# ACOUSTICAL ANALYSIS AND TAXONOMY OF PERFORMANCE HALLS IN EARLY REPUBLICAN PERIOD IN ANKARA: RESIM HEYKEL MÜZESİ, KÜÇÜK TİYATRO AND OPERA

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**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 cıted and referenced all materıal and results that are not original to this work.**

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# ABSTRACT

## ACOUSTICAL ANALYSIS AND TAXONOMY OF PERFORMANCE HALLS IN EARLY REPUBLICAN PERIOD IN ANKARA: RESIM HEYKEL MÜZESİ, KÜÇÜK TİYATRO AND OPERA

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Comprehensive studies are required to understand the design of the performance halls in Turkish Early Republican Period. Acoustics, a significant parameter in performance hall design, has been chosen to contribute the studies. Three pioneers of the period, Resim Heykel Museum, Küçük Theatre and Opera Halls, are chosen as cases. The acoustical qualities of performance halls of Turkish Early Republican period in Ankara is studied in parallel to the acoustical design of performance halls in Europe which may reveal similarities in case halls. Detailed 3-D models of the halls for acoustical simulations based on the original design data have been prepared and results are to be compared with acoustically recognized halls in the world.

Keywords: Early Republic Performance Halls, Acoustical Performance

# ÖZ

## ERKEN CUMHURİYET DÖNEMİ'NDE ANKARADA YAPILAN PERFORMANS SALONLARININ AKUSTİK ANALİZİ VE SINIFLANDIRILMASI: RESİM HEYKEL MÜZESİ, KÜÇÜK TİYATRO VE OPERA

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Türkiye'de Erken Cumriyet Dönemi performans salonlarının tasarımını anlayabilmek için kapsamlı çalışmalara ihtiyaç duyulmaktadır. Performans salonu tasarımında önemli bir parametre olan Akustik, konuya değerli katkı sağlaması amacıyla bu çalışmada ele alınmıştır. Bahsi geçen dönemin üç öncüsü olan Resim Heykel Müzesi, Küçük Tiyatro ve Opera Binası salonlarıyla örnek durum çalışmaları yürütülmüştür. Erken Cumhuriyet Dönemi'nde Ankara'da bulunan salonların akustik tasarımı, bu salonlarla benzerlik gösterebilecek Avrupa'daki performans salonlarının tasarımlarıyla paralel olarak çalışılmıştır. Örnek salonların detaylı üç boyutlu mimari ve akustik modelleri üretilmiş ve elde edilen akustik veriler dünyadaki başarılı salonların verileriyle karşılaştırılmıştır.

Anahtar Kelimeler: Erken Cumhuriyet Dönemi Performans Salonları, Akustik Performans

**To My Family**

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# CHAPTER 1

# INTRODUCTION

The history of performance space dates back to early ages and it has not finished its evolution yet. The design of performance space has always been given substantial consideration during its history and has become a more complex task in the recent decades. Acoustics, the main determinant of the performance of a space, has been studied more by professionals since late 19$^{th}$ century. The basic subjective and objective parameters contributing to the acoustics of spaces have been investigated more since the beginning of 20$^{th}$ century first with the advent of telecomunication, radio, television then signal processing and computational technologies.

It is known that, acoustics has been long time concern of architects, engineers and scientists. Yet, it is the late 19$^{th}$ and early 20$^{th}$ century when studies on modern acoustics have been started. Significant developments in this field resulted in the design of several acoustically designed successful performance halls first in Europe then in the world. In this context, eventhough Turkey had been having intense challenges as the country battled in the World War I and the new Republic of Turkey was scarcely founded, it was able to catch the level of successful performance halls that Europe had. Early Republican Turkish cases interestingly resembled European foremost examples in terms of form, material and dimensions.

This study first aims to evaluate the acoustical behavior of the Early Republican period performance halls in the capital city Ankara through three significant examples: Resim Heykel Müzesi Multipurpose Hall (Türk Ocağı Binası), Küçük Tiyatro Hall (II.Evkaf Apartmanı) and Opera Hall (Büyük Tiyatro). The comparison of these halls with their contemporaries and introduction of the similarities in between are among the goals of the study. The second objective of the study is the evaluation of these performance halls with reference to worldy accepted contemporary halls of that period. The adequate assessment of the acoustical performance is aimed to be done via the digital modeling of case halls. The detailed architectural models are planned to be used in the acoustical calculations through room acoustic software providing the documentation in acoustical terms. This documentation will be a useful guide for the future renovation activities. The third aim is to collect the information on recent studies on acoustics and provide concise tables for the data on the subject.

This study is focused on the assessment of acoustical qualites of the three pioneers of performance halls in Early Republican Period in Ankara in order to better assess their performances in terms of architectural acoustics. In the realm of the study, first these three halls have been investigated regarding their plan typologies to compare with the examples belonging to the same period examples in other countries belonging to that era are examined and their influence in terms of materials, architecture and thus acoustics on the design of buildings studied in the thesis are explored in order reveal similarities between Turkish and European halls of the period .

In the realm of the study the detailed 3-D simulation models of the halls enabling not only acoustical analysis but also further structural and thermal analysis have been prepared based on the original drawings and documents. Detailed acoustical analysis of these halls have been carried out and the results are compared with acoustically acknowledged halls in the world aiming to evaluate the acoustical qualities of these Early Republican performance halls.. It is also aimed to provide the timeline of performance halls in Turkey and their development in the course of time. In addition to those goals, solid models developed for the study can be considered as a way of documentation of these historically important halls for the prospect renovations.

The thesis study is divided into six chapters. In the Introduction part, problem definition and aim of the study is interpreted. As well as explanation of the general content of the study, Introduction part summarizes the chapters included. The scope and objective of the study will be defined here.

The second chapter, Literature Survey, is a more condensed part where background information is given, the subject is broaden and detailed. Performance halls and their development since the Early Periods as well as the formation of different typologies ranging from semicircular Greek amphitheatres to incredible shoebox halls of the 20$^{th}$ century is explained in this part with the knowledge that performance hall typologies evolved throughout the history. Another concentration of this survey part is the Architectural

Acoustics of Performance Halls and the development of Acoustics. A general summary of concepts of acoustics will be given. The late 19th and early 20$^{th}$ century is the time when modern acoustics have been studied and forerunners of performance halls are introduced. How these studies on modern acoustics in the last century affected the design of performance spaces of today and the situation in Turkey versus Europe in the Early Republic Period is also answered in this chapter.

The third chapter, namely Materials and Methodology, will be an explanation of the methodology of the study. The steps of modelling of three cases within the framework of the architectural acoustics will be interpreted. The abstraction of the materials used in these performance halls during the architectural 3-D modelling stage is described. Determination of accurate absorbtion and scattering coefficients for materials used in these halls is another significant step that will be defined in this chapter. In this chapter, a very detailed table summarizing the evaluation criteria and parameters taken into account in modern acoustics has been developed based on an extensive research aiming to provide a consice guide for the future research studies.

The fourth chapter is Case Studies in which the three cases, Resim Heykel Müzesi Multipurpose Hall, Küçