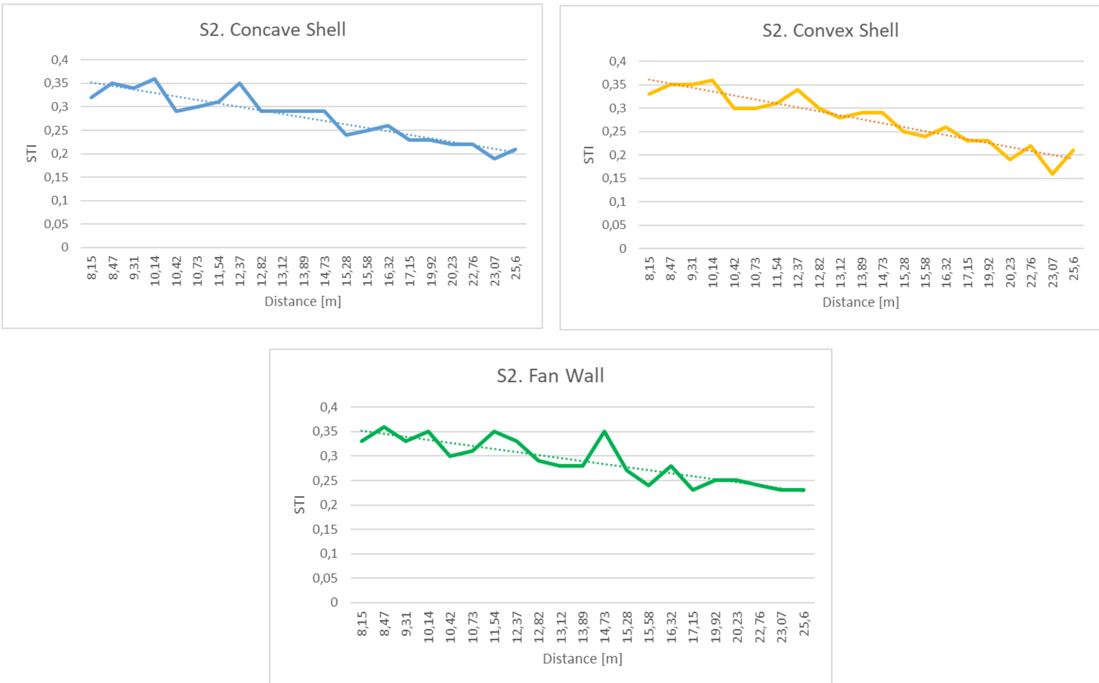


Figure 4.34. Simulated STI values when the source (S2) is on the stage.

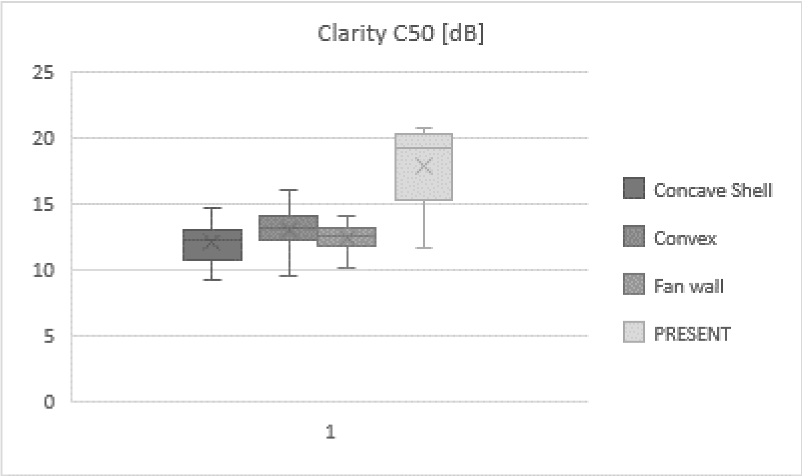


Figure 4.35. Simulated C50 values when the source (S1) is in the orchestra.

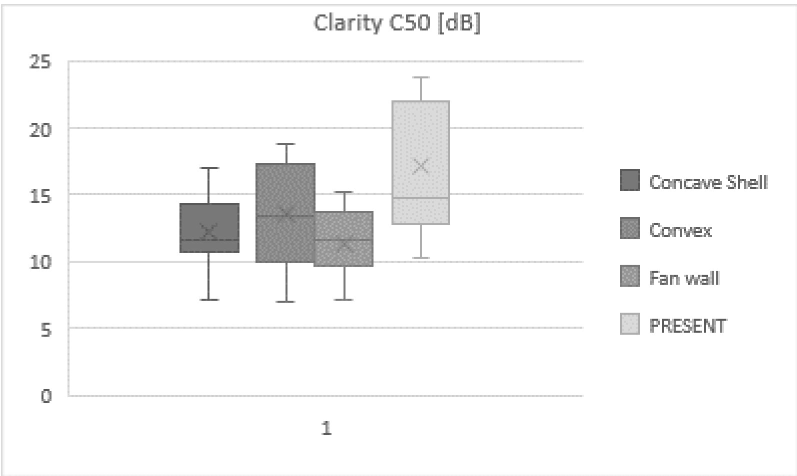


Figure 4.36. Simulated C50 values when the source (S2) is on the stage.

