ALMA MATER STUDIORUM - UNIVERSITÀ DI BOLOGNA

SCUOLA DI INGEGNERIA E ARCHITETTURA

DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

CORSO DI LAUREA IN INGEGNERIA EDILE-ARCHITETTURA

TESI DI LAUREA

in
Acustica applicata ed Illuminotecnica

QUALIFICATION AND ACOUSTICAL IMPROVEMENT OF GERMANY'S FIRST MUNICIPAL THEATRE

CANDIDATO:
Marco Lampati

RELATORE
Chiar.mo Prof. Massimo Garai

RELATORE ESTERO
Chiar.mo Prof. Jörn Hübelt

CORRELATRICE
Ing. Giulia Fratoni

Anno Accademico 2022/2023

Sessione II

Contents

List of Figures

List of Tables

Ringraziamenti

Vorrei riservare questo spazio a tutti coloro che hanno avuto un ruolo fondamentale durante il mio percorso di studi fino alla stesura di questa tesi.

Innanzitutto vorrei ringraziare il Professor Massimo Garai per merito del quale ho avuto modo di conoscere ed approfondire l'ambito dell'acustica architettonica; la capacità di condividere efficacemente la sua profonda conoscenza ha contribuito a consolidare in me una forte passione.

Un ringraziamento speciale è destinato al Professor Jörn Hübelt che durante il periodo di ricerca trascorso in Germania è stato un punto di riferimento e di sostegno fondamentale, sia per quanto riguarda il progetto di tesi, sia umanamente, facendomi sentire accolto come un amico. (Ein besonderer Dank gebührt Professor Jörn Hübelt. Während meines Forschungsaufenthalts in Deutschland war er ein wichtiger Bezugspunkt und eine wichtige Stütze, sowohl in Bezug auf das Dissertationsprojekt als auch menschlich, indem er mir das Gefühl gab, als Freund willkommen zu sein.)

Ringrazio l'Ing Giulia Fratoni, correlatrice di questa tesi, per avermi seguito e supportato in maniera meticolosa, fornendomi dei punti di vista importanti che hanno contribuito a rendere questo lavoro per me così soddisfacente.

Ringrazio mia madre Anna per la sua estrema dedizione e per essere veramente la madre migliore del mondo. Attraverso il suo costante e sincero amore è stata capace di crescere una persona felice della propria vita.

Ringrazio mio padre Stefano, il suo punto di vista è stato chiave nel farmi diventare un uomo. Lo ringrazio per i suoi suggerimenti dai quali, tra l'altro, ho appreso che la vita si scrive subito in bella copia.

Ringrazio mio fratello Matteo per essere stato luce e guida nei momenti di difficoltà. Tutt'ora un modello d'esempio ed un amico sincero. Ringrazio di poter far parte della sua bellissima famiglia ed anche per quel leggendario CD di Reggae italiano che mi ha cambiato la vita.

Grazie a Paolo e Graziella, i miei fantastici nonni, sempre ricchi di affetto e consigli preziosi, custodi di quella saggezza e cultura dalla quale traggo forza vitale.

Grazie ai miei amici di sempre Sam, Dario e Jonas. Le avventure vissute assieme mi hanno fatto comprendere il signicato di amicizia, un bellissimo fiore colorato e profumato con qualche spina che merita davvero di essere annaffiato ogni giorno.

Ringrazio Giulio, fedele compagno di questo viaggio durato sette anni attraverso i sette mari. Alla fine ne siamo usciti vivi e siamo arrivati assieme ad aprire il forziere del tesoro.

Ringrazio Sofia, la mia ragazza, per essermi così vicina, interessata ai dettagli e di grande supporto morale e spirituale. Un raggio di sole che spero vorrà illuminarmi e scaldarmi ancora a lungo.

Concludo ringraziando la Musica, costante fondamentale in tutti questi anni, in fondo l'oggetto chiave di questa tesi, senza la quale laurearsi serenamente sarebbe stato impossibile.

Sommario

L'acustica è un elemento spesso trascurato ma profondamente influente. La sua presenza in ogni ambiente è tra i fattori che più condizionano l'esperienza umana. Questa tesi si concentra sulla riqualificazione acustica del Teatro di Freiberg, il più antico teatro municipale della Germania. Il progetto, avviato nel settembre 2022, si è avvalso dell'esperienza dell'Università di Mittweida e dell'Università di Bologna che, attraverso un fruttuoso progetto di tesi all'estero, hanno guidato l'Autore verso lo studio delle problematiche acustiche del Teatro ed il concepimento di una proposta di intervento. Secondo il parere comune di spettatori ed artisti che lo frequentano, il Teatro di Freiberg è caratterizzato da un'acustica troppo "asciutta", poco riverberante, che riduce la qualità delle esperienze artistiche che hanno luogo all'interno delle sue mura.

Il lavoro inizia con una introduzione ai concetti base necessari alla comprensione del fenomeno acustico e dell'acustica architettonica. Nel primo capitolo, vengono spiegati gli elementi essenziali relativi alla definizione del fenomeno sonoro, compresi la sua generazione, la propagazione e la sua misurazione. Inoltre, il capitolo approfondisce le teorie fondamentali alla base dell'acustica degli spazi interni dedicati alla musica, servendo da base teorica essenziale per comprendere e contestualizzare le fasi successive della ricerca.

Il punto focale della tesi, il Teatro di Freiberg, situato nella regione tedesca della Sassonia, viene quindi descritto meticolosamente nel suo contesto storico. Questo capitolo sottolinea la rilevanza architettonica del teatro e la sua importanza culturale. Essendo il teatro municipale gestito da un'istituzione pubblica più longevo in Germania, ha svolto un ruolo fondamentale nella definizione dell'identità della comunità sassone e nell'arricchimento del suo tessuto culturale. Il capitolo inoltre delinea in maniera qualitativa le problematiche acustiche di cui il Teatro è soggetto e che hanno stimolato l'inizio del progetto di tesi.

Il terzo capitolo, dedicato alle misurazioni acustiche, descrive dettagliatamente la campagna di misurazioni condotta durante il periodo di ricerca tesi a Mittweida. L'obiettivo era catturare dati fondamentali relativi alla distribuzione del suono all'interno del teatro, fornendo preziose informazioni sulle sue caratteristiche acustiche. Il capitolo sottolinea la natura meticolosa del processo di raccolta dati, descrive gli strumenti utilizzati e enfatizza l'importanza dell'analisi della distribuzione dell'energia sonora. Questa analisi è necessaria per definire oggettivamente le percezioni soggettive attraverso l'utilizzo di specifici parametri acustici.

La tesi procede poi introducendo il concetto di simulazione acustica virtuale, un approccio che richiede la creazione di un modello 3D dettagliato del Teatro, il quale deve essere opportunamente calibrato al fine di riflettere le condizioni del mondo reale. Utilizzando due dei software di simulazione acustica più riconosciuti, Odeon e Ease, la ricerca esplora sistematicamente l'impatto potenziale di variazioni nella geometria e nei materiali sui parametri acustici. Questa fase della ricerca è cruciale per la proposta di soluzioni efficaci, avvalorate da dati oggettivi.

Il capitolo cinque contiene la proposta di intervento concepita a seguito dei risultati derivati dalle misurazioni e dalle simulazioni. L'intervento ha come obbiettivo il miglioramento delle condizioni acustiche del teatro nel rispettto dei vincoli architettonici, nonché l'allineamento della qualità dell'ambiente acustico alle aspettative del pubblico, degli artisti e dell'amministrazione del teatro. Il capitolo fornisce anche una proiezione dei potenziali costi dell'interventi proposto, enfatizzando la praticità e l'applicabilità delle soluzioni proposte.

Nel capitolo finale della tesi, è presente il confronto tra i risultati ottenuti attraverso le due diverse piattaforme software di simulazione acustica utilizzate durante la ricerca. Analizzando le differenze e le congruenze nei valori dei criteri acustici tra queste soluzioni software, la tesi mira a stabilire una solida base per le decisioni riguardanti l'ottimizzazione dell'ambiente acustico del teatro.

Abstract

Acoustics, often an overlooked element, possesses profound influence, permeating every space and shaping the human experience. This thesis explores the acoustics field within spaces dedicated to the performing arts, with a particular focus on the historic Freiberg Theatre, Germany's oldest municipal theatre.
Initiated in September 2022, this project draws on the collective expertise of the Hochschule Mittweida and the University of Bologna, fostering international collaboration for a meaningful thesis endeavour. The overarching goal is to address the persistent acoustic challenges faced by the Freiberg Theatre, challenges that have significantly impacted both performers and spectators, diminishing the quality of artistic experiences held within its walls.

The work commences with an introduction to the foundational concepts of acoustic phenomena and architectural acoustics. Within the first chapter, the essential elements of sound, encompassing its generation, propagation, and measurement, are explained. Furthermore, the chapter delves into the core theories founding room acoustics, serving as the indispensable theoretical foundation essential for comprehending and contextualizing the subsequent phases of the research.

The thesis's focal point, the Freiberg Theatre, situated in the German region of Saxony, is then meticulously described within its historical context. This chapter underscores the theatre's architectural significance and its cultural importance. As the longest-enduring theatre managed by a public institution in Germany, it has played an instrumental role in shaping the identity of the Saxon community and enriching its cultural fabric. The chapter further delves into a qualitative exploration of the acoustic challenges faced by the Theatre which led to the thesis project's initiation.

Chapter three is dedicated to the process of acoustic measurements. This section of the work meticulously details the measurement campaign conducted

during the research period on-site. The objective was to capture vital data pertaining to sound distribution within the theatre, providing valuable insights into the theatre's acoustic characteristics. The chapter highlights the meticulous nature of data collection process, the advanced tools utilized, and the importance of sound distribution analysis. This analysis is necessary in order to objectively defining subjective perceptions through the application of specific acoustic criteria.

The thesis proceeds by introducing the concept of virtual acoustic simulation, an approach that necessitates the creation of a detailed 3D model of the Theatre, which must face a detailed process of calibration to mirror real-world conditions. Employing two of the most widely recognized simulation software, Odeon and Ease, the research systematically explores the potential impact of alterations in geometry and materials on acoustic parameters. This phase of the research is crucial in proposing effective solutions.

Chapter five unveils the acoustic interventions proposed in response to the findings derived from the measurements and simulations. The primary objective of these interventions is to elevate the theatre's acoustic conditions while scrupulously adhering to architectural constraints. Central to these interventions is the alignment of the acoustic environment with the quality expectations of the audience, the artists, and the theatre administration. Furthermore, the chapter provides a projection of potential budgetary requirements, enhancing the practicality and applicability of the proposed solutions.

In its final chapter, the thesis offers a rigorous comparative analysis of results obtained through the two distinct acoustic simulation software platforms used during the research, Odeon and Ease. By scrutinizing disparities and congruences in acoustic criteria values between these software solutions, the thesis aims to establish a robust foundation for informed decision-making concerning the optimization of the theatre's acoustic environment.

Introduction

Acoustics, often overlooked yet pivotal matter, permeate every space, shaping the auditory environment while influencing human experiences. Within the context of spaces dedicated to art appreciated through the sense of hearing, be it for artists or spectators, optimal acoustics stand as a fundamental element. Few places hold greater significance for the performing arts than a theatre. Here, artists' work materializes in the creation of emotions through notes and movements, while the audience opens themselves to the enchantment of art. However, the commitment and time invested in these experiences could be spoiled by inadequate acoustic conditions. This thesis centres on the acoustic revitalization of the Freiberg Theatre, Germany's oldest and most enduring municipal theatre. Its acoustics in fact is considered excessively "dry" and consequently unpleasant from the point of view of both performers and spectators who frequent the Theatre.
The project began in September 2022, involving resources and expertise from the Hochschule Mittweida, where a research period was undertaken, and the University of Bologna. The intent is to undertake an acoustic treatment project following the state of art practices. Therefore the ultimate goal, once the acoustic situation is thoroughly understood, is to propose a sensible solution supported by objective data, economically feasible, and worthy of serious consideration by the Theatre administration for future intervention. In order to do so the present work begins providing a comprehensive yet concise overview of all the necessary aspects to fully grasp the field of acoustics.

Commencing with a discussion on the generation and characteristics of sound waves, an emphasis is placed on the measurement of sound pressure describing also its unit of measure, the Decibel. Subsequent exploration pertains to the sensitivity of the human auditory system in response to variations in atmospheric pressure. Following this, an examination into acoustic measurements is conducted, with a focus on the analysis of electrical signals generated by measurement systems, which play an indispensable role in comprehending sound characteristics. Attention is dedicated to the realm of room acoustics,

introducing essential components such as reflection, absorption, and sound transmission. Furthermore, comprehensive explanation is provided on the concept of reverberation time, the absorbing properties exhibited by various materials, diffusion, resonance phenomena, normal modes of resonance, as well as the analysis of impulse responses.
This chapter culminates with a comprehensive analysis of the theories that have historically founded primary approaches and methodologies in the study of sound fields within spaces designated for musical performances during the modern era. Each concept introduced within this chapter serves as a foundational element for understanding and subsequently applying acoustic principles in the following chapters of this thesis.

To provide a comprehensive context for the primary research subject, the Freiberg Theatre, situated in the Saxony region of Germany, a meticulous historical exploration is undertaken in this chapter.
The architectural significance and profound cultural importance of the Theatre within the community are underscored and its history, spanning from the 1700s to the present day, is presented in detail. Its origins, originating from itinerant religious performances, and its perception as a viable investment opportunity by entrepreneurs are discussed. Noteworthy is the pioneering insight of the Freiberg municipal administration, which became one of the first in Europe to recognize that investing in the arts could positively impact community development. From an architectural standpoint, a comprehensive description of the physical attributes of the theatre is provided.
A profound understanding of the layout and design elements of the theatre is essential to fully appreciate its acoustic challenges. Notably, the Theatre has been perceived as acoustically dry, and spatial constraints have posed challenges for musicians in the orchestra pit. These served as the impetus for the initiation of this thesis project.
As this chapter progresses, the historical fabric enveloping the Freiberg Theatre is unveiled, shedding light on its enduring legacy and its integral role in shaping the cultural identity of the Saxon community. The exploration of acoustic issues within this historical context will lay the groundwork for the subsequent phases of research.

Chapter three delves into the process of acoustic measurements, a crucial phase in the research.
This section meticulously details the on-site measurement campaign conducted to capture vital data concerning sound distribution within the theatre. The primary objective was to gain comprehensive insights into the theatre's acoustic characteristics. This measurement process was executed

in two distinct phases: the first, conducted by students under the guidance of Professor J. Hübelt from the Hochschule Mittweida, focused on the auditorium, while the second, carried out by the Author, centred on the orchestra pit. This comprehensive approach ensured a thorough assessment of sound distribution throughout the theatre.
The measurement campaign involved various configurations of sound sources and receivers, employing specialized tools such as omnidirectional sound sources and microphones. The resulting impulse responses were then processed using MATLAB software to extract the necessary acoustic parameters critical for evaluating the acoustic conditions of the space.
Specifically, these parameters included energy parameters such as the Reverberation Time (EDT, T20, T30), sound Clarity (C80, C50), and Support (ST, ST extended). The measurements provided an objective basis for comprehending the Theatre's acoustic environment, revealing a notably short reverberation time, particularly for certain frequency bands, with values falling below one second. This objective data forms a crucial foundation for the subsequent phases of the research.

The thesis continues with the introduction to the concept of virtual acoustic simulation, a fundamental step towards proposing effective solutions. In this phase, the research employs two widely recognized simulation software, Odeon and Ease, respectively provided by the University of Bologna and the Hochschule Mittweida, to comprehensively explore the potential impact of alterations in the theatre's geometry and materials on acoustic parameters.
To initiate this process, a detailed 3D model of the Theatre is meticulously created, ensuring that it faithfully represents the real-world conditions within the venue. This step is essential for the simulation to provide accurate predictions and insights. The model is designed to account for various architectural elements, with each surface specified in terms of its corresponding material and associated absorption coefficients. This level of detail must ensure that the simulation closely mirrors the physical characteristics of the theatre and so a calibration plays a critical role. The simulated results are carefully adjusted to align with the measured values obtained during the acoustic measurements phase with the aim of reducing as much disparities as possible between the simulated and real-world acoustic data to ensure the accuracy of the simulation. It's important to note that a certain degree of approximation is utilized, supported by relevant bibliographic sources.
By employing this virtual acoustic simulation approach, the research gains valuable insights into how modifications to the theatre's geometry and materials can impact various acoustic parameters. This knowledge forms the basis for proposing effective and data-driven solutions to enhance the the-

atre's acoustic conditions while adhering to architectural constraints.

At this point it has been possible to present the acoustic interventions proposed in response to the findings derived from the measurements and simulations. These interventions are meticulously designed to enhance the theatre's acoustic conditions while scrupulously adhering to architectural constraints. Central to these interventions is the alignment of the acoustic environment with the quality expectations of the audience, the artists, and the theatre administration.
The proposed solutions aim to address the specific acoustic challenges identified earlier in the research process. To avoid significant alterations to the theatre's architecture, particularly in consideration of its historical significance and the restrictions imposed by heritage authorities, the interventions focus on strategic enhancements. The approach chosen ensures that the acoustic improvements do not compromise the aesthetics of the theatre, as transparent materials are considered to maintain its visual integrity. Furthermore, simulations indicate that by introducing reflective materials to the walls of both the main hall and the backstage area, it is possible to increase the reverberation time, addressing the perception of dryness in the acoustic environment.
In the orchestra pit, efforts are made to render sound propagation more uniform, primarily by attenuating high-frequency components that were identified as bothersome through a questionnaire administered to musicians.
To provide a comprehensive understanding of the proposed interventions, the chapter includes a projection of potential budgetary requirements. This information enhances the practicality and applicability of the proposed solutions, allowing for a more informed decision-making process regarding their implementation.

The final chapter of this research, presents a comparative analysis of the results obtained through the utilization of the two distinct acoustic simulation software platforms. The comparison shows disparities and congruences in acoustic criteria values between these software, shedding light on the strengths and weaknesses of each platform. Notably, the analysis reveals that, despite inputting identical coefficients of absorption and maintaining consistent geometry, there are discernible discrepancies, particularly in the lower frequency ranges. These variations can be attributed to the inherent limitations of ray tracing technology, which struggles to accurately approximate the behaviour of sound waves with wavelengths significantly larger compared to the theatre's dimensions.
This comprehensive evaluation serves as a robust foundation for informed

decision-making regarding the optimization of the Theatre's acoustic environment. By discerning the areas where simulation results align and where they diverge, is possible to make well-informed choices about the proposed acoustic interventions and their potential impact on the theatre's auditory experience.

Chapter 1

Brief summary of room acoustics

1.1 Fundamentals

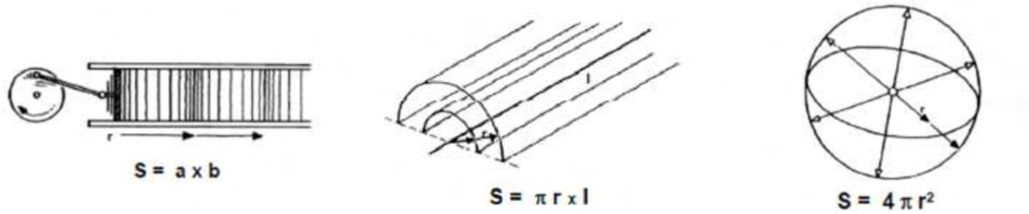
Acoustics is a highly interdisciplinary field, it encompasses a wide range of scientific disciplines which converge to investigate the generation, propagation, perception, and measurement of sound. It integrates principles from rational mechanics to understand sound generation, mathematical physics to study wave propagation, physiological and psychological aspects to explore human reception and electronic techniques for precise wave measurement [1] [2].

Sound generation The generation of sound can be understood considering the capacity of a vibrating membrane to induce oscillatory motion to the adjacent particles. As the membrane oscillates, it imparts oscillations to the neighbouring particles through a chain reaction of particle motion that propagates the disturbances throughout the medium. The physical medium of propagation considered in this work is the air, which possesses specific properties of elasticity and inertia.
The sound wave, resulting from the propagation of particle oscillation, constitutes a longitudinal compression and rarefaction wave, wherein the local particle oscillation velocity does not coincide with the overall wave propagation velocity.
The wave propagation velocity in air, defined as c, the speed of sound, can be derived through thermodynamic considerations and corresponds to the square root of γ (the ratio of specific heat capacities of air, c_p and c_v) multiplied by the ratio of static pressure, p_0 , to static density, ρ_0. This latter ratio can be obtained from the equation of state for ideal gases. Finally, the formula can be further simplified by using the temperature in Celsius.

The resulting value of the wave propagation velocity in air is approximately $331.6 + 0.6t$ (in m/s), this implies that the wave velocity increases gradually with the absolute temperature, with an increment of 0.6 meters per second for each degree of temperature rise.

$$c = \sqrt{\gamma \frac{p_0}{\rho_0}} = \sqrt{\gamma RT} = 331.6 + 0.6t \quad [m/s] \tag{1.1}$$

Wave models The wave models provides a framework for understanding sound propagation since it is possible to analyse complex sound fields as combinations of individual waves. Three fundamental wave models , plane waves, cylindrical waves and spherical waves, approximate sound level decrease during propagation.



(a) Plane waves (b) Cylindrical waves (c) Spherical waves

Figure 1.1: Wave Models

A plane wave represents a quantity with a constant value across perpendicular planes.

$$p(t) = P_o cos(kr) \tag{1.2}$$

Where:

Po = amplitude [Pa]

r = spatial coordinate [m]

$k = 2\pi/\lambda$ = wave number [rad/m]

Spherical waves depict the reduction in sound intensity as a sound wave spreads uniformly in all directions away from a source. They are used to approximate the behaviour of a source located at a considerable distance. Cylindrical waves, on the other hand, represent a propagation that is not uniform in all directions from a source but rather resembles pulsating lines.

Sound pressure In the realm of acoustic phenomena, sound pressure assumes significance as it quantifies the deviation from atmospheric pressure caused by the vibration of an object. This measurable quantity serves as a fundamental parameter that characterises the oscillatory behaviour of the particles of air and represents the transfer of acoustic energy from the vibrating object to the surrounding medium.
Due to its minimal variations the atmospheric pressure can be considered as static in the realm of time and space, the sound pressure, instead, has quantifiable variations. Therefore, is possible to state that the total pressure at a point is equal to the atmospheric pressure (static) p_0 plus the fluctuation of the wave in that point p.

$$p(tot) = p_0 + p, \quad p << p_0 \tag{1.3}$$

Decibels The introduction of decibels (dB) in sound measurement during World War II served multiple purposes. Firstly, it provided a simpler and more comprehensible way to express measured values, such as 20 x 10^{-6} Pa, compared to the previous linear scale measurements. Secondly, it addressed the issue of varying measurement errors by adopting a logarithmic scale, which reduced uncertainty across a wide range of values, from around 200 Pa to 20 x 10^{-6} Pa. Importantly, decibels were employed to better approximate the non-linear and logarithmic response of the human auditory system.
Defining decibels involved several steps. Since direct measurement of sound energy was not feasible, energy was inferred from pressure measurements by squaring the pressure values. To achieve a dimensionless representation, a reference value ($\mathrm{p_0}$) was introduced, resulting in the expression $\mathrm{p/p_0^2}$. By selecting an appropriate reference value, such as $\mathrm{p_0}$ = 1000 Hz at 20 Pa (the threshold of audibility for a pure tone), the resulting numerical values became more manageable.
Recognizing the broad dynamic range of the auditory system, further refinement was needed. Thus, the logarithm of the dimensionless quantity was taken using a base-10 logarithm. This logarithmic transformation compressed the numerical range, condensing the progression from 10 to 100, and 1000 on a linear scale. To extend the numerical range and enhance measurement capabilities, the decibel (dB), which is one-tenth of a Bel, was adopted. This involved multiplying the logarithmic value by 10. The resulting for-

mulation, known as sound pressure level (Lp), provided an effective mean of representing sound pressure (p) in a logarithmic and more expansive manner.

$$lg\left[\frac{p(t)}{p_0}\right]^2 \quad bel[B]; \quad L_p = 10lg\left[\frac{p(t)}{p_0}\right]^2 \quad decibel[dB] \tag{1.4}$$

Human auditory system In order to have a complete view of the acoustic phenomena related to human activities, it is important to understand the characteristics of the human auditory system. It can be divided into three parts: the external ear, the middle ear, and the inner ear.
The external ear consists of the auricle and the ear canal. The shape of the auricle influences sound waves which travel through the closed ear canal. The wave then vibrates the eardrum, which marks the end of the outer ear.
In the middle ear the vibration of the eardrum sets in motion a chain of three small bones: the hammer, anvil, and stirrup. These bones transmit the vibration to the oval window, a membrane that connects to a complex system of canals. The middle ear also includes the Eustachian tube, which balances the pressure in the ear canal. Finally, the inner ear comprises the cochlea, a coiled organ filled with a saline solution, at this point, the sound wave becomes a pressure wave in the liquid. Within the cochlea is the organ of hearing, which is connected to the auditory nerve, here, the signal undergoes its final transformation into an electrochemical signal that propagates along the auditory nerve to the brain.

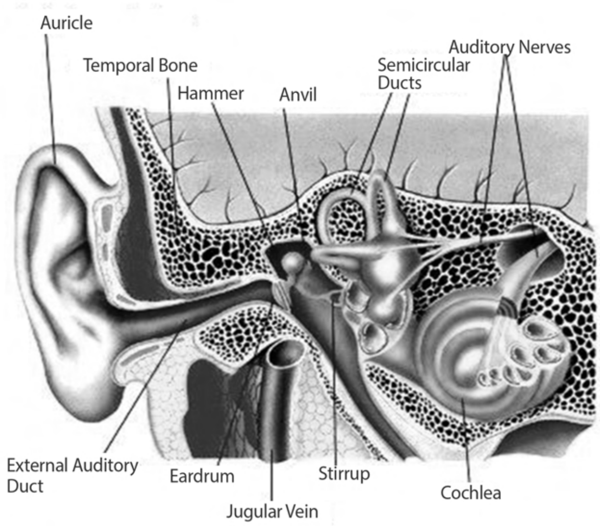


Figure 1.2: Human auditory system

Hearing behaviour Due to the non linear characteristics of human hearing across frequencies, the Fletcher-Munson diagram has been created. It depicts variations in sensitivity across frequencies, highlighting our reduced sensitivity to lower frequencies. It also introduces the concept of psychoacoustic equivalence, where subjective comparisons are made based on a numerical value representing sound levels at 1000 Hz.
The Fletcher-Munson diagram illustrates how the shape of curves changes with increasing sound pressure, showing variations in sensitivity across frequencies at lower levels and more consistent perception at higher levels. The Fletcher-Munson diagram enhances our understanding of human hearing complexities, including sensitivity variations, psychoacoustic equivalence, and perception variations depending on sound pressure levels.

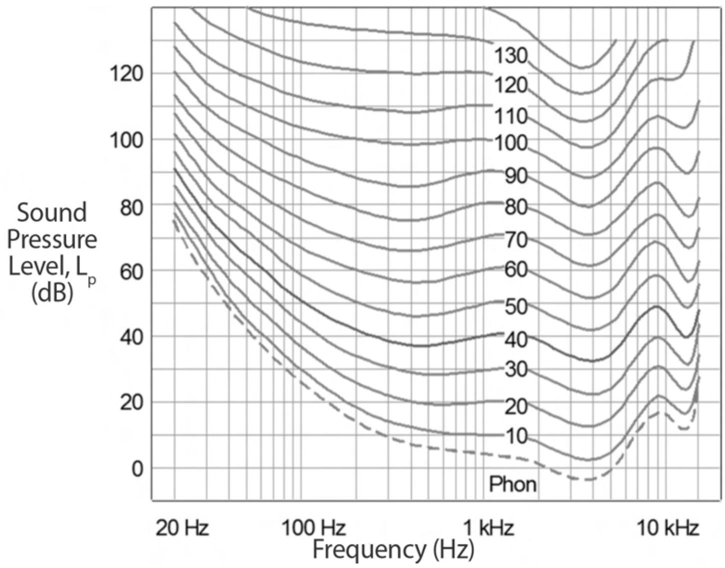


Figure 1.3: Fletcher-Munson diagram

Sound measurements and signal analysis Aiming to grant comfort, sound quality and prevent excessive auditory damage, sound must be measured and processed. An accurate and comprehensive assessments of sound can be achieved considering three key factors: the energy carried by sound waves, the temporal distribution of energy, and the frequency content.
The energy carried by a sound wave is well represented by the sound level expressed in decibels (dB). The sound level provides insight into the intensity of the sound and its impact on the receiver. By quantifying the energy using decibel measurements, an objective assessment can be made.

The temporal distribution of energy, ergo the duration of a sound, plays a crucial role in its effect on human perception. A sound with a high sound level can have different consequences depending on its duration. Consideration should be given to the temporal distribution of energy, as sounds lasting for brief moments versus extended periods can produce distinct responses. The distribution of energy across different frequencies significantly influences perceptions. Sounds that distribute their energy evenly across the audible frequency range provide a balanced auditory experience, however, sounds concentrated on a few specific frequencies, known as atonal sounds, can be more bothersome.

To comprehensively evaluate sound, decibel measurements alone are insufficient. Additional indicators are necessary to account for the temporal and frequency distributions accurately. The root mean square (RMS) is a widely adopted measure of the energy content of a sound signal. It provides an indirect indication of the energy by squaring the instantaneous values, obtaining an average over a relevant time period, and taking the square root. The resulting RMS value, along with temporal weighting and frequency analysis, enables a more precise characterisation of sound properties.

The correlation between time and frequency is a fundamental concept in sound signal analysis. Investigating this correlation provides valuable insights into the behaviour of periodic and random phenomena, enabling efficient analysis and processing of signals.
Complex periodic signals can be decomposed into a series of repeating peaks, each representing a harmonic frequency. Although individual frequencies may not be observed, the presence of these harmonics allows for the analysis and understanding of the underlying periodic patterns. On the other hand, random signals, like the sound of rain, exhibit energy that is uniformly distributed over a certain frequency range.
Fourier analysis serves as a powerful mathematical tool for relating temporal phenomena to frequency phenomena since it enables the determination of energy distribution in the frequency domain. Fourier analysis facilitates the quantification of the contribution of different frequencies within a signal.

Bandpass filters are indispensable in signal analysis for measuring energy within specific frequency intervals. These filters selectively allow a desired frequency range to pass through, simplifying the signal in the time domain to resemble a sinusoidal waveform. Although individual frequencies may not be observed, bandpass filters provide valuable information regarding the energy distribution within the analysed signal.

For finer analysis, octave filters with specific frequency ratios, such as doubling or halving frequencies, are employed. Each octave filter can be further divided into three, resulting in one-third octave filters. These filters provide enhanced resolution and enable detailed analysis of signal components within specific frequency bands.

1.2 Room Acoustics

Architectural acoustics, also known as room acoustics, is a branch of acoustical engineering which deals with the design, analysis, and optimization of the acoustic properties of enclosed spaces. It focuses on how sound behaves within these spaces and how it interacts with various architectural and design elements.
The primary goal of architectural acoustics is to create optimal sound conditions within a space for its intended purpose. This involves considering factors such as sound reflection, absorption, diffusion, reverberation, and noise control. By manipulating the physical characteristics of a room, architectural acoustics could be used to achieve desirable soundproofing, speech intelligibility, musical clarity, and overall acoustic comfort [3].

Reflection, Absorption and Transmission When a sound energy wave encounters a material layer, it undergoes reflection, absorption, and transmission. Since perfect absorption materials are still being developed, a fraction of the energy is always reflected or transmitted. Within an enclosed environment, the reflected energy is of primary interest, while in another room, the transmitted energy becomes significant.
To quantify these phenomena, three coefficients—reflection (r), absorption (a), and transmission (τ)—are defined. These coefficients adhere to the principle of energy conservation, where their sum is always equal to 1 and represent the ratios of reflected, absorbed, and transmitted power, to the total incident power.

$$r = \frac{W_r}{W_i} \quad a = \frac{W_a}{W_i} \quad \tau = \frac{W_t}{W_i} \tag{1.5}$$

$$W_i = W_r + W_a + W_t \quad r + a + \tau = 1 \tag{1.6}$$

The sum of the absorption and transmission coefficients represents the power not reflected, this quantity captures the apparent acoustic absorption. It is commonly used, referred to as the acoustic absorption coefficient (α).
Furthermore, the absorption coefficient is employed to calculate the sound absorptive power, denoted as A, which is the product of the material's surface area (S) and its absorption coefficient.

$$A = \alpha S \tag{1.7}$$

The acoustic isolation is associated with the transmission coefficient (τ), where smaller values indicate higher isolation. To account for the logarithmic nature of human perception, the isolation is expressed in decibels (dB). The logarithm of the ratio between the total incident power and the transmitted power, multiplied by 10, yields a positive dB value. This concept is called the sound reduction index (R), which quantifies the intrinsic isolation capacity of a material.

$$R = 10lg\frac{1}{\tau} = 10lg\frac{W_i}{W_t} \quad [dB] \tag{1.8}$$

The transmission of sound through materials and structures involves complex interactions of reflection, absorption, and transmission. By understanding the coefficients and their relationships, it is possible to optimise the design of materials and structures to enhance acoustic absorption and isolation.

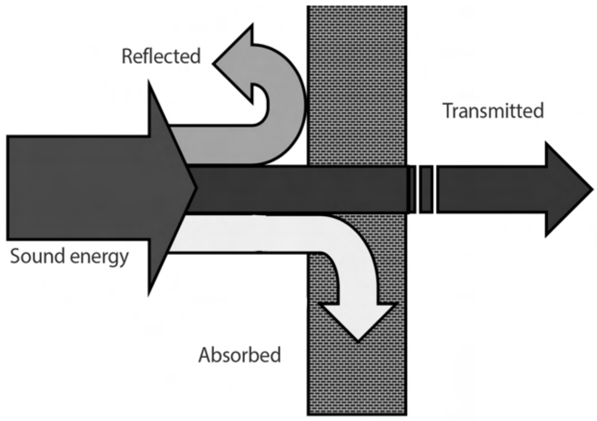


Figure 1.4: Sound wave interacting with a material layer

Reverberation time Fundamental concept in the field of architectural acoustics is Reverberation time, particularly in the study of "room acoustics" or the acoustics of indoor spaces. It refers to the duration it takes for sound to decay in a room after the sound source has been turned off.

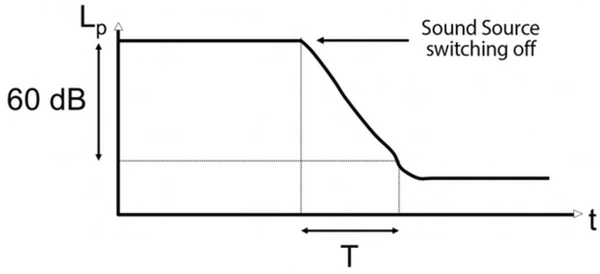


Figure 1.5: Sound pressure level over time

By examining the graph depicting sound pressure level in decibels over time, we observe that when a sound source, such as a speaker emitting sound across various frequencies, is activated, the sound level eventually stabilises, reaching a constant level. When the source is abruptly switched off, the sound gradually decreases rather than disappearing instantly. This phenomenon occurs because sound waves continue to travel in space, bouncing off the walls until they eventually diminish. The point at which the sound level reaches a significantly low level, represented by a second horizontal line indicates the point of extinction.
Reverberation time is commonly defined as the decay of sound by 60 decibels and the corresponding time it takes to reach this decay, measured in seconds. It represents a conventional measure of sound energy decay, often referred to as the "tail" of sound energy. The concept of reverberation time is utilized in various ways in the field of architectural acoustics and the specific value of reverberation time varies significantly depending on the characteristics of the room.
To quickly estimate the reverberation time without direct measurement, a formula widely used in practice is:

$$T = 0.16\frac{V}{A} \quad [s] \tag{1.9}$$

Where T represents the reverberation time in seconds, V is the volume of the room in cubic meters, and A is the equivalent absorption in square meters.

The absorption value, denoted by α, accounts for the average absorption coefficient of the room, which is calculated by multiplying the surface area of each component (walls, floor, ceiling) by their respective absorption coefficients. For more precise calculations, individual specific coefficients are determined for each surface at different frequencies, resulting in a frequency-dependent calculation.

$$A = \alpha S = \alpha_1 S_1 + \alpha_2 S_2 + ... + \alpha_n S_n \quad [m^2] \tag{1.10}$$

The formula for reverberation time was introduced by Wallace Sabine, a prominent professor at Harvard University, in the late 19th and early 20th centuries [4]. Consequently, it is commonly known as the Sabine formula and Sabine is recognized as one of the founders of modern acoustics.
Reverberation time is a vital aspect of room acoustics and it is influenced by factors such as room size, surface materials, and sound absorption properties.

Reverberation room and anechoic chambers Equivalent acoustic absorption (A) defined as the multiplication of a surface area by its apparent absorption coefficient, represents an "ideal" acoustic absorber surface. Considering closed environments, this definition encompasses two extreme scenarios. When the entire space is clad in a material with an approximate α value of 1, there will be no wall reflections or echoes. Such an environment is termed an anechoic chamber. On the other hand, if the environment features hard, smooth, and highly reflective walls, the α value approaches 0. In this case, sound waves persistently bounce off the walls, resulting in a reverberant chamber.

Figure 1.6: Anechoic chamber

While achieving these two ideal conditions may be unattainable in practice, it is possible to come remarkably close. The anechoic chamber has walls, ceiling, and floor covered in deep wedges of sound-absorbing materials.
The wedge shape significantly enhances the wall surface area compared to a flat surface, and the material possesses exceptional absorption qualities. Consequently, sound waves are almost entirely absorbed, creating a reflection-free zone that emulates an outdoor environment.
The contrary scenario of a reverberation chamber is characterised by smooth walls designed to maximise sound reflections. This set-up is employed for acoustic absorption testing. By measuring the chamber's response with and without the material, the differential outcome reveals the material's impact, specifically its acoustic absorption performance. The ISO 354 standard serves as a crucial reference for such measurements. The quantification of α in a reverberation chamber entails measuring the decay of sound pressure level over time, with the sample representing the sole point of acoustic absorption. Achieving an exact α value of 0 is practically infeasible.

Figure 1.7: Reverberation chamber

Electro-Acoustic analogy In order to understand how materials affect sound waves it is possible to consider the electro-acoustic analogy.
The Ohm's law is drawn from electrical circuit theory and brought to the acoustics field to describe the behaviour of acoustic systems. Therefore Ohm's acoustic law relates the variables of sound pressure, particle velocity, and acoustic impedance in a manner similar to Ohm's law in electrical circuits. Ohm's law states that the current flowing through a conductor is

directly proportional to the voltage applied across it and inversely proportional to the resistance of the conductor. Similarly, in acoustic systems, the acoustic Ohm's law relates sound pressure, particle velocity, and acoustic impedance. The acoustic Ohm's law can be expressed as follows:

$$p = Zs * u \quad [Pa] \tag{1.11}$$

Where:

p represents the sound pressure (Pascals),

Zs represents the acoustic impedance (Pa·s/m or Rayls),

u represents the particle velocity (m/s).

In this equation, sound pressure (p) represents voltage, particle velocity (u) is analogous to current, and acoustic impedance (Zs) to resistance.
Acoustic impedance (Zs) represents the opposition or resistance encountered by sound waves as they propagate through a medium. It is determined by the properties of the medium, such as density and speed of sound.
Different materials exhibit varying degrees of acoustic impedance, materials with high acoustic impedance tend to reflect or block sound waves, while materials with low acoustic impedance allow for greater sound transmission.
By understanding the acoustic impedance of materials and their relationship with sound pressure and particle velocity, the acoustic Ohm's law helps in predicting and manipulating the acoustic behaviour of materials. However, it's important to note that the acoustic Ohm's law is an analogy and does not imply a direct equivalence between electrical and acoustic systems. Instead, it provides a conceptual framework for understanding and analysing acoustic phenomena using principles borrowed from electrical circuit theory.

Sound-absorbing materials Despite understanding the concept of acoustic impedance is key in order to study materials acoustic characteristics, a simpler classification is often provided dividing materials into three categories.
The first category encompasses materials that exhibit acoustic absorption due to porosity. These materials have a significant percentage of voids (around 98-99%). They consist of a solid matrix with numerous interconnected air-filled pores. The absorption occurs because these channels within the solid matrix communicate with each other and the external environment.
The oscillating acoustic airflow enters these narrow channels and dissipates

its energy through friction, resulting in the absorption of a substantial portion of the wave's energy. Various materials can be used, such as vegetable fibres, rock wool, glass wool, as well as artificially foamed materials like open-cell polyester or polyurethane foams, and melamine.

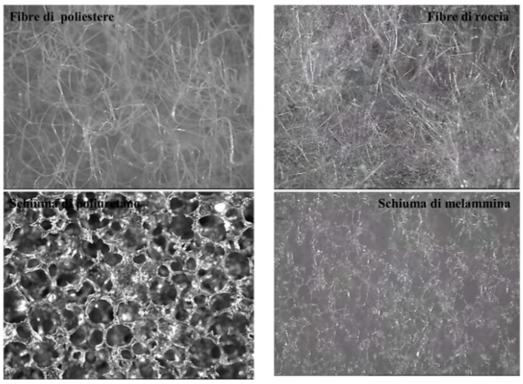


Figure 1.8: Porous materials

In general, at lower frequencies, porous materials panels demonstrates limited absorption capabilities,. However, as the frequency increases, the panel's absorption coefficient rises more steeply, indicating its improved performance at higher frequencies. The material's thickness plays a role in its absorption characteristics, increasing the thickness of the material causes a shift in the absorption curve towards lower frequencies. This means that a thicker material not only enhances absorption at higher frequencies but also extends its effectiveness to lower and mid-low frequencies.

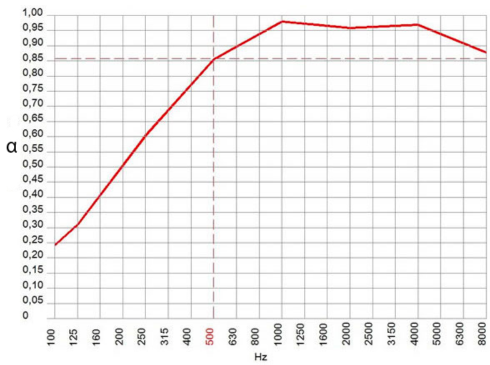


Figure 1.9: Example of α for a porous material absorber

Excessive use of these materials can result in sound distortion by selectively removing high-frequency components while leaving the lower ones intact. Thus, relying solely on porous materials for acoustic treatment may not be suitable, especially in music applications. This is a common mistake encountered in practice.

The second category of materials achieve sound absorption through membrane resonance. These materials are characterized by a specific structure explainable as an infinitely rigid wall with a thin elastic layer with an areal mass, denoted as m' (expressed in kg/m^2) positioned in front of this wall and in the central region, an elastic material, such as plasterboard panels with fiberglass insulation.
Upon the application of pressure to the thin elastic material, the fiberglass layer responds in an elastic manner. Consequently, the panel acts as an equivalent mass while the material situated behind functions as an equivalent spring. This configuration establishes a harmonic oscillator.
Despite the high damping properties of the elastic material, meaning it efficiently converts energy into heat, the absorption curve of these materials exhibits a resonant peak akin to resonant systems. However, the peak appears broad and damped. The resonance frequency, where the peak achieves its maximum value, can be determined using the following formula:

$$f = \frac{c_0}{2\pi}\sqrt{\frac{\rho_{cav}}{m'd}} \quad [Hz] \tag{1.12}$$

Here, c_0 represents the speed of sound in air, ρ_{cav} denotes the density of the material within the cavity (rock wool density if present, otherwise air density), *m'* represents the areal mass of the panel in kg/m^2, and d signifies the thickness of the cavity.

