ACOUSTICAL ANALYSIS OF A MULTIPURPOSE HALL BY COMPUTER SIMULATION METHOD: METU NORTHERN CYPRUS CAMPUS AUDITORIUM (NCCA) AS A CASE STUDY

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

BY

TANSU YILMAZ

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

FEBRUARY 2005

Approval of the Graduate School of Natural and Applied Sciences

Prof. Dr. Canan Özgen
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Assoc.Prof. Dr. Selahattin Önür
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Assist. Prof. Dr. Arzu G. Sorguç
Supervisor

Examining Committee Members:

Prof. Dr. Can Baykan (METU,ARCH) ____________________

Assist. Prof. Dr. Arzu Gönenç Sorguç (METU,ARCH) ____________________

Instr.Dr. Ayşe Tavukçuoğlu (METU,ARCH) ____________________

Instr.İlhan Selim Kural (METU,ARCH) ____________________

Instr.Dr. Semiha Yılmazer (BİLKENT) ____________________

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Tansu Yılmaz

Signature:

ABSTRACT

ACOUSTICAL ANALYSIS OF A MULTIPURPOSE HALL BY COMPUTER SIMULATION METHOD: METU NORTHERN CYPRUS CAMPUS AUDITORIUM (NCCA) AS A CASE STUDY

Yılmaz, Tansu

M.S. in Building Science, Architecture
Supervisor: Assist. Prof. Dr. Arzu Gönenç Sorguç

February 2005, 138 Pages

In this study, impulse response of a multipurpose hall, namely METU Northern Cyprus Campus Auditorium (NCCA) is analyzed and the acoustical quality of the auditorium is evaluated. Suggestions to increase the acoustical satisfaction has been made and to overcome the probability of bass-rise caused by the noise of HVAC systems, a proposal has been made to control low frequency sounds by introducing the volume resonators for the specified frequency. For the study, Odeon, which is used effectively in computer based acoustical simulation studies, is used for the analysis part. In the analysis, a 3D drawing of the hall has been produced by the help of the exact dimensions derived from the original submission of the project by the permission of the authorities.

Keywords: Acoustics, Auditoria, Resonators, Low Frequency Sound Control, Computer simulation methods.

ÖZ

BİLGİSAYAR DESTEKLİ BENZEŞİM YÖNTEMİYLE ÇOK AMAÇLI BİR SALONUN AKUSTİK ANALİZİ: ODTÜ KUZEY KIBRIS KAMPÜSÜ AMFİSİ

Yılmaz, Tansu

Yüksek Lisans, Yapı Bilgisi Ana Bilim Dalı, Mimarlık Bölümü
Tez Yöneticisi: Yrd. Doç. Dr. Arzu Gönenç Sorguç

Şubat 2005, 138 Sayfa

Bu çalışmada, çok amaçlı olarak tasarlanan ODTÜ Kuzey Kıbrıs Kampüsü Dörtlü Amfi Salonu'nun akustik davranışı çalışıldı ve salonun akustik kalitesi değerlendirildi. Akustik memnuniyeti arttıracak öneriler geliştirildi ve mekanik sistemlerden kaynaklanacak gürültü nedeniyle oluşabilecek bas seslerdeki artış olasılığını ortadan kaldırmak amacıyla, seçilen düşük frekans için tasarlanan hacim rezonatörlerinin kullanımıyla bas seslerin denetimi amaçlı bir öneri sunuldu. Çalışmanın analiz kısmı için bilgisayar destekli akustik benzeşim çalışmalarında çok etkin bir biçimde kullanılan Odeon bilgisayar yazılımı kullanıldı. 3 boyutlu modelin oluşturulabilmesi için gerekli izinler alınarak salonun gerçek ölçülerinin yer aldığı özgün projeden faydalanıldı.

Anahtar Kelimeler: Akustik, Oditoryum, Rezonatör, Düşük Frekanslı Ses Kontrolü, Bilgisayar destekli benzeşim.

To My Supervisor

ACKNOWLEDGEMENTS

I am deeply grateful to my supervisor, Assist. Prof. Dr. Arzu Gönenç Sorguç, for her guidance, advice, criticism, strong encouragement and support throughout the duration of this thesis.

I would like to thank Prof. Dr. Mehmet Çalışkan for his suggestions and comments, and for providing the acoustical simulation software, Odeon, to be used for the analysis part.

I would also like to thank Instr. İlhan Selim Kural, for his architectural knowledge and advice that he shared.

I wish to express my gratitude to my family, who were with me from the beginning to the end. I also wish to express my love to my grandmother, who is, I know, watching me.

I also wish to express my gratitude to Prof. Hagiwara and the students of Mechanical Engineering Department of Tokyo Institute of Technology for their support and friendship.

The author wants to send his special thanks to other attending jury members, Prof.Dr. Can Baykan, Instr. Dr. Vuslat Demirçay, Instr. Ayşe Tavukçuoğlu and Instr. Dr. Semiha Yılmazer for their criticism and advice in the evaluation of the study, and also thanks to Instr. Türel Saranlı for his guidance and comments.

The author also wants to send his special thanks to people who had contribution in this study by all means.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1. General

Acoustics which can be described as the study of the phenomenon of sound is an interdisciplinary science providing many valuable tools for engineering, medicine, oceanography, communication and many more and also creating pleasant living spaces by controlling noise and/or by serving to design acoustically proper environments for architects and engineers. In the case of architectural acoustics, it is certain that good acoustics will be achieved as long as an architect has an understanding of principles of acoustics and how to apply them to the design process.

It is a known fact that achieving and evaluating acoustical quality in concert halls, opera houses, theatres and auditoriums is rather difficult. Acoustics is both an objective and subjective phenomenon, and consist of several qualitative and quantitative parameters necessary to be understood. Barron (1993) describes the objective parameters as; reverberation time, early decay time, early-to-late sound index, early lateral energy fraction and total sound level. Fullness of tone, definition of clarity, fullness and definition, intimacy, timbre, tone color and brilliance are stated as subjective parameters by Beranek (1998). All these parameters are involved in the nature of acoustics to establish the most pleasant performances in halls and auditoriums. Designing to achieve 'good acoustics' always requires a deep understanding of acoustic parameters and their relations with geometry and material configurations, which are important issues to be concerned in the very beginning of the design process.

1.2. Scope and Objective

The objective of the thesis is to present guidance for acoustical design of multi-purpose halls by clearly discussing the objective and subjective parameters that should be achieved in the design process. In accordance with these discussions, the impulsive response of the METU Northern Cyprus Campus Auditorium (NCCA) where acoustical design is carried out simultaneously with the architectural design is extensively analyzed, to evaluate the acoustical quality of the hall.

During the analysis process, highly recognized design and acoustical simulation software Odeon is employed. The results about the acoustical satisfaction of the hall are discussed and a methodology to enhance the acoustical response of the hall by using an array resonator without modifying the hall configuration and the overall response is proposed. It has been decided to present the overall thesis study in seven chapters as:

In the first chapter, an introduction to acoustics is made, and the scope and objective of the study is explained.

In the second chapter, an overall literature survey is carried out. The developments and researches made in the history of acoustics are reviewed. A short summary on the general concepts of acoustics is presented in this chapter by the help of definitions and the relations between these concepts are explained.

In the third chapter, the architectural, structural and acoustical information about METU Northern Cyprus Campus Auditorium is given. Size, volume, shape and other design features of the hall is presented and their correlations with the acoustical parameters are underlined during the design process of the hall.

Chapter four is mainly about the analysis methods and their usage in retrieving the data about the hall to be interested in. In the first phase, computer simulation methods are described and the Odeon Acoustics Software, which is used in the analysis of the auditorium, is underlined. In the second phase, the modeling process is described and the acoustical inputs for the evaluation of the hall are explained.

In chapter five, the 3D model of the auditorium is analyzed with the help of Odeon Acoustics Software. The analysis is carried out for the two modes of the hall, namely, auditorium mode and concert mode. Then regarding the results of analysis, the acoustical quality of the hall is discussed.

In the sixth chapter, an enhancement system by using an array of Helmholtz resonators is introduced to increase the acoustical quality of the auditorium in a specific frequency without modifying/changing the hall configuration and the overall acoustical response. The results and the efficiency of the proposed method are then discussed.

In the last chapter of the study, conclusions are presented for the concert and auditorium mode of the hall. The simulation results are compared with the objective and subjective determining parameters of 'good' acoustics in literature. The effect of the resonator array in the specified frequency of the hall in auditorium mode is discussed and further research topics are stated for the continuation of the study.

CHAPTER 2

THE LITERATURE SURVEY

2.1. Sound and Auditorium Acoustics

2.1.1 Introduction

Design of auditoriums, which compromises advanced structural and acoustical solutions supporting the form, has always been a challenging problem for architects and engineers. The phenomenon of sound and its propagation in indoor and outdoor spaces have been studied since ages. The Roman amphitheatres, the Gothic and Baroque churches, the opera houses and the halls for symphonic music are some examples of spaces for which acoustics contributes the architectural design, and among them there are halls recognized by their acoustical qualities. But, since Sabine's reverberation theory, acoustics becomes a field and a concrete theory, and parameters evaluating acoustics are introduced.

Today, with the introduction of computational technologies and simulation methods, acoustics coupled to the pre-design process resulting in high quality halls. And with the researches and developments that carried out, many acoustically satisfactory halls seem to be constructed in the following years.

2.1.2 Acoustics of Concert Auditoria

Beranek (1992) states that the modern age of concert hall acoustics established with the development of the empirical reverberation equation proposed by Wallace C. Sabine in 1895. Until World War II, very few remarkable developments were made in designing of halls. After World War II, the development of broadcasting studios, the evaluation methods of halls with computer systems and the production of many acoustical materials reflected to the field of acoustics, and with the help of various researches, many acoustically satisfactory halls were constructed.

In the historical progress of hall design, it is observed that there are basically four hall types categorized according to their floor plans, namely; the classical rectangular hall; the shoebox hall; the fan-shape hall; the reverse fan-shape hall and the arena type hall, which support large audience capacities with vineyard seat plans composed of elevated and segmented plans for seats surrounding the stage to allow the optimization of distance between audience and stage. (Figure 1) These plans are directly related with the performance taken place in these enclosed spaces and the social and cultural involvement of public to these performances. Today, in addition to these plan types, curvilinear forms are also observed with their successful acoustical design provided by simulation techniques.

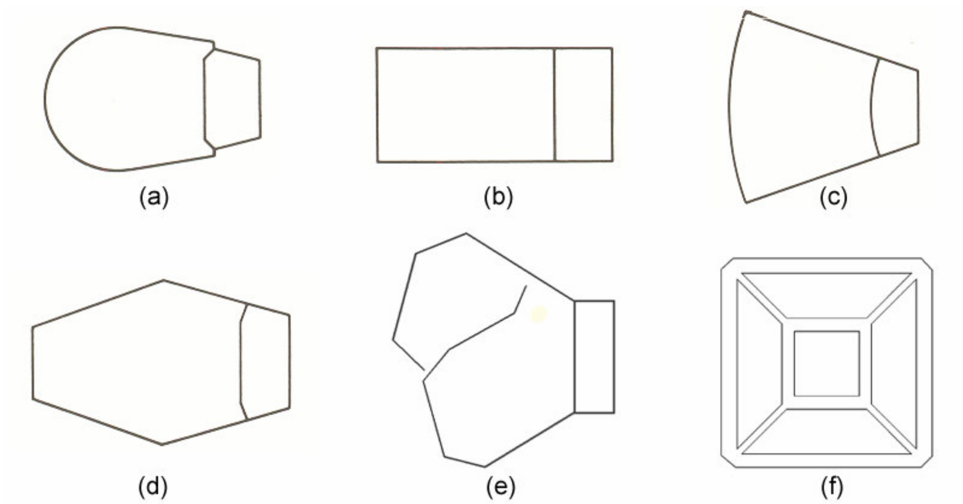


Figure 1: Simple plan forms for concert halls; a) shoebox b) rectangular c) fan-shaped d) reverse fan-shaped e) vineyard f) arena.

In the early 1900's, shoebox type rectangular halls were very popular among the designers for architectural and acoustical purposes. With the help of its shoe like floor plan, it was possible to create a uniform distribution of sound energy among the audience. Besides, they were generally constructed with high ceiling heights and as a narrow and longer rectangular floor plan. In addition of enhancing objective parameters of acoustics, the subjective concepts were also satisfactory because of this geometry. However, as they were designed as narrower and longer, it was quite difficult to provide for all the listeners to be close to the stage, and that was creating sightline problems and poor conditions for the listeners, who were attending the performance from the rear seats. Usher Hall (1914), designed by Stockdale Harrison & Sons and H.H. Thompson, is a representative of a shoebox hall type giving a common opinion about hall types in the early 1900's (Figure 2).

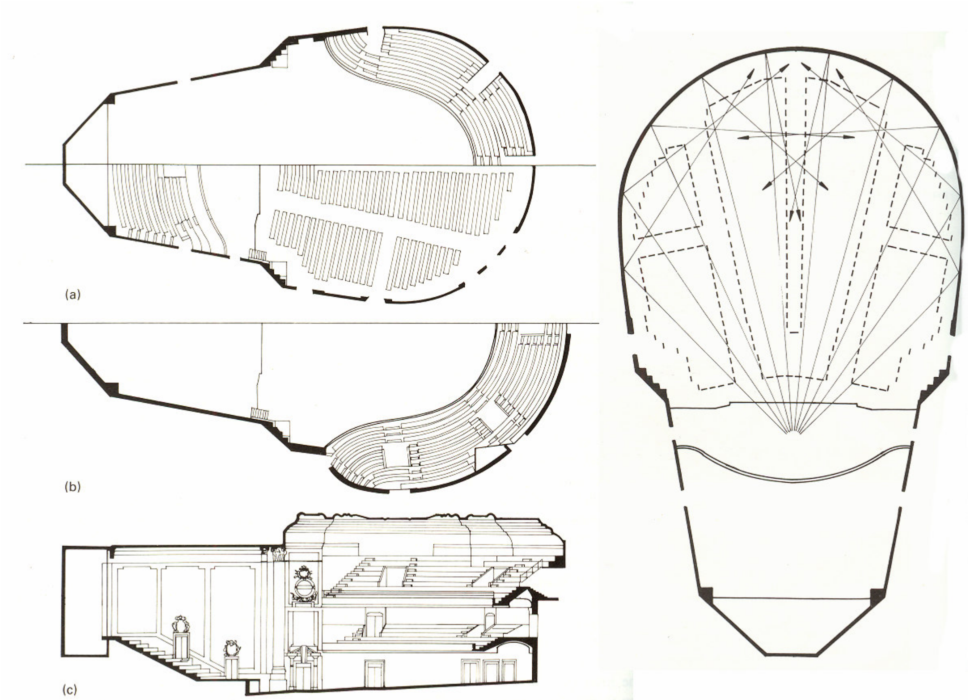


Figure 2: Plans of Usher Hall (1914) which has a shoebox hall type:

a) plan of the hall b) balcony plan c) section

d) sound paths for reflections from the curved wall (Barron, 1993).

The rectangular hall type was also popular during that period, and that was mainly because of a satisfactory acoustical performance of the rectangle geometry, which was very convenient for creating the diffuse field of sound. The lateral reflections are better in a rectangular hall as the sidewalls are perpendicular to the stage and the sound can be reflected more efficiently. On the other hand, due to depth of these halls and parallel walls, echo and low sound pressure level distribution at rear parts of these halls are potential problems that should be solved by proper arrangement of absorptive-reflective surface configurations and design of overhead reflectors and side diffusers. Besides, many ornaments were used on the reflecting surfaces of the halls not only to overcome these problems, but also to increase diffusion. Yet, rectangular halls are still preferred today with their potential for multipurpose use for small and medium size performances. Boston Symphony Hall (1900), designed by McKim, Mead and White, can be given as an example for classical rectangular halls (Fig 3).

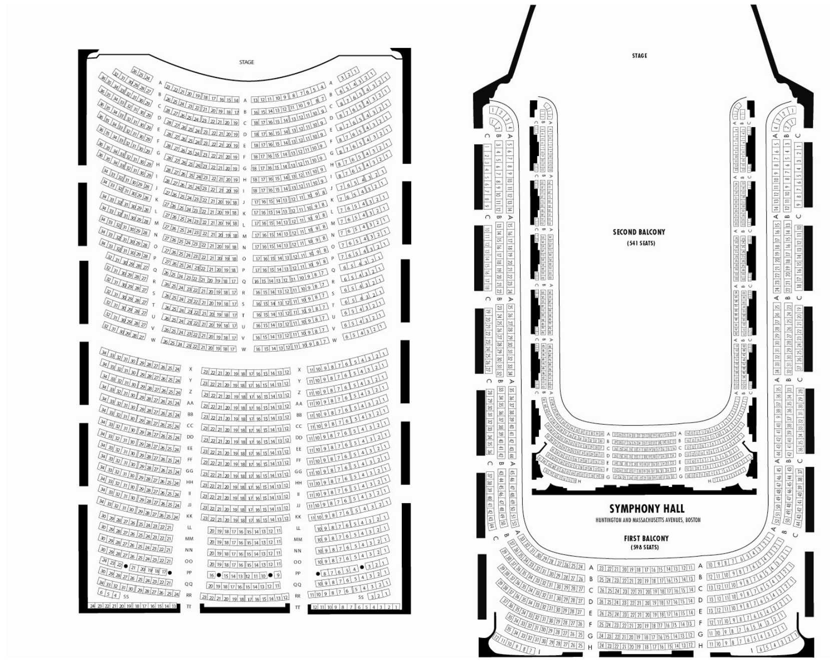


Figure 3: Seating plan of Boston Symphony Hall (1900); as a classical rectangular hall, first floor plan (left), second floor plan (right)[37]

The fan-shape type halls, which were common in the mid 20th century, were geometrically convenient for creating better sightlines. Because of its inclined sidewalls, it was less desirable with respect to the rectangular hall plan for providing better lateral reflections, but since the listeners were close to the stage enclosure, the ceiling and rear wall reflections were much more effective. Today, in many open-air theatres and small-scale hall types, fan-shape plans can be observed. Alvar Aalto, the Finnish architect, designed one of the famous examples, Finlandia Hall in 1971, as a fan-shape plan (Figure 4). To be able to reflect sound better in the hall, the architect used diffuser panels on the surface of the sidewalls for better reflection, diffusion and uniform distribution of sound.

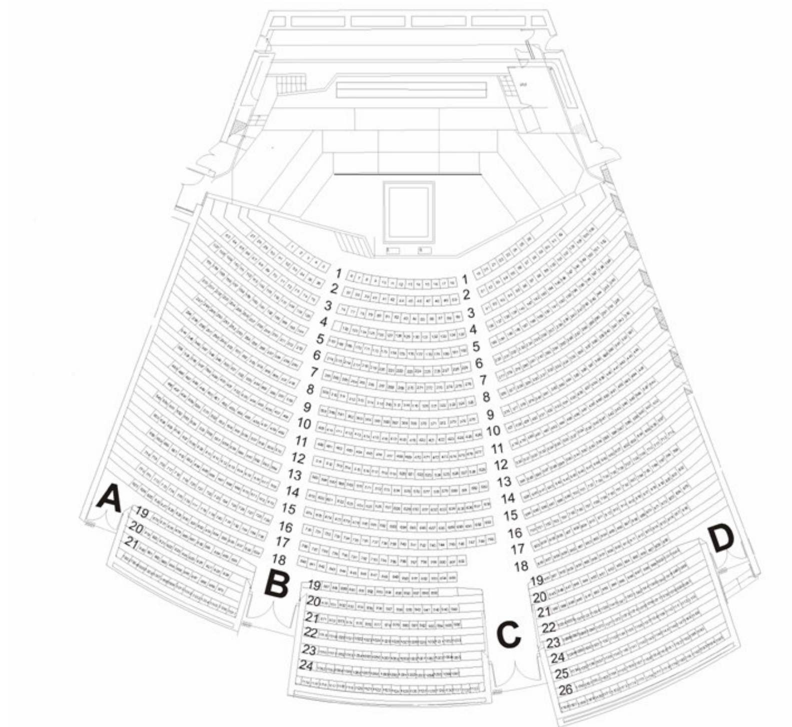


Figure 4: The seating plan of Finlandia Hall, designed by the famous architect, Alvar Aalto, in 1971.

The reverse fan-shape type is similar to the fan-shape hall design, in terms of sightline principle, but differs at the sidewalls which are inclined as getting narrower through the back seats of the hall. This is designed to prevent long delayed reflections and to provide better lateral reflections. Tokyo Metropolitan Festival Hall (1961), designed by Nikken Sekkei Ltd., can be given as an example for the reverse fan-shape type of halls (Figure 5).

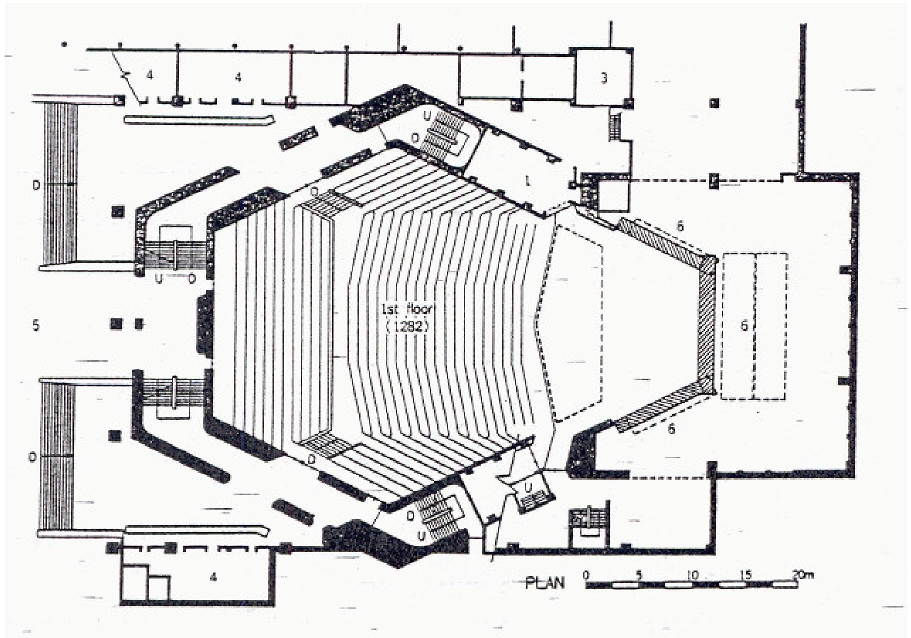


Figure 5: Plan of Tokyo Metropolitan Festival Hall (1961) designed as reverse fan-shape (Talaske, Wetherill and Cavanaugh, 1982).

Another floor plan, which is considered to be suitable for large audience capacity with reasonable eyesight levels and acoustics, is the arena type, where the stage is surrounded by audience area. The arena-type of halls are mostly designed in vineyard form by introducing different seating planes for very large audiences. Berlin Philharmonie Hall (1963), designed by the architect Hans Scharoun and by Lother Cremer as the acoustician, is a good example for arena type halls. (Figure 6) It is also a good example for a vineyard type hall plan, where stalls in the hall are elevated and segmented through the stage. The Suntory Hall (1986) in Japan, designed by Yasuhisa Toyota, also has a vineyard type hall plan which provides successful diffusion of sound (Figure 7).

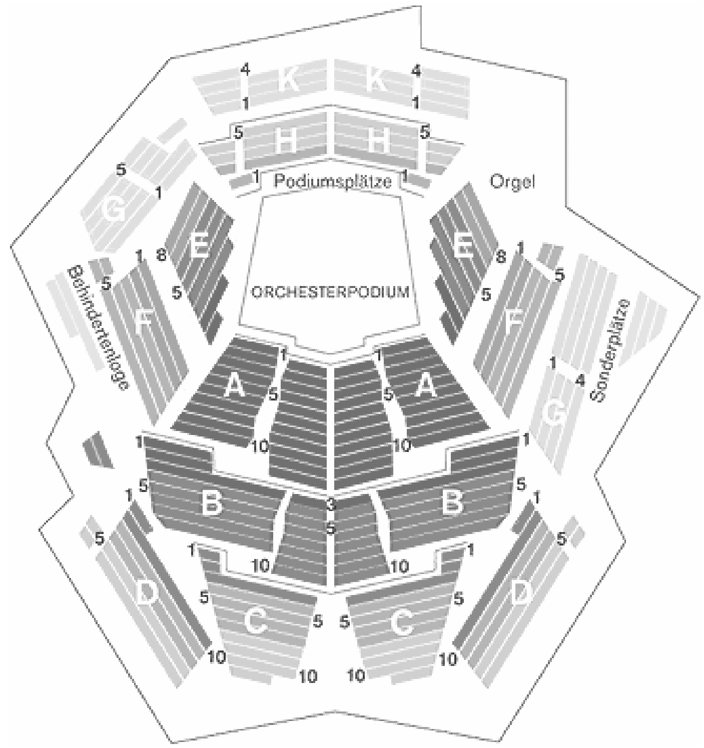


Figure 6: The seating plan of Berlin Philharmonie Hall opened in 1963.

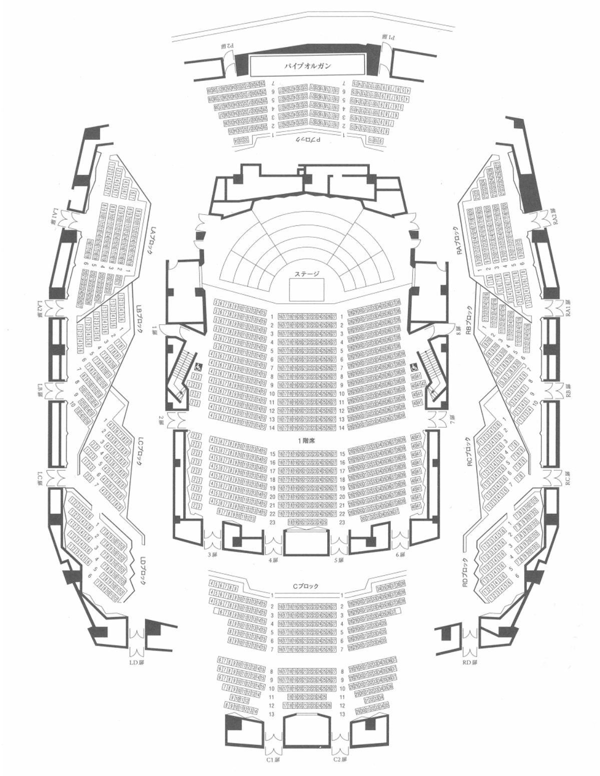


Figure 7: The seating plan of Suntory Hall in Japan opened in 1986.

Until the pioneering work of Wallace Clement Sabine, starting about 1895, criteria for good listening conditions in halls were largely nonexistent (Egan, 1971). At that time, it was hardly recognized that it would stay as an important parameter of today's concert hall design. Schroeder in 1965, and Kawakami and Yamaguchi in 1981, also enlarged the studies about reverberation time by introducing new calculation procedures. Today, many advanced techniques are used to calculate the reverberation times of the performance halls, either by computer programs including simulation softwares, or by scale modeling of the halls made in different sizes.

Beside those four classical hall plans, curvilinear forms, which are aroused from the developments of acoustical analysis techniques as well as construction technologies, are also observed in auditorium designs. As it is discussed above, each hall form has some advantages and disadvantages and together with the activities performed in these halls, deciding the form of the hall is a complex issue. Here, it should be noted that, no matter which hall form is chosen, the following acoustical criteria should be satisfied in the designs; (1) acceptable reverberation time; (2) adequate loudness; (3) a short initial time delay gap between the direct sound and the first reflection reaching a listener; (4) a number of early lateral reflections that immediately follow the first reflection-these contribute to the feeling of "spaciousness"; (5) a diffuse sound field created by an adequate number of reflections from all angles plus irregularities and ornamentation to eliminate acoustical "glare"; (6)the ratio of energy in the first 80ms to that in the next 2s; and (7)warmth of the sound by properly shaping the reverberation-time curve at low frequencies"(Beranek,1992).

In case of all these acoustical criteria, it has always been important to be in acceptable ranges, because they are extremely important in providing the acoustical satisfaction of the listeners. Beranek(1992) underlines two measures of reverberation time as EDT, early decay time, defined as six times the time period during which the first 10dB of sound decay occurs, and RT, the extended reverberation time, equal to double the time period during which the sound has a decrease from –5 to –35. Unlike Sabine's reverberation time equation, which assumes that sound waves in the medium are incident on the various absorbing surfaces, Eyring (1933) and some other acousticians derived an alternative equation of reverberation time equation where it is assumed that the absorbing materials are uniformly distributed and these waves are incident on them at the same instant. Although this assessment is acceptable, Cremer and Muller(1982) found "The Sabine Equation" more encouraging and accurate in calculating the reverberation time of the hall. Kutruff(1973) also suggested the same equation, too.

In the period between 1920 and 1950, only three acousticians were prominent; Paul E. Sabine, F.R.Watson and Vern O. Knudsen. Sabine stated the designer's problems in achieving good acoustics in concert halls as high reverberation time values and preventing the noise of HVAC systems whereas Watson focused on the successful conditions of auditorium acoustics.

Other than the reverberation time case, the importance of diffuse reverberant field was already known before 1958's, however; there were still difficulties in measuring and evaluating this parameter, which requires perfect modeling of the field. In most cases, 3D molded plasters, carved wood ornamentations, coffered ceilings and niches were used to create necessary sound diffusion. There was also another fact which was known since 18th century, the use of overhead sound reflecting surfaces, which is an important improvement for the acoustics of lecture halls and auditoriums. As Beranek(1992) states, some of the earliest examples for overhead sound reflectors can be found in London's Royal Albert Hall(1871), Munich's Hercules Hall(1953), the Kresge Auditorium in Cambridge(1955) and the Aula Magna in Caracas(1954).

With the continuing studies on improving lateral reflections of the auditoriums, Meyer and Kuhl(1952) made experiments by placing large reflectors on both sides of a proscenium stage Marshall(1979) found out that the existence of the lateral reflections creates a sense of envelopment, which is also called as spatial impression based on the sound level. Beranek used the term “lateral reflections” as all the reflections that lie between $\pm 20°$ and $\pm 90°$ angle from an imaginary vertical plane between the source and the listener. Barron and Marshall also concluded that these early lateral reflections are highly essential for creating the spatial impression between the frequencies of 125Hz and 1000Hz; and the overhead reflectors on the ceiling do not mask these reflections.

The first studies on audience (seating) absorption started after the measurements of Sabine, then Beranek made an important contribution by finding out that the absorbing power of a seated audience or orchestra increases in proportion to the floor area they occupy. Sabine suggested a total absorption per person at 500Hz of 0.44m2 and Beranek, concerning modern concert halls, proposed an absorption value of 0.57m2 at 500Hz per person. Meyer also made experiments on determining the absorbing coefficients of various materials used in the design of concert halls and auditoriums.

In the post-World War II period, Beranek, who established a large survey based on subjective rankings, introduced another important parameter. After the evaluation, Beranek found out that these rankings are well correlated with the width of the halls, which mainly depend on the difference in arrival times between the direct sound from the orchestra and the first reflections, generally from the side wall or balcony faces. He named this time difference as Initial Time Delay Gap (ITDG), which is recognized as one of the seven evaluation criteria of musical acoustical quality in concert halls (Beranek, 1992). He also discovered that a short initial time delay gap would result a high spatial impression.

2.1.3 Speech and Music Sounds

In understanding the acoustics, it is important to know that a sound field either in indoor or outdoor space results from sound source- its propagation and its perception by the receiver.

In outdoors, sound energy is absorbed by air, since there is no reflecting or absorptive surface that will change the sound distribution path and with a simple nondirective source, the sound intensity will fall off the distance from the source is increased. The sound wave moving outward from the source spreads its energy over an ever-increasing spherical area. This commonly observed decay of sound level with distance in a "free field" acoustical environment follows the so called inverse square law, where for simple point sources, it is the falloff rate of 6dB per doubling of distance from the source (Cavanaugh & Wilkes, 1999).

In indoors, however, sound intensity will fall off with distance only very near the source. As one continues to move away from the source, the reflected sound from the floor, walls, and ceiling of the room begins to overwhelm the direct sound component that continues to be emitted from the source. Within the reflected or so-called reverberant sound field, the sound level remains generally constant throughout the room no matter how far away from the source a listener is located (Cavanaugh & Wilkes, 1999).

When sound is generated in a room, the initial sound paths from source to room surfaces are considered the near and direct fields. The near field is closest to the source, and its extent depends on the size and radiation characteristics of the source. Within distances comparable to the dimensions of the source, the sound level may decrease, be constant or even increase with distance. Prediction of sound levels within the near field requires detailed information on source radiation characteristics (Templeton, 1987).

The direct field is between the limits of the near field and room surfaces. Since no reflection has taken place yet, the sound behaves as if in open space, decreasing at a rate of 6dB per doubling distance. Once the sound has undergone a number of reflections, it becomes more evenly distributed throughout the enclosure. This is considered as the reverberant field, and if the reflections are evenly distributed, a diffuse sound field. The interaction between the near, direct and reverberant fields is shown in Figure 8, for rooms with varying amounts of acoustical absorption.

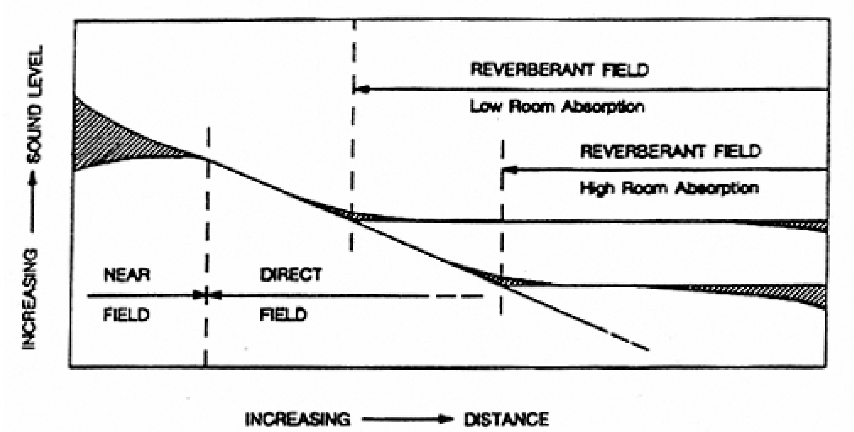


Figure 8: The interaction between the near, direct and reverberant fields (Irvine & Richards, 1998).

The near and direct fields are unaffected by room absorption, but the level of the reverberant field is inversely proportional to the absorption. In a highly reverberant room, therefore, the space where the direct field is predominant is small compared to a room with high absorption and less reverberation. In very large rooms with high absorption, the reverberant field will not be uniform, but will diminish with distance from the source (Templeton, 1987).

Thus, in this section, the basic concepts are introduced related with sound indoors both for speech and music, since the acoustical performances related with sound take place in enclosed spaces.

Sound is an alteration in pressure, a particle displacement in an elastic medium like air. And physiologically speaking, sound is an auditory sensation produced by those pressure alterations Sound travels from the vibrating body to the receiver as a disturbance through the medium between them, in fact it is the transmission of energy from one place to another in the form of longitudinal waves which is usually referred to as sound. In air, at normal temperatures, the speed of sound is approximately 344m/s. A sound source is described by its frequency, its wavelength and with its waveform. A simple formulation can be given as:

$$\text{Speed of Sound (C)} = \text{Frequency (f)} \times \text{Wavelength} (\lambda) \quad [1]$$

“The number of cycles that the air particles move back and forth in one second in a sound wave is called the *frequency* of the wave. Its unit is *cycles* in per second (c/s), which is also termed *Hertz (Hz)* after the Austrian physicist Heinrich Hertz (1857-94). Frequency of sound is an important acoustical concept since the properties of building materials and construction assemblies vary with the frequency of sound. Additionally, the behavior of sound in an enclosure is also dependent on its frequency (Mehta, Johnson & Rocafort 1999)”.

“The attribute of any auditory sensation which enables us to order sounds on a scale extending from low to high frequency is called *pitch*. It is the subjective physiological equivalent of frequency. The pitch depends primarily upon the frequency of the sound stimulus: the higher the frequency, the higher the pitch will be (Doelle 1972)." The frequency and intensity of sound, which are purely physical characteristics, produce the corresponding psychological sensations of pitch and loudness. High pitched sounds, such as whistles, squeaks, or treble notes of a voice or musical instrument, are high frequency sounds, and low pitched sounds, which we describe as rumbles, roars, or bass notes, are characterized by low frequencies.

There is another physical phenomenon related with frequency, called as *resonance*, by which a material object vibrates at an amplified level when exposed to a specific frequency of sound energy. Such a vibrating object produces a sound of definite pitch. Actually, the object vibrates at one of its resonant frequencies. The closer the frequency of the exciting noise to a resonant frequency of the object, the greater will be the response of the resonant vibration. Room resonance, on the other hand, occurs with the generation of standing waves in a room at specific frequencies associated with the dimensions of the room.

The wavelength is the distance between adjacent pressure maxima (or minima). (Figure 9)

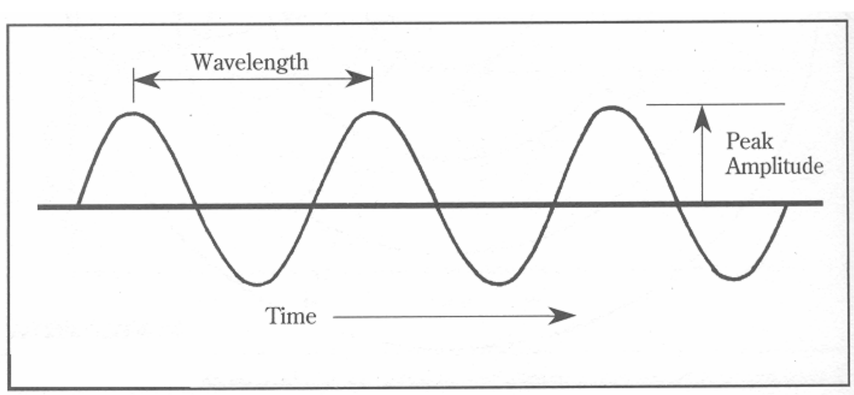


Figure 9: Wavelength is the distance a wave travels in the time it takes to complete one cycle. (Everest, 2000)

The wavelength for a sound in the middle of the frequency range of 1000 Hz is thus 0.343m. The range of wavelength of audible sounds is between 17m at 20 Hz and 17mm at 20 kHz. (Table 1) This implies that these wavelengths are comparable to dimensions of room surfaces and common objects (Barron 1993).

Table 1 Relationship between frequency and wavelength over the audible range. (Cowan 2000)

Frequency (Hz)	Wavelength
20	17m
50	7m
100	3m
500	0,7m
1000	0,3m
5000	0,07m
10000	0,03m
20000	0,02m

There exists a tendency of low frequency sounds which have high wavelengths to bend around objects, whereas, at high frequencies the sound waves behave such as light by creating shadow zones on its traveling route.

Another important concept in identifying the properties of sound source in relation with its propagation is the sound intensity, which can be defined as the sound energy per unit area. Intensity and loudness are directly proportional. The greater the intensity, the louder is the sound. At seating locations in an auditorium close to the stage, the intensity of sound is greater, by giving the sense of a louder sound, whereas at rear parts the sound is perceived as faint because of the increased distance from the sound source. In a free field, sound intensity can be defined as; (which is also known as *inverse square law*)

$$\text{Sound intensity} = \text{Sound power} / 4\pi(\text{the distance from sound source})^2 \qquad [2]$$

Another important characteristic is the directivity of the sound source, which depends on the frequency. The high-frequency speech sounds is more pronounced along the longitudinal axis of the sound source, while the distribution of the medium and low frequencies is more uniform in all directions. This can be observed particularly in excessively wide auditoriums where the high frequency components of speech are not as efficiently radiated to the side seats of the front rows as to the center seats, resulting in a noticeable loss of intelligibility at these side seats. This creates serious problems in the design of open stage or arena type theatres where a performer can face only one section of the audience at a time.

The human ear can detect the frequencies between 20Hz to 20,000 Hz. Since the frequency range is so large, it is impossible to deal with all individual frequencies. So, these frequencies are divided into *octave bands (or octaves)*, which is a band of frequencies whose upper limit is twice the lower one. (Figure 10) Frequencies below 20Hz are known as infrasonic. These frequencies, although not audible to most people, can be felt as vibrations. This is due to the fact that our internal organs resonate at frequencies between 5Hz and 15Hz. Exposure to sounds near the resonance frequency of a material causes it to vibrate more than when exposed to other frequencies. In extreme cases, high levels of infrasound can interfere with the healthy operation of our internal organs.

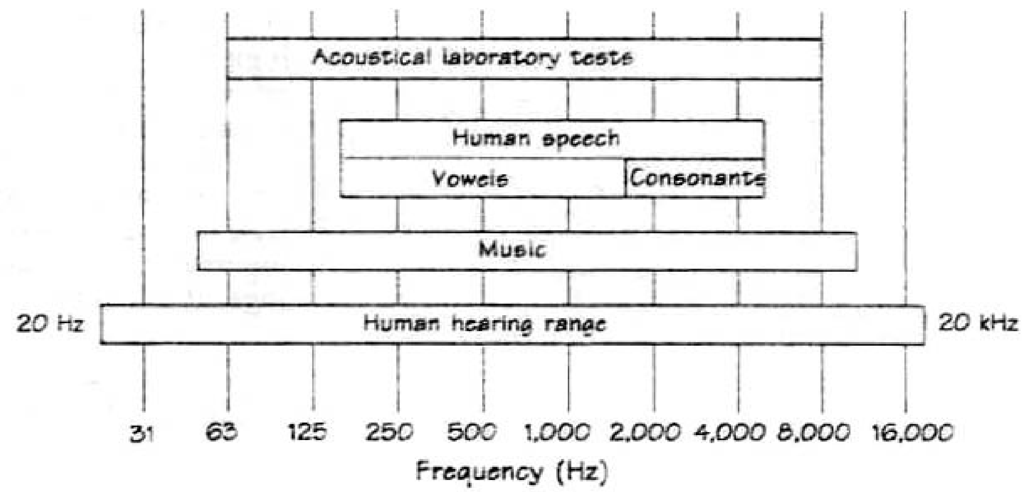


Figure 10: Octave bands and frequency ranges of acoustical laboratory tests, human speech, and music (Mehta, Johnson & Rocafort 1999).

The human ear has a range for sound pressure level (SPL), which is shown in the Figure 11. Sound pressure level (SPL) is the logarithmic representation of sound pressure measured in *decibels (dB)*.

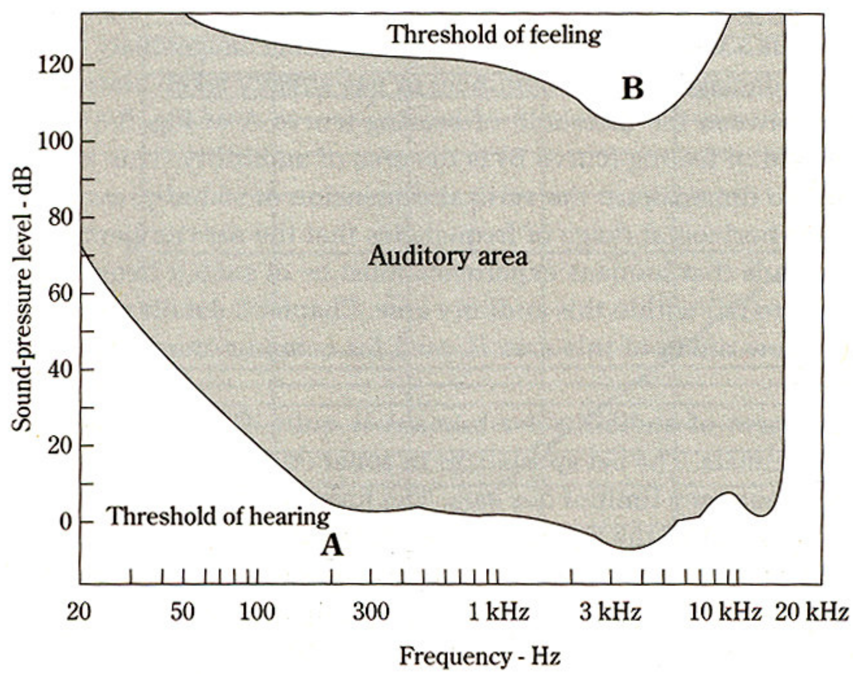


Figure 11:"The auditory area of the human ear is bounded by two threshold curves, (A) the threshold of hearing delineating the lowest level sounds the ear can detect, and (B) the threshold of feeling at the upper extreme. All of our auditory experiences occur within this area." (Everest, 2001)

In Figure 11, the total auditory range is shown for all types of sound production. However, for speech and music, the graph can be redrawn according to the portions used by speech and music, specifically. In Figure 12 and Figure13, the dynamic range of speech and music can be seen, respectively. For speech, a frequency range from 170Hz to 4000Hz is produced which has recognizable sound pressure levels of 40dB up to 80dB. In music, however, the frequency range lies in a wider portion, starting from 50Hz up to 8500Hz, between recognizable sound pressure levels of 30dB to 100dB. It is very usual that in auditoriums, frequencies close to 500Hz and 1000Hz are important in evaluating the acoustical quality of the medium, whereas in concert halls, all the frequencies between 63Hz to 8000Hz octave bands are of great concern for the musical quality. It should also be noted that dynamic range of music is much wider than speech.

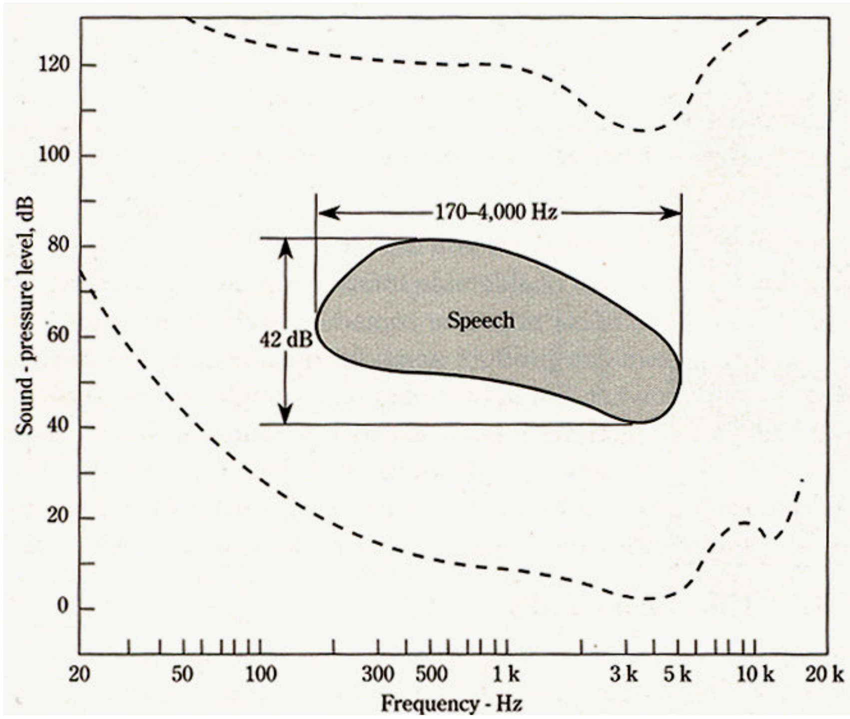


Figure 12: "The portion of the auditory region utilized for typical speech sounds." (Everest, 2000)

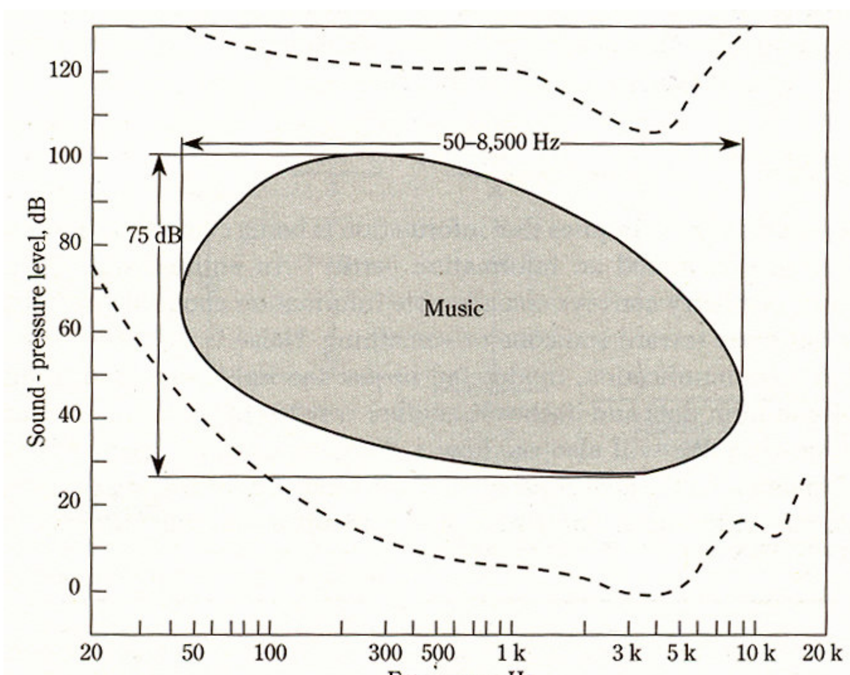


Figure 13: "The portion of the auditory region utilized for typical music sounds." (Everest, 2000)

2.2 Sound Propagation

2.2.1 Sound in Enclosed Spaces

In a hall for acoustical performances, a well-established diffuse field should be created for better distribution on sound pressure level and a homogenous acoustical response for the whole audience. When a sound wave reflects off a convex or uneven surface in an enclosed space, its energy is spread evenly rather than being limited to a discrete reflection, called as diffusion, which can be useful in an auditorium or concert facility to spread sound evenly throughout an audience and ensure that all audience members hear the same sound quality. This minimizes the potential for acoustically bad seats, at least from an acoustical standpoint (Cowan 2000). To achieve the necessary diffuseness, ornaments and some diffuser materials can be used on sidewalls, ceilings and rear walls. If necessary diffuseness in a hall cannot be provided, acoustical defects like echoes and sound concentration may be observed. Besides, in a diffuse field, the reflection of low frequencies and high frequencies from a finite size reflector is different. As in the case of suspended reflectors, high frequency sounds will tend to behave like light, by creating sound shadow zones along the propagation path. However, low frequency sounds, which have higher wavelengths as compared to the high frequencies, will tend to bend around the object, by causing diffraction where the wave fronts will recombine again. Generally speaking, diffraction is a low frequency phenomenon where the size of the reflector is small as compared to the wavelength of the low frequency sound.

In the existence of a non-diffuse field in an enclosed space, several acoustical defects can be observed. There are mainly four types of acoustical defects that can be observed in auditoriums and concert halls. (Figure 14) The first one is echo, which is one of the most disturbing occurrences that can be heard during an acoustical performance. In a hall, echo is created when the sound energy after the first 80msec. is highly closer to the level of direct sound, which causes a sound energy concentration in particular times and giving the sense of the sound repeats itself. Parallel materials without diffuser surfaces and with low absorption coefficients can cause echoes that are usually used on sidewalls of the halls. The rear parts of the halls are also dangerous in producing echoes if inadequate absorptive materials are used.

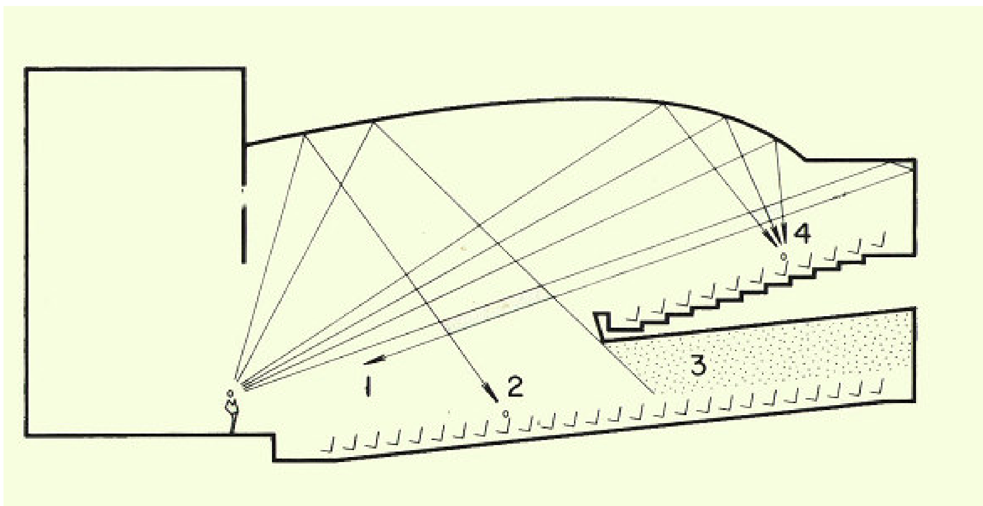


Figure 14: Acoustical defects in auditorium.
1-Echo 2-Long Delayed Reflection
3- Sound Shadow 4- Sound Concentration (Doelle, 1972)

Another occurrence that defects the acoustical quality of a hall are long delayed reflections, which are mainly because of side and ceiling reflectors that located too far as compared to the direct sound path. After the direct sound has reached to the listener's ears, it occurs when the secondary reflections from distant reflection surfaces concentrates on a specific time interval. The sound concentration, on the other hand, is a geometrical defect that it is the focusing of sound rays like concave surfaces in constant parts of the seating area. Most of the time, it is a problem of fan-shape type halls where the rear wall is concave in form. Using acoustically absorptive materials can lead to solve the problem.

The last issue, sound shadow, generally occurs under balcony type hangings due to difficulties in reflecting and diffusing. The problem can simply be solved in the design stage, by making the balcony or overhang depth shorter than the height in dimensions or at least at the same length. In concert halls, this depth can be no more than two times of the height. (Figure 15)

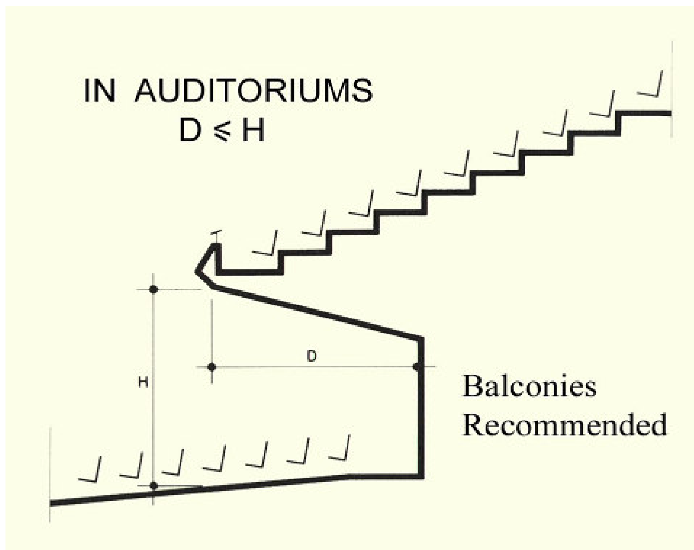


Figure 15: Balconies or overhangs recommended in the design stage of a hall to prevent sound shadows (Doelle, 1972).

The perception of sound field by the audience is subjective and in evaluating a hall, terms like clarity, intimacy, liveness, warmth, loudness, diffusion and balance are employed. Although these terms appear to be "subjective", they actually strongly related with the measurable quantities of response of the enclosed space to the source. In Table 2, music listening conditions along with room acoustic properties, which influence the corresponding subjective judgments of music performance, can be seen.

Table 2: Music listening conditions along with room acoustic properties, which influence the corresponding subjective judgments of music performance. (Egan, 1988).

SUBJECTIVE MUSIC CONDITIONS	ACOUSTICAL PROPERTIES OF ROOM
Clarity and Intimacy	1. Initial time delay gap (<20ms) 2. Shape and proportion (e.g., length-to-width ratio <2, or use suspended sound reflecting panels 3. Avoidance of deep underbalconies
Reverberance or "liveleness"	1. Volume (8,5m^3 / person for rectangular halls, 12,75m^3 / person for surround halls) to provide sufficient reverberance (1.6 to 2.4s at mid-frequencies) 2. Shape and proportion 3. Furnishings and finishes (sound reflecting walls and ceiling) 4. Audience capacity and seat spacing (<0,84m^2 / person including aisles)
Warmth	1. Relationship of absorption at low frequencies to mid frequencies (bass ratio > 1,2) 2. Thick, heavy enclosing surfaces 3. Width of room (height to width ratio > 0,7) 4. Size and shape of sound reflecting side walls 5. Coupled spaces (stagehouses, understage moats)
Loudness	1. Volume (and other reverberance properties listed above) 2. Distribution of sound absorbing finishes 3. Stage enclosure and sound reflecting surfaces at front end of room
Diffusion	1. Large scale wall and ceiling surface irregularities, quadratic residue diffusers 2. Shape and proportion (e.g., narrow widths, large height-to-width ratios) 3. Finishings and furnishings
Balance and onstage hearing	1. Size of stage enclosure (and use of risers for musicians) 2. Shape of sound reflecting panels near orchestra (stage enclosure design) 3. Distribution of sound absorbing finishes (and audience seating in surround hall) 4. Adjustability of overhead sound reflecting panels

Other subjective effects with music of a single side reflection can be seen in the Figure 16 below:

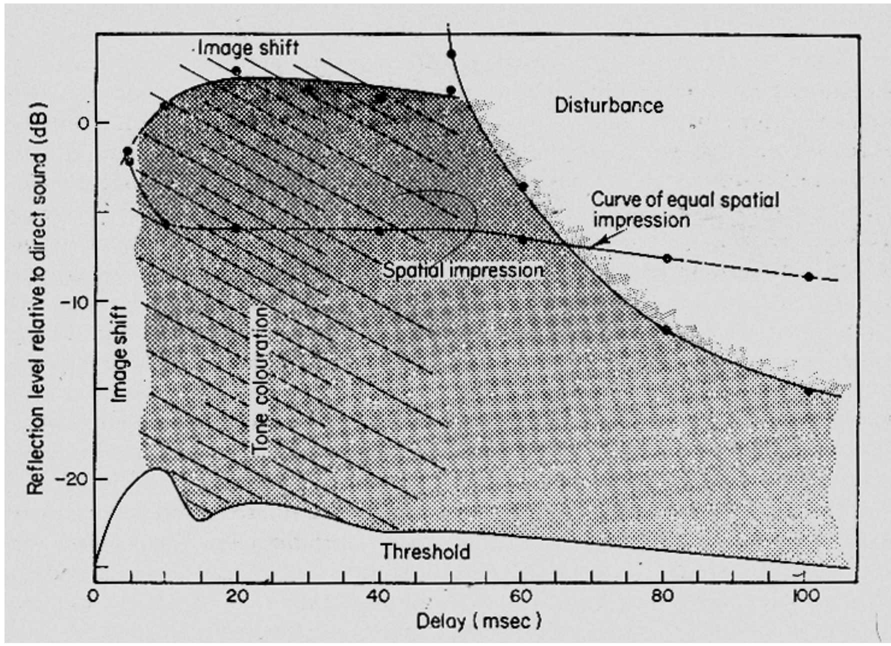


Figure 16: The subjective effects with music of a single side reflection (Barron, 1993).

From the graph, it can be concluded that late, loud reflections are perceived as disturbing echoes. Early loud reflections cause what is called "image shift", to sound appears to be coming from a direction intermediate between the direct and reflected sound directions. A lesser image shift also occurs for short delays less than about 7ms. For delays around 20ms, the tone of the music appears to be sharpen and harsher. Tone coloration is noticeable in halls with reflections from large plane surfaces; the effect is stronger for overhead reflections and constitutes one of the major reasons for avoiding suspended horizontal reflecting surfaces in concert halls. With a lateral reflection, one has the sensation that the source broadens, that one is involved in a 3D sound experience with a sense of envelopment by the sound, which is called as "spatial impression". This effect was first suggested as significant by Marshall (1967) and is now considered to be a property of the best concert halls, including the classical rectangular designs (Barron).

In a diffuse field, after the sound energy is getting in contact with the enclosure surface, it will be reflected, absorbed, diffracted, dispersed or transmitted through the medium of the enclosure or the enclosed space. (Figure 17)

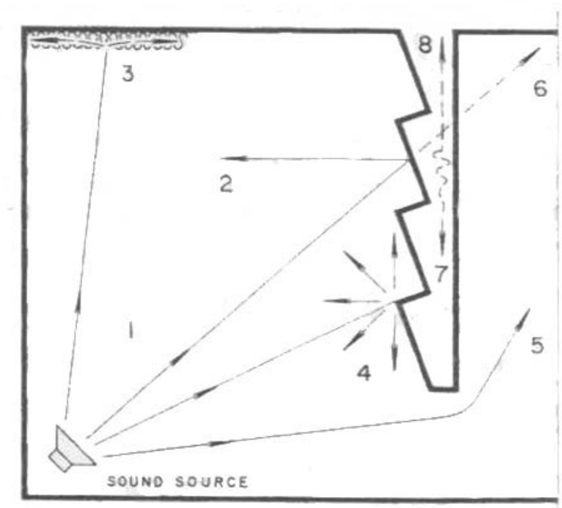


Figure 17: Behavior of sound in an enclosed space.(1) Incident or direct sound; (2) reflected sound; (3) sound absorbed by surface treatment; (4) diffused or dispersed sound; (5) diffracted or bent sound; (6) transmitted sound; (7) sound dissipated within the structure; (8) sound conducted by the structure (Doelle1972).

2.2.1.1 Sound Reflection

When the sound energy strikes on the boundary of an enclosure, some part of its energy is reflected back, whereas the remaining part is either absorbed or transmitted by the boundary element. (Figure 18) Other than reflecting from a plane surface, the sound can be reflected from convex or concave surfaces, which are also the elements of the regular geometry. A convex surface will disperse sound whereas a concave one will focus it which is not desired most of the time. A convex surface can safely be used in auditoriums and concert halls, as the reflecting material itself will diffuse sound. However, if the focal point of the concave surface is close to the audience or the performers, it is likely that the sound will be heard as an echo. Otherwise, if the extended circle of the concave surface includes neither the source nor the listeners, the behavior will be more likely to disperse sound, which will contribute to the sound diffusion.

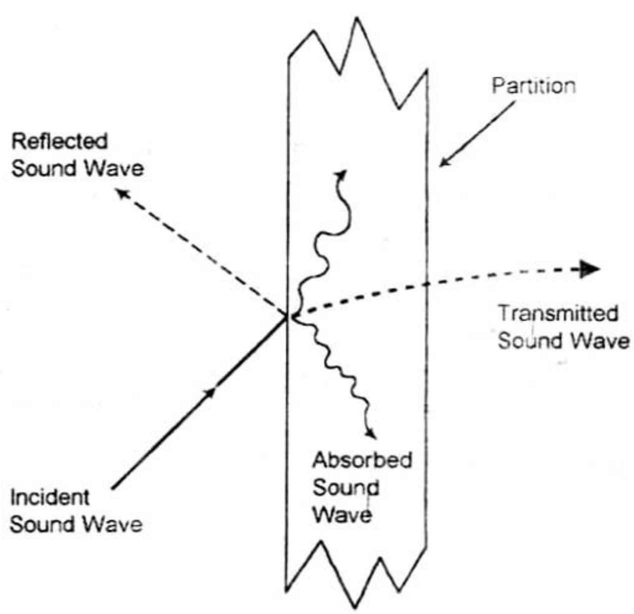


Figure 18: Reflection of a sound wave to interaction with a partition (Cowan 2000).

2.2.1.2 Sound Absorption

Doelle (1972) defined *sound absorption* as the change of sound energy into some other form of energy, usually heat, when it strikes a surface or passing through the material. However, the energy converted into heat is extremely small and the speed of sound is not affected by the absorption phenomena. What can be defined as *sound absorption coefficient* is the ratio of the amount of energy that is absorbed to the incident sound energy. If the amount of sound energy is totally absorbed by the material, the coefficient is 1, and conversely, if it is totally reflected the coefficient is taken as 0. Materials with high absorption coefficients are referred as sound absorbing (usually >0.5), and with low coefficients are referred as sound reflecting (usually <0.2). Due to the difference in coefficients, human ear also detects those differences in a distinct subjective way (Table 3).

Table 3: Subjective evaluation of absorption coefficient changes by the human ear. (Egan 1988)

Difference in Coefficient	Effect of Most Situations
< 0.10	Little (usually not noticeable)
0.10 to 0.40	Noticeable
> 0.40	Considerable

The absorption of sound can be provided with three methods; with porous materials, with panels and absorption by resonators. In porous absorption, high frequencies are absorbed more efficiently as compared to low frequencies due to its air-celled structure. In most cases, to increase the absorption effect of porous materials at low frequencies, the thickness of the material is increased, which may cause some structural and economical problems. As a more practical and effective solution, providing an air space behind the absorber will behave as a continuation of the material, which is commonly used in suspension ceiling systems of many offices.

Unperforated panel absorbers are made up of a solid panel installed over a rigid surface with an air space in between. The effective frequency at which the absorption occurs the most lies in between 50Hz up to 500Hz. These types of absorbers are absorbing the energy of the sound by damping, with the help of the fact that the panel is never fully elastic. They act like a mass-spring assembly. A mass-spring system loses energy due to the damping forces and gradually stops oscillating after the exciting force is withdrawn. And similarly, the same phenomenon occurs in the panel, and damping forces influences the panel's vibration. These forces increase as the velocity of the mass increases, and it is maximum at its resonant frequency, concluding that a panel absorber has a maximum absorption coefficient α value at its resonant frequency. In frequencies other than the resonant frequency, the α value decreases. Unperforated panel absorbers are much more efficient against low frequencies

In perforated panel absorbers, the perforation on the material acts as the neck of a Helmholtz Resonator. Each hole created by perforation acts as a series of coupled resonators with the air cavity behind the material. (Figure 19)

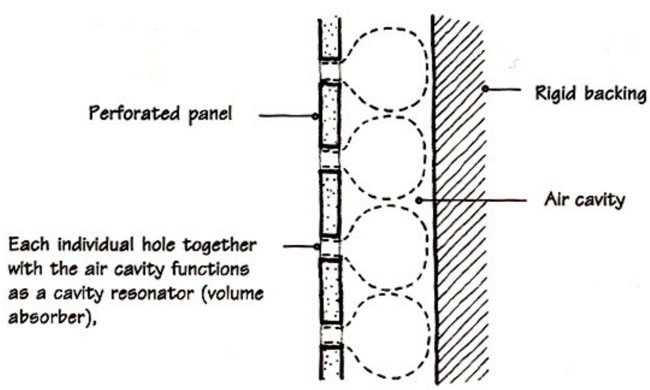


Figure 19: A perforated panel as an absorber (Everest, 2000).

In a situation where sound waves strike perpendicularly to the surface of the perforated panel absorber, there is no loss in the efficiency of the absorption characteristics of the system. But in the case where these waves strike with an angle other than 90°, the α value drastically decreases. To prevent this decrease, the cavity behind the perforated face is divided into sections with the help of a corrugated paper or such materials. The resonant frequency of a perforated panel can be found as: (for circular holes)

$$F_o=200\sqrt{P/d\,t} \qquad [3]$$

where, F_o, is the resonant frequency, P, is the perforation percentage or hole area divided by the panel area, *t,* is the effective hole length in inches ((panel thickness)+(0.8)(hole diameter)) and *d* is the depth of air space in inches.

As the formula implies, when the amount of perforation increases, the targeted resonance frequency is also increases. If a porous material is placed in the air cavity, the total absorption coefficient of the absorber increases because it produces more damping in the system. Generally fiberglass and mineral wool are used as porous materials. The thickness of this porous material should also be at least 2/3 of the air cavity for full efficiency.

The volume absorbers are highly used to provide adequate absorption at low frequencies. The volume absorbers, or namely Helmholtz resonators, are consisting of a volume of air connected to the environment with a smaller volume of air channel, which can be called as a "neck". This type of resonators looks like an open bottle, where the cross-section area and volume of the neck and the volume of the body of the bottle defines the resonant frequency as:

$$F_{res}=\frac{55000\ S}{\sqrt{V\ v}} \qquad [4]$$

where, *S,* is the cross-section area of the neck, *v,* is the volume of the neck and , *V,* is the volume of the body in mm.

It can also be expressed as:

$$F_{res}=\frac{\upsilon}{2\pi}\sqrt{S / I\,V} \qquad [5]$$

where, υ, is the speed of sound in meters, *S,* is the cross-section area of the neck in meters, *I,* is the length of the neck in meters and, *V,* is the volume of the cavity in meter cubes.

Hermann Von Helmholtz (1821-1894) made some experiments about resonators. He used a series of metal spheres of graded sizes with necks to be able to provide a high absorption coefficient α value by tuning it to a specific frequency. In history, similarly, Greeks and Romans used large pots and bronze jars to be able to satisfy the desired reverberation, as well as providing the necessary absorption. Approximately 1000 years ago, Helmholtz resonators were used in the walls of churches with pots embedded inside of those walls in Sweden and Denmark. (Figure 20) A series of slots and cavities can be observed on the walls of Tapiola Church in Helsinki, Finland.

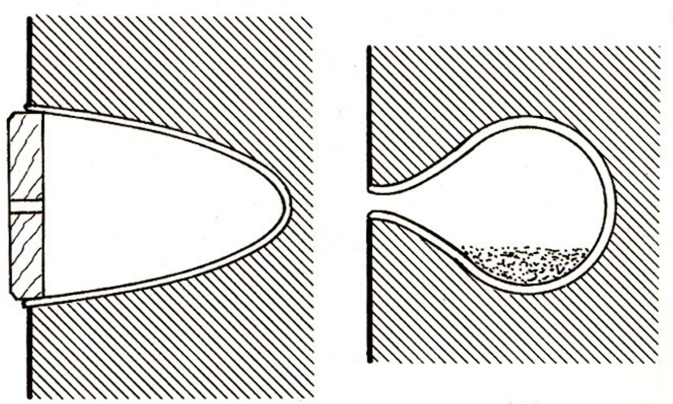


Figure 20: Pots embedded inside of those walls in Sweden and Denmark served as Helmholtz resonators (Everest, 2001).

Today, Helmholtz Resonator types are available which are used in different locations of a hall. Like pots, single rectangular bottle resonators can be used or they can be stacked in multiple rows to form a series of resonators. (Figure 21)

The separating surfaces in the air cavity can be eliminated without destroying the resonator action, but it should be noted that subdividing the air space could improve the action of perforated face or slit resonators only because this reduces unwanted modes of vibration being set up within the air cavity. An application of that type of resonators can be seen in the Queen Elizabeth Hall in London. (Figure 22)

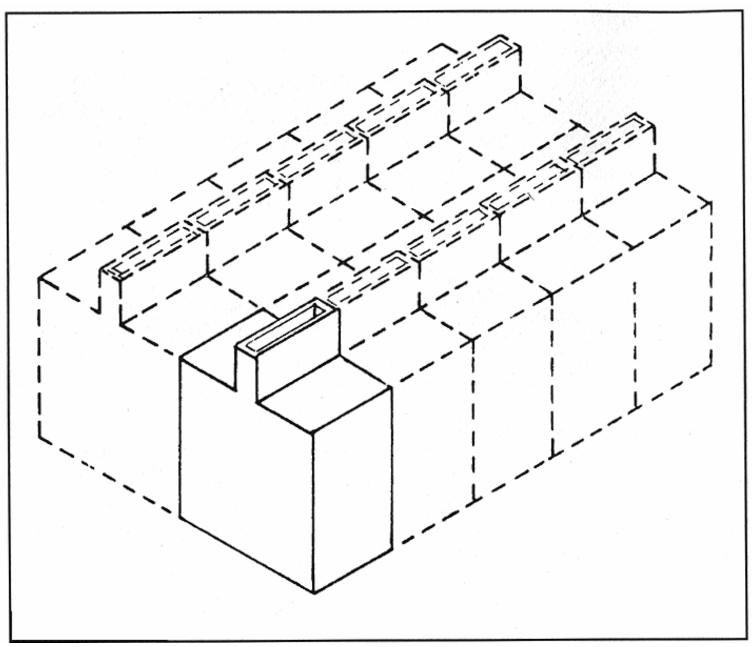


Figure 21: Multiple rows of resonators (Everest, 2000).

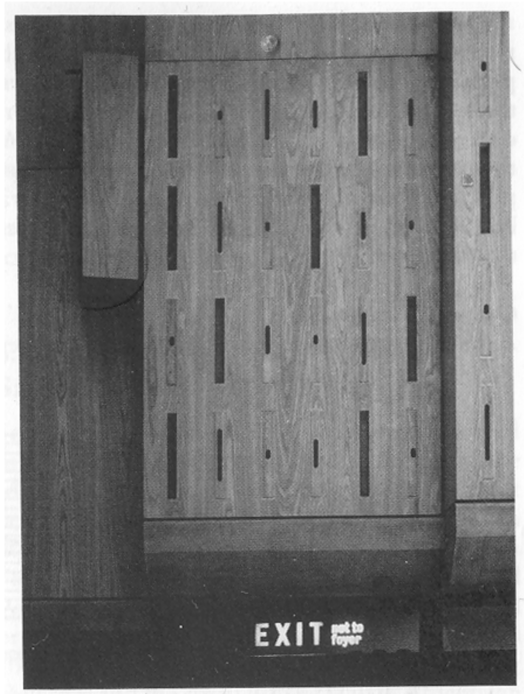


Figure 22: Helmholtz Resonator absorbers in the Queen Elizabeth Hall in London (Barron, 1993).

Placing a porous material inside the neck can increase the efficiency of a Helmholtz resonator. It can also be placed inside the body of the volume absorber, but it causes a few absorption effects on the frequency range, whereas it is more convenient to place it there. In some cases, rather than porous materials, metal septums are used inside the body of the volume absorber to provide the same efficiency.

As the sound energy at specific frequencies is highly absorbed by the Helmholtz resonators, the unabsorbed energy is reradiated through the medium, which tends to make it as a hemisphere, geometrically. This means that, a Helmholtz resonator that is tuned to a specific frequency to achieve maximum absorption of that frequency, creates a diffusion of sound in all frequency ranges.

2.2.1.3 Sound Diffusion

If the auditoriums and concert halls are considered, diffusion of sound can be created in many ways. Providing surface irregularities, sound reflective and absorptive surface treatments applied alternatively and random distributions of sound absorptive materials are some ways in achieving the diffusion of sound. An example of irregularities created by diffuser panels can be seen in De Doelen Chamber Music Hall (1966) (Figure 23).

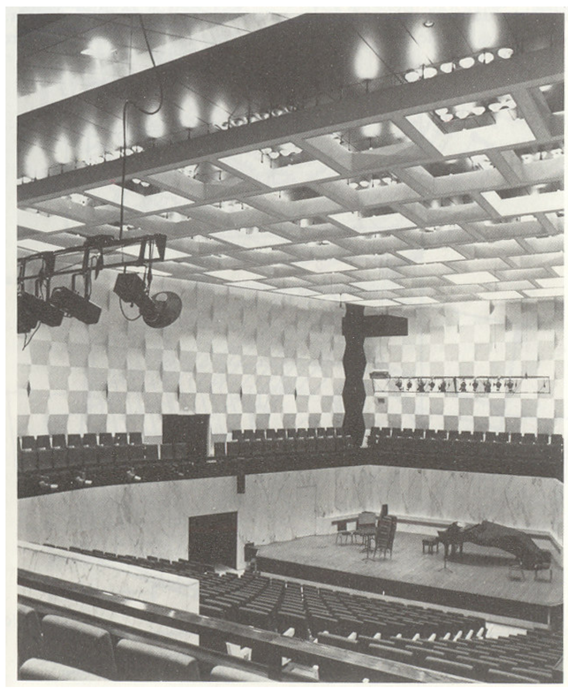


Figure 23: Diffuser panels in De Doelen Chamber Music Hall (1966) (Barron, 1993).

There is another type of sound diffuser, namely Quadratic Residue Diffusers (QRD), which is formed by the creation of a series of slots on the reflecting material (Figure1.14). A Quadratic Residue Diffuser is designed to be a surface which would produce optimum diffusion (Cox & Lam,1993). It is first discovered by the German Acoustician Manfred R. Schroeder of the University of Gottingen, Germany, and AT&T Laboratories at Murrey Hill, New Jersey. He found out an idea of number theory that a wall with grooves arranged in a certain way will diffuse sound to a degree unattainable in the past.

By definition, a quadratic residue diffuser consists of an array of linear slits (or wells) of constant width. (Mehta 1999) Thin rigid plates called fins separate those wells. The depths of the wells are determined by a number sequence established by Schroeder, and each sequence is repeated to be able to obtain the required diffuser size. In Figure 24, a pair of suspended quadratic residue reflectors can be seen in the Glasgow Royal Concert Hall, Scotland.

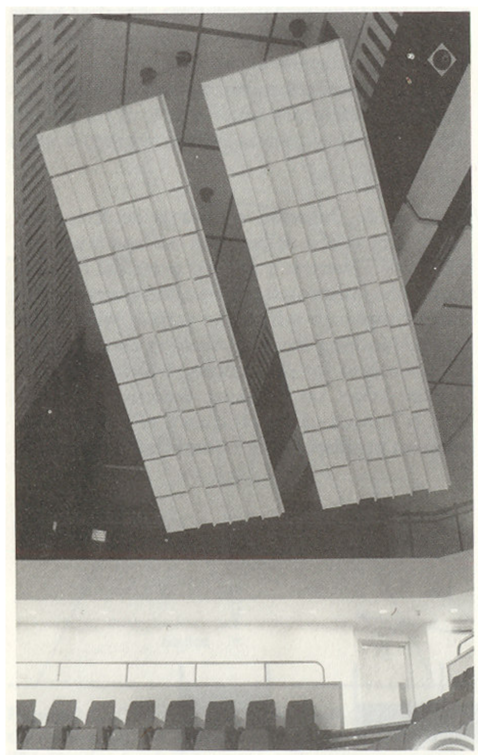


Figure 24: A pair of suspended quadratic residue reflectors can be seen in the Glasgow Royal Concert Hall, Scotland (Barron, 1993).

2.3 The Evaluation of Room Response

“The acoustic sound field in a room is very complex, yet our ears are highly selective in the way they interpret the acoustic pressure on the ear drums. It was realized around 1950’s that, in order to discover what makes good concert hall acoustics, an understanding was required of the hearing system. This led to the first major progress since Sabine’s work on reverberation time.“ (Barron, 38). Haas carried out some simulations in 1951 for speech and a result was reported such that the ear uses the first arriving sound to locate the source, but that the early reflections contribute to intelligibility. The time difference between the arrival of the direct sound and the first significant reflection is called as Initial Time Delay Gap (ITDG), which is desired to be shorter for acoustical performances. (Figure 25) The satisfactory concert halls of the world have short ITDG values of 21 ms. or less to have a better acoustic intimacy perception.

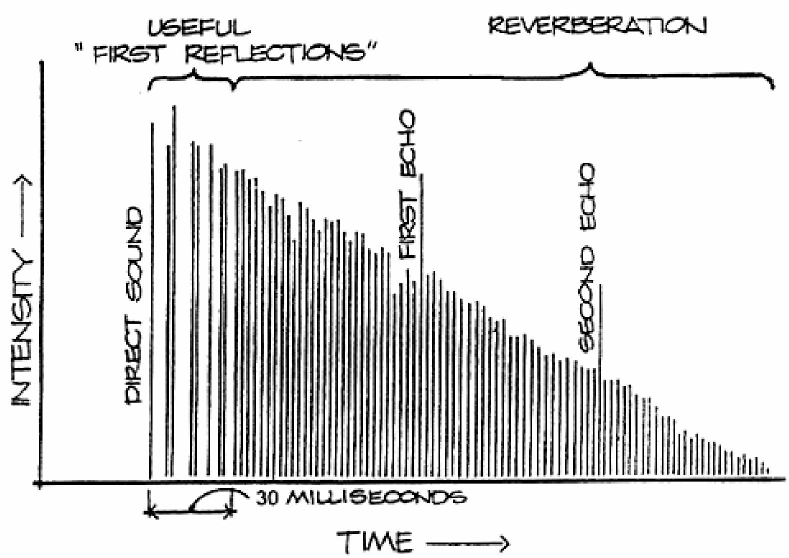
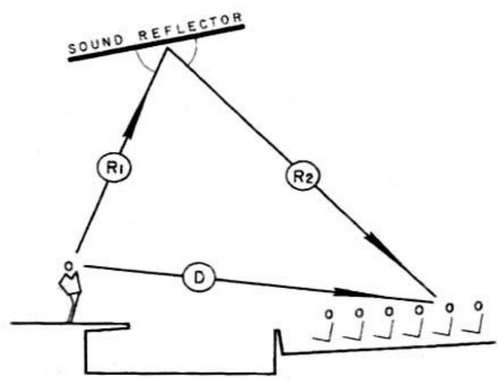


Figure 25: The intensity graph of direct sound and reflections with respect to time (Irwine & Richards, 1998).

2.3.1 Initial Time Delay Gap (ITDG)

In evaluating the quality of concert hall acoustics, the listeners generally would like to be surrounded or enveloped by music. This feeling of being close to the source of sound is called as intimacy. To provide intimacy in concert halls, the short-delayed reflections should be achieved. Beranek proposed a measurement to calculate the direct and the first-reflected sound at a certain receiver position by the time difference, named as Initial Time Delay Gap (ITDG). The concept of ITDG can be shown as in Figure 26:



TIME DELAY IN MILISECONDS:

$$\frac{R1 + R2 - D}{0.34} \quad \text{IF DIMENSION IN METERS}$$

Figure 26: Reflected sound beneficially reinforces the direct sound if the time delay between them is relatively short, that is, a maximum of 30 ms (Doelle 1972).

It is obvious that in smaller halls ITDG will be short because of short reflection patterns as a result of closer reflecting surfaces and consequently, the listener will feel more enveloped by the music. But this condition of being enveloped can vary due to the location of the listener. The listeners sitting close to the sidewalls will feel the hall more intimate, that's because the path difference between the direct and the first-reflected sound will be shorter. To be able to get the exact values of ITDG of halls, the measurements are therefore performed at an approximate center of halls, somewhere between the stage and the first balcony front. As the ITDG increases, the overall rating of the hall decreases. The concert halls, which have shorter ITDG's such as 12 to 25 milliseconds, are found to be more intimate. Shorter ITDG values, in other words better intimacy, may be achieved by adding and correct placement of ceiling reflectors or protrusions from the walls.

2.3.2 Reverberation Time (RT)

The common quality criteria for acoustics in an enclosure are most of the time is determined by the decay of sound energy in that space, referred to as the room's reverberation. The reverberation in a room is characterized by the reverberation time (RT). By definition, reverberation time is the time it takes for the sound level to decay by 60dB or for the sound energy in the space to decay to one millionth of its original case. (Figure 27) It is found out that reverberation character of an enclosed space is directly related with the enclosure volume and total absorption in the room, which was formulated as;

$$RT = 0.16\, V / \Sigma A \qquad [6]$$

$$\Sigma A = (S_1\alpha_1 + S_2\alpha_2 + \ldots\ldots) + mv$$

where RT, is reverberation time in seconds,V, is the room volume in m^3, ΣA, is the total absorption in the room in metric sabins, $S_1, S_2, \ldots$, are the surface areas of the enclosure in m^2 and $\alpha_1, \alpha_2, \ldots$, are the corresponding absorption coefficients and mv, is the air absorption, which is too small to be considered.

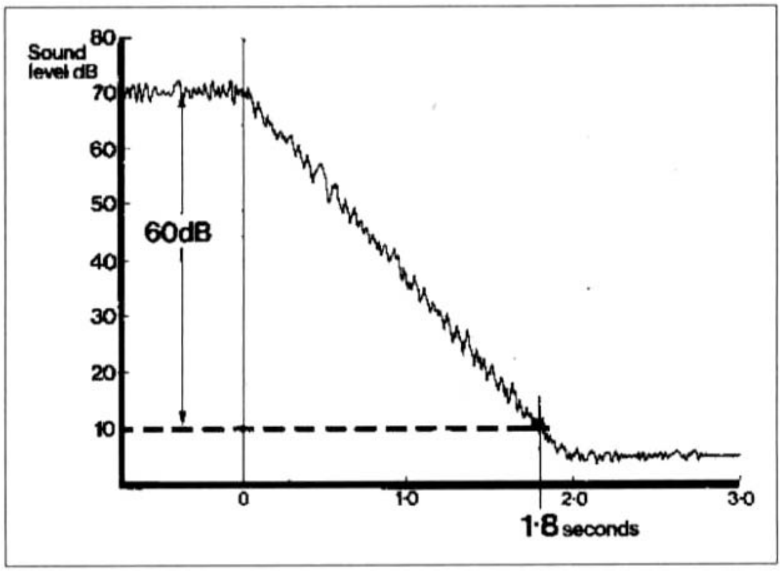


Figure 27: Reverberation time definition with sample decay.

As the advances in acoustics develops by time, the reverberation time phenomenon still remains as a valuable measurable acoustical quantity. With the advantage that it is considerably equal in an enclosed space such as a room, an auditorium or a concert hall; listeners can make same subjective judgment about the reverberation quality. For different performances that take place in such places, different reverberation times are required. Longer reverberation most of the time accentuates music, but may cause speech to be muddled. For concert halls, which have longer reverberation time such as 1.5 – 2.0, the hall can be referred as being “live”, whereas in the case that reverberation is shorter it may be referred as being “dead”. Desired reverberation times for different performances can be seen on Table 4.

Table 4: Optimum mid-frequency RT values for various occupied facilities. (Cowan 2000)

Type of Facility	Optimum Midfrequency RT_{60} (sec)
Broadcast Studio	0.5
Classroom	1.0
Lecture / Conference room	1.0
Movie / Drama theater	1.0
Multipurpose auditorium	1.3-1.5
Contemporary church	1.4-1.6
Rock concert hall	1.5
Opera house	1.4-1.6
Symphony hall	1.8-2.0
Cathedral	3.0 or more

Due to the fact that the absorption coefficients will be different in each frequency, different RT values will be obtained. So, reverberation times, which are used as a single number, are the values for mid-frequency ranges, averaged between 500Hz and 1000Hz. Because of air absorption, reverberation time relatively decreases in high frequencies, which makes mid and low frequencies controllable by the designer.

2.3.3 Early Decay Time (EDT)

"Early decay time is a modified measure of reverberation time. Reverberation time is the time required for a sound to decay 60dB whereas the early decay time is the time required for the first 10dB of decay multiplied by 6 to extrapolate the result to 60dB decay. Early decay time was proposed by Jordan based on previous research that suggested "the later part of a reverberant decay excited by a specific impulse in running speech or music is already masked by subsequent signals once it has dropped by about 10dB." (Cremer and Muller,

1982) A study by Cervone showed a significant relation between early decay time and overall music impression rated by listeners at live concert performances." (Cavanaugh and Wilkes, 1999).

2.3.3.1 Bass Ratio (BR)

Bass ratio based on early decay time was proposed by Beranek to evaluate timbre or tonal balance, especially *warmth*. Warmth is a term used to describe a cozy smoothness to the music. Its counterpart may be considered to be brilliance, which refers to a bright, clear, ringing sound. If a sound field is too warm, the hall can be undesirably "dark". With too much brilliance, the sound (Beranek 1962) It is measured by the ratio of (a) the sum of the early decay times at 125Hz and 250Hz to (b) the sum of the early decay times at 500Hz and 1000Hz. This is the reverberation times in the lower frequencies divided by the reverberation times in the middle frequencies (Cavanaugh & Wilkes).

$$BR(RT) = \frac{RT\ (125)Hz + RT\ (250)Hz}{RT\ (500)Hz + RT\ (1000)Hz} \qquad [7]$$

2.3.3.2 Treble Ratio (TR)

Treble ratio based on early decay time is proposed to evaluate timbre or tonal balance, especially *brilliance*. (Chiang 1994) It is measured by the ratio of the high frequency reverberation times to the middle frequency reverberation times. Chiang has also expressed it as the ratio of (a) the sum of the early decay times at 2000Hz and 4000Hz to (b) the sum of the early decay times at 500Hz and 1000Hz. This measure was developed because treble and bass have been evaluated separately in the questionnaires used in several major live listening studies of acoustical qualities of rooms. (Cavanaugh & Wilkes)

$$TR(RT) = \frac{RT\ (2000)Hz + RT\ (4000)Hz}{RT\ (500)Hz + RT\ (1000)Hz} \qquad [8]$$

2.3.4 Clarity (C80)

"The measurement of clarity, or early-to-late sound index in other words, is the ratio of the energy in the early sound compared to that in the reverberant sound, expressed in dB. Early sound is what is heard in the first 80ms (C50 - 50 ms) after the arrival of the direct sound. It is a measure of the degree to which the individual sounds stand apart from one another.

$$C80 = 10 \log \frac{E_{0\text{-}80\ ms}}{E_{80\text{-}\infty\ ms}} \qquad [9]$$

If the clarity is too low, the fast parts of the music are not "readable" anymore. C80 is a function of both the architectural and the stage set design. If there is no reverberation in a dead room, the music will be very clear and C80 will have a large positive value. If the reverberation is large, the music will be unclear and C80 will have a relatively high negative value. C80 becomes 0 dB, if the early and the reverberant sound is equal. The acceptable values for clarity can be classified as: (Table 5)

Table 5: The acceptable values for clarity. (Makrinenko, 1993)

QUALITY STEPS	C80 Values, dB	
	Front rows	Back rows
Good	From +3 to +8	From 0 to +5
Acceptable	> +8 and –2 to +3	From +5 to +9
Unacceptable	< -2	> +9 , <-5

Often the values for 500Hz, 1000Hz and 2000Hz are averaged. This will be expressed by the symbol C80(3). For orchestral music a C80 of 0dB to -4dB is often preferred, but for rehearsals often conductors express satisfaction about a C80 of 1dB to 5dB, because every detail can be heard. For singers, all values of clarity between +1 and +5 seem acceptable. C80 should be generally in the range of -4dB and +4dB.

For speech, in comparison to music, the Clarity will be measured as the ratio of the first 50 msec (C50) instead of 80 msec (C80) for music.

2.3.5 Definition (D50)

Definition is the ratio of early sound energy to the total sound energy. The effective energy includes both the direct sound energy and the energy of the reflections delayed with respect to the direct sound by up to 50msec. It can be described with the following expression:

$$D50 = 10 \log \frac{E_{0\text{-}50\,msec}}{E_{0\text{-}\infty\,msec}} \qquad [10]$$

In concert hall acoustics it refers to the degree to which individual strands in a musical presentation can be differentiated from each other. *Horizontal Definition* defines the degree to which sounds that follow one another stand apart. *Vertical Definition* defines the degree to which simultaneous sounds can be heard separately. For speech intelligibility, good definition values should be achieved in halls.

\

2.3.6 Lateral Fraction (LF80 or LEF)

Lateral (energy) fraction, or objective envelopment in other words, is the ratio of the integrated sound energy in the first 80msec after the direct sound measured from the sides of the listener's head compared to the total integrated energy level of the early sound at the same location. The lateral energy fraction is supposed to relate to a sense of spatial impression with higher values of LF80 providing a greater sense of spatial impression. (Irvine & Richards, 1998)

$$\text{LEF} = \frac{\text{Energy arriving laterally within 80msec of direct sound}}{\text{Energy arriving totally within 80msec of direct sound}} \qquad [11]$$

The graph of energy fluctuation of right and left ear with respect to time at the existing receiver position is also called as the Binaural Impulse Response (BRIR), and in evaluating the lateral fraction aurilizations, it provides an objective point of view. Initial time delay gap and other parameters, including echo possibilities can be detected with the help of BRIR calculations, as well as providing information about the sound pressure levels on each listener ear, which is directly related with the lateral energy fraction.

2.3.7 Sound Transmission Index (STI)

The Sound Transmission Index (STI) has strongly been promoted for predicting speech intelligibility through impulse response. It accommodates both the signal-to-noise ratio and the impulse response aspects, which affect intelligibility. The idea behind this measure is that for good speech intelligibility, the envelope of the signal should be preserved. It allows for the different contributions of the various frequency bands to speech quality, and also for the mutual masking between adjacent frequency bands occurring in our hearing system. (Kutruff, 1991) The relation between STI and intelligibility can be expressed as: (Table 6)

Table 6: The relation between STI and intelligibility. (Beranek, 1988)

Quality Score	STI (RASTI) Value
Bad	0 – 0,32
Poor	0,32 – 0,45
Fair	0,45 – 0,60
Good	0,60 – 0,75
Excellent	0,75 – 1,0

To summarize the objective parameters corresponding to the subjective attributes in hall design, Table 7 is given below:

Table 7: A summary of summarize the objective parameters corresponding to the subjective attributes in hall design.

THE OBJECTIVE PARAMETERS	THE SUBJECTIVE PARAMETERS
Initial Time Delay Gap (ITDG) *12msec< ITDG <25msec*	**Intimacy**
Reverberation Time (RT) *Lecture / Conference room 1.0* *Multipurpose auditorium 1.3-1.5*	**Reverberance, Fullness of tone**
Early Decay Time (EDT) *EDT < RT or EDT = RT (approx.)*	**Reverberance**
Clarity (C80) *+3 to +8 for front rows* *0 to +5 for back rows*	**Subjective Clarity**
Definition (D50) *D50 > 65%*	**Intelligibility**
Lateral Fraction (LF80) *0.1 < LF80 < 0.35*	**Envelopment**
Sound Transmission Index (STI) *0.6 < STI <1.0*	**Intelligibility**
Sound Pressure Level (SPL) *Close to original level*	**Loudness**
Bass Ratio (BR) *1.1< BR < 1.25*	**Tonal Balance, Warmth**
Treble Ratio (TR)	**Tonal Balance, Brilliance**

CHAPTER 3

THE METU NORTHERN CYPRUS CAMPUS AUDITORIUM (NCCA)

3.1 General Information

METU Northern Cyprus Campus (NCCA) was initiated by an international agreement signed by the Turkish and Turkish Cypriot Governments and METU on March 27, 2000. The Campus, with a land area of 3000 decares (approx. 750 acres), is located approximately 50 km west of Lefkoşa (Nicosia) and 6 km north of Güzelyurt (Morfou). The construction of a modern campus with exemplary facilities is currently underway. The Campus will become fully operational by September 2005.

The METU NCCA (Middle East Technical University Northern Cyprus Campus Auditorium) is one of the educational buildings in the Northern Cyprus Metu Campus, located in the one of the central axis of the campus. (Figure 28) Its construction is going underway and assumed to be finished in the fall of 2005.

Figure 28: Site plan of the campus and the auditorium building, as indicated with number 3.

The building, which is including seminar and lecture rooms, and a multipurpose hall, was designed by Ilhan Selim Kural (Architect, MA, Metu) and the overall project was finished in June, 2004. The acoustical projects of the hall were completed by Arzu Gönenç Sorguç (Assist. Prof. Dr.,Metu) after an accommodating study with the architect to provide best acoustical conditions for the hall designed.

For the whole project, the design team was formed as follows:

Architect: Ilhan S. Kural (Instructor, Architect, MA, Metu)
Acoustic Consultant: Arzu Gönenç Sorguç (Assist. Prof. Dr.,Metu)
Architec. & Struct. Supervision: Ziya Necati Özkan (Architect, MA, Metu)
Structural Consultant: Mehmet Şapcı
Mechanical Consultant: Yazman Engineering Ltd.
Electrical Consultant: Nüvit Karaibrahimoğlu
Desıgn Team: Ilhan S. Kural (Instructor, Architect, MA, Metu)
Ali Kural (Architect, MA, GSD Harvard)
Tansu Yılmaz (Architect, Metu)
Yasemin Eren (Architect, Metu)

The multipurpose hall, NCCA, which is designed for 585 people, is both convenient for performances of both speech and music. Related drawings can be seen from in Figure 29 to Figure 34 about the settlement and the location of the auditorium in the building.

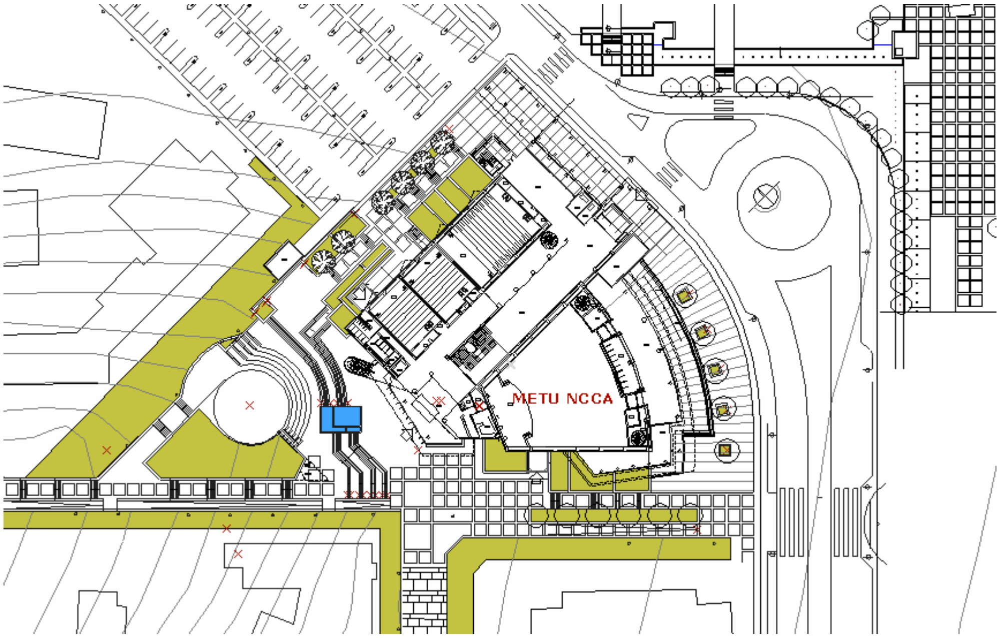


Figure 29: Site plan of the auditorium building and the location of NCCA in the complex (By Ilhan S. Kural).

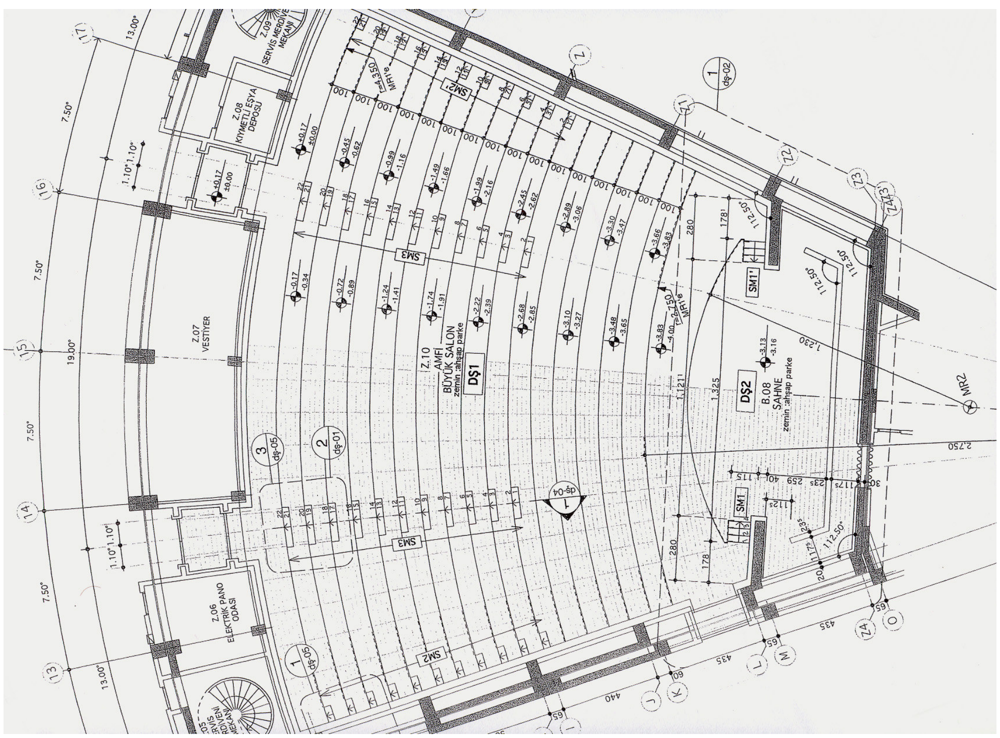


Figure 30: Floor plan of NCCA (By Ilhan S. Kural).

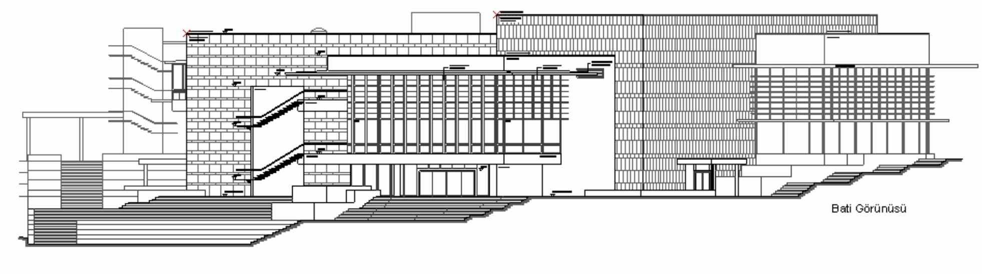


Figure 31: West elevation of NCCA building. (By Ilhan S. Kural)

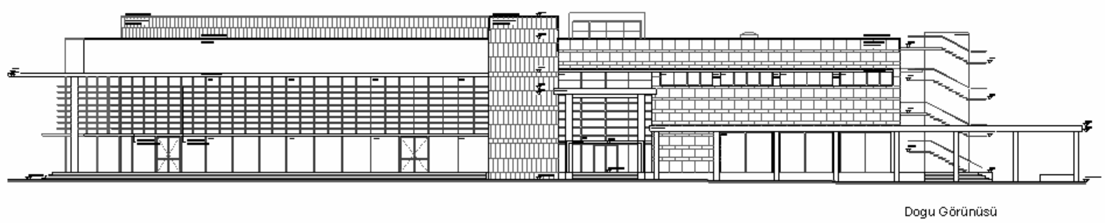


Figure 32: East elevation of NCCA building. (By Ilhan S. Kural)

Figure 33: North elevation of NCCA building. (By Ilhan S. Kural)

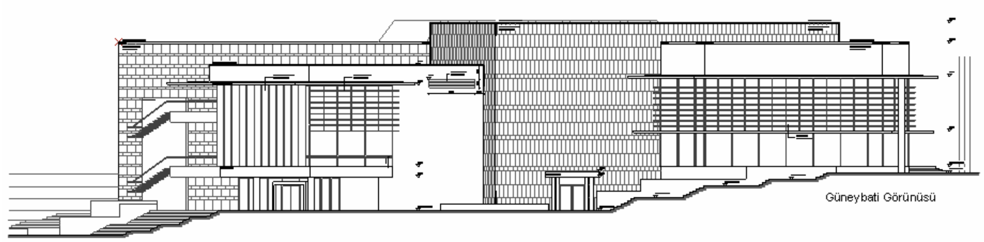


Figure 34: South-west elevation of NCCA building. (By Ilhan S. Kural)

3.2 Architectural, Structural and Acoustical Details

METU NCCA has a volume of 6200m^3 was designed in the form of fan-shape where the distance of the stage to the audience is minimized. In the early stages of the design, the hall considered to be 5000m^3, but to provide better reverberation time values and sound pressure levels, a hall volume of 6200m^3 is decided. The distance from the back of the stage to the rear wall of the auditorium is 22m, where it is in the limits of suggested dimensions for multipurpose halls for sightline purposes. Except for the stage front and the aisles, total hall area is 445m^2, which results with an area/seat ratio of 0,76m^2 and the volume/seat ratio of 7,8m^3. The area/seat ratio is satisfied and in the limits of preferable ranges where the volume/seat ratio is twice the number of desired ranges because of its multipurpose function. However, this difference has been tolerated by the proper selection of material type and configuration.

The design of hall is made by the proper geometrical acoustical methods. The interior section, the volume, the sizes, the selection of materials are all determined to be providing the acoustical satisfaction, and designed after the process of necessary calculations. The dynamic frequency range of speech and music is considered, and the surfaces of reflections are designed to bigger in sizes to be able to cover all frequency ranges.

To begin with the stage; the rear and sidewalls of the stage enclosure are wooden cladding over concrete and the same cladding is applied on the surface of the stage floor. The front face of the stage floor is also wooden cladding. The sidewalls of the stage, facing with the hall volume, are travertine stone up to 2.8meters, and the remaining part up to the ceiling is wooden cladding as it was on the sidewalls of the stage enclosure. The audience floor is parquet over concrete and the seats are medium thickness upholstered. The rear wall is covered with perforated wooden acoustical panels, which have a highly absorptive property of each frequency level. (A special product responding the need of design, which has a brand name of Topakustik) The purpose of selecting such a kind of material is to absorb sound energy to prevent sound concentrations and echoes that may occur because of the concave surface of the rear wall. The same approach is followed on the surface treatment of the translations room extension, which is finished with a highly absorptive material again (A special product responding the need of design, which has a brand name of Ecophon). The travertine lining on sidewalls are continuous on the rear wall with an height of 1m and above them, there are wooden panels perpendicularly installed on the surface of sidewalls, which can be folded on itself allowing the highly absorptive material underneath to come out. On upper part of the panels, the gypsum board panels are mounted on the surface. On the ceiling, there exist gypsum board panels and slit wooden linings in between for the reflection and diffusion of sound rays. In Figure 35, a section from the main axis of the hall can be seen, giving information about the chosen and applied material configuration.

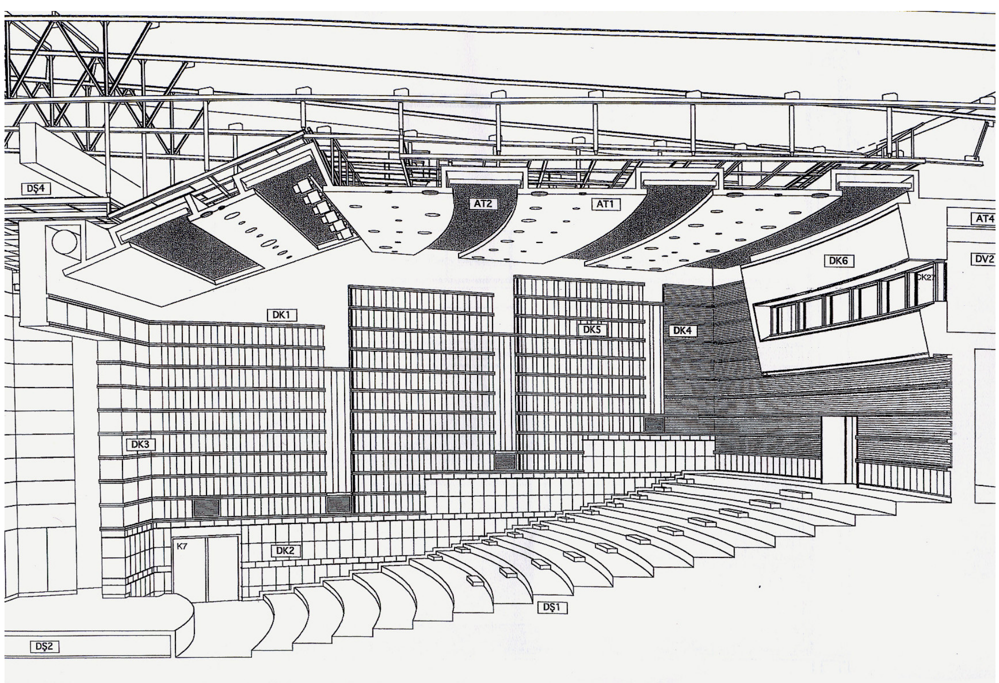


Figure 35: Section of NCCA. (By Ilhan S. Kural)

Since the hall designed as multipurpose, it has two different modes of acoustical performance, one for the auditorium and the other for concert purposes. As it is mentioned before, reverberation time being the most identical one, speech and music sounds have different values of acoustical parameters. To be able to adjust the reverberation time and other acoustical concepts, simply folding wooden panels on sidewalls has carried out a flexible solution. For the auditorium mode, the panels are folded on themselves to be able to face the highly absorptive material underneath with the hall medium. From Figure 36 to Figure 38, the folded wooden panels on themselves can be seen. From Figure 39 to Figure 41, concert mode created by the folding of wooden panels on the highly absorptive material. The material configuration and the total area of each surface with their absorption coefficients are listed due to auditorium mode and due to concert mode in Appendix A, which is prepared and designed by Assist. Prof. Dr. Arzu Gönenç Sorguç, the acoustic consultant of the project.

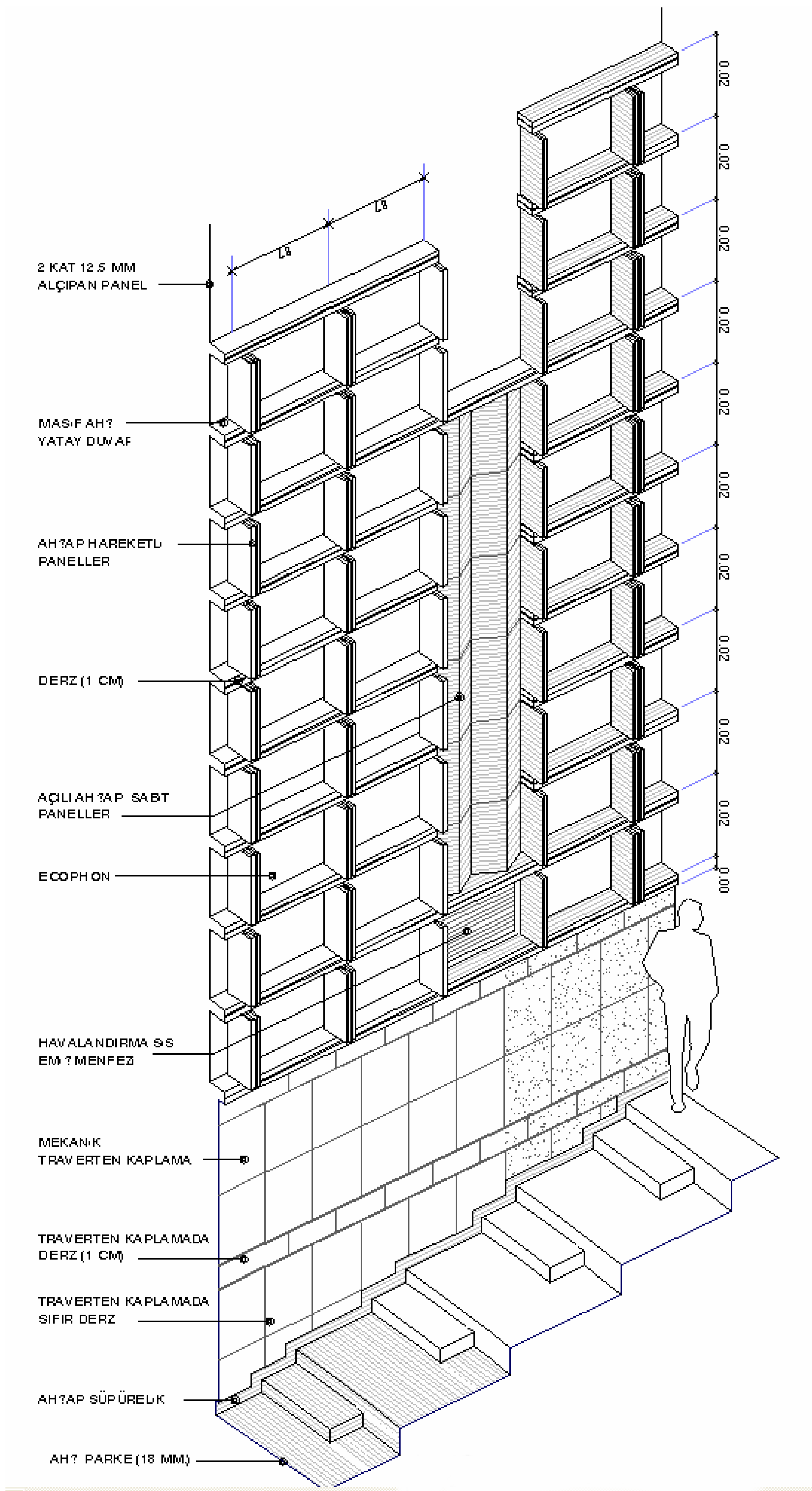


Figure 36: Wooden panels are folded on themselves for the auditorium mode.
(Design by Ilhan S. Kural, drawn by Oya Caymaz)

Figure 37: Interior render of wooden panels are folded on themselves for the auditorium mode. (By Ilhan S. Kural)

Figure 38: Interior perspective render of wooden panels are folded on themselves for the auditorium mode. (By Ilhan S. Kural)

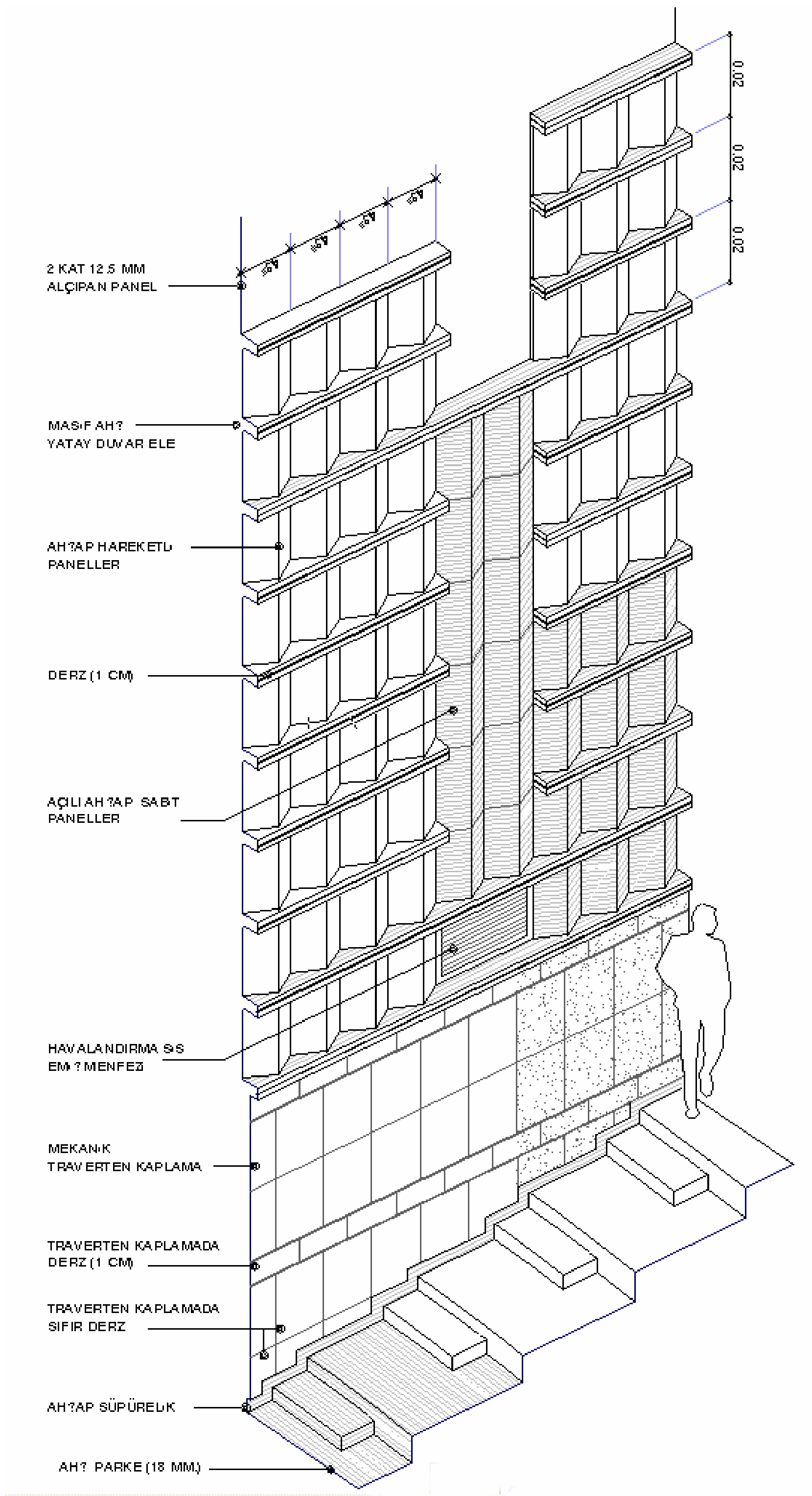


Figure 39: Wooden panels are folded on highly absorptive material for the concert mode. (Design by Ilhan S. Kural, drawn by Oya Caymaz)

Figure 40: Interior render of wooden panels are folded on highly absorptive material for the concert mode. (By Ilhan S. Kural)

Figure 41: Interior perspective render of wooden panels are folded on highly absorptive material for the concert mode. (By Ilhan S. Kural)

CHAPTER 4

THE MODELLING PROCESS AND THE ANALYSIS OF METU NCCA

4.1 Computer Simulation Methods and The Odeon Software

After decades of development room acoustical computer models have matured. Hybrid methods combine the best features from image source models and ray tracing methods and have lead to a significantly reduced calculation times. Due to the wave nature of sound, it has been necessary to simulate scattering effects in the models. Today's room acoustical computer models have several advantages compared to scale models. They have become reliable and efficient design tools for acoustic consultants, and the results of a simulation can be presented not only for the eyes but also for the ears with new technologies for auralisation (Rindel, 1995).

Today, with the help of these developments, many acoustical simulation softwares have been produced for the aim of 'good concert hall acoustics". One of these softwares, Odeon, was developed by the Department of Acoustic Technology and six Danish consulting companies back in 1984 with the purpose of providing reliable yet easy to use room acoustics prediction software. Continuous development, immense experience and acoustic know-how have resulted in software that allows prediction of acoustics in public venues as well as in industrial environments. A screenshot from the interface of software can be seen in Figure 42.

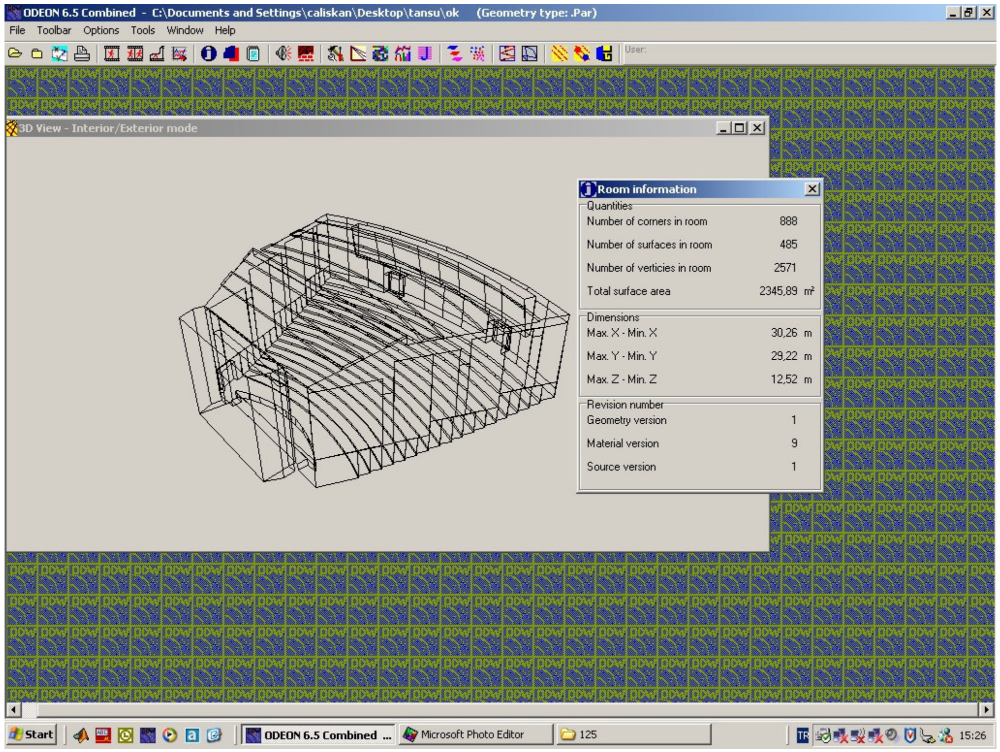


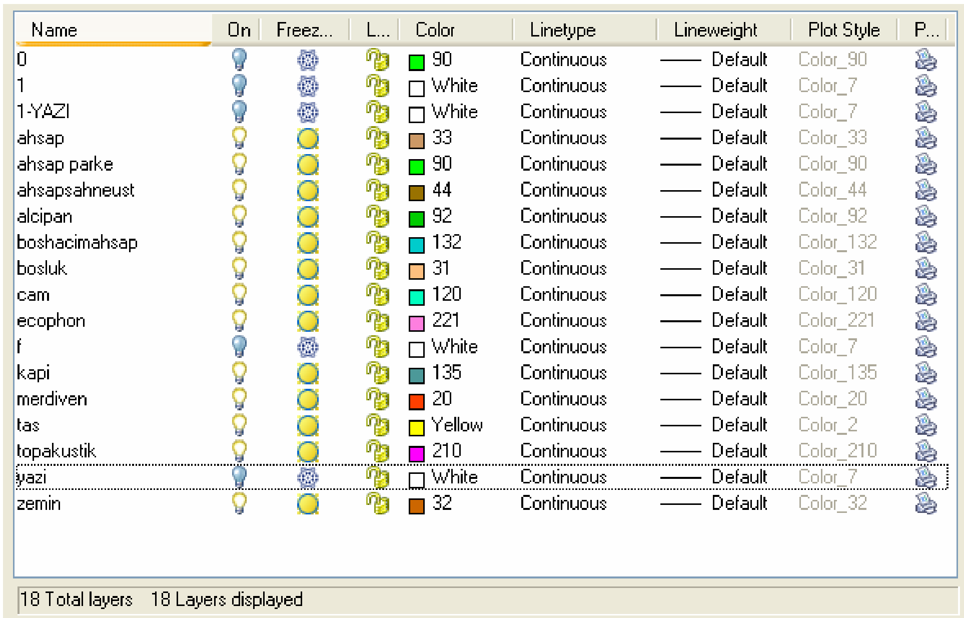
Figure 42: A screenshot from the software.

ODEON covers room acoustics, noise control, and auditorium acoustics and is available in three editions – Industrial, Auditorium and Combined, all running Windows® 98, Me, NT®, 2000 and XP.

4.2 The Modeling Process

The simulation of the hall is decided to be made in Odeon software for its easy-to-use interface and the evaluation precision. For the analysis part, a 3D model of the hall has been drawn as a dxf format with the help of AutoCAD software, and all different material types are divided into separate layers because since all the materials used in the design have different sound absorption coefficients, the concert mode and the auditorium mode are analyzed separately.

There are 13 different material types and 13 different layers representing them as; (Figure 43)



Name	On	Freez...	L...	Color	Linetype	Lineweight	Plot Style	P...
0				90	Continuous	Default	Color_90	
1				White	Continuous	Default	Color_7	
1-YAZI				White	Continuous	Default	Color_7	
ahsap				33	Continuous	Default	Color_33	
ahsap parke				90	Continuous	Default	Color_90	
ahsapsahneust				44	Continuous	Default	Color_44	
alcipan				92	Continuous	Default	Color_92	
boshacimahsap				132	Continuous	Default	Color_132	
bosluk				31	Continuous	Default	Color_31	
cam				120	Continuous	Default	Color_120	
ecophon				221	Continuous	Default	Color_221	
f				White	Continuous	Default	Color_7	
kapi				135	Continuous	Default	Color_135	
merdiven				20	Continuous	Default	Color_20	
tas				Yellow	Continuous	Default	Color_2	
topakustik				210	Continuous	Default	Color_210	
yazi				White	Continuous	Default	Color_7	
zemin				32	Continuous	Default	Color_32	

18 Total layers 18 Layers displayed

Figure 43: Layer system in the AutoCAD software.

The model produced in the AutoCAD software is associated with this layer system and all the surfaces of the model were drawn as a 3D face in order to be compatible for the Odeon software surface interface. (Figure 44 and 45) Then the model was imported in the Odeon software for further evaluation of the study.

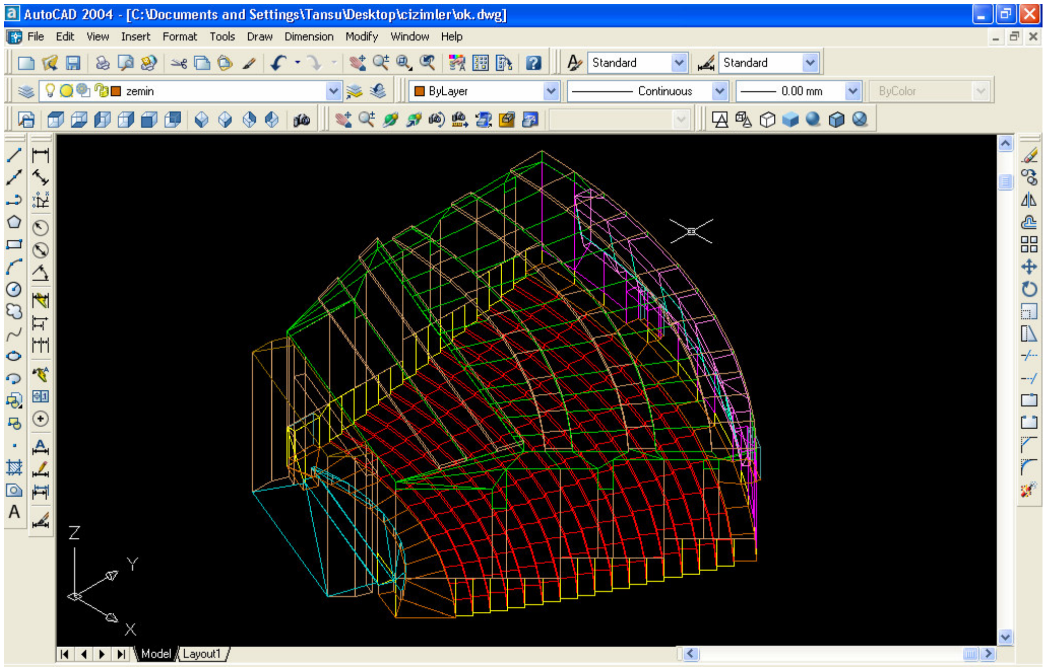


Figure 44: 3D model drawn with 3D faces in the AutoCAD software.

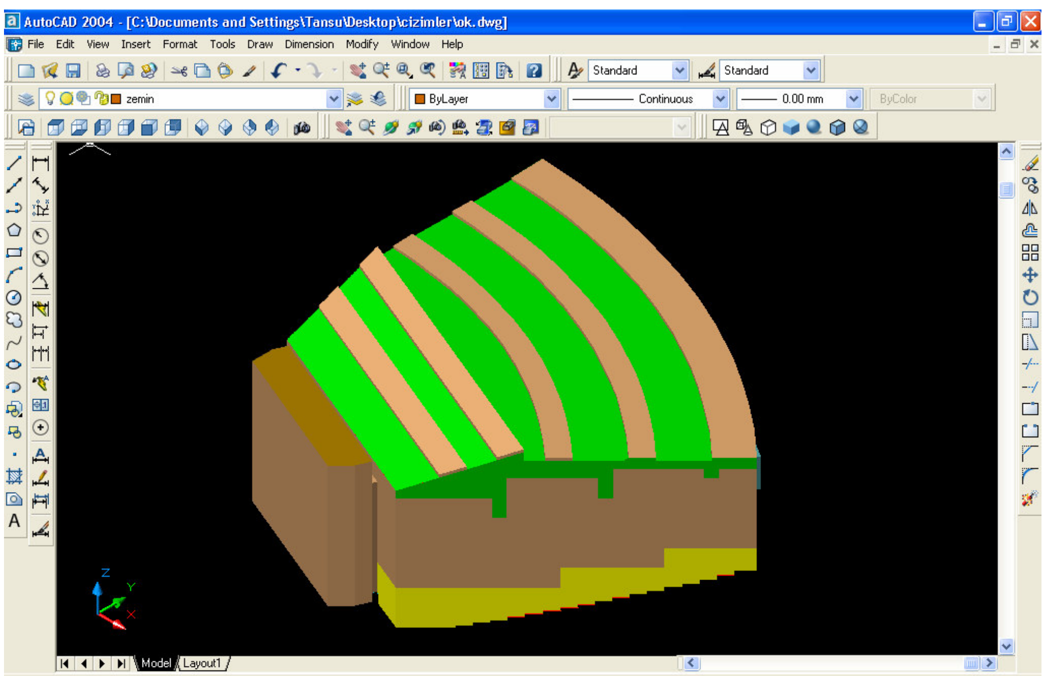


Figure 45: 3D faces rendered in the AutoCAD software.