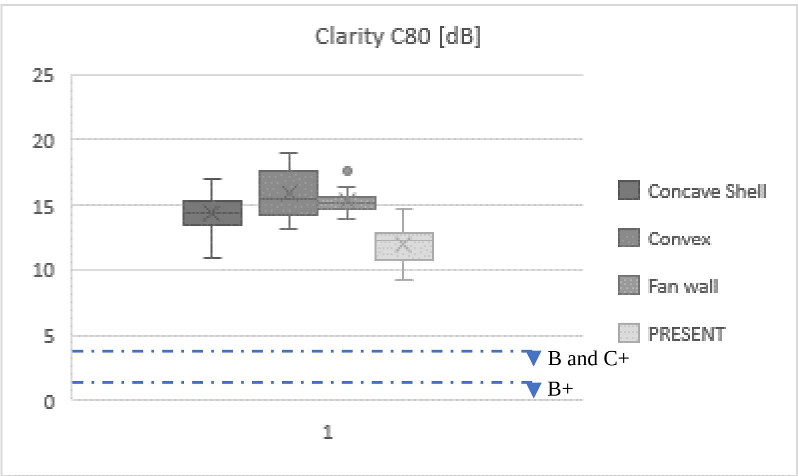


Figure 4.37. Simulated C80 values when the source (S1) is in the orchestra.

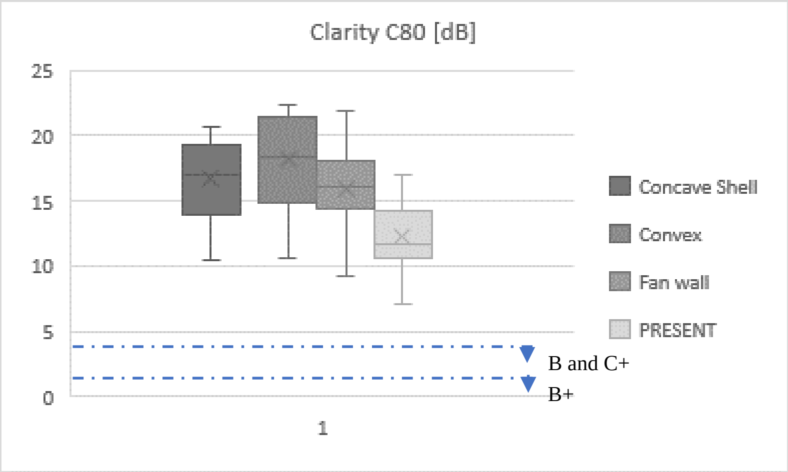


Figure 4.38. Simulated C80 values when the source (S2) is on the stage.

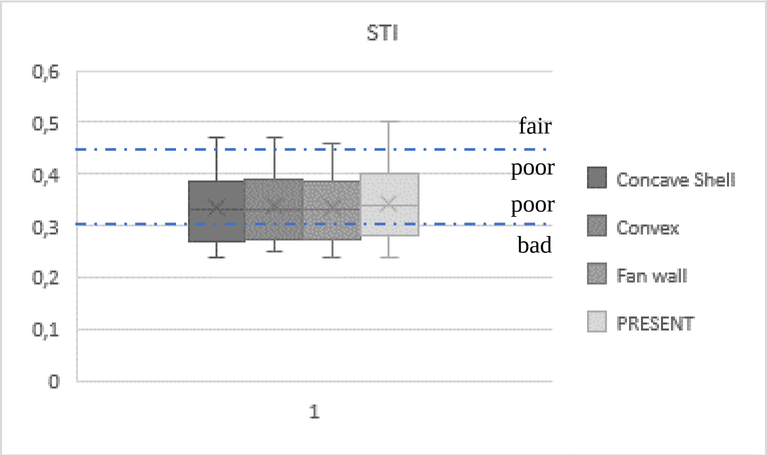


Figure 4.39. Simulated STI values when the source (S1) is in the orchestra.

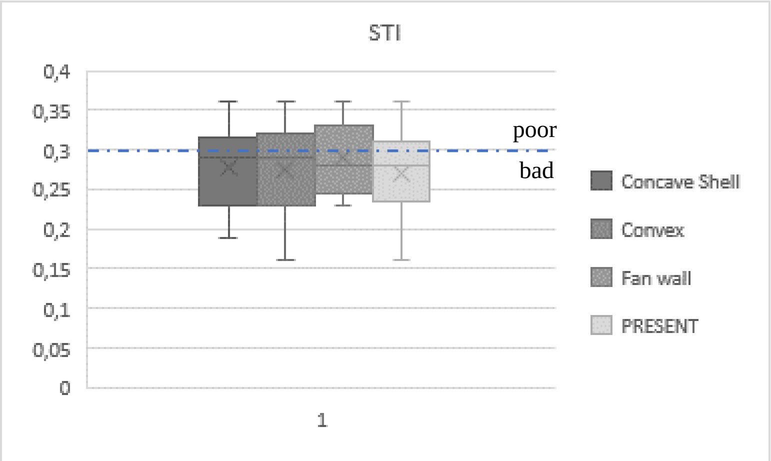


Figure 4.40. Simulated STI values when the source (S2) is on the stage.

Since the Convex Shell is the shell design that gives the best results in speech function, a further study can be carried out by assigning different materials to this geometry. Even though C50 values (Figure 4.35 and 4.36) were reduced in use of each shell designs the values are still provides good clarity. Moreover, none of the proposed configurations could provide the theatre with a significantly better speech intelligibility according to the STI results (Figure 4.39 and 4.40). When musical activities are considered (Figure 4.37 and 4.38), the designed shells again did not provide an improvement.

The acoustics in the current state of the Metropolis Ancient Theatre was tried to be improved. For this purpose, three different proposals for an acoustic shell have been investigated. Each of the three shells has been tried at two different locations. However, the proposed shell designs achieve better acoustic field neither for speech nor for musical performances. A further study could be carried out on positioning of reflective panels above the stage. Thereby, some of the sound energy lost towards the sky can be redirected towards the audience.

CHAPTER 5

EFLATUN PINAR WATER SANCTUARY

This chapter focuses on the simulation model and auralization studies to help in reaching a better understanding of how the acoustic environment at the Eflatun Pınar water sanctuary was during the Hittite period. First, the site will be described. Then, the on-site measurements at this open-air space will be explained. Then, the simulation models for both existing and original states are presented. Finally, how sample auralizations are produced for understanding how water sounds are experienced along with ritual music is described. The main purpose of the study is to reconstruct the sanctuary's sound field in a virtual environment to experience the atmosphere at the religious ceremonies and rituals performed at the ancient ages.