The third class is represented by Helmholtz resonators which operate based on resonance within their cavities. The cavity is connected to the surrounding environment through a narrow neck and a relatively small opening referred to as the "resonator mouth." The resonance behaviour exhibited by Helmholtz resonators is characterized by distinct peak responses. The specific resonance frequency can be determined by considering several factors, including the speed of sound (c_0), the resonator mouth area (S), the volume of the cavity (V), and the length of the neck (l).

$$f = \frac{c_0}{2\pi}\sqrt{\frac{S}{lV}} \quad [Hz] \tag{1.13}$$

In modern applications, Helmholtz resonators find usage in various treatments aimed at sound absorption. One example involves the use of wood slatting with slots or perforated panels. These elements are positioned at a certain distance from the underlying surface, creating a cavity that serves as the resonator. Each slot or perforation acts as an individual resonator, forming a community of resonators sharing the common cavity space.
Adjustments can be made to the resonator's surface area and cavity volume and so by increasing or decreasing these criteria, the resonance frequency can be tuned to target specific frequencies of interest. Additionally, introducing sound-absorbing materials, such as polyester fiber, within the resonator cavity further enhances the absorption capabilities of the system.

Reflections and diffusers In order to comprehend the behaviour of indoor sound fields is necessary to include concepts related to how sound reflects off surfaces.
Specular reflection is a common pattern where sound or light energy is emitted from a source and reflects off a surface towards a receiver, following the same angle of incidence. In cases where the surface is smooth and the wavelength is small, a simplified approach involving a virtual source and a straight path calculation can be used. Diffuse reflection, on the other hand, occurs when energy spreads in all directions regardless of the angle of incidence. This is the most common scenario for non-smooth surfaces. Mixed reflection combines elements of both specular and diffuse reflection, with a predominant direction of diffusion but significant components in other directions.
To understand how sound spreads during reflection, additional criteria are needed. The scattering coefficient s and diffusion coefficient d have been standardized to account for directionality. The diffusion coefficient d measures the uniformity of sound diffusion in all directions and depends on the angle of incidence θ.
The idea of measuring the diffusion coefficient originated from the study of Schroeder diffusers, which are objects with irregular surfaces designed for a controlled and predictable sound diffusion in all directions. The use of Schroeder diffusers can be particularly useful in architectural acoustics and audio engineering applications.

Figure 1.10: Schroeder diffuser

Room modes In a closed environment, the sound field is not uniformly distributed; rather, it is distributed according to three cosines. The non-uniform distribution of the sound field arises due to the spatial solution of the Helmholtz equation, which is expressed in terms of three cosine functions: Px(x), Py(y), and Pz(z), corresponding to the three spatial coordinates. These cosine functions describe the spatial variation of the sound field along each coordinate axis and exhibit maximum and minimum values.

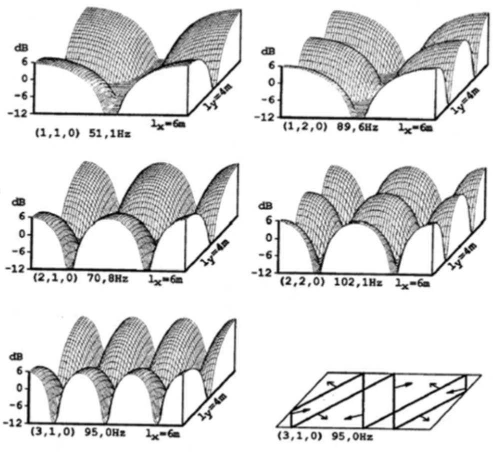


Figure 1.11: Normal modes

The presence of maxima and minima within the sound field is a consequence of the boundary conditions imposed by perfectly rigid walls.

At the walls, the pressure reaches a maximum, causing the energy to momentarily accumulate and then reflect back. This leads to the formation of stationary waves within the closed environment. This contribute to significant variations in sound level at different locations. As moving within the environment and encounter different areas of maximum and minimum pressure, the sound level changes significantly. Certain points may exhibit 70 dB, while others may have 65 dB or even lower. Considerable oscillations are observed.
The bouncing modes between walls can be classified into three forms, known as normal modes. The first form is axial modes (1D), where sound bounces back and forth between two flat and parallel walls. The second form is tangential modes (2D) bouncing in two dimensions, forming a plane. The third form is oblique modes (3D) and the bouncing occurs in three dimensions. The number of normal modes increases rapidly with the cube of the maximum frequency, while the modal density increases with the square of the frequency. At low frequencies, there are few well-spaced modes, resulting in noticeable energy gaps. At high frequencies, there are numerous modes, with peaks compensating for the gaps, leading to a more uniform distribution. Musicians in small untreated environments may encounter listening difficulties at low frequencies, while changes in position can significantly affect the experience.

Acoustic environment study approaches Depending on its characteristics it is possible to study acoustic environments using three different approaches. The first is the *wave theory*, which offers greater accuracy but entails analytical complexity, making it suitable for simpler environments. The second is the *geometrical approximation*, where sound is treated as propagating along sound rays orthogonal to wave surfaces. This approximation is employed when the wavelength is smaller than the typical size of the surfaces being considered. It eliminates the wave concepts of wavelength and phase, focusing solely on the path and trajectory of energy propagation. Lastly, there is the *energetic-statistical* approximation, which considers only the average behaviour of reflections and the energy that bounces off walls. This approach was adopted in the past due to limitations in computational resources and provides a diffuse sound field.

Schroeder frequency (named after its discoverer), as a convention, is used to determine the transition between modal regime (well-separated normal modes) and statistical regime (modes overlapping significantly). Above the Schroeder frequency, it is better to treat all modes statistically.

Schroeder frequency can be defined with the following equation:

$$f_c = \sqrt{\frac{3c^3}{2ln10^6}}\sqrt{\frac{T}{V}} \approx 2000\sqrt{\frac{T}{V}} \quad [Hz] \tag{1.14}$$

Where T is the reverberation time of the room in seconds

V is the volume of the room in square meters

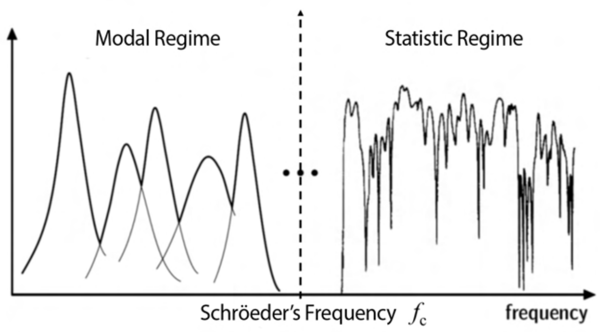


Figure 1.12: Modal and statistic regime

Impulse response The impulse response is a fundamental concept in acoustics that characterizes how a system (a room in the case of architectural acoustics) responds to an intense and brief input signal called impulse. It provides valuable information about the system's behaviour over time in modifying the acoustic input. In practice, the impulse response is obtained by introducing a impulse into the environment from a sound source. As the impulse propagates through the environment, the microphone detects the resulting pressure fluctuations.
Analysing the squared impulse response provides insights into the energy decay characteristics of the environment. Integrating this response over time yields a decay curve, which can be used to determine the reverberation time. The shape and duration of the impulse response offer valuable information about the environment's acoustic properties.
Additional analysis and techniques can be applied to the impulse response to extract further information such as the criteria used to judge a space's acoustic quality.

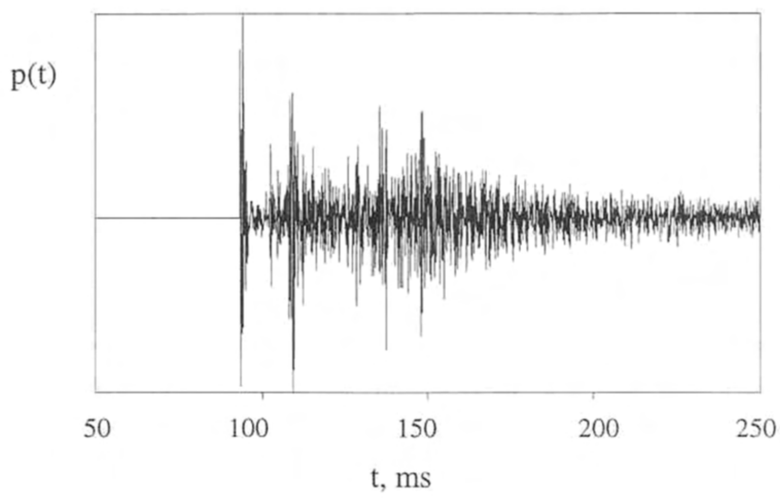


Figure 1.13: Impulse response shown as sound pressure over time

Auralization Auralization is the process of creating a virtual acoustic environment in order to replicate the acoustics of a non-existent space.
By combining the simulated characteristics of the acoustic space with a signal recorded in an anechoic room, is possible to generate and auralised signal. Ideally, this signal is experienced through headphones.
The process startS with the Room Impulse Response (RIR) that characterizes the acoustic behaviour of the environment, the Head Impulse Response (HIR) for each ear is then incorporated. Through convolution, the Binaural Room Impulse Response (BRIR) is obtained, representing the empty acoustic response without music. The recorded anechoic signal is then introduced, undergoing convolution once again. This generates the complete binaural response, capturing an immersive audio experience on how the room would affect the acoustics within itself [5].

1.3 Theatres and concert halls acoustics

The acoustics of theatres and concert halls rely on a combination of objective and subjective criteria to define and ensure the desired sound quality. Within this context various topics are addressed to understand and optimize acoustics and different eras and theories that have contributed to the development of these spaces must be analysed. Although definitive indicators have not yet been established, existing criteria have been refined, and ongoing work is being conducted in this ever-evolving field. The subject of concert hall acoustics remains open to further study and discoveries.

Sabine's Theory Modern acoustics took a significant leap with Sabine's theory emerging in the early 1900s. Prior to that, the field lacked an effective theory, heavily relying on empiricism. Sabine's pioneering work introduced a groundbreaking shift by offering an objective framework to understand sound behaviour within enclosed spaces, introducing the revolutionary concept of reverberation time [4].
. Sabine's theory, though revolutionary, had its boundaries. It was grounded in a drastic approximation, assuming uniform sound energy distribution across environments. This simplification ignored the presence of normal modes, which substantially influence sound distribution patterns. Additionally, the theory predominantly focused on reverberation time as its primary parameter, disregarding other influential effects and criteria relevant to human auditory perceptions.
Despite its limitations, Sabine's theory formed a robust foundation for analysing acoustic environments. Nevertheless, as time progressed, more comprehensive approaches emerged. These approaches considered not only the physical aspects but also the subjective elements of sound perception. Psychoacoustic studies have been undertaken to comprehend how individuals perceive and assess acoustic quality. By merging objective measurements with subjective evaluations, a more holistic comprehension of acoustic quality can be attained. This amalgamation yields more refined methodologies for designing and optimizing acoustic environments, effectively bridging the gap between scientific understanding and human experience.

Beranek's Theory The renewal of studies on concert halls had to wait until the 1960s. Beranek dedicated his life to studying acoustics, with a particular focus on concert halls and in this period, significant works began to be published. His approach involved analysing the best halls in the world, studying their acoustics and consulting renowned musicians and music critics

to incorporate subjective evaluations.
Beranek aimed to establish correlations between physical sound descriptors and psychoacoustic judgments. This bridge between the technical and musical aspects is essential for a comprehensive understanding of acoustic perception. Additionally, Beranek's attempt to introduce evaluation scales for concert halls and opera further emphasized the importance of subjective perception in acoustic design. The goal was to connect physical criteria to the perceived experience of the listener, considering factors such as intimacy, clarity, timbre, and color of sound [6]. However, his theory also presented some inevitable shortcomings. The descriptors used are interdependent, for instance, the reverberation time and sound clarity are related: an increase in reverberation can enhance clarity but at the expense of sound definition. Additionally, the initial attempt to establish a rating scale was arbitrary and ambiguous, leading to its subsequent abandonment.
Despite these limitations, Beranek's acoustic theory remains a milestone in bridging objective acoustic criteria and subjective musical perception.

Barron's Revised Theory Barron, a distinguished figure in the field of acoustics, presents the Revised Theory as a significant departure from the established Sabine's theory. While Sabine's theory presupposes a uniform distribution of reverberation throughout an enclosed space, Barron's ground breaking work challenges this notion. Through meticulous analysis of 40 different concert halls, Barron's investigations illuminate a remarkable revelation: the intensity of reverberation diminishes as the distance from the sound source increases. This departure from Sabine's assumptions has profound implications for our understanding of sound behaviour in enclosed environments.
In Barron's pioneering study, he undertakes an empirical journey, meticulously measuring sound levels within these diverse concert halls [7]. Through careful correlation with his Revised Theory, Barron establishes a compelling concordance between the theoretical predictions and the experimental observations. This alignment substantiates the efficacy of Barron's approach and underscores the significance of his findings.
Central to Barron's contributions are the pivotal criteria he introduces. Notably, the G parameter emerges as a cornerstone concept. G encapsulates the concept of relative sound level, contrasting the energy at a specific point with that at a reference distance of 10 meters. This parameter not only allows for a nuanced assessment of sound intensity but also opens avenues for informed acoustic design decisions.
Additionally, Barron places particular emphasis on the concept of clarity, as

represented by C80. In Barron's view, sound quality is intricately linked to clarity, and C80 serves as a pivotal indicator in evaluating it. By considering the energy arrivals within the initial 80 milliseconds and beyond, Barron offers a comprehensive perspective on sound clarity, providing a novel parameter for assessing and optimizing auditory experiences.
Barron's innovative methodology extends beyond theoretical frameworks. He employs logarithmic diagrams, which elegantly illustrate the relationships between different acoustic components. Analysing the interplay between early and late energy arrivals, Barron skilfully calculates the G and C80 criteria, offering a sophisticated means of regulating crucial aspects of sound behaviour. This method resonates with the earlier findings of Beranek, fortifying the understanding of how sound interacts with enclosed spaces.
In essence, Barron's work marks a pivotal advancement in acoustical theory. His Revised Theory, supported by empirical evidence, challenges prevailing assumptions and provides new tools for designing optimal acoustic environments. Barron's emphasis on the G and C80 criteria, along with his incorporation of early and late energy arrivals, reshapes our understanding of sound behaviour and its perceptual implications. As the field of acoustics evolves, Barron's legacy endures as a beacon guiding our pursuit of superior auditory experiences.

Ando's Theory Ando introduces the "Theory of Orthogonal Factors" for acoustic analysis, proposing an innovative and rigorous approach. In contrast to the excessive number of descriptors in other theories, Ando identifies an essential set of parameters that represent the fundamental acoustic characteristics of musical pieces. These factors are linearly independent and define a preference scale [8].
Furthermore, Ando's theory presents a comprehensive methodology that leverages a cognitive model inspired by neural network functioning in the brain. By simulating how the brain processes auditory information, Ando aims to bridge the gap between objective acoustic analysis and subjective human perception. This involves comparing the results of the sound field's objective analysis with the subjective judgements of volunteers, who participate in tests that include physiological measurements like electroencephalograms. These measurements provide insights into how the brain responds to different soundscapes, enabling a more holistic understanding of acoustic preferences.
The obtained results are subjected to intricate mathematical and statistical analyses. These analyses aim to establish correlations between the orthogonal factors identified by Ando's theory and traditional acoustic descriptors,

such as reverberation time. By quantitatively linking the fundamental parameters to well-established acoustic metrics, Ando's theory adds a layer of rigor to the evaluation process.
In practical terms, this theory offers a robust method for assessing the listening quality of various acoustic environments. By characterizing venues based on sound preferences, Ando's approach provides a valuable framework for designing and optimizing spaces such as concert halls and theatres. It merges the subjective experiences of listeners with objective scientific analyses, enhancing our ability to create acoustic environments that cater to both human perception and acoustic principles.

Chapter 2

The Freiberg Municipal Theatre

2.1 Die Kunst gehört dem Volke: Freiberg Municipal Theatre's history

Figure 2.1: Freiberg Municipal Theatre

The Freiberg Theatre, object of this study, is located in the municipality of Freiberg, in the Saxony region of Germany. It is recognized as the oldest and most enduring municipal theatre in Europe and holds a prominent place among Germany's long-standing active theatres. Situated in the historic center of the town, it assumes a prestigious position facing the magnificent Nikolai church [9].

The theatre building itself is an exquisite example of German historical architecture, serving as a tangible testament to the region's long-standing theatrical tradition. Throughout the centuries, it has hosted a variety of performances, concerts, and artistic presentations, enriching the cultural fabric of Freiberg and attracting numerous enthusiasts of the performing arts.

Today, the Freiberg Theatre houses a resident theatre company and an orchestra dedicated to preserving and advancing the region's theatrical heritage. Audiences can experience a unique atmosphere within the elegant theatre hall, which still shows the charm and sophistication of its historical past.

This theatre stands as a living symbol of the profound passion for the performing arts and bears witness to Freiberg's cultural and historical significance. It represents a venue that has helped shape the local community's identity over the centuries, providing high-quality entertainment and fostering the cultural development of the region.

It is an artistic and historical treasure that continues to play a significant role in Saxony's cultural life, offering audiences unforgettable theatrical experiences and celebrating the profound importance of art as a vehicle for knowledge and people's expression.

The effigy *Die Kunst gehört dem Volke* -The art belongs to the people- which dominates the façade of the theatre, depicts the essence of its history.

Early History The earliest forms of theatre in the city date back to the medieval period and are associated with religious performances.

Initially, religious plays were performed inside the church, with indirect references to theatrical representations in Freiberg's main church, the Dom St. Marien. There is no direct evidence of spiritual plays before 1500, but there are indications of possible theatrical involvement in the carvings of the original monumental western portal of the dome, known as the "Golden Gate". Over time, the Easter plays moved from the church to the Obermarkt, a square in Freiberg, in 1509.

This shift marked an increasing independence of theatre from the church and coincided with the city's economic expansion.

Figure 2.2: Public plays in *Obermarkt*

The Easter plays in Freiberg attracted thousands of spectators and featured elaborate performances, involving the clergy and occasionally supplemented by travelling minstrels and vagabonds. These plays mainly depicted the the birth, suffering, death, and resurrection of Christ. In addition to the Easter plays, Freiberg also hosted Worship Games during the Pentecost period. These games involved various guilds of craftsmen and included representations of the Last Judgment and themes related to biblical history.
The presence of theatre in Freiberg was strongly influenced by religious traditions and the city's cultural context of the time. Its evolution saw a transition from the ecclesiastical setting to public spaces such as squares and dedicated halls, reflecting a greater independence and expansion of theatrical forms. These early forms of theater in Freiberg constituted an important part of entertainment and civic culture, engaging the community and providing opportunities for artistic expression and reflection on religious and human themes.

The Theater situated *am Buttermarkt* in Freiberg, which originated from a town house built in 1623, stands as one of the oldest municipal theatres in Germany. The construction of municipal theatres was not uncommon during the 18th century, with several cities establishing their own theatres to showcase cultural status. However, the Freiberg project was unique in its historical context.

The theater's story reflects the aspirations and struggles involved in its construction. The initial resistance faced by the city council in Leipzig regarding the construction of a new theatre highlights the distinctiveness of the Freiberg initiative. The theater's establishment was aligned with the philanthropic spirit of the time, as citizens contributed to the cultural and educational development of their community.

The construction of the Theater involved the conversion of a medieval residential building into a theatre within a short span of three months during the winter season. The theatre's architectural design included galleries that formed a half-oval shape above the parterre, although this arrangement hindered the view from the side seats.

The theatre emphasized communal space for socializing and communication, with the audience itself becoming part of the performance. The theatre's design remained intact since its opening in 1790, providing an intimate setting for encounters between performers and spectators. The construction process involved adding neighbouring houses to expand the theatre complex, accommodating functional needs such as the foyer and stairwell. The theatre operated as a travelling show house until 1875 when it came under municipal management.

Figure 2.3: Freiberg Theatre *am Buttermarkt* in 1870

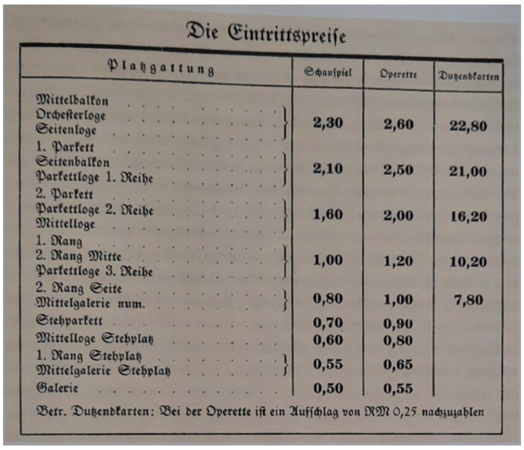
The decision by the Freiberg city council to purchase the theatre in 1791 was driven by factors such as the city's surplus funds, the desire for better management, and the belief that - *the theatre would improve the standard of living for the public* [9]. The acquisition of the theatre showcased Freiberg's dedication to nurturing the arts, setting a precedent for other municipalities and establishing the theatre as a cultural asset and symbol of the city's identity.
Overall, the birth of theatre in Freiberg represents a unique historical development that reflects the evolving understanding of theatre as an art form, a communal space, and a cultural and societal asset.

From 18th Century to WWII The Freiberg Theatre saw the rise of an amateur theatre trend in the late 18th century, characterized by plays which emphasized progress and social responsibility, using performances as a means to support charitable causes. The theatre performances took place in the municipal department store hall, and the donations collected were used to purchase firewood for the less fortunate citizens.
The aim was to attract bourgeois families and promote business ethics, personal decency, and moral moderation. The performances not only provided entertainment but also served as a platform for social interaction and the expansion of personal relationships. The Theatre group consisted of prominent individuals from Freiberg, including mining officials, council members, and influential figures from academia and the military.
The Freiberg City Theatre was established in the late 18th century and underwent renovations and expansions over the years to accommodate a growing audience. It became a venue for professional theatre productions, including grand operas. The city council actively sought guest performances and provided excellent facilities for touring companies. The theatre played a significant role in the cultural development of the city, attracting both local and foreign talent.
Dr. Max Neumann, as the Director of the Freiberg theatre, revolutionized the music theatre scene and brought in professional singers to enhance the ensemble's repertoire. The theatre experienced notable performances and engaged talented Kapellmeisters, such as Georg Jarno and Leon Jessel, who later gained recognition as opera composers.
Throughout the years, the theatre directors in Freiberg displayed exceptional talent and versatility, directing renowned works and exploring thought-provoking plays that challenged societal norms. They contributed to the evolving perspectives of society and the cultural development of the city.

Figure 2.4: Plays in early 1900's

Alexander Oscar Erler, as the theatre director in the 1920s and 1930s, navigated the cultural upheaval of the "Golden Twenties" and embraced contemporary works, including avant-garde performances and political cabarets. Despite financial challenges, Erler managed the theatre with artistic integrity, contributing to the cultural development of the era. During its history the Theatre's building underwent renovations and modernization, incorporating electric lighting in 1913, which significantly enhanced the audience's experience. It continued to adapt to changing times, presenting a diverse repertoire and overcoming challenges, such as financial constraints during WWI.

Also during WWII Freiberg Theatre faced bureaucratic constraints and limitations imposed by the Nazist regime. The Theatre became the city's "director's office," with an appointed intendant who had limited decision-making authority. Even minor decisions required approval from the municipal head of the theatre department. This bureaucratic control extended to matters such as the selection of plays and the hiring of personnel.
The archive files provide insight into the challenges faced by the theatre but despite these limitations, the administration continued its operations. Strategies were implemented to attract more viewers, ticket prices varied based on seating options and the financial means of the individual spectators.



Die Eintrittspreise

Platzgattung	Schauspiel	Operette	Dutzendkarten
Mittelbalkon Orchesterloge Seitenloge	2,30	2,60	22,80
1. Parkett Seitenbalkon Parkettloge 1. Reihe	2,10	2,50	21,00
2. Parkett Parkettloge 2. Reihe Mittelloge	1,60	2,00	16,20
1. Rang 2. Rang Mitte Parkettloge 3. Reihe	1,00	1,20	10,20
2. Rang Seite Mittelgalerie num.	0,80	1,00	7,80
Stehparkett	0,70	0,90	
Mittelloge Stehplatz	0,60	0,80	
1. Rang Stehplatz Mittelgalerie Stehplatz	0,55	0,65	
Galerie	0,50	0,55	

Betr. Dutzendkarten: Bei der Operette ist ein Aufschlag von RM 0,25 nachzuzahlen

Figure 2.5: Price list in 1937/38

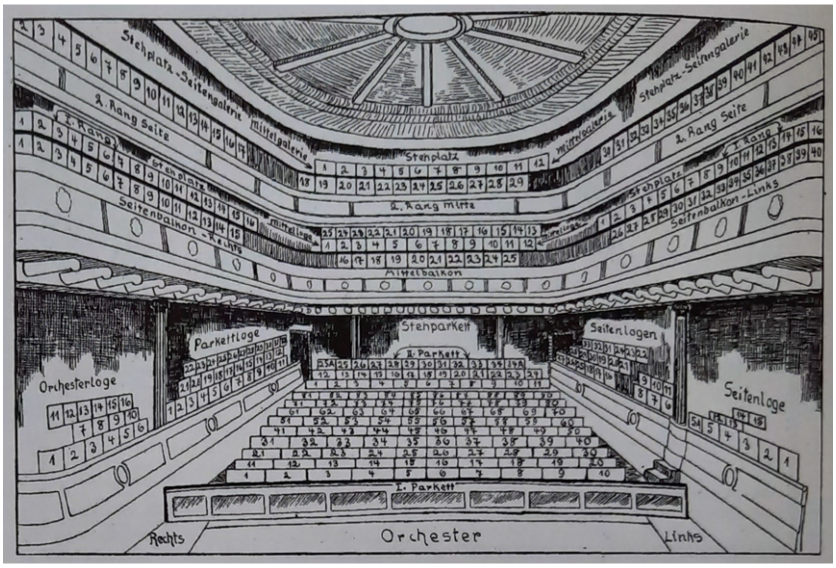


Figure 2.6: View of the hall from stage, 1937

The police supervised performances, although specific evidence of this is scarce. Overall, the Freiberg Theatre faced bureaucratic constraints and had limited decision-making authority during the Nazi era. Despite these challenges, the theatre continued its performances, adapting to the prevailing political climate and implementing strategies to attract audiences.
After the reopening of the theatre in Freiberg following the end of World War II, the first season featured an impressive repertoire of plays and op-

eras. Despite the limited ensemble, the theatre managed to deliver captivating performances to the audience. Günther Sauer, the first director of the new season, displayed incredible energy and involvement, participating as an actor in almost every performance, directing productions. Once again in Freiberg Theatre history the plays aimed to reflect the people's feelings, in this case the prevailing political helplessness and spiritual uncertainty experienced by the population at the time.
Overall, the reopening of the theatre in Freiberg marked a significant moment in the city's post-war reconstruction. The dedication and resilience of the artists and technicians involved in reviving the theatre played a vital role in bringing back cultural life and providing a sense of normalcy in the aftermath of the war. The productions staged during this period reflected the societal soul, capturing the prevailing political climate and the collective experiences of the audience.

Freiberg Theatre in Eastern Germany In the post-war era the Theatre faced challenges and changes influenced by political factors and cultural trends. The emergence of socialist realism as a guiding principle in East Germany, along with the persistence of traditional theatrical forms inherited from the Nazist era, shaped the theatre scene. Freiberg Theatre performances featured a mixture of Soviet plays adhering to socialism and occasional Western European plays, reflecting the contrasting theatre landscapes in East and West Germany.
Despite the political divergence between Eastern and Western Germany during the Cold War, the aesthetics of staging remained consistent in both regions, continuing the tradition of naturalism. The theatre repertoire in East Germany focused on plays that reflected historical struggles and everyday Soviet life, while Western Germany saw the prominence of American and Western European plays. The concept of "socialist realism" in East Germany emphasized universality and the positive aspects of Easter Germany lifestyle.
The theatre scene also faced challenges in terms of maintaining audience numbers. The advent of television and the erosion of traditional cultural ties led to a decline in theatre attendance nationwide. However, Freiberg Theatre managed to maintain a relatively high number of visitors, attributed to the city's deep-rooted cultural traditions and the loyalty of its audience.
Throughout the years, Freiberg Theatre adapted to changing cultural landscapes and remained an important cultural institution in the city. The theatre management carefully selected plays to align with broader themes contributing still to the vibrant cultural fabric of Freiberg.

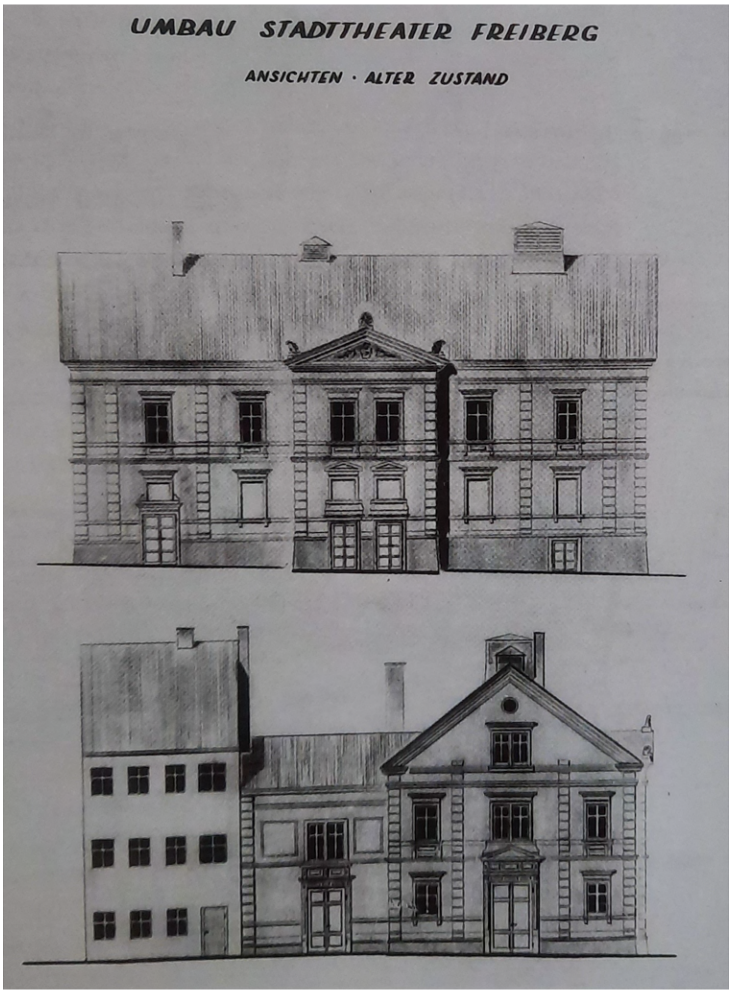


Figure 2.7: Prospects of Freiberg Theatre in 1963

The theatre's repertoire encompassed a variety of genres, including classical, comedic, and contemporary dramas, as well as operas, operettas, and musicals. The programming aimed to cater to diverse audience preferences and attract younger visitors. The theatre's adaptability and commitment to delivering well-executed performances allowed it to maintain its significance and appeal to the community [9].

Figure 2.8: Aereal view before renovation in 1981

From 1980s to present days During the 1980s, the Freiberg theatre faced an important challenge: the reconstruction of its building. Despite the difficulties, the theatre continued to actively engage the local community and foster artistic collaborations through guest performances and cultural exchanges. However, the working conditions and infrastructure of the theatre posed problems, and the deteriorating state of the building necessitated frequent repairs. To address these issues, reconstruction plans were initiated during the early 1980s, and actual construction work began in 1983.

During the reconstruction phase, innovative methods were employed in order to save time, such as the use of helicopters in the placement of prefabricated roof trusses [9]. The aim of the reconstruction was to preserve the historical character of the theatre while ensuring functionality and safety. The auditorium underwent modifications to raise both the audience and the stage area by approximately two meters, yet the original tiers, balustrades, cast-iron columns, and intricately designed stucco ceiling were retained. Meticulous efforts were made to recreate the original colours and restore elements such as the inner portal and slender columns to their former glory.

Figure 2.9: Renovation works

Figure 2.10: View of the from the back of the façade

The theatre's reconstruction took place during a period of complex changes, coinciding with social and political transformations of the time. Nevertheless, through dedication and perseverance, the restoration proved to be a resounding success. The theatre reopened its doors in June 1991, symbolising a moment of great symbolic importance for the reunification of Germany and the establishment of a European order of peace. The reopening of the theatre signified the return of its central role in the cultural life of Freiberg and made a significant contribution to the rich cultural heritage of Central Saxony in the 21st century.

Figure 2.11: Helicopter

Figure 2.12: Truss placement

The Mittelsächsisches Theatres Freiberg Theatre, alongside the Döbelner Theatre situated in the nearby town of Döbeln, are part of the *Mittelsächsisches Theatre und Philarmonie GmbH*, a distinguished cultural institution founded in 1993. While sharing members of the orchestra and the troupe and a common goal of providing exceptional theatrical experiences, the two theatres showcase architectural differences that reflect their individual histories.
The Döbelner Theater, underwent an important renovation following the devastating fire it experienced durning the 20th century. The reconstruction resulted in a modernized appearance, compared to the more classical look of Freiberg Theatre, blending contemporary design elements with the historical essence of the theatre.
Since their opening both theatres have continued to present a diverse range of captivating performances, catering to various artistic preferences and interests. The repertoire has included classical plays, contemporary dramas, musical productions, operas, and ballet performances, ensuring a dynamic and engaging program for theatre enthusiasts. The Mittelsächsisches Theatres administration has also embraced innovative and experimental productions, pushing the boundaries of traditional theatre and captivating audiences with

thought-provoking performances. With their commitment to artistic excellence and their ability to adapt to changing theatrical trends, the theatres in Freiberg and Döbeln have solidified their positions as cultural pillars within the region. Their programming choices aim to entertain, inspire, and challenge audiences, ensuring a vibrant and enriching theatre experience for all.

2.2 Freiberg Theatre's existing condition

Location The Theatre of the city of Freiberg is situated in a geographically significant location in the region of Saxony, Germany. The municipality of Freiberg stands as a historic city renowned for its architectural heritage and cultural eminence, characterized by medieval structures of notable significance and a thriving academic community.
In the surroundings lie other notable urban centres of significance. Dresden, the capital of Saxony, garners acclaim for its exemplary baroque architecture and Renaissance artistry. Chemnitz, a neighbouring city, distinguishes itself through contemporary architectural marvels, exhibiting a unique fusion of modern design concepts. Leipzig, a city of vibrancy, boasts a rich musical tradition and serves as a hub for an enthralling artistic milieu. Natural landscapes surround the area, the Ore Mountains, easily accessible along Czech-German border, present awe-inspiring hiking trails and panoramic views. The Elbe River, traversing the vicinity, offers opportunities for leisurely river cruises and outdoor pursuits along its banks. In essence, this location engenders a captivating fusion of historical legacy, cultural prominence, and natural splendour, inviting visitors to explore of the region's diverse attractions.

Figure 2.13: Freiberg old city

Figure 2.14: Freiberg Theatre block in front of Nikolai Church

Figure 2.15: Freiberg Theatre

Architectural features Freiberg Theatre, occupying an entire city block, has gradually assimilated adjacent structures over time, resulting in a comprehensive complex that extends far beyond the main theatre hall. Alongside the auditorium, the theatre encompasses various additional rooms and spaces dedicated to rehearsals, dining facilities, instrument and equipment storage, dressing rooms and administrative offices. Well-designed access areas further facilitate seamless navigation between the different areas, the main hall and the balconies.

Figure 2.16: View of the hall from stage

The focal point of the theatre, the elegant main hall, comprehend a ground-floor and two tiers of beautifully designed balconies. The interior walls of the hall feature meticulously crafted brickwork, adorned with a smooth red plaster finish. The balconies exhibit a fusion of wooden framework, painted in a crisp white hue, accentuated by exposed timber joists. The meticulously crafted balustrades, showcasing intricate gold bas-reliefs, provide a touch of opulence. Supporting the balconies are slender, metal lobed columns adorned with Corinthian capitals, adding an element of grace and grandeur.Above, the ceiling is adorned with a striking chandelier, its intricate design complemented by stucco decorations of hight quality, featuring captivating floral motifs. Additionally, the ceiling showcases tasteful frescoes, depicting scenes that harmoniously blend artistic and architectural elements.

The seating within the theatre radiates an air of refinement, with plush velvet upholstery in a rich shade of red adorning both the seats and backs. The main hall's flooring features a meticulously laid, lightly-hued parquet. The same attention to detail extends to the balcony floors, creating a cohesive and visually pleasing atmosphere throughout the theatre.
In terms of capacity, the theatre comfortably accommodates a modest audience of fewer than 400 spectators, ensuring an intimate and engaging experience. The stage itself is generously proportioned, boasting an orchestra pit beneath that serves as a concealed space for the musicians accessible through a system of stairs located in the backstage area.
The theatre has flexibility features enhanced by a hydraulic piston system, enabling part of the orchestra pit's floor to be raised and aligned with the rest of the stage when the orchestra is not present. The compact orchestra pit, capable of accommodating approximately 40 musicians, showcases walls constructed of exposed reinforced concrete painted black, creating a visually homogeneity with wooden flooring. This deliberate design choice adds depth to the pit and character to the overall architectural composition.
Completing the architectural ensemble, concealed from the audience's view, a hidden space above the stage provides a dedicated area for technical components such as lighting apparatus and suspended objects. This space also serves as a practical location for storing ropes, chains, and other stage-related equipment, contributing to the seamless execution of captivating and dynamic stage productions.

Figure 2.17: View of the ceiling and chandelier

Pictures and architectural drawings In order to grant a better understanding of the Theatre's characteristics, in the following pages the pictures taken on site and the architectural drawing produced by the Author based on those provided by the Theatre's administration are shown.