After importing the model into Odeon, information about the model revised and a test conducted by producing numerous sound rays in the model to check if the model produced was airtight. (Figure 46)

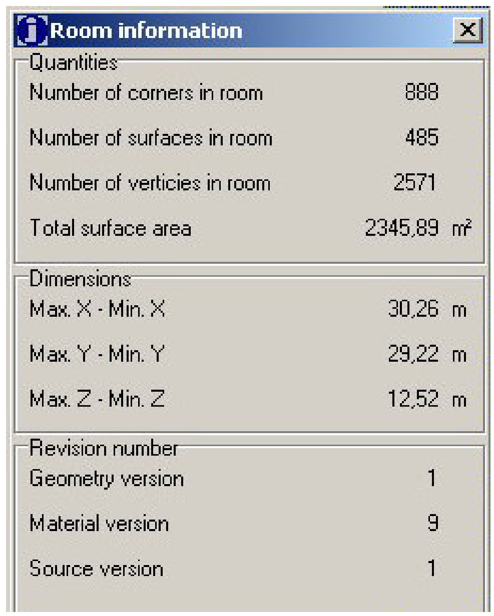


Figure 46: Information about the model imported in Odeon.

A sound source with a gain of 32dB was located on the center axis of the stage just 2m away from the stage front. The single point receiver was also located in the middle center of the main hall just 13m away from the stage front. The source height was decided to be 1,5m whereas the receiver height was selected to be only 1,1m, which is generally the eyesight of a human head when he/she sits on the seat. In Figure 47 and 48, the source can be seen as a red point symbol and the receiver as a blue one. From Figure 49 to Figure 51, view from source, view from receiver and a sectional render can be seen, respectively.

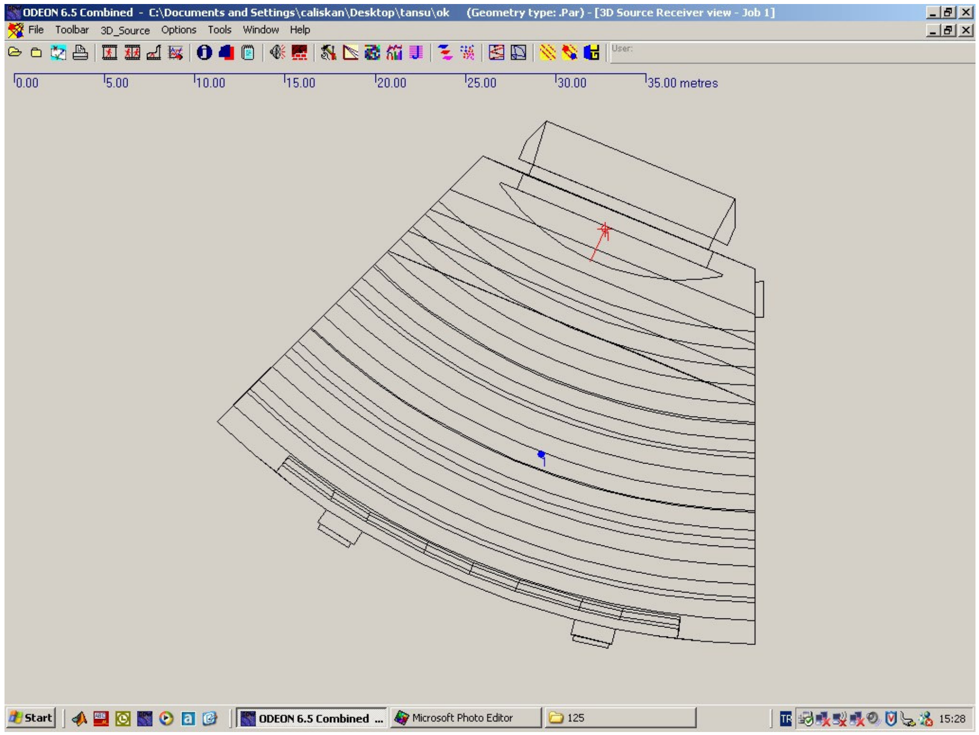


Figure 47: Top view of the sound source and the receiver in the model.

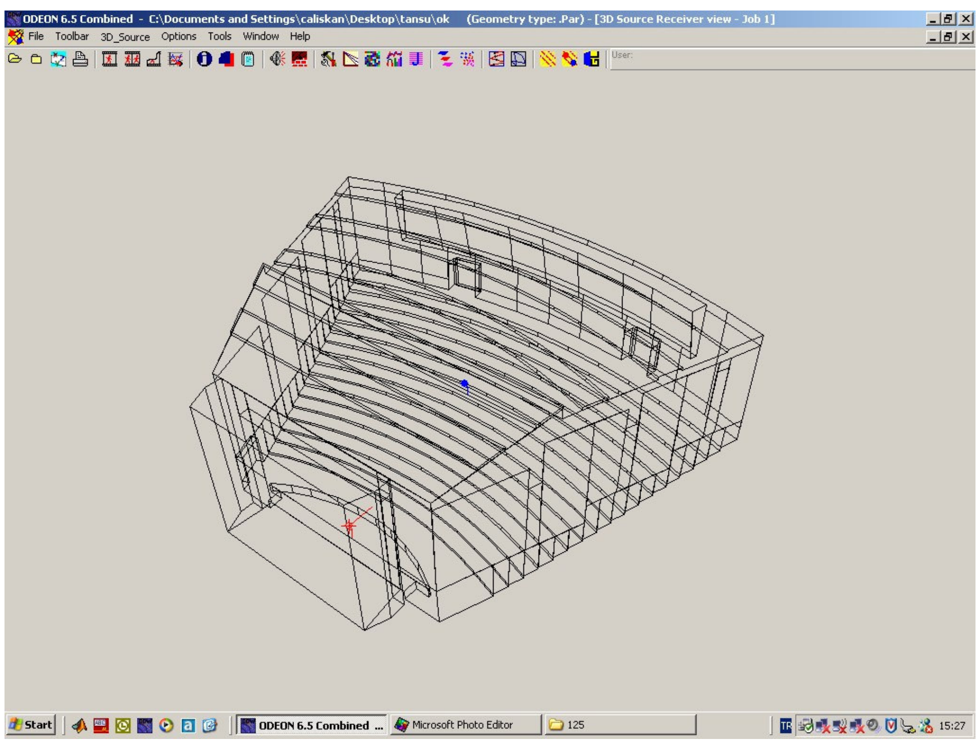


Figure 48: Axonometric view of the sound source and the receiver in the model.

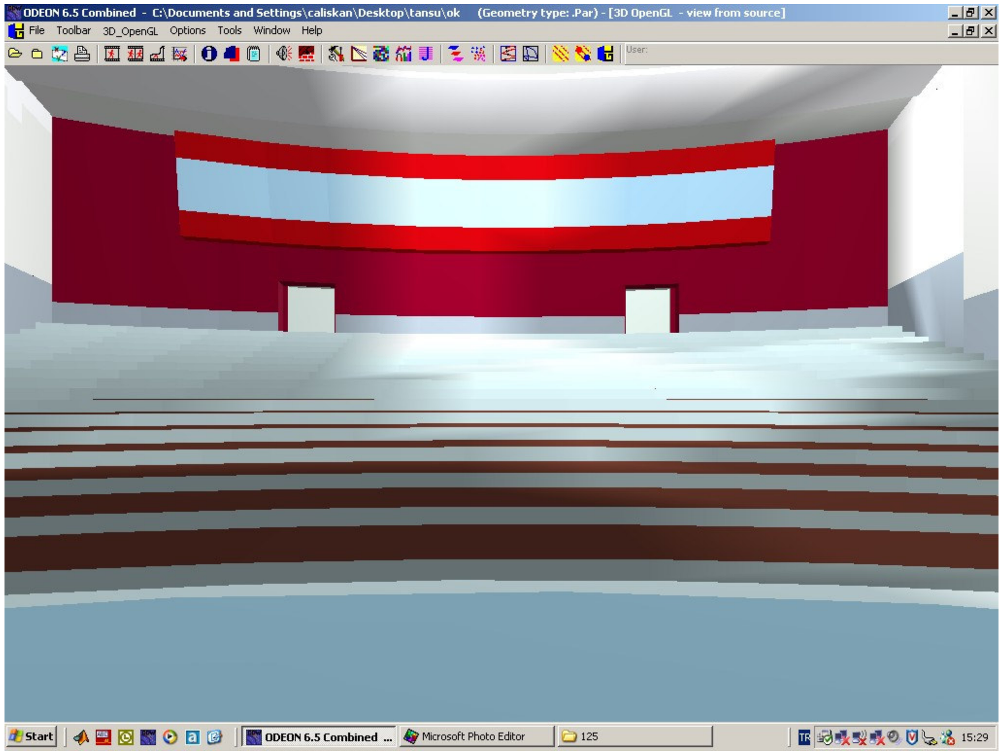


Figure 49: View from the source in the model.

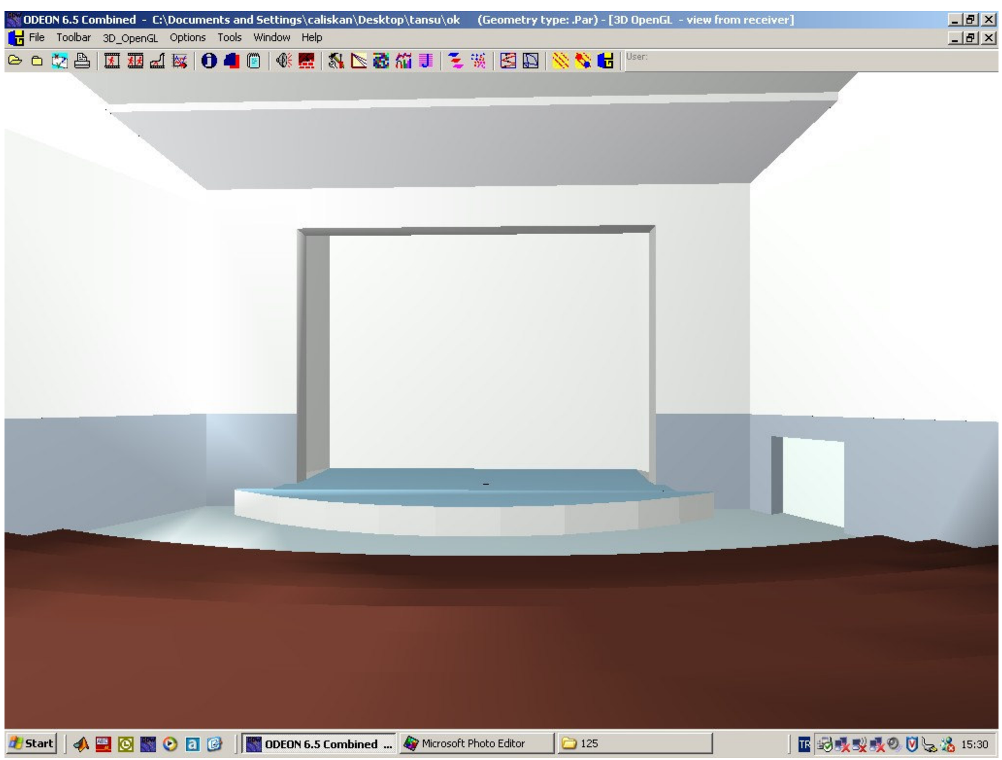


Figure 50: View from the receiver in the model.

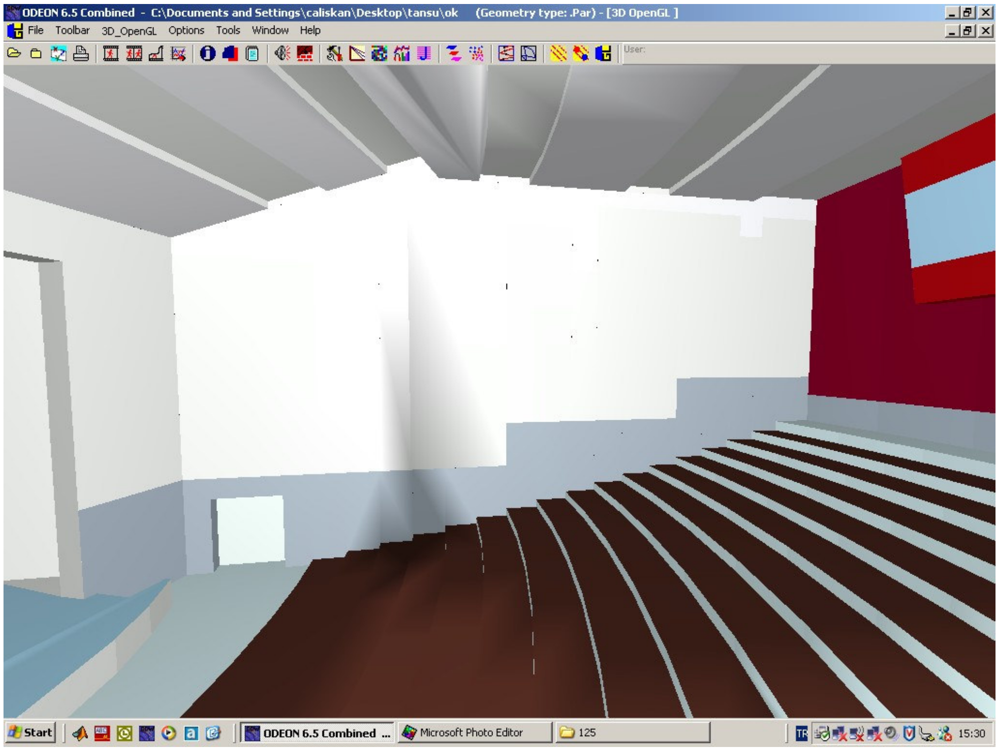


Figure 51: Sectional render looking through the sidewall.

4.3 Analysis of THE METU NCCA

4.3.1 The Auditorium Mode

In the analysis stage of the auditorium, the following sound source, receiver and the grid system were used;

Sound source: at 2m back from the center stage front and 1,5m height from stage floor
Receiver: at middle center of the hall at 13m away from the stage front
Grid: constructed as 1x1m alignments with an ear height of 1,1m from the main floor. All the measurements are made for a hall fully occupied by the listeners.

Odeon is also capable of providing data on absorptive surfaces designed in the model. In Figure 52 and 53, the amount of absorption area used effectively by the material can be seen. It is quite logical that materials, which have high absorption values, will be efficient in the whole designed area, whereas materials with low absorption coefficients will be reflecting the sound energy in large quantities, and few areas of absorption will be used by the material.

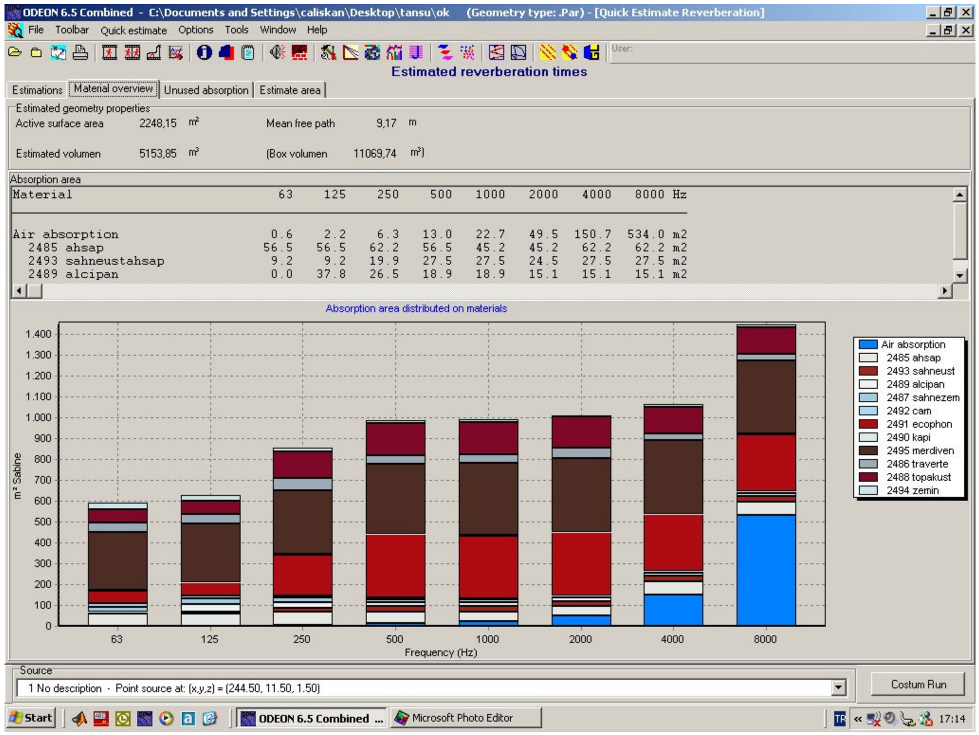


Figure 52: Material absorption areas in auditorium mode.(Fully occupied)

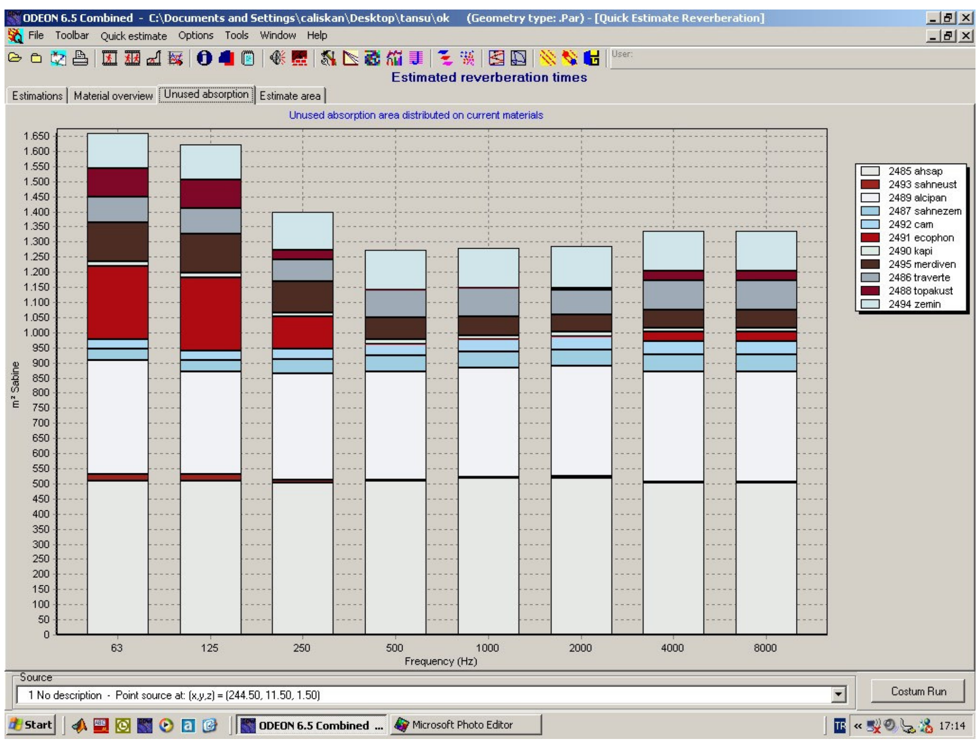


Figure 53: Unused absorption areas of materials in auditorium mode.

(Fully occupied)

In the initial phase of the analysis, the model was tested with the wooden panels on sidewalls folded and the absorptive material underneath is exposed. (Please see Fig 36) To compare with the objective and the subjective parameters defined in the previous chapters, the values for the receiver impulse response were evaluated in the first step.

In Figure 54, which shows the Binaural Impulse Response of the receiver at 13m away from the sound source, it is observed that the direct sound arrives at the listener's ears at approximately in 0,08ms. ,and the first useful reflections begin to occur 0,12-0,13ms.

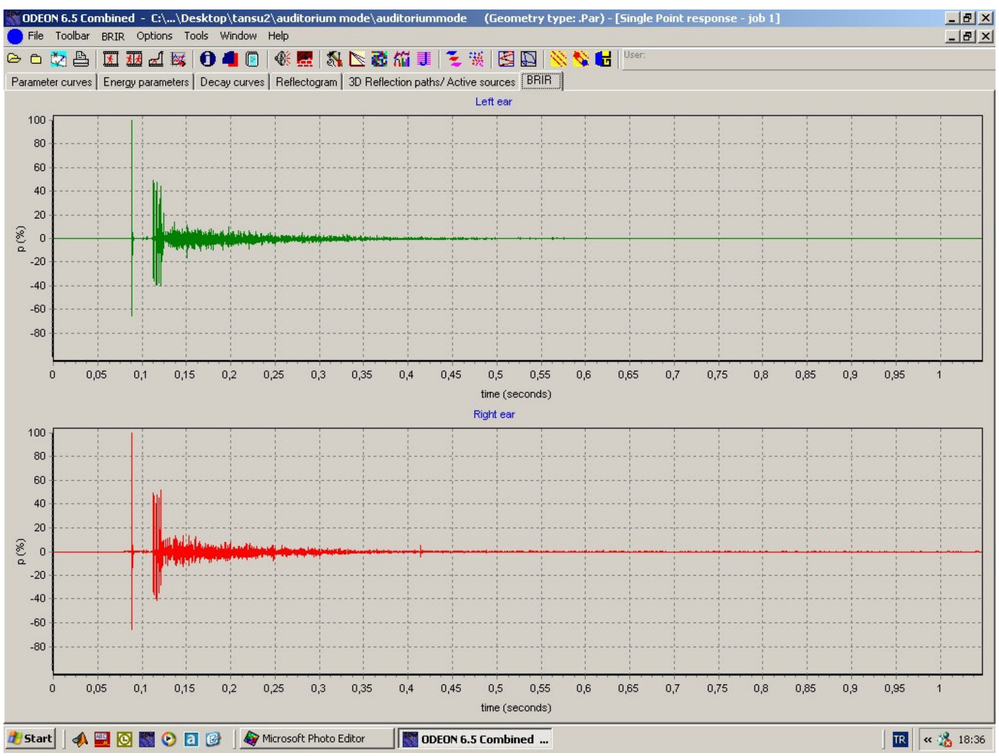


Figure 54: Binaural Impulse Response of the receiver at 13m.

Yet, in Figure 55, which is measured by placing the receiver at 20m away from the sound source and just in front of the rear wall on the central axis, the direct sound arrives at the listener’s ears at approximately in 0,12ms. , and the first useful reflections begin to occur 0,14-0,16ms.These results already satisfy the suggested initial time delay gap values that is expected to be observed for speech purposes in auditoriums, lying in between 12ms up to 25ms. As the sound is perceived in a short period of initial time delay gap interval, the hall can be considered as promising in providing an intimate condition for the selected listener. It is also considerable that after the first useful reflections, the graph follows a smooth decay without causing any peaks, which could have been considered as an echo problem at that particular time interval.

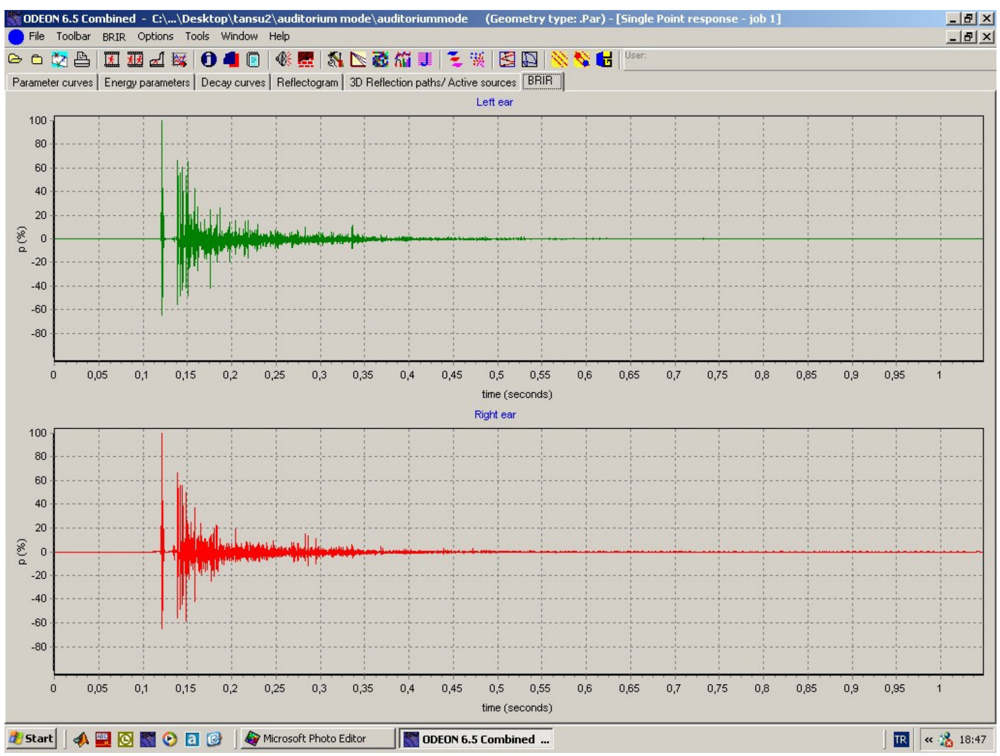


Figure 55: Binaural Impulse Response of the receiver at 20m.

From the early decay time graph, in Figure 56, it can also be observed that early decay time values are quite acceptable, except for the significant rise of EDT value at 125Hz. However, in evaluating the results, rather than commenting on a single receiver response, it will be meaningful to look for the global EDT and RT values, which will be reflecting the overall response characteristics of all listeners.

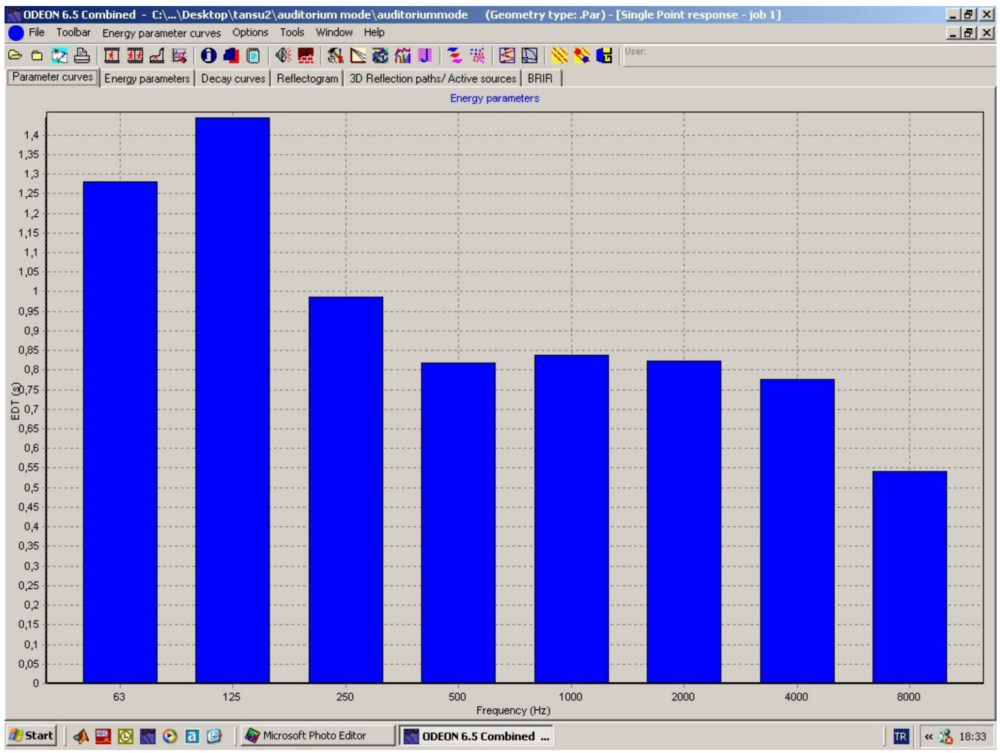


Figure 56: EDT values of the selected receiver.

In Odeon, the graph of global reverberation time indicates the entire response of the model imported, with all the surfaces are layered due to their absorption properties. For the auditorium mode, global reverberation time values for the grid system constructed is shown in Figure 57. From the graph, the following values are obtained for the reverberation time calculation of the hall:

Reverberation Times in auditorium mode (in seconds):

	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
RT	1,58	1,10	1,10	1,16	1,10	0,99

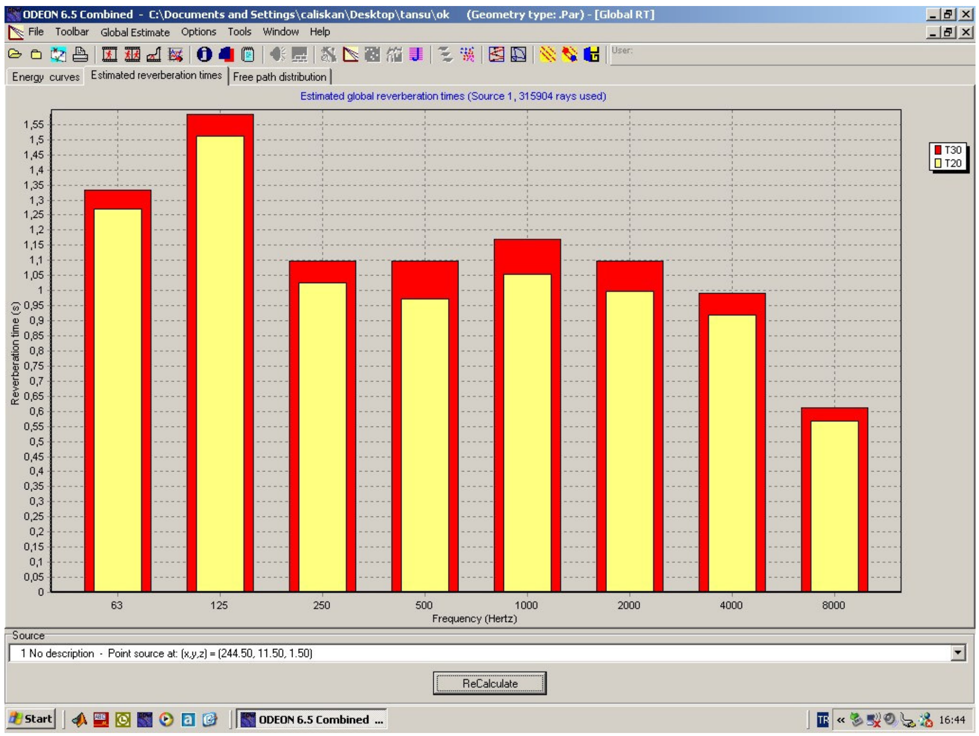


Figure 57: Global reverberation times in auditorium mode.(Fully occupied)

From the results, it can be observed that the hall has a reverberation time of 1,16s. in the frequencies which are related to speech. When dominant frequencies for speech are considered, which lies between 500Hz to 2000Hz, it is seen that the hall is in the optimum levels for the auditorium mode. In halls, acoustical warmth, namely bass ratio is desired for smoothness in the music. Its counterpart may be called as brilliance, which is thought to be a bright, ringing and clear sound. If the bass ratio of a sound is too high, or in other words, if the hall is too warm, the medium can be perceived as too "dark". The bass ratio of the hall, according to the analysis results calculated as 1,185, lies in the suggested range of 1,1 and 1,25 and acoustically can be perceived as "warm". However, a bass rise can be quite problematic if it coincides with another low frequency sound such as sound emitted by HVAC. Both sound levels at the same frequency may enhance each other and cause undesired excessive "warmth", giving a sense of "dark" hall.

In Figure 58, the free path distribution of the hall can be observed, which indicates the amount of sound rays concentrated on the listeners with respect to distance from the source. From the graph, a peak can be observed at about 11m away from the sound source showing that the sound rays are concentrated in the middle-center of the hall. That indicates the success of the ceiling and sidewall reflectors applied, to be able to provide a better diffusing sound, concentrating the central section of the listening area. Although another peak is observed in between 2 - 4m, it is quite negligible and most probably is the result of reflections coming from the stage front.

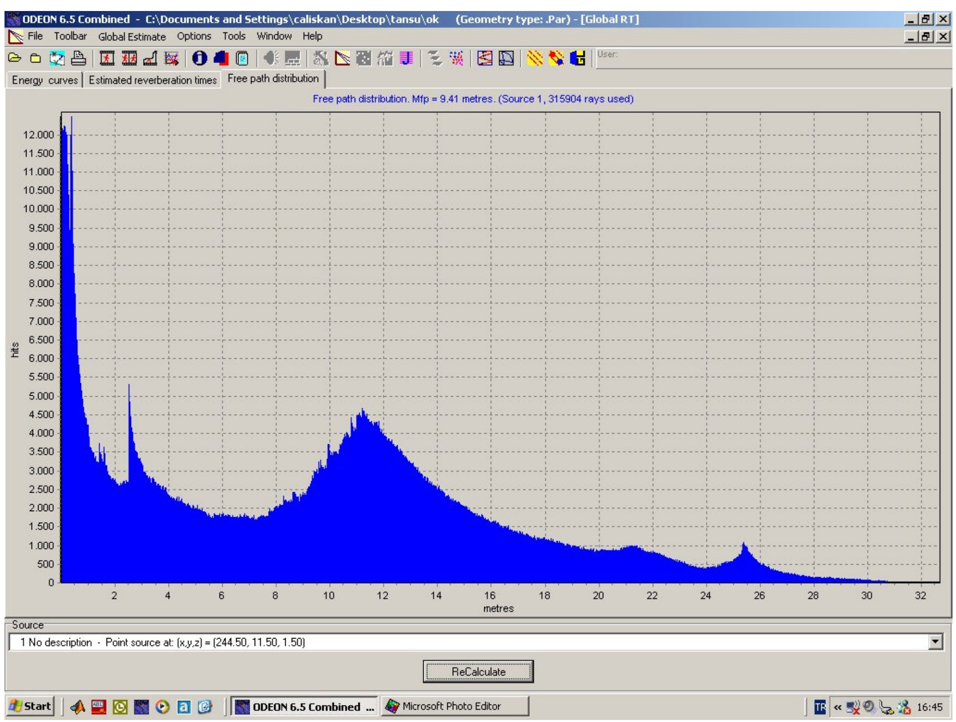


Figure 58: Free path distribution in auditorium mode.(Fully occupied)

As it is the case for the auditorium mode, it is necessary to evaluate the results in the effective dynamic range of speech, at frequencies of 500Hz, 1000Hz and 2000Hz. It will be quite understandable to indicate the values found for acoustical parameters separately and for each frequency.

First evaluation was carried about the sound pressure level (SPL) distribution among the audience area at 500Hz, 1000Hz and 2000Hz, respectively (From Figure 59 to 61). In each frequency, the sound energy distributed uniformly among the audience area, again with a uniform decrease in the SPL value, because of the increasing distance from the sound source. The hall was satisfactory in providing a diffuse sound energy in that sense.

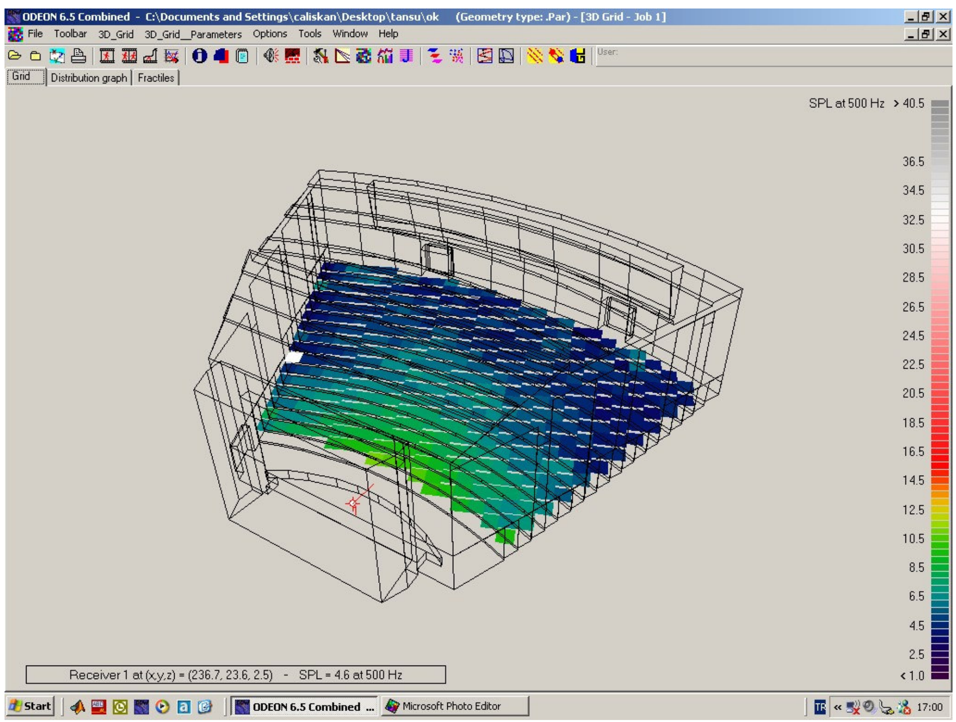


Figure 59: Sound Pressure Levels (SPL) at 500Hz in auditoriummode. (Fully occupied)

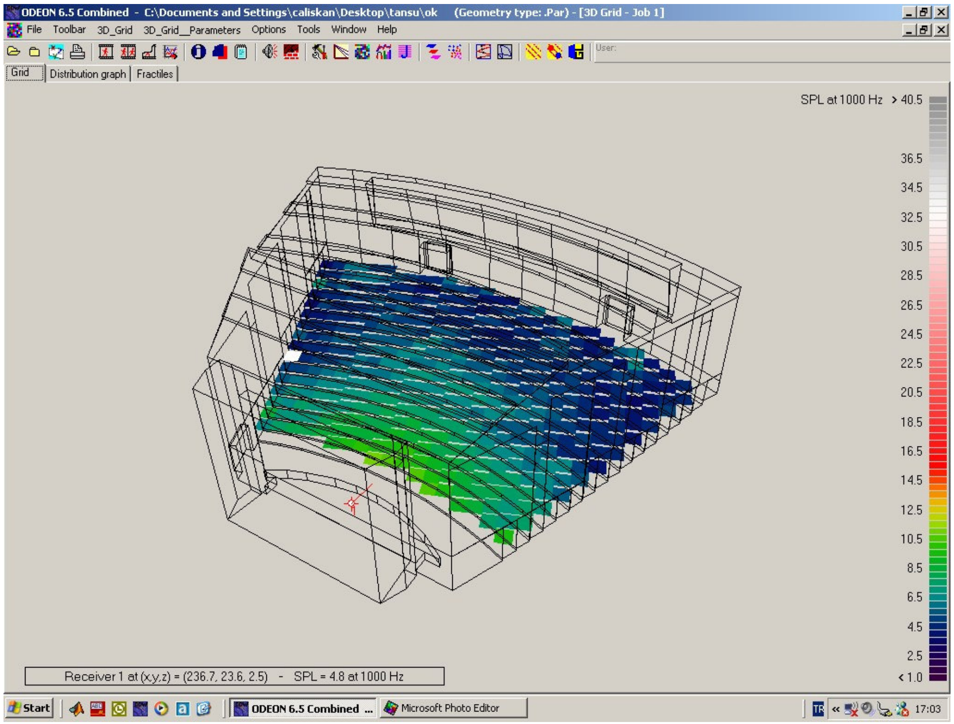


Figure 60: Sound Pressure Levels (SPL) at 1000Hz in auditorium mode.(Fully occupied)

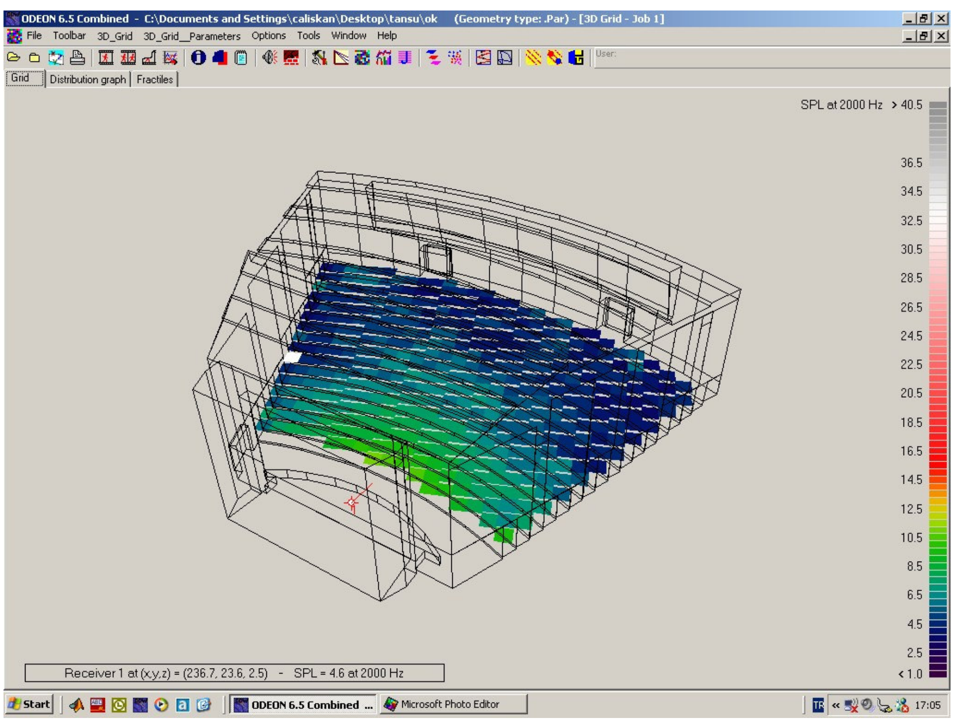


Figure 61: Sound Pressure Levels (SPL) at 2000Hz in auditorium mode.(Fully occupied)

A-Weighted SPL value (SPL(A)), which indicates the sound pressure level perceived by the human ear as a subjective judgment of SPL, are also clearly indicates the decrease in the sound energy and intensity, with the increasing distance. The graph, in that sense, didn't show any unexpected distribution among the listeners. (Figure 62)

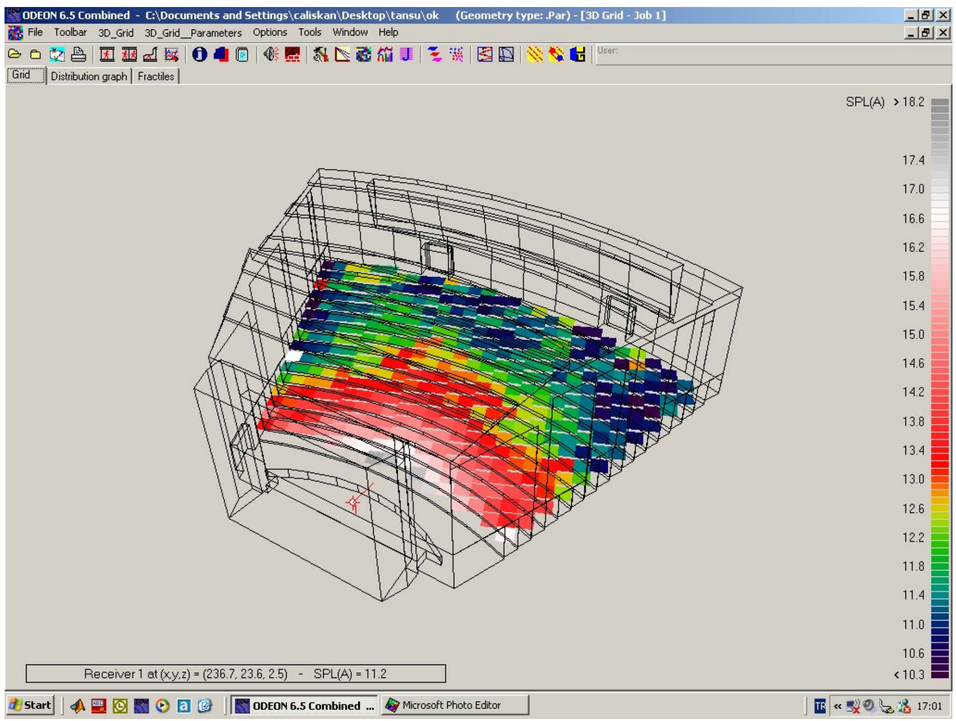


Figure 62: Sound Pressure Level (SPL(A)) (A-weighted) in auditorium mode.(Fully occupied)

Second evaluation was carried about the Early Decay Time (EDT) values among the audience area at 500Hz, 1000Hz and 2000Hz, respectively. (From Figure 63 to 65) Since EDT is a representative of RT, the sound decay occurs uniformly in the hall, with an average value of 0,89, indicating that the hall is diffuse and the reverberation is perceived uniformly by the listeners. From the graph, at 1000Hz, the value is uniformly distributed between 1,05 and 1,25, which is very consistent with the RT values. From the graph, the rear parts of the hall are of a slight lower value, mainly because of highly absorptive materials located on interior surfaces of the corners. This is a common feature of any designed hall that rear seats of the hall are generally lacking with acoustic quality, and a sightline problem is always permanent. But in this case, the decrease is almost negligible.

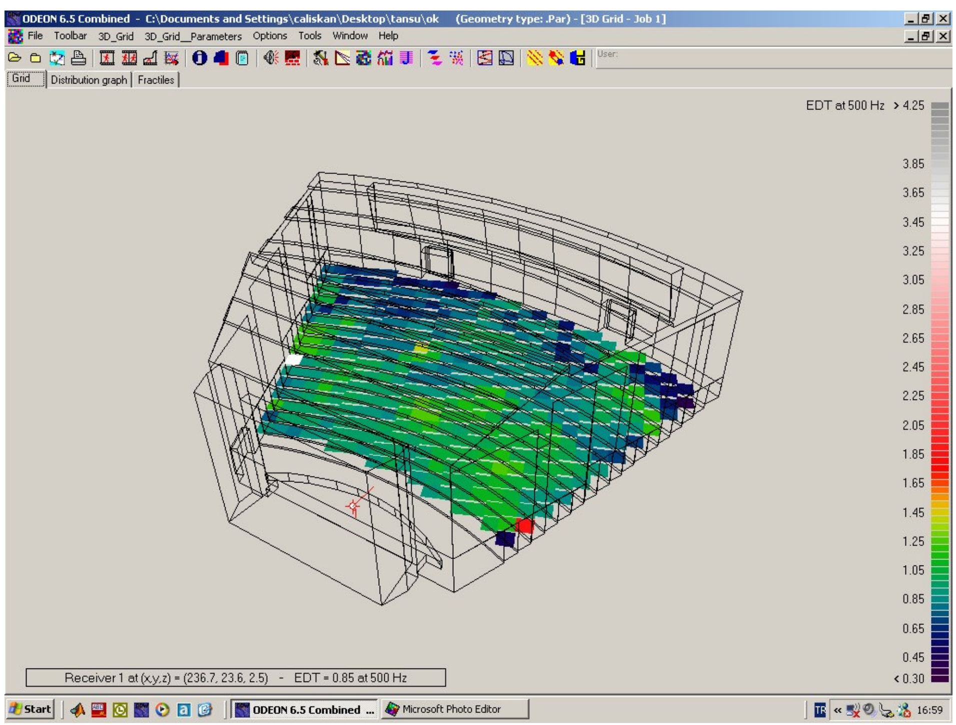


Figure 63: Early Decay Time (EDT) at 500Hz in auditorium mode. (Fully occupied)

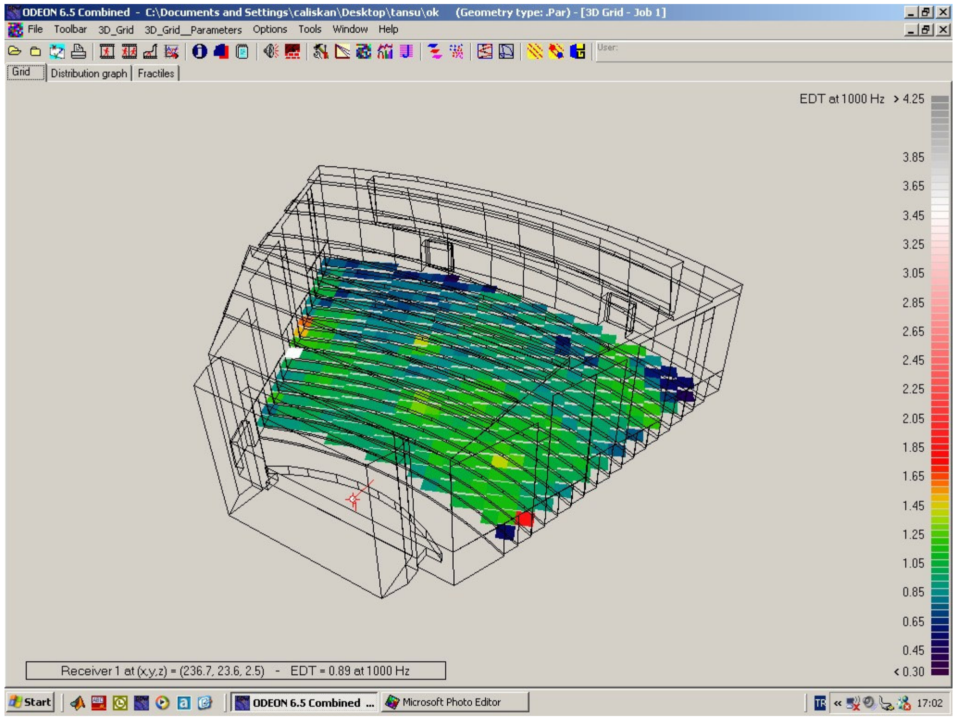


Figure 64: Early Decay Time (EDT) at 1000Hz in auditorium mode. (Fully occupied)

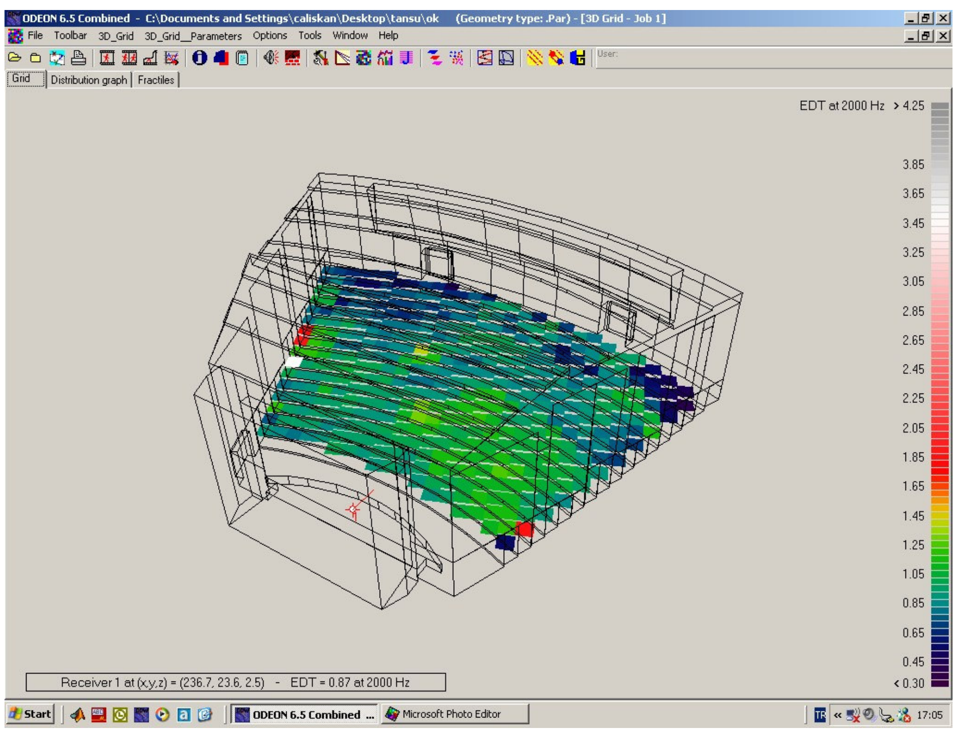


Figure 65: Early Decay Time (EDT) at 2000Hz in auditorium mode. (Fully occupied)

Third evaluation was carried about Clarity (C80) values among the audience area at 500Hz, 1000Hz and 2000Hz, respectively. (From Figure 66 to 68) Again, it can clearly be observed that the hall has a uniform distribution of C(80) value, which is approximately same at each frequency lying in between 5,6 to 5,9. Since the suggested C(80) values for halls are:

Good: for front rows from +3 to +8, and for back rows from 0 to +5

Acceptable: for front rows from >+8 and –2 to +3, and for back rows from +5 to +9

Unacceptable: for front rows from <-2, and for back rows from +9< , <-5,

The results for the front row are almost successful, while it is acceptable for back rows very close to the "good" level.

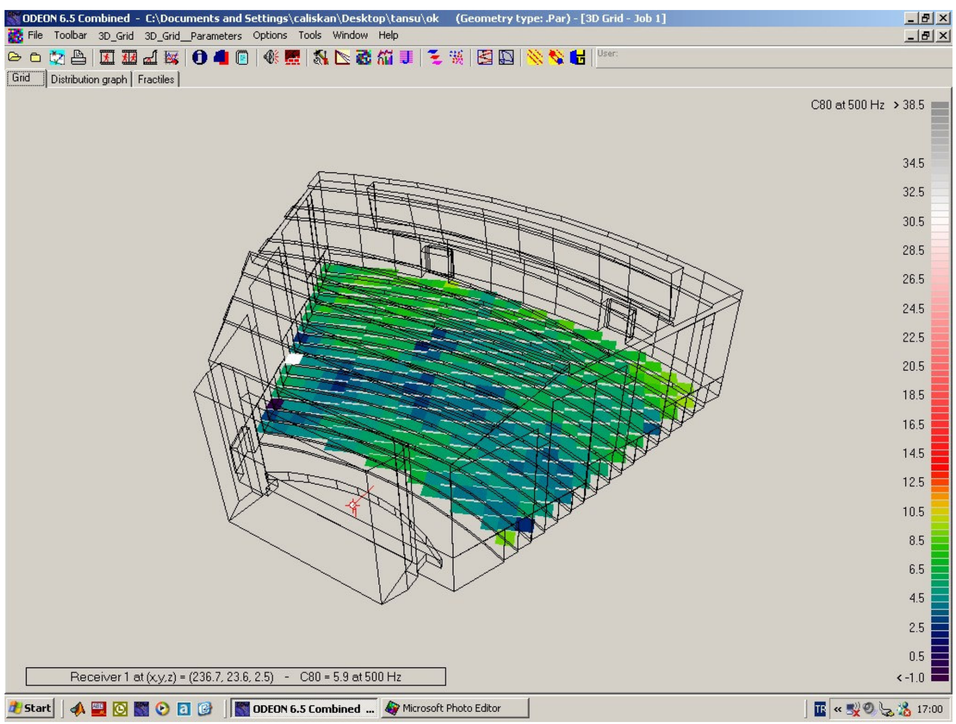


Figure 66: Clarity index at 500Hz in auditorium mode.(Fully occupied)

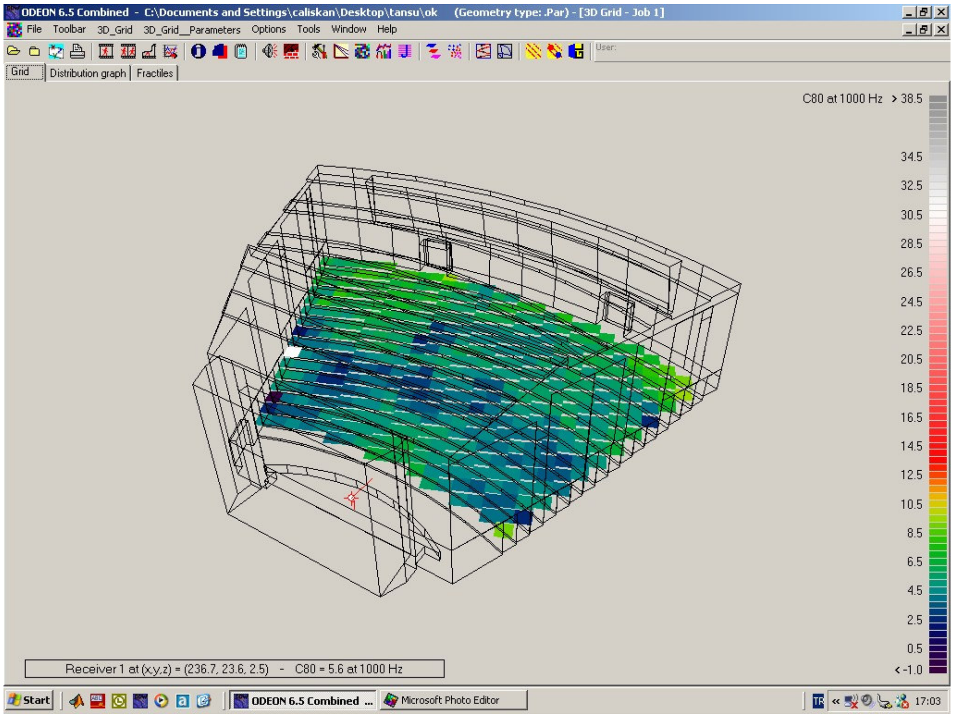


Figure 67: Clarity index at 1000Hz in auditorium mode.(Fully occupied)

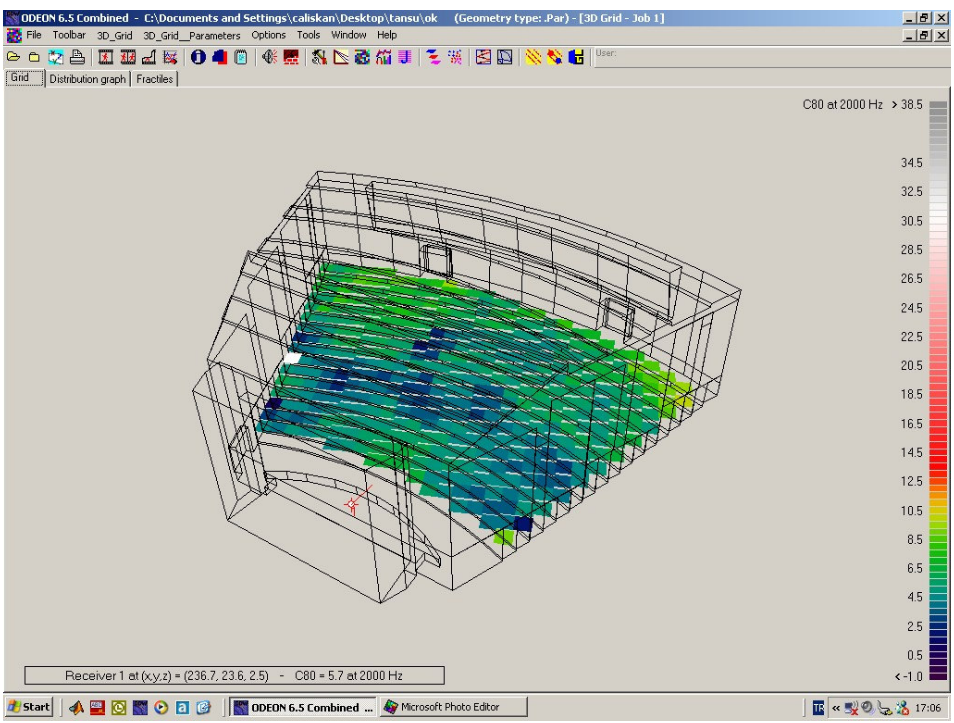


Figure 68: Clarity index at 2000Hz in auditorium mode.(Fully occupied)

Fourth evaluation was carried about Definition (D50) values among the audience area at 500Hz, 1000Hz and 2000Hz., (From Figure 69 to 71), and the results are found to be 0,72-0,70 and 0,70 for each frequency, respectively. In a satisfactory multipurpose auditorium, 65% of the words spoken should be clearly understood by the listeners, especially during lectures and seminars. The values show that approximately 70% of the words spoken in NCCA are clearly understood, and that's why the hall can be considered as acoustically intelligent", for D(50) is directly related with the speech intelligibility. The consistency of the results can be seen by the uniform distribution of definition levels in the hall, at each frequency.

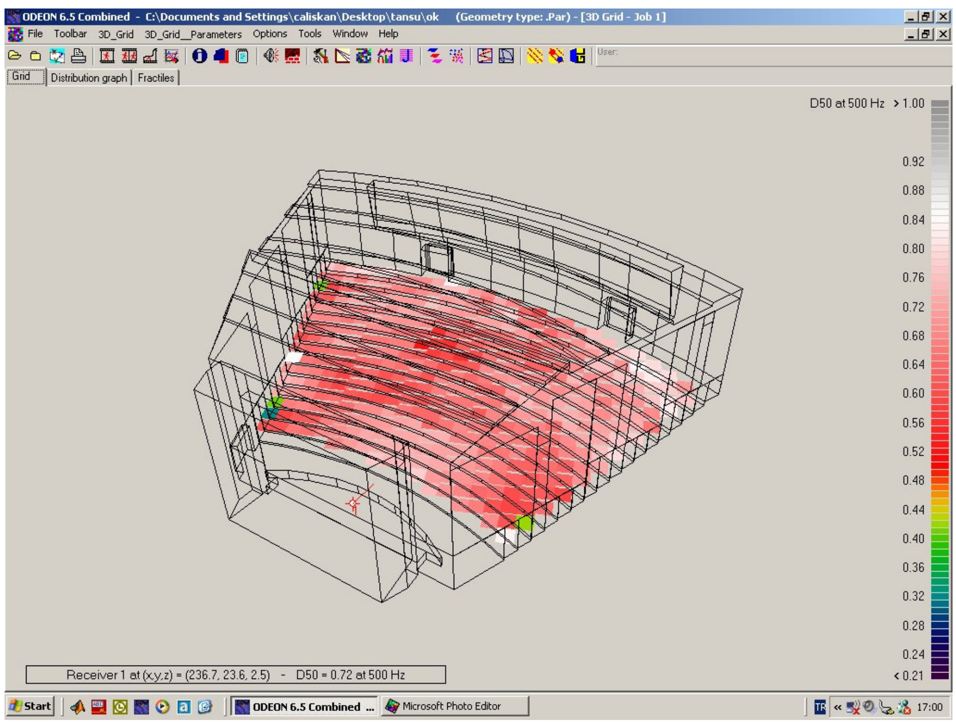


Figure 69: Definition index at 500Hz in auditorium mode.(Fully occupied)

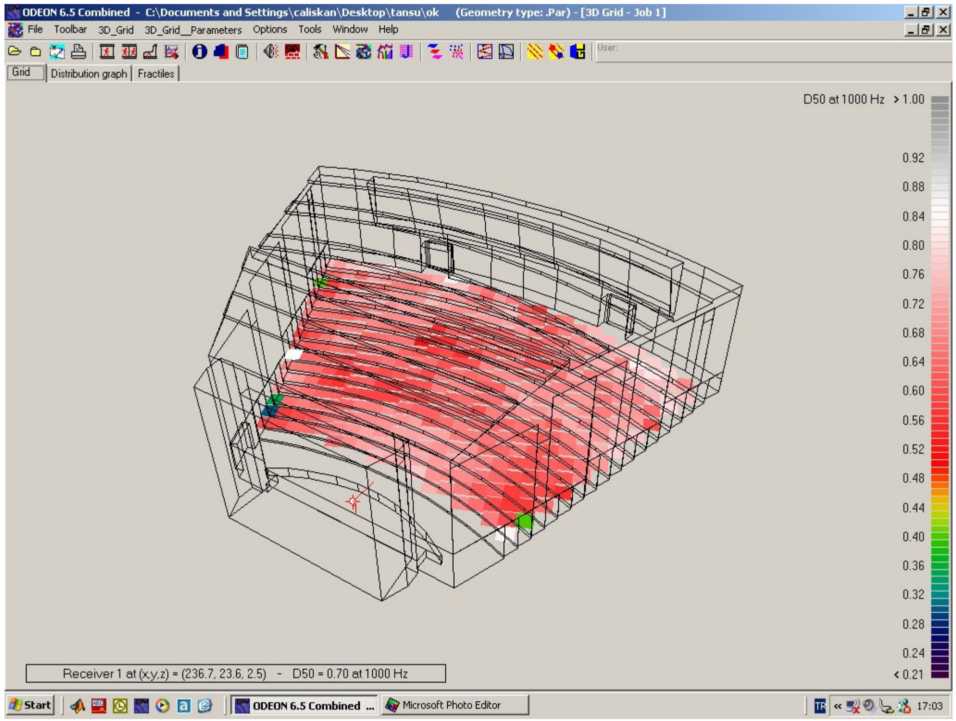


Figure 70: Definition index at 1000Hz in auditorium mode.(Fully occupied)

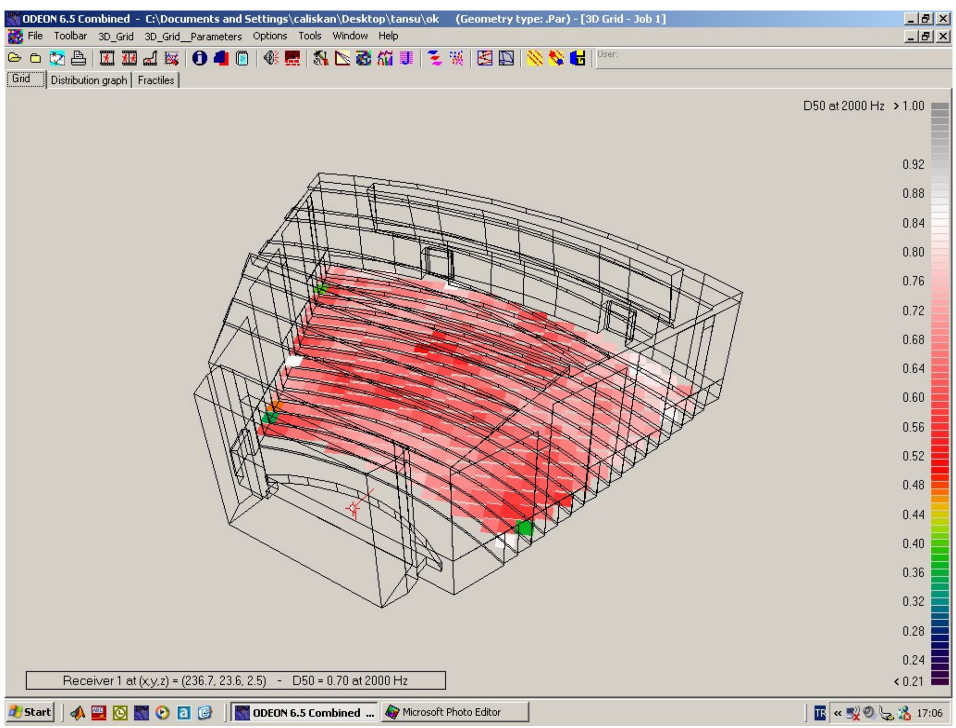


Figure 71: Definition index at 2000Hz in auditorium mode.(Fully occupied)

Fifth evaluation was carried about Lateral Fraction (LF80) values among the audience area at 500Hz, 1000Hz and 2000Hz. (From Figure 72 to 74) From the graph, it can be seen that listeners close to the sidewalls receive more lateral sound energy as compared to the listeners sitting on the central axis. And in that distribution configuration, the listeners sitting on the sides at the back rows have slightly poor values as compared to the ones sitting close to the stage, this is resulted mainly because of the fan-shape type of plan of the hall, as the lateral reflections at distant sidewalls from the stage are significantly lower as a result of longer direct sound path. Since the LF80 is related with the subjective parameter of envelopment, in the light of these results it can be told that the hall preserves "intimacy" and the feeling of "envelopment". The value at the receiver location is approximately 0,070 in each frequency range, but this is the lowest value, the other rows have nearly 0,2, which is already in the satisfaction range of LF80, considered to be between 0,1 and 0,35.

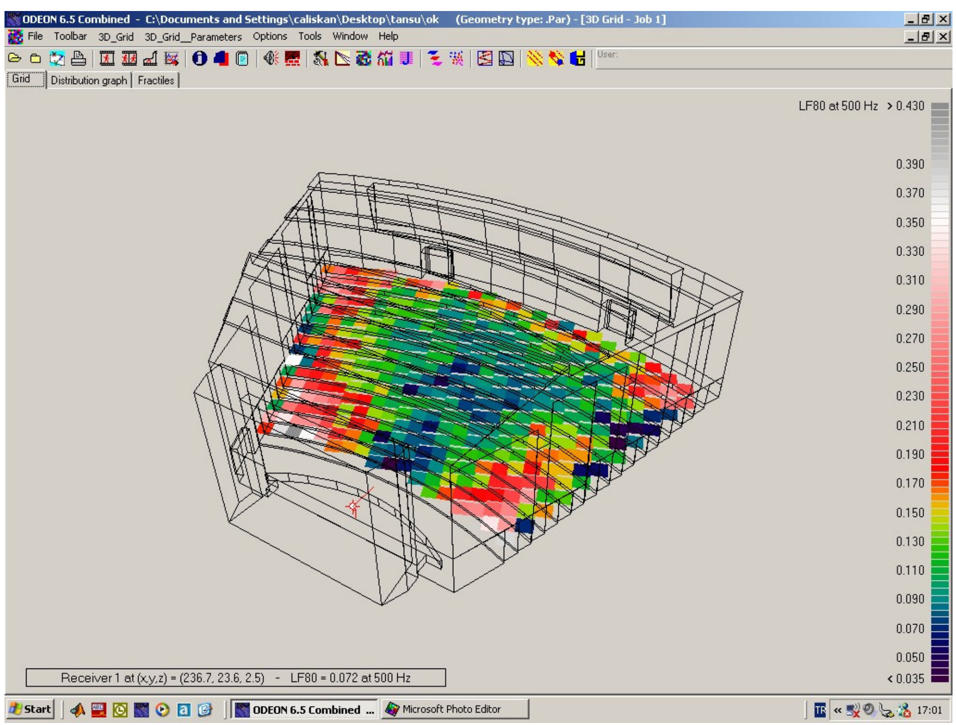


Figure 72: Lateral Fraction (LF80) at 500Hz in auditorium mode. (Fully occupied)

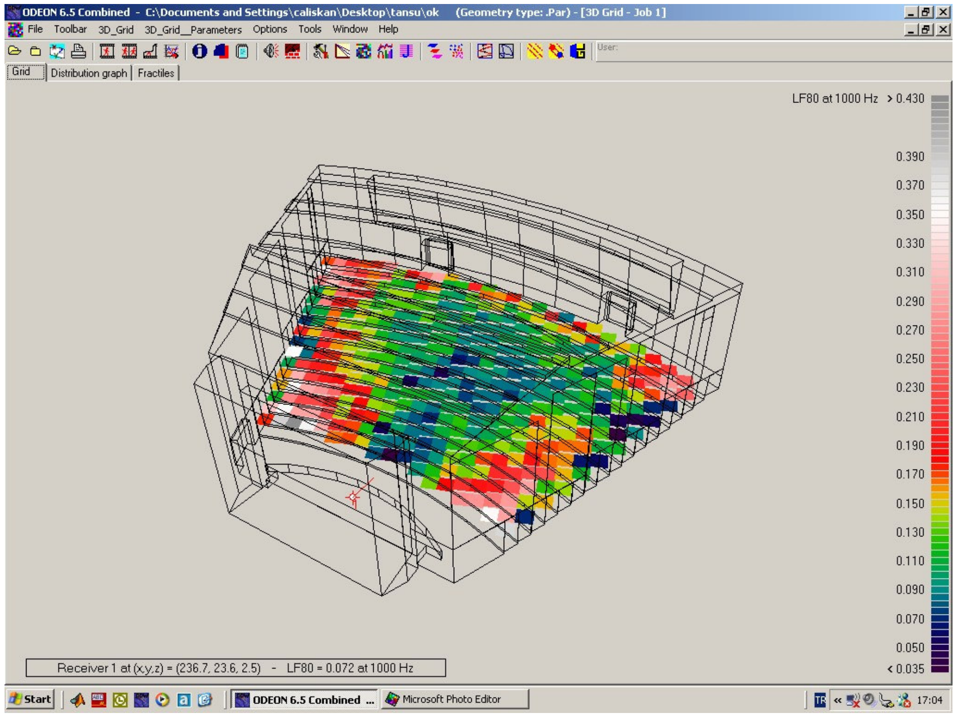


Figure 73: Lateral Fraction (LF80) at 1000Hz in auditorium mode.
(Fully occupied)

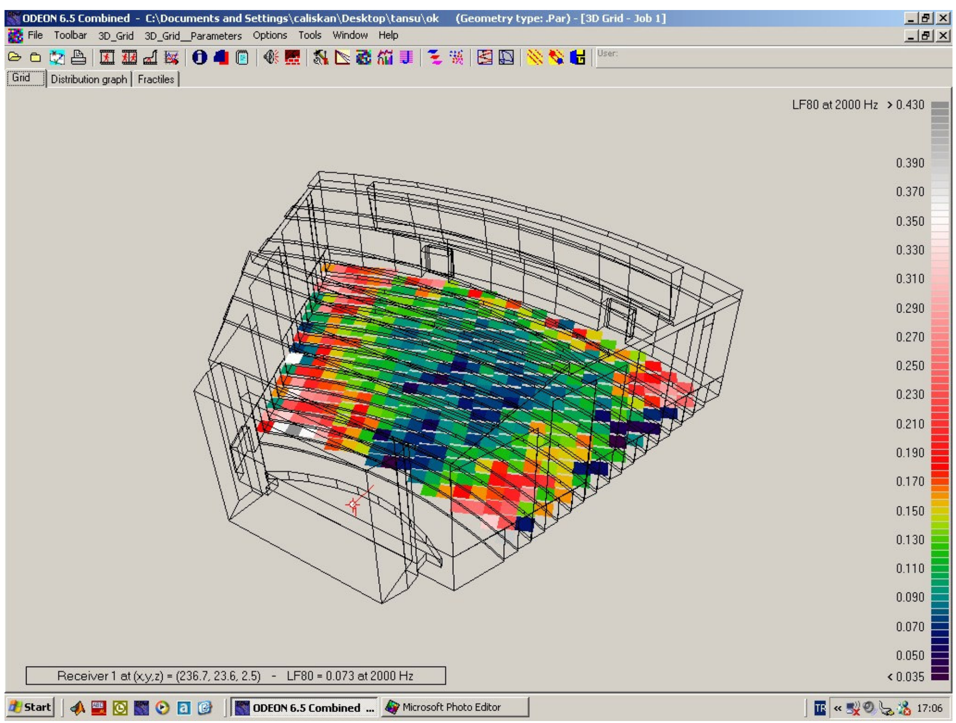


Figure 74: Lateral Fraction (LF80) at 2000Hz in auditorium mode.
(Fully occupied)

Sixth evaluation was carried about Sound Transmission Index (STI) value among the audience area. (Figure 75) The STI of the hall is found out to be 0,66, which satisfies the range for good speech intelligibility value, as the value lies in between 0,60 and 0,75. The graph can be considered as a uniform distribution. The slight decrease in central region can be explained as a result of sharp ceiling and lateral reflections, which will tend to decrease intelligibility, as the localization of sound source is rather difficult in that region and the slight increase at rear seats occurs as a result of highly absorbing materials, which tend to absorb sound energy and enhance the intelligibility.

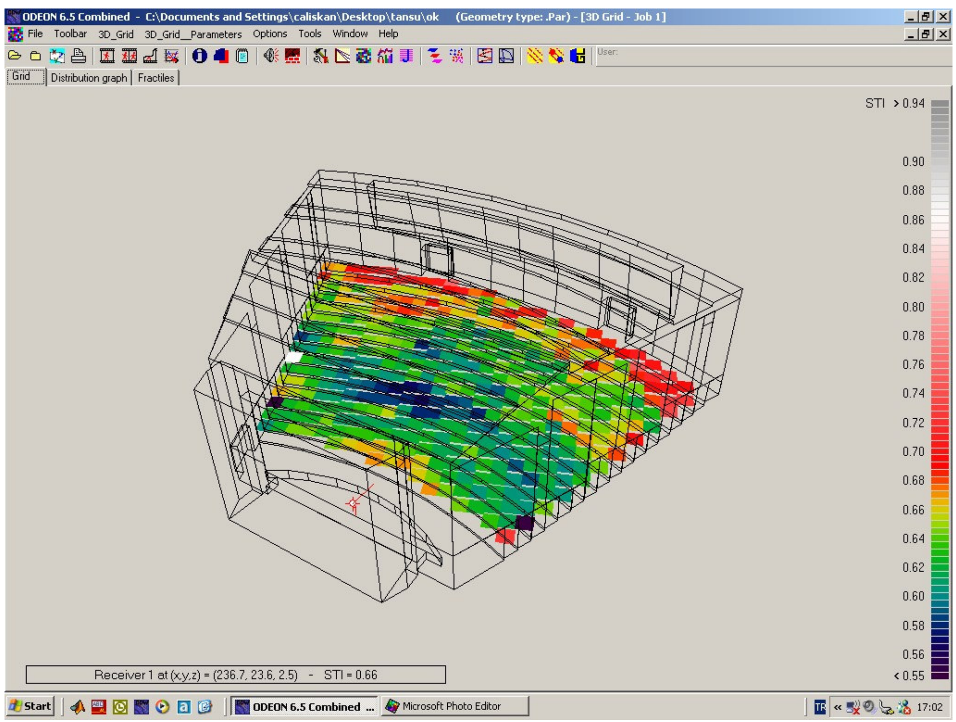


Figure 75: Sound Transmission Index (STI) in auditorium mode.
(Fully occupied)

The summary of the analysis results in auditorium mode and comparison of these results with the acceptable ranges of objective acoustical parameters can be seen in the following Table 10:

Table 8: Summary of the analysis results in auditorium mode and comparison of these results with the acceptable ranges of objective acoustical parameters.

THE OBJECTIVE PARAMETERS	THE ANALYSIS RESULTS	PERFORMANCE
Initial Time Delay Gap (ITDG) *12msec< ITDG <25msec*	ITDG= 0.08 to 0,12msec	Acceptable
Reverberation Time (RT) *Lecture / Conference room 1.0sec* *Multipurpose auditorium 1.3-1.5sec*	RT= 1,16sec	Very Good
Early Decay Time (EDT) *EDT < RT or EDT = RT (approx.)*	EDT= around 1,1msec	Acceptable
Clarity (C80) *+3 to +8 for front rows* *0 to +5 for back rows*	5,6 < C80 <5,9	Excellent
Definition (D50) *D50 > 65%*	D50= 0,7	Good
Lateral Fraction (LF80) *0.1 < LF80 < 0.35*	0.07 < LF80 < 0.2	Very Good
Sound Transmission Index (STI) *0.6 < STI <1.0*	STI= 0,66	Good
Sound Pressure Level (SPL) *Close to original level*	SPL= 4,8 SPL(A)= 11,2 (uniform)	Good
Bass Ratio (BR) *1.1< BR < 1.25*	BR= 1,185	Very Good

4.3.2 The Concert Mode

In the analysis stage of the concert, the following sound source, receiver and the grid system were used;

Sound source: at 2m back from the center stage front and 1,5m height from stage floor
Receiver: at middle center of the hall at 13m away from the stage front
Grid: constructed as 1x1m alignments with an ear height of 1,1m from the main floor. All the measurements are made for a hall fully occupied by the listeners.

Odeon is also capable of providing data on absorptive surfaces designed in the model. In Figure 76 and 77, the amount of absorption area used effectively by the material can be seen. As they have been in the auditorium case, materials with high absorption values will occupy a larger area of absorption as compared to the materials with low absorption coefficients. As an example, the upholstered seats layered in claret red color occupies a larger area of sound absorption because of its high absorption property, while, from the Figure 77, it can be observed that gypsum board panel, layered in white color reflects the great amount of its energy and has a big value of unused absorption area.

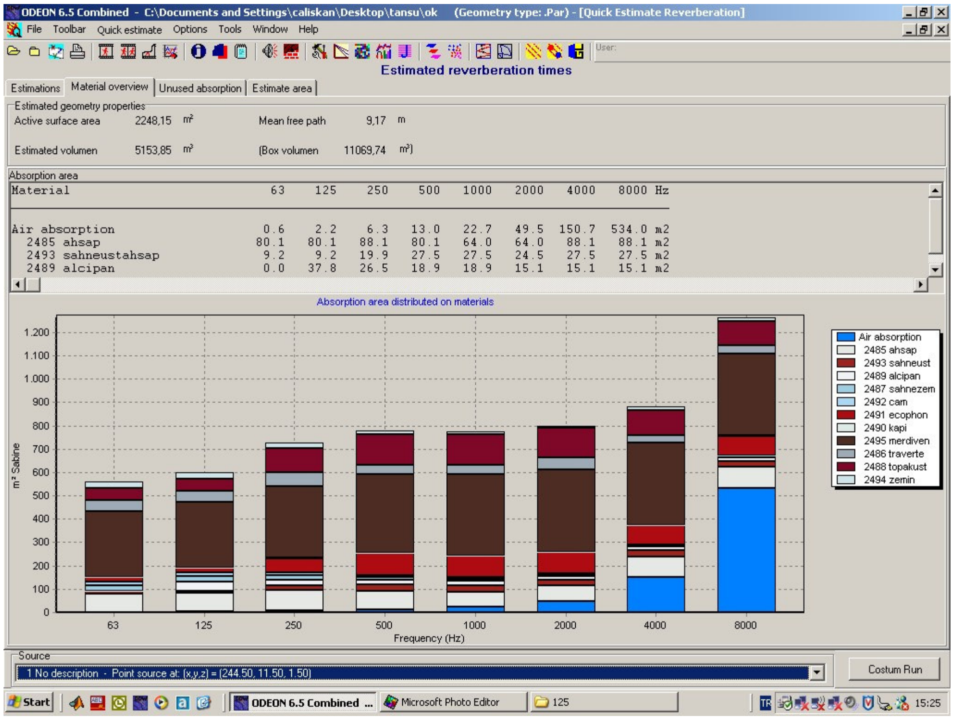


Figure 76: Material absorption areas in concert mode.(Fully occupied)

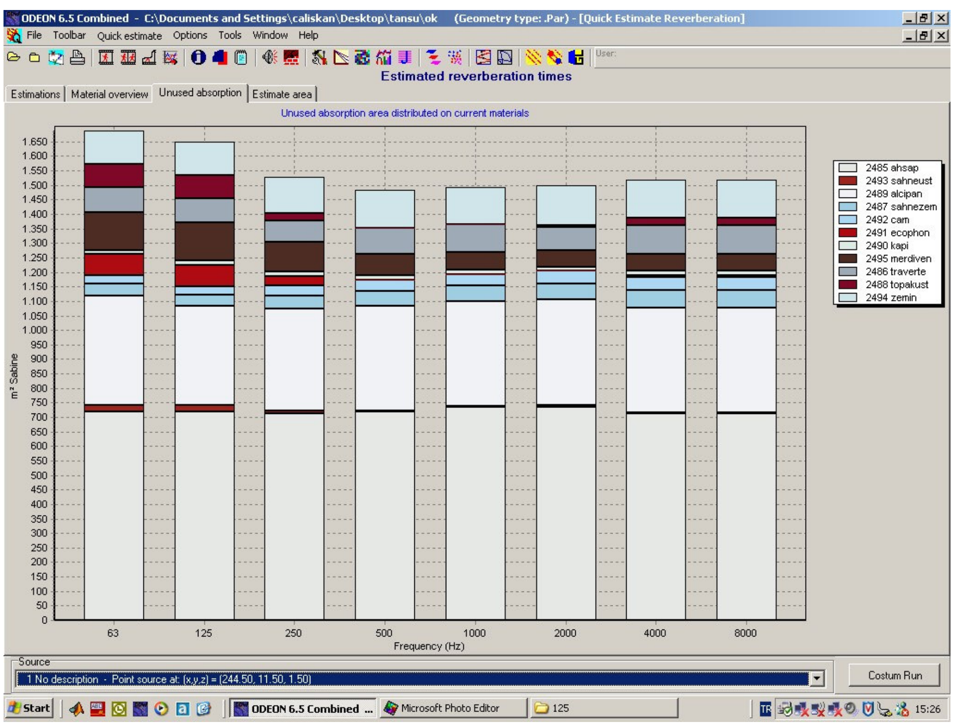


Figure 77: Unused absorption areas of materials in concert mode.
(Fully occupied)

In the second phase of the analysis, the model was tested with the wooden panels on sidewalls folded on the absorptive material, and a diffuser surface is created by the proper alignment of them (see Figure 39). To compare with the objective and the subjective parameters defined in the previous chapters, the values for the receiver impulse response were evaluated in the first step.

For the auditorium mode, global reverberation time values for the grid system constructed is shown in Figure 78. From the graph, the following values are obtained for the reverberation time calculation of the hall:

<u>Reverberation Times in concert mode (in seconds):</u>

	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
RT	1,64	1,21	1,24	1,33	1,24	1,1

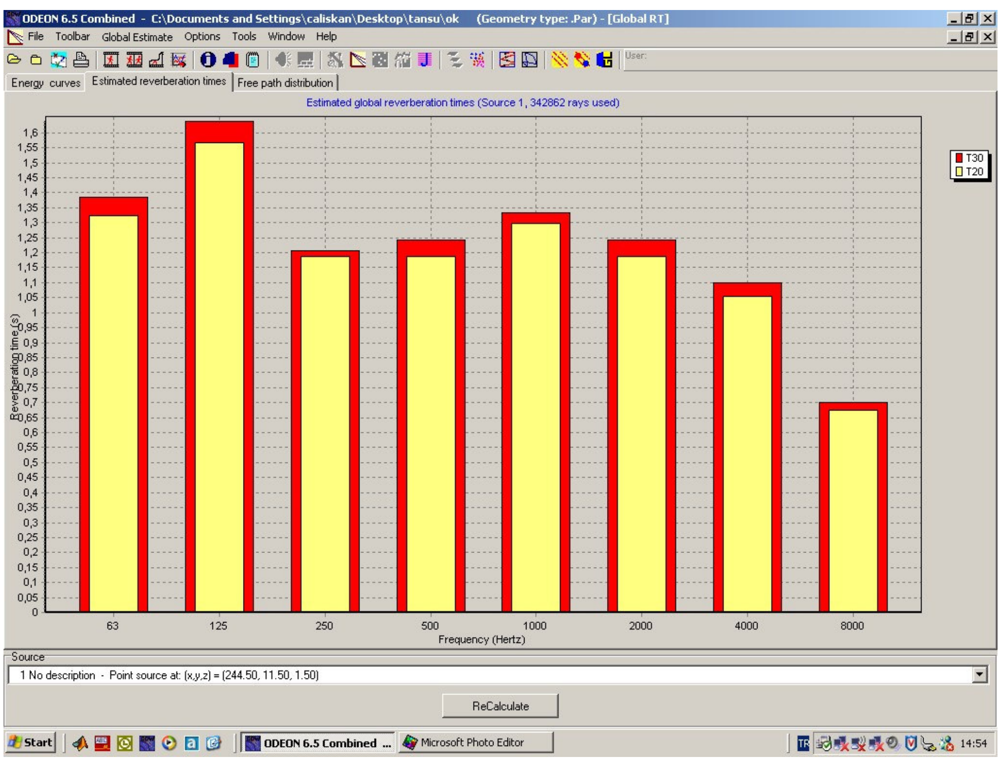


Figure 78: Global reverberation times in concert mode.(Fully occupied)

From the results, it can be observed that the hall has a reverberation time of 1,33s. in the frequencies which are related to sound. When important frequencies for speech is considered, which lies between 125Hz to 4000Hz, it is seen that the hall is in the optimum levels for the concert mode, and can be considered as "reverberant" or "live" hall. Besides, the bass ratio of the hall, according to the analysis results calculated as 1,108, lies in the suggested range of 1,1 and 1,25 and acoustically can be perceived as "warm". However, as in the case if auditorium results, a bass rise can still be quite problematic if a coincidence with the HVAC sound producing low frequency occurs. Both sound levels at the same frequency may enhance each other and cause undesired excessive "warmth", giving a sense of "dark" hall for the musical quality.