5.1. Detailed Description of Eflatun Pınar

Eflatun Pınar is located 100 kilometers west of Konya (in Turkey) which is near the lake of Beyşehir and settled on an almost dry and mountainous agricultural topography. Eflatun Pınar is translated as "Lilac colored spring". The spring is a source of cold and clear water at the top of a river valley (Bachmann, 2001).

Figure 5.1. A picture showing present state of the Eflatun Pınar.
(Taken on 21st of September, 2022)

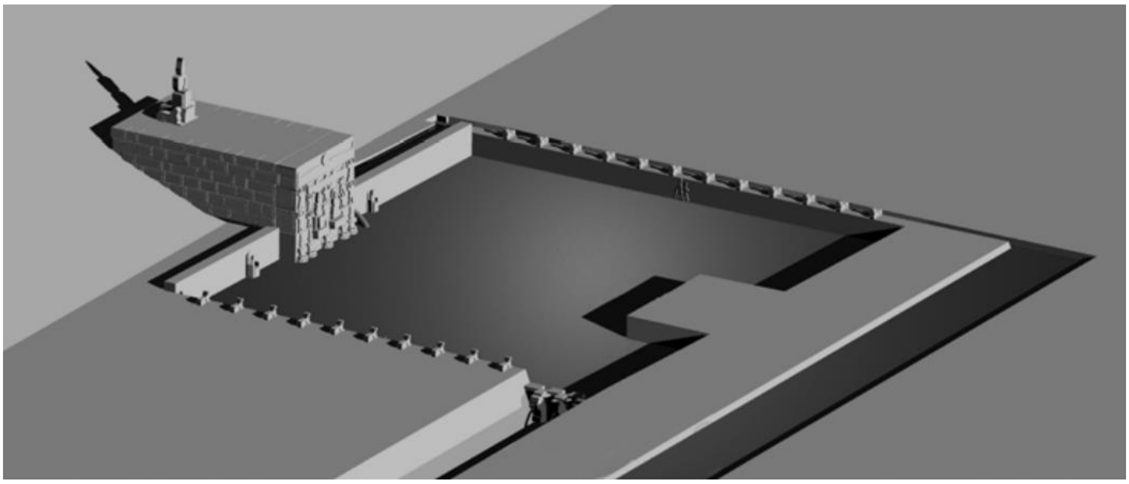


Figure 5.2. Reconstruction of the basin with the new found sculptures.
(Source: Bachmann, 2001)

Eflatun Pınar water sanctuary (Figure 5.1) has the plan of a large basin measured 34 meters by 31 meters (Figure 5.2). The main monument is positioned on the north façade at the basin. It is over 6 meters high and built as a whole with the closed fountain house. It was built with large cut stone works. Figures of five mountain gods are at the bottom of the monument that is approximately 2.35 meters high. The three figures in the middle has drill holes in their skirts, through which water flows (Figure 5.3a and 5.3b). It was intended to prevent overflow through bull protomes sculpted near the monument. Methods of evacuating the excess water or redirecting it to the basin have been considered in building this sanctuary. Therefore, the sanctuary is representative of advanced water engineering structures of the Hittites (Bachmann, 2001).

As a result of the arid agricultural activities in the Hittites, mountains and rocks were representing gods and water sources were representing goddesses. In order to avoid disasters, gifts were presented to the weather and vegetation gods and spring goddesses at the sacral ceremonies. People made gifts to spring, sometimes released charming objects floating on the water on a characteristic boat. Incantation rituals were performed to bring rain to the earth. Rocks were thought to be gods by Hittites. Therefore, places where rocks, as a representation of mountains, meet with water have been chosen for cultic activities. This leads those characteristic places to become open-air sanctuaries. These open-air sanctuaries had an important meaning therefore they endowed these sanctuaries with monumental pieces.

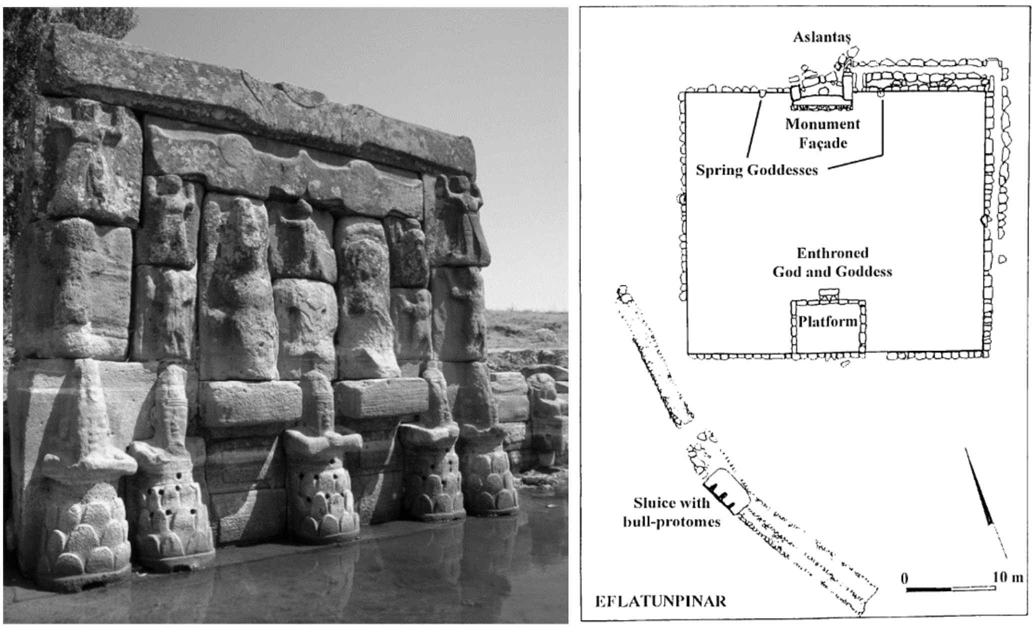


Figure 5.3. a: The main monument of Eflatun Pınar after excavation 2001. (Source: Bachmann, 2001) b: Plan of the spring sanctuary at Eflatun Pınar. (Source: Okse, 2011)