Figure 2.18: Stalls

Figure 2.19: View of the stage

Figure 2.20: 2nd balcony

Figure 2.21: 1st balcony

Figure 2.22: Another view of the 2nd balcony

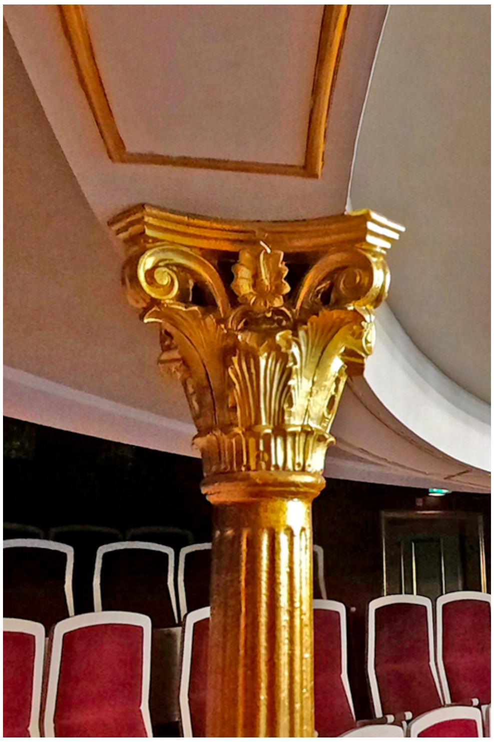


Figure 2.23: Column capitol

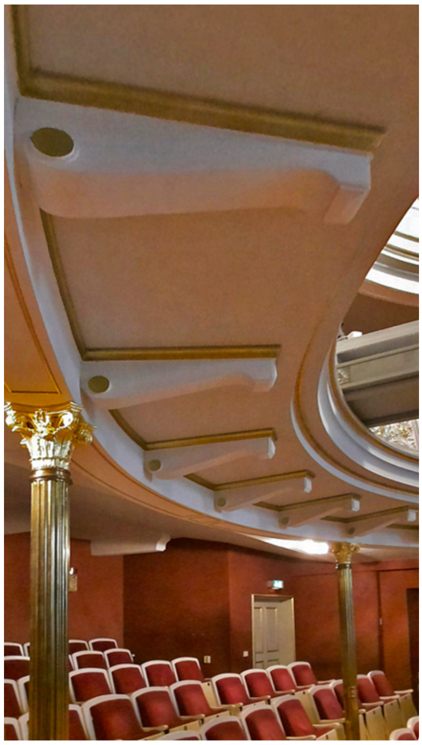


Figure 2.24: Wooden joists

Figure 2.25: Detail of 1st balcony decoration

Figure 2.26: Stage from 2nd floor

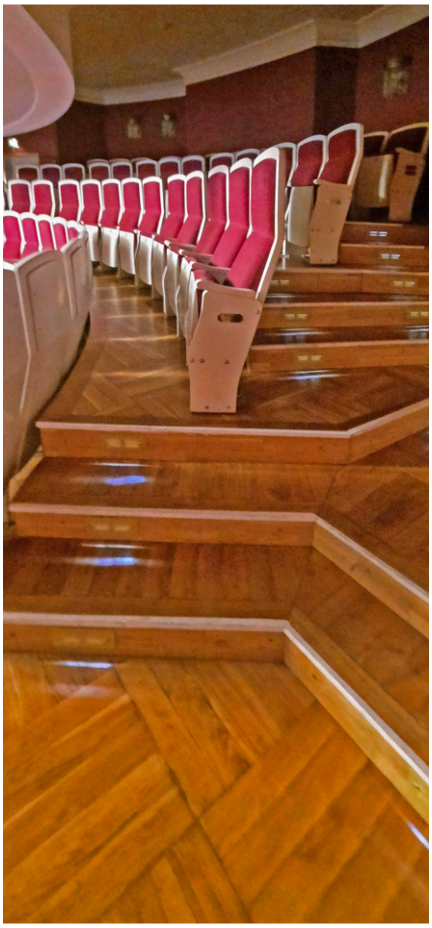


Figure 2.27: Parquet

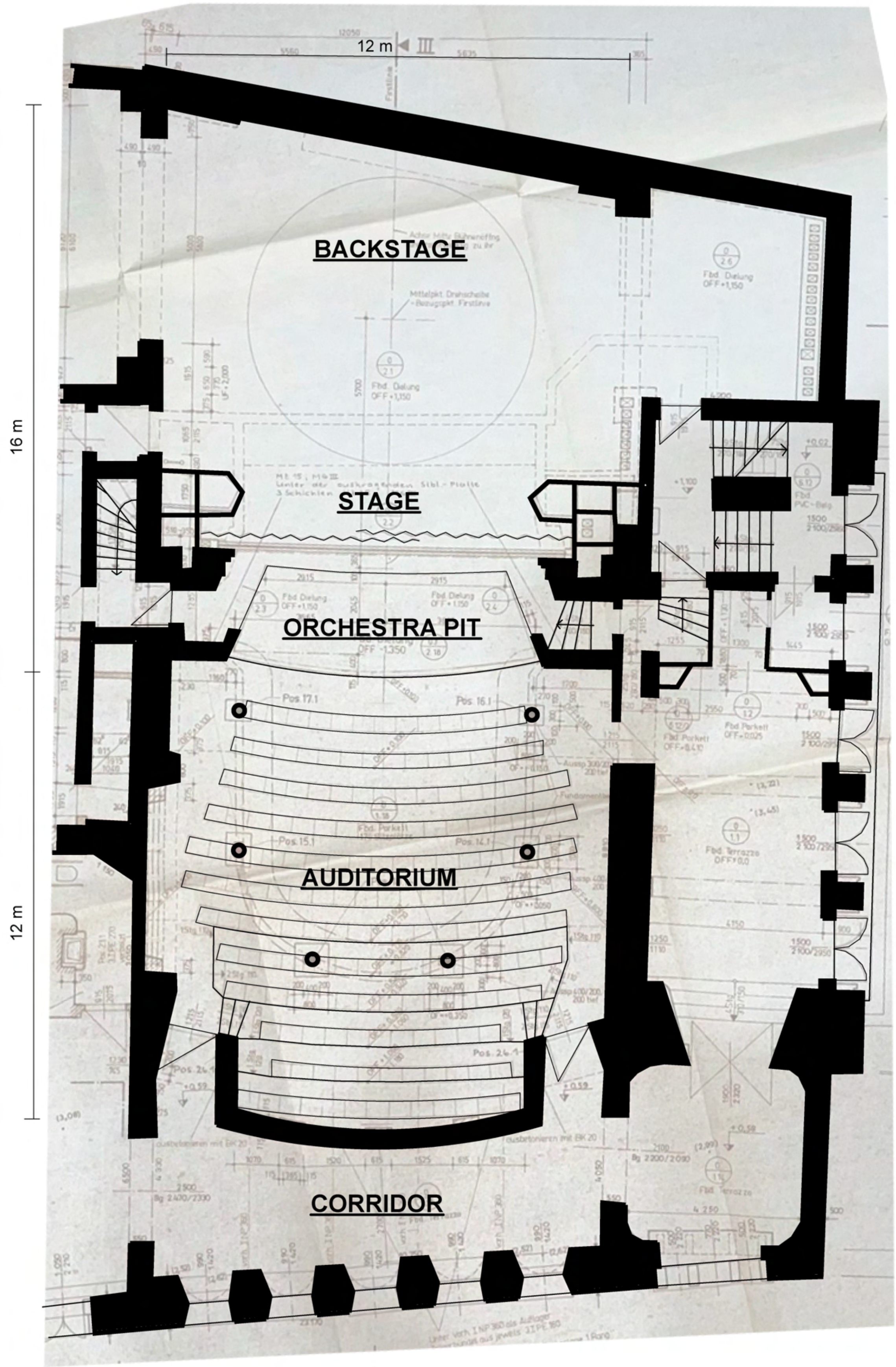


Figure 2.28: Ground floor

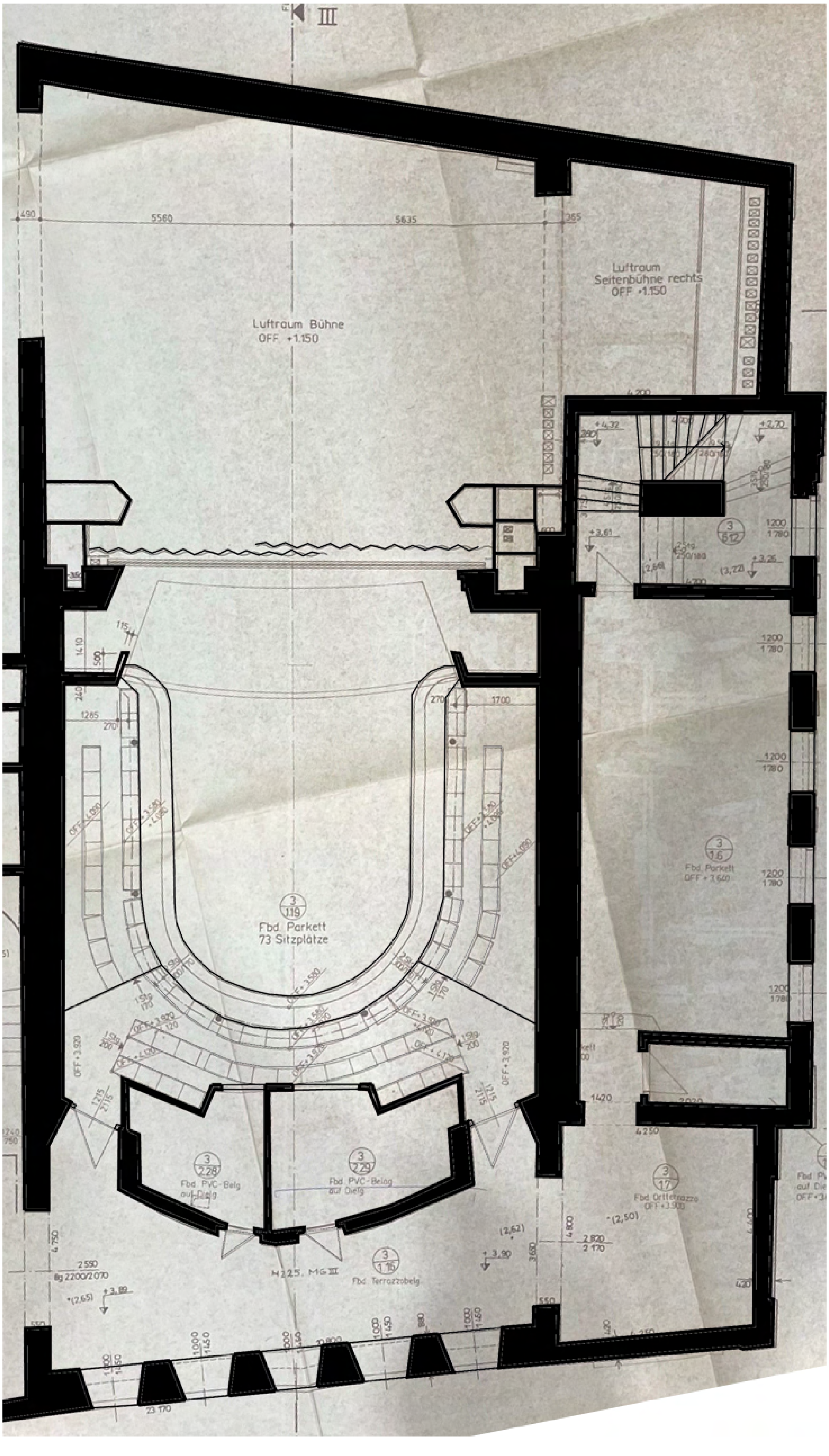


Figure 2.29: 1st floor

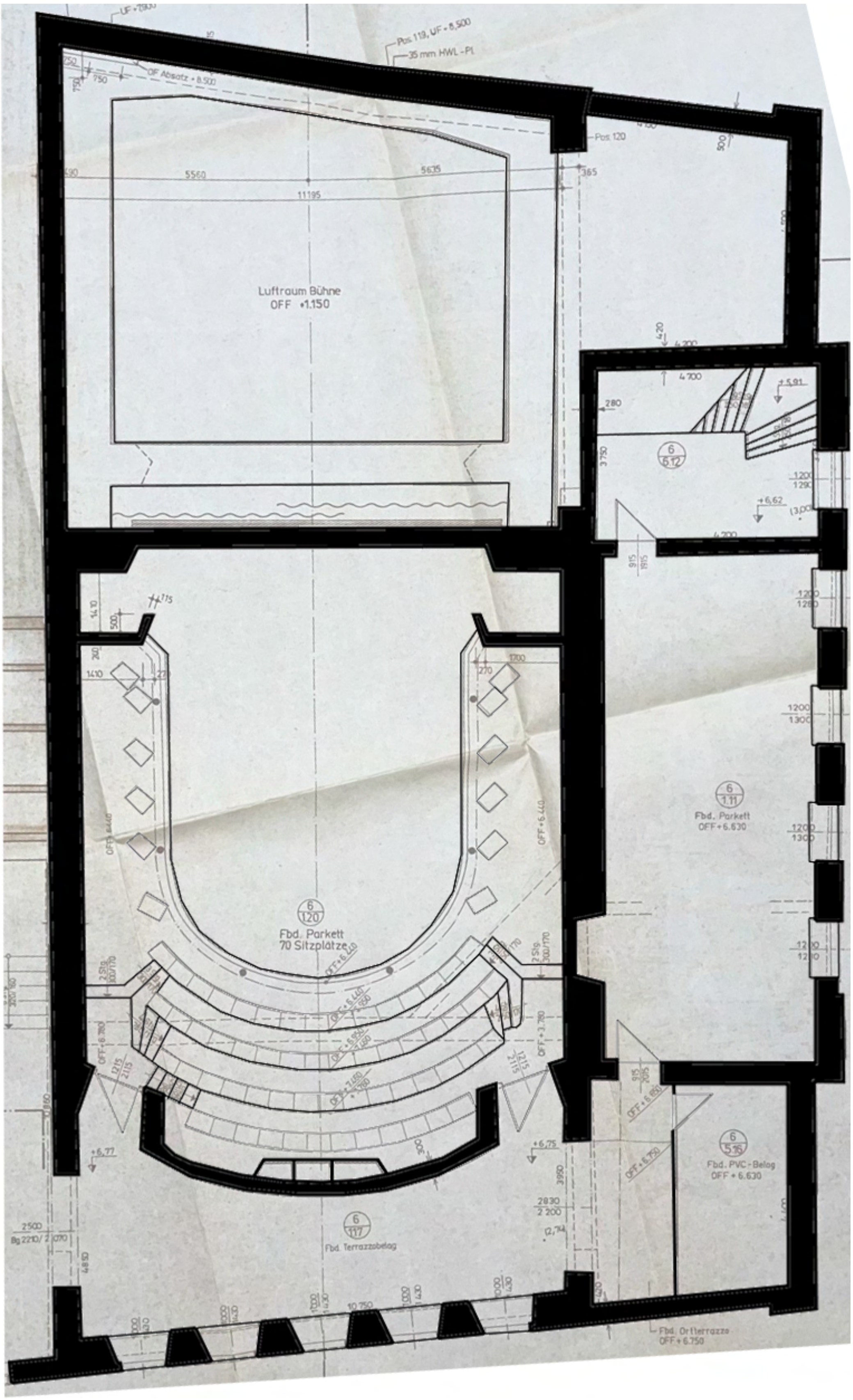


Figure 2.30: 2nd floor

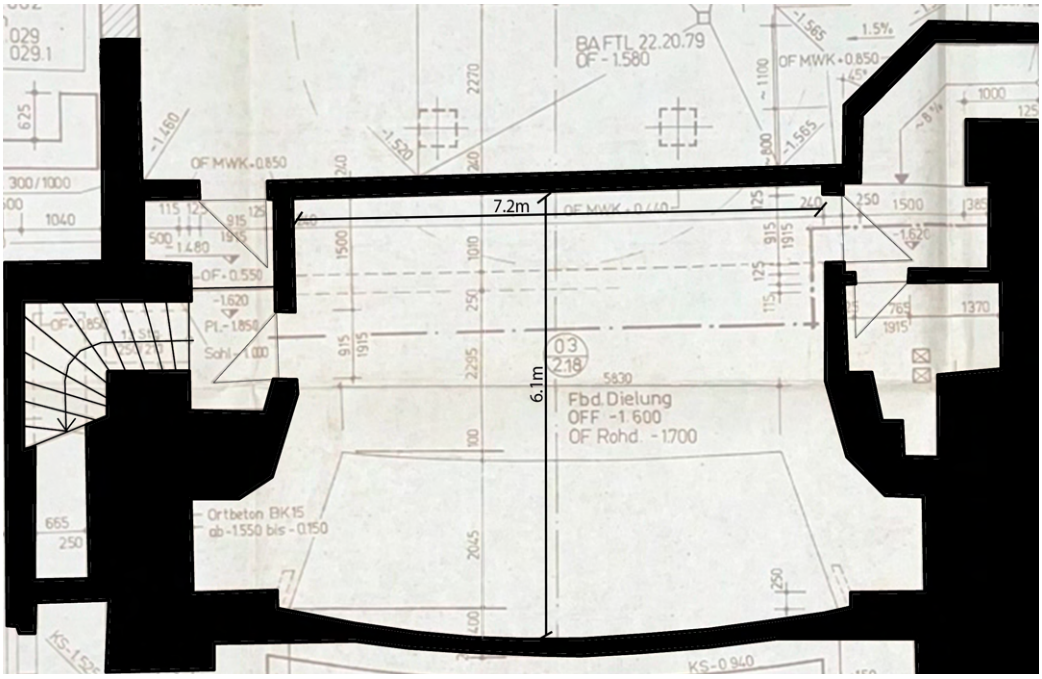


Figure 2.31: Orchestra pit

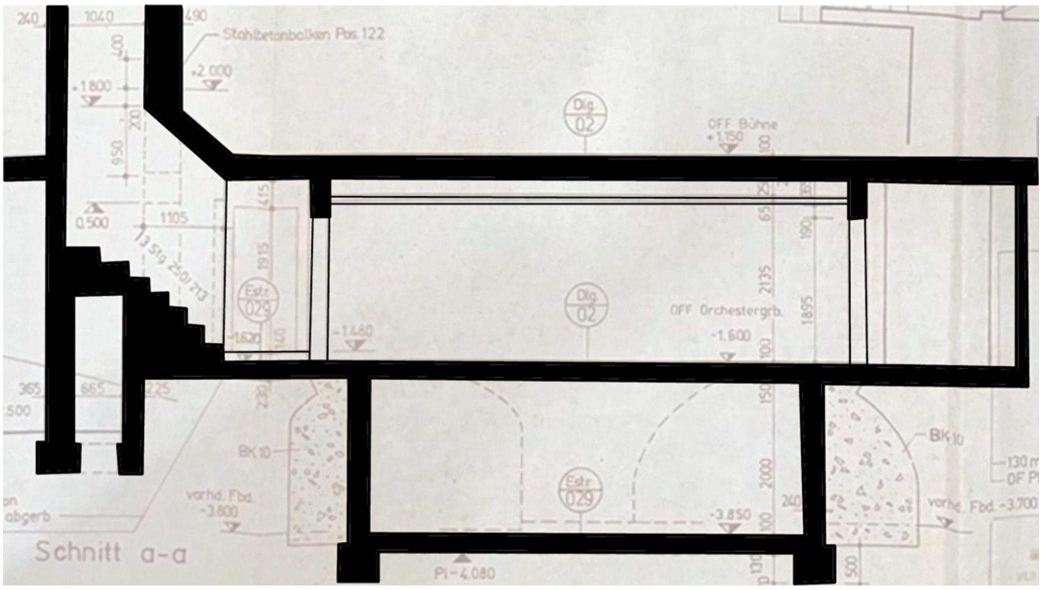


Figure 2.32: Cross section of the pit

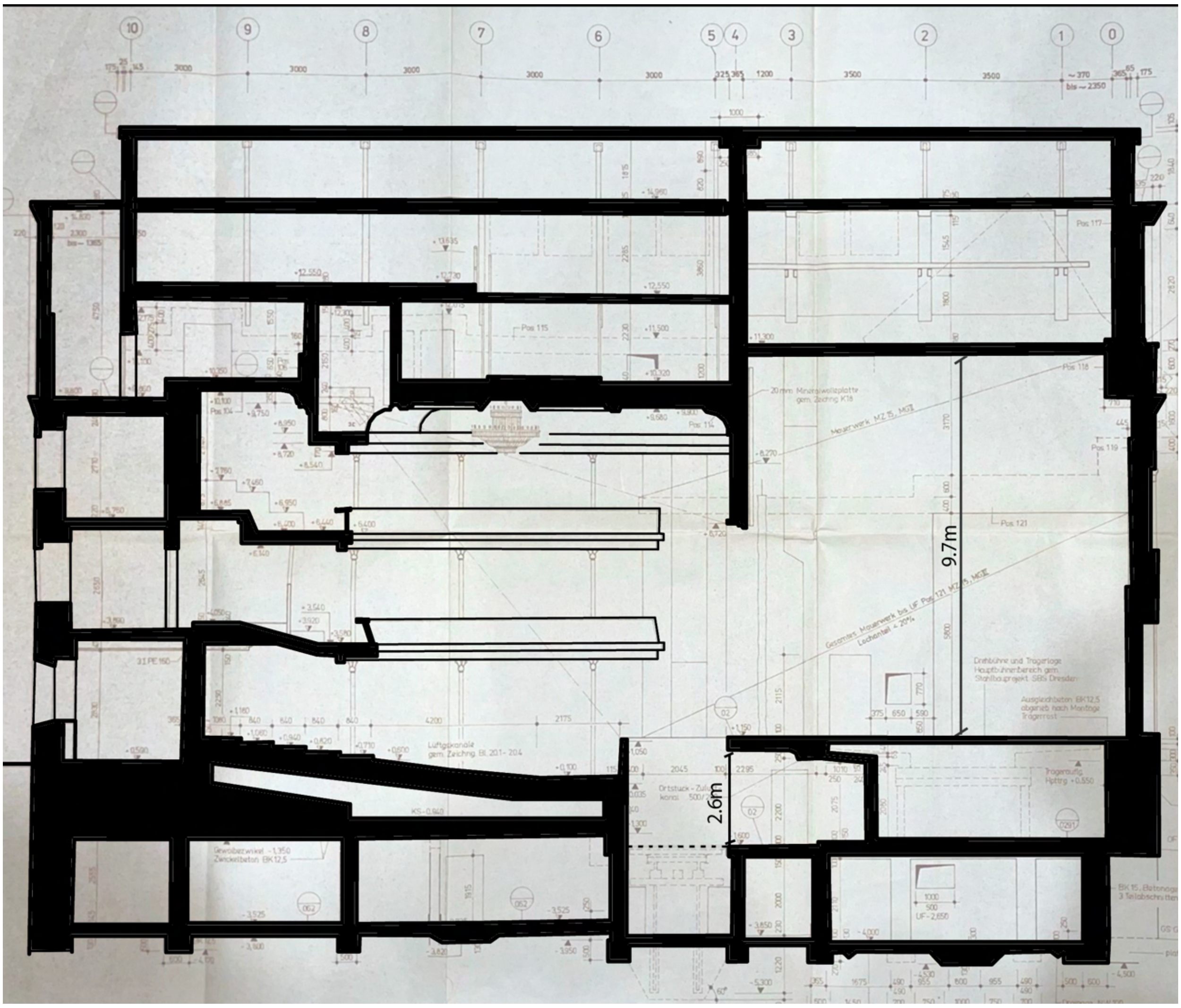


Figure 2.33: Longitudinal section

2.3 Acoustic issues

Public and artist's perception During the year 2021, the administration of the Theatre has approached the Acoustic department of the Hochschule Mittweida for the improvement of the overall acoustic quality of the venue. The theatre has been experiencing certain issues related to suboptimal sound perception, both for the audience and the performers. Through interviews, it was revealed that the audience's experience was perceived as too "dry," with the sound struggling to create a sense of complete immersion in the music, resulting in a lack of emotional engagement. Consequently, the performances are hindered by conditions that are incongruous with the dedication and preparation of the artists.
From the perspective of the performers, the acoustic conditions are not ideal. The main issue identified resides in the orchestra pit, where musicians face difficulties in perceiving the sound produced by their own instruments, as well as that of their fellow musicians. In some cases, according to the musicians' opinions, the unfavourable conditions of the orchestra pit even lead to auditory discomfort, primarily related to an excessive perception of certain instruments, such as brass instruments.

Preliminary evaluation An initial qualitative assessment suggests that the underlying causes of these problems may be attributed to the small size of the theatre hall. The limited dimensions, indeed, do not allow enough sound energy reverberation to ensure the necessary liveliness needed to appreciate concerts and theatrical performances, whether sung or spoken, with or without orchestral accompaniment.
Concerning the orchestra pit, a similar issue seems to arise. The restricted dimensions of the space beneath the theatre not only hinder proper reverberation, resulting in a poor sound amalgamation, but also prevent musicians from positioning themselves with sufficient distance, thus compromising comfort. Additionally, the orchestra pit itself is quite narrow, with a rather small opening. This characteristic poses challenges in sound propagation towards the hall, resulting in a perceived lack of quality for the audience.

Necessity for rigorous assessment In conclusion, the aforementioned challenges point towards the need for comprehensive acoustic improvements within the theatre. Addressing the issues related to sound perception for both the audience and the performers will require careful consideration of the hall's dimensions, the orchestra pit, and the overall architectural characteristics. Such enhancements will contribute to a more immersive and

engaging experience, ensuring that the artistic efforts of the performers are fully appreciated by the audience.
While obtaining a preliminary understanding of the potential causes of the problem is valuable, qualitative assessments alone are insufficient for devising an accurate and effective solution. The following chapter provides a comprehensive description of the acoustic measurement and survey process, which has allowed for the identification of parameters necessary for an objective evaluation of the situation. Based on these findings, it has been possible to present a feasible solution to the problem.

Chapter 3

Measurements and criteria calculation

3.1 Description of measurements procedure

The acoustic measurements of the Freiberg Theatre were conducted in two distinct phases, capturing fundamental data to analyse the intricacies of its acoustic behaviour. The initial phase occurred during the academic year 2021-2022, meticulously carried out by the students of the Hochschule Mittweida (HSMW) under Prof. Jörn Hübelt supervision. This undertaking focused on acquiring detailed insights into the main hall's acoustic response. It is worth noting that the theatre, due to the prevailing Covid-19 plandemic circumstances, lacked seating in the auditorium during this period
The second phase entailed a comprehensive investigation into the acoustics of the orchestra pit, aiming to objectively understand its acoustic properties and the sonic experience from the perspective of the musicians. The measurements were carried out as part of the thesis project by the Author in December 2022, meticulously capturing valuable insights into this captivating subject.
To achieve the objectives, in both cases it has been employed an array of configurations to capture impulse responses from various points. The primary focus of the measurements phase was to gather information on the spatial distribution of sound within the theatre. By assessing the propagation and reflection patterns of sound waves across different areas, it has been sought to unravel the intricate interplay between the architectural elements and the acoustic response of the theatre.
In the following pages the entire process completed to acquire objective results is described in details.

3.2 Equipment

During the measurements conducted at the Freiberg Theatre, a multitude of hardware and software tools were used in order to acquire the desired data. The instruments set provided by Hochschule Mittweida includes:

Computer with Matlab installed The computer is a crucial component for acoustic measurements. In both Freiberg theatre measurement sessions it was equipped with Matlab software, a powerful computational and programming environment largely used in the acoustics field. Along with the ITA toolbox plug-in [10], provided by the Institute of Technical Acoustics of the RWTH Aachen University, which allow to operate specific functions for analysis and manipulation of acoustic signals. In these cases it has been used to produce and record the sweep signal necessary for the acquirement of the impulse responses.

Audio Interfaces The audio interfaces utilised during the measurement sessions are the Focusrite Scarlett, for the first session carried by the Hochschule's stdents and the RME Fireface UC for the second session completed by the Author. Both are professional audio interface used to connect the computer with the sound emission and reception instruments. They were chosen due to their compliance with the technical requirements of the regulations [11]. In specific the Fireface UC offers a wide range of connections, including two microphone pre-amplifiers with phantom power, four analogue inputs, eight analogue outputs, a MIDI port, an ADAT port for input and output expansion, and a USB 2.0 port for computer connection. It supports audio resolution up to 192 kHz and provides professional sound quality thanks to its high-fidelity AD/DA converters.

Figure 3.1: Fireface UC

Amplifier The Hochschule Mittweida provied an AMG Mini Hybrid portable amplifier, produced by Ntek, used to amplify and balance the sound energy directed towards the omnidirectional sound source. This amplifier model includes a rechargeable lithium battery kit, allowing the system to function even in the absence of electrical power. The presence of a pink and white noise generator, along with a potentiometer to manage the emitted sound energy, enables greater versatility in acoustic measurement operations. The AMG Mini Hybrid is equipped with a two-channel remote control that allows for powering on/off the unit and, through the second channel, turning off the cooling fan for 30 seconds. This option is particularly useful in situations where the fan noise could affect the measurements, such as in silent environments. The amplifier is connected to the audio interface using a BNC cable.

Figure 3.2: AMG Mini amplifier

Omnidirectional sound source The utilised omnidirectional sound source is often referred as 'Dodecahedron' type. It employs a geometric configuration in the shape of a dodecahedron to emit sound uniformly in all directions in three-dimensional space. This type of source is valued for its uniform and natural frequency response, devoid of distortions or directional alterations of sound. In the specific case, the source employed is the OMNI 4" HP model produced by Ntek with 4" speakers mounted. The source is connected to the audio interface via a Speakon cable, through which the audio signal is transmitted to an amplifier and then emitted uniformly in the acoustic space.

Figure 3.3: Omnidirectional sound source

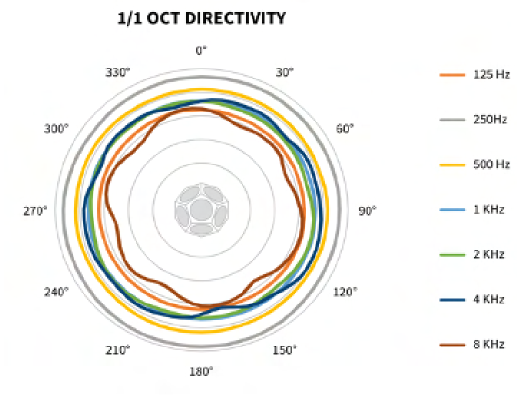


Figure 3.4: Directivity pattern

Microphones The microphone utilized for the acoustic measurements is the NTi M4261, a high-quality condenser microphone manufactured by NTi Audio. This microphone features a 1/4-inch (6.35 mm) diameter membrane and is designed to deliver excellent performance in terms of accuracy and frequency response. The condenser technology employed in the NTI M4261 microphone ensures a linear frequency response and high sensitivity from 20 Hz to 20 kHz, covering the entire audible spectrum of human perceptible sound. This characteristic makes it ideal for precise sound measurement and analysis applications. The microphone boasts a dynamic range of 131 dB, enabling the recording of both faint and loud sounds without undesirable distortions. It is equipped with a robust metal body and a grille-protected membrane, making it resilient and suitable for use in various environments, including professional settings and outdoor applications. The NTI M4261 microphone is connected to the audio interface using an XLR cable.

Figure 3.5: NTI M4261

Cables In the acoustic measurements carried in Freiberg Theatre, various types of cables were employed to connect the audio instruments. BNC, XLR, Jack, and Speakon cables are common in the context of acoustic measurements. The BNC connector (Bayonet Neill-Concelman) is a type of coaxial connector primarily used for high-frequency connections, such as between the audio interface and the amplifier. The XLR connector is a three-pole connector used for balanced audio connections, as seen in the microphone-to-audio interface link. The Jack connector, also known as a TRS (Tip-Ring-Sleeve) connector, is utilized for audio and video connections. Lastly, the Speakon connector is employed for high-power audio connections, as seen in the connection between the amplifier and the omnidirectional sound source.

3.3 Measurement sessions

Measurements in the hall In December 2021, students from Hochschule Mittweida conducted measurements in the hall with the aim of obtaining impulse responses. The measurements involved placing the sound source both on the stage and in the orchestra pit, while receivers were positioned in the auditorium and on the balconies. Building upon the insights gained from previous studies, the students meticulously prepared for the measurement session, carefully selected and calibrated the necessary equipment. The measurements were conducted with precision, adhering to established protocols and international standards [12].
To capture the full acoustic characteristics of the hall, impulse responses were recorded from multiple source-receiver configurations. The students placed the sound source on the stage and in the orchestra pit to simulate performances. Receivers were strategically positioned in the audience area, including both the main seating area and the balconies. This set-up allowed for a comprehensive assessment of the hall's acoustics from various listening perspectives.
The measurements aimed to gather accurate and reliable data to analyse the hall's behaviour. The acquired data would be further processed and analysed using advanced techniques and software tools, ensuring a thorough evaluation of the hall's acoustics.
By conducting these measurements, the students sought to deepen the understanding of the hall's acoustic properties and evaluate its suitability for different types of performances. The results would contribute to identifying areas for improvement and potentially informing future modifications to enhance the overall acoustic experience for both performers and audiences.

Figure 3.6: 1st measurement session, stage

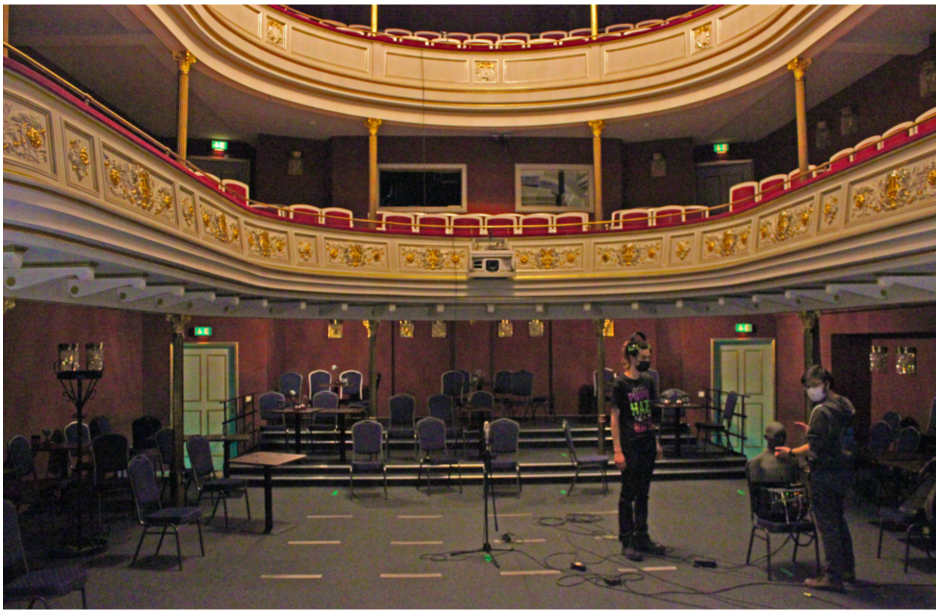


Figure 3.7: 1st measurement session, hall

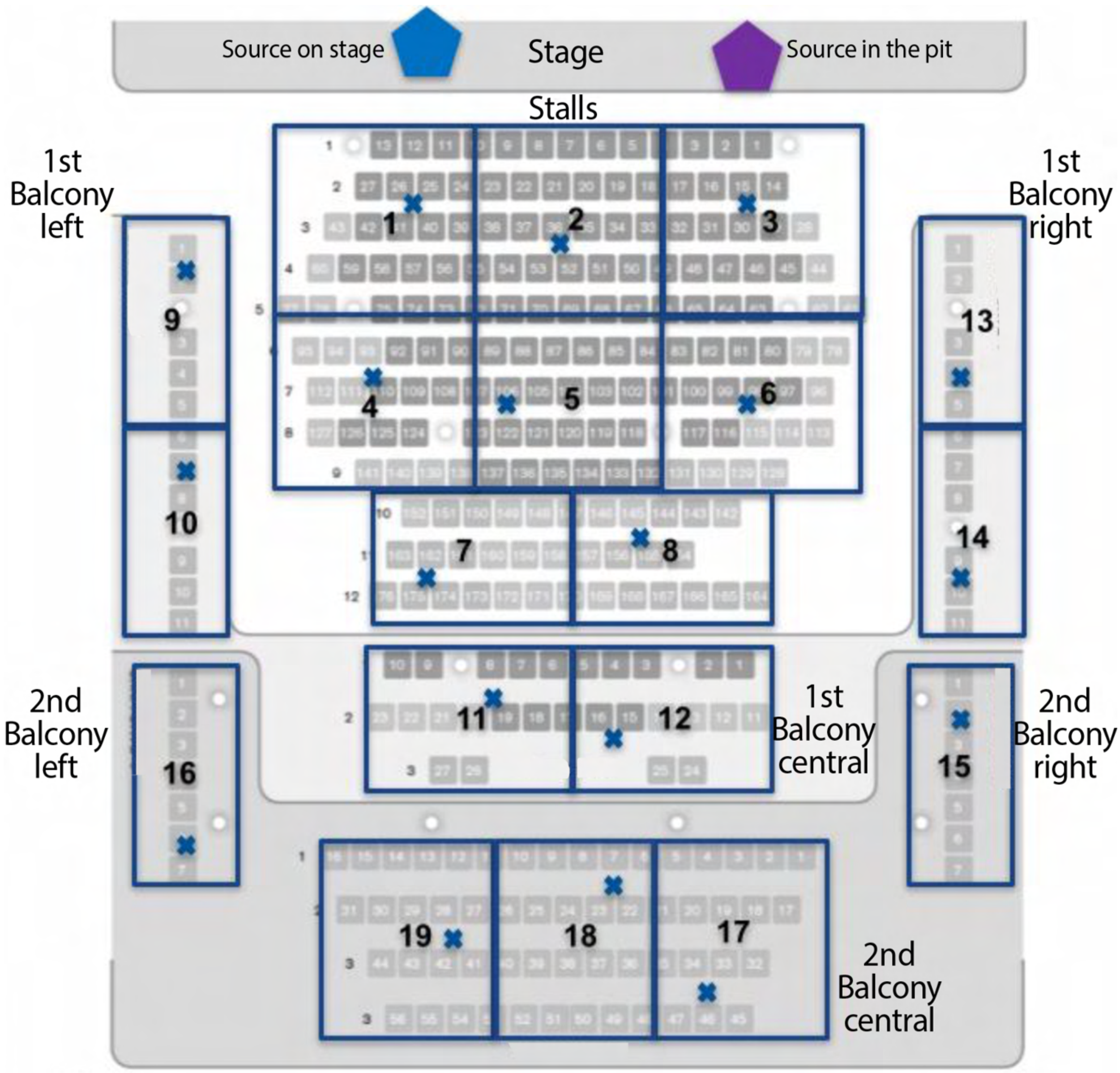


Figure 3.8: Source-receiver position

Measurements in the pit During a six-month period of research at the Hochschule Mittweida, the second round of measurements was carried out at the Theatre by the Author. In order to do so a detailed protocol was prepared, outlining the procedures and operations to be carried out. This protocol served as a comprehensive guide for the measurement session, ensuring consistency and accuracy throughout the process.

The impulse response measurements were conducted at Freiberg Stadtteathre on December 1st, 2022. The room, which at that time had the seats back in place in the auditorium, was cleared and the orchestra pit was emptied in preparation for the measurements. The necessary acoustic equipment, including a computer with Matlab software and ITA Toolbox, a Fireface UC sound card, power supply cables, an AMG mini amplifier with a gain of 18, and a dodecahedron sound source with a Speakon rod and cable, were meticulously prepared. High-quality NTI M4261 microphones with 1/4" membranes, pre-calibrated for accuracy, were utilized along with rods and BCN cables.

Once the hardware and software set-up was complete, the source and receiver's positions were marked according to the protocol map [Figure 3.13]. In order to understand the behaviour of sound from the perspective of the musicians, the orchestra pit has been divided into sections correspondent to different groups of musical instruments. During the measurements each section has been considered as a source position and as a receiver position with the aim of acquiring useful information on how each section perceives the others and vice-versa, on how each section is perceived by the others during performances.

During the measurement process the availability of channels in the interface, allowed for the simultaneous recording of impulse responses for two sections. This efficient approach which permitted to save time, led to the inclusion of three additional source positions in the protocol. These positions consisted of a central location, a lateral position corresponding to the Contrabass position in the Freiberg orchestra's typical configuration, and a position centred below the edge of the orchestra pit opening. The room temperature during the measurements ranged between 18-23°C.

The previously developed Matlab script, designed for acquiring impulse responses via ITA-Toolbox, was configured to ensure a Signal-to-Noise Ratio (SNR) exceeding 40dB and a sine sweep duration of 6 seconds spanning frequencies from 50 to 4000 Hz.

On the day of measurements, two impulse responses were obtained for each source-receiver configuration. The sound source was moved to the next section only after collecting data from all receiver positions. In cases where the source and receiver positions coincided within the same section (e.g., S1_R1 and S1_R2), a distance of 1 meter between them was considered to evaluate the Support parameter. The transducers were aligned with the conductor's position in section number 8. Consequently, a total of 180 impulse responses (20x9) were calculated on, accounting for the conductor's position as a receiver only.

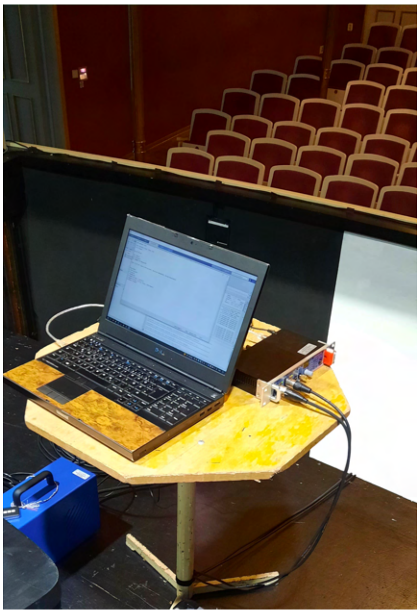


Figure 3.9: Computer connected to audio interface

Figure 3.10: Measurement in the pit

Figure 3.11: Omnidirectional source placement

Figure 3.12: Microphone placement

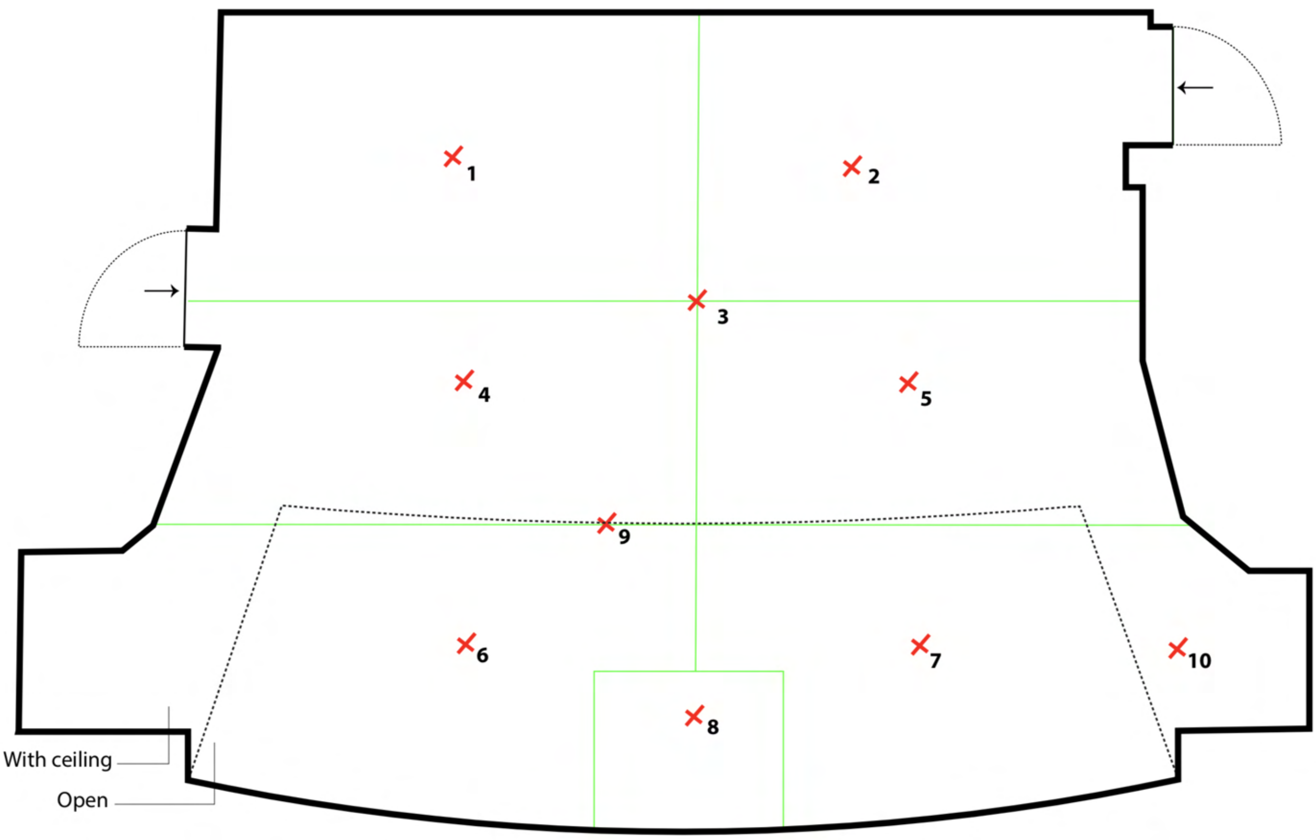


Figure 3.13: Orchestra pit protocol map divided in sections

Table 3.1: Sections

Instruments			Source-receiver distance in cm									
			1	2	3	4	5	6	7	8	9	10
1	BRASSES	Trumpet, Trombone...	-	304	216	170	388	370	516	464	302	668
2	PERCUSSIONS	Drums, Timpani...		-	156	338	170	467	369	437	330	444
3	CENTRAL POSITION				-	188	173	309	313	316	183	452
4	WOODWINDS	Clarinet, Oboe...				-	339	200	403	306	154	581
5	OTHERS	Harp, Piano...					-	391	201	305	253	288
6	BOWED STRINGS 1	Violins						-	350	176	141	542
7	BOWED STRINGS 2	Viola, Cello							-	185	256	197
8	CONDUCTOR									-	158	378
9	DIFFRACTION POSITION										-	445
10	CONTRABASS											-

3.4 Criteria calculation

Once the impulse responses were acquired in .mat and .wav format, they were processed using the computational software Matlab, along with the ITA Toolbox plugin. These tools, using the script included in the Appendx A, facilitated the efficient calculation of the criteria required to objectively evaluate the acoustic characteristics of the theatre.
Most of the criteria used in room acoustics for theatres and concert halls, are extensively covered in the ISO 3382 standard [12], a comprehensive framework that outlines the proper procedures for measuring and capturing accurate impulse responses in order to calculate these criteria. The standard not only provides detailed guidelines for calculating each parameter in terms of equations and logical explanation of the parameter's nature, but also sheds light on essential aspects such as their unit of measurement, optimal value range derived by experiments and experience, and their just noticeable difference, the parameter value's smallest perceptible change.
By adhering to the ISO 3382 guidelines, is possible to derive precise conclusions and make informed judgements about acoustic quality based on the resulting measurement values. This standardized approach allows for a systematic assessment of acoustic properties, enabling a more thorough and insightful understanding of the subject matter.
In the following pages the characteristics of the criteria considered in this work are explained.

3.4.1 Criteria description

Reverberation Time (T20, T30) In the field of acoustics, the reverberation time is a crucial parameter that quantifies the decay of sound in a space. The original definition, introduced by Sabine, is often referred to as the T60, representing the time it takes for the sound to decay by 60 dB. However, in practical scenarios, factors like background noise can significantly impact the measurement, prompting the need for alternative approaches. A commonly employed technique is to evaluate the decay based on a 20 or a 30 dB drop, these values are then multiplied by 3 or 2 to obtain equivalent T60 measurements known respectively as the T20 and T30 [2].
Visually, the reverberation time is illustrated by a steady-state level, followed by a decay. As said if the background noise level prevents reaching the full 60 dB decay, a 20 or 30 dB drop can be used instead. This estimation starts from -5 dB after the decay has already begun, aiming for the mitigation of the challenges posed by fluctuations in the transition point from the steady

state level to decay.

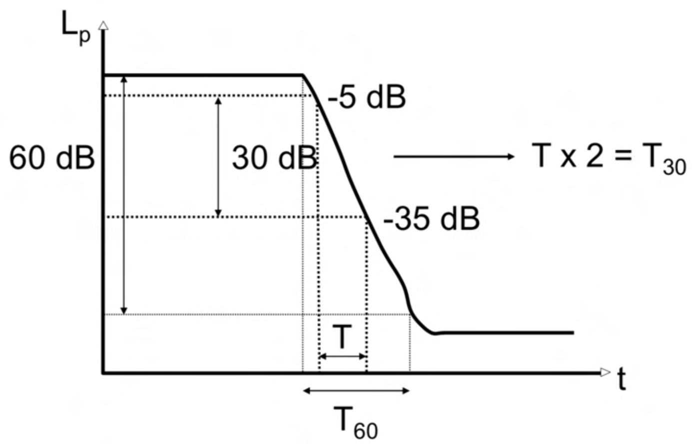


Figure 3.14: T30 explanation

The presence of these fluctuations makes it difficult to establish a straight line that accurately represents the decay slope, potentially leading to measurement imprecisions. Starting from -5 dB helps minimize such uncertainties and enhances the reliability of the measurement.

Early Decay Time (EDT) Regarding as well the reverberation time, the EDT refers to a parameter that solely considers the initial 10 dB decay of sound, disregarding any fluctuations.
This parameter was primarily designed to understands the behaviour of individual musical notes [1]. When a note is played followed by another note in quick succession, there is not sufficient time to perceive the complete decay of the first note by 60 dB, or even by 30 dB or 15 dB. The duration of the individual note is very brief, with subsequent notes quickly following. Consequently, only the initial portion of the decay is significant, as the remaining decay is effectively lost. Waiting for a 5 dB decrease, which may take fractions of a second, is impractical. Therefore, immediate measurement is necessary. Interestingly a separate term has been introduced to describe this initial decay. While there is the conventional term "Reverberation", the term "Reverberance" is used specifically to depict this initial impression of decay. The intention is to emphasize that it represents a distinct phenomenon. This concept also applies to speech perception. When hearing a phoneme, the subsequent phoneme arrives within a few milliseconds. To

assess the decay characteristics of the phoneme accurately, the initial decay must be considered. Hence, EDT is employed both for the initial musical impression and the initial impression in speech. However, this approach unavoidably introduces increased uncertainty. Opting for EDT to obtain a closer approximation to the subjective sensation of "Reverberance" comes at the cost of accepting greater imprecision, although numerical values can be derived, they inherently carry a higher degree of uncertainty.