In Figure 79, the free path distribution of the hall can be observed. From the graph, a peak can be observed at about 11m away from the sound source, similar to the auditorium case, showing that the sound rays are concentrated in the middle-center of the hall. As mentioned in the previous analysis, that indicates the success of the ceiling and sidewall reflectors applied, to be able to provide a better diffusing sound, concentrating the central section of the listening area.

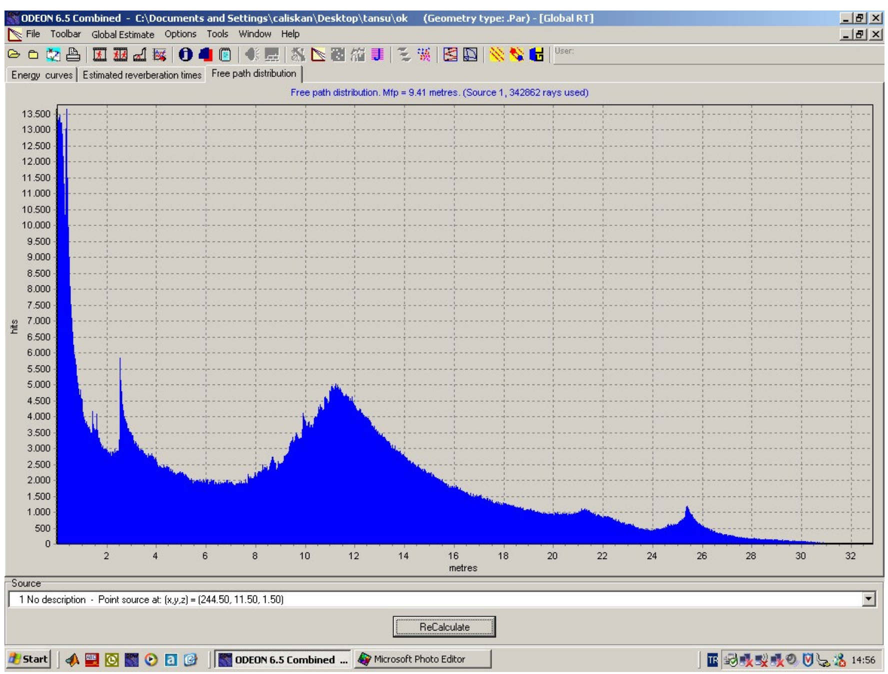


Figure 79: Free path distribution in concert mode.(Fully occupied)

In the case for the concert mode, it is necessary to evaluate the results in the effective dynamic range of sound, at frequencies of 125Hz, 1000Hz and 4000Hz. It will be quite understandable to indicate the values found for acoustical parameters separately and for each frequency, as systematically done in auditorium case.

First evaluation was carried about the sound pressure level (SPL) distribution among the audience area at 125Hz, 1000Hz and 4000Hz, respectively. (From Figure 80 to 82) In each frequency, the sound energy distributed uniformly among the audience area, again with a uniform decrease in the SPL value, because of the increasing distance from the sound source. The hall was satisfactory in providing a diffuse sound energy in that sense. It should also be noted that as the frequency increases, the values show a decrease because of the high frequency absorption ability of the hall, which are obvious in the reverberation time and total absorption values of materials.

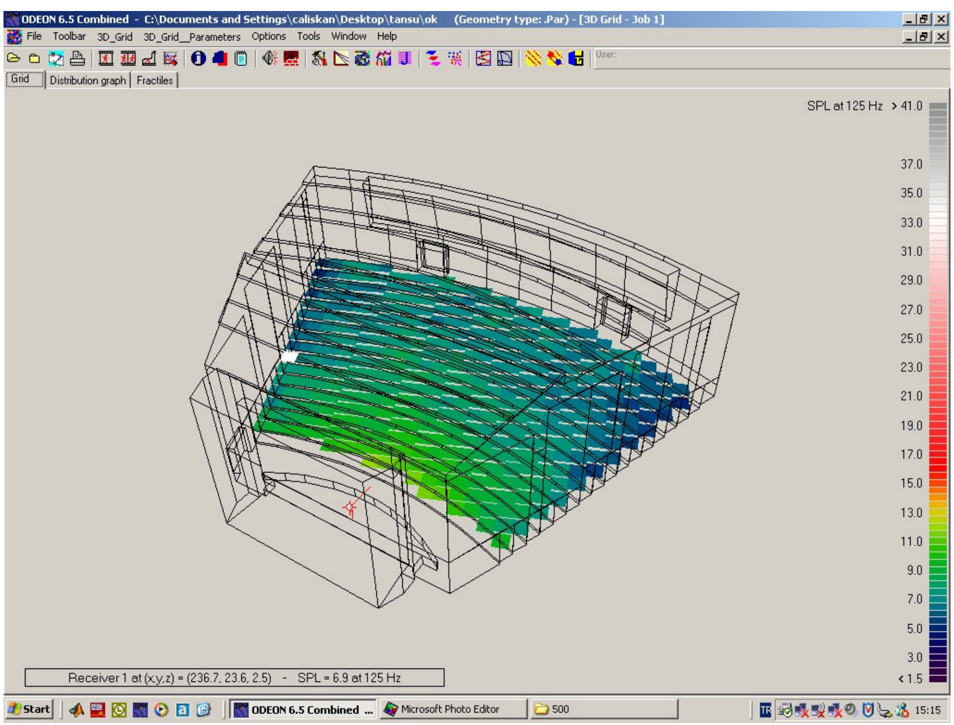


Figure 80: Sound Pressure Levels (SPL) at 125Hz in concert mode.(Fully occupied)

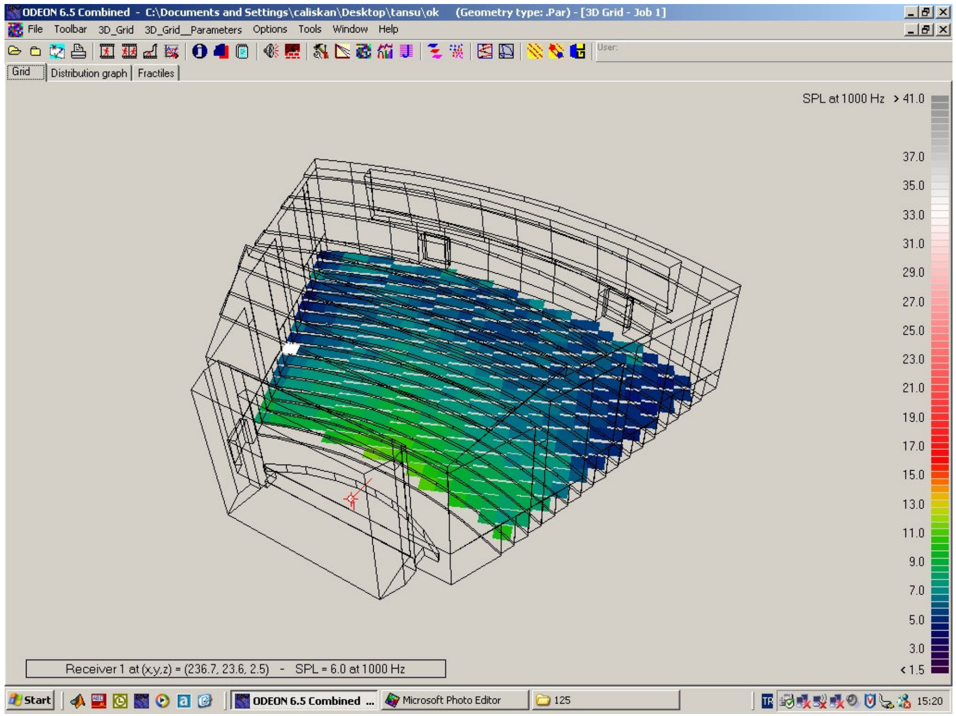


Figure 81: Sound Pressure Levels (SPL) at 1000Hz in concert mode.(Fully occupied)

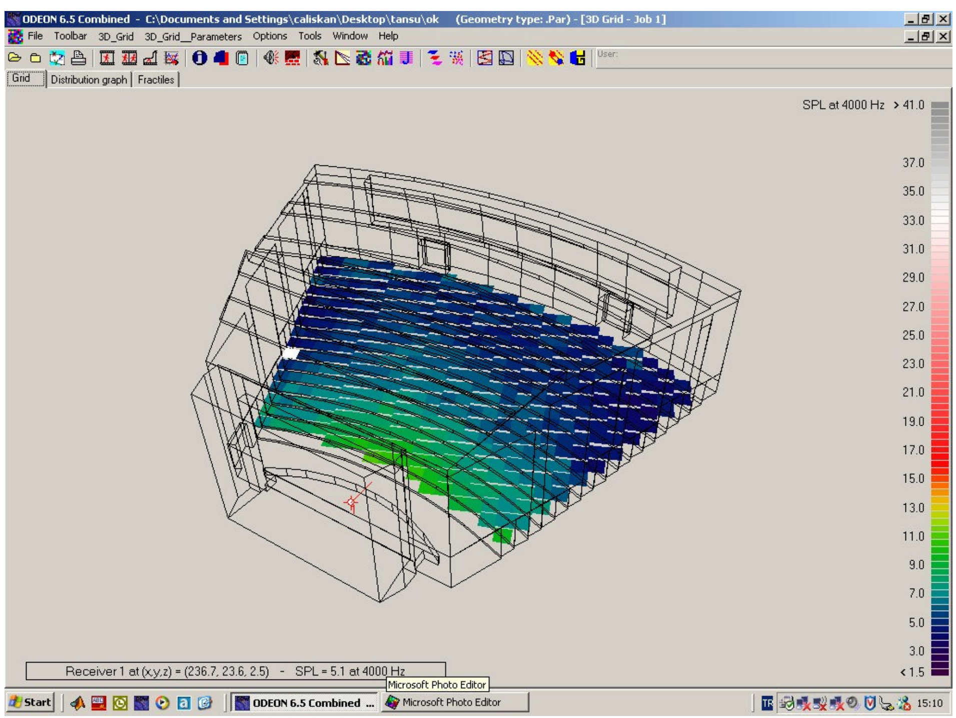


Figure 82: Sound Pressure Levels (SPL) at 4000Hz in concert mode.(Fully occupied)

A-Weighted SPL value (SPL(A)), again with a similar distribution graph, also clearly indicates the decrease in the sound energy and intensity, with the increasing distance. The graph, in that sense, didn't show any unexpected distribution among the listeners. (Figure 83)

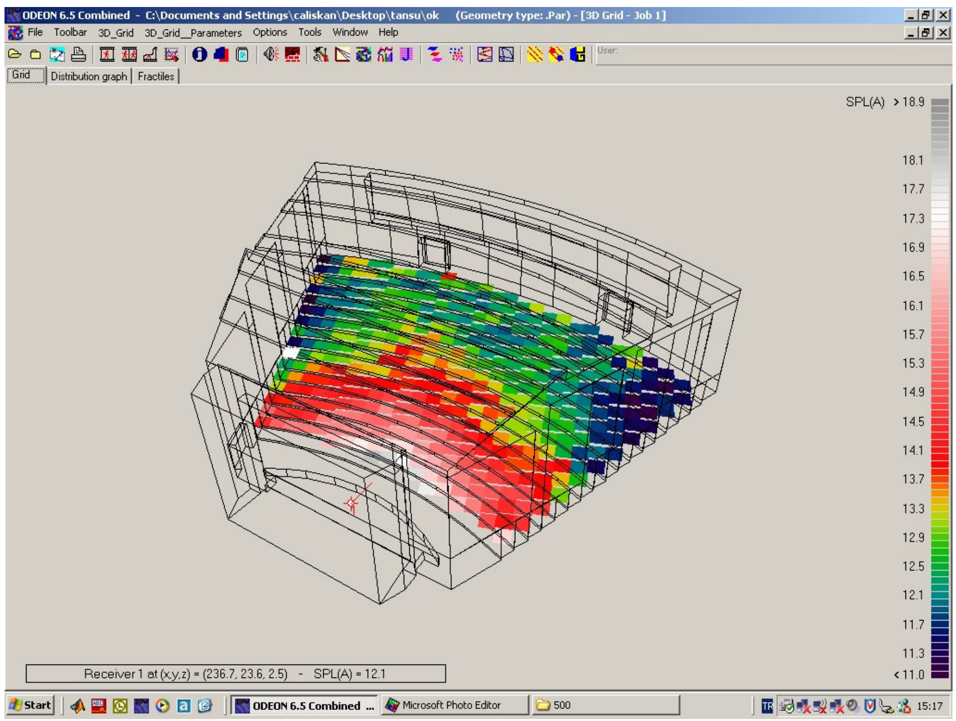


Figure 83: Sound Pressure Level (SPL(A)) (A-weighted) in concert mode.(Fully occupied)

Second evaluation was carried about the Early Decay Time (EDT) values among the audience area at 125Hz, 1000Hz and 4000Hz, respectively. (From Figure 84 to 86) Since EDT is a representative of RT, the sound decay occurs uniformly in the hall, with an average value of 1,94, indicating that the hall is diffuse and the listeners perceive the reverberation uniformly. It can be seen that the uniform distribution at 1000Hz lies between 1,1 and 1,5, which is very consistent with the RT values for the concert mode. The slight lower values at the rear parts of the hall because of highly absorptive materials located on interior surfaces of the corners, which is very probable.

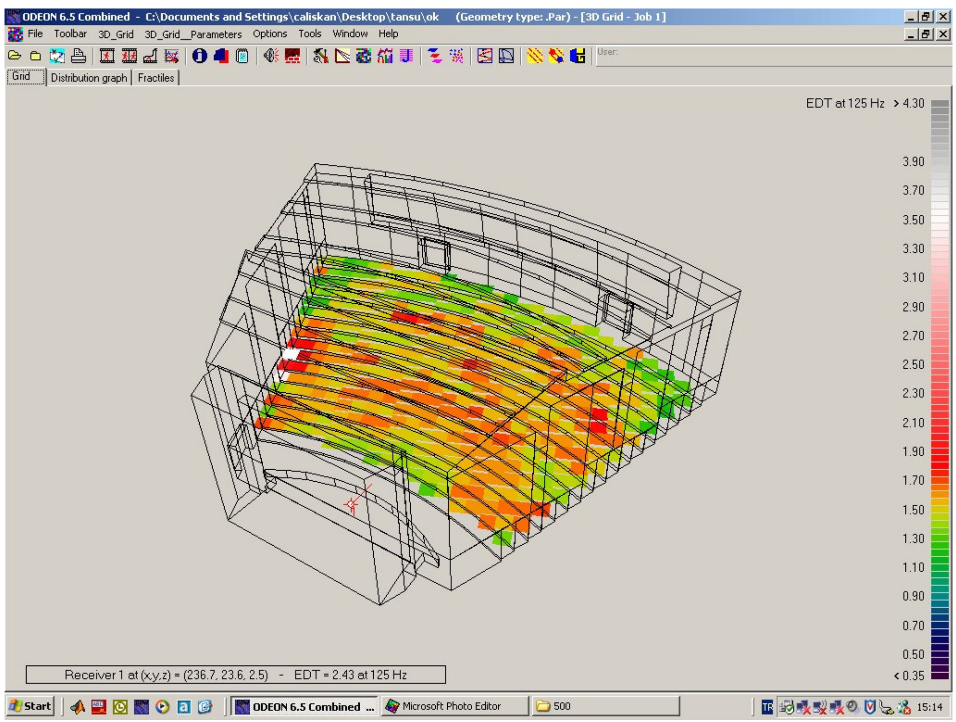


Figure 84: Early Decay Time (EDT) at 125Hz in concert mode.
(Fully occupied)

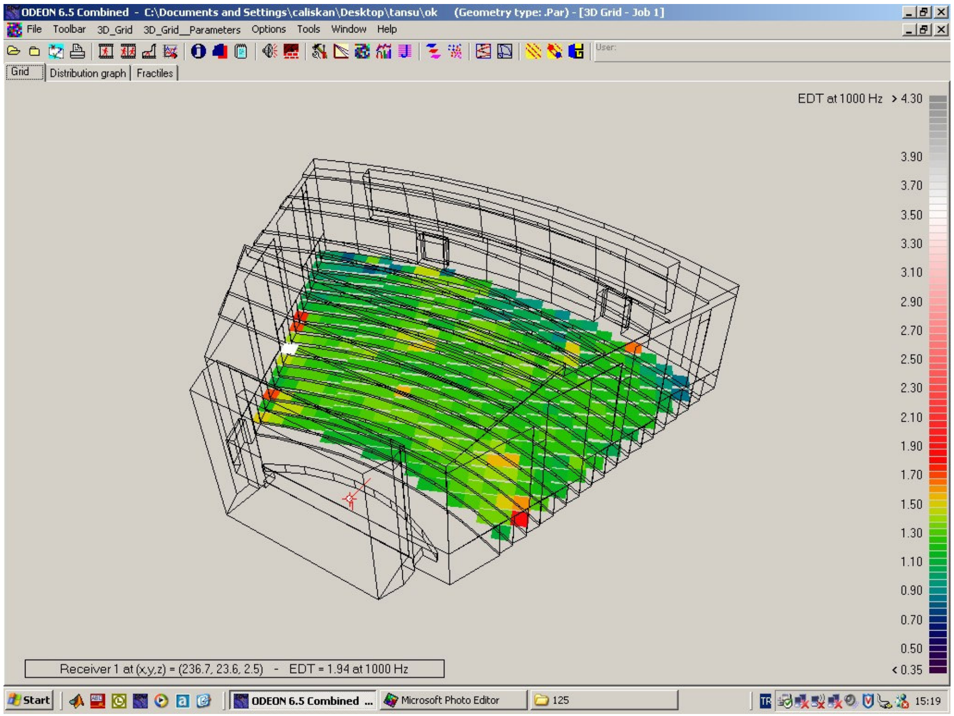


Figure 85: Early Decay Time (EDT) at 1000Hz in concert mode. (Fully occupied)

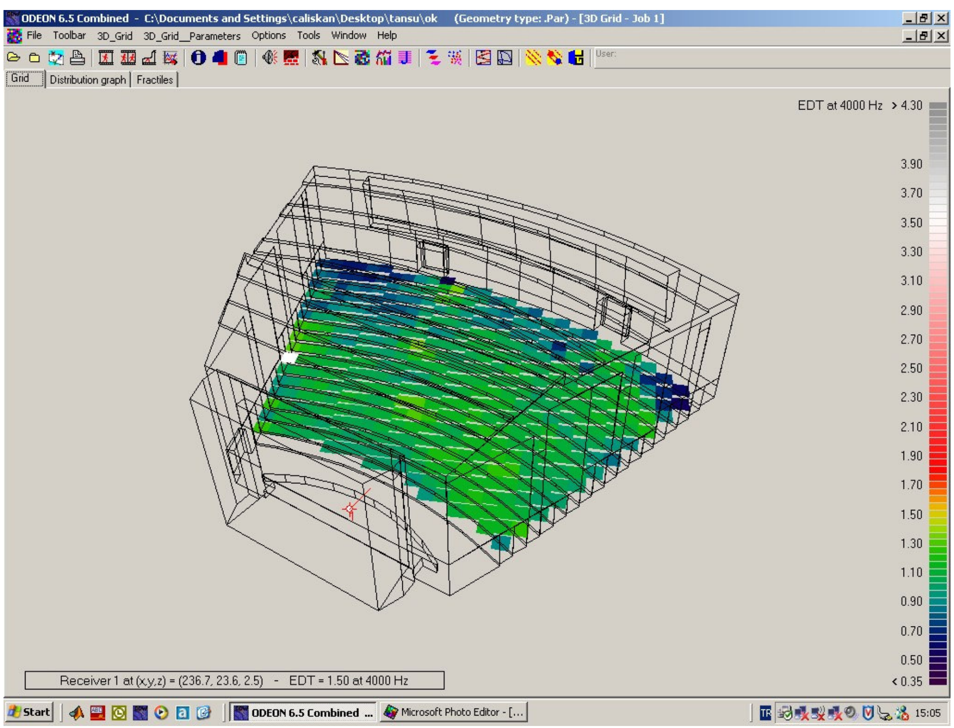


Figure 86: Early Decay Time (EDT) at 4000Hz in concert mode. (Fully occupied)

Third evaluation was carried about Clarity (C80) values among the audience area at 125Hz, 1000Hz and 4000Hz, respectively. (From Figure 87 to 89) Again, it can clearly be observed that the hall has a uniform distribution of C(80) value, which is approximately same at each frequency lying in between –0,1 to 3,8. Since the suggested C(80) values for halls are:

Good: for front rows from +3 to +8, and for back rows from 0 to +5

Acceptable: for front rows from >+8 and –2 to +3, and for back rows from +5 to +9

Unacceptable: for front rows from <-2, and for back rows from +9< , <-5,

The results for both front rows and for the back rows are lying in the range of “good” in terms of clarity. The hall can be considered to be “clear”, which enhances musical harmony and intelligibility.

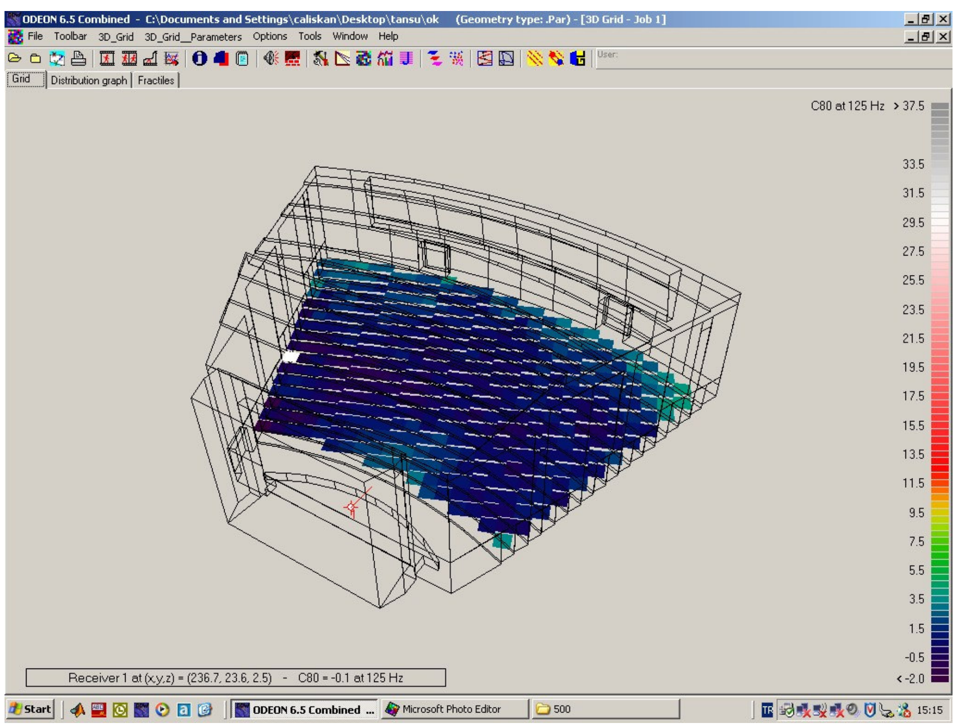


Figure 87: Clarity index at 125Hz in concert mode.(Fully occupied)

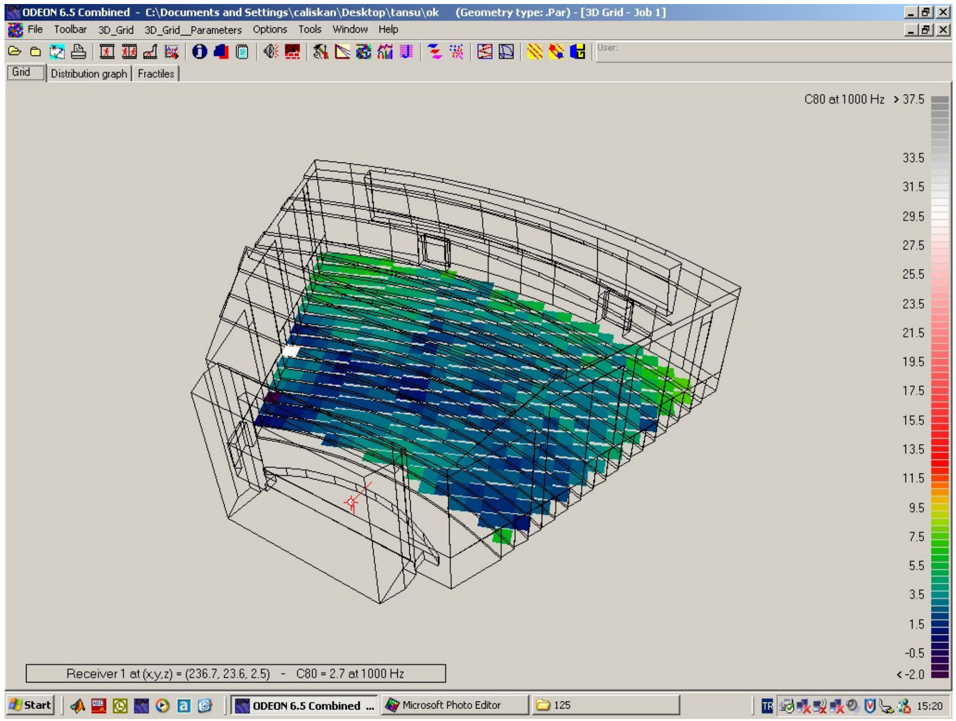


Figure 88: Clarity index at 1000Hz in concert mode.(Fully occupied)

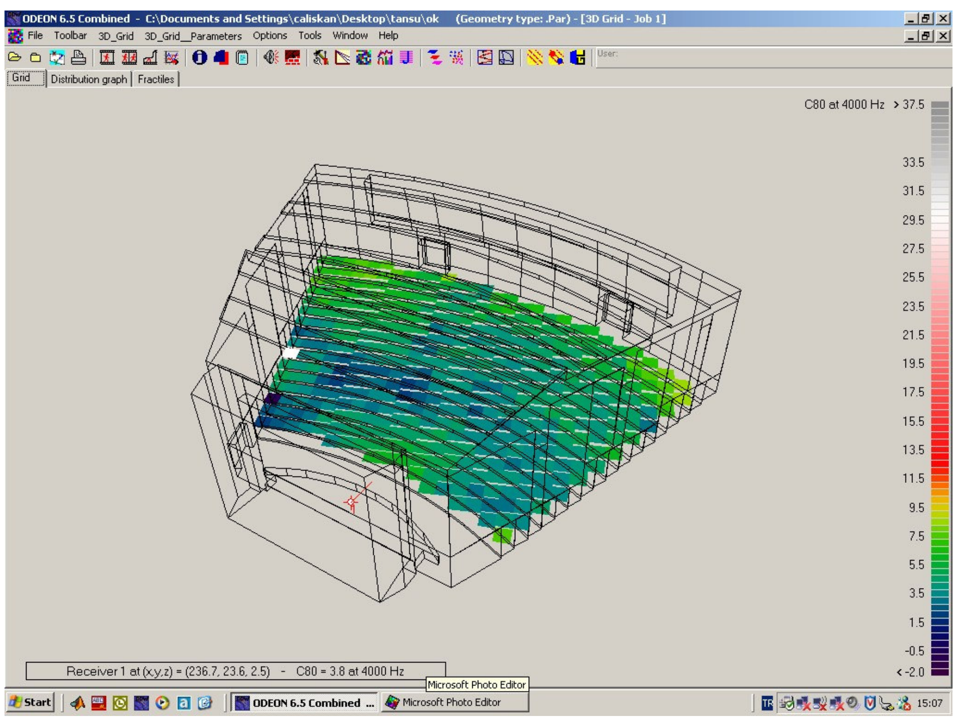


Figure 89: Clarity index at 4000Hz in concert mode.(Fully occupied)

Fourth evaluation was carried about Definition (D50) values among the audience area at 125Hz, 1000Hz and 4000Hz., (From Figure 90 to 92), and the results are found to be 0,42-0,56 and 0,62 for each frequency, respectively. In a satisfactory multipurpose auditorium, the definition values are much more important in auditorium purposes as compared to the concert performances. In that sense, the average value of D50 lies around 56%, which is slightly lower than the expected value of 65%, but it should also be underlined that it is considerable to have a lower value, since the priority of the term “definition” is vital in the auditorium mode. In addition, the consistency of the results can be seen by the uniform distribution of definition levels in the hall, at each frequency.

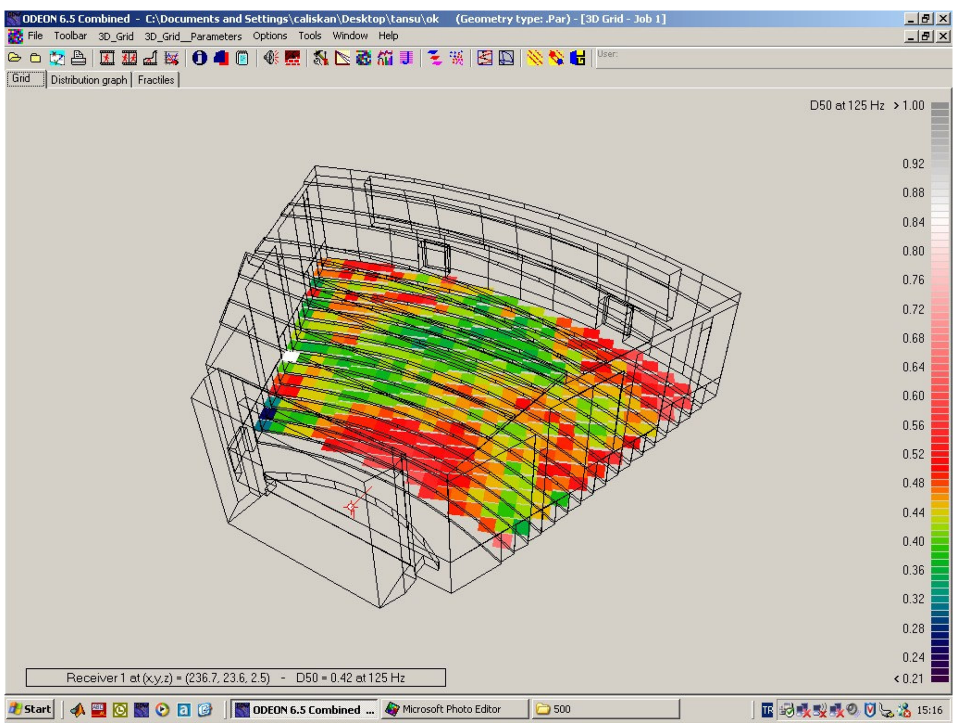


Figure 90: Definition index at 125Hz in concert mode.(Fully occupied)

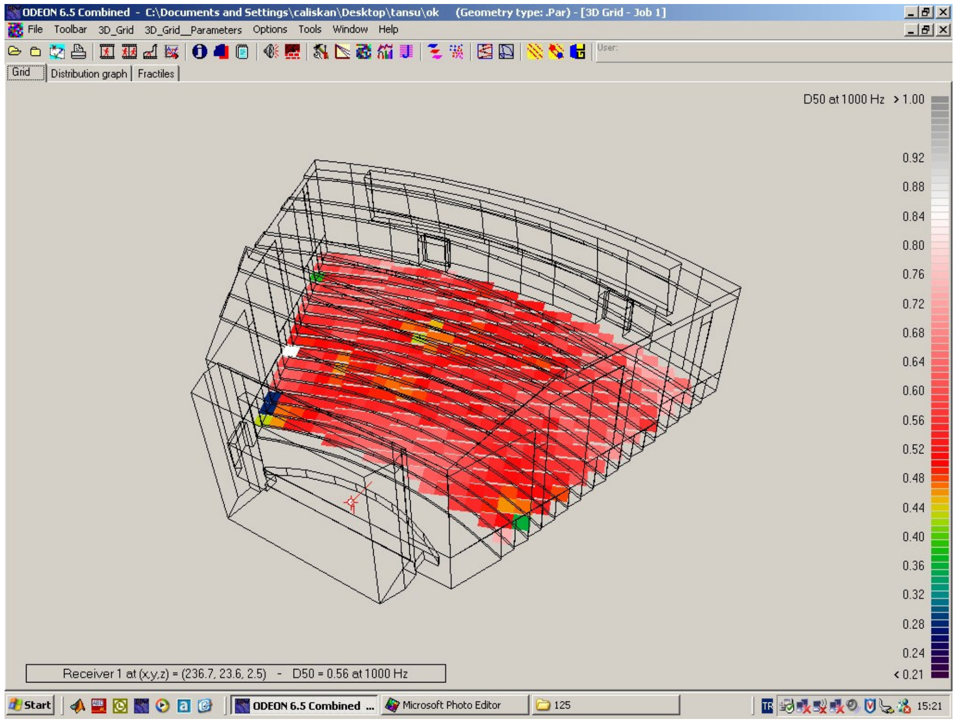


Figure 91: Definition index at 1000Hz in concert mode.(Fully occupied)

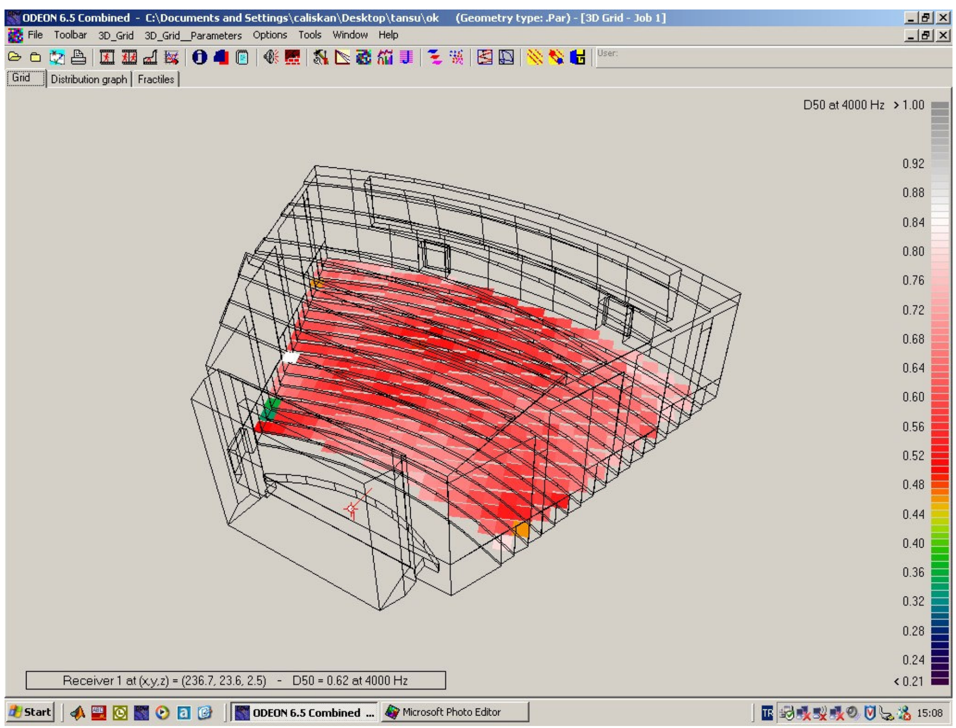


Figure 92: Definition index at 4000Hz in concert mode.(Fully occupied)

Fifth evaluation was carried about Lateral Fraction (LF80) values among the audience area at 125Hz, 1000Hz and 4000Hz. (From Figure 93 to 95) From the graph, it can be seen that listeners close to the sidewalls receive more lateral sound energy as compared to the listeners sitting on the central axis. And in that distribution configuration, the listeners sitting on the sides at the back rows have slightly poor values as compared to the ones sitting close to the stage, this is resulted mainly because of the fan-shape type of plan of the hall, as mentioned previously in the auditorium mode analysis, as the lateral reflections at distant sidewalls from the stage are significantly lower as a result of longer direct sound path.

Since the LF80 is related with the subjective parameter of envelopment, in the light of these results it can be told that the hall preserves "intimacy" and the feeling of "envelopment". The value at the receiver location is approximately 0,1 in each frequency range, but this is the lowest value, the other rows have nearly 0,23, which is already satisfied in terms of LF80, considered to be between 0,1 and 0,35. From the graph, it is also obvious that the acoustical door enclosure on the left wall creates some extra reflections, which can be seen in the graph with high value indicators, as "white". This issue can easily be solved by the proper treatment of door enclosure, probably by using a more absorptive treatment inside the enclosure or to close it with the help of a movable panel.

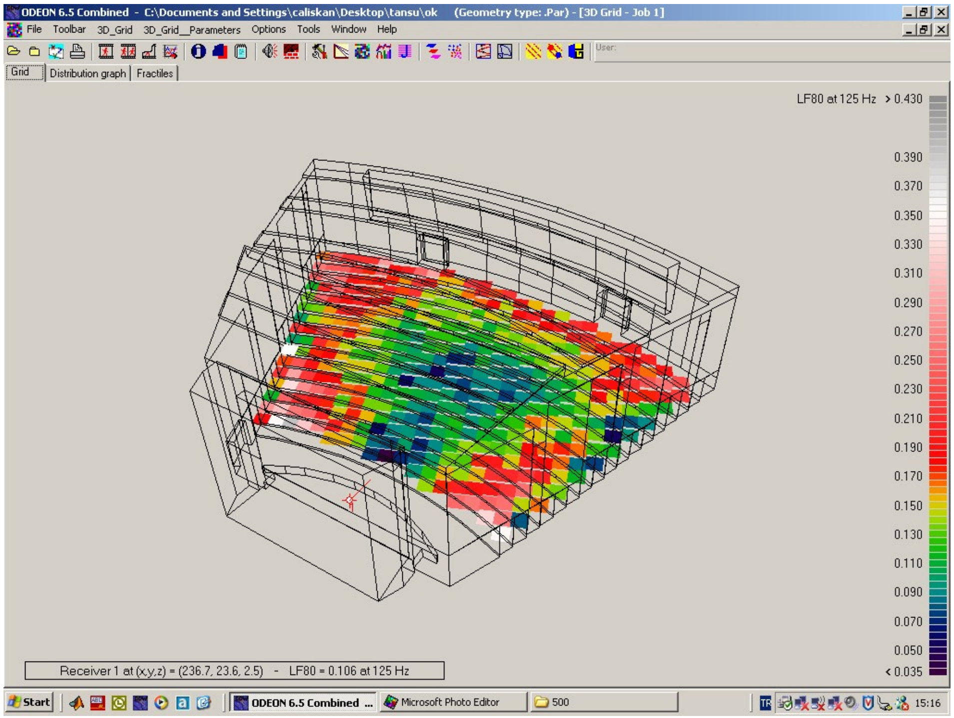


Figure 93: Lateral Fraction (LF80) at 125Hz in concert mode.
(Fully occupied)

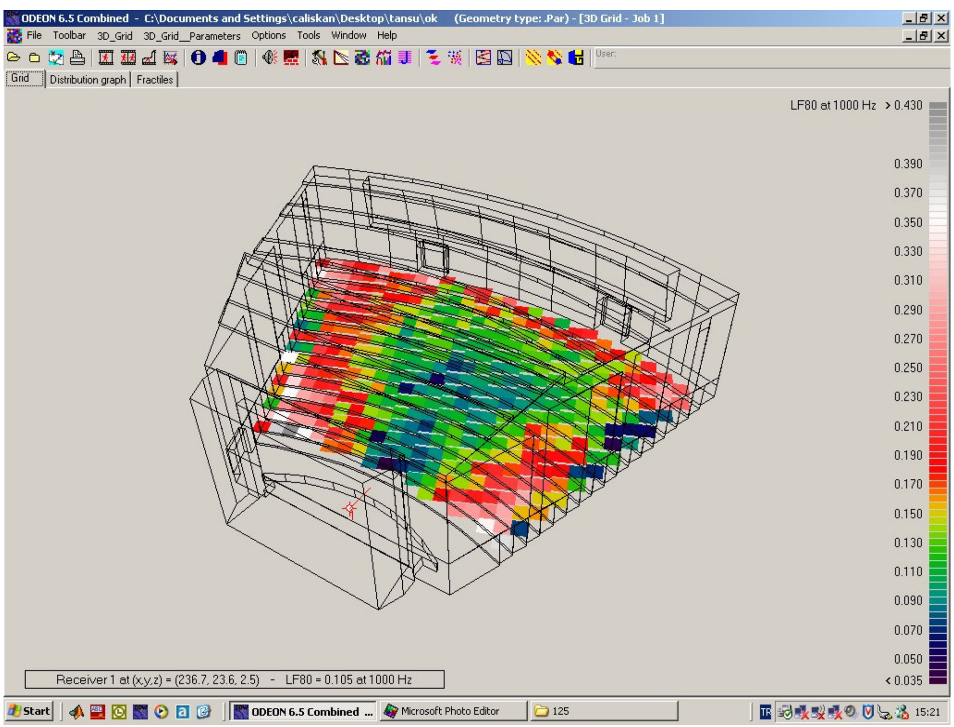


Figure 94: Lateral Fraction (LF80) at 1000Hz in concert mode.
(Fully occupied)

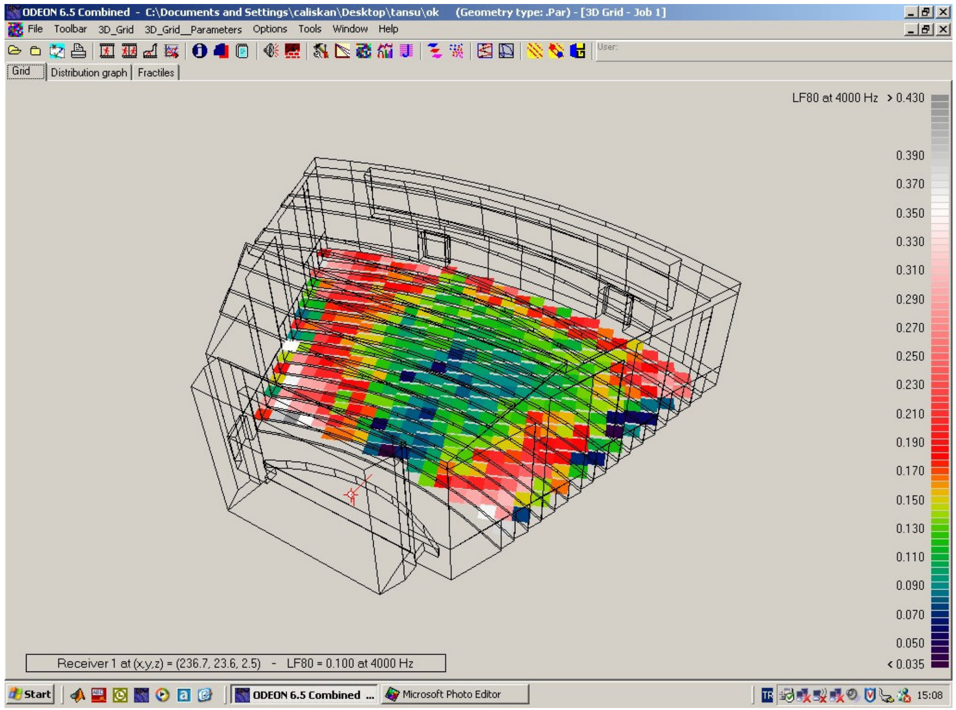


Figure 95: Lateral Fraction (LF80) at 4000Hz in concert mode. (Fully occupied)

Sixth evaluation was carried about Sound Transmission Index (STI) value among the audience area. (Figure 96) The STI of the hall is found out to be 0,58, which is slightly below the range for good speech intelligibility value, as the value lies in between 0,60 and 0,75. The graph can be considered as a uniform distribution. The slight decrease in central region can be explained as a result of sharp ceiling and lateral reflections, which will tend to decrease intelligibility, as the localization of sound source is rather difficult in that region and the slight increase at rear seats occurs as a result of highly absorbing materials, which tend to absorb sound energy and enhance the intelligibility.