The spring monument was fed from a spring on the north-east side. A square-shaped basin collects this rich spring water from the north side. The basin was planned with a wall on the northern edge which was 6.55 meters high and 7 meters wide, built using solid stone blocks. The reliefs on the blocks were carrying a large winged sun disc embracing the entire scene at the top. In front of the monument, on the southern edge, a rectangular podium was placed made of large square-cut stones. On this platform's northern side there is an altar with an enthroned god and a goddess sculpted into a single large block of stone. All these show that Hittites were using Eflatun Pınar open-air sanctuary not only for the agricultural intentions but also for their rituals and sacred ceremonies. (Okse, 2011).

5.2. Acoustic Reconstruction of Eflatun Pınar Water Sanctuary

In this section, the acoustics of Hittite Open Air Water Sanctuary is investigated through measurements, simulations, and auralizations.

5.2.1. Measurements

Reverberation time measurements were conducted on 21 September 2021 in the sanctuary with a sound level meter (Brüel & Kjaer – 2260 Investigator) using a balloon pop as an impulse response. It should be kept in mind that the flow rate of running water is different in each season. Although the site is completely open reverberation times were still measured at two points for model calibration purposes: 1) behind the monument 1.5 m away from the walls, and 2) on the east side of the monument 3 m away from the wall.

Water sounds were recorded as sound sources at points where water cascades out of the spring, flows into the pool, and flows out of the pool. Also sounds were recorded at three receiver positions for comparison and calibration purposes. For sound recordings; a laptop, a G.R.A.S. 40AE 1/2" microphone, a G.R.A.S. 26CA 1/2" preamp and 01dB dB4 four channel sound recorder and 01dB dBFA software were used. Calibrated sound recordings were taken from 8 different locations (Figure 5.4). Five of them are where water sounds are recorded to be used as sources. Sounds were recorded 1 m away from these sources. The other three locations are receiver positions where recordings were taken for comparison of actual sounds to simulated auralizations.

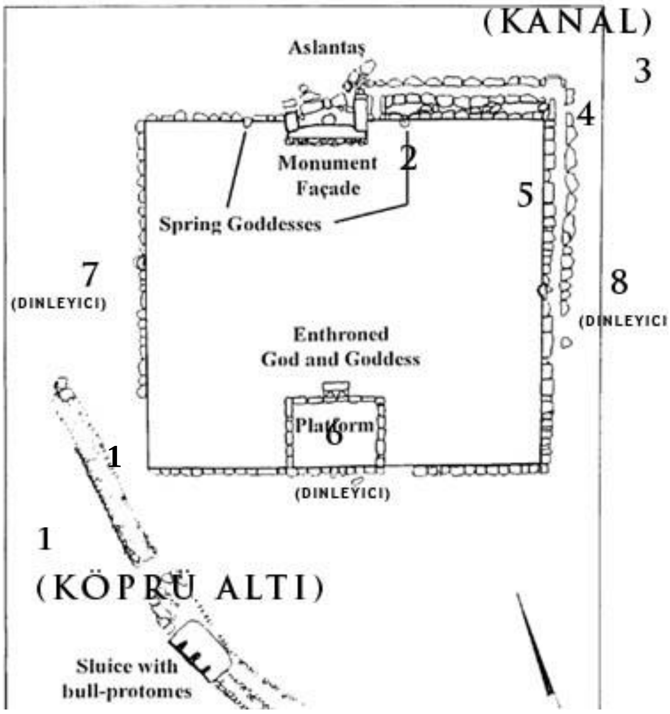


Figure 5.4. Site plan of the sanctuary indicating the measurement points: 1,2,3,4 and 5 are record water sound sources; 6,7, and 8 are receiver positions.

The points where the water spring first meets the basin and where excess water is discharged from the basin are shown at the pictures below. The place where the water sound recorded from the measurement point number 1 can be seen in Figure 5.6 the place where sound recorded from measurement points number 2 and 4 can be seen in Figure 5.5.

Figure 5.5. A view from the point where water spring reaches the basin.

Figure 5.6. A view from the point where excess water leaves the basin.

5.2.2. Modelling Scenarios

The subject of this study has been a place for enchantments, religious ceremonies and incantation rituals as it was mentioned before. Since the aim of this study to reconstruct the auditory environment which represents the original use in the old times, a scenario suitable for this function was applied. A piece which consists of the musical instruments that are thought to be played in the Hittite culture at that time was composed. These instruments are lyre, cymbal, tambourine and lute. It is assumed that this piece, heard in the background while the priest was chanting the liturgy, was performed on the platform of the sanctuary. While people watch around, priest completes this ceremony where the spring first reaches the basin. The procession, which also includes statesmen, passes into the enclosed room at the back of the monumental façade located in the north to complete the ritual.

5.2.3. Simulations and Auralizations

In this research auralization studies were carried out using the acoustical software Odeon Combined v14. Auralizations are created with no audience around during the incantation. Firstly, the model in its present condition is created in 3D environment using SketchUp Make 2017 (Figure 5.7). Layers are defined for each material and surfaces are assigned to these layers to simplify material assignments in Odeon. Then the model is imported into Odeon using SU2Odeon plugin. Model check process is applied to see if there are multiple surfaces in the model or to prevent any leakage causing unreliability during the analysis. Sources are placed at the five points where the water flows into the pond, out of the pond, or cascades from the spring. The five sources can be seen in Figure 5.8 below. One of the receivers is located on the platform and the other two are located in the middle of the right (Rright) and left (Rleft) sides of the basin. The water sound recordings taken from the site are assigned to the related source positions in the model. Materials assigned to surfaces are given in Table 5.1 below.