Clarity (C50, C80) The concept of clarity, represented by the criteria C50 and C80, arises from the division of the impulse response into two energy components: useful energy and detrimental energy. The division point between these components is crucial, as it determines the evaluation of the ratio between useful and detrimental energy [3].
The parameter C, short for Clarity, is logarithmic in scale, measured in decibels.

$$C_{80} = 10lg\frac{\int_0^{80ms} p^2(t)\,dt}{\int_{80ms}^{+\infty} p^2(t)\,dt} \quad [dB] \tag{3.1}$$

The numerator represents the squared energy associated with the impulse response within the first 80 milliseconds considered useful for musical perception. The denominator represents the energy arriving after 80 milliseconds and extends to infinity. Consequently, C80 quantifies the ratio between useful energy (arriving within the first 80 milliseconds) and detrimental energy (arriving afterwards). This ratio is expressed logarithmically in decibels.
A positive value in decibels indicates that the majority of energy arrives within the first 80 milliseconds, resulting in good clarity. Conversely, a negative value signifies that the major energy portion arrives after 80 milliseconds, leading to poor clarity.
It is worth noting that an alternative value of clarity, C50, can be obtained by considering the separation point at 50 milliseconds instead of 80 milliseconds.

$$C_{50} = 10lg\frac{\int_0^{50ms} p^2(t)\,dt}{\int_{50ms}^{+\infty} p^2(t)\,dt} \quad [dB] \tag{3.2}$$

The choice between C50 and C80 depends on the musical context. For music with slower tempos, particularly romantic music such as Adagio, 80 milliseconds is deemed more appropriate. The numerator captures a slightly larger contribution of reverberation. However, in the case of faster music or vocal performances, such as opera, where the voice rapidly decays or there is intricate phrasing, a shorter separation point of 50 milliseconds is preferred.

Both C80 and C50 find their application in evaluating orchestral music and opera.

Early and Late Support ($\mathbf{ST}_{early}$, $\mathbf{ST}_{late}$) These descriptors are devised not for the audience but to capture the musicians' perspective on the hearing of their own instrument. Their definitions have remained a subject of ongoing discussion due to their initially rigid nature. Particularly, the ISO 3382 standard defines these descriptors based on a fixed distance of 1 m between the source and the receiver. However, in reality, the receiver can be a musician in close proximity or even their own instrument, making the 1-meter distance relatively inflexible. It could vary significantly, either shorter or longer.
The parameter under consideration is called Support ST [13], which encompasses two versions: one referring to the early portion of the impulse response and the other to the late portion. Both versions involve integrals of p^2 over time, representing the energy within the impulse response.

$$ST_{early} = 10lg\frac{\int_{20ms}^{100ms} p^2(t)\,dt}{\int_{0}^{10ms} p^2(t)\,dt} \quad [dB] \tag{3.3}$$

In the ST_{early}, the denominator captures the energy arriving within the first 10 milliseconds which can be considered as the direct sound. In the numerator, the energy immediately following is considered, between 20 and 100 milliseconds. This encompasses the initial energy reflections from the floor or nearby surfaces and any energy arriving after 20 milliseconds. The resulting value is logarithmically scaled to obtain the measurement in decibels. The aim here is to capture how musicians perceive the hearing of the own instrument within a 100-millisecond window.

$$ST_{early} = 10lg\frac{\int_{100ms}^{1000ms} p^2(t)\,dt}{\int_{0}^{10ms} p^2(t)\,dt} \quad [dB] \tag{3.4}$$

The ST_{late} descriptor focuses on the energy arriving between 100 and 1000 milliseconds, encompassing the room's response as well. In one second, sound covers a distance of 340 meters, allowing it to propagate to the far end of the room, bounce back, and interact with various surfaces. By calculating the ratio between this late energy and the energy arriving within the first 10 milliseconds, is possible to evaluate the influence of the room's response and exclude intermediate reflections. The returned energy contributes to the perception of a sense of reverberation, as experienced by the musician.
These two descriptors, along with other criteria, have been devised to capture

the subjective perception of sound while taking into account the practicality of measuring the impulse response.

Early and Late Support Extended ($\mathbf{ST}_{early,d}$, $\mathbf{ST}_{late,d}$) The necessity to extend the Support parameter, also known as STearly,d or Support Extended, arises from the findings presented in Wenmaekers's publication [14]. According to various psychoacoustic research studies, Early Reflections that arrive within 100 milliseconds after sound emission play a significant role in the perceived quality of the ensemble hearing experience for musicians at different distances (d). Architectural analysis of average stage dimensions has further confirmed that 1st order reflections within the first 100 milliseconds contribute significantly to the total reflected sound energy. The time interval between the arrival of the direct sound and the maximum delayed 1st order reflection is inversely proportional to the source-receiver distance. On the other hand, late reflections that arrive after 100 milliseconds contribute to creating a sense of reverberance.
To assess the importance of early reflections at various distances, it is necessary to exclude the direct sound from the analysis. This can be achieved by setting the start of the time interval approximately 9 to 13 milliseconds after the arrival of the direct sound. Gade's ST_{early} and ST_{late} parameters are commonly used to evaluate the quality of hearing one's own instrument. However, Wenmaekers' extensions, ST_{early} and ST_{late}, aim to define the quality of hearing other musicians' instruments.

$$ST_{early,d} = 10log_{10}\frac{\int_{10}^{103-delay} p_d^2(t)dt}{\int_0^{10} p_{1m}^2(t)dt} \quad [dB] \tag{3.5}$$

$$ST_{late,d} = 10log_{10}\frac{\int_{103-delay}^{+\infty} p_d^2(t)dt}{\int_0^{10} p_{1m}^2(t)dt} \quad [dB] \tag{3.6}$$

In the extended version proposed by Wenmaekers, the denominator of $\mathrm{ST}_{early,d}$ represents the time interval from 0 to 10 milliseconds, approximating the arrival and end of the direct sound at a 1-meter source-receiver distance. The numerator starts from 10 milliseconds, which is considered the end time of the direct sound at 1 meter, and extends up to 103-delay. The value of 103-delay takes into account a 100-millisecond window that encompasses the useful Early Reflections. The initial 10ms represents the time it takes for sound to travel a distance of 1 meter, and then it decreases based on the source-receiver distance (delay). As the source-receiver distance increases, the time interval between the direct and first reflected sound becomes smaller.

The proposed Support Extended $ST_{early,d}$ parameter allows for an investigation of the contribution of early reflections to ensemble playing at increasing source-receiver distances. It provides valuable insights into the support provided by early reflections for individual instruments and facilitates a better understanding of orchestra's acoustics. Conversely, the $ST_{late,d}$ parameter is expected to be independent of the source-receiver distance, as the sound level in a diffuse sound field is not significantly affected by distance outside the critical distance.
Further research is needed to determine the subjective impressions of ensemble playing at various distances and to establish preferred values for $ST_{late,d}$.

The intention to consider this parameter in the thesis work arises from the need to objectively evaluate how orchestral musicians perceive each other. Currently, this cannot be determined through standard parameters. Therefore, an experimental parameter has been employed, which will be compared to the results of a questionnaire administered to the musicians, in order to contribute to the research in this specific field.

In the following pages the values obtained from the calculation of the aforementioned parameters are presented.

3.4.2 Criteria values in the hall

EDT, source on stage In the following tables are shown the values of the EDT parameter, in seconds, correspondent to the measurements with the sound source positioned on stage and the receivers placed throughout the hall.

Table 3.2: EDT (s), source on stage, receivers in the auditorium

Octave band (Hz)	Receivers								Average
	1	2	3	4	5	6	7	8	
125	1.04	1.12	1.18	0.55	1.67	0.98	0.90	1.27	0.93
250	1.18	1.05	0.72	1.12	0.66	0.67	1.06	0.95	0.89
500	0.98	1.05	1.00	0.92	0.85	0.93	0.83	0.59	0.89
1k	0.71	0.75	0.85	0.69	0.78	0.84	0.76	0.60	0.77
2k	0.69	0.81	0.72	0.69	0.54	0.65	0.56	0.54	0.65
4k	0.49	0.55	0.60	0.48	0.43	0.46	0.40	0.37	0.49

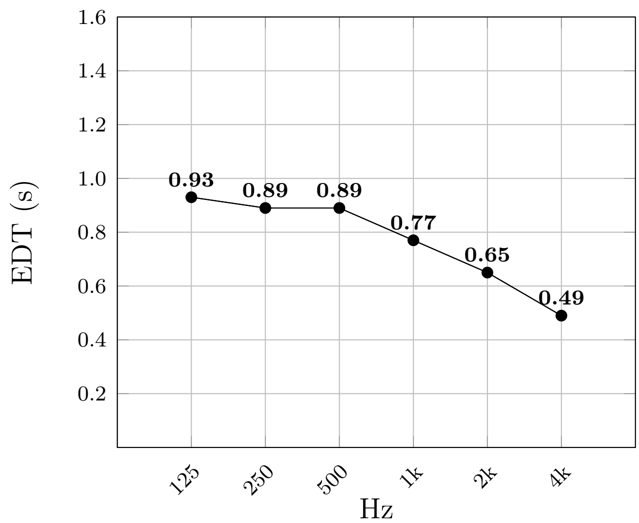


Figure 3.15: Average EDT, S stage, R auditorium

Table 3.3: EDT (s), source on stage, receivers in the 1st balcony

Octave band (Hz)	Receivers						Average
	9	10	11	12	13	14	
125	0.80	0.62	0.86	0.85	1.06	1.25	0.96
250	1.16	0.95	0.80	0.91	0.66	0.94	0.85
500	1.05	1.16	0.80	0.86	1.00	0.80	0.90
1k	0.71	0.94	0.90	0.98	0.76	0.60	0.78
2k	0.75	0.84	0.76	0.76	0.72	0.70	0.74
4k	0.53	0.57	0.65	0.7	0.56	0.55	0.57

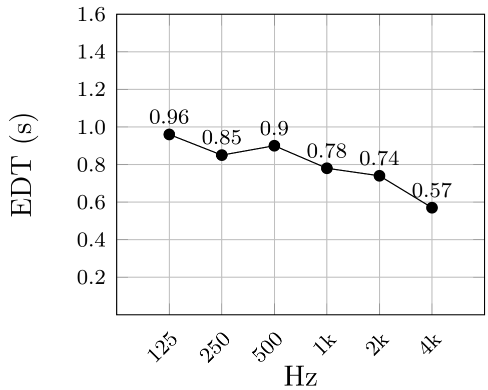


Figure 3.16: Average EDT, S stage, R 1st balcony

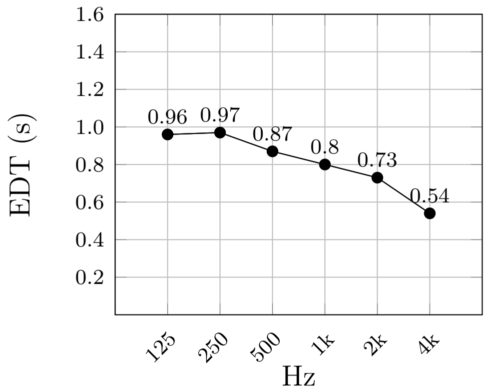


Figure 3.17: Average EDT, S stage, R 2nd balcony

Table 3.4: EDT (s), source on stage, receivers in the 2nd balcony

Octave band (Hz)	Receivers					Average
	15	16	17	18	19	
125	0.7	1.27	0.85	1.56	1.14	0.96
250	0.59	1.14	1.00	1.00	0.73	0.97
500	0.61	1.04	1.08	0.86	0.75	0.87
1k	0.73	1.10	0.92	0.85	0.71	0.80
2k	0.67	0.85	0.78	0.62	0.75	0.73
4k	0.53	0.77	0.60	0.54	0.50	0.54

EDT, source in the pit In the following tables are shown the values of the EDT parameter, in seconds, correspondent to the measurements with the sound source positioned in the pit and the receivers placed throughout the hall in the same positions as before.

Table 3.5: EDT (s), source in the pit, receivers in the auditorium

Octave band (Hz)	Receivers								Average
	1	2	3	4	5	6	7	8	
125	0.55	1.16	1.12	1.21	0.90	0.84	1.40	0.77	1.11
250	1.23	1.15	1.61	1.17	1.50	1.27	1.28	1.29	1.31
500	0.97	0.71	1.16	0.81	1.08	0.99	0.99	1.28	1.04
1k	1.01	1.01	0.78	0.90	0.91	0.75	1.07	1.04	0.96
2k	0.76	0.86	0.83	0.74	0.78	0.80	0.76	0.78	0.80
4k	0.61	0.57	0.55	0.62	0.65	0.59	0.59	0.70	0.62

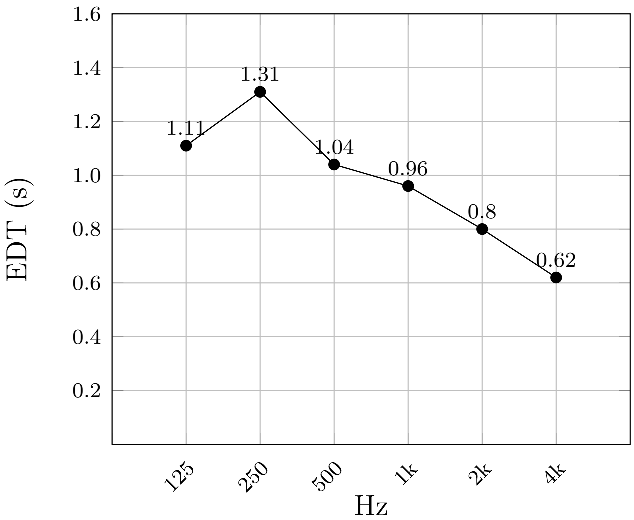


Figure 3.18: Average EDT, S pit, R auditorium

Table 3.6: EDT (s), source in the pit, receivers in the 1st balcony

Octave band (Hz)	Receivers						Average
	9	10	11	12	13	14	
125	0.83	0.46	0.99	1.51	1.15	0.67	1.11
250	1.03	0.91	0.94	0.99	0.96	1.39	1.06
500	0.96	1.06	0.50	1.23	0.95	0.80	1.00
1k	0.82	0.82	0.79	0.72	0.82	0.87	0.82
2k	0.84	0.72	0.61	0.82	0.86	0.82	0.79
4k	0.63	0.54	0.49	0.73	0.79	0.68	0.65

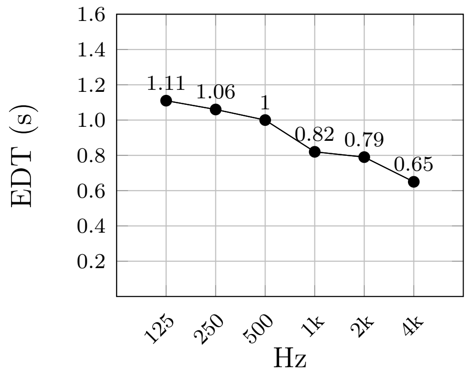


Figure 3.19: Average EDT, S pit, R 1st balcony

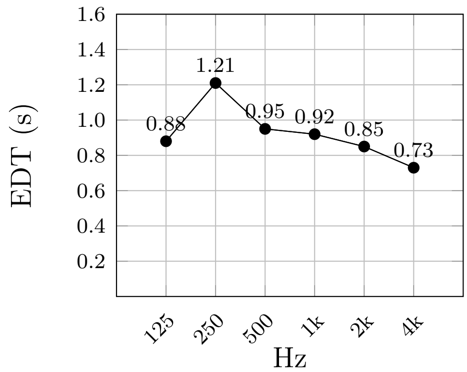


Figure 3.20: Average EDT, S pit, R 2nd balcony

Table 3.7: EDT (s), source in the pit, receivers in the 2nd balcony

Octave band (Hz)	Receivers					Average
	15	16	17	18	19	
125	0.96	0.74	0.66	1.02	0.59	0.88
250	1.00	1.18	1.49	1.15	1.23	1.21
500	0.86	0.95	1.02	0.99	0.92	0.95
1k	0.73	1.02	1.01	0.94	0.88	0.92
2k	0.80	0.82	0.93	0.86	0.86	0.85
4k	0.70	0.76	0.85	0.74	0.73	0.73

T20, source on stage In the following tables are shown the values of the T20 parameter, in seconds, correspondent to the measurements with the sound source positioned on stage and the receivers placed throughout the hall in the same positions as before.

Table 3.8: T20 (s), source on stage, receivers in the auditorium

Octave band (Hz)	Receivers								Average
	1	2	3	4	5	6	7	8	
125	0.86	1.17	0.81	0.94	1.42	1.05	1.03	1.02	1.04
250	1.08	1.05	1.34	1.22	1.09	0.94	1.23	0.87	1.10
500	0.99	0.94	0.93	0.82	0.85	0.96	0.85	1.04	0.92
1k	0.90	0.85	0.72	0.95	0.84	0.77	0.79	0.85	0.83
2k	0.75	0.73	0.79	0.70	0.78	0.65	0.68	0.67	0.72
4k	0.59	0.59	0.56	0.61	0.54	0.57		0.58	0.58

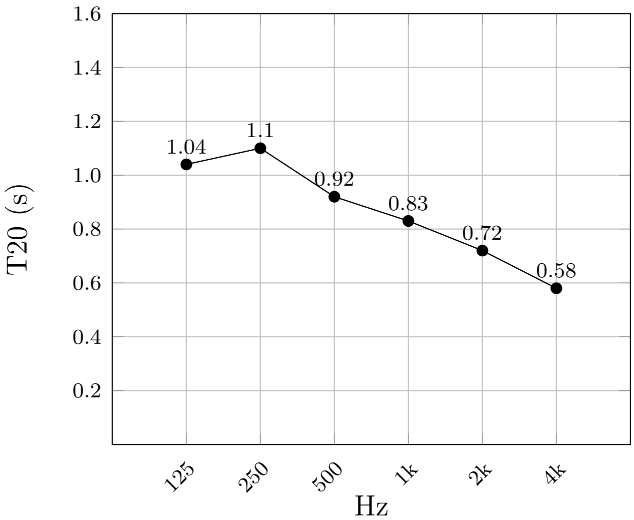


Figure 3.21: Average T20, S stage, R auditorium

Table 3.9: T20 (s), source on stage, receivers in the 1st balcony

Octave band (Hz)	Receivers						Average
	9	10	11	12	13	14	
125	1.00	1.02	1.11	0.96	1.01	0.97	1.01
250	0.95	0.93	1.25	0.94	1.06	1.05	1.03
500	0.89	0.83	0.94	1.06	0.95	0.97	0.94
1k	0.81	0.81	0.86	0.84	0.92	0.93	0.86
2k	0.82	0.74	0.72	0.71	0.77	0.77	0.76
4k	0.61	0.62	0.58	0.60	0.61	0.56	0.60

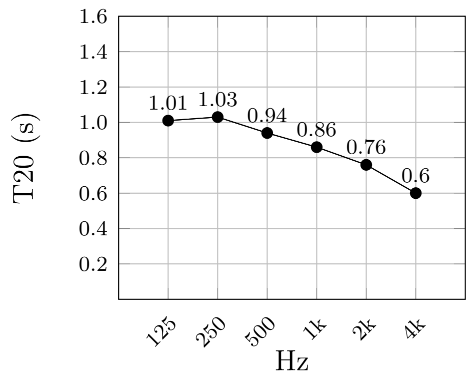


Figure 3.22: Average T20, S stage, R 1st balcony

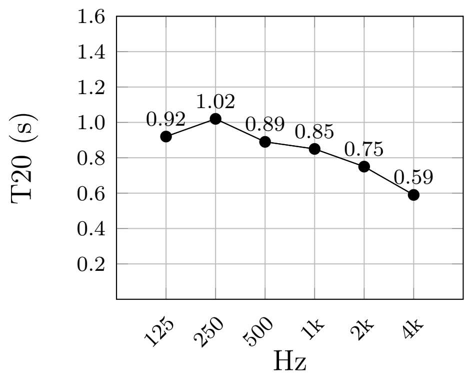


Figure 3.23: Average T20, S stage, R 2nd balcony

Table 3.10: T20 (s), source on stage, receivers in the 2nd balcony

Octave band (Hz)	Receivers					Average
	15	16	17	18	19	
125	0.97	0.99	1.10	0.79	0.76	0.92
250	1.02	0.88	1.11	1.02	1.05	1.02
500	0.94	0.94	0.91	0.90	0.78	0.89
1k	0.78	0.90	0.81	0.84	0.94	0.85
2k	0.73	0.78	0.76	0.74	0.75	0.75
4k	0.57	0.57	0.61	0.62	0.60	0.59

T20, source in the pit In the following tables are shown the values of the T20 parameter, in seconds, correspondent to the measurements with the sound source positioned in the pit and the receivers placed throughout the hall in the same positions as before.

Table 3.11: T20 (s), source in the pit, receivers in the auditorium

Octave band (Hz)	Receivers								Average
	1	2	3	4	5	6	7	8	
125	0.85	0.81	1.18	1.11	0.78	1.10	0.85	1.15	0.98
250	1.09	1.08	1.25	0.95	0.91	1.26	0.97	0.99	1.06
500	0.96	1.14	0.98	1.06	0.84	0.98	0.76	0.86	0.92
1k	0.81	0.82	0.87	0.85	0.77	0.78	0.80	0.77	0.81
2k	0.74	0.74	0.72	0.77	0.73				0.74
4k	0.59	0.60	0.59	0.62	0.57	0.55	0.61	0.60	0.59

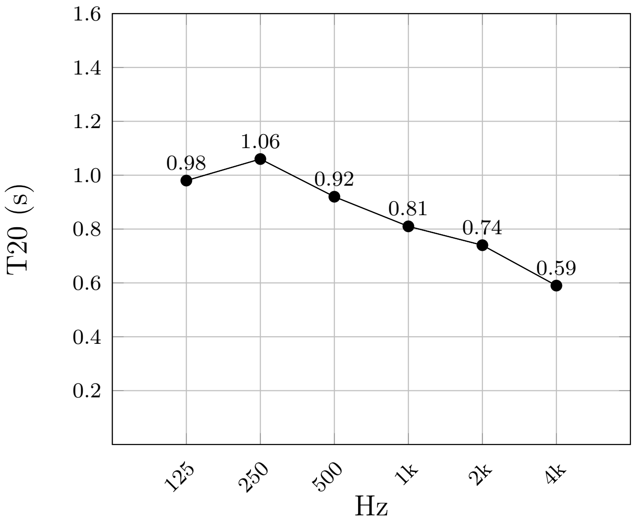


Figure 3.24: Average T20, S pit, R auditorium

Table 3.12: T20 (s), source in the pit, receivers in the 1st balcony

Octave band (Hz)	Receivers						Average
	9	10	11	12	13	14	
125	0.82	1.16	1.12	1.23	1.00	0.99	1.05
250	1.06	1.34	0.89	1.07	1.21	1.00	1.10
500	0.96	0.90	0.79	0.82	1.05	1.04	0.93
1k	0.85	0.80	0.75	0.83	0.93	0.92	0.85
2k	0.76	0.73	0.74	0.73	0.75	0.76	0.75
4k	0.61	0.60	0.56	0.56	0.59	0.62	0.60

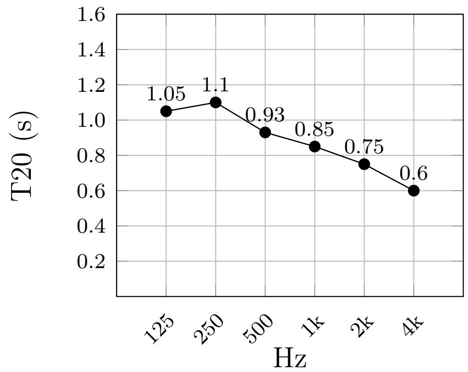


Figure 3.25: Average T20, S pit, R 1st balcony

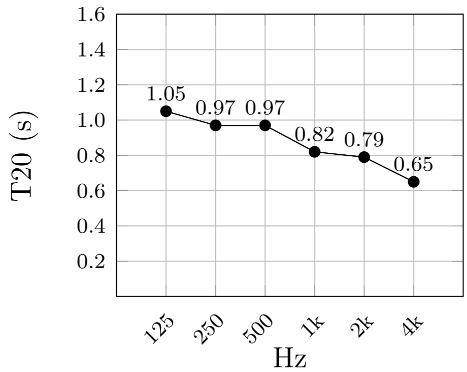


Figure 3.26: Average T20, S pit, R 2nd balcony

Table 3.13: T20 (s), source in the pit, receivers in the 2nd balcony

Octave band (Hz)	Receivers					Average
	15	16	17	18	19	
125	0.95	1.34	1.01	0.90	1.04	1.05
250	0.93	1.02	0.87	1.09	0.93	0.97
500	0.99	0.81	1.14	0.97	0.96	0.97
1k	0.78	0.83	0.84	0.88	0.79	0.82
2k	0.83	0.76	0.84	0.79	0.74	0.79
4k	0.63	0.66	0.65			0.65

C50, source on stage In the following tables are shown the values of the C50 parameter, in Decibels, correspondent to the measurements with the sound source positioned on stage and the receivers placed throughout the hall in the same positions as before.

Table 3.14: C50 (dB), source on stage, receivers in the auditorium

Octave band (Hz)	Receivers								Average
	1	2	3	4	5	6	7	8	
500	3.0	0.9	4.2	-1.2	-1.5	0.6	-0.6	1.3	0.8
1k	0.9	2.3	2.0	0.2	2.0	2.7	3.2	3.4	2.1
2k	3.4	2.9	4.2	2.4	4.7	4.6	3.9	4.4	3.8
4k	4.4	3.5	4.9	5.2	5.9	5.5	5.1	6.1	5.1

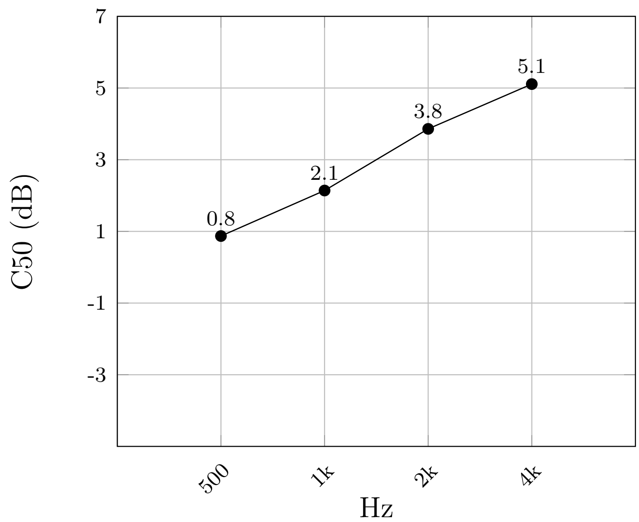


Figure 3.27: Average C50, S stage, R auditorium

Table 3.15: C50 (dB), source on stage, receivers in 1st balcony

Octave band (Hz)	Receivers						Average
	9	10	11	12	13	14	
500	0.7	-4.0	-1.6	-0.8	-2.0	3.3	-0
1k	1.1	-1.1	-1.0	1.0	3.6	3.0	1.5
2k	3.4	0.5	0.2	-1.5	1.9	2.9	1.8
4k	5.6	2.7	0.8	0.9	4.6	3.9	3.5

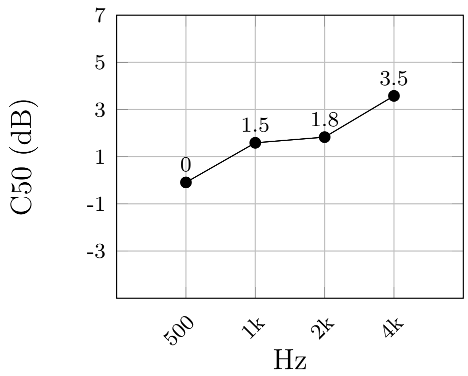


Figure 3.28: Average C50, S stage, R 1st balcony

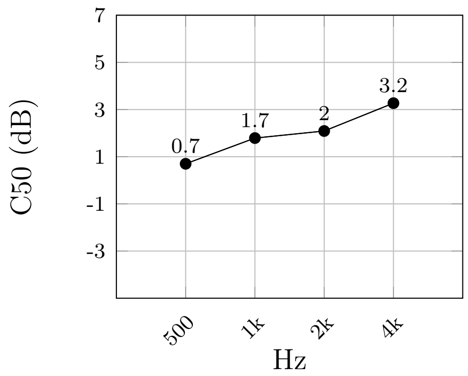


Figure 3.29: Average C50, S stage, R 2nd balcony

Table 3.16: C50 (dB), source on stage, receivers in 2nd balcony

Octave band (Hz)	Receivers					Average
	15	16	17	18	19	
500	2.3	-3.3	-0.9	3.4	1.9	0.7
1k	2.5	0.1	0.1	3.3	2.7	1.7
2k	3.6	-0.0	0.6	3.2	2.9	2.0
4k	4.6	0.2	1.9	3.1	3.3	3.2

C50, source in the pit In the following tables are shown the values of the C50 parameter, in Decibels, correspondent to the measurements with the sound source positioned in the pit and the receivers placed throughout the hall in the same positions as before.

Table 3.17: C50 (dB), source in the pit, receivers in the auditorium

Octave band (Hz)	Receivers								Average
	1	2	3	4	5	6	7	8	
500	-0.8	-2.9	0.0	-4.3	-2.7	-4.8	-2.8	-5.0	-3.8
1k	-0.3	-0.6	0.3	-2.3	-1.2	-1.0	-2.8	-4.4	-1.8
2k	0.3	-0.6	2.1	-0.9	-1.5	-0.9	-1.9	-2.6	-1.1
4k	1.2	1.6	4.6	-0.9	0.2	0.6	0.6	-0.7	0.3

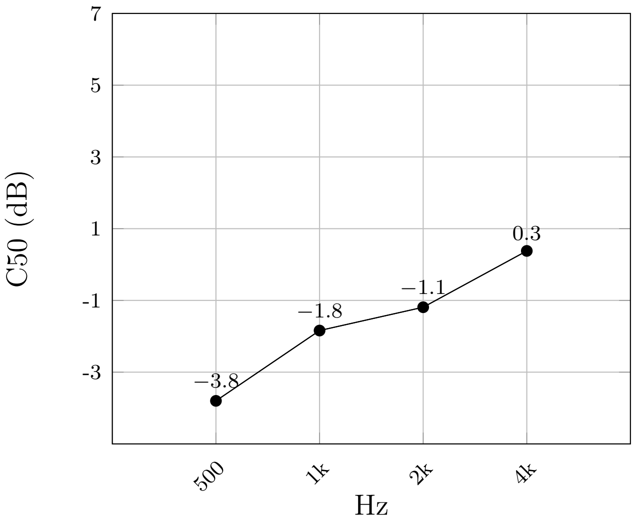


Figure 3.30: Average C50, S pit, R auditorium

Table 3.18: C50 (dB), source in the pit, receivers in the 1st balcony

Octave band (Hz)	Receivers						Average
	9	10	11	12	13	14	
500	2.0	-0.6	5.2	-1.7	-4.4	-0.2	0.0
1k	2.8	1.8	5.0	0.9	-2.3	-3.8	-0.1
2k	3.0	1.9	4.5	-0.7	-4.0	-2.0	0.4
4k	5.4	4.4	5.0	0.7	-0.9	-0.8	2.3

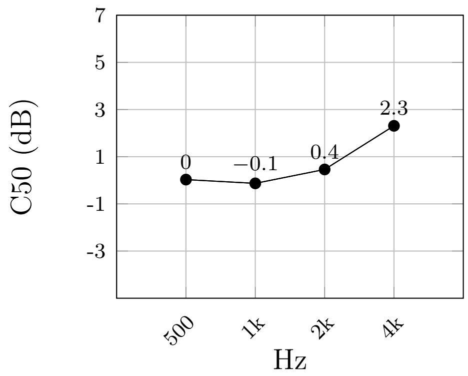


Figure 3.31: Average C50, S pit, R 1st balcony

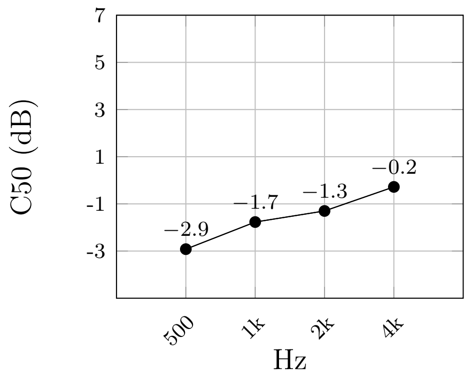


Figure 3.32: Average C50, S pit, R 2nd balcony

Table 3.19: C50 (dB), source in the pit, receivers in the 2nd balcony

Octave band (Hz)	Receivers					Average
	15	16	17	18	19	
500	-3.4	-5.1	-3.9	-1.2	-0.8	-2.9
1k	0.4	-2.5	-5.0	-1.9	0.2	-1.7
2k	0.4	-3.3	-3.6	-0.4	0.5	-1.3
4k	-0.2	-3.5	-2.3	0.4	1.0	-0.2

C80, source on stage In the following tables are shown the values of the C80 parameter, in Decibels, correspondent to the measurements with the sound source positioned on stage and the receivers placed throughout the hall in the same positions as before.

Table 3.20: C80 (dB), source on stage, receivers in the auditorium

Octave band (Hz)	Receivers								Average
	1	2	3	4	5	6	7	8	
500	5.1	4.1	5.9	3.6	3.4	2.6	2.6	5.1	4.0
1k	4.9	5.5	5.8	4.5	5.6	4.8	4.9	7.3	5.4
2k	7.0	6.4	7.1	6.3	7.8	7.8	8.4	7.9	7.5
4k	8.4	7.7	8.4	9.1	9.5	9.2	9.7	9.7	9.0

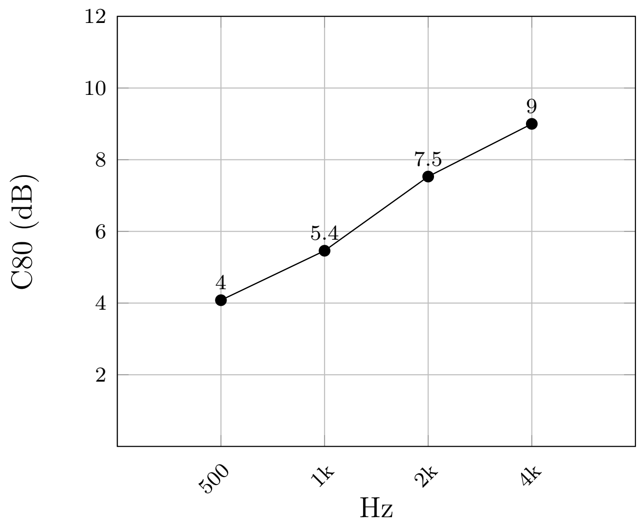


Figure 3.33: Average C80, S stage, R auditorium

Table 3.21: C80 (dB), source on stage, receivers in the 1st balcony

Octave band (Hz)	Receivers						Average
	9	10	11	12	13	14	
500	4.8	0.1	3.1	2.9	3.0	5.9	3.7
1k	5.3	3.1	2.8	3.9	5.8	5.9	4.5
2k	6.8	3.7	4.1	3.4	5.2	6.4	5.0
4k	8.6	6.6	4.8	4.8	8.7	7.5	7.2

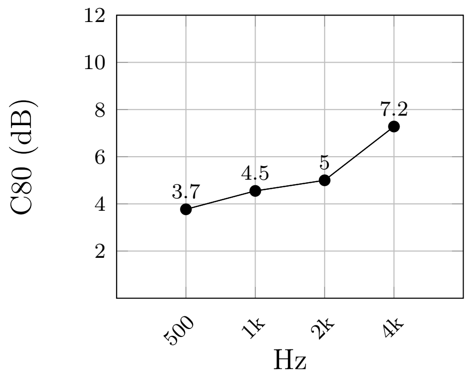


Figure 3.34: Average C80, S stage, R 1st balcony

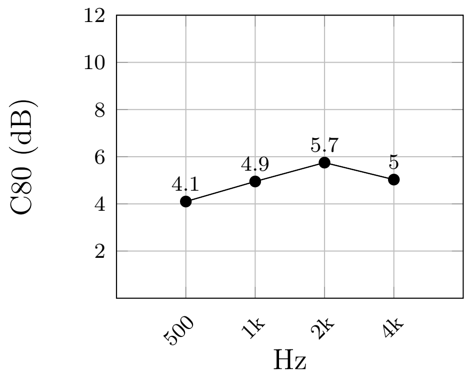


Figure 3.35: Average C80, S stage, R 2nd balcony

Table 3.22: C80 (dB), source on stage, receivers in the 2nd balcony

Octave band (Hz)	Receivers					Average
	15	16	17	18	19	
500	6.5	0.8	2.3	6.6	5.0	4.1
1k	5.9	3.3	3.8	6.2	6.3	4.9
2k	7.1	3.8	4.4	7.1	5.5	5.7
4k	8.2	4.4	5.6	7.5	7.3	5.0

C80, source in the pit In the following tables are shown the values of the C80 parameter, in Decibels, correspondent to the measurements with the sound source positioned in the pit and the receivers placed throughout the hall in the same positions as before.

Table 3.23: C80 (dB), source in the pit, receivers in the auditorium

Octave band (Hz)	Receivers								Average
	1	2	3	4	5	6	7	8	
500	1.9	1.9	3.6	0.6	0.6	1.1	0.7	6.0	1.6
1k	3.9	3.0	4.5	1.7	2.9	2.9	1.0	0.2	2.2
2k	4.0	3.5	5.4	3.6	2.2	2.7	3.0	2.6	3.1
4k	5.8	6.2	8.2	4.9	4.2	4.6	5.4	4.0	5.0

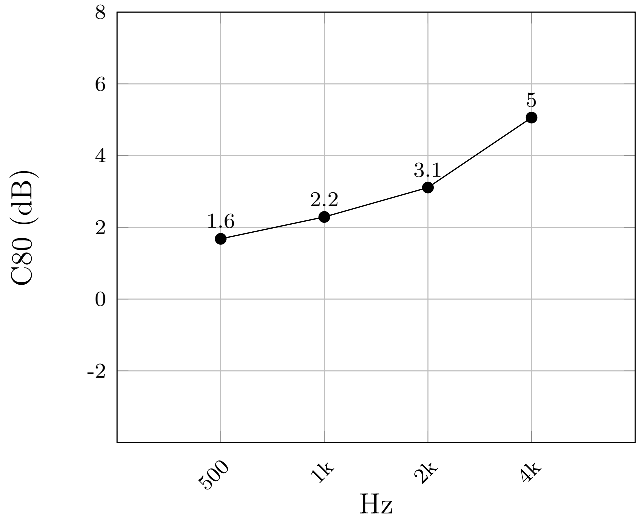


Figure 3.36: Average C80, S pit, R auditorium

Table 3.24: C80 (dB), source in the pit, receivers in the 1st balcony

Octave band (Hz)	Receivers						Average
	9	10	11	12	13	14	
500	4.2	2.4	8.6	1.9	0.6	4.1	3.6
1k	5.7	4.6	7.5	3.9	2.3	0.6	4.1
2k	6.2	5.0	7.7	3.4	1.0	2.5	4.2
4k	9.0	7.9	9.4	5.0	2.7	4.1	5.9

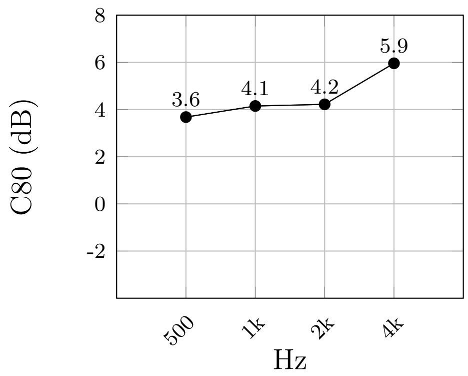


Figure 3.37: Average C80, S pit, R 1st balcony

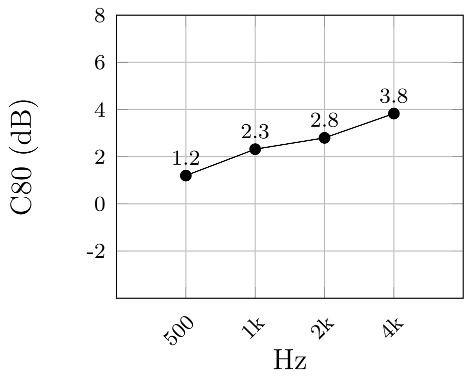


Figure 3.38: Average C80, S pit, R 2nd balcony

Table 3.25: C80 (dB), source in the pit, receivers in the 2nd balcony

Octave band (Hz)	Receivers					Average
	15	16	17	18	19	
500	0.9	-0.5	-0.1	2.5	3.0	1.2
1k	3.8	1.8	-0.0	2.3	3.5	2.3
2k	3.4	1.1	0.5	3.0	4.1	2.8
4k	4.2	2.0	1.6	4.4	4.6	3.8

3.4.3 Criteria values in the orchestra pit

With regard to the pit orchestra, it is advisable to adhere to the nomenclature prescribed by the protocol used during the measurement campaign, wherein the arrangements of sources and receivers are referred to as follows: Sx_Rx, where S and R denote sources and receivers, and x represents the respective orchestra pit section number.

EDT, orchestra pit In the following tables are shown the values of the EDT parameter, in seconds, correspondent to the measurements with the sound source and receivers positioned in section number 1, 2, 6, 7.

Table 3.26: EDT (s), orchestra pit, S1, S2

Octave band (Hz)	Receivers				Averages	
	S1_R6	S1_R7	S2_R6	S2_R7	S1	S2
125	0.80	1.14	0.76	1.07	0.97	0.91
250	0.75	0.58	0.72	0.78	0.66	0.75
500	0.80	0.74	0.60	0.74	0.77	0.67
1k	0.69	0.97	0.75	0.79	0.83	0.77
2k	0.73	0.92	0.76	0.71	0.83	0.74
4k	0.62	0.76	0.71	0.69	0.69	0.70

Table 3.27: EDT (s), orchestra pit, S6, S7

Octave band (Hz)	Receivers				Averages	
	S6_R1	S6_R2	S7_R1	S7_R2	S6	S7
125	0.76	0.81	1.12	1.14	0.79	1.13
250	0.76	0.76	0.80	0.61	0.76	0.70
500	0.58	0.77	0.63	0.72	0.68	0.68
1k	0.77	0.73	0.73	0.98	0.75	0.86
2k	0.82	0.71	0.68	0.77	0.77	0.72
4k	0.65	0.63	0.64	0.75	0.64	0.70

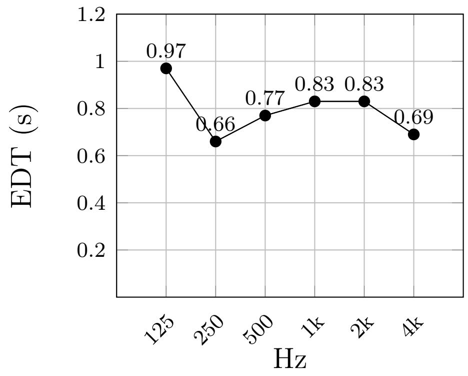


Figure 3.39: Average EDT, orchestra pit, S1

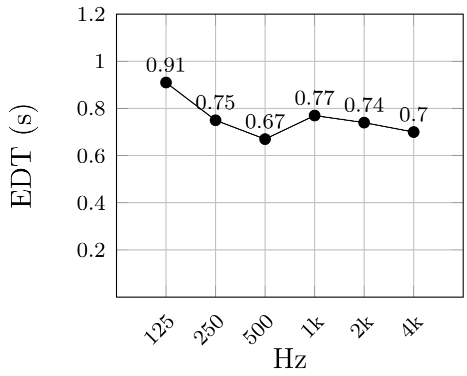


Figure 3.40: Average EDT, orchestra pit, S2

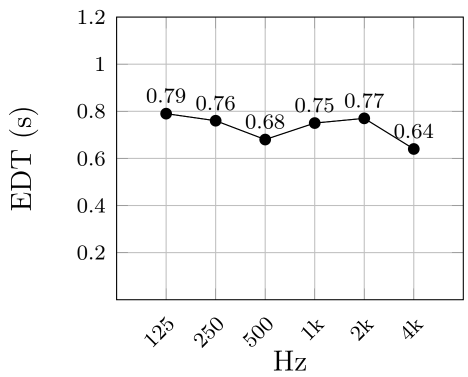


Figure 3.41: Average EDT, orchestra pit, S6

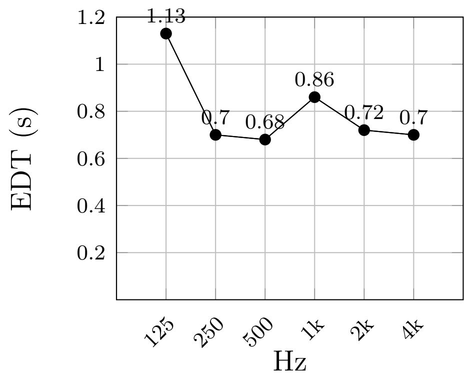


Figure 3.42: Average EDT, orchestra pit, S7

T30, orchestra pit In the following tables are shown the values of the T30 parameter, in seconds, correspondent to the measurements with the sound source and receivers positioned in section number 1, 2, 6, 7.