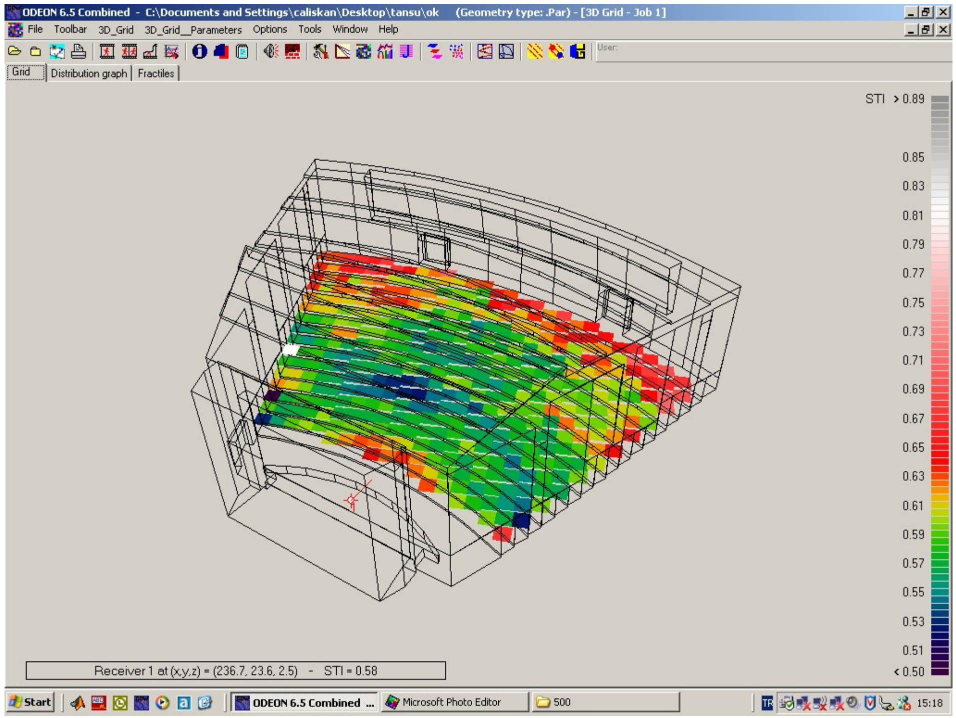


Figure 96: Sound Transmission Index (STI) in concert mode.
(Fully occupied)

The summary of the analysis results in concert mode and comparison of these results with the acceptable ranges of objective acoustical parameters can be seen in the following Table 9:

Table 9: Summary of the analysis results in concert mode and comparison of these results with the acceptable ranges of objective acoustical parameters.

THE OBJECTIVE PARAMETERS	THE ANALYSIS RESULTS	PERFORMANCE
Initial Time Delay Gap (ITDG) *12msec< ITDG <25msec*	ITDG= 0.08 to 0,12msec	Acceptable
Reverberation Time (RT) *Lecture / Conference room 1.0sec* *Multipurpose auditorium 1.3-1.5sec*	RT= 1,33sec	Very Good
Early Decay Time (EDT) *EDT < RT or EDT = RT (approx.)*	EDT= 1,3msec	Acceptable
Clarity (C80) *+3 to +8 for front rows* *0 to +5 for back rows*	-0,1 < C80 <3,8	Excellent
Definition (D50) *D50 > 65%*	D50= 0,56	Average
Lateral Fraction (LF80) *0.1 < LF80 < 0.35*	0.1 < LF80 < 0.106	Good
Sound Transmission Index (STI) *0.6 < STI <1.0*	STI= 0,58	Average
Sound Pressure Level (SPL) *Close to original level*	SPL= 4,8 SPL(A)= 11,2 (uniform)	Good
Bass Ratio (BR) *1.1< BR < 1.25*	BR= 1,108	Good

CHAPTER 5

EVALUATION OF THE RESULTS OF METU NCCA

5.1 Evaluation of Analysis Results

The analysis results of concert and auditorium modes of the METU NCCA have shown that the hall satisfies the acoustical qualities both for speech and music performances. Very minor threats related with the acoustical quality have been observed, but none of them were in the considerable ranges to pay attention for. It should be noted that the analysis made initially was not to establish any optimization methods for the auditorium. Both in the auditorium and the concert modes, only a considerable increase in 125Hz is observed, which is many because of the lack of vibrating panel structures in the hall, which will absorb low frequency sound energy.

If it is examined, the results regarding the bass ratio of the hall for both modes is still in acceptable ranges. However, after the hall is constructed, it should be noted that the mechanical system noise, which is generally produced at low frequencies, may coincide with the existing value of 125Hz, and can enhance each other creating an excessive value at the end. Since the construction will be completed and the hall itself will be structurally rigid, it will be difficult to overcome the problem by making structural changes in the acoustical layout of the hall. Not only it will be costly in terms of material substitution, but also the application process will be highly difficult, as the hall geometry is structurally not flexible.

To be able to prevent this threat, as mentioned previously in the second chapter, practical resonator systems can be introduced. The volume resonators are practical in that sense for application, cost and effectiveness purposes. In that sense, it is found convenient to use volume resonators, in front of the stage platform, where the structural constraints are minimum.

5.2 Proposal for Low Frequency Sound Control

In the design of the volume absorbers to be able to absorb low frequency sounds, here 125 Hz, the location of the resonator is of great important. As it is explained in detail in chapter 2, it is clearly defined that the resonators that will be imposed in the model should be located where the possible low frequency sound pressure levels are high. After the hall is constructed, it is likely that many modes for each specific frequency will occur within the hall volume, and to insert resonators in a specific location will cause another mode distribution. As the mechanical system noise is considered, a bass rise has a probability to occur inside the hall and any rigid structure formation is incapable of absorbing low frequency sounds. So that for NCCA, the hall has a rigid structural formation, any vibrating panel and air space behind will aid in reducing the bass rise.

As the stage platform is constructed with an air space underneath, it is a natural “bass trap”, by creating a vibrating environment inside by air, which will be efficient in absorbing low frequency sounds. In the second model drawn, the stage front was found put to be suitable for placing volume resonators, since it is the only suitable place as few structural constraints are imposed. Besides, it is considered to be functional as the accessibility of the stage front is quite easy, and any changes related with the acoustical adjustments can be performed without any difficulties.

The volume resonator is decided to be formed as a longitudinal cut off the stage front, which is considered to be architecturally convenient as emphasizing the continuation of the stage front. (Figure 97)

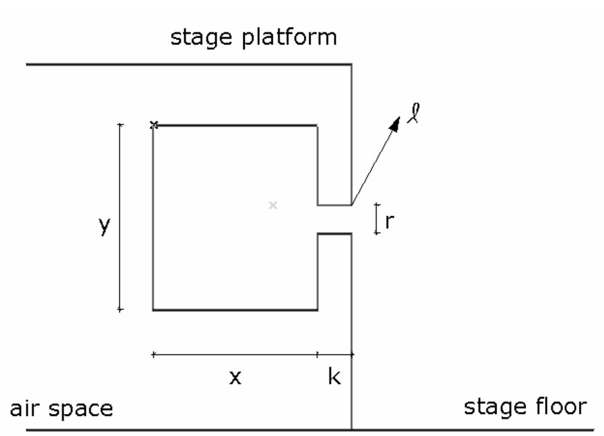


Figure 97: Section of the volume resonator constructed on the surface of the stage front.

where; ℓ = is the longitudinal measure of the neck, k= is the depth of the neck, r = is the height of the neck, x= is the depth of the cavity ,and y= is the height of the cavity.

If the volume resonator formula from the Equation 5;

$$F_{res} = \frac{\upsilon}{2\pi} \sqrt{S / I V} \qquad [5]$$

where, υ, is the speed of sound in meters, *S,* is the cross-section area of the neck in meters, *I,* is the length of the neck in meters and *V,* is the volume of the cavity in meter cubes.

From the equation, as the stage dimensions are considered, the dimensions of the volume resonator is decided to be as:

x = 43.5cm   y=43.5cm   k=4cm r=4cm

A section of the model imposed can be seen in Figure 98, and a perspective view is shown in Figure 99 below:

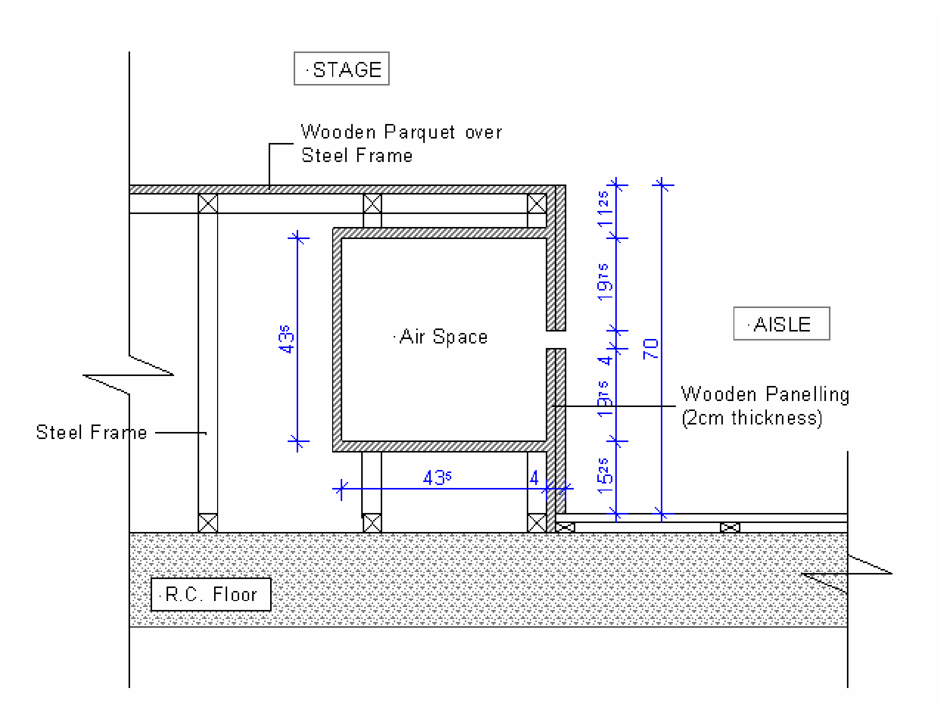


Figure 98: Detailed section of the volume resonator constructed on the surface of the stage front.

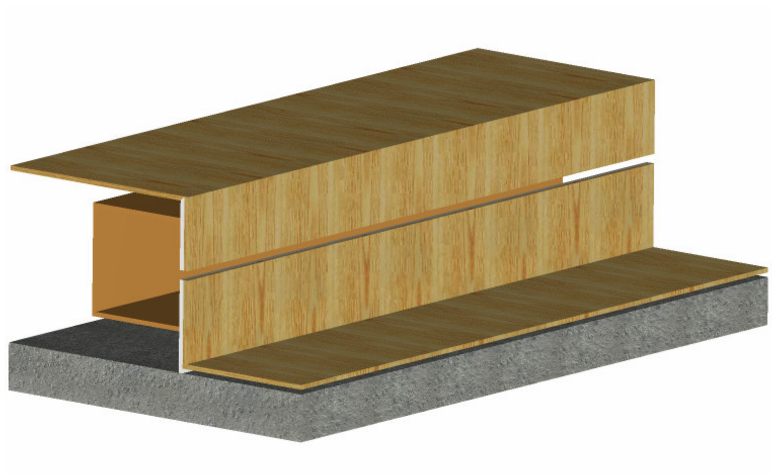


Figure 99: Perspective view of the volume resonator constructed on the surface of the stage front.

After necessary calculations are made according to the formulation given in Equation 5, the design is imposed in the model for further evaluation, as it is decided to be designed with wooden panels. The global reverberation time results are found as; (Fig 100)

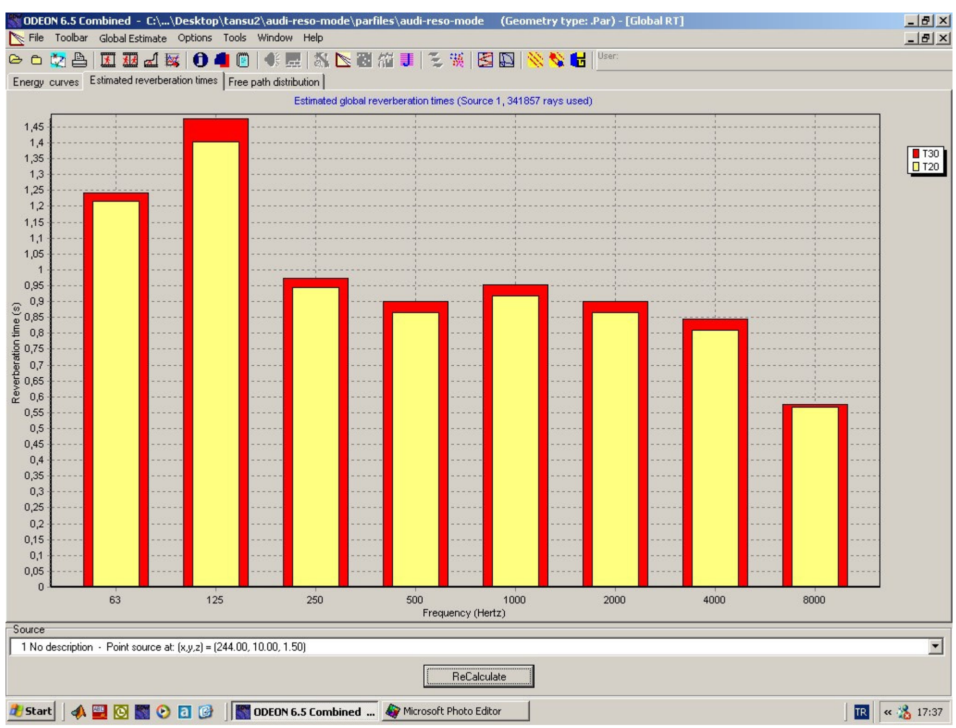


Figure 100: The global reverberation time results.

In the final analysis, it is found that a decrease of about 1,5 s. in reverberation time values of 125 Hz has been achieved. Although the other values differ slightly, the decrease has been more in the aimed frequency. As in the case of mechanical noise, the absorbtion of low frequency sounds will be quite high with the help of the constructed resonator. Since it is not just for 125Hz, it will be remarkably effective for the frequencies close to 125Hz, starting from 63Hz up to 250Hz.

Even in this simple evaluation about volume resonators, it is shown that volume resonators are effective in the tuned frequency without disturbing the overall optimum level of reverberation distribution. It should also be noted that variations and further calculations can be carried out to optimize the efficiency of the resonators, by further regarding the room modes, sound pressure level distributions and material configurations.

CHAPTER 6

CONCLUSION

6.1 Conclusion

In this study, impulse response of METU Northern Cyprus Campus Auditorium (NCCA) is analyzed and the acoustical quality of the auditorium is evaluated due to the results. For the analysis part to be concluded, an overall survey about concert hall acoustics is carried out starting from the general concepts, and objective and subjective acoustical parameters are studied, with the explanation of relations between them. Following this information, METU Northern Cyprus Campus Auditorium (NCCA) is introduced by providing detailed information, both architecturally and acoustically. In the latter case, a 3D model is produced with computer simulation software for the acoustical evaluation of the hall. With another software, namely with Odeon, acoustical response of the hall is analyzed both auditorium and concert mode cases. The resulting graphs are discussed and the results are compared with the suggested values for the 'good' acoustics. For the final part, a volume resonator is designed on the stage front to provide an optimization for 125Hz, where the results of this frequency for the reverberation time values are considerably high, causing a possible enhancement of low frequency sounds produced by the mechanical noise.

In the study, it is concluded that, in auditorium and in concert mode cases, the hall proves satisfactory in the parameters like RT, C80 and LF80, which influence the acoustical performance quality of a hall, especially. If we refer to Table 8, the following results can be summarized for the auditorium case:

Table 8: Summary of the analysis results in auditorium mode and comparison of these results with the acceptable ranges of objective acoustical parameters.

THE OBJECTIVE PARAMETERS	THE ANALYSIS RESULTS	PERFORMANCE
Initial Time Delay Gap (ITDG) *12msec< ITDG <25msec*	ITDG= 0.08 to 0,12msec	Acceptable
Reverberation Time (RT) *Lecture / Conference room 1.0sec* *Multipurpose auditorium 1.3-1.5sec*	RT= 1,16sec	Very Good
Early Decay Time (EDT) *EDT < RT or EDT = RT (approx.)*	EDT= around 1,1msec	Acceptable
Clarity (C80) *+3 to +8 for front rows* *0 to +5 for back rows*	5,6 < C80 <5,9	Excellent
Definition (D50) *D50 > 65%*	D50= 0,7	Good
Lateral Fraction (LF80) *0.1 < LF80 < 0.35*	0.07 < LF80 < 0.2	Very Good
Sound Transmission Index (STI) *0.6 < STI <1.0*	STI= 0,66	Good
Sound Pressure Level (SPL) *Close to original level*	SPL= 4,8 SPL(A)= 11,2 (uniform)	Good
Bass Ratio (BR) *1.1< BR < 1.25*	BR= 1,185	Very Good

And also for the concert mode case, the following results are found as described in Table 9:

Table 9: Summary of the analysis results in concert mode and comparison of these results with the acceptable ranges of objective acoustical parameters.

THE OBJECTIVE PARAMETERS	THE ANALYSIS RESULTS	PERFORMANCE
Initial Time Delay Gap (ITDG) *12msec< ITDG <25msec*	ITDG= 0.08 to 0,12msec	Acceptable
Reverberation Time (RT) *Lecture / Conference room 1.0sec* *Multipurpose auditorium 1.3-1.5sec*	RT= 1,33sec	Very Good
Early Decay Time (EDT) *EDT < RT or EDT = RT (approx.)*	EDT= 1,3msec	Acceptable
Clarity (C80) *+3 to +8 for front rows* *0 to +5 for back rows*	-0,1 < C80 <3,8	Excellent
Definition (D50) *D50 > 65%*	D50= 0,56	Average
Lateral Fraction (LF80) *0.1 < LF80 < 0.35*	0.1 < LF80 < 0.106	Good
Sound Transmission Index (STI) *0.6 < STI <1.0*	STI= 0,58	Average
Sound Pressure Level (SPL) *Close to original level*	SPL= 4,8 SPL(A)= 11,2 (uniform)	Good
Bass Ratio (BR) *1.1< BR < 1.25*	BR= 1,108	Good

All other values of acoustical parameters are also found to be in optimum ranges, and these results are summarized at the end of each section for better understanding. Following the evaluations, controlling low frequency sound energy is studied by using volume resonators, and to analyze the proposal another model is designed to be evaluated for a specified frequency, 125Hz. At the end of the analysis, it is observed that tuning low frequency sounds in halls, which have structural constraints, is possible by using volume resonators without changing the optimum level of hall acoustical response, such as reverberation time. The location, dimensions and the type of the resonator are highly influential on tuning of the low frequency sounds. It is also concluded that during the design process, computer simulation models for the acoustical analysis of halls are highly influential in providing the satisfactory conditions and to eliminate the possible noises that can be aroused by mechanical systems.

6.2 Recommendations for Future Study

For further studies, the detailed response of volume resonators can be studied, by modifying the location, array size, volume, shape and the material type for an optimization process. Other analysis methods can be employed in evaluating the multipurpose hall designs, and optimization of low frequency sounds can be focused, maybe as following a constructional manner, by making experiments with scaled models and compare with the simulated results. The effectiveness of the resonator types can be enhanced and a methodology in designing volume resonators can be formed. The parameters of the resonator design such as material type, geometry, dimensions etc. can be changed to achieve a better tuning characteristic, as these parameters are highly dependent on the resonance performance.

REFERENCES

[1] Ando, Y., "Architectural Acoustics: *Blending Sound Sources, Sound Fields, and Listeners*", Springer-Verlag New York Inc., New York, 1998

[2] Barron, M. and Lee, L-J.," *Energy relations in concert auditoriums.I*", Acoustical Society of America, Volume 84(2), 618-628, August 1988

[3] Barron, M., "Auditorium Acoustics and Architectural Design", 1st Ed, E & FN Spon, London, 1993

[4] Barron, M., "*Bass sound in concert auditoria*", Journal of Acoustic Society of America, February 1995, 97(2), 1088-1098

[5] Beranek, Leo L.," *Concert hall acoustics-1992*", Acoustical Society of America, Volume 92(1), 1-39, July 1992

[6] Beranek, Leo L. "Acoustical Measurements", 3rd Edition, New York, ASA, 1998

[7] Beranek, Leo L., "*Acoustical Design of the opera house of the New National Theatre, Tokyo, Japan*", Acoustical Society of America, Volume 107(1), 355-367, January 2000

[8] Bradley, J.S.," *A comparison of three classical concert halls*", Acoustical Society of America, Volume 89(3), 1176-1192, March 1991

[9] Cavanaugh, W. J.; Wilkes, J. A., "Architectural Acoustics: *Principles and Practice*", John Wiley & Sons, Inc., New York, 1999

[10] Cowan, J., "Architectural Acoustics Design Guide", Mc-Graw Hill, New York, 2000

[11] Cremer, L.; Helmut A. M.; Theodore, J. S., "Principles and Applications of Room Acoustics, *Volume 1*", Applied Science Publishers, London, 1978

[12] Doelle, L., L., "Environmental Acoustics", McGraw-Hill, New York, 1972

[13] Egan, M. D., "Architectural Acoustics", Mc-Graw Hill, New York, 1988

[14] Egan, M. D., “Concepts in Architectural Acoustics”, Mc-Graw Hill, New York, 1972

[15] Everest, F. A., “Master Handbook of Acoustics”, 4th Ed., Mc-Graw Hill, New York, 2000

[16] Fahy, F. J.; Schofield, C., “*A note on the interaction between a helmholtz resonator an an acoustic mode of an enclosure*”, Journal of Sound & Vibration, 1980, 72(3), 365-378

[17] Irvine, L. K.; Richards, R. L., “Acoustics and Noise Control Handbook for Architects and Builders”, Krieger Publishing Company, Malabar, Florida, 1998

[18] Knudsen, V. O.; Harris, C. M., “Acoustical Designing in Arcitecture”, John Wiley & Sons, Inc., New York, 1962

[19] Kuttruff, H., “Room Acoustics”, 4th Ed, Elsevier Science Publishers, New York, 1991

[20] Lawrence, A., “Architectural Acoustics”, Elsevier Pub. Co., Amsterdam, New York, 1970

[21] Lord, P.; Templeton, D., “The Architecture of Sound: *Designing Places of Assembly*”, Architectural Press Limited, London, 1986

[22] Makrinenko, L. I., “Acoustics of Auditoriums in Public Buildings”, J.S. Bradley, Ottowa, May 1993

[23] Marshall, A. H.,” *Acoustical conditions preferred for ensemble*”, Acoustical Society of America, Volume 64(5), 1437-1447, November 1978

[24] Marshall, A.H.,” *Acoustical design and evaluation of Christchurch Town Hall, New Zealand*”, Acoustical Society of America, Volume 65(4), 951-957, April 1979

[25] Mason, J. M.; Fahy, F. J., “*The use of acoustically tuned resonators to improve the sound transmission loss of double-panel partitions*”, Journal of Sound & Vibration, 1988, 124(2), 367-379

[26] Mehta, M.; Johnson, J.; Rocafort, J., “Architectural Acoustics: Principles and Design”, Prentice Hall, Upper Saddle River, N.J, 1999

[27] Moore, J. E., “Design for Good Acoustics and Noise Control”, Macmillan Education Ltd., London, 1978

[28] Norris, A. N.; Wickham, G., "*Elastic helmholtz resonators*", Journal of Acoustic Society of America, February 1993, 93(2), 617-630

[29] Rindel, J. H.,"*Computer Simulation Techniques for Acoustical Design of Rooms*", Journal of Acoustics Austrlia, Volume 23 No:3, 1995

[30] Schroeder, M.R.," *Binaural dissimilarity and optimum ceilings for concert halls; More lateral sound diffusion*", Acoustical Society of America, Volume 65(4), 958-963, April 1979

[31] Sü, Zühre, "Acoustical Performance Analysis of Bilkent University Amphitheater-Odeon", Master of Fine Arts Thesis, Bilkent University, August 2004

[32] Takyuki H.; Beranek, LeoL.," *Objective and subjective evaluations of twenty-three opera houses in Europe, Japan, and the Americas*", Acoustical Society of America, Volume 107(1), 368-383, January 2000

[33] Talaske, R.; Wetherill, E., and Cavanaugh, W., "Halls for Music Performance", American Institute of Physics, NewYork, 1982

[34] Templeton, D.; Saunders, D., "Acoustic Design", The Architectural Press, London, 1987

[35] Warnock, A. C. C., "*Sound transmission through slotted concrete blocks with attached gypsum board*", Journal of Acoustic Society of America, November 1993, 94(5), 2713-2720

APPENDIX A

1	Material Selection of METU Northern Cyprus Auditorium								
2	Amphitheatre Mode								
3				Absorbtion Coefficients					
4	**Surface**	**Material**	**Area**	**125**	**250**	**500**	**1000**	**2000**	**4000**
5	Stage Wall Left (Wooden)	Wooden mounting over concrete	15,68	0,10	0,11	0,10	0,08	0,08	0,11
6	Stage Wall Left (Travertine)	Porous and unpolished concrete	5,04	0,36	0,44	0,31	0,29	0,39	0,25
7	Stage Wall Right (Wooden)	Wooden mounting over concrete	15,68	0,10	0,11	0,10	0,08	0,08	0,11
8	Stage Wall Right (Travertine)	Porous and unpolished concrete	5,04	0,36	0,44	0,31	0,29	0,39	0,25
9	Stage Wall	Wooden mounting over concrete	83,6	0,10	0,11	0,10	0,08	0,08	0,11
10	Stage Platform	Wooden floor over empty volume	27	0,40	0,30	0,20	0,17	0,15	0,10
11	Stage Platform Side Surface	Wooden mounting over concrete	7,875	0,10	0,11	0,10	0,08	0,08	0,11
12	Rear Wall (Absorbtive, Wooden)	(Absorbtive) Top Acoustics 5/3 M,12%	112,8	0,40	0,80	1,00	1,00	0,95	0,80
13	Rear Wall (Gypsum-board)	2xmin.1,5cm gypsum-board panels+glasswool+supports	4	0,10	0,07	0,05	0,05	0,04	0,04
14	Rear Wall (Travertine)	Porous and unpolished concrete	15,96	0,36	0,44	0,31	0,29	0,39	0,25
15	Acoustic Door (2 in quantity)	Acoustic door	15,12	0,14	0,10	0,06	0,08	0,10	0,10
16	Walls of Translation Room	Ecophon	47,4	0,20	0,65	1,00	1,00	1,00	0,90
17	Window of Translation Room	Glass	24,75	0,35	0,25	0,18	0,12	0,07	0,04
18	Ceiling (Gypsum-board)	2xmin.1,5cm gypsum-board panels+glasswool+supports	374,25	0,10	0,07	0,05	0,05	0,04	0,04
19	Ceiling (Wooden, Reflective)	Wooden mounting over concrete	141,75	0,10	0,11	0,10	0,08	0,08	0,11
20	Ceiling (Wooden, Absorbtive)	Wooden mounting with glasswool over concrete behind perfora	49,5	0,30	0,65	0,90	0,90	0,80	0,90
21	Ventilation Shafts (30x0,5x0,5)	30x0,5x0,5	7,5	0,30	0,40	0,50	0,50	0,50	0,50
22	Side Wall Left (Wooden, Absorbtive)	Ecophon	113,86	0,20	0,65	1,00	1,00	1,00	0,90
23	Side Wall Left (Wooden, Absorbtive)	(Absorbtive) Top Acoustics 5/3 M,12%	8,4	0,40	0,80	1,00	1,00	0,95	0,80
24	Side Wall Left (Gypsum-board)	2xmin.1,5cm gypsum-board panels+glasswool+supports	21,85	0,10	0,07	0,05	0,05	0,04	0,04
25	Side Wall Left (Travertine)	Porous and unpolished concrete	28,34	0,36	0,44	0,31	0,29	0,39	0,25
26	Ventilation Grills	4x0,6x0,8	1,92	0,30	0,40	0,50	0,50	0,50	0,50
27	Side Wall Left Acoustic Door	Acoustic door	7,56	0,14	0,10	0,06	0,08	0,10	0,10
28	Side Wall Right (Wooden, Absorbtive)	Ecophon	113,86	0,20	0,65	1,00	1,00	1,00	0,90
29	Side Wall Right (Wooden, Absorbtive)	(Absorbtive) Top Acoustics 5/3 M,12%	8,4	0,40	0,80	1,00	1,00	0,95	0,80
30	Side Wall Right (Gypsum-board)	2xmin.1,5cm gypsum-board panels+glasswool+supports	21,85	0,10	0,07	0,05	0,05	0,04	0,04
31	Side Wall Right (Travertine)	Porous and unpolished concrete	28,34	0,36	0,44	0,31	0,29	0,39	0,25
32	Ventilation Grills	4x0,6x0,8	1,92	0,30	0,40	0,50	0,50	0,50	0,50
33	Side Wall Right Acoustic Door	Acoustic door	7,56	0,14	0,10	0,06	0,08	0,10	0,10
34	Floor (Parquet)	Wooden parquet floor	127,8	0,20	0,15	0,10	0,10	0,05	0,10
35	Audience Seat Full Occupied (585 in quantity)	Upholstered seat with medium thickness (fabric)	585	0,68	0,75	0,82	0,85	0,86	0,86
36	Audience Seat Half Occupied (585 in quantity	Upholstered seat with medium thickness (fabric)	585	0,56	0,64	0,70	0,72	0,68	0,62

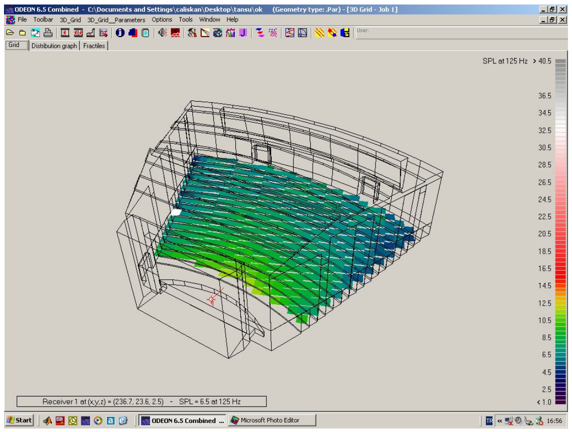
Fig A1: Material selection of METU NCCA in auditorium mode.

1	Material Selection of METU Northern Cyprus Auditorium								
2	Concert Mode								
3				Absorbtion Coefficients					
4	**Surface**	**Material**	**Area**	**125**	**250**	**500**	**1000**	**2000**	**4000**
5	Stage Wall Left (Wooden)	Wooden mounting over concrete	15,68	0,10	0,11	0,10	0,08	0,08	0,11
6	Stage Wall Left (Travertine)	Porous and unpolished concrete	5,04	0,36	0,44	0,31	0,29	0,39	0,25
7	Stage Wall Right (Wooden)	Wooden mounting over concrete	15,68	0,10	0,11	0,10	0,08	0,08	0,11
8	Stage Wall Right (Travertine)	Porous and unpolished concrete	5,04	0,36	0,44	0,31	0,29	0,39	0,25
9	Stage Wall	Wooden mounting over concrete	81,36	0,10	0,11	0,10	0,08	0,08	0,11
10	Stage Platform	Wooden floor over empty volume	27	0,40	0,30	0,20	0,17	0,15	0,10
11	Stage Platform Side Surface	Wooden mounting over concrete	7,875	0,10	0,11	0,10	0,08	0,08	0,11
12	Rear Wall (Absorbtive, Wooden)	(Absorbtive) Top Acoustics 5/3 M,12%	112,8	0,40	0,80	1,00	1,00	0,95	0,80
13	Rear Wall (Gypsum-board)	2xmin.1,5cm gypsum-board panels+glasswool+supports	4	0,10	0,07	0,05	0,05	0,04	0,04
14	Rear Wall (Travertine)	Porous and unpolished concrete	15,96	0,36	0,44	0,31	0,29	0,39	0,25
15	Acoustic Door (2 in quantity)	Acoustic door	15,12	0,14	0,10	0,06	0,08	0,10	0,10
16	Walls of Translation Room	Ecophon	47,4	0,20	0,65	1,00	1,00	1,00	0,90
17	Window of Translation Room	Glass	24,75	0,35	0,25	0,18	0,12	0,07	0,04
18	Ceiling (Gypsum-board)	2xmin.1,5cm gypsum-board panels+glasswool+supports	374,25	0,10	0,07	0,05	0,05	0,04	0,04
19	Ceiling (Wooden, Reflective)	Wooden mounting over concrete	141,75	0,10	0,11	0,10	0,08	0,08	0,11
20	Ceiling (Wooden, Absorbtive)	Wooden mounting with glasswool over concrete behind perfora	49,5	0,30	0,65	0,90	0,90	0,80	0,90
21	Ventilation Shafts (30x0,5x0,5)	30x0,5x0,5	7,5	0,30	0,40	0,50	0,50	0,50	0,50
22	Side Wall Left (Wooden, Reflective)	Wooden mounting over concrete	113,86	0,10	0,11	0,10	0,08	0,08	0,11
23	Side Wall Left (Wooden, Absorbtive)	(Absorbtive) Top Acoustics 5/3 M,12%	8,4	0,40	0,80	1,00	1,00	0,95	0,80
24	Side Wall Left (Gypsum-board)	2xmin.1,5cm gypsum-board panels+glasswool+supports	21,85	0,10	0,07	0,05	0,05	0,04	0,04
25	Side Wall Left (Travertine)	Porous and unpolished concrete	28,34	0,36	0,44	0,31	0,29	0,39	0,25
26	Ventilation Grills	4x0,6x0,8	1,92	0,30	0,40	0,50	0,50	0,50	0,50
27	Side Wall Left Acoustic Door	Acoustic door	7,56	0,14	0,10	0,06	0,08	0,10	0,10
28	Side Wall Right (Wooden, Reflective)	Wooden mounting over concrete	113,86	0,10	0,11	0,10	0,08	0,08	0,11
29	Side Wall Right (Wooden, Absorbtive)	(Absorbtive) Top Acoustics 5/3 M,12%	8,4	0,40	0,80	1,00	1,00	0,95	0,80
30	Side Wall Right (Gypsum-board)	2xmin.1,5cm gypsum-board panels+glasswool+supports	21,85	0,10	0,07	0,05	0,05	0,04	0,04
31	Side Wall Right (Travertine)	Porous and unpolished concrete	28,34	0,36	0,44	0,31	0,29	0,39	0,25
32	Ventilation Grills	4x0,6x0,8	1,92	0,30	0,40	0,50	0,50	0,50	0,50
33	Side Wall Right Acoustic Door	Acoustic door	7,56	0,14	0,10	0,06	0,08	0,10	0,10
34	Floor (Parquet)	Wooden parquet floor	127,8	0,20	0,15	0,10	0,10	0,05	0,10
35	Audience Seat Full Occupied (585 in quantity)	Upholstered seat with medium thickness (fabric)	585	0,68	0,75	0,82	0,85	0,86	0,86
36	Audience Seat Half Occupied (585 in quantity	Upholstered seat with medium thickness (fabric)	585	0,56	0,64	0,70	0,72	0,68	0,62

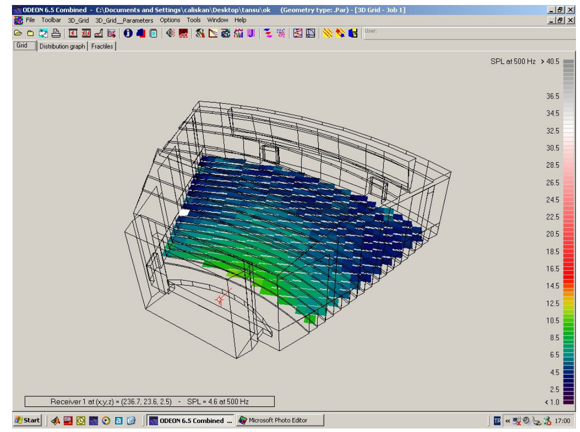
Fig A2: Material selection of METU NCCA in concert mode.

APPENDIX B

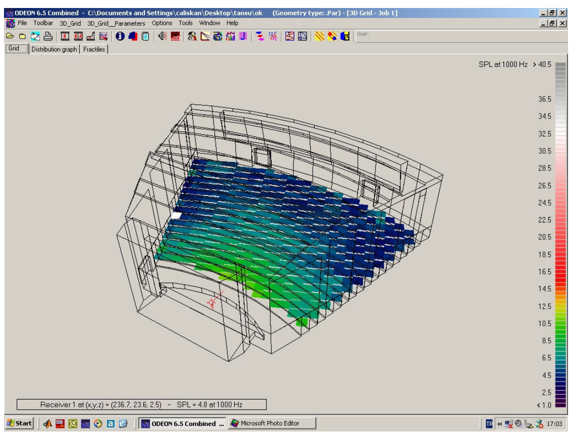
125Hz



500Hz



1000Hz



2000Hz

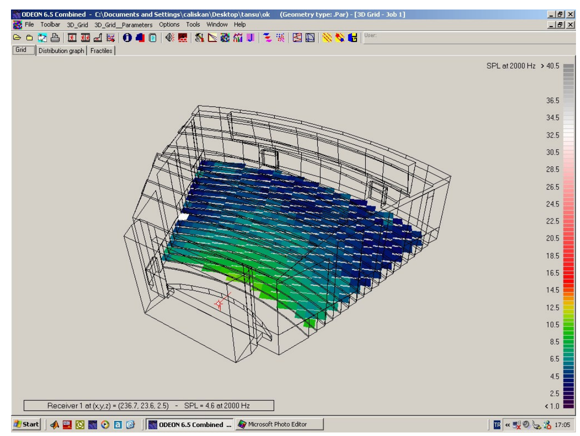


Fig B1: Sound Pressure Levels (SPL) of NCCA in auditorium mode at 125Hz, 500Hz, 1000Hz and 2000 Hz.

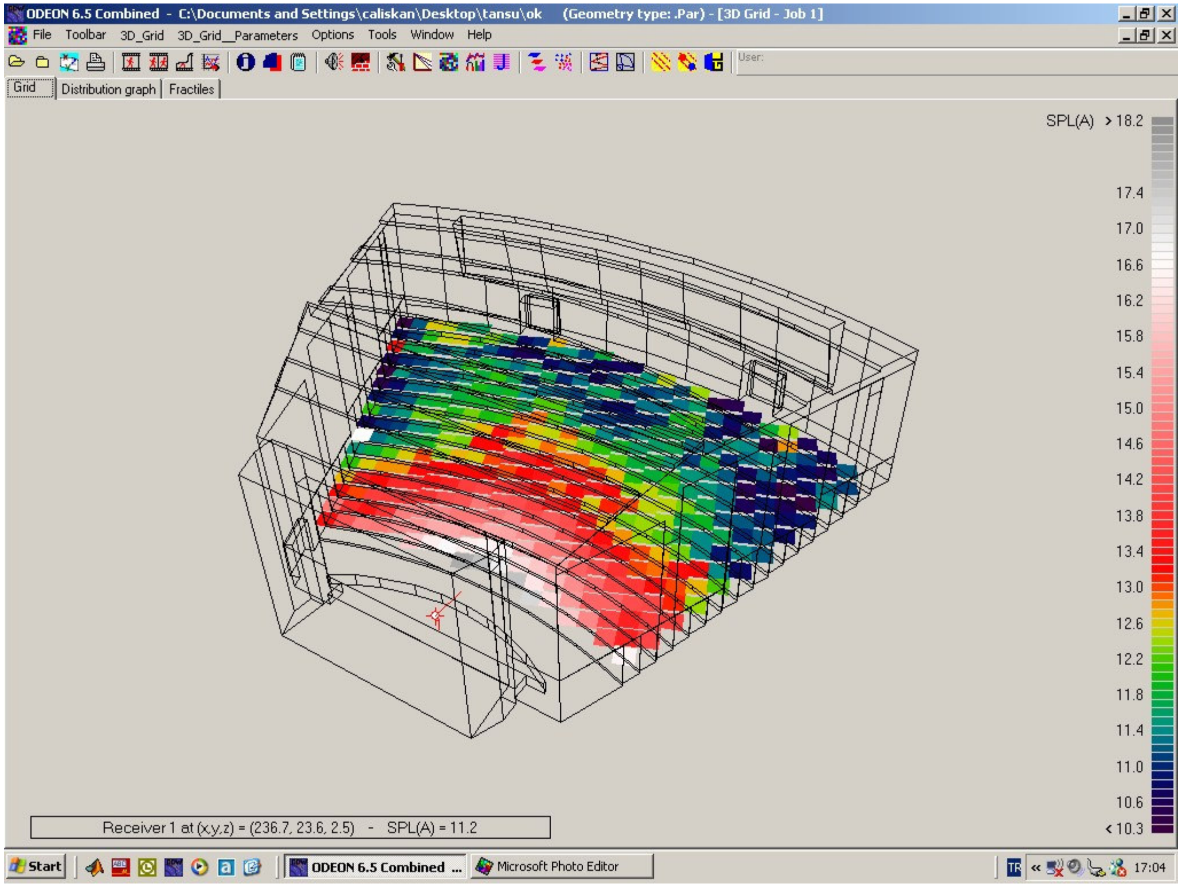
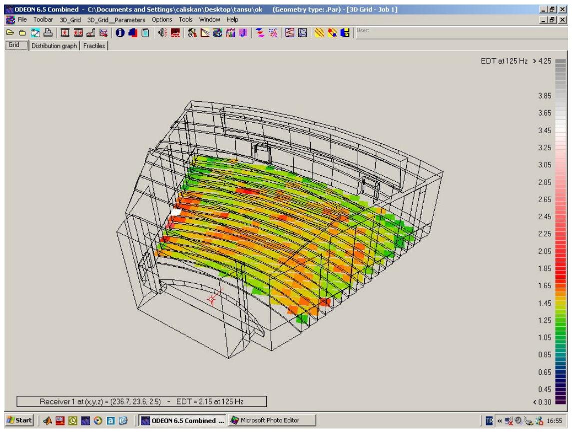
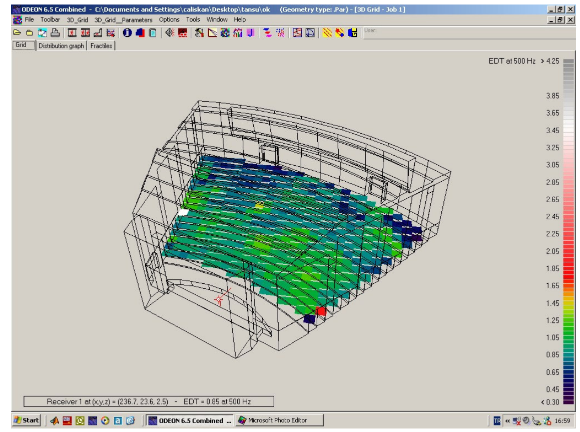


Fig B2: A-Weighted Sound Pressure Level (SPLA) of NCCA in auditorium mode.