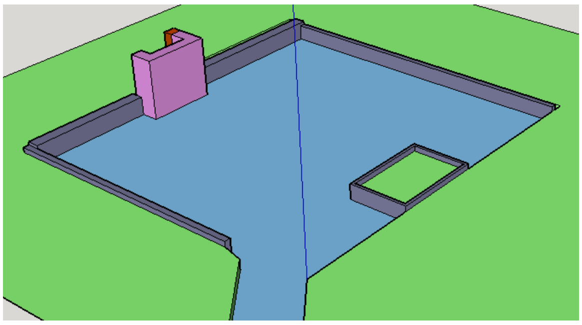


Figure 5.7. A perspective view from the 3D model of the present condition of the Eflatun Pınar Water Sanctuary.

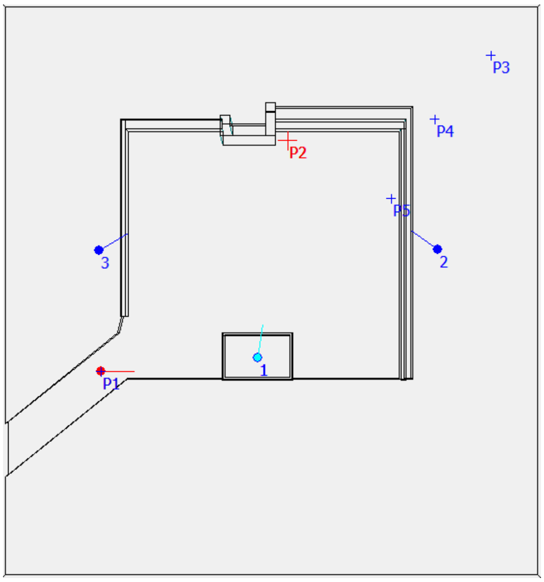


Figure 5.8. Sanctuary plan at the present condition. Sound sources positioned on the plan: P1, P2, P3, P4 and P5 are sources of water sounds; 1, 2 and 3 are the receiver points.

Table 5.1. Material assignment to the surfaces at Eflatun Pınar Water Sanctuary.

Layer name	Material	Scattering Coef.	Absorption Coefficients					
			125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4kHz
Air	100% absorbent	0.01	1	1	1	1	1	1
Earth	Grass, marion grass (Kim, 2011)	0.01	0,11	0,26	0,6	0,69	0,92	0,99
Northern facade Platform Side walls Water room	Marble/glazed tile (Harris,1991)	0.01	0,01	0,01	0,01	0,01	0,02	0,02
Water	Water surface (Knudsen,Harris,1950,1978)	0.01	0,01	0,01	0,01	0,01	0,02	0,02

For auralizations, first jobs are defined to calculate binaural room impulse responses (BRIR) at the three listener positions for each of the five sound sources. In the auralization settings, for each listener, recordings are assigned to the source of each BRIR and all five are convolved to create the auralization at the listener point.

For both simulation models, overall recording level is set to 58 dB in order to keep each auralization outputs between 0 and -10 dB. Analysis was taken using the precise degree of simulation adjusted in the room setup in Odeon. Convolved files are displayed clear at Rmid and Rleft. The sound recordings taken from the site and taken from the software are compared. Calibrated model, which was confirmed by subjective evaluations, was made ready to be used for further exploration.

After the calibration was done on the present model, reconstructed model is simulated using the same material assignments. (Table 5.1). For the virtual reconstruction of the original state, a second SketchUp model is built based on Bachmann's model (Bachmann, 2001). This model shown in Figure 5.9 is imported into Odeon using the same methods. Figure 5.10 shows the position of sources and receiver points. The same five sources for water sounds are placed in the model. Additionally, a sixth source (Rmid) is created on the platform at a height of 1.5 meters and a music recording is assigned to it. This recording consists of a short music composed specifically for this study. The music is synthesized to be anechoic using four instruments mixed onto a single channel.

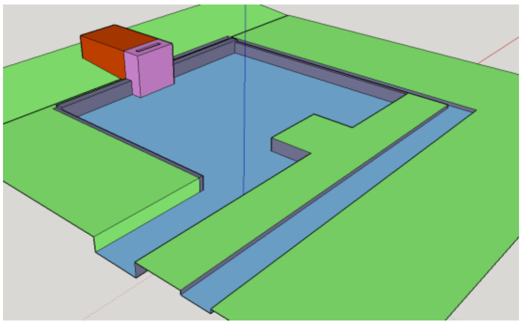


Figure 5.9. A perspective view from the 3D model of the reconstructed Eflatun Pınar Water Sanctuary.

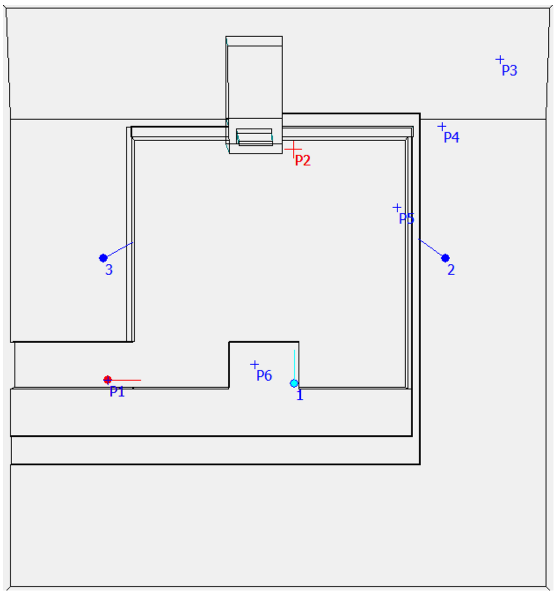


Figure 5.10. Sanctuary plan of the reconstruction. Sound sources positioned on the plan of the sanctuary: P1, P2, P3, P4 and P5 are sources of water sounds; 1, 2 and 3 are receiver points. P6 is the source that plays the Hittite ritual music.

The same auralization processes used for the present condition, were used for the virtual reconstruction of the original Eflatun Pınar water sanctuary. Using the five original recordings of water sounds and the original Hittite ritual music, auralizations for three receiver positions were created. The positions of the two receivers on the right and left are the same as they are in the present condition model but the receiver on the platform is positioned at the right bottom corner of the platform with as much distance as possible from the music source. The reason is to prevent a possible deterioration in the output of the auralization taken from that point. Overall recording level was set to 51 dB.

Sample auralizations created can be found in the included CD under auralizations folder. The files provided are as in the Table 5.2.

Table 5.2. The auralization files in the included CD under auralizations folder.

On-site Recordings	eP_(R1)_norm_out
	eP_(R2)_norm_out
	eP_(R3)_norm_out
Auralization Present State	eflatunpnr_present_receiver1_odeon.MixAural01_norm20_out
	eflatunpnr_present_receiver2_odeon.MixAural02_norm20_out
	eflatunpnr_present_receiver3_odeon.MixAural03_norm20_out
Auralization Reconstructed State with Hittite Song	eflatunpnr_reconstructed_Hittitesong_R1_odeon.MixAural11
	eflatunpnr_reconstructed_Hittitesong_R2_odeon.MixAural12
	eflatunpnr_reconstructed_Hittitesong_R3_odeon.MixAural13
Auralization Reconstructed State only Water Sound	eflatunpnr_reconstructed_onlywater_R1_odeon.MixAural01
	eflatunpnr_reconstructed_onlywater_R2_odeon.MixAural02
	eflatunpnr_reconstructed_onlywater_R3_odeon.MixAural03

With this study, a virtual environment was created in which archaeologists working on Hittite Eflatun Pınar Water Sanctuary have the opportunity to test their hypotheses about how the area was used in ancient times. Studies in this field contributes to the preservation of acoustic heritage, which is assessed by UNESCO under the field of uncountable cultural heritage. Acoustic memory is just as worthy of protection as well as visual heritage, and it becomes even more important in some ancient spaces where acoustic features at the forefront. In parallel with the development in computer simulation techniques, the number of researches conducted in real-time auralizations are increasing and the use areas of auralizations are constantly changing. Creating a sensory-rich environment has been on the agenda of some researchers lately. If we bring another perspective to the topic, some architects have used the auditory environment as a tool to remind important events in history by taking advantage of the sound characteristics of the materials used in their designs. Additionally, there are some works which leads the designer to take steps for creating an acoustically valuable environment by giving them cues about acoustic characteristics of a place in the early stages of design.

For the further work related to this thesis topic; another research can be carried out on the subjects of these thesis study which consists of a real-time auralization in a dynamic environment which allows for modifications in source and receiver placements. With the moving sources, a rich sensory-stimuli environment can be experienced.

CHAPTER 6

CONCLUSION

6.1. Analysis Results Summary

6.1.1. Metropolis Ancient Theatre

The reconstructed empty theatre has reverberation times between 0.77-0.93 s. When fully occupied the reverberation times in the reconstructed theatre rages between 0.54-0.91 s. In its present condition, the empty theatre has reverberation times between 0.49-0.54 s and when it is fully occupied the reverberation times range between 0.41 and 0.54 s.

Clarity of speech (C50) values in the reconstructed empty theatre vary between 2.7 and 4.2 dB. When fully occupied, this range increases, as expected, to between 3.8 and 10.7 dB. Clarity values at 500 and 1000 Hz, where speech function applies, are above 6 dB when it is fully occupied with audiences. With values greater than 6 dB it is assumed that speech can be understood clearly in classrooms (Christensson, 2017). Therefore, it can be said that Metropolis provides a clearly understandable sound field when it is fully occupied. In its present condition, the theatre has C50 values that are even higher. C50 varies between 11.3 and 12.8 dB when empty; 12.9 and 21.6 dB when full. The average C50 average for mid-frequencies is 11.9 dB in the empty condition and 18.57 dB in the fully occupied theatre.

Recommended range for clarity for music (C80) in concert halls is between -4 and 1 dB. (Mehta, Johnson, and Rocafort, 1999) Reconstructed theatre's C80 values vary between 4.32 and 5.93 dB when it is empty and 5.46 and 13 dB when it is fully occupied. It can be said that the acoustics of the reconstructed theatre does not provide enough reverberant energy and therefore is not appropriate for musical performances. In the present state of the theatre, with shorter reverberation times, C80 values are even higher. Empty theater has C80 values in the range of 14.33 and 16.26 dB. The fully occupied theater C80 value range is 15.92 – 25.77 dB.

STI lower than 0,45 is rated as poor (Rindel, 2014). With the actual background noise levels measured on-site, the theatre has a poor or bad speech rating when it is both empty and fully occupied in its reconstructed condition. As expected STI values decreased with the increase in the distance from the source. In the present condition, both empty and fully occupied conditions provide poor speech intelligibility to the human ear. The average STI value is 0.34 for the present theatre.

Alternative acoustic shell designs for the stage do not significantly improve the acoustics of the present theatre neither for speech nor for musical performances. They caused an increase in clarity for music values instead of decreasing them while decreasing the clarity for speech values. For an improved acoustic field required for speech-based performances, with the reflectors STI values were expected to increase. However, all of the reflective panel configurations failed to provide an improvement.

Virtual reality tools enable us to develop guidelines for the preservation of the acoustic field while continuing to use these archaeological sites. This study has recreated the sound field of the Metropolis Ancient Theatre. In the reconstructed state, clarity values for speech found excellent and it performs good clarity for speech especially when it is occupied with the audiences. For musical performances the reverberation times are low and clarity for music is higher than recommended values. STI values are shown to be poor; however, the analysis is based on actual measured background noise levels that are considerably high. It is a fact that Roman open-air theatres provide a high clarity of sound in contrast to their low sound strength so these theatres are more appropriate for speech functions (Rindel and Nielsen, 2006). For these reasons, Metropolis Ancient Theatre can be best utilized for speech oriented use rather than for musical performances and its present condition is suitable to its original use scenario.

All in all, thinking that the Odeon room acoustic software gives the results that does not require a calibration process in this study, this may be an indication that the software is suitable for use in amphitheater acoustic simulations. A passive solution was proposed to improve the acoustic quality of a performance involving theatrical or speech-based function performed in the scene. However, none of the three shell designs could achieve a better sound field for speech.

Comparison of results with the previous studies realized on the other ancient theatres

The comparisons will be only made for the reconstructed theatre due to the different preservation levels of the present theatres. In the example of Theatre of the Pythion average RT value is 0.61 s at 500 Hz and 0.59 s at 1000 Hz filled with spectators (Manzetti, 2020). In comparison, reconstructed Metropolis theatre performs higher average RT which is at 0.74 and 0.68 s in the corresponding frequencies. The measured average T30 (s) values in mid-frequencies (500-1000 Hz) of Aspendos reconstructed theatre is 1.95 s when it is empty and 1.59 s with the audience area (Rindel and Nielsen, 2006). Metropolis theater performs very low T30 values, it shows approximately half of these values (1.95s >0.91s and 1.59s >0.71s). Jerash Theatre has higher average T30 values at 1.54 and 1.06 s respectively (Rindel and Nielsen, 2006). The measured T30 values in Syracuse theatre is at 1.81 and 1.67 s (Rindel and Nielsen, 2006). T30 values measured for Benevento ancient theatre is at around 1.8 and 1.7 s without audiences at the mid-frequencies (Iannace and Trematerra, 2014). Metropolis has T30 values at 0.92 s (at 500 Hz) and 0.91 s (at 1000 Hz) when it is empty, so the theatre is reverberant almost half in amount in comparison to Benevento when it is empty.

According to the calculated C50 values, Metropolis theatre has a better clarity for speech when it is occupied by audiences. C50 values varies between 3.8 and 10.7 dB.

The C80 value below 3 dB is more appropriate for musical function while the speech function is best experienced above 3 dB (Manzetti, 2020). Calculated average results for the clarity of music (C80) are demonstrated for Pythion as 8.24 (at 500 Hz) and 8.5 dB (at 1000 Hz) with audiences (Manzetti, 2020). Metropolis’ values are 9.2 and 10.65 dB correspondingly. Simulated C80 in Aspendos theatre is 1.17 dB with no audience and 4.08 dB with audience (Rindel and Nielsen, 2006). The values represent averages at mid-frequencies. Calculated results in Metropolis theatre is 4.45 and 9.92 dB at its average correspondingly. Jerash theatre’s average C80 values at around 3.46 (empty) and 6.88 dB (with audience) (Rindel and Nielsen, 2006). Simulated C80 in Syracuse is 4.07 (empty) and 8.25 dB (with audience) (Rindel and Nielsen, 2006). Syracuse shows close results to the Metropolis (4.45 no audience; 9.92 with audience). C80 results calculated for Benevento are 2 (500 Hz, empty) and 2.1 dB (1000 Hz, empty) (Rindel and Nielsen, 2006). Metropolis calculation shows the results at 4.42 (500 Hz, empty) and 4.49 dB (1000 Hz, empty) which is higher and not providing better sound environment in terms of the clarity of music in comparison to Benevento (Iannace and

Trematerra, 2014). STI values calculated in Aspendos are 0.53 (empty) and 0.61 (with audience) (Rindel and Nielsen, 2006). In Metropolis it is 0.25 and 0.26 (with the measured background noise). Jerash theatre has STI values at 0.62 and 0.7 (Rindel and Nielsen, 2006); Syracuse has at 0.62 and 0.70 (Rindel and Nielsen, 2006). STI refers to a better condition towards 1 so Metropolis has a poor STI value in comparison to the theatres of Aspendos, Jerash and Syracuse.

Table 6.1 below, shows the simulated results of reconstructed ancient theatres mentioned above.

Table 6.1. Comparison of simulated results between other reconstructed ancient theatres.

	T30 (avg. 500-1000Hz) [dB]		C80 (avg. 500-1000Hz) [dB]		STI	
	empty	full	empty	full	empty	full
Aspendos	1,95	1,59	1,17	4,08	0,53	0,61
Jerash	1,54	1,06	3,46	6,88	0,62	0,7
Syracuse	1,81	1,67	4,07	8,25	0,62	0,7
Benevento	1,75		2,05			
Pythion		0,6		8,37		
Metropolis	0,91	0,71	4,45	9,92	0,25	0,26

6.1.2. Hittite Open Air Water Sanctuary

An auralization study was carried out to experience the reconstructed sound environment of the sanctuary during a Hittite incantation ritual. It was realized using an originally composed Hittite ritual music. After careful subjective evaluations of the auralization files based on the sanctuary's present condition, recreating the original sound field of the sanctuary became meaningful. Thus, one more contribution has been made to the studies in the field of archaeoacoustics and attention has been drawn to the importance of the water monuments that are significant in Hittite culture and their auditory identities as well as their visual identities in accordance with their intended use.

6.2. Limitations

Carrying out a study related to ancient times using simulation techniques unavoidably comes with serious limitations and this study is not an exception.

First, while this study was being carried out, Arslan and Aybek published a paper on the reconstruction of the Metropolis Theater stage in April, 2022. Due to the time constraints, this study has been conducted according to the estimated dimensions before their research was completed on the reconstruction of the stage. Estimation has been done by contacting the excavation team; however, as the information obtained from the excavation increased by time, the estimations on stage dimensions changed as it can be seen in the Table 6.2 below. In addition, the marble material selected from the software's library may not correspond to a material that exactly matches with the construction techniques of the past.

Table 6.2. Modelled and estimated dimensions of the reconstructed scene of Metropolis Theatre.

	length (m)	width (m)	height (m)
Simulated model	28,13	7,07	12,55
Hellenistic period estimated dimensions	19,53	7,5	4,83
Roman period estimated dimensions	28,56	5,2	12,82

The height of the proskenion (m)	
Simulated model	2,82
Estimation	2,66

Second, at the auralization part of this study, instead of using anechoic recording of a piece, a composition synthesized using computational tools was utilized to represent the incantation ceremony. The music is produced dry, without any reverberation, but is not an anechoic recording of original instruments.

Calibration of the sanctuary was done only subjectively. A more rigorous method employing a survey with a group of experts was not feasible due to time constraints.

6.3. Discussion

Main approach to the protection of archeological sites is mostly about preserving their visual identities. However, acoustic field becomes predominant in some cases at historical sites such as in the example of Roman and Greek amphitheaters, mosques and churches. Moreover, in some venues, such as religious ceremonies, rituals, and enchantments performed in ancient times, are accompanied by instrumental sound. Even sounds produced by the natural objects around becomes crucial because they are also playing an instrumental role for people's spiritual completion living in ancient times.

This study was centred around seven research questions set forth in the first chapter. The first two questions were about evaluating the acoustics in the Metropolis Ancient Theatre in its original and existing states, comparing them, and determining the functions appropriate for this venue. Metropolis Ancient Theatre is a Hellenistic period amphitheatre which is used for many theatrical and musical events today. For acoustical heritage preservation Metropolis ancient theatre has been investigated in its current state, then, it has been reconstructed virtually in its original state to understand its original acoustics and identify its original purpose of use. The theatre's original acoustic field has been found suitable for speech oriented functions. The reverberation time was too low to be appropriate for musical performances. In its current state, the reverberation times are even shorter, increasing the already high values of clarity for speech and clarity for music. The venue is still more appropriate for speech oriented use.

The third research question focused on evaluating the effect of placing reflector panels on the stage and at the orchestra level in order to improve the acoustics in the Metropolis ancient theater. Three alternative panel configurations were evaluated both at the orchestra level and on the stage. None were able to provide a significant improvement. At the orchestra level, reflector panels redirected the sound energy that would otherwise be reflected from the existing stage walls. On the stage, the reflector panels were able to redirect some sound energy that would otherwise be lost. This slightly increased reverberation times as expected. However, the overall improvement was not significant. Reflector panels with limited height failed to provide the desired improvements.

The fourth research question was focused on evaluating the usefulness of available simulation tools. Odeon Combined v14 was used for this study and the models that were created following the guidelines and application notes in literature were found to be useful. Relying solely on materials available through the software material database, percentage error of simulation results was in an acceptable range. It can be stated that available simulation tools and techniques are useful estimation tools in evaluation of acoustic heritage.

The fifth research question was centred around whether a virtual acoustic reconstruction study could enable us to rediscover the original acoustic environment of Eflatun Pınar water sanctuary. Eflatun Pınar is a significant ancient space where water sound becomes crucial to experience its original acoustics during a ritual performance in ancient times. It is considered that many religious ceremonies, incantations, or rituals were held in this place in the presence of clergy, public and statesmen. Therefore, Eflatun Pınar was reconstructed in a virtual environment to experience its original acoustics through auralizations. In line with the auralizations listened to, it is found that the virtual acoustic reconstruction of Eflatun Pınar made through auralizations are useful to recreate its original acoustics.

The sixth research question was focused on whether an auralization study helps us better understand the intangible heritage within the scope of archaeoacoustics. The original acoustics of Eflatun Pınar water sanctuary has been rediscovered through auralizations. The way to protect heritage site is to first understand why they are of historical importance. Considering most of the heritage sites are damaged due to the natural disasters or touristic activities over time, virtual reconstruction studies make their original acoustic environment accessible. The auralization studies carried on Eflatun Pınar were able to revive the original acoustic memory of this place. Therefore, it can be stated that auralization studies provide a better understanding of intangible heritage.

The seventh research question was focused on usefulness of available computer simulation tools in investigating original acoustics of heritage sites. In this study, original acoustics of Metropolis ancient theatre and Eflatun Pınar has been investigated using two different methods. A room acoustic tool has been utilized to analyze these open-air ancient sites having in mind that there are previous studies conducted in the literature using the same simulation tool. At the end of this study, both methods made it possible to investigate the original acoustics from different perspectives; original acoustics has been explored through objective assessments of Metropolis ancient theatre and valuable auralizations for the original state of Eflatun Pınar have been produced for subjective evaluations. Therefore, it can be stated that available computer simulation tools are useful for a better understanding of the original acoustics of heritage sites.

6.4. Future Directions

Clarity for music values are defined for indoor spaces; however, there is a need to approve if these clarity ratings is suitable for the assessments of the outdoor spaces. Because outdoor spaces are also a venue for musical performances in many cases as in some of the heritage sites like ancient amphitheaters, or sanctuaries.

There is a need to develop objective methods of comparing actual recordings to convolved auralizations.

Knowing that real-time auralization studies have been carried out in the archaeoacoustics before, the rituals and ceremonies in ancient spaces can be experienced better with an advanced study which better reflects the dynamic environment with moving sources. Then, various combination of auralizations can be experienced in a more sensory-stimuli rich environment making exploration of many other scenarios possible.

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