Table 3.28: T30 (s), orchestra pit, S1, S2

Octave band (Hz)	Receivers				Averages	
	S1_R6	S1_R7	S2_R6	S2_R7	S1	S2
125	0.80	0.90	0.85	0.93	0.85	0.89
250	0.78	0.88	0.81	0.87	0.83	0.84
500	0.87	0.93	0.83	0.83	0.90	0.83
1k	1.08	1.18	0.92	0.93	1.13	0.92
2k	0.88	0.93	0.86	0.88	0.91	0.87
4k	0.99	1.08	0.86	0.88	1.04	0.87

Table 3.29: T30 (s), orchestra pit, S6, S7

Octave band (Hz)	Receivers				Averages	
	S6_R1	S6_R2	S7_R1	S7_R2	S6	S7
125	0.83	0.80	0.94	0.89	0.82	0.61
250	0.82	0.82	0.86	0.86	0.82	0.57
500	0.86	0.85	0.86	0.92	0.85	0.59
1k	0.92	0.98	0.93	1.14	0.95	0.69
2k	0.87	0.94	0.86	0.94	0.90	0.60
4k	0.91	1.02	0.86	1.15	0.96	0.67

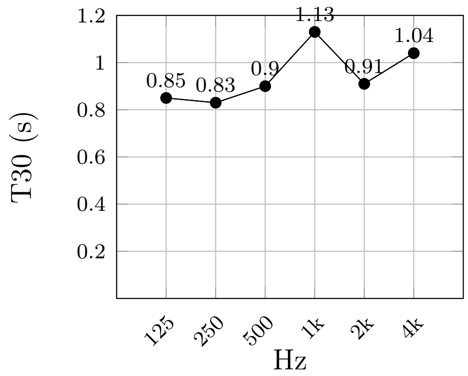


Figure 3.43: Average T30, orchestra pit, S1

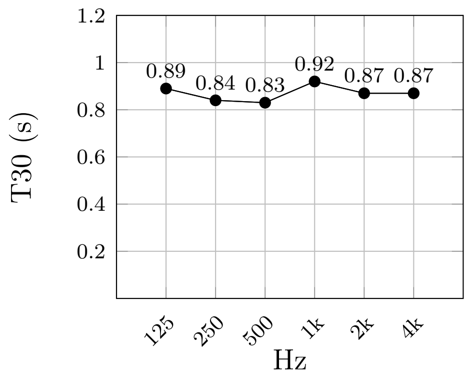


Figure 3.44: Average T30, orchestra pit, S2

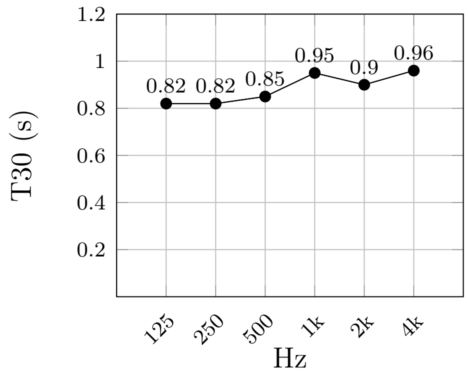


Figure 3.45: Average T30, orchestra pit, S6

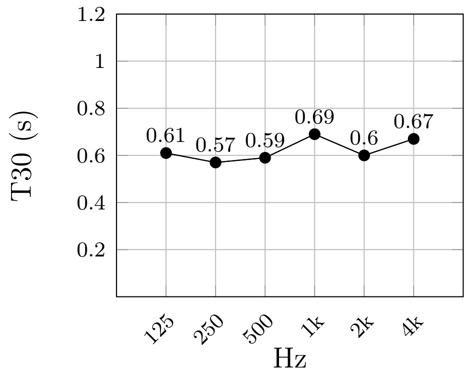


Figure 3.46: Average T30, orchestra pit, S7

C50, orchestra pit In the following tables are shown the values of the C50 parameter, in Decibels, correspondent to the measurements with the sound source and receivers positioned in section number 1, 2, 6, 7.

Table 3.30: C50 (dB), orchestra pit, S1, S2

Octave band (Hz)	Receivers				Averages	
	S1_R6	S1_R7	S2_R6	S2_R7	S1	S2
125	1.4	1.5	0.2	5.4	1.4	2.8
250	3.5	4.2	5.7	4.5	3.8	5.1
500	4.0	0.4	0.9	2.0	2.2	1.5
1k	1.8	1.0	0.3	2.5	1.4	1.4
2k	1.5	2.7	2.5	4.2	2.1	3.4
4k	4.2	2.8	3.6	4.2	3.5	3.9

Table 3.31: C50 (dB), orchestra pit, S6, S7

Octave band (Hz)	Receivers				Averages	
	S6_R1	S6_R2	S7_R1	S7_R2	S6	S7
125	1.4	-0.1	1.1	4.9	0.6	3.0
250	3.4	5.9	3.6	4.8	4.6	4.2
500	4.0	0.9	0.4	2.4	2.4	1.4
1k	1.9	0.9	2.2	1.8	1.4	2.0
2k	1.4	1.0	2.5	3.7	1.2	3.1
4k	3.5	2.6	3.7	3.8	3.0	3.7

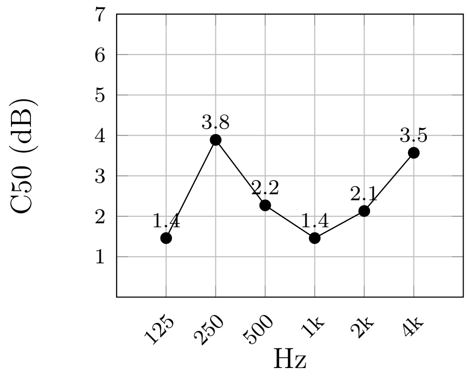


Figure 3.47: Average C50, orchestra pit, S1

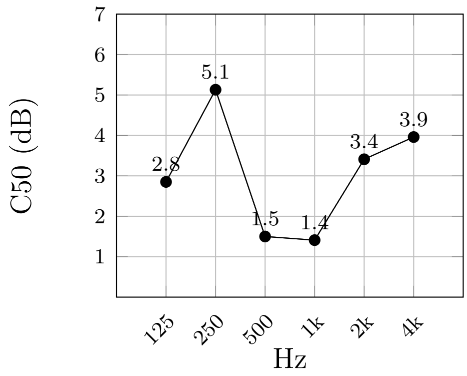


Figure 3.48: Average C50, orchestra pit, S2

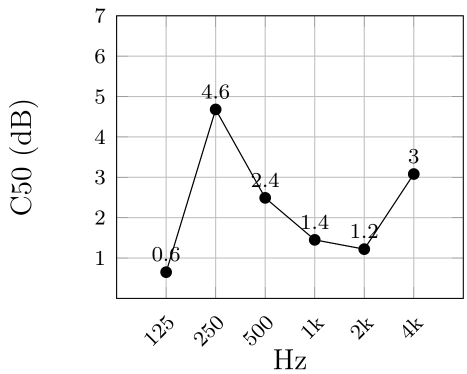


Figure 3.49: Average C50, orchestra pit, S6

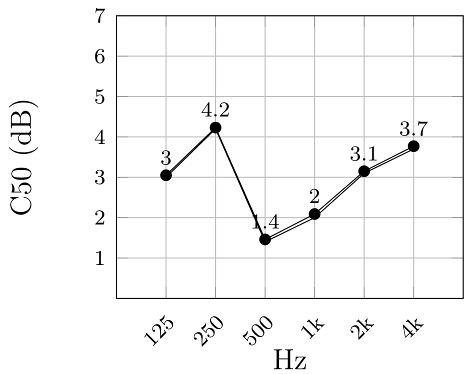


Figure 3.50: Average C50, orchestra pit, S7

C80, orchestra pit In the following tables are shown the values of the C80 parameter, in Decibels, correspondent to the measurements with the sound source and receivers positioned in section number 1, 2, 6, 7.

Table 3.32: C80 (dB), orchestra pit, S1, S2

Octave band (Hz)	Receivers				Averages	
	S1_R6	S1_R7	S2_R6	S2_R7	S1	S2
125	4.0	5.3	6.0	1.5	4.7	3.8
250	4.6	8.5	5.3	4.4	6.5	4.9
500	4.8	6.2	7.4	3.6	5.5	5.5
1k	7.0	4.4	7.3	5.4	5.7	6.4
2k	6.2	4.1	6.2	6.1	5.2	6.2
4k	7.0	6.9	7.1	6.0	7.0	6.5

Table 3.33: C80 (dB), orchestra pit, S6, S7

Octave band (Hz)	Receivers				Averages	
	S6_R1	S6_R2	S7_R1	S7_R2	S6	S7
125	6.1	3.9	1.6	5.4	5.0	3.5
250	4.8	4.0	4.0	8.0	4.4	6.0
500	7.7	5.1	5.3	6.3	6.4	5.8
1k	6.6	6.3	6.0	4.7	6.5	5.3
2k	5.9	5.5	6.7	5.3	5.7	6.0
4k	7.3	6.8	6.8	6.3	7.1	6.5

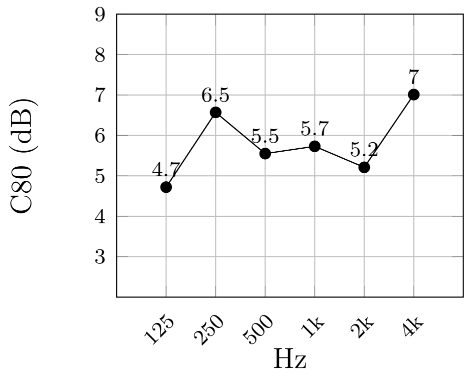


Figure 3.51: Average C80, orchestra pit, S1

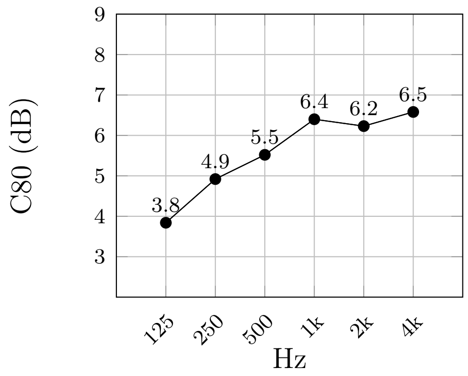


Figure 3.52: Average C80, orchestra pit, S2

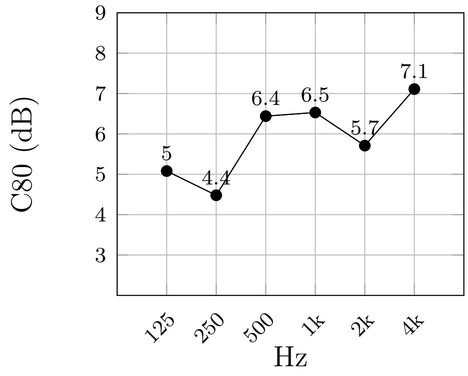


Figure 3.53: Average C80, orchestra pit, S6

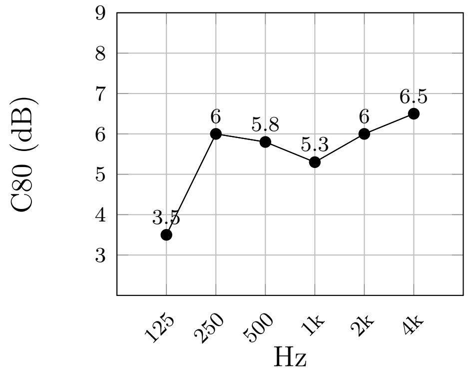


Figure 3.54: Average C80, orchestra pit, S7

Support ST$_{early}$, ST$_{late}$, orchestra pit In the following tables are shown the values in Decibels of the ST$_{early}$ and ST$_{late}$ parameter correspondent to the measurements with the sound source and receivers positioned in every section

Table 3.34: ST$_{early}$, ST$_{late}$ (dB), orchestra pit

S_R setup	ST$_{early}$	ST$_{late}$
S1_R1	-2.03	-8.51
S2_R2	0.22	-6.5
S3_R3	0.24	-6.18
S4_R4	-2.87	-8.12
S5_R5	-1.03	-6.99
S6_R6	-2.87	-7.25
S7_R7	-2.18	-7.46
S9_R9	-1.45	-6.39
S10_R10	-3.04	-8.12

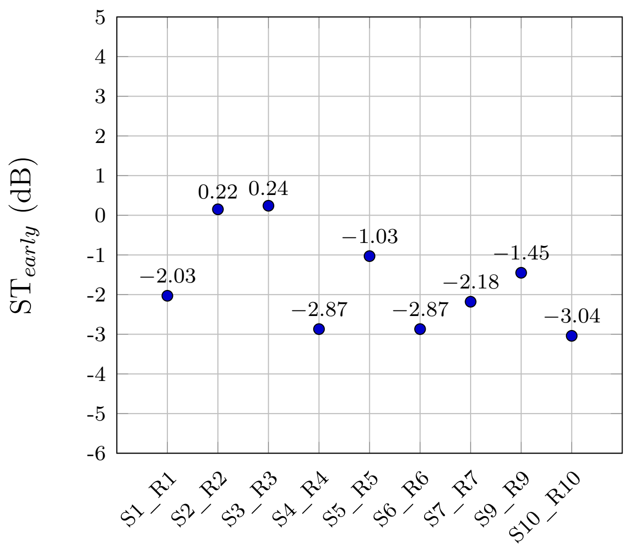


Figure 3.55: ST$_{early}$, orchestra pit

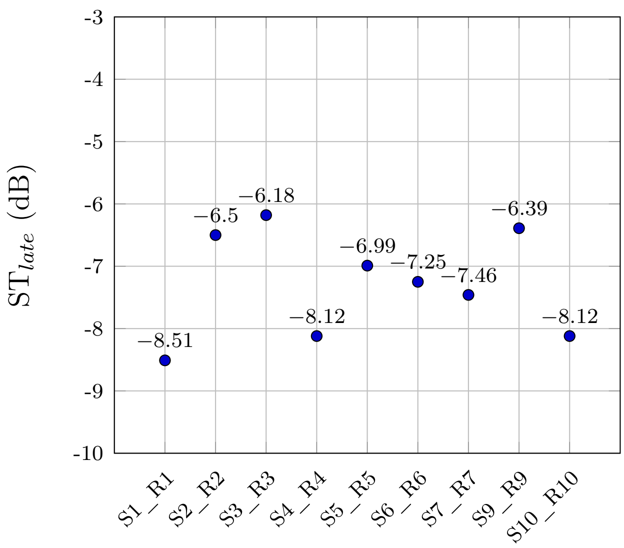


Figure 3.56: ST$_{late}$, orchestra pit

Support Extended $ST_{early,d}$, $ST_{late,d}$, orchestra pit In the following tables are shown the values in Decibels of the $ST_{early,d}$ and $ST_{late,d}$ parameter correspondent to the measurements with the sound source and receivers positioned in every section

Table 3.35: $ST_{early,d}$, $ST_{late,d}$ (dB), S1

S_R setup	$ST_{early,d}$	$ST_{late,d}$
S1_R2	2.11	-5.78
S1_R3	-0.26	-7.97
S1_R4	-2.33	-9.21
S1_R5	-1.47	-7.62
S1_R6	-4.76	-10.72
S1_R7	-5.78	-10.6
S1_R8	-0.42	-6.01
S1_R9	1.27	-5.2
S1_R10	-3.98	-8.11

Table 3.36: $ST_{early,d}$, $ST_{late,d}$ (dB), S2

S_R setup	$ST_{early,d}$	$ST_{late,d}$
S2_R1	2.29	-5.74
S2_R3	-3.23	-10.62
S2_R4	-3.33	-10.17
S2_R5	0.2	-7.14
S2_R6	-3.72	-9.42
S2_R7	-1.26	-7.86
S2_R8	-5.43	-10.12
S2_R9	-2.22	-7.89
S2_R10	-1.21	-7.41

Table 3.37: $ST_{early,d}$, $ST_{late,d}$ (dB), S3

S_R setup	$ST_{early,d}$	$ST_{late,d}$
S3_R1	2.12	-5.39
S3_R2	-1.13	-8.32
S3_R4	-2.54	-9.42
S3_R5	-0.07	-7.18
S3_R6	-5.80	-11.91
S3_R7	-2.79	-8.27
S3_R8	-0.61	-5.94
S3_R9	-2.03	-8.27
S3_R10	-1.26	-6.9

Table 3.38: $ST_{early,d}$, $ST_{late,d}$ (dB), S4

S_R setup	$ST_{early,d}$	$ST_{late,d}$
S4_R1	-3.26	-10.17
S4_R2	-4.34	-11.51
S4_R3	-4.51	-11.60
S4_R5	-3.75	-10.30
S4_R6	-4.29	-9.52
S4_R7	-4.99	-9.71
S4_R8	-5.41	-12.02
S4_R9	-5.12	-11.15
S4_R10	-4.34	-9.63

Table 3.39: $ST_{early,d}$, $ST_{late,d}$ (dB), S5

S_R setup	$ST_{early,d}$	$ST_{late,d}$
S5_R1	-0.33	-6.10
S5_R2	-2.19	-9.34
S5_R3	-2.08	-8.73
S5_R4	-2.69	-9.37
S5_R6	-1.19	-6.46
S5_R7	-1.65	-7.78
S5_R8	-7.09	-13.06
S5_R9	-4.34	-10.56
S5_R10	-2.19	-8.87

Table 3.40: $ST_{early,d}$, $ST_{late,d}$ (dB), S6

S_R setup	$ST_{early,d}$	$ST_{late,d}$
S6_R1	2.19	-4.02
S6_R2	2.58	-2.88
S6_R3	2.19	-3.89
S6_R4	0.53	-5.21
S6_R5	1.85	-2.98
S6_R7	1.33	-4.17
S6_R8	-0.86	-6.11
S6_R9	1.81	-4.32
S6_R10	0.31	-4.69

Table 3.41: $ST_{early,d}$, $ST_{late,d}$ (dB), S7

S_R setup	$ST_{early,d}$	$ST_{late,d}$
S7_R1	-1.83	-6.86
S7_R2	-3.00	-9.35
S7_R3	-3.35	-9.01
S7_R4	-3.62	-8.99
S7_R5	-2.72	-8.92
S7_R6	-3.13	-8.62
S7_R8	-3.61	-8.79
S7_R9	-4.33	-9.55
S7_R10	-1.26	-8.72

Table 3.42: $ST_{early,d}$, $ST_{late,d}$ (dB), S9

S_R setup	$ST_{early,d}$	$ST_{late,d}$
S9_R1	-0.51	-7.74
S9_R2	-3.31	-9.43
S9_R3	-4.26	-10.41
S9_R4	-1.43	-7.95
S9_R5	0.77	-5.62
S9_R6	-3.52	-9.81
S9_R7	-6.04	-11.56
S9_R8	-4.99	-10.01
S9_R10	-1.52	-7.22

Table 3.43: $ST_{early,d}$, $ST_{late,d}$ (dB), S10

S_R setup	$ST_{early,d}$	$ST_{late,d}$
S10_R1	-5.80	-9.51
S10_R2	-2.64	-9.31
S10_R3	-5.33	-11.32
S10_R4	-3.94	-9.33
S10_R5	-3.91	-10.63
S10_R6	-2.01	-6.23
S10_R7	0.16	-7.20
S10_R8	-4.55	-11.13
S10_R9	-2.42	-8.52

Graphic representation of the Support extended In order to provide a better understanding of the experimental Support extended values, series of graphic representation of the values distribution are presented:

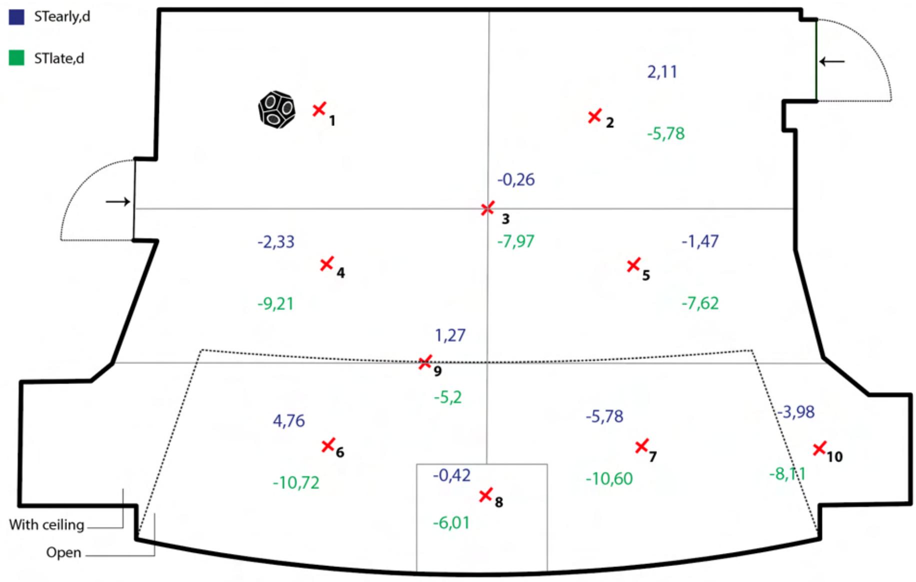


Figure 3.57: ST extended, S1

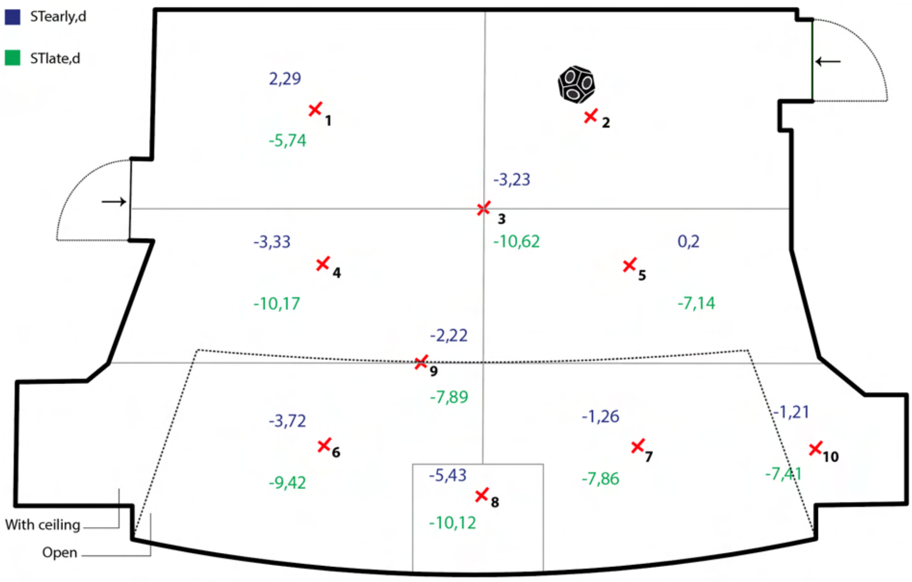


Figure 3.58: ST extended, S2

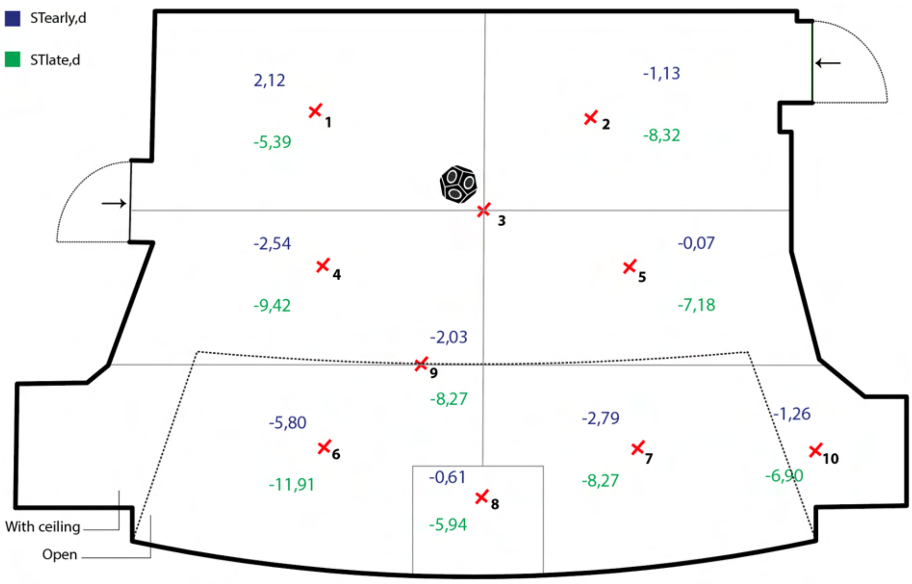


Figure 3.59: ST extended, S3

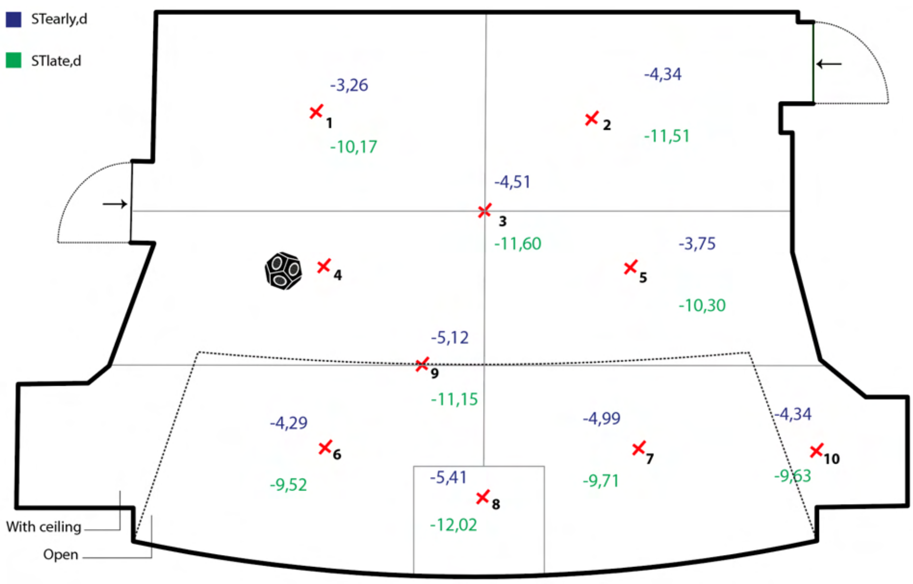


Figure 3.60: ST extended, S4

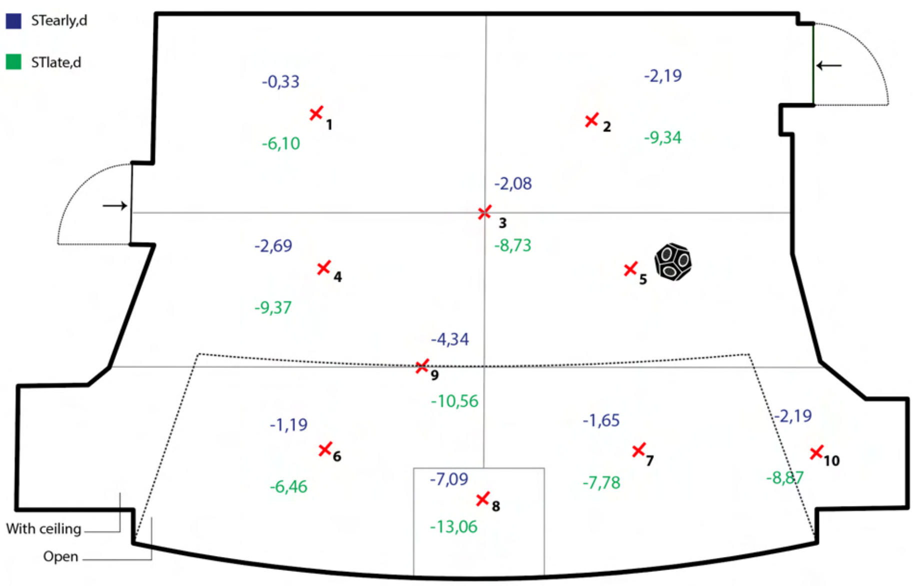


Figure 3.61: ST extended, S5

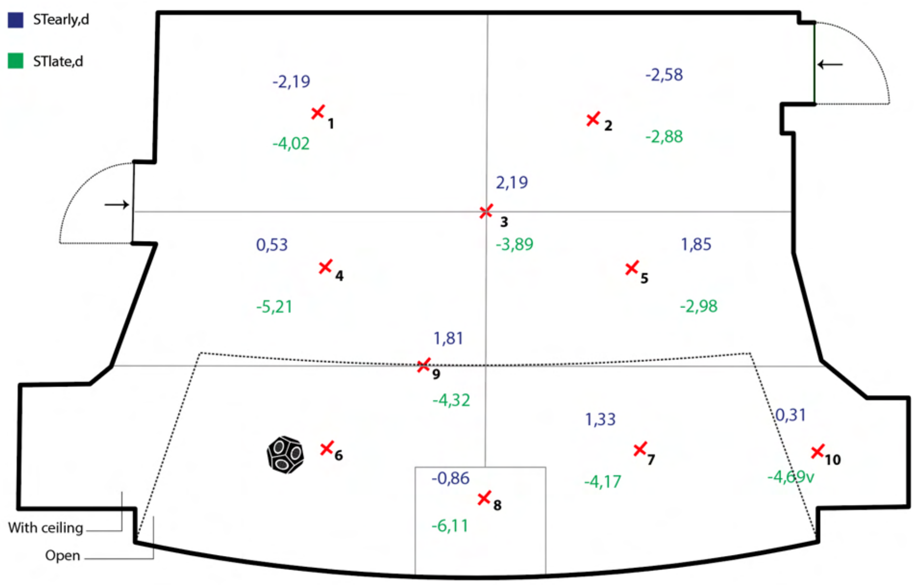


Figure 3.62: ST extended, S6

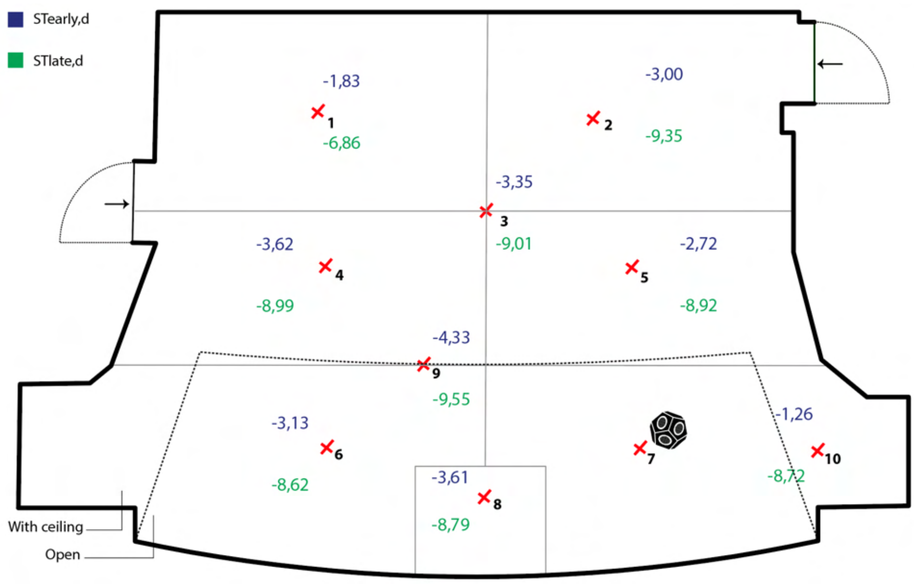


Figure 3.63: ST extended, S7

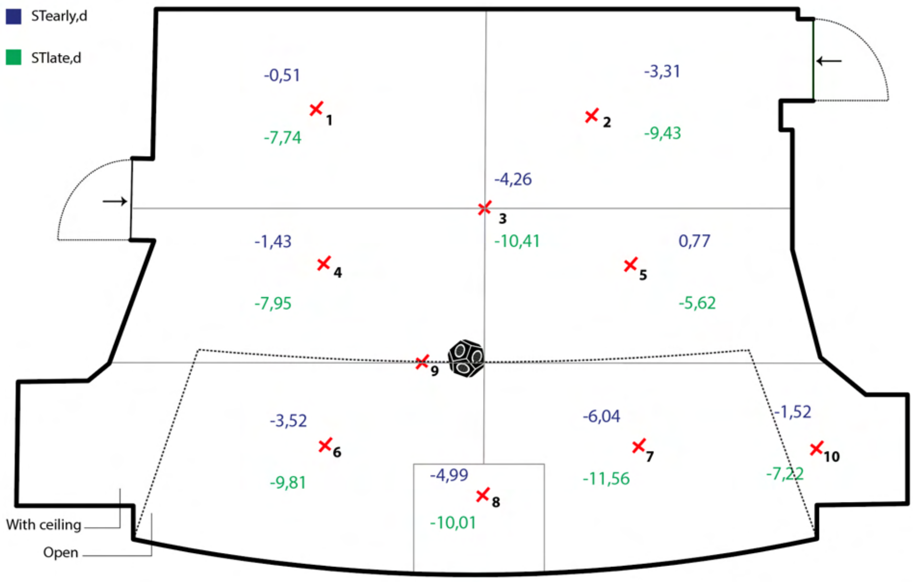


Figure 3.64: ST extended, S9

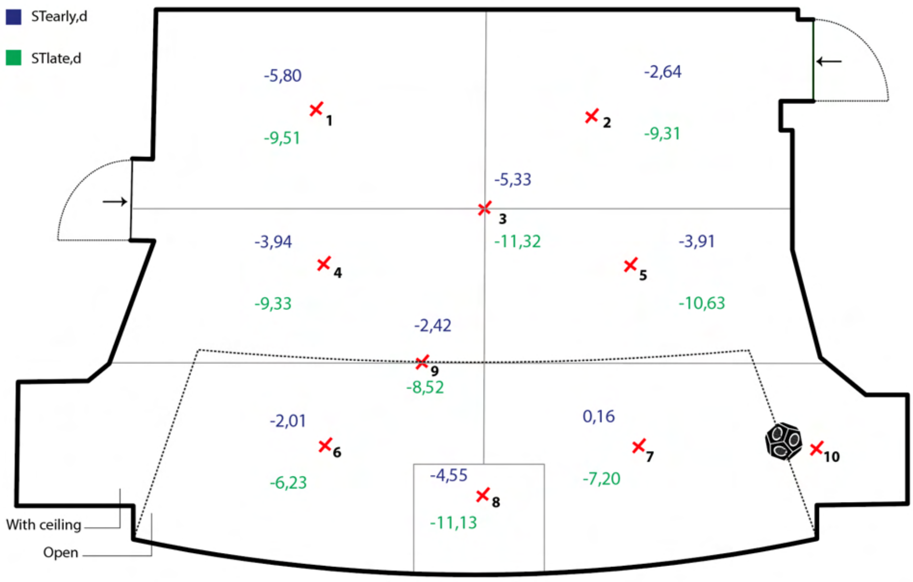


Figure 3.65: ST extended, S10

3.5 Survey of orchestral musicians

The subsequent pages display graphical depictions of the survey outcomes obtained from the members of the Freiberg Theatre Orchestra. The survey aimed to investigate the correlation between their subjective viewpoints and the objective measurements recorded.
In the survey, the musicians were requested to share insights regarding their general auditory perception within the orchestra pit during performances, specifically identifying the instruments they perceive with greater accuracy and those with lesser accuracy.

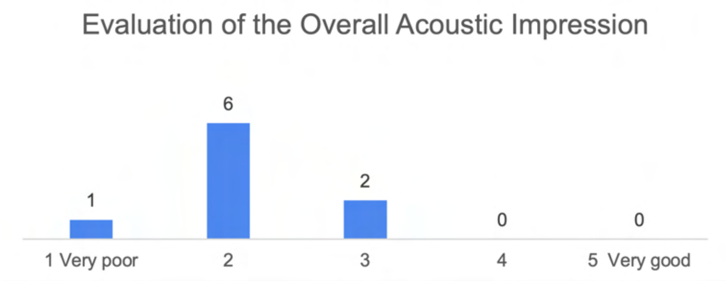


Figure 3.66: Survey 1

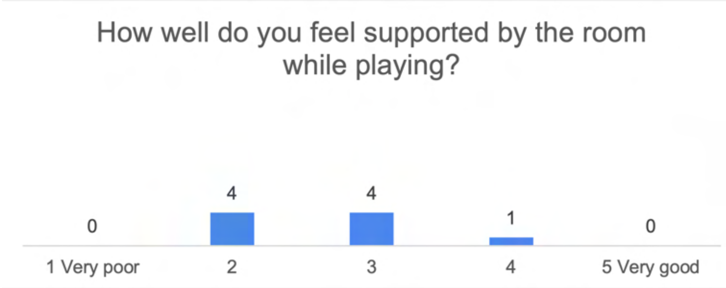


Figure 3.67: Survey 2

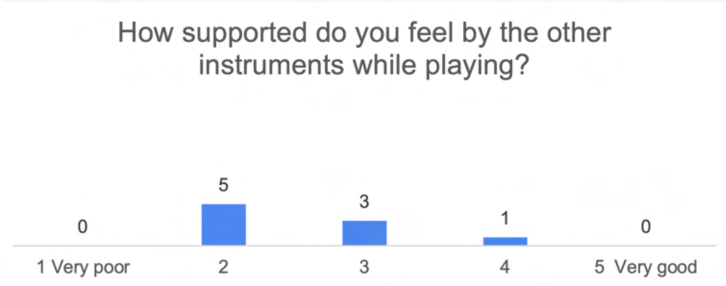


Figure 3.68: Survey 3

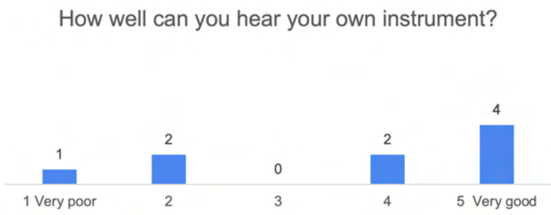


Figure 3.69: Survey 4

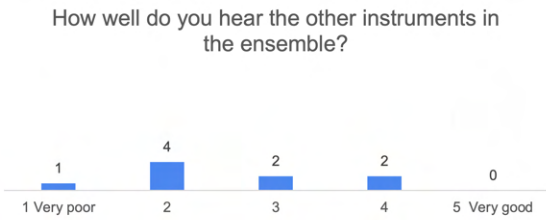


Figure 3.70: Survey 5

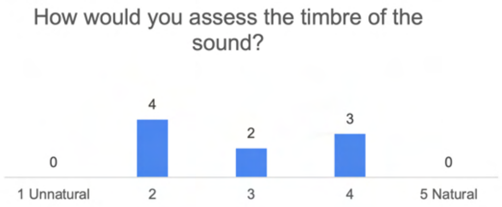


Figure 3.71: Survey 6

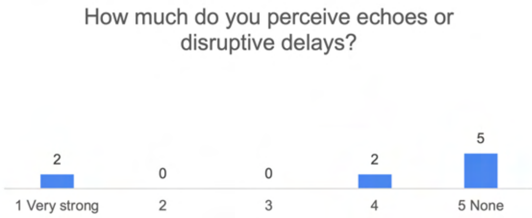


Figure 3.72: Survey 7

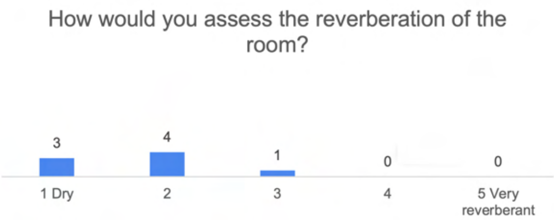


Figure 3.73: Survey 8

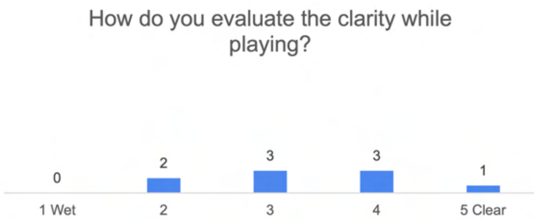


Figure 3.74: Survey 9

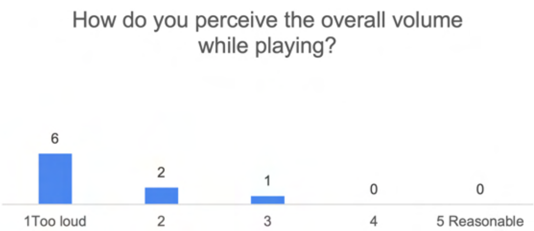


Figure 3.75: Survey 10

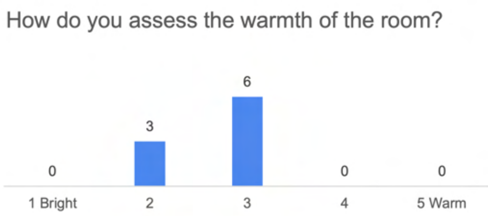


Figure 3.76: Survey 11

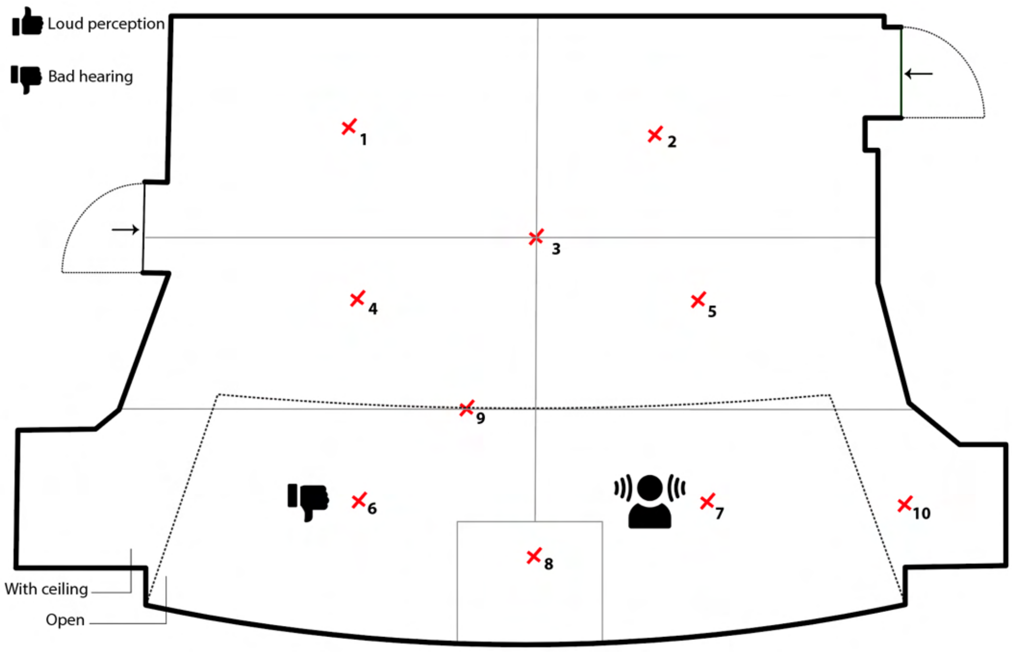


Figure 3.77: Survey Cello

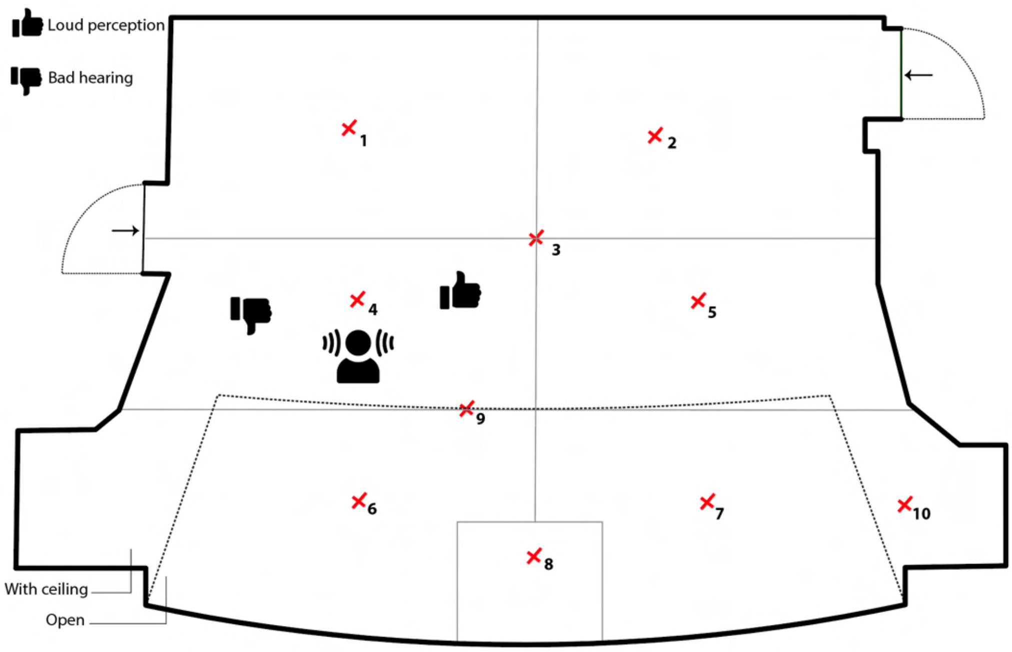


Figure 3.78: Survey Flute

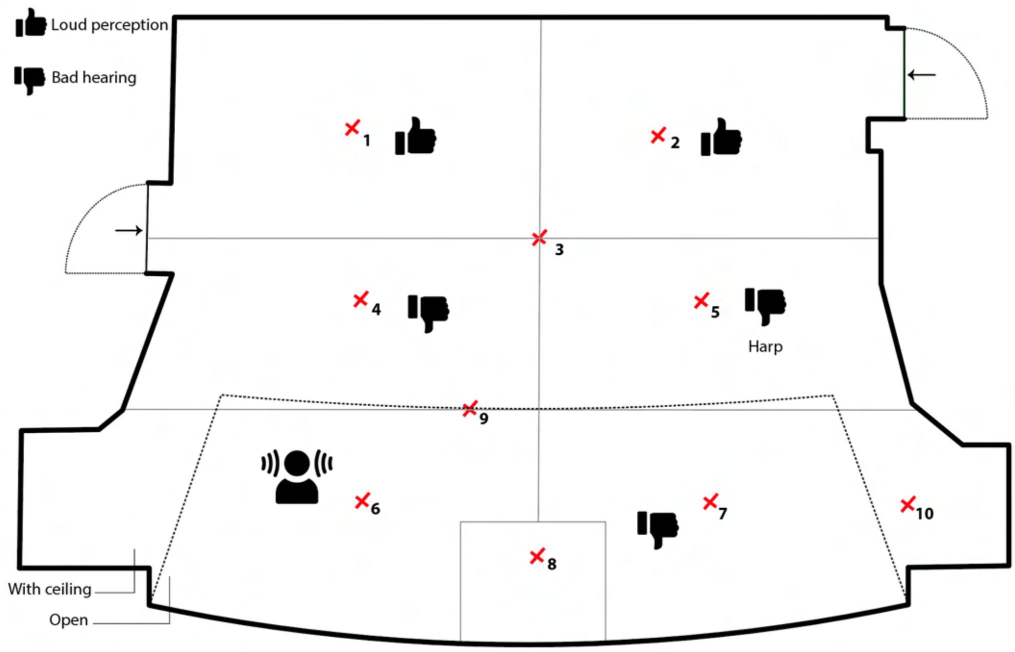


Figure 3.79: Survey Violin

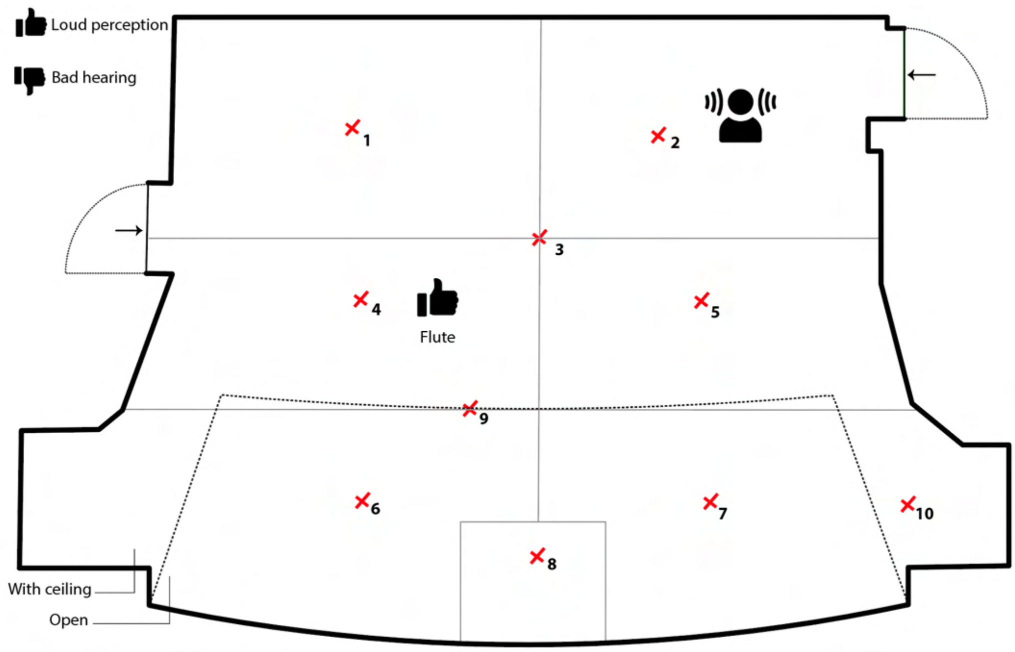


Figure 3.80: Survey Drums

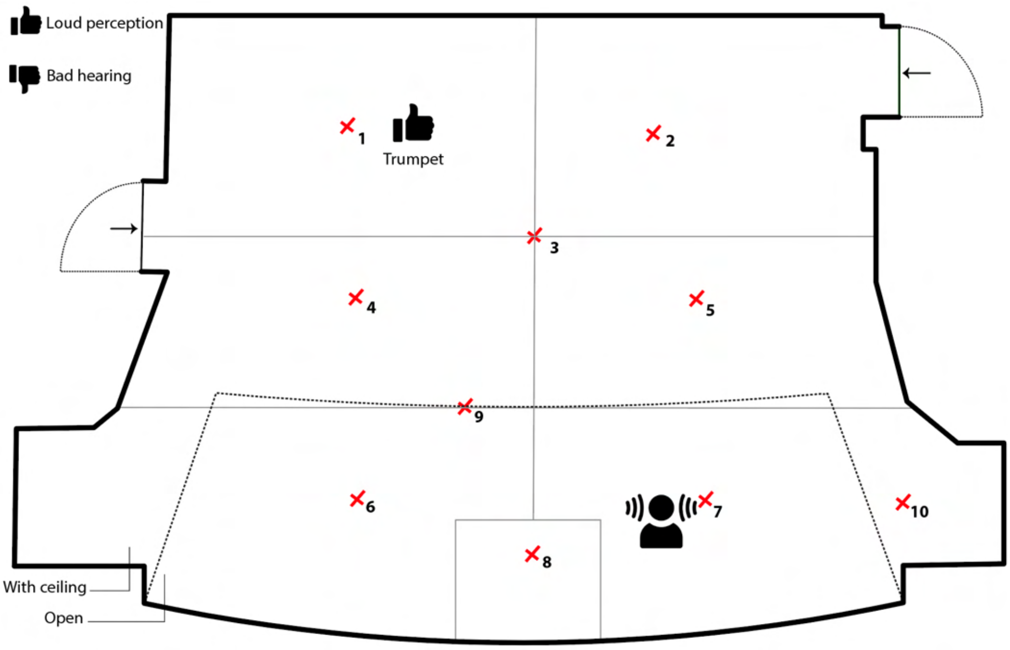


Figure 3.81: Survey Viola

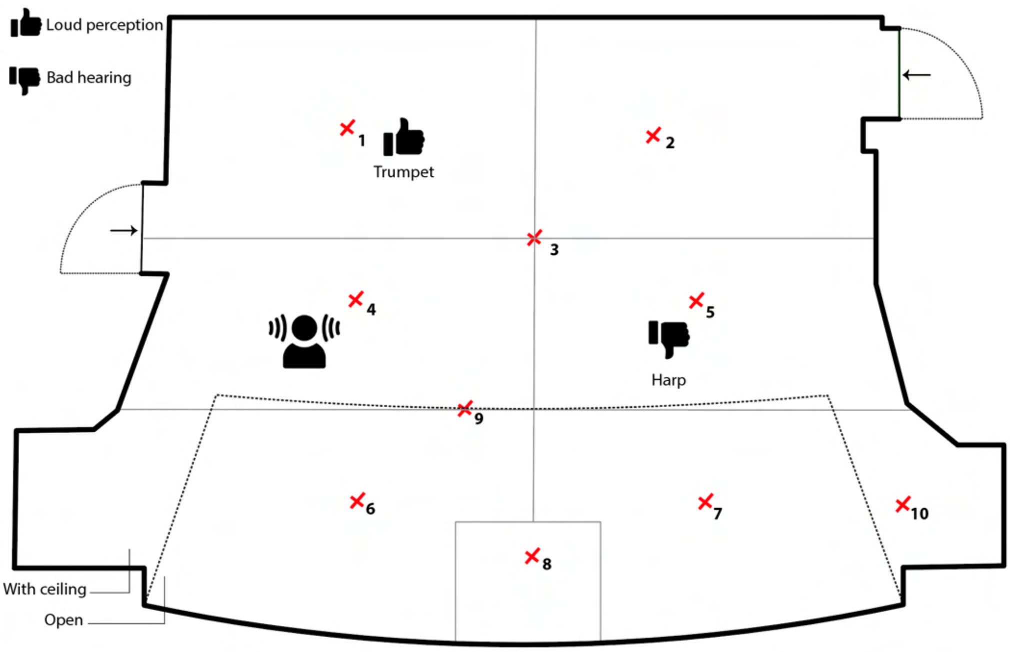


Figure 3.82: Survey Bassoon

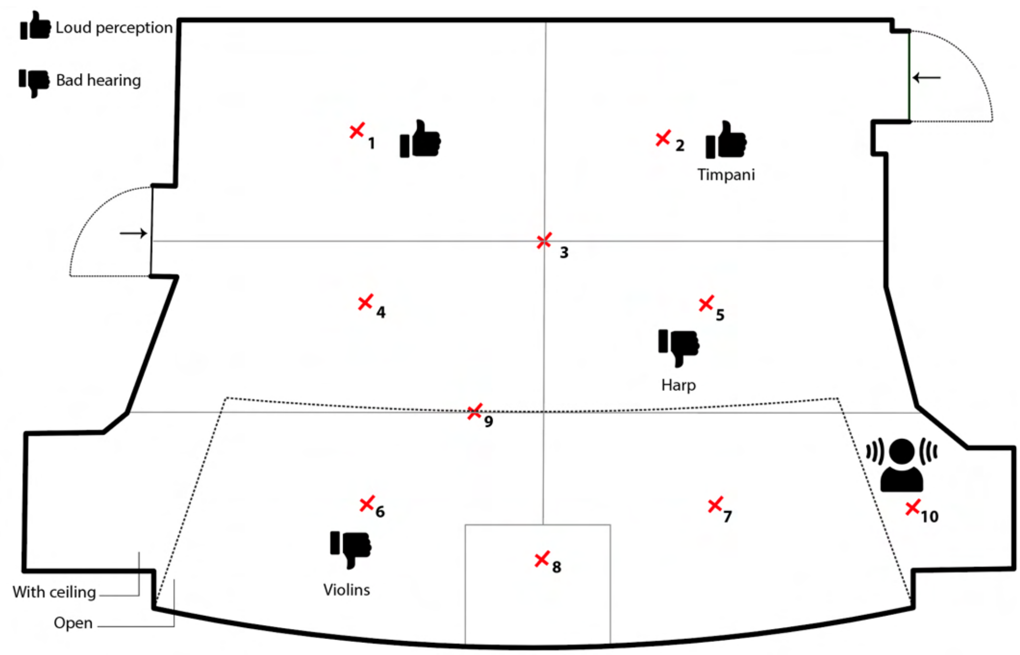


Figure 3.83: Survey Contrabass

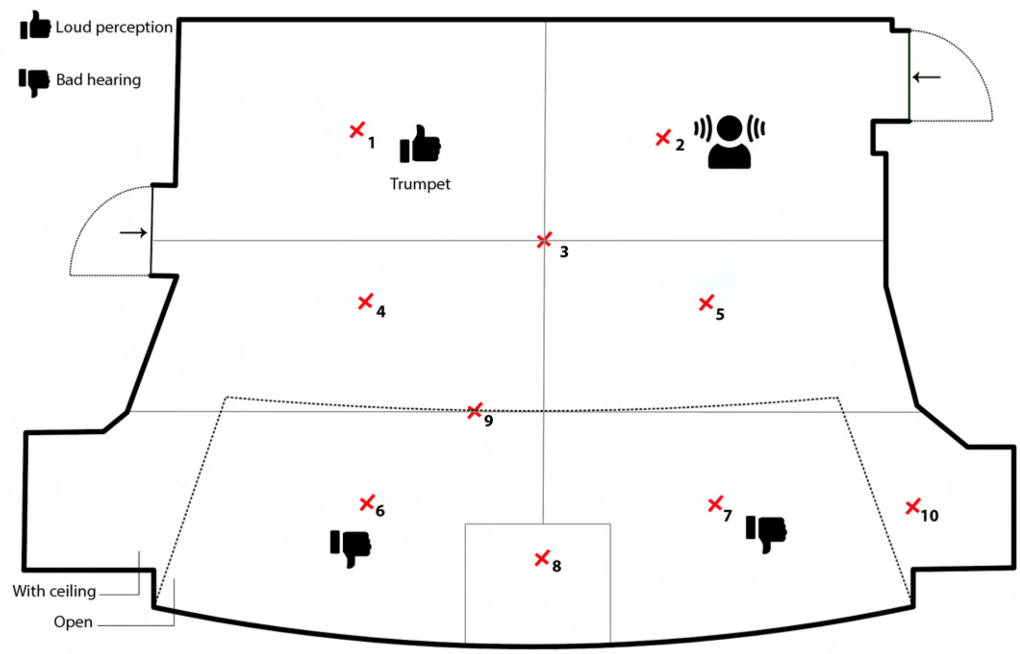


Figure 3.84: Survey Percussions

3.6 Considerations

Hall The obtained measurement results support the anticipated acoustical characteristics of the theatre, aligning closely with the initial expectations. In terms of the Early Decay Time (EDT), it was unsurprising to observe values consistently below one second, particularly within the medium to high frequency range. This concurs with the subjectively perceived acoustics of the theatre, which were expected to exhibit relatively rapid sound decay. Notably, measurements conducted in both the auditorium and the balconies yielded similar trends, further reinforcing the envisioned scenario. However, when the sound source was positioned in the orchestra pit, a marginal increase in parameter values was anticipated, given the specific characteristics of the orchestra cavity. Furthermore, a slight improvement, albeit not reaching optimal levels, was observed in the frequency band centred around 250Hz, underscoring the intricate relationship between sound propagation and the architectural elements of the theatre.

Regarding the reverberation time measurements (T20), the findings respect as well the subjective perception of the theatre as having a suboptimal reverberant quality. Higher frequencies exhibit a greater degree of energy absorption, aligning with the preconceived notion. Interestingly, the positioning of the sound source, whether on the stage or in the orchestra pit, had a negligible impact on the overall reverberation time which struggles to surpass the threshold of the second.

Lastly, regarding the Clarity parameter, it is not surprising that the sound is perceived as overly clear throughout the venue, surpassing the suggested thresholds defined by ISO 3382 standards, particularly in the medium to high frequency range. This finding reinforces the notion that achieving an optimal balance between clarity and liveliness can be a complex endeavour. Notably, the 2nd balcony showcased a slightly less pronounced clarity, while the auditorium exhibited a minor improvement. Positioning the sound source in the orchestra pit yielded a marginal reduction in clarity, in line with the expected attenuation of sound distinctiveness emanating from that location.

Orchestra pit In the case of measurements conducted in the orchestra pit, the values of EDT are more consistent compared to those in the hall. Although the sound decay value is still lower than the optimal range, its distribution remains uniform across all frequency bands. The same applies to the reverberation time T30, which fails to exceed one second but exhibits similar values across the considered frequency bands. A slight decrease in T30 is observed from the perspective of the receivers positioned in the narrow section of the orchestra pit when the sound source is placed at the opening of the pit.

The values of Clarity, in both its variations, show fluctuations depending on the frequency band considered. In general, C_{50} remains slightly within the optimal range, while C_{80} deviates, indicating a situation where the sound is perceived as less vibrant. Concerning C_{80}, slightly higher values can be observed in the mid-high frequency range.

Regarding the Support values, both for ST_{early} and ST_{late}, they are significantly higher than the optimal values defined in the ISO 3382-1 [12]. This is probably due to the confined dimensions of the orchestra pit where the musicians perform. High values of this parameter indicate a substantial amount of energy from the early reflections. Generally, this parameter is used to evaluate on-stage performances rather than narrow orchestra pits like the one in the present study. However, by considering a combination of objective measurements and the subjective opinions of the musicians provided in the questionnaire, it is possible to gain a fairly accurate understanding of the situation. In this case, as the musicians express dissatisfaction with the situation in the orchestra pit, also in hearing the own instrument, thematic taken into account by the ST parameter, it can be inferred that the problem may lie in the excessive energy from the early reflections.

By cross-referencing the values of the experimental parameter ST extended and the survey results, it has not been possible to identify a precise correlation between the optimal listening conditions for other instruments and the parameter values. However, for example, considering the values obtained when the source was positioned in section number 6, it can be presumed that positive parameter values correspond to a suboptimal perception from the point of view of the other musicians. On the other hand, position 4, which generates the lowest parameter values, is generally perceived as acceptable by the musicians who expressed their opinion in the survey.

General situation These results generally validate the initial assessments and underscore the need for refining and optimizing the acoustical environment to achieve a harmonious balance between in the overall auditory experience. Leveraging these findings will aid in the creation of an acoustical ambiance that fully embraces the art of sound and enhances the performances

for both artists and audiences.
In order to devise a precise and effective intervention proposal, the state of the art in architectural acoustics calls for the utilization of the latest available technologies [15]. In the following chapter, the virtual simulation process of the Theatre spaces is described, employing and comparing two powerful dedicated software tools. This approach enables a sufficiently accurate testing of the acoustic interventions' impact on the architectural space, based on the insights derived from on-site measurements.

Chapter 4

Simulation

4.1 Generalities

Architectural acoustic simulation through the use of dedicated software is a fundamental process for the understanding and control of the acoustics phenomena within architectural environments. This approach allows for the prediction and evaluation of acoustic characteristics within a room or a building.
An essential consideration in acoustic simulation is the imperative of incorporating accurate data into the software. True data entails precise information regarding the geometry, the materials employed within the room, their absorption coefficients and scattering coefficients. Throughout the simulation process, a comprehensive but simplified 3D model of the room is created [16], ensuring it respects the software's specific requirement. Each surface of the model must be associated with a material possessing experimentally defined absorption and scattering coefficients, subsequently the model must be subjected to the calibration procedure. This latter process ensures that the simulation results align with those obtained from measurements taken in the actual site.
Model calibration involves the accurate placement of sound sources and receivers within the 3D model in the software, mirroring their positions during on-site measurements. Impulse responses are then simulated, and relevant acoustic parameters are extracted. By manipulating the geometry and absorption and scattering coefficients, diverse conditions can be generated, thereby influencing parameter outcomes until a situation akin to reality, where the virtual values of the parameters match those obtained from the impulse responses measured on-site, is achieved,.
Once the model has been calibrated, it becomes possible to introduce mod-

ifications to the virtual model and observe their impact on the acoustic parameters. It is important to note that assuming these same modifications are implemented in the real context, similar results can be expected to those simulated. This capability facilitates the exploration of various design options and informed decision-making processes aimed at optimizing the acoustics of architectural spaces.
In this study two distinct simulation software were employed. *Odeon* utilizing the license held by the University of Bologna and *Ease* utilizing the license held by the Hochschule Mittweida. These software packages possess different features, and given the inherent challenge of precisely defining the acoustic phenomenon, particularly in the realm of low frequencies, variations in results arising from different physical principles are observed. These disparities will be meticulously evaluated in Chapter 6.

4.2 Theatre virtualization

3D model The information provided by the Theatre Administration, along with the data acquired through on-site surveys and measurements, has facilitated the creation of a faithful 3D model of the Freiberg Theatre using Sketchup software. The model encompasses the main hall, consisting of the auditorium and the two balconies, the orchestra pit, the stage, and the backstage area. Additionally, it includes the space above the stage dedicated to technical installations and a lighting room situated in the ceiling area of the second balcony divided from the hall by a sound-permeable grid.
Below, a selection of images showcasing the Theatre model prior to its importation into the software is presented.

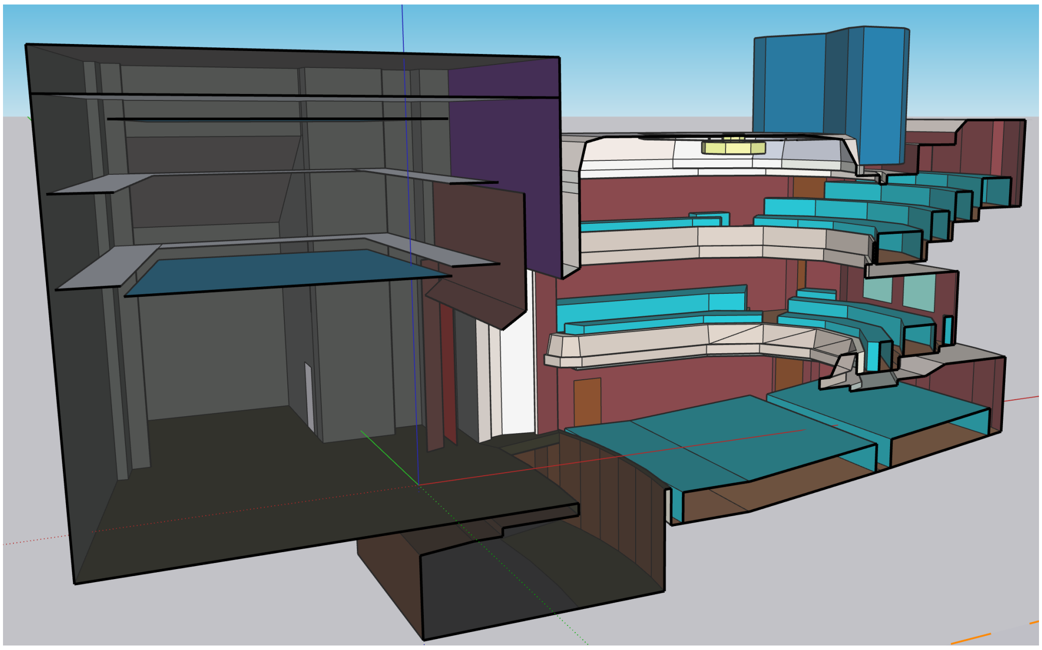


Figure 4.1: 3D model, Longitudinal section

The model has been meticulously designed with all the necessary measures and approximations for its proper integration and utilization within acoustic software [16]. Specifically, it is evident that different materials correspond to different layers, represented by distinct colors in this case. Additionally, the center of the axes is located on the stage, with the x-axis facing the audience. The audience is depicted by the blue boxes, each assigned a specific scattering coefficient, as it provides the most accurate approximation of their presence for acoustic purposes.

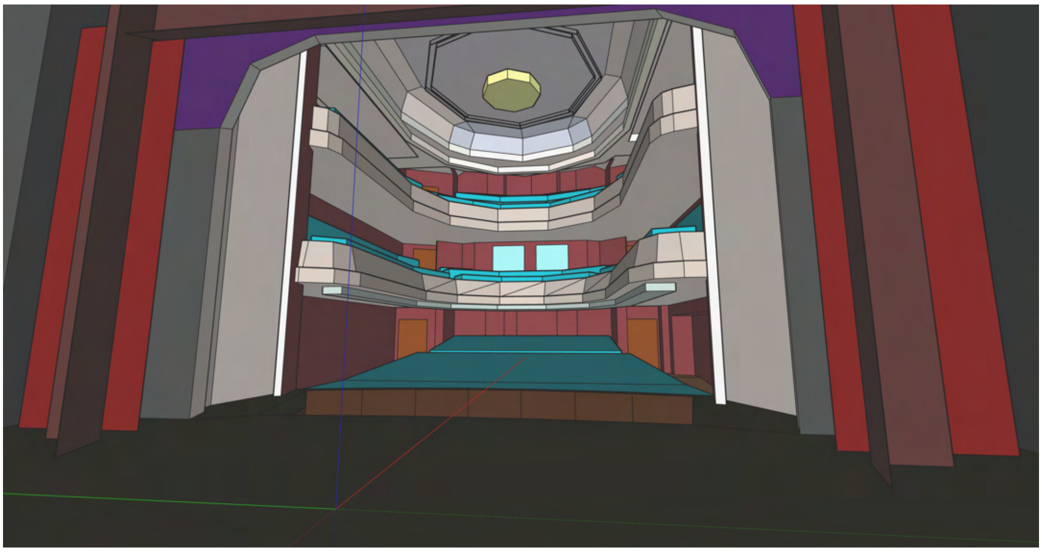


Figure 4.2: 3D model, view from stage

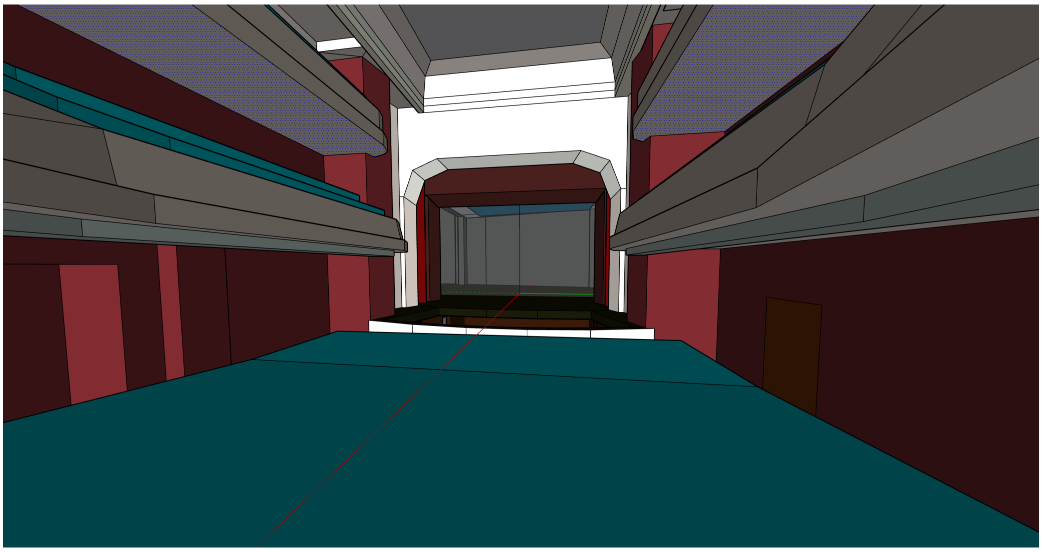


Figure 4.3: 3D model, view of the stage

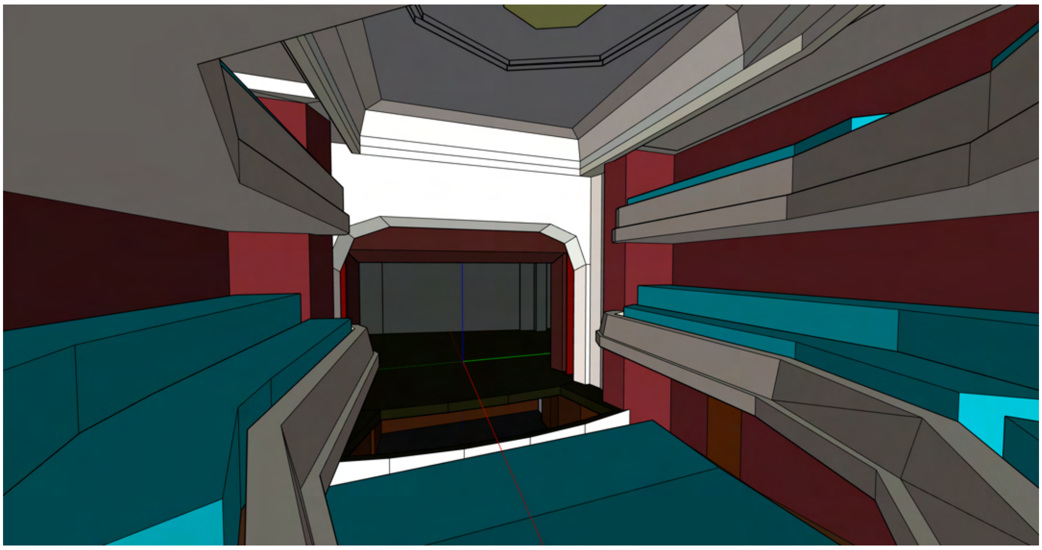


Figure 4.4: 3D model, view from 1st balcony

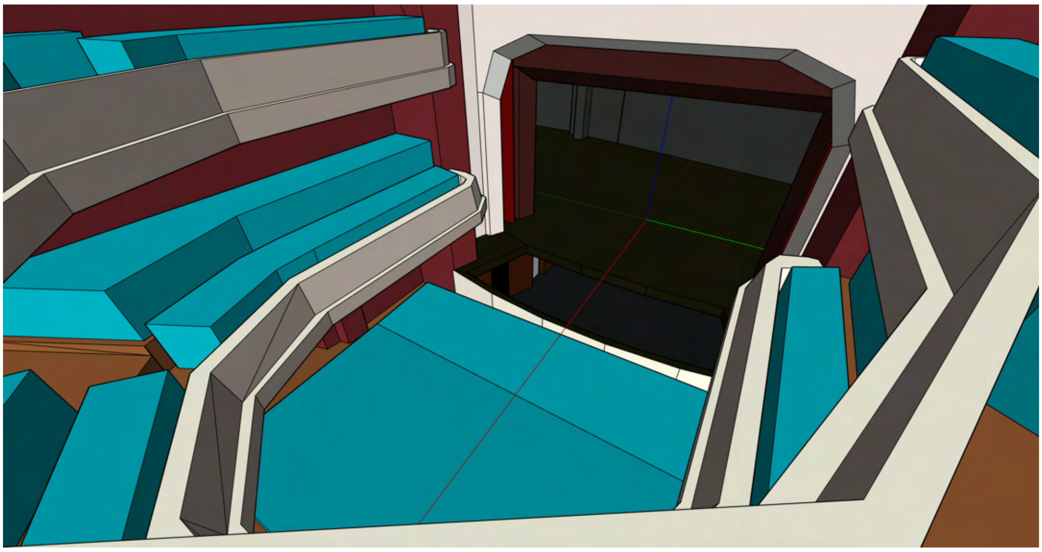


Figure 4.5: 3D model, view from 2nd balcony

Software import The process of importing into the software entails simplifying the model to exclude non-essential details for the purpose of simulation. Both software packages allow for the model to be imported in various digital formats [17] [18]. In this particular case, the .dxf format was utilized for the software provided by the Hochschule Mittweida, while the other software employed a specific plug-in within the 3D modeling software.
For an accurate simulation, all surfaces of the model must face inward, and there should be no holes or open spaces that would allow the simulated "sound rays" to escape. The software relies on Ray tracing technology, which approximates sound as rays bouncing off surfaces.
The following are images showcasing the 3D model once it has been imported into both software platforms.

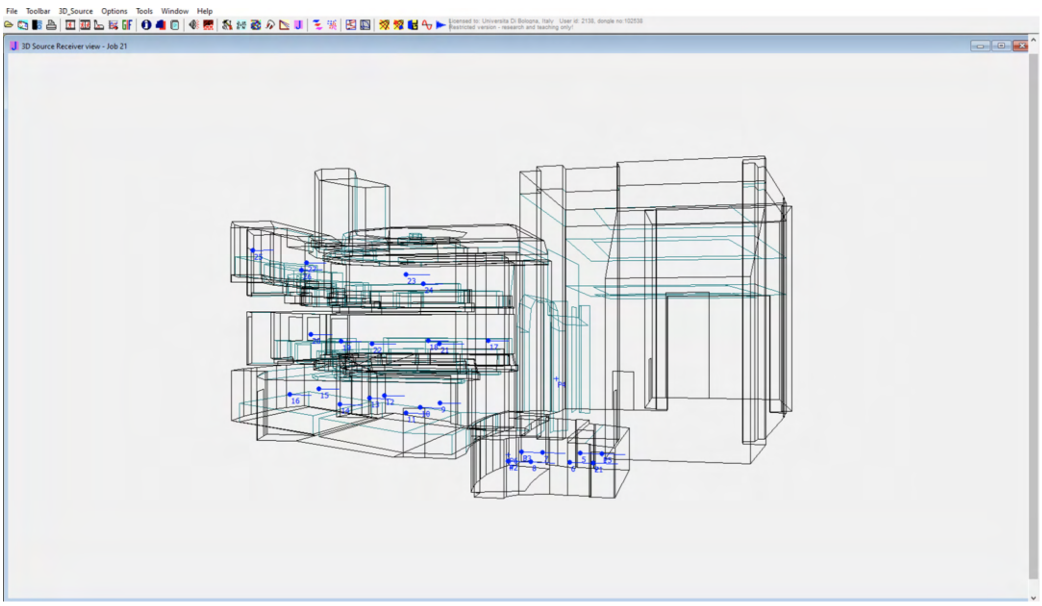


Figure 4.6: Unibo software view

It is possible to notice through the wireframe visualization, the position of source and receivers highlighted in blue.

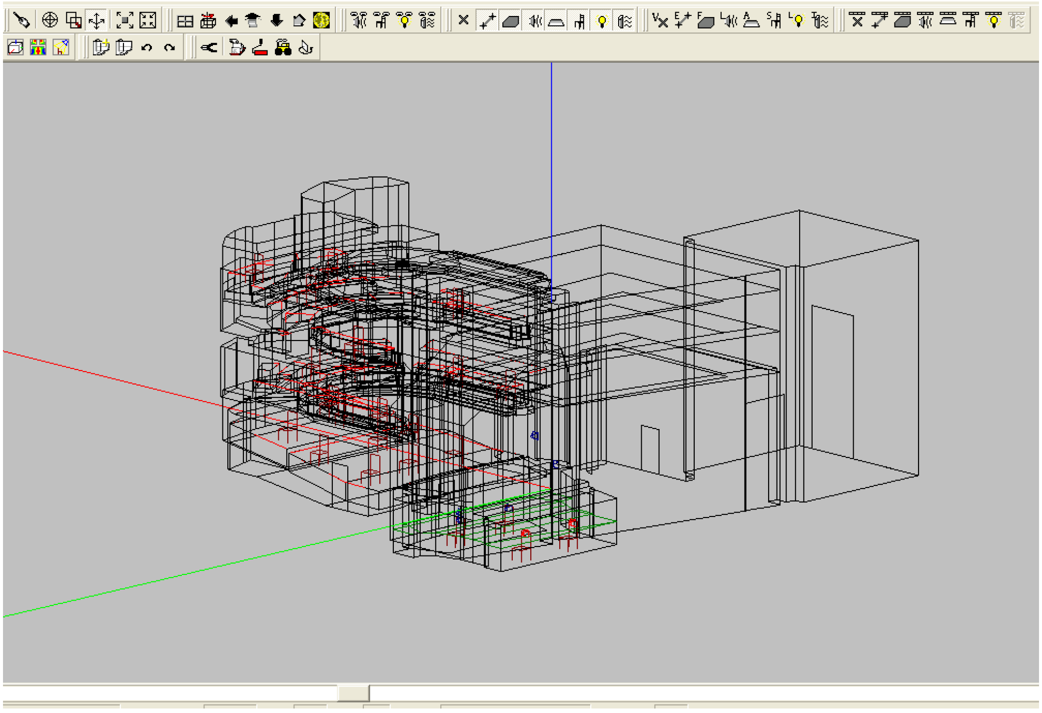


Figure 4.7: HSMW software view

Materials After having the model imported into the software, each surface has been associated with the corresponding material. Thanks to the availability of precise databases [5] [19] [20] [21] [22] containing experimental information on absorption coefficients of the most commonly used construction materials, it has been possible to define the characteristics of the materials present in the Theater as follows:

Table 4.1: Materials original absorption coefficients

Stage			Absorption coefficients					
Material	Position	Scatter.	125	250	500	1k	2k	4k
Stage floor	Floor	0.05	0.21	0.09	0.08	0.07	0.16	0.23
Brick masonry	Backstage walls	0.3	0.16	0.13	0.08	0.11	0.12	0.1
Plaster	Ceiling	0.05	0.14	0.1	0.06	0.04	0.04	0.03
Plastic	Above stage	0.5	0.06	0.1	0.1	0.2	0.3	0.2
Curtain	Curtain	0.05	0.03	0.35	0.64	0.62	0.58	0.64
Steel panel	Backstage doors	0.05	0.05	0.1	0.1	0.1	0.07	0.02
Painted wood	Stage decoration	0.05	0.11	0.12	0.12	0.12	0.1	0.1
Plastic	Instrumentation	0.05	0.06	0.1	0.1	0.2	0.3	0.2
Orchestra pit								
Wood	Floor	0.05	0.03	0.04	0.04	0.05	0.05	0.05
Concrete	Walls, ceiling	0.05	0.01	0.01	0.01	0.02	0.02	0.02
Felt mat	Right wall	0.05	0.07	0.07	0.2	0.41	0.75	0.97
Hall								
Wood	Doors	0.05	0.28	0.22	0.17	0.09	0.1	0.11
Window	Control room	0.05	0.28	0.2	0.11	0.06	0.03	0.02
Perforated panel	Lightroom walls	0.1	0.2	0.64	0.77	0.85	0.9	0.78
Metal grid	Lightroom grid	0.05	0.05	0.1	0.1	0.1	0.07	0.02
Parquet	Floor	0.05	0.1	0.07	0.05	0.06	0.06	0.06
Upholstered seats	Chairs	0.6	0.49	0.66	0.8	0.88	0.82	0.7
Painted wood	Balconies limits	0.3	0.14	0.1	0.06	0.04	0.04	0.03
Painted bricks	Walls	0.05	0.16	0.13	0.08	0.11	0.12	0.1
Acoustic plaster	Ceiling	0.3	0.49	0.43	0.5	0.68	0.65	0.53
Glass	Chandelier	0.4	0.28	0.2	0.11	0.06	0.03	0.02

The scattering coefficient considers a center frequency of 707Hz in the software provided by the Unibo. The software provided by the Hochschule Mittweida allows to relate the scattering coefficient with the frequency bands instead. These values have been chosen following the guidelines included in Unibo software's manual [17].

4.3 Model calibration

In the following pages the process of calibration of the Theatre's model into the acoustic software is presented.

Table 4.2: Materials absorption coefficients after calibration

Stage			Absorption coefficients					
Material	Position	Scatter.	125	250	500	1k	2k	4k
Stage floor	Floor	0,05	0.21	0.09	0.08	0.07	0.16	0.30
Brick masonry	Backstage walls	0,3	0.21	0.22	0.24	0.24	0.25	0.32
Plaster	Ceiling	0,05	0.16	0.15	0.16	0.15	0.16	0.17
Plastic	Above stage	0,7	0.07	0.10	0.10	0.20	0.30	0.20
Curtain	Curtain	0,05	0.03	0.04	0.70	0.65	0.62	0.67
Steel panel	Backstage doors	0,05	0.05	0.10	0.10	0.10	0.07	0.02
Painted wood	Stage decoration	0,1	0.13	0.14	0.14	0.14	0.12	0.12
Plastic	Instrumentation	0,1	0.07	0.10	0.10	0.20	0.30	0.20
Orchestra pit								
Wood	Floor	0,05	0.10	0.10	0.08	0.05	0.05	0.05
Concrete	Walls, ceiling	0,05	0.01	0.01	0.01	0.02	0.02	0.02
Felt mat	Right wall	0,05	0.07	0.07	0.20	0.41	0.75	0.97
Hall								
Wood	Doors	0,05	0.28	0.22	0.17	0.09	0.10	0.11
Window	Control room	0,05	0.10	0.20	0.08	0.03	0.01	0.01
Perforated panel	Lightroom walls	0,2	0.26	0.50	0.70	0.75	0.75	0.70
Metal grid	Lightroom grid	0,15	0.05	0.10	0.10	0.10	0.07	0.02
Parquet	Floor	0,05	0.01	0.09	0.06	0.09	0.13	0.14
Upholstered seats	Chairs	0,6	0.55	0.60	0.45	0.50	0.60	0.70
Painted wood	Balconies limits	0,4 / 0,8	0.13	0.14	0.14	0.14	0.12	0.12
Painted bricks	Walls	0,06	0.18	0.19	0.19	0.22	0.24	0.30
Acoustic plaster	Ceiling	0,3	0.51	0.46	0.55	0.70	0.69	0.57
Glass	Chandelier	0,4	0.28	0.20	0.11	0.06	0.03	0.02

In order to achieve precise calibration, a meticulous iterative process was employed. The calibration involved gradual modifications to the absorption coefficients of various surfaces within the Theatre until a situation was attained that yielded coherent results with those obtained from the measurements.

In the Stage area, adjustments were made as follows:
The absorption coefficient of the "Stage floor" material needed to be increased at the frequencies of 250 Hz (by 11.1%) and 4 kHz (by 30.4%).
The "Brick masonry" used for the backstage walls exhibited a notable increase in the absorption coefficient at the frequencies of 125 Hz (by 31.3%), 250 Hz (by 69.2%), and 4 kHz (by 32.0%).
The "Plaster" material applied to the ceiling required an increase in the absorption coefficient at the frequencies of 125 Hz (by 14.3%), 500 Hz (by 166.7%), and 4 kHz (by 33.3%). The "Plastic" material used for the technical gear above the stage needed an increase in the absorption coefficient at the frequencies of 125 Hz (by 16.7%), 1 kHz (by 100.0%), and 2 kHz (by 50.0%).
The "Curtain" showed an increase in the absorption coefficient at the frequencies of 250 Hz (by 14.3%) and 500 Hz (by 9.4%), while a decrease was observed at 2 kHz (by 6.5%).
The absorption coefficient of the "Steel panel" for the backstage doors required an increase at the frequency of 250 Hz (by 100.0%), while a decrease was noticed at 2 kHz (by 30.0%).
The absorption coefficient of the "Painted wood" used for the stage decorations needed to be increased across all analysed frequencies, ranging from 16.7% to 33.3%.
Lastly, the "Plastic" material used for the general instrumentation present in the backstage exhibited an increase in the absorption coefficient at the frequencies of 125 Hz (by 16.7%), 1 kHz (by 100.0%), and 2 kHz (by 50.0%).