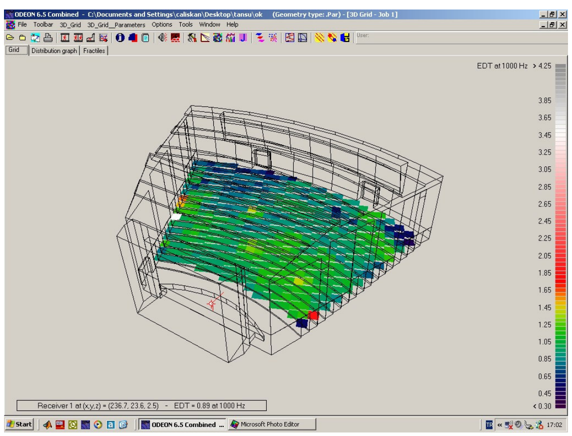
125Hz



500Hz



1000Hz



2000Hz

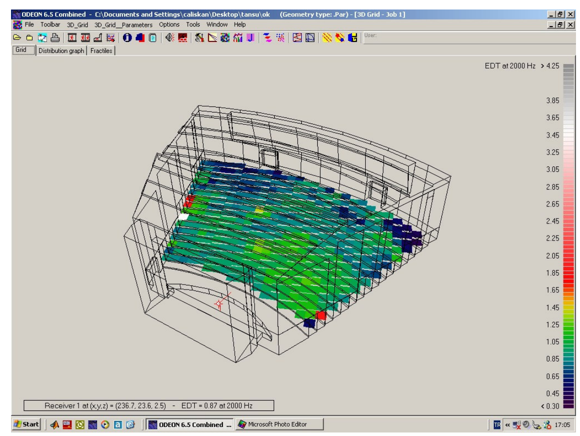
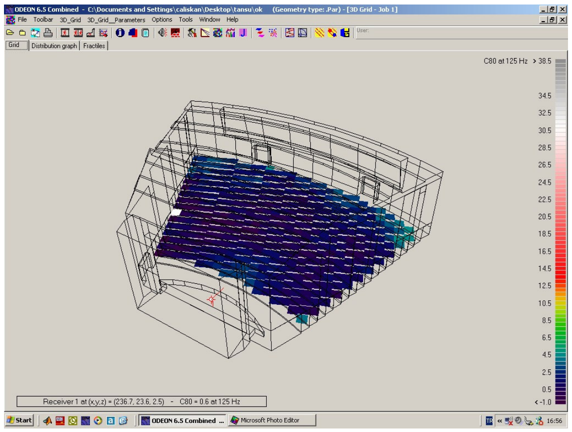
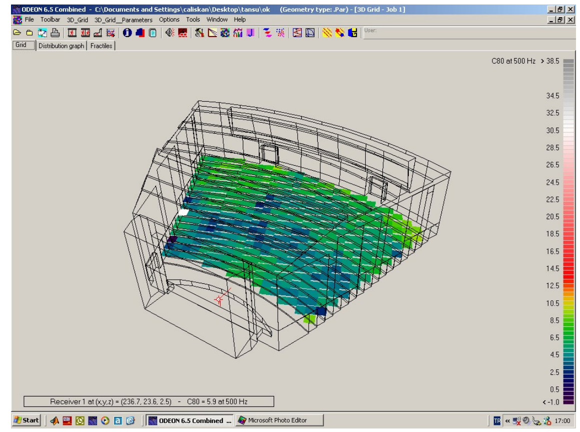


Fig B3: Early Decay Time (EDT) of NCCA in auditorium mode at 125Hz, 500Hz, 1000Hz and 2000 Hz.

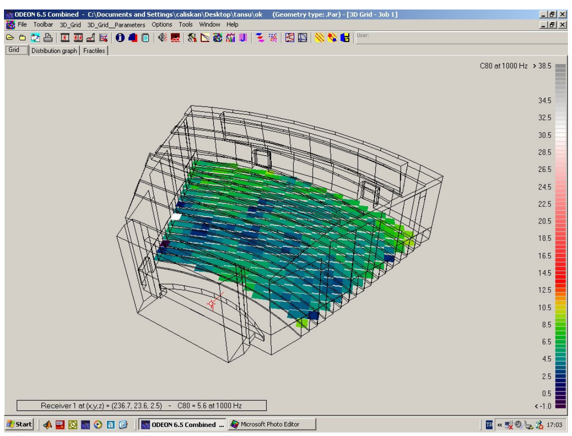
125Hz



500Hz



1000Hz



2000Hz

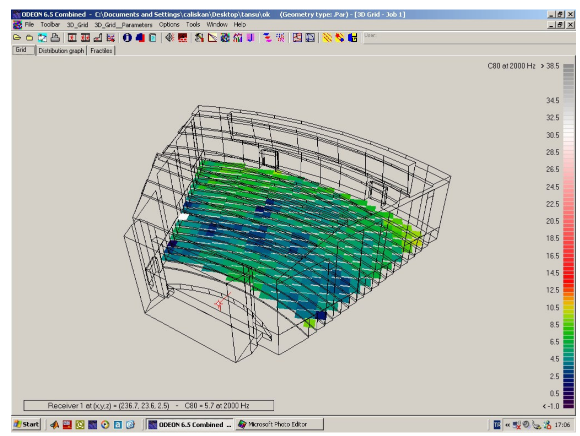
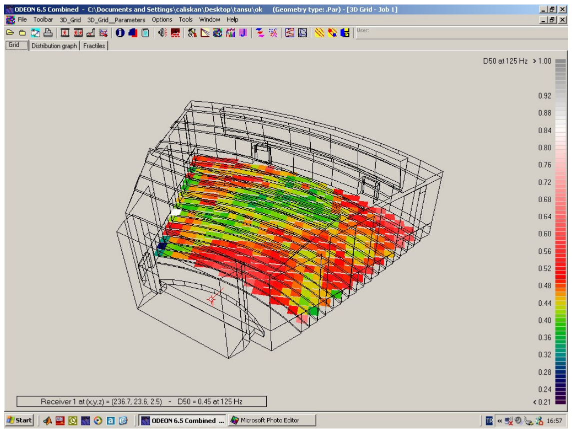
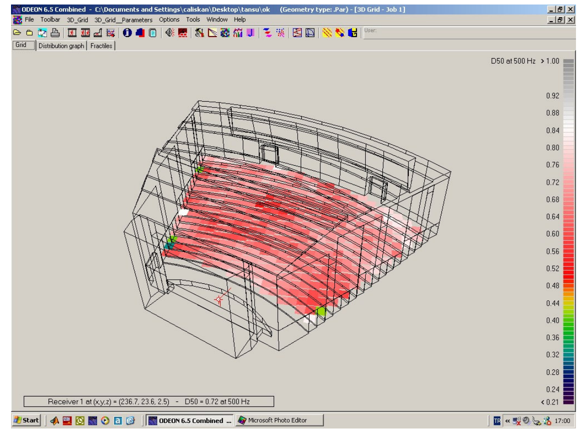


Fig B4: Clarity Index (C80) of NCCA in auditorium mode at 125Hz, 500Hz, 1000Hz and 2000 Hz.

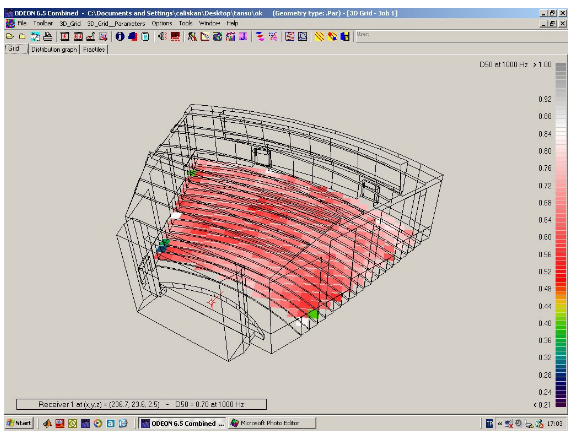
125Hz



500Hz



1000Hz



2000Hz

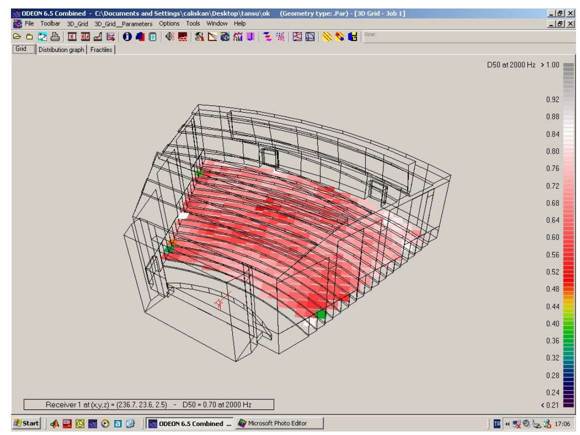
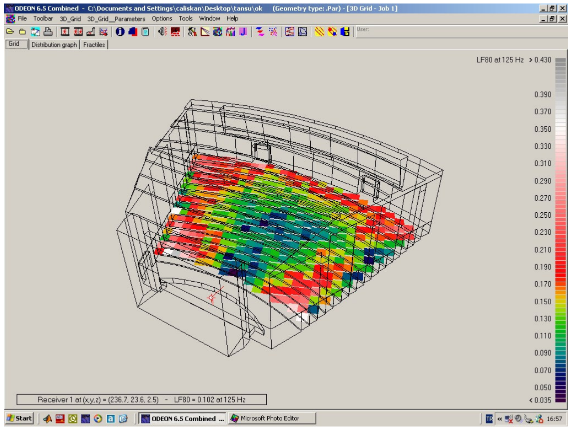
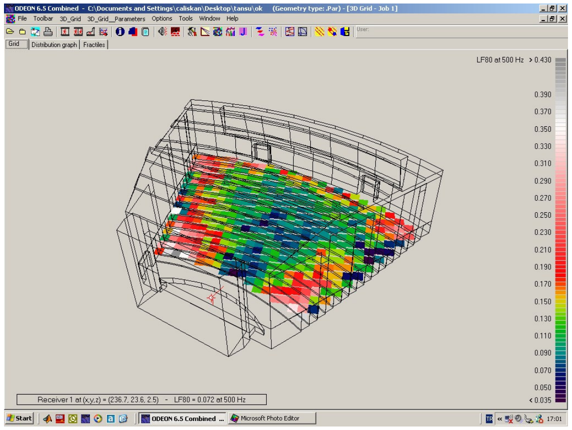


Fig B5: Definition Index (D50) of NCCA in auditorium mode at 125Hz, 500Hz, 1000Hz and 2000 Hz.

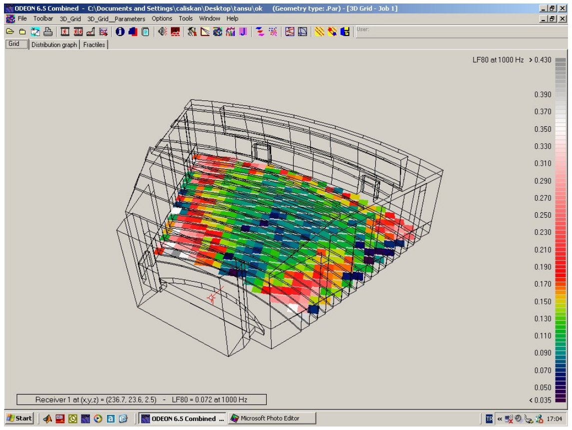
125Hz



500Hz



1000Hz



2000Hz

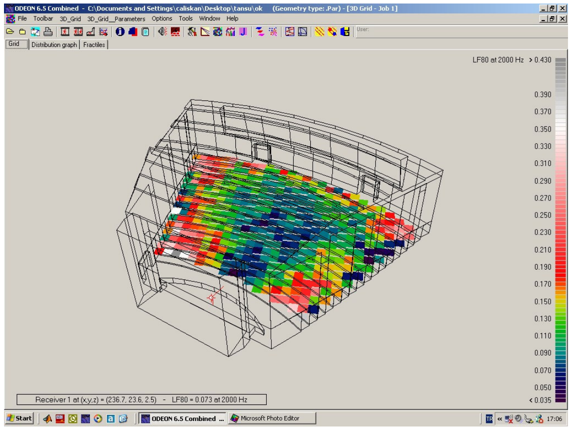


Fig B6: Lateral Fraction (LF80) of NCCA in auditorium mode at 125Hz, 500Hz, 1000Hz and 2000 Hz.

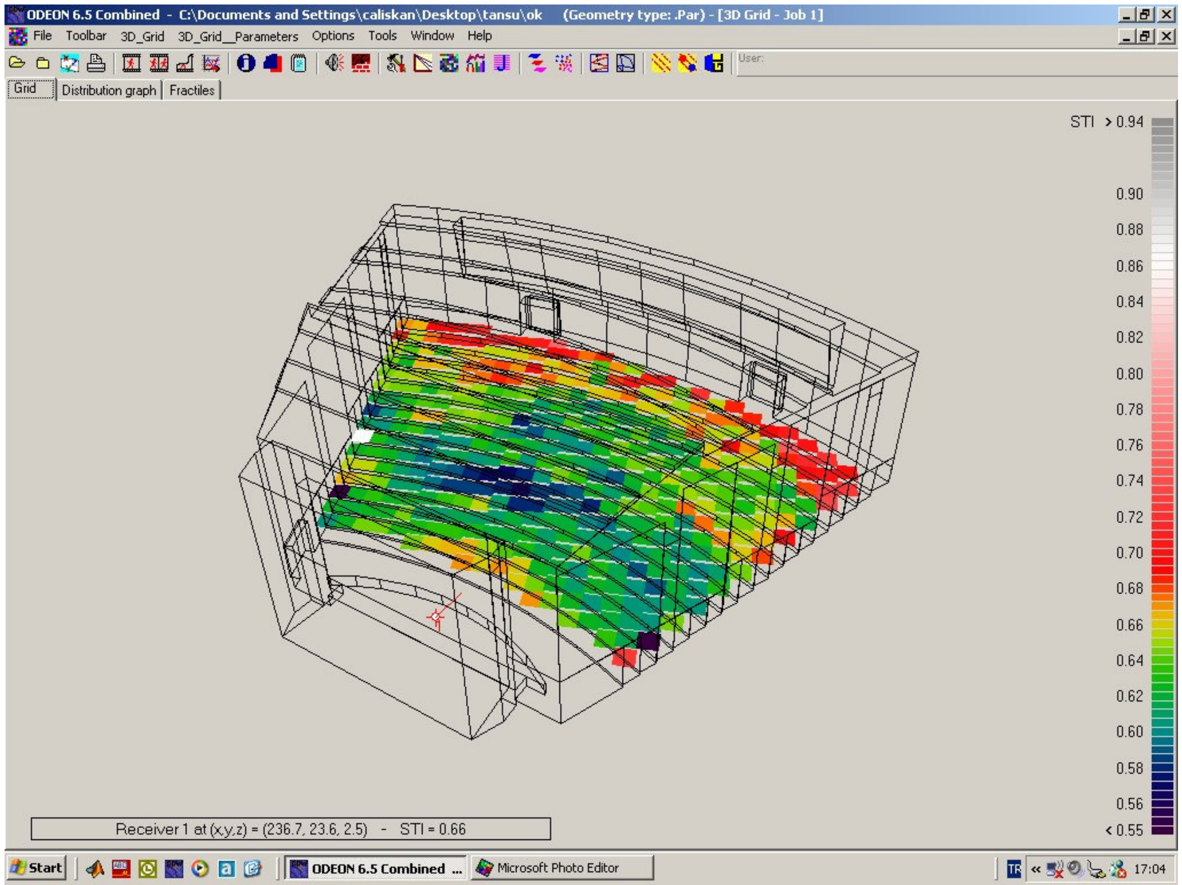
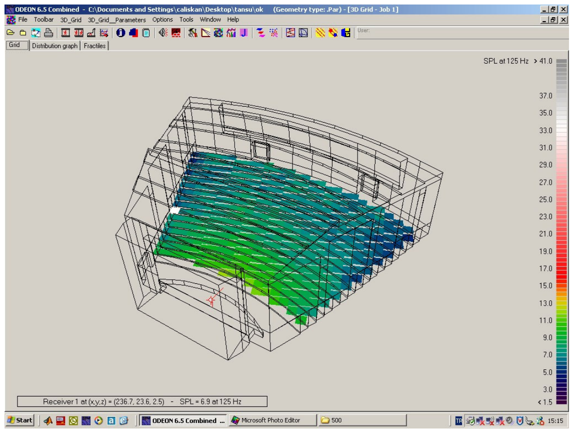


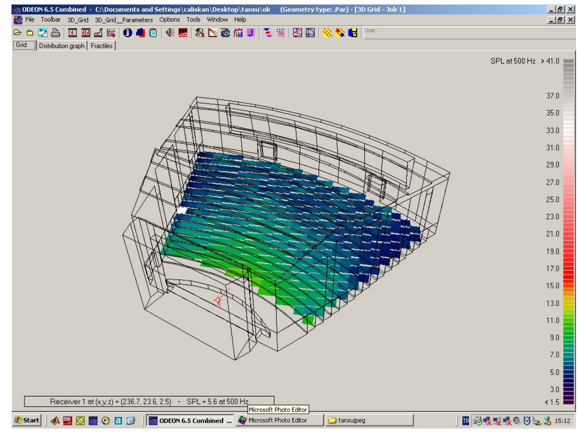
Fig B7: Sound Transmission Index (STI) of NCCA in auditorium mode.

APPENDIX C

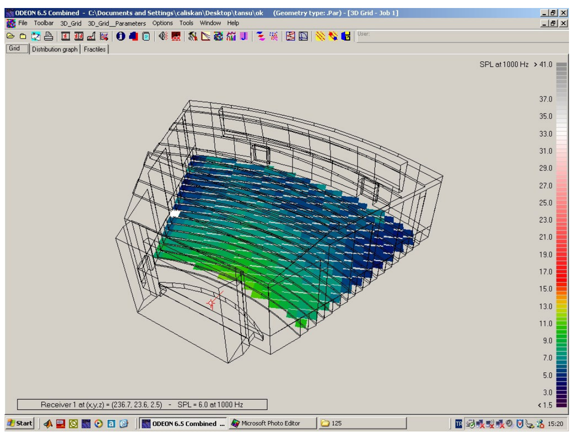
125Hz



500Hz



1000Hz



4000Hz

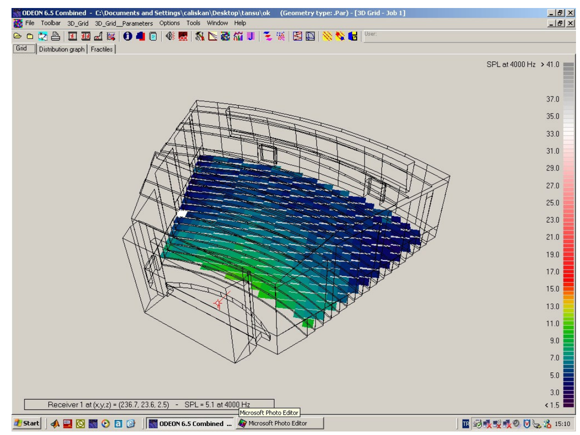


Fig C1: Sound Pressure Levels (SPL) of NCCA in concert mode at 125Hz, 500Hz, 1000Hz and 4000 Hz.

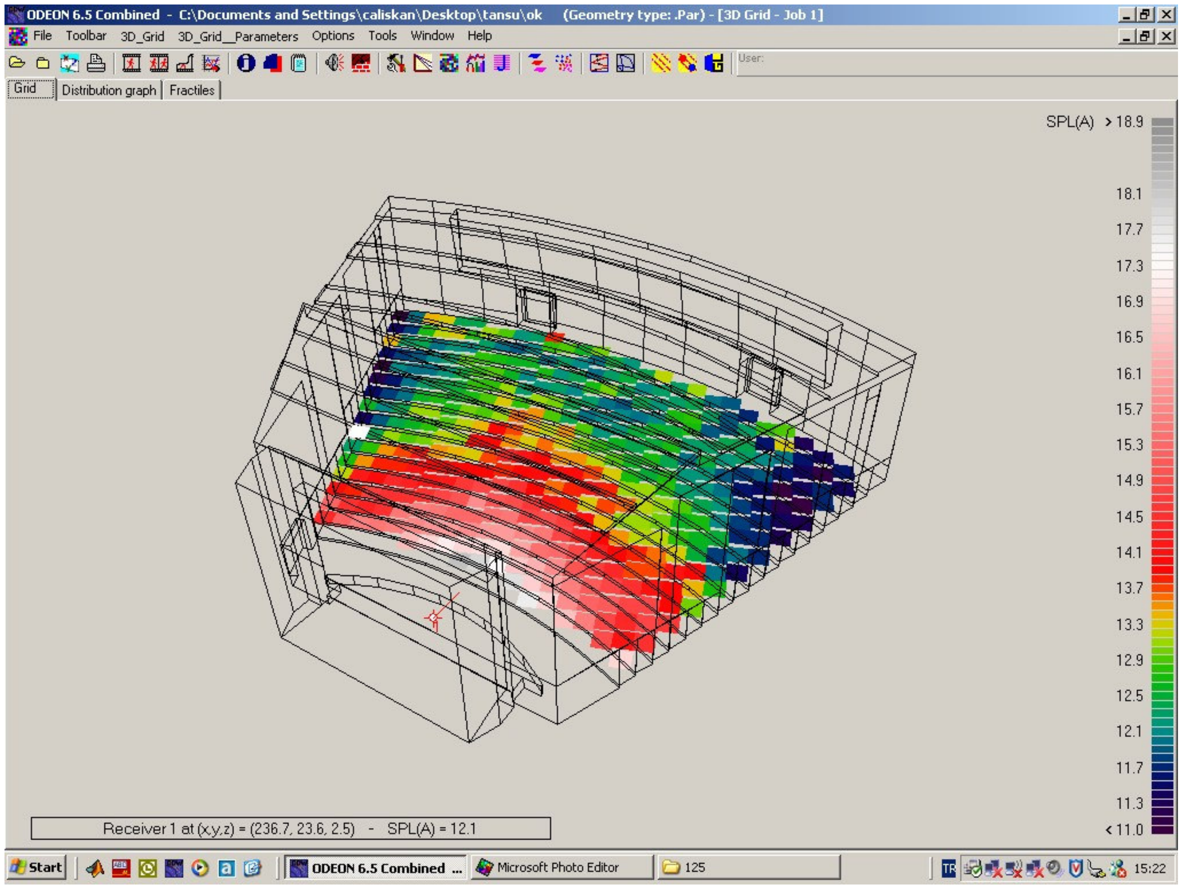


Fig C2: A-Weighted Sound Pressure Level (SPLA) of NCCA in concert mode.

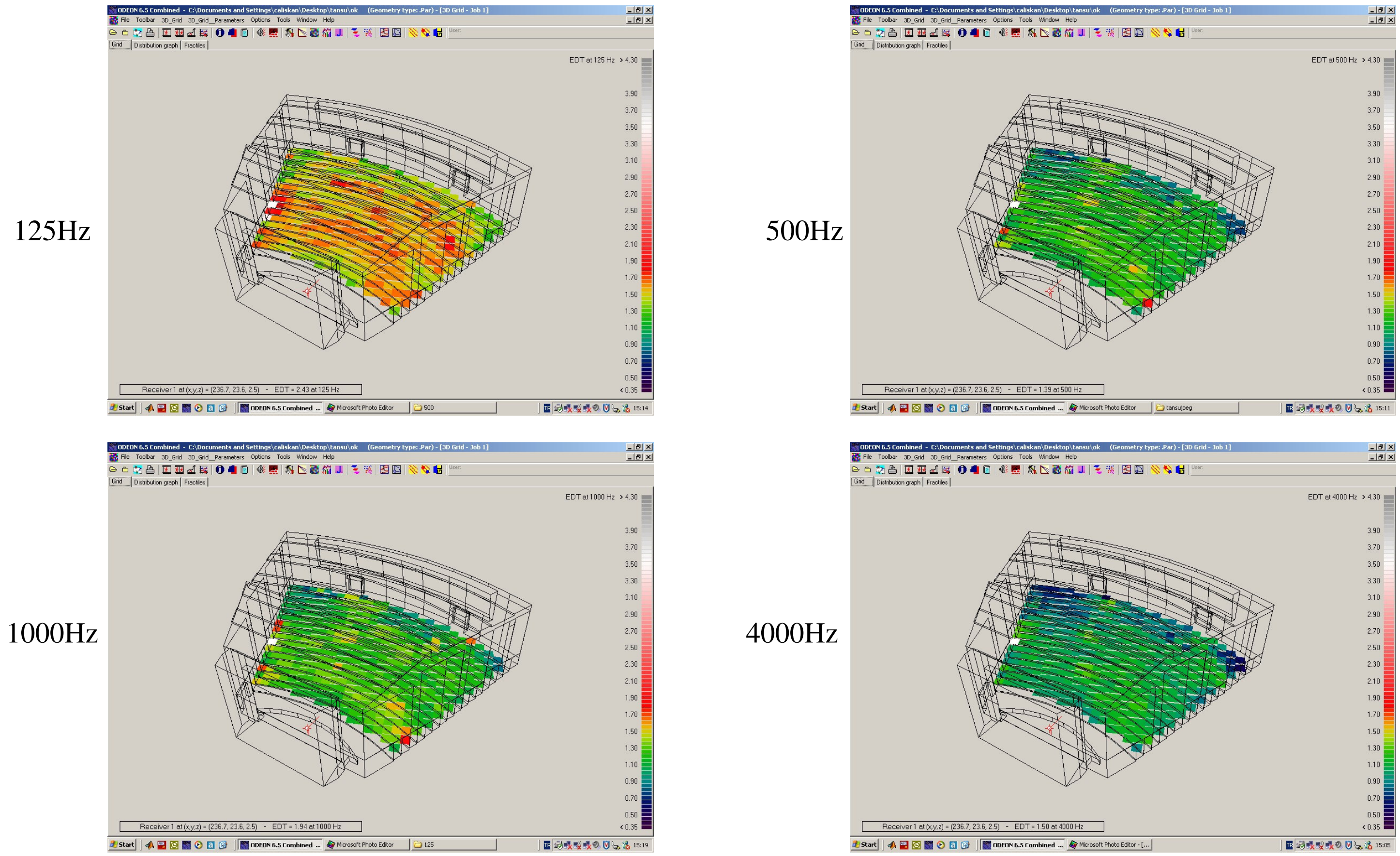
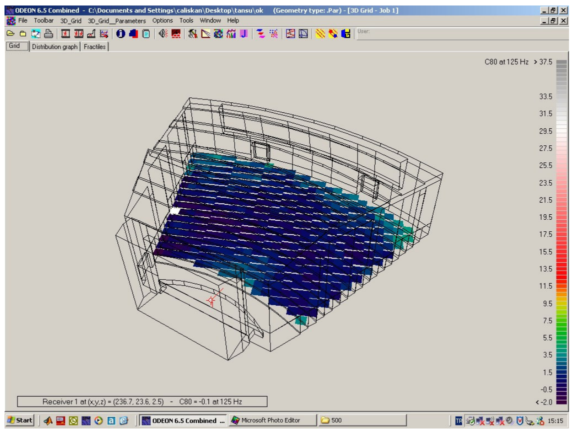
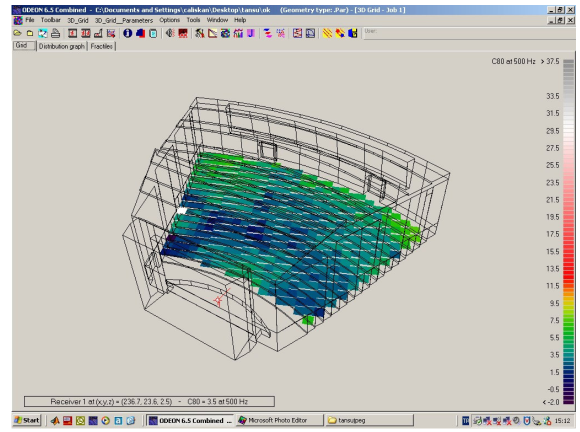


Fig C3: Early Decay Time (EDT) of NCCA in concert mode at 125Hz, 500Hz, 1000Hz and 4000 Hz.

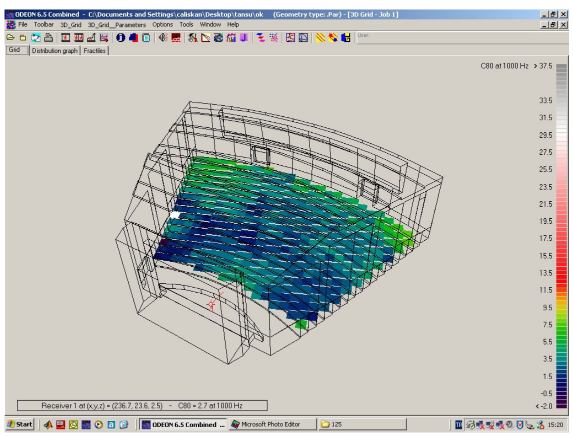
125Hz



500Hz



1000Hz



4000Hz

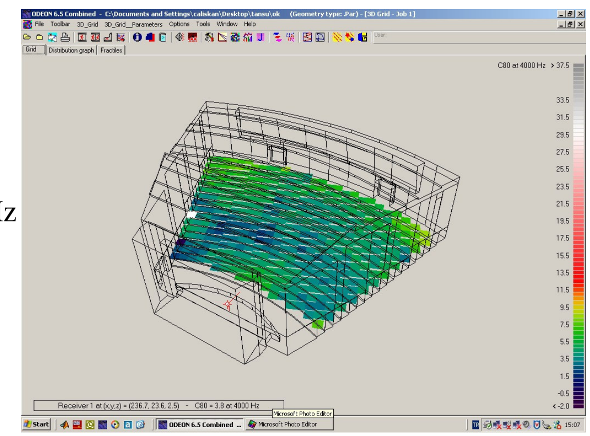


Fig C4: Clarity Index (C80) of NCCA in concert mode at 125Hz, 500Hz, 1000Hz and 4000 Hz.

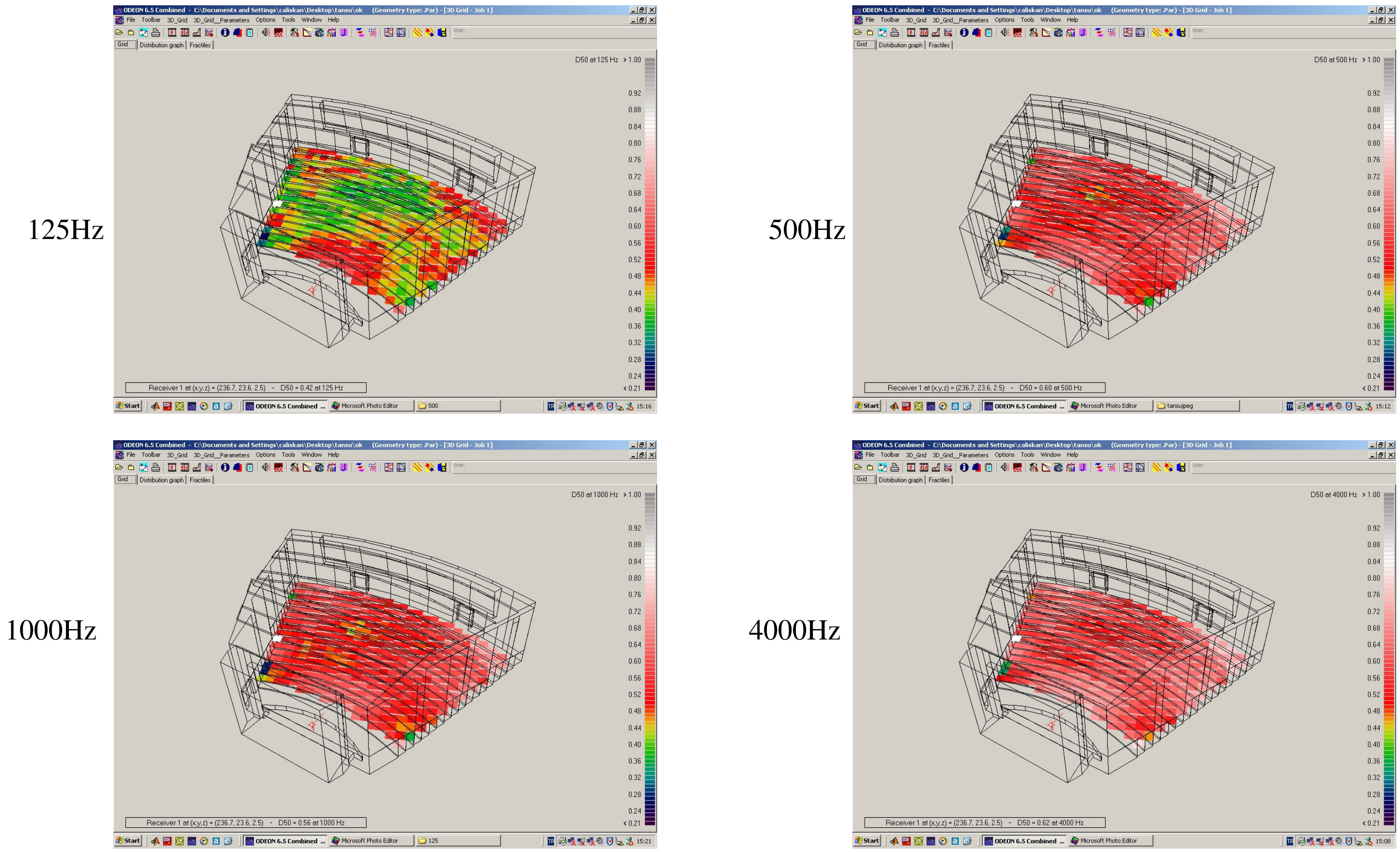
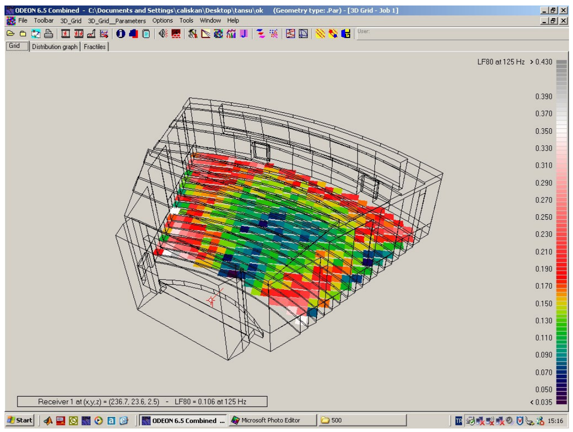
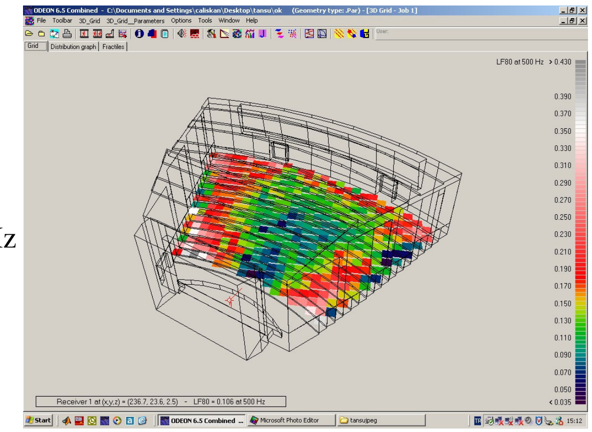


Fig C5: Definition Index (D50) of NCCA in concert mode at 125Hz, 500Hz, 1000Hz and 4000 Hz.

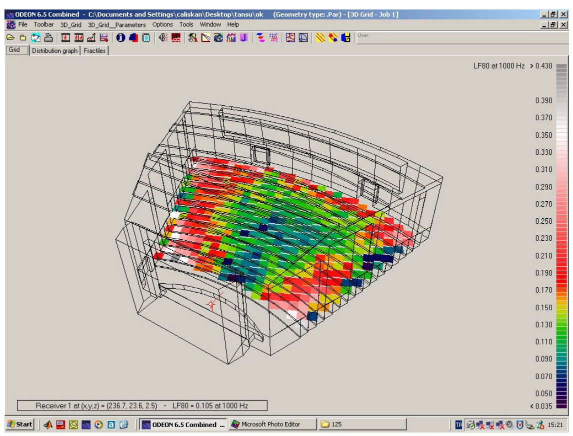
125Hz



500Hz



1000Hz



4000Hz

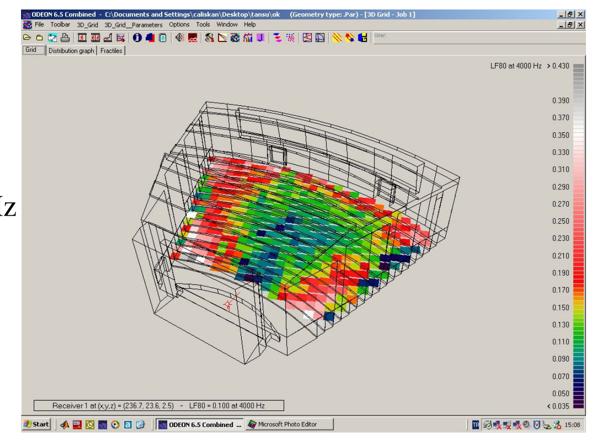


Fig C6: Lateral Fraction (LF80) of NCCA in concert mode at 125Hz, 500Hz, 1000Hz and 4000 Hz.

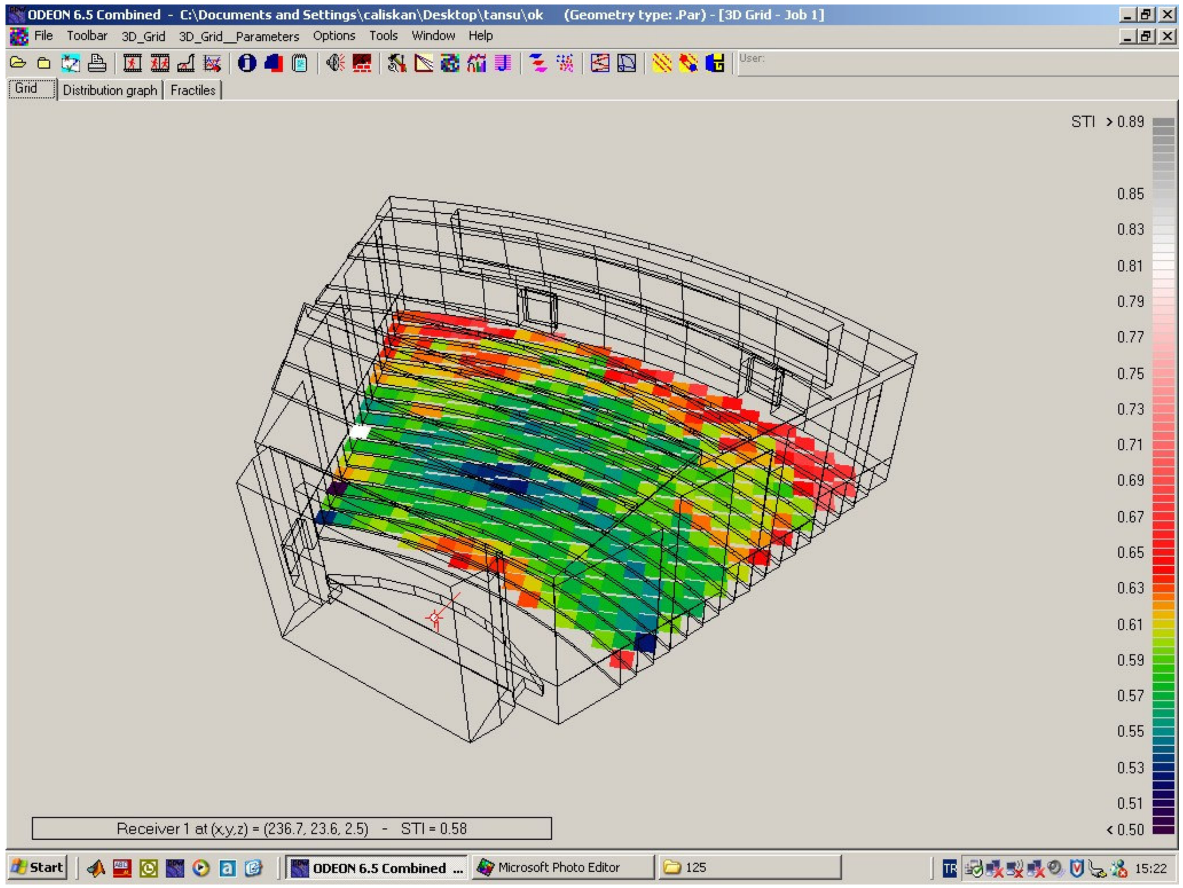


Fig C7: Sound Transmission Index (STI) of NCCA in concert mode at 125Hz, 500Hz, 1000Hz and 4000 Hz.