Within the Orchestra pit, the following variations were necessary: The absorption coefficient of the "Wood" material used for the floor required an increase at the frequency of 250 Hz (by 11.1%).
Slight increases were recorded for the absorption coefficients of the "Concrete" used for the walls and Ceiling, although the changes were minimal.

In the Hall area, the following adjustments were made:
The absorption coefficient of the "Wood" used for the doors required an increase at the frequency of 250 Hz (by 22.2%).
The absorption coefficient of the "Window" in the control room needed to be increased at the frequency of 1 kHz (by 100.0%).
The absorption coefficient of the "Parquet" used for the floor required increases at the frequencies of 500 Hz (by 44.4%) and 4 kHz (by 40.0%).
Increases in the absorption coefficients were necessary for the "Upholstered seats" of the chairs across all analysed frequencies, ranging from 10.0% to 40.0%.
The absorption coefficients of the "Painted bricks" used for the walls required

increases ranging from 18.2% to 30.0% across all analysed frequencies.
Significant increases were necessary for the absorption coefficients of the "Acoustic plaster" used for the hall's ceiling across all analysed frequencies, ranging from 46.7% to 70.0%. The "Glass" material used for the chandelier exhibited an increase in the absorption coefficient at the frequency of 125 Hz (by 16.7%) and a decrease at 2 kHz (by 33.3%).

4.4 Criteria results

Given the intricate nature of the virtualiation and simulation process, which is influenced by a multitude of variables, calibration can be deemed acceptable and accurate within a certain degree of approximation [23]. The entire process of acoustic simulation, while striving for high precision, can still prove highly valuable, even if it merely provides a general overview of the context, liberating the operator from absolute uncertainty and pure subjectivity in judgement. It is essential to acknowledge that acoustic simulation is a relatively recent undertaking, and not all its aspects are governed by precise standards.

In this thesis, the Author's endeavour has been to provide data as accurate as possible while adhering to the state of art procedure [15]. Specifically, the goal was to consider simulated values of EDT, T20, and T30 as entirely acceptable if they deviated within approximately 10% from the values obtained through measurements. As for the Clarity parameter, the Author sought to maintain deviations within 1dB.

The simulations were conducted using a room set-up that prescribed an impulse response length of 3000 milliseconds. Additionally, in accordance with the recommendations provided by the Unibo software the simulation employed a number of late rays set at 1139.

4.4.1 Software Unibo

In the following pages the values of the simulation results' average deviation from the measurements, obtained using the software provided by Unibo are presented. In bold are those who exceed the optimal calibration range.
Theatre hall

Table 4.3: EDT (s), source on stage

Band (Hz)	Average deviation %
125	7.6
250	5.2
500	5.1
1k	6.6
2k	8.0
4k	7.1

Table 4.4: T20 (s), source on stage

Band (Hz)	Average deviation %
125	8.5
250	5.8
500	8.0
1k	4.6
2k	2.0
4k	5.4

Table 4.5: C50 (dB), source on stage

Band (Hz)	Avg. deviation (dB)
500	1.5
1k	1.1
2k	1.6
4k	**2.4**

Table 4.6: C80 (dB), source on stage

Band (Hz)	Avg. deviation (dB)
500	1.4
1k	1.4
2k	**2.1**
4k	**3.6**

Table 4.7: EDT (s), source in the pit

Band (Hz)	Average deviation %
125	7.4
250	7.6
500	6.0
1k	5.0
2k	6.3
4k	5.2

Table 4.8: T20 (s), source in the pit

Band (Hz)	Average deviation %
125	3.7
250	5.9
500	6.1
1k	9.1
2k	5.9
4k	3.2

Table 4.9: C50 (dB), source in the pit

Band (Hz)	Avg. deviation (dB)
500	0.8
1k	1.2
2k	1.2
4k	1.5

Table 4.10: C80 (dB), source in the pit

Band (Hz)	Avg. deviation (dB)
500	1.1
1k	1.1
2k	0.9
4k	1.2

Orchestra pit

Table 4.11: EDT (s), Orchestra pit

Band (Hz)	Average deviation %
125	**15.3**
250	**34.9**
500	**29.7**
1k	8.9
2k	6.0
4k	5.9

Table 4.12: T30 (s), Orchestra pit

Band (Hz)	Average deviation %
125	1.0
250	5.2
500	0.2
1k	**14.9**
2k	9.8
4k	**30.0**

Table 4.13: C50(dB), Orchestra pit

Band (Hz)	Avg. deviation (dB)
125	0.3
250	3.7
500	1.9
1k	0.8
2k	0.4
4k	1.1

Table 4.14: C80 (dB), Orchestra pit

Band (Hz)	Avg. deviation (dB)
125	0.9
250	1.8
500	**2.3**
1k	**2.3**
2k	0.9
4k	1.4

4.4.2 Software Hochschule Mittweida

In the following pages the values of the simulation results' average deviation from the measurements, obtained using the software provided by Hochschule Mittweida are presented. In bold are those who exceed the optimal calibration range.

Theatre hall

Table 4.15: EDT (s), source on stage

Band (Hz)	Average deviation %
125	9.7
250	7.3
500	6.0
1k	8.3
2k	**12.1**
4k	7.9

Table 4.16: T20 (s), source on stage

Band (Hz)	Average deviation %
125	8.2
250	**11.5**
500	7.4
1k	8.7
2k	6.8
4k	**16.5**

Table 4.17: C50 (dB), source on stage

Band (Hz)	Avg. deviation (dB)
500	**2.5**
1k	**2.0**
2k	**2.4**
4k	**2.4**

Table 4.18: C80 (dB), source on stage

Band (Hz)	Avg. deviation (dB)
500	**2.0**
1k	**2.1**
2k	**2.5**
4k	**3.3**

Table 4.19: EDT (s), source in the pit

Band (Hz)	Avgerage deviation %
125	**29.7**
250	**34.2**
500	**36.8**
1k	**34.6**
2k	**38.0**
4k	**53.1**

Table 4.20: T20 (s), source in the pit

Band (Hz)	Avgerage deviation %
125	**34.5**
250	**41.3**
500	**47.4**
1k	**29.1**
2k	**27.3**
4k	**41.5**

Table 4.21: C50(dB), source in the pit

Band (Hz)	Avg. deviation (dB)
500	1.7
1k	**2.5**
2k	**2.5**
4k	**2.6**

Table 4.22: C80 (dB), source in the pit

Band (Hz)	Avg. deviation (dB)
500	0.8
1k	0.7
2k	0.8
4k	1.1

Orchestra Pit

Table 4.23: EDT (s), Orchestra pit

Band (Hz)	Avgerage deviation %
125	**47.0**
250	**85.2**
500	**79.1**
1k	**24.9**
2k	9.8
4k	**14.6**
8k	11.0

Table 4.24: T30 (s), Orchestra pit

Band (Hz)	Avgerage deviation %
125	**60.2**
250	**58.5**
500	**48.7**
1k	2.0
2k	2.3
4k	**23.1**
8k	2.0

Table 4.25: C50 (dB), Orchestra pit

Band (Hz)	Avg. deviation (dB)
125	1.7
250	**5.2**
500	**3.2**
1k	1.3
2k	0.8
4k	1.7
8k	1.1

Table 4.26: C80 (dB), Orchestra pit

Band (Hz)	Avg. deviation (dB)
125	**2.7**
250	**3.6**
500	**4.0**
1k	**2.8**
2k	1.3
4k	1.9
8k	1.2

The values just shown exhibit the deviation averaged on all the receivers in the Theatre hall and orchestra pit. A more detailed representation of the deviation percentage, divided for the receivers placed in the auditorium and on each balcony, is included in the Appendix B.

Chapter 5

Acoustic intervention

In this chapter, a targeted solution is proposed to enhance the acoustic conditions within the Freiberg Theatre. This proposal emerges from extensive measurements and analyses of acoustic characteristics conducted during the thesis work. The primary objective is to align the environment with the quality requirements of both the audience and the theatre administration, while adhering to the architectural constraints imposed by the preservation authority [24].

5.1 Proposal

Theatre hall The main theatre hall, being a historically significant architecture, is subject to architectural constraints mandated by the preservation authority. Consequently, any intervention must adhere to limitations intended to preserve the historical prestige and original aesthetic. To ameliorate the acoustics of the main hall, the application of transparent panels made of rigid plastic material on the vertical walls of the orchestra and balconies is suggested. Rigid plastic, thanks to its reflective nature, would mitigate sound energy absorption compared to the current plastered walls, thereby extending the reverberation time. The utilization of transparent material, mounted on the vertical walls through supports that aesthetically match the style of the Theatre, would grant an acoustic amelioration ensuring minimal visual impact on the theatre's interior environment [25].
To further extend the reverberation time, a similar solution is envisaged for the backstage walls. During simulations rigid plastic material has been considered as highly reflective, with an absorption coefficient below 0.1 across all considered frequency bands.
Simulation results indicate a significant increase in the reverberation time,

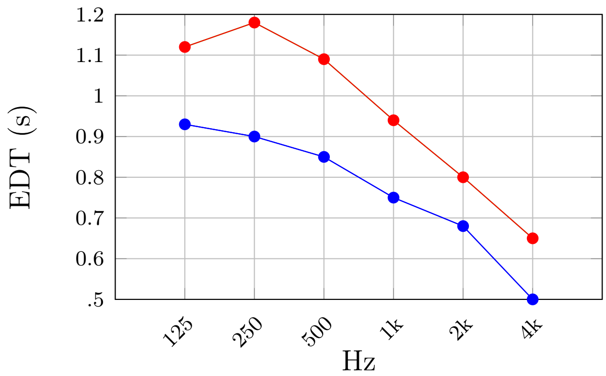
demonstrating the feasibility of resolving the issue of excessively short reverberation time without compromising the aesthetic aspect of the space. Moreover the panels could be placed at a small distance from the walls in order to create a cavity that could resonate creating a further enhancement of low-mid frequency bands. Distancing the plastic panel from the wall could be also seen and a way to pay respect to the original architecture.

Orchestra pit In the case of the orchestra pit, the limited spatial dimensions and complaints regarding excessive sound energy necessitated consideration. To address these concerns and without specific exigence of leaving the aspect of the pit unaltered, two specific solutions have been proposed:
The first involves the application of an acoustic carpet on the orchestra pit floor. This solution could control sound propagation and attenuate the excessive sound energy lamented by the musicians especially in the mid-high frequency range, while leaving the mid-low range still reverberant. The second entails the installation of a wooden Schroeder diffuser on the vertical rear orchestra pit wall. This solution could ensure a more uniform sound propagation [26]. Considering the simulation results which are shown in the next pages, applying these solutions to the Freiberg Theatre could lead to a significant increase in the Clarity parameter, suggesting enhanced sound clarity within the orchestra pit and a clearer perception for the musicians.

In the next pages the values of the parameters considered before and after the proposed intervention calculated with the software provided by the Unibo are shown.

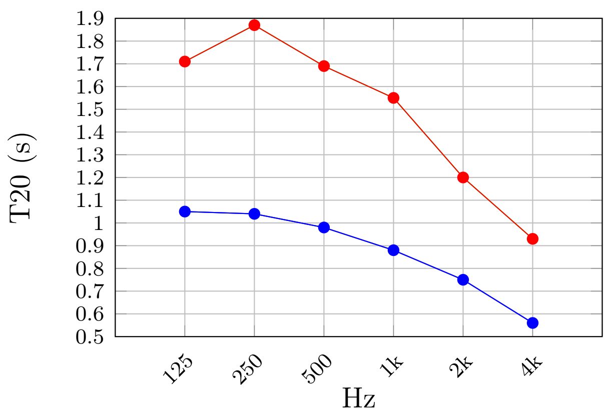
5.2 Results

Theatre hall



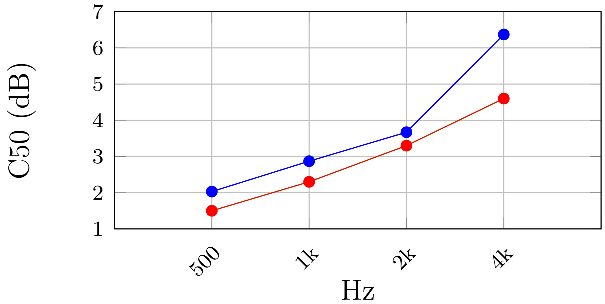
Band	Before	After
125	0.93	1.12
250	0.90	1.18
500	0.85	1.09
1k	0.75	0.94
2k	0.68	0.80
4k	0.50	0.65

Figure 5.1: EDT, S on stage



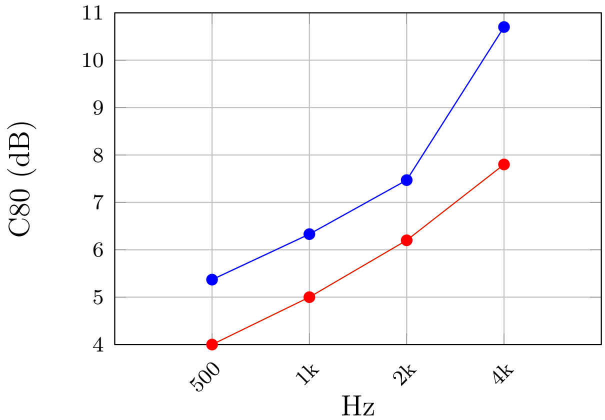
Band	Before	After
125	1.05	1.71
250	1.04	1.87
500	0.98	1.69
1k	0.88	1.55
2k	0.75	1.20
4k	0.56	0.93

Figure 5.2: T20, S on stage



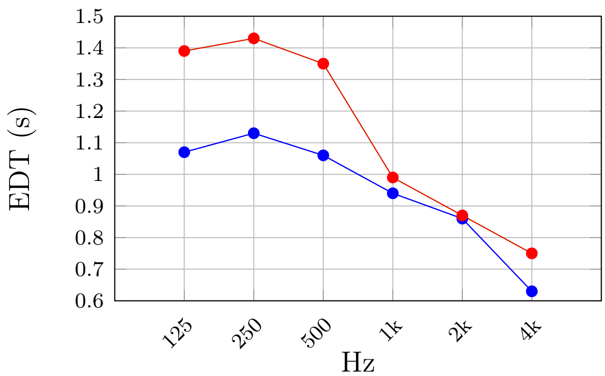
Band	Before	After
500	2.0	1.5
1k	2.8	2.3
2k	3.6	3.3
4k	6.3	4.6

Figure 5.3: C50, S on stage



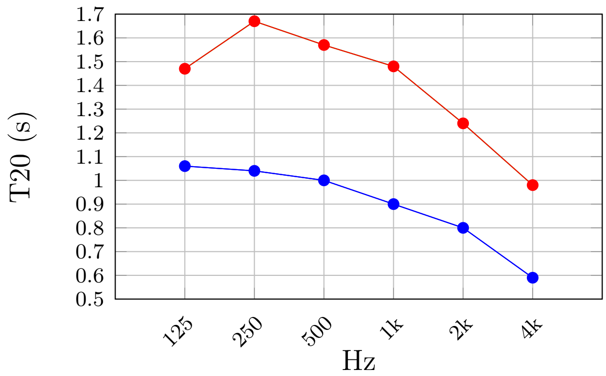
Band	Before	After
500	5.3	4.0
1k	6.3	5.0
2k	7.4	6.2
4k	10.7	7.8

Figure 5.4: C80, S on stage



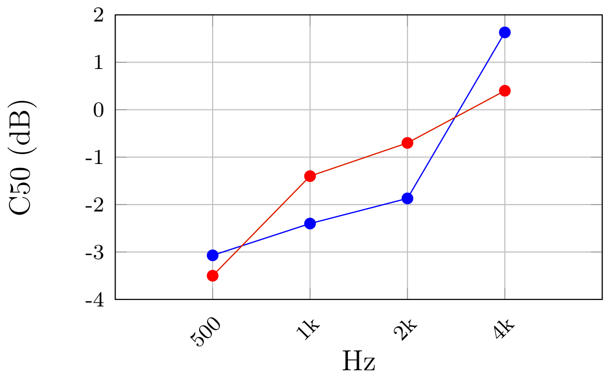
Band	Before	After
125	1.07	1.39
250	1.13	1.43
500	1.06	1.35
1k	0.94	0.99
2k	0.86	0.87
4k	0.63	0.75

Figure 5.5: EDT, S in the pit



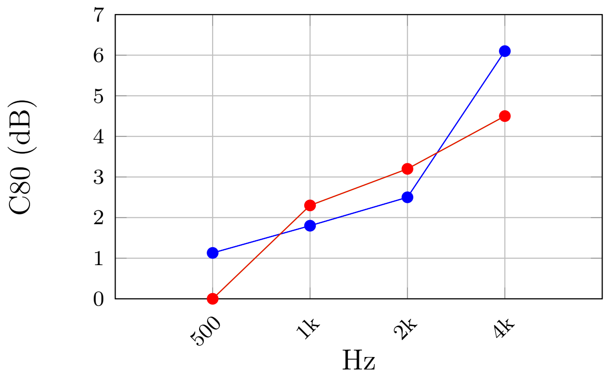
Band	Before	After
125	1.06	1.47
250	1.04	1.67
500	1.00	1.57
1k	0.90	1.48
2k	0.80	1.24
4k	0.59	0.98

Figure 5.6: T20, S in the pit



Band	Before	After
500	-3.07	-3.5
1k	-2.40	-1.4
2k	-1.87	-0.7
4k	1.63	0.4

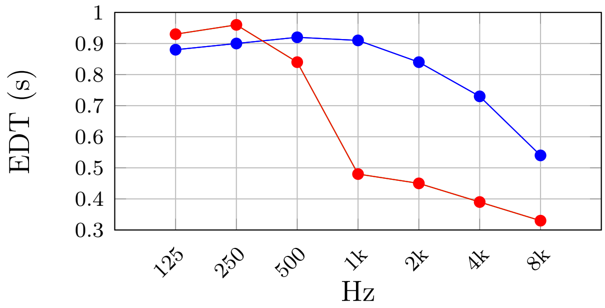
Figure 5.7: C50, S in the pit



Band	Before	After
500	1.13	0
1k	1.80	2.3
2k	2.50	3.2
4k	6.10	4.5

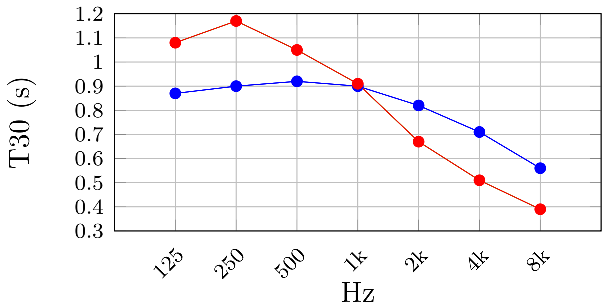
Figure 5.8: C80, S in the pit

Orchestra pit



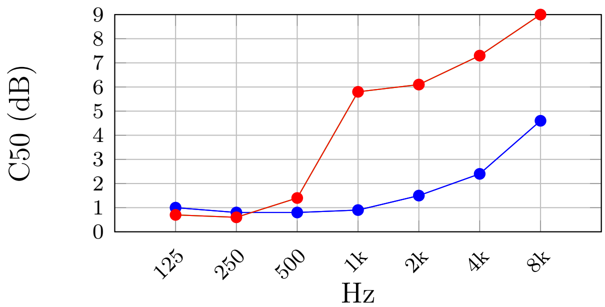
Band	Before	After
125	0.88	0.93
250	0.90	0.96
500	0.92	0.84
1k	0.91	0.48
2k	0.84	0.45
4k	0.73	0.39
8k	0.54	0.33

Figure 5.9: EDT, Orchestra pit S1



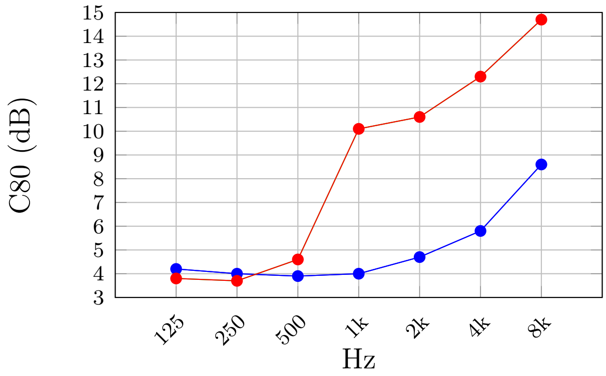
Band	Before	After
125	0.87	1.08
250	0.90	1.17
500	0.92	1.05
1k	0.90	0.91
2k	0.82	0.67
4k	0.71	0.51
8k	0.56	0.39

Figure 5.10: T30, Orchestra pit S1



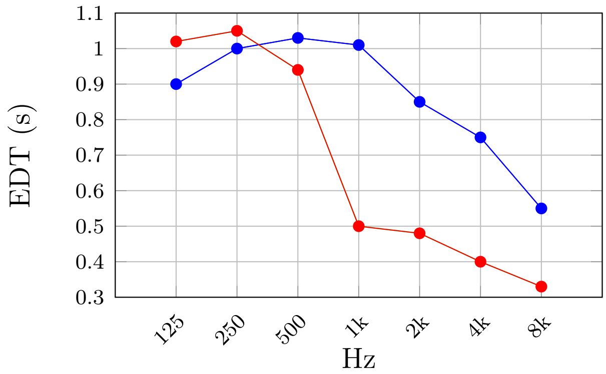
Band	Before	After
125	1.0	0.7
250	0.8	0.6
500	0.8	1.4
1k	0.9	5.8
2k	1.5	6.1
4k	2.4	7.3
8k	4.6	9

Figure 5.11: C50, Orchestra pit S1



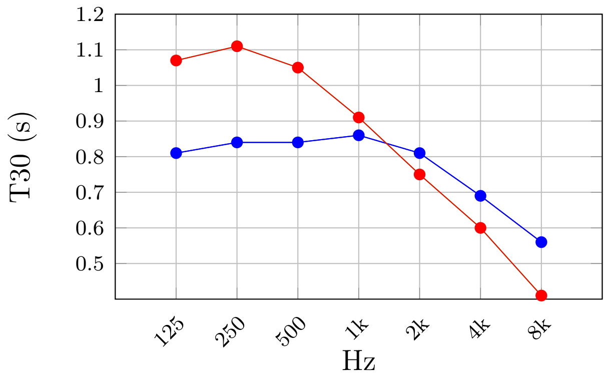
Band	Before	After
125	4.2	3.8
250	4.0	3.7
500	3.9	4.6
1k	4.0	10.1
2k	4.7	10.6
4k	5.8	12.3
8k	8.6	14.7

Figure 5.12: C80, Orchestra pit S1



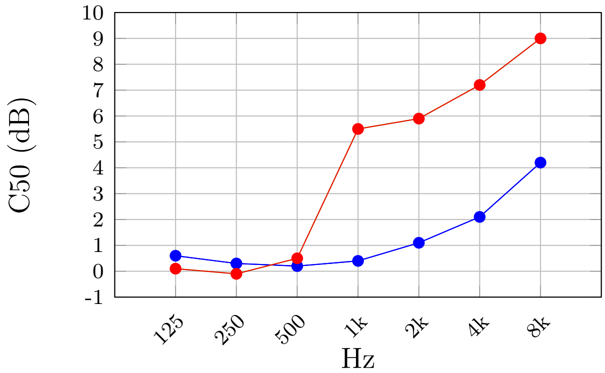
Band	Before	After
125	0.90	1.02
250	1.00	1.05
500	1.03	0.94
1k	1.01	0.50
2k	0.85	0.48
4k	0.75	0.40
8k	0.55	0.33

Figure 5.13: EDT, Orchestra pit S6



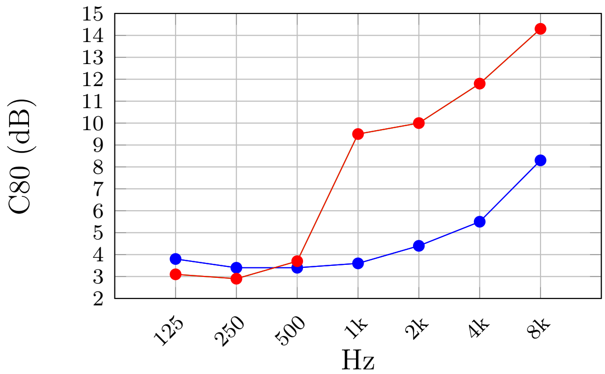
Band	Before	After
125	0.81	1.07
250	0.84	1.11
500	0.84	1.05
1k	0.86	0.91
2k	0.81	0.75
4k	0.69	0.60
8k	0.56	0.41

Figure 5.14: T30, Orchestra pit S6



Band	Before	After
125	0.6	0.1
250	0.3	-0.1
500	0.2	0.5
1k	0.4	5.5
2k	1.1	5.9
4k	2.1	7.2
8k	4.2	9

Figure 5.15: C50, Orchestra pit S6



Band	Before	After
125	3.8	3.1
250	3.4	2.9
500	3.4	3.7
1k	3.6	9.5
2k	4.4	10.0
4k	5.5	11.8
8k	8.3	14.3

Figure 5.16: C80, Orchestra pit S6

5.3 Conclusion and budget forecast

The proposed solutions for improving the acoustic conditions in the Theatre have proven effective in optimizing the reverberation time and sound clarity while simultaneously adhering to the architectural and aesthetic constraints imposed by the preservation authority which explains that *owners and custodians of cultural monuments must handle them with care and preserve them in a reasonable way* [24].

Considering the the surface to cover inside the hall and backstage which would be approximatively around 500m^2, 2cm panels of transparent PVC which has a specific weight of 1450kg/m^3 (circa 14500kg of material needed) and according to the German website *plasticker.de*, an industrial price of 0,67 EUR/kg, the Theatre administration would have to spend around €10,000 to buy the transparent panels.
Considering also the possible cost of the orchestra pit's solution which would be around €2000-4000 for the wooden diffusers plus around €200 for the acoustic carpet (32m^2 of orchestra pit floor surface by 6 EUR/m^2 according to *euroakustik.com*), the administration would have to handle around €15,000 investment.

The proposed intervention would represent a significant step towards the overall enhancement of the acoustic experience within the theatre, ensuring an optimal acoustic environment for both the audience and the artists.

5.4 Renderings

On the following pages, renderings depicting the appearance of the Theatre after the proposed intervention will be displayed.

Figure 5.17: View of the hall

Figure 5.18: View from the 1st balcony

Figure 5.19: Another view from the 1st balcony

Figure 5.20: View from the 2nd balcony

Figure 5.21: View from the auditorium

Figure 5.22: Lateral view of the hall

Figure 5.23: Lateral view of the orchestra pit

Figure 5.24: View inside the orchestra pit

Figure 5.25: Another lateral view of the orchestra pit

Figure 5.26: Detail of the diffuser and acoustic carpet

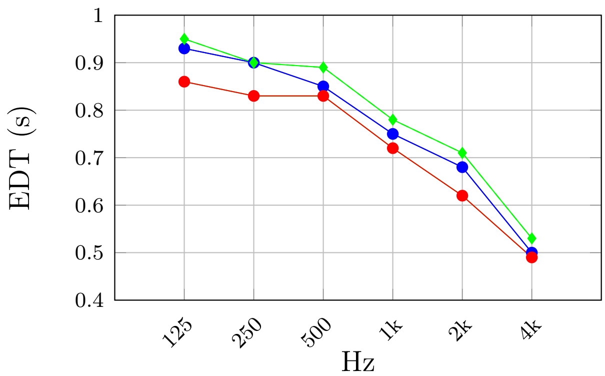
Chapter 6

Software Comparison

In the following pages the values of the acoustic criteria considered obtained using the two aforementioned software are shown and compared. The values represented in blue are those relative to the software provided by the Unibo, those in red are relative to the software provided by the Hochschule Mittweida (HSMW), those in green are relative to the measurements on site.

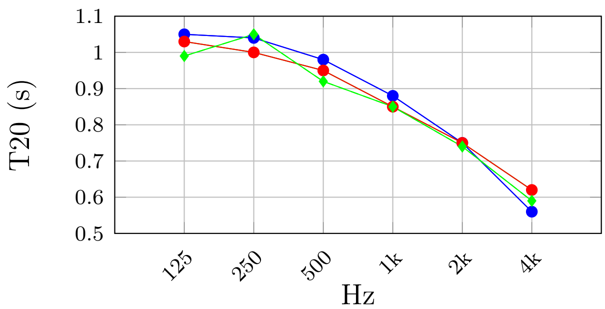
6.1 Model calibration

Theatre hall



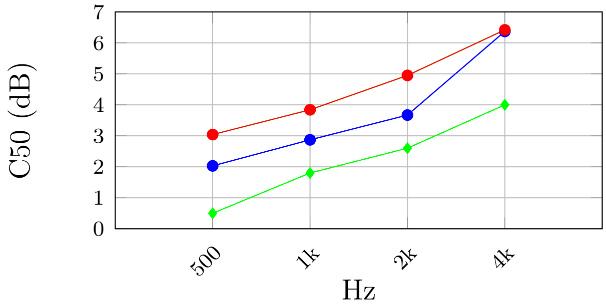
Band	Unibo	HSMW
125	0.93	0.86
250	0.90	0.83
500	0.85	0.83
1k	0.75	0.72
2k	0.68	0.62
4k	0.50	0.49

Figure 6.1: EDT, S on stage



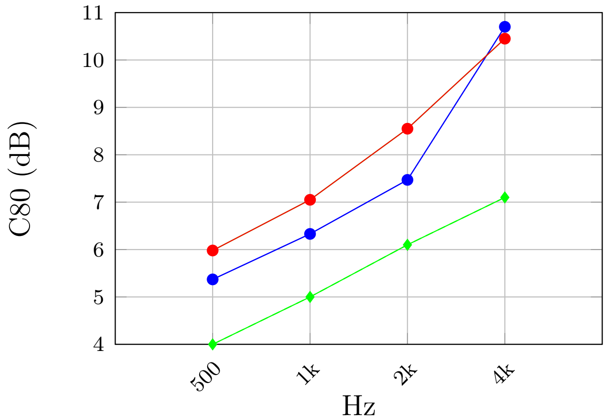
Band	Unibo	HSMW
125	1.05	1.03
250	1.04	1.00
500	0.98	0.95
1k	0.88	0.85
2k	0.75	0.75
4k	0.56	0.62

Figure 6.2: T20, S on stage



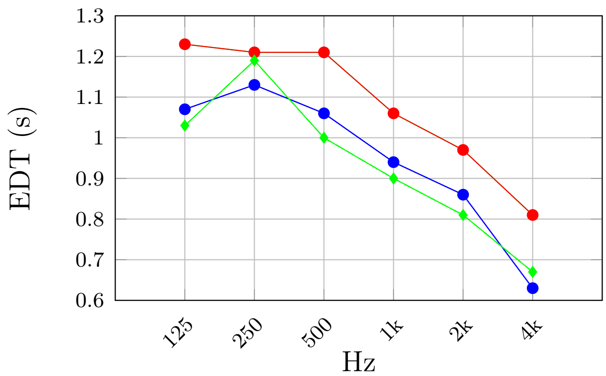
Band	Unibo	HSMW
500	2.0	3.0
1k	2.8	3.8
2k	3.6	4.9
4k	6.3	6.4

Figure 6.3: C50, S on stage



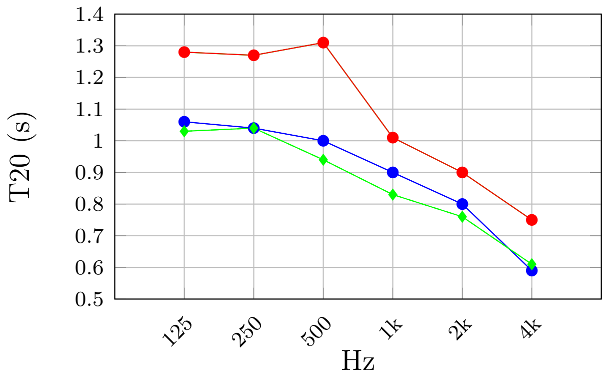
Band	Unibo	HSMW
500	5.3	5.9
1k	6.3	7.0
2k	7.4	8.5
4k	10.7	10.4

Figure 6.4: C80, S on stage



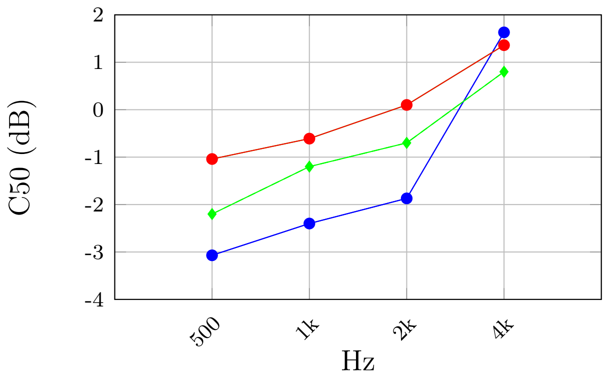
Band	Unibo	HSMW
125	1.07	1.23
250	1.13	1.21
500	1.06	1.21
1k	0.94	1.06
2k	0.86	0.97
4k	0.63	0.81

Figure 6.5: EDT, S in the pit



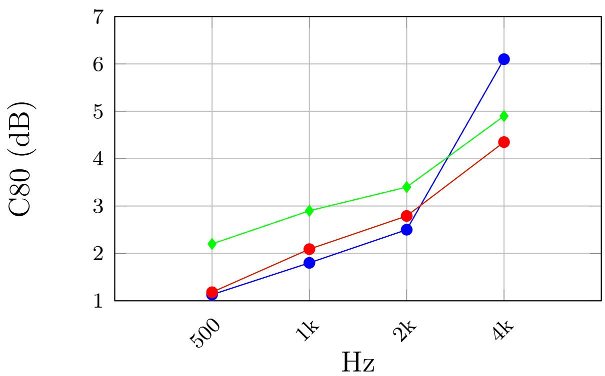
Band	Unibo	HSMW
125	1.06	1.28
250	1.04	1.27
500	1.00	1.31
1k	0.90	1.01
2k	0.80	0.90
4k	0.59	0.75

Figure 6.6: T20, S in the pit



Band	Unibo	HSMW
500	-3.0	-1.0
1k	-2.4	-0.6
2k	-1.8	0.1
4k	1.6	1.3

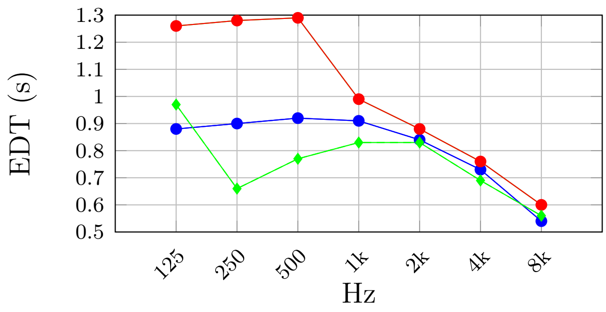
Figure 6.7: C50, S in the pit



Band	Unibo	HSMW
500	1.1	1.1
1k	1.8	2.0
2k	2.5	2.7
4k	6.1	4.3

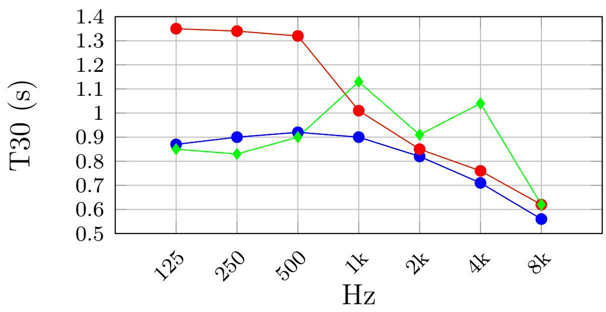
Figure 6.8: C80, S in the pit

Orchestra pit



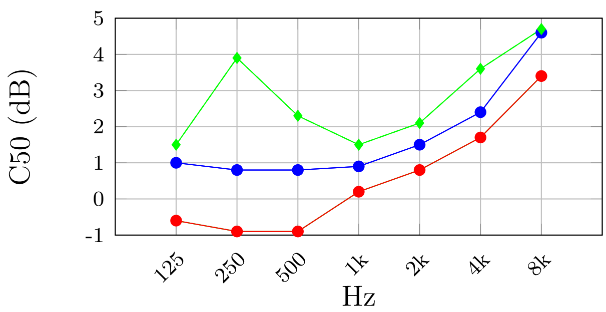
Band	Unibo	HSMW
125	0.88	1.26
250	0.90	1.28
500	0.92	1.29
1k	0.91	0.99
2k	0.86	0.88
4k	0.73	0.76
8k	0.54	0.60

Figure 6.9: EDT, Orchestra pit S1



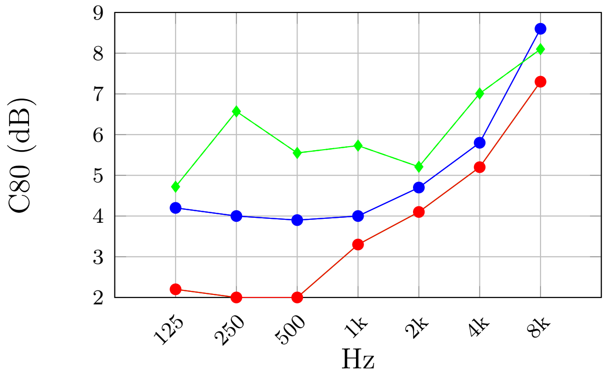
Band	Unibo	HSMW
125	0.87	1.35
250	0.90	1.34
500	0.92	1.32
1k	0.90	1.01
2k	0.82	0.85
4k	0.71	0.76
8k	0.56	0.62

Figure 6.10: T30, Orchestra pit S1



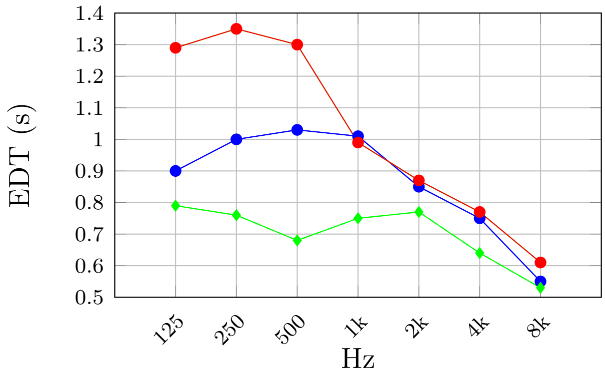
Band	Unibo	HSMW
125	1.0	-0.6
250	0.8	-0.9
500	0.8	-0.9
1k	0.9	0.2
2k	1.5	0.8
4k	2.4	1.7
8k	4.6	3.4

Figure 6.11: C50, Orchestra pit S1



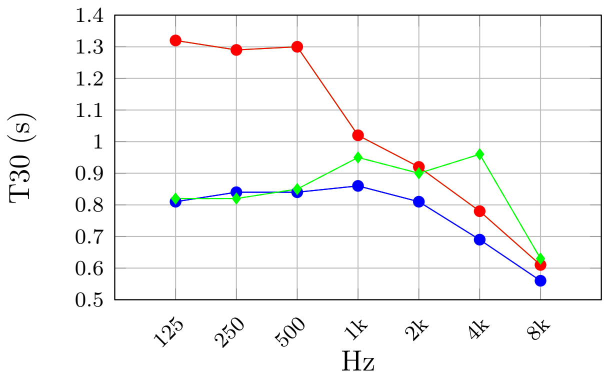
Band	Unibo	HSMW
125	4.2	2.2
250	4.0	2.0
500	3.9	2.0
1k	4.0	3.3
2k	4.7	4.1
4k	5.8	5.2
8k	8.6	7.3

Figure 6.12: C80, Orchestra pit S1



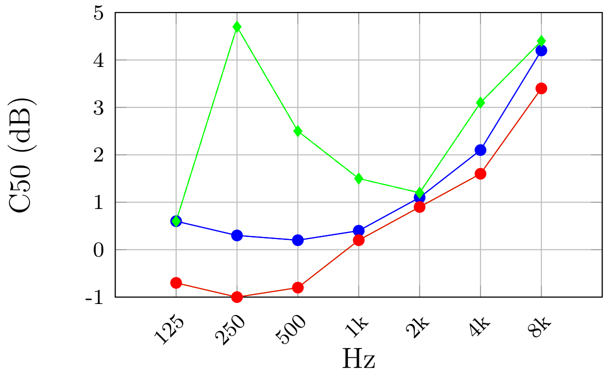
Band	Unibo	HSMW
125	0.90	1.29
250	1.00	1.35
500	1.03	1.30
1k	1.01	0.99
2k	0.85	0.87
4k	0.75	0.77
8k	0.55	0.61

Figure 6.13: EDT, Orchestra pit S6



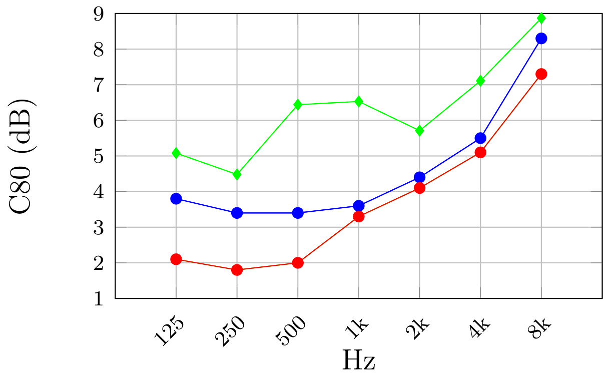
Band	Unibo	HSMW
125	0.81	1.32
250	0.84	1.29
500	0.84	1.30
1k	0.86	1.02
2k	0.81	0.92
4k	0.69	0.78
8k	0.56	0.61

Figure 6.14: T30, Orchestra pit S6



Band	Unibo	HSMW
125	0.6	-0.7
250	0.3	-1.0
500	0.2	-0.8
1k	0.4	0.2
2k	1.1	0.9
4k	2.1	1.6
8k	4.2	3.4

Figure 6.15: C50, Orchestra pit S6

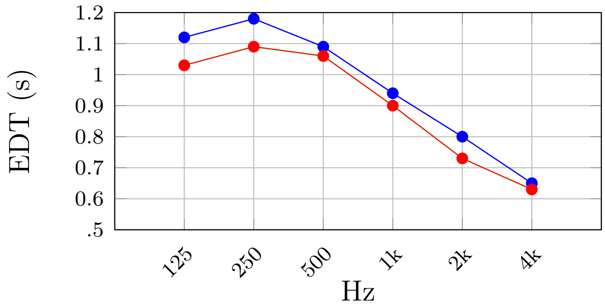


Band	Unibo	HSMW
125	3.8	2.1
250	3.4	1.8
500	3.4	2.0
1k	3.6	3.3
2k	4.4	4.1
4k	5.5	5.1
8k	8.3	7.3

Figure 6.16: C80, Orchestra pit S6

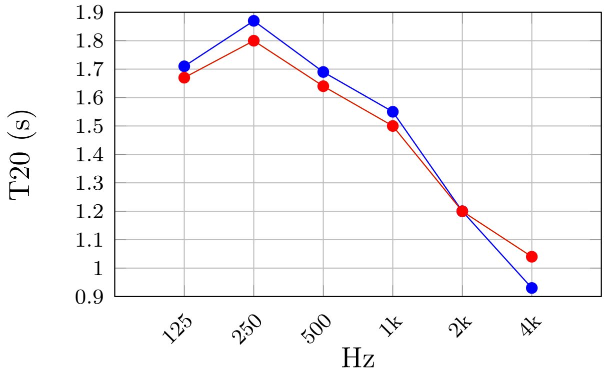
6.2 Intervention results

Theatre hall



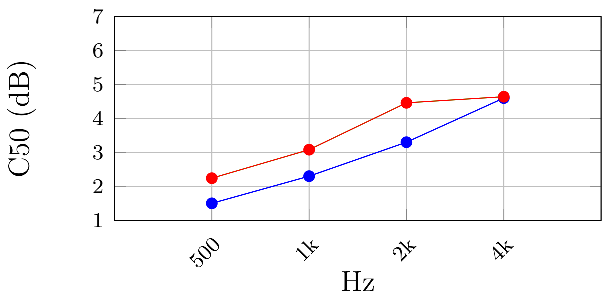
Band	Unibo	HSMW
125	1.12	1.03
250	1.18	1.09
500	1.09	1.06
1k	0.94	0.90
2k	0.80	0.73
4k	0.65	0.63

Figure 6.17: EDT, S on stage



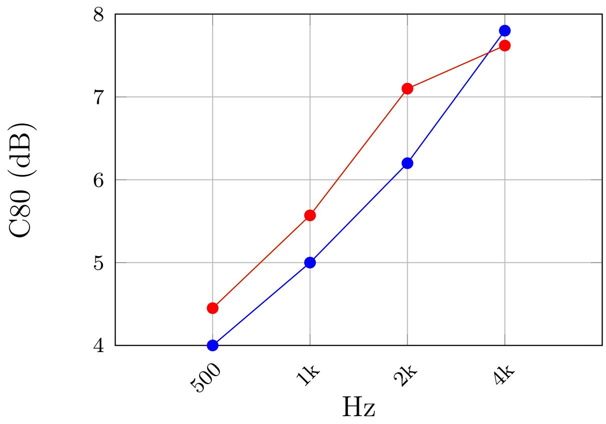
Band	Unibo	HSMW
125	1.71	1.67
250	1.87	1.80
500	1.69	1.64
1k	1.55	1.50
2k	1.20	1.20
4k	0.93	1.04

Figure 6.18: T20, S on stage



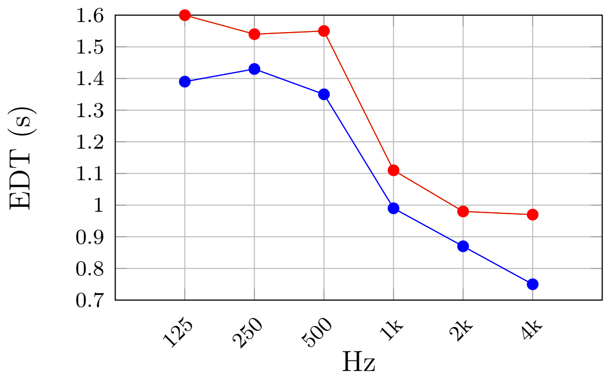
Band	Unibo	HSMW
500	1.5	2.2
1k	2.3	3.0
2k	3.3	4.4
4k	4.6	4.6

Figure 6.19: C50, S on stage



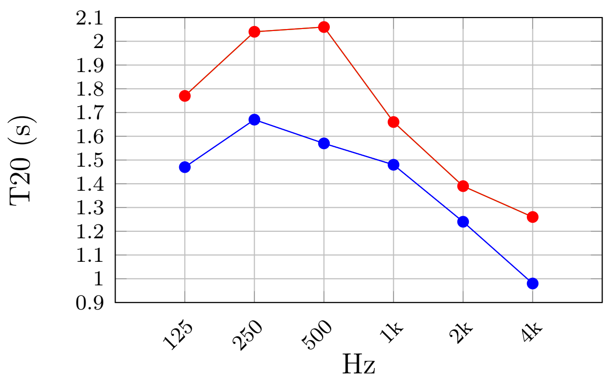
Band	Unibo	HSMW
500	4.0	4.4
1k	5.0	5.5
2k	6.2	7.1
4k	7.8	7.6

Figure 6.20: C80, S on stage



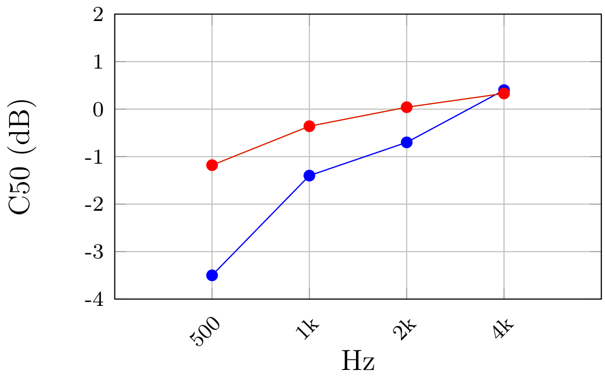
Band	Unibo	HSMW
125	1.39	1.60
250	1.43	1.54
500	1.35	1.55
1k	0.99	1.11
2k	0.87	0.98
4k	0.75	0.97

Figure 6.21: EDT, S in the pit



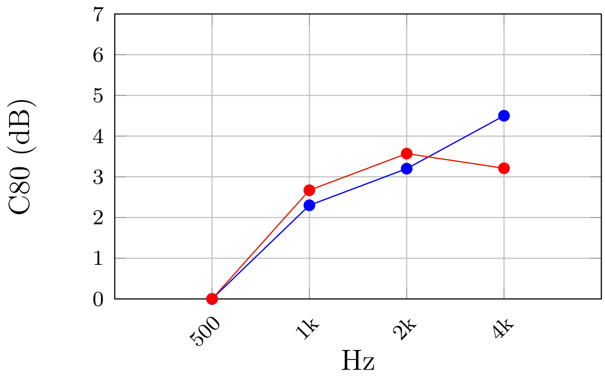
Band	Unibo	HSMW
125	1.47	1.77
250	1.67	2.04
500	1.57	2.06
1k	1.48	1.66
2k	1.24	1.39
4k	0.98	1.26

Figure 6.22: T20, S in the pit



Band	Unibo	HSMW
500	-3.5	-1.1
1k	-1.4	-0.3
2k	-0.7	0
4k	0.4	0.3

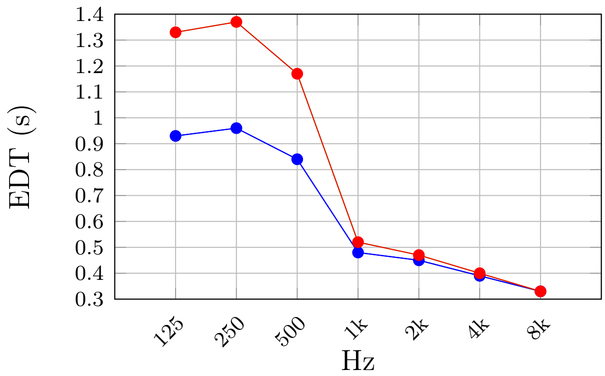
Figure 6.23: C50, S in the pit



Band	Unibo	HSMW
500	0	0
1k	2.3	2.6
2k	3.2	3.5
4k	4.5	3.2

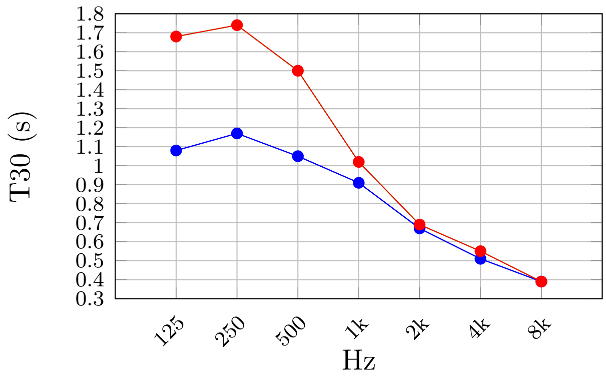
Figure 6.24: C80, S in the pit

Orchestra pit



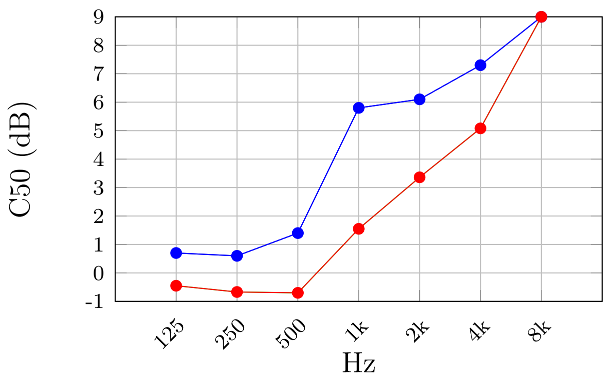
Band	Unibo	HSMW
125	0,93	1.33
250	0,96	1.37
500	0,84	1.17
1k	0,48	0.52
2k	0,45	0.47
4k	0,39	0.40
8k	0,33	0.33

Figure 6.25: EDT, Orchestra pit S1



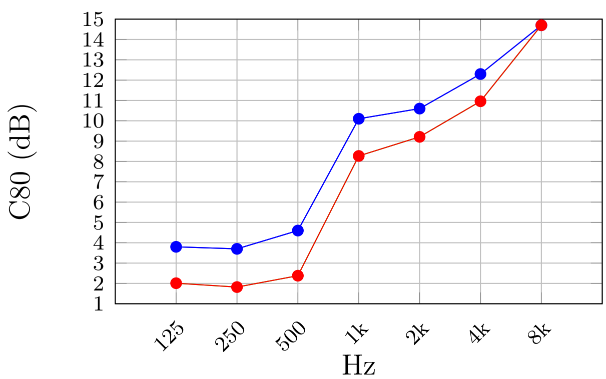
Band	Unibo	HSMW
125	1.08	1.68
250	1.17	1.74
500	1.05	1.50
1k	0.91	1.02
2k	0.67	0.69
4k	0.51	0.55
8k	0.39	0.39

Figure 6.26: T30, Orchestra pit S1



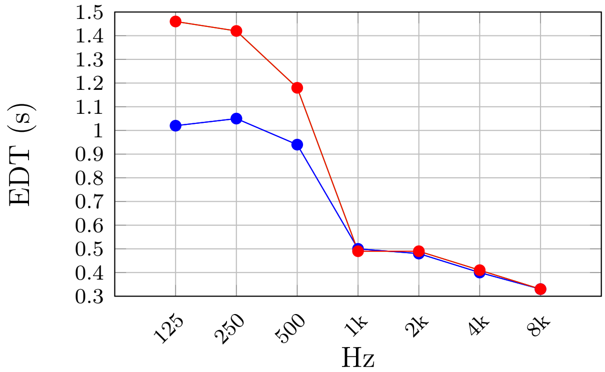
Band	Unibo	HSMW
125	0.7	-0.4
250	0.6	-0.6
500	1.4	-0.7
1k	5.8	1.5
2k	6.1	3.3
4k	7.3	5.0
8k	9.0	9.0

Figure 6.27: C50, Orchestra pit S1



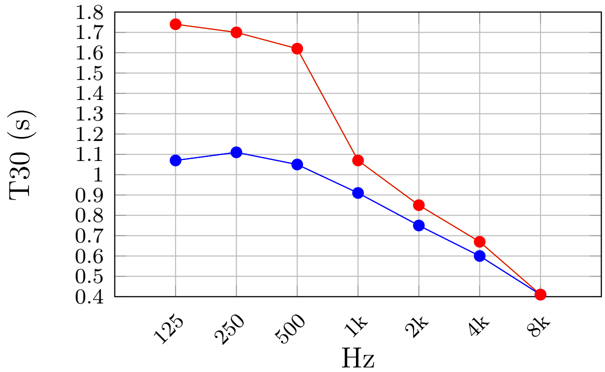
Band	Unibo	HSMW
125	3.8	2.0
250	3.7	1.8
500	4.6	2.3
1k	10.1	8.2
2k	10.6	9.2
4k	12.3	10.9
8k	14.7	14.7

Figure 6.28: C80, Orchestra pit S1



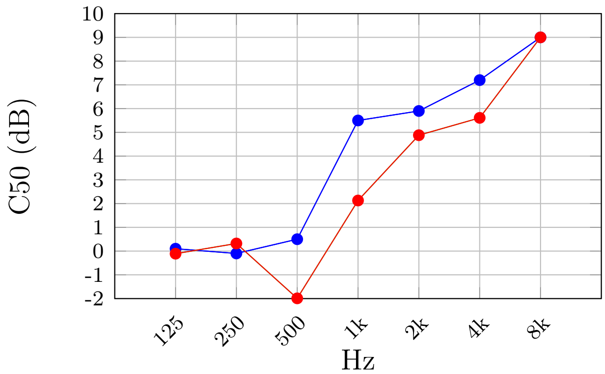
Band	Unibo	HSMW
125	1.02	1.46
250	1.05	1.42
500	0.94	1.18
1k	0.50	0.49
2k	0.48	0.49
4k	0.40	0.41
8k	0.33	0.33

Figure 6.29: EDT, Orchestra pit S6



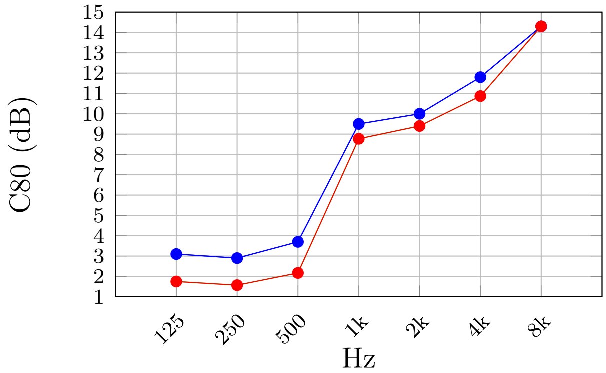
Band	Unibo	HSMW
125	1.07	1.74
250	1.11	1.70
500	1.05	1.62
1k	0.91	1.07
2k	0.75	0.85
4k	0.60	0.67
8k	0.41	0.41

Figure 6.30: T30, Orchestra pit S6



Band	Unibo	HSMW
125	0.1	-0.1
250	-0.1	0.3
500	0.5	-1.9
1k	5.5	2.1
2k	5.9	4.8
4k	7.2	5.6
8k	9	9

Figure 6.31: C50, Orchestra pit S6



Band	Unibo	HSMW
125	3.1	1.7
250	2.9	1.5
500	3.7	2.1
1k	9.5	8.7
2k	10.0	9.4
4k	11.8	10.8
8k	14.3	14.3

Figure 6.32: C80, Orchestra pit S6

6.3 Considerations

In comparing the values obtained through the two software provided by Unibo and Hochschule Mittweida, it becomes evident that the results exhibit a degree of similarity, albeit with slight discrepancies. These disparities can be attributed to the distinct computational methodologies employed by each software, coupled with the fact that both rely on ray tracing technology for their calculations [18] [17]. It is worth noting that ray tracing technology does not account for the intricate interactions of sound energy within enclosed spaces, where portions of sound energy, sharing the same frequency but differing in phase, may either cancel each other out or combine, thereby altering the values of the parameters under consideration.
Upon closer examination of the comparative graphs, it becomes apparent that greater congruence exists at medium to high frequencies for both the reverberation (EDT, T_{20}, T_{30}) and clarity (C_{50}, C_{80}) parameters. This phenomenon can be attributed to the fact that the behaviour of sound waves in this frequency range is more amenable to approximation through ray-tracing technology. Conversely, at lower frequencies, notable discrepancies arise due to the inherent complexity of predicting their behaviour through computational means, as these frequencies remain less comprehensively understood from a physical standpoint [27]. Is also possible to notice more discrepancies are found in the measurements related to the orchestra pit. In fact, due to the relatively small size of the room, here the frequency bands that can be well precisely approximated through ray tracing are only those with a shorter wavelength, generally above 1kHz
The utilization of these software tools serves as a valuable resource for anticipating the behaviour of an acoustic field. However, it is essential to acknowledge that, given the substantial challenge of providing precise input data to the computational models, a degree of approximation is necessitated. Consequently, these tools excel in verifying the validity of subjective impressions, underscoring their significance in the realm of acoustical analysis.

In the following pages the differences in the results between the two software are analysed in detail:

Theatre Hall

Frequency Band (Hz)	Difference (s)	Percentage Diff. (%)
125	0.25	18.1
250	0.31	16.4
500	0.24	14.2
1k	0.19	12.7
2k	0.14	11.8
4k	0.22	17.6
Average	**0.21**	**14.38**

Table 6.1: Averaged difference for reverberation criteria, source on stage

Frequency Band (Hz)	Difference (s)	Percentage Diff. (%)
125	0.21	13.1
250	0.23	14.4
500	0.20	13.0
1k	0.20	13.1
2k	0.21	15.1
4k	0.18	15.7
Average	**0.2**	**14.51**

Table 6.2: Averaged difference for reverberation criteria, source in the pit

Frequency Band (Hz)	Difference (dB)	Percentage Diff. (%)
500	2.7	45.7
1k	2.6	46.3
2k	2.7	49.4
4k	2.2	46.4
Average	**2.5**	**46.9**

Table 6.3: Averaged difference for clarity criteria, source on stage

Frequency Band (Hz)	Difference (dB)	Percentage Diff. (%)
500	1.1	104.5
1k	0.3	164.9
2k	-0.7	-72.9
4k	0.8	34.7
Average	**0.3**	**80.7**

Table 6.4: Averaged difference for clarity criteria, source in the pit

Orchestra pit

Frequency Band (Hz)	Difference (s)	Percentage Diff. (%)
125	-0.50	-30.3
250	-0.49	-28.7
500	-0.42	-26.0
1k	-0.11	-10.2
2k	-0.05	-5.5
4k	-0.06	-8.3
8k	0.00	0.0
Average	**-0.22**	**-17.79**

Table 6.5: Averaged difference for reverberation criteria

Frequency Band (Hz)	Difference (dB)	Percentage Diff. (%)
125	1.4	391.0
250	1.4	341.2
500	1.7	169.6
1k	2.0	228.2
2k	1.6	39.2
4k	1.7	28.6
8k	0.0	6.21
Average	**1.4**	**173.1**

Table 6.6: Averaged difference for clarity criteria

Chapter 7

Conclusions

Over the course of more than a year of research, this project has achieved significant milestones that are worth consideration. The author takes great satisfaction in the accomplishment of providing detailed information about the Freiberg Theatre in English, addressing a long-standing gap where such information was predominantly available only in German. This achievement not only contributes to a broader understanding of the Theatre's cultural and historical significance but also makes it more accessible to a wider international audience.

The knowledge gained during the acoustic measurement phase of this project is particularly appreciated by the author. This practical experience not only served as a valuable learning opportunity but also enabled a deep understanding of the methodology and the challenges involved in measuring acoustic parameters. Through the utilization of complex mathematical software and the handling of extensive datasets, the author made a contribution by producing objective and data-driven insights into the acoustic characteristics of this historically significant building.

The construction of an accurate and precise 3D model of the Freiberg Theatre stands out as a significant achievement. This model served as a pivotal tool for learning and proficiently employing two of the most reputable acoustic simulation software platforms available, Odeon and Ease. The author's dedication to mastering these software tools led to useful and practical results in the acoustic simulation process.
It has been possible to demonstrate that the overall reverberation time in the theatre frequently falls below 1 second, corroborating the dissatisfaction expressed by many users regarding the sound perception during performances inside the theatre. Furthermore, through the questionnaire conducted among

musicians, a documented issue in the orchestra pit has been identified. In an effort to address this concern, an objective experimental parameter was employed and cross-referenced with the subjective opinions of the orchestra members, aiming to provide more insights into the utilization of this space.

In conclusion, the primary goal set at the outset of this thesis project in September 2022 has been satisfactorily accomplished. The administration of the Freiberg Theatre now possesses a wealth of information about the theatre's acoustic conditions, supported by objective data. This information not only enhances awareness of the theatre's acoustic challenges but also provides a robust foundation for considering potential interventions to address these issues. The author has also proposed an approximate budget for the suggested interventions, adding a practical dimension to the project. This budgetary estimation enhances the practicality and applicability of the proposed solutions, allowing for a more informed decision-making process regarding their implementation.
The proposed interventions have been carefully designed to strike a delicate balance between preserving the historical architecture of the theatre, minimizing substantial and aesthetic changes to the space, and enhancing its acoustic qualities. It is worth noting that the proposed solution for the main hall aligns with a methodology that has been successfully implemented by other acousticians, as referenced in the bibliography.
Furthermore, the author takes great satisfaction in having produced a reliable rendering of the theatre. This rendering serves not only as a visualization tool for potential modifications to the space but also as a persuasive instrument when engaging with the municipal administration of Freiberg. It allows stakeholders to envision the proposed interventions and facilitates productive discussions aimed at finding possible solutions for the theatre's acoustic enhancement while respecting its historical significance and aesthetic integrity.
The author's commitment to this project extends to the desire to continue the work by creating an auralization of the acoustic conditions within the space. This auralization, when coupled with a video representation of the rendering, will provide both a visual and auditory experience of the potential new environment. This multimedia approach will further aid in conveying the proposed changes and their impact to all stakeholders, ensuring a comprehensive understanding of the project's potential benefits.

Additionally, this research project has shed light on the disparities in utilization and output between the two among the most referenced simulation software platforms, Odeon and Ease. These insights hold significant value, particularly as these software tools continue to undergo substantial research and development efforts. In summary, this research project represents a substantial step forward in improving the acoustic conditions of the Freiberg Theatre while meticulously preserving its historical and architectural integrity. It facilitates informed decision-making regarding potential acoustic interventions that could ultimately enhancing the auditory experience for both performers and audiences.

Appendix A

In the Appendix A is presented the Matlab script co-written and used by the Author in order to calculate the values of the acoustic criteria from the impulse responses obtained after the measurement campaign at the Freiberg Theatre.

```
clear
%File Dialog

[file,path] = uigetfile('*.mat');
if isequal(file,0)
   disp('User␣selected␣Cancel');
else
   disp(['User␣selected']);
   disp([fullfile(path)]);
   disp([fullfile(file)]);
   input = strcat(path,file);
end

%IR reading and showing
Var = load(input);
%[Impulsantwort, fs] = audioread();
fs = 44100;
Impulseresponse = Var.RIR_new;
Impulseresponse = Impulseresponse(:,1);
time_imp = length(Impulseresponse);
time_imp = linspace(0,(time_imp/fs),time_imp);
plot(time_imp,Impulseresponse)
xlabel("Time [s]")

Impuls_flip = flipud(Impulseresponse);
Impuls_qua = Impuls_flip.^2;
Impuls_Sum = cumsum(Impuls_qua);
Impuls_Sum = flipud(Impuls_Sum);
rt60 = 10*log10(Impuls_Sum);
time_ind = length(Impulseresponse);
time_ind = linspace(0,(time_ind/fs),time_ind);

%T30
```

```
max = rt60(1,1);
[minus5] = find(rt60<(max-5),1);
[minus35] = find(rt60<(max-35),1);
anzahlSample = minus35 - minus5;
startpointT30 = rt60(minus5,1);
endpointT30 = rt60(minus35,1);
RT30 = anzahlSample*(1/fs);
time = RT30*2;
disp("T30:")
disp(time);

plot(time_ind(minus5:minus35),rt60(minus5:minus35));
title("T30")
%disp("T60:")
%plot(time_ind,rt60);

%EDT
max = rt60(1,1);
[minus0] = find(rt60<(max-0),1);
[minus10] = find(rt60<(max-10),1);
anzahlSample = minus10 - minus0;
startpunktEDT = rt60(minus0,1);
endpunktrtEDT = rt60(minus10,1);
EDT = anzahlSample*(1/fs);
time = EDT*6;

plot(time_ind(minus0:minus10),rt60(minus0:minus10));
title("EDT Ausschnitt")
%disp("T60:")
%plot(time_ind,rt60);

disp("EDT:")
disp(time);

% STearly, STlate
STeo = sum(Impulseresponse((0.02*fs):(0.1*fs)).^2);
STeu = sum(Impulseresponse(1:(0.01*fs)).^2);
STearly = 10*log10(STeo/STeu)

STlo = sum(Impulseresponse((0.1*fs):fs).^2);
STlu = sum(Impulseresponse(1:(0.01*fs)).^2);
STlate = 10*log10(STlo/STlu)

STto = sum(Impulseresponse((0.02*fs):fs).^2);
STtu = sum(Impulseresponse(1:(0.01*fs)).^2);
STtotal = 10*log10(STto/STtu)

% Clarity C80 C50
C80up = sum(Impulseresponse(1:(0.08*fs)).^2);
```

```
C80down = sum(Impulseresponse((0.08*fs):(length(
    Impulseresponse))).^2);
C80 = 10*log10(C80up/C80down)

C50up = sum(Impulseresponse(1:(0.05*fs)).^2);
C50down = sum(Impulseresponse((0.05*fs):(length(
    Impulseresponse))).^2);
C50 = 10*log10(C50up/C50down)

%Third octave filter
octFiltBank = octaveFilterBank('1/3␣octave','FrequencyRange'
    ,[125,4000],'SampleRate',fs);
FilterImpulseresponse = octFiltBank(Impulseresponse);

% Support Third ocatve band
k = 1;
STearlyf = [];
STlatef = [];
Rt30_timef = [];

while k <= size(FilterImpulseresponse,2)
 Impulseresponse = FilterImpulseresponse(:,k);

STeo = sum(Impulseresponse((0.02*fs):(0.1*fs)).^2);
STeu = sum(Impulseresponse(1:(0.01*fs)).^2);
STearly = 10*log10(STeo/STeu);

STearlyf = [STearlyf, STearly];

Impuls_flip = flipud(Impulseresponse);
Impuls_qua = Impuls_flip.^2;
Impuls_Sum = cumsum(Impuls_qua);
Impuls_Sum = flipud(Impuls_Sum);
rt60 = 10*log10(Impuls_Sum);
time_ind = length(Impulseresponse);
time_ind = linspace(0,(time_ind/fs),time_ind);

%T30 thrid octave band
max = rt60(1,1);
[minus5] = find(rt60<(max-5),1);
[minus35] = find(rt60<(max-25),1);
anzahlSample = minus35 - minus5;
startpunktt30 = rt60(minus5,1);
endpunktrt30 = rt60(minus35,1);
RT30 = anzahlSample*(1/fs);
time = RT30*3;

Rt30_timef = [Rt30_timef,time];

```

```
STlo = sum(Impulseresponse((0.1*fs):fs).^2);
STlu = sum(Impulseresponse(1:(0.01*fs)).^2);
STlate = 10*log10(STlo/STlu);

STlatef = [STlatef, STlate];

k = k+1;
end

Terzband =[125,160,200,250,315,400,500,630,800,1000,
1250,1600,2000,2500,3150,4000];


plot(Terzband,STearlyf);
xlabel('Frequenz␣[Hz]')
%ylim([-8,8]);
title('STearly␣Third␣octave␣band')
hold on

Earlymax = zeros(16,1) -8;
plot(Terzband, Earlymax);

Earlymin = zeros(16,1) -24;
plot(Terzband, Earlymin);

hold off

plot(Terzband,STlatef);
xlabel('Frequenz␣[Hz]');
%ylim([-12,6]);
title('STlate␣Third␣octave␣band')
hold on

Latemax = zeros(16,1) -10;
plot(Terzband, Latemax);

Latemin = zeros(16,1) -24;
plot(Terzband, Latemin);

hold off

plot(Terzband,Rt30_timef)
xlabel('Frequenz␣[Hz]')
ax.XScale = 'log';
ylabel("Reverberation time [s]")
ylim([0,2]);
title('T30␣Third␣octave␣band')
```

Listing 7.1: Script to get ST EDT T30 Clarity

Appendix B

In the Appendix B are shown the values of the software calibration divided by receivers in the auditorium on the balconies and in the orchestra pit.

Software Unibo

Theatre hall

Table 7.1: EDT (s), source on stage

	Auditorium		1st balcony		2nd balcony		
Band (Hz)	Value	Dev. %	Value	Dev. %	Value	Dev. %	Average %
125	1.01	8.6	0.91	-5.6	0.88	-8.7	7.6
250	0.94	5.6	0.87	2.1	0.89	-8.0	5.2
500	0.91	1.8	0.83	-8.0	0.82	-5.5	5.1
1k	0.80	4.1	0.72	-7.9	0.74	-7.8	6.6
2k	0.69	6.2	0.67	-9.2	0.67	-8.7	8.0
4k	0.50	2.6	0.52	-9.1	0.49	-9.7	7.1

Table 7.2: T20 (s), source on stage

	Auditorium		1st balcony		2nd balcony		
Band (Hz)	Value	Dev. %	Value	Dev. %	Value	Dev. %	Average %
125	1.01	-2.7	1.06	4.8	1.09	18.2	8.5
250	1.00	-9.3	1.06	2.9	1.07	5.3	5.8
500	0.91	-1.4	0.99	5.3	1.05	17.4	8.0
1k	0.82	-1.6	0.89	3.3	0.93	8.9	4.6
2k	0.73	1.6	0.74	-2.0	0.77	2.4	2.0
4k	0.57	-1.2	0.55	-7.7	0.55	-7.4	5.4

Table 7.3: C50 (dB), source on stage

	Auditorium		1st balcony		2nd balcony		
Band (Hz)	Value	Dev. (dB)	Value	Dev. (dB)	Value	Dev. (dB)	Avg. (dB)
500	1.10	0.2	2.90	3.0	2.10	1.4	1.5
1k	2.10	-0.0	3.60	2.0	2.90	1.1	1.1
2k	3.00	-0.9	4.60	2.8	3.40	1.3	1.6
4k	5.40	0.3	7.20	3.6	6.50	3.2	**2.4**

Table 7.4: C80 (dB), source on stage

	Auditorium		1st balcony		2nd balcony		
Band (Hz)	Value	Dev. (dB)	Value	Dev. (dB)	Value	Dev. (dB)	Avg. (dB)
500	4.20	0.1	6.20	2.4	5.70	1.6	1.4
1k	5.40	-0.1	7.10	2.6	6.50	1.5	1.4
2k	6.50	-1.0	8.30	3.3	7.60	1.9	**2.1**
4k	9.70	0.7	11.40	4.1	11.00	6.0	**3.6**

Table 7.5: EDT (s), source in the pit

	Auditorium		1st balcony		2nd balcony		
Band (Hz)	Value	Dev. %	Value	Dev. %	Value	Dev. %	Average %
125	1.20	8.6	1.06	-4.5	0.96	9.1	7.4
250	1.19	-9.3	1.10	3.6	1.09	-9.9	7.6
500	1.14	9.6	1.05	5.0	0.98	3.4	6.0
1k	1.00	4.2	0.90	9.2	0.93	1.5	5.0
2k	0.87	9.3	0.86	8.9	0.86	0.7	6.3
4k	0.59	-4.6	0.64	-1.2	0.66	-9.9	5.2

Table 7.6: T20 (s), source in the pit

	Auditorium		1st balcony		2nd balcony		
Band (Hz)	Value	Dev. %	Value	Dev. %	Value	Dev. %	Average %
125	1.01	7.3	1.06	0.6	1.08	3.1	3.7
250	1.02	-4.0	1.05	-4.1	1.06	9.5	5.9
500	0.98	6.5	1.01	9.0	1.00	2.7	6.1
1k	0.89	9.3	0.92	8.7	0.90	9.2	9.1
2k	0.80	8.1	0.81	8.7	0.80	1.0	5.9
4k	0.57	-3.6	0.56	-6.0	0.63	0.0	3.2

Table 7.7: C50 (dB), source in the pit

	Auditorium		1st balcony		2nd balcony		
Band (Hz)	Value	Dev. (dB)	Value	Dev. (dB)	Value	Dev. (dB)	Avg. (dB)
500	-5.00	-1.2	-1.20	-1.2	-3.00	-0.1	0.8
1k	-4.10	-2.3	-0.80	-0.7	-2.30	-0.5	1.2
2k	-3.50	-2.3	-0.20	-0.7	-1.90	-0.6	1.2
4k	-0.60	-1.0	2.80	0.5	2.70	3.0	1.5

Table 7.8: C80 (dB), source in the pit

	Auditorium		1st balcony		2nd balcony		
Band (Hz)	Value	Dev. (dB)	Value	Dev. (dB)	Value	Dev. (dB)	Avg. (dB)
500	-0.20	-1.9	2.30	-1.4	1.30	0.1	1.1
1k	0.80	-1.5	2.70	-1.4	1.90	-0.4	1.1
2k	1.60	-1.5	3.40	-0.8	2.50	-0.3	0.9
4k	5.40	0.3	6.90	0.9	6.00	2.2	1.2

Orchestra pit

Table 7.9: EDT (s), Orchestra pit

	S1		S6		
Band (Hz)	Value	Dev. %	Value	Dev. %	Avg. %
125	0.88	-9.4	0.89	-21.1	**15.3**
250	0.90	35.9	0.94	33.8	**34.9**
500	0.92	19.2	0.95	40.3	**29.7**
1k	0.91	9.3	0.93	8.4	8.9
2k	0.84	1.4	0.80	10.5	6.0
4k	0.73	5.8	0.74	6.0	5.9

Table 7.10: T30 (s), Orchestra pit

	S1		S6		
Band (Hz)	Value	Dev. %	Value	Dev. %	Avg. %
125	0.87	2.7	0.81	-0.8	1.0
250	0.90	7.9	0.84	2.6	5.2
500	0.92	1.7	0.84	-1.3	0.2
1k	0.90	-20.4	0.86	-9.3	**14.9**
2k	0.82	-9.4	0.81	-10.2	9.8
4k	0.71	-31.5	0.69	-28.4	**30.0**

Table 7.11: C50 (dB), Orchestra pit

	S1		S6		
Band (Hz)	Value	Dev. (dB)	Value	Dev. (dB)	Avg. (dB)
125	1.0	-0.5	0.6	-0.0	0.3
250	0.8	-3.1	0.3	-4.4	3.7
500	0.8	-1.5	0.2	-2.3	1.9
1k	0.9	-0.6	0.4	-1.1	0.8
2k	1.5	-0.6	1.1	-0.1	0.4
4k	2.4	-1.2	2.1	-1.0	1.1

Table 7.12: C80 (dB), Orchestra pit

	S1		S6		
Band (Hz)	Value	Dev. (dB)	Value	Dev. (dB)	Avg. (dB)
125	4.2	-0.5	3.8	-1.3	0.9
250	4.0	-2.6	3.4	-1.1	1.8
500	3.9	-1.7	3.4	-3.0	**2.3**
1k	4.0	-1.7	3.6	-2.9	**2.3**
2k	4.7	-0.5	4.4	-1.3	0.9
4k	5.8	-1.2	5.5	-1.6	1.4

Software Hochschule Mittweida

Theatre hall

Table 7.13: EDT (s), source on stage

	Auditorium		1st balcony		2nd balcony		
Band (Hz)	Value	Dev. %	Value	Dev. %	Value	Dev. %	Average %
125	0.87	-6.7	0.87	-10.0	0.84	-12.5	9.7
250	0.84	-6.2	0.85	-0.4	0.82	-15.2	7.3
500	0.81	-9.8	0.83	-8.4	0.87	0.0	6.0
1k	0.69	-10.4	0.73	-7.1	0.74	-7.3	8.3
2k	0.59	-9.5	0.62	-16.3	0.66	-10.5	**12.1**
4k	0.46	-6.1	0.50	-12.6	0.52	-4.9	7.9

Table 7.14: T20 (s), source on stage

	Auditorium		1st balcony		2nd balcony		
Band (Hz)	Value	Dev. %	Value	Dev. %	Value	Dev. %	Average %
125	1.03	11.2	1.05	8.4	1.01	5.0	8.2
250	1.04	16.7	0.97	14.2	1.00	3.6	**11.5**
500	1.01	12.9	0.93	3.5	0.92	5.8	7.4
1k	0.87	12.7	0.87	11.7	0.82	1.7	8.7
2k	0.72	10.8	0.73	-1.5	0.79	8.0	6.8
4k	0.62	26.5	0.65	13.3	0.60	9.7	**16.5**

Table 7.15: C50 (dB), source on stage

	Auditorium		1st balcony		2nd balcony		
Band (Hz)	Value	Dev. (dB)	Value	Dev. (dB)	Value	Dev. (dB)	Avg. (dB)
500	3.58	2.7	3.73	3.8	1.80	1.1	**2.5**
1k	4.26	2.1	4.42	2.8	2.85	1.1	**2.0**
2k	5.51	1.7	5.03	3.2	4.32	2.2	**2.4**
4k	6.80	1.7	6.79	3.2	5.66	2.4	**2.4**

Table 7.16: C80 (dB), source on stage

	Auditorium		1st balcony		2nd balcony		
Band (Hz)	Value	Dev. (dB)	Value	Dev. (dB)	Value	Dev. (dB)	Avg. (dB)
500	6.40	2.3	6.54	2.8	4.99	0.9	**2.0**
1k	7.58	2.1	7.38	2.8	6.20	1.2	**2.1**
2k	9.11	1.6	8.66	3.7	7.88	2.1	**2.5**
4k	10.83	1.8	10.82	3.5	9.71	4.7	**3.3**

Table 7.17: EDT (s), source in the pit

	Auditorium		1st balcony		2nd balcony		
Band (Hz)	Value	Dev. %	Value	Dev. %	Value	Dev. %	Average %
125	1.27	36.4	1.20	24.2	1.24	28.4	**29.7**
250	1.24	39.7	1.16	36.2	1.23	26.8	**34.2**
500	1.23	37.2	1.17	29.2	1.25	44.0	**36.8**
1k	1.05	36.2	1.05	34.5	1.07	33.0	**34.6**
2k	0.96	47.7	0.99	33.7	0.97	32.5	**38.0**
4k	0.83	69.9	0.83	44.8	0.79	44.7	**53.1**

Table 7.18: T20 (s), source in the pit

	Auditorium		1st balcony		2nd balcony		
Band (Hz)	Value	Dev. %	Value	Dev. %	Value	Dev. %	Average %
125	1.36	45.7	1.33	37.6	1.16	20.3	**34.5**
250	1.35	51.3	1.25	46.1	1.22	26.4	**41.3**
500	1.35	51.5	1.31	44.8	1.27	45.9	**47.4**
1k	1.06	37.3	1.00	27.2	0.99	22.7	**29.1**
2k	0.89	37.3	0.90	22.2	0.90	22.3	**27.3**
4k	0.75	53.2	0.75	30.4	0.77	41.0	**41.5**

Table 7.19: C50 (dB), source in the pit

	Auditorium		1st balcony		2nd balcony		
Band (Hz)	Value	Dev. (dB)	Value	Dev. (dB)	Value	Dev. (dB)	Avg. (dB)
500	-1.98	-2.9	0.14	0.2	-1.27	-2.0	1.7
1k	-0.96	-3.1	0.22	-1.4	-1.10	-2.9	**2.5**
2k	-0.22	-4.1	0.63	-1.2	-0.10	-2.2	**2.5**
4k	0.77	-4.3	2.30	-1.3	1.03	-2.2	**2.6**

Table 7.20: C80 (dB), source in the pit

	Auditorium		1st balcony		2nd balcony		
Band (Hz)	Value	Dev. (dB)	Value	Dev. (dB)	Value	Dev. (dB)	Avg. (dB)
500	0.72	-0.1	1.45	1.5	1.37	0.7	0.8
1k	1.66	-0.5	2.95	1.4	1.66	-0.1	0.7
2k	2.88	-1.0	2.84	1.0	2.64	0.6	0.8
4k	4.05	-1.1	4.51	0.9	4.50	1.2	1.1

Orchestra pit

Table 7.21: EDT (s), Orchestra pit

	S1		S7		
Band (Hz)	Value	Dev. %	Value	Dev. %	Avg. %
125	1.26	29.7	1.29	64.2	**47.0**
250	1.28	93.3	1.35	77.1	**85.2**
500	1.29	66.5	1.30	91.8	**79.1**
1k	0.99	18.4	0.99	31.4	**24.9**
2k	0.88	6.2	0.87	13.4	9.8
4k	0.76	9.5	0.77	19.6	**14.6**
8k	0.60	7.7	0.61	14.3	11.0

Table 7.22: T30 (s), Orchestra pit

	S1		S6		
Band (Hz)	Value	Dev. %	Value	Dev. %	Avg. %
125	1.35	59.3	1.32	61.1	**60.2**
250	1.34	60.0	1.29	57.0	**58.5**
500	1.32	45.4	1.30	52.1	**48.7**
1k	1.01	-11.1	1.02	7.0	2.0
2k	0.85	-6.1	0.92	1.4	2.3
4k	0.76	-26.7	0.78	-19.6	**23.1**
8k	0.62	-1.3	0.61	-2.7	2.0

Table 7.23: C50 (dB), Orchestra pit

	S1		S6		
Band (Hz)	Value	Dev. (dB)	Value	Dev. (dB)	Avg. (dB)
125	-0.6	-2.1	-0.7	-1.3	1.7
250	-0.9	-4.8	-1.0	-5.6	**5.2**
500	-0.9	-3.1	-0.8	-3.3	**3.2**
1k	0.2	-1.2	0.2	-1.3	1.3
2k	0.8	-1.3	0.9	-0.3	0.8
4k	1.7	-1.9	1.6	-1.4	1.7
8k	3.4	-1.3	3.4	-1.0	1.1

Table 7.24: C80 (dB), Orchestra pit

	S1		S6		
Band (Hz)	Value	Dev. (dB)	Value	Dev. (dB)	Avg. (dB)
125	2.2	-2.5	2.1	-2.9	**2.7**
250	2.0	-4.6	1.8	-2.6	**3.6**
500	2.0	-3.5	2.0	-4.4	**4.0**
1k	3.3	-2.5	3.3	-3.2	**2.8**
2k	4.1	-1.1	4.1	-1.6	1.3
4k	5.2	-1.8	5.1	-2.0	1.9
8k	7.3	-0.8	7.3	-1.5	1.2

Bibliography

[1] R. Spagnolo, *Manuale di acustica applicata.* De Agostini Scuola - Città Studi Edizioni, 2008.

[2] T. D. Rossing, *Handbook of Acoustics 2nd edition.* Springer, 2014.

[3] J. Hübelt, *Vorlesung Grundlagen der Akustik.* Hoschschule Mittweida, 2015.

[4] W. Sabine, *Collected Papers on Acoustics.* Harvard University Press, 1922.

[5] M. Vorländer, *Auralization.* Springer, 2008.

[6] L. Beranek, *Concert halls and opera houses: How they sound.* Acoustical Society of America, 1996.

[7] M. Barron, *Energy relations in concert auditoriums.* Acoustical Society of America, 1988.

[8] Y. Ando, *Architectural Acoustics, Blending Sound Sources, Sound Fields, and Listeners.* Springer, 1998.

[9] Dressler, R. and Klecker, C., *Zur Geschichte des Freiberger Theaters.* Verlag Klaus Gumnior, 2015.

[10] Dietrich, "Matlab toolbox for the comprehension of acoustic measurement and signal processing." Institute of Technical Acoustics, RWTH Aachen University, 2010.

[11] "ISO 3382-2." International Organization for Standardization (ISO), 2009.

[12] "ISO 3382-1." International Organization for Standardization (ISO), 2009.

[13] A. C. Gade et al., "Practical aspects of room acoustical measurements on orchestra platforms," *Proc. of 14th ICA Beijing*, pp. Paper F3–5, 1992.

[14] Wenmaekers et al., "On measurements of stage acoustic parameters: Time interval limits and various source–receiver distances," *Acta Acustica united with Acustica*, vol. 98, pp. 776–789, 2012.

[15] F. Brinkmann et al., "A round robin on room acoustical simulation and auralization," *J. Acoust. Soc. Am*, vol. 145(4), p. 2746–2760, 2019.

[16] S. Siltanen et al., "Geometry reduction in room acoustics modeling," *cta Acust. united Acust.*, vol. 94(3), p. 410–418, 2008.

[17] Odeon, "Odeon user's manual," 2020.

[18] "Ease user's manual." AFMG, 2010.

[19] "Ramsete database." Genesis, 2002.

[20] "DIN 18041." European Standard, 2016.

[21] C. Harris, *Handbook of Acoustical Measurements and Noise Control.* McGraw Hill, 1991.

[22] "Ease datenbank." AFMG, 2010.

[23] M. Vorländer et al., "Computer simulations in room acoustics: Concepts and uncertainties," *JASA*, vol. 133, p. 1203–1213, 2013.

[24] "Sächsisches Denkmalschutzgesetz." Saxon Monument Protection Act, 1993.

[25] A. Struiksma, M. Tenpierik, A. Snijder, F. Veer, B. Botterman, M. Hornikx, H. Van der Water, and F. Migchielsen, "Sound absorbing glass: Transparent solution for poor acoustics of monumental spaces," *SPOOL*, vol. 4(2), 2017.

[26] Magne Skalevik, "Small room acoustics – the hard case." Forum Acusticum, 2011.

[27] M. Barron, "Bass sound in concert auditoria," *J. Acoust. Soc. Am*, vol. 97(2), p. 1088–1098, 1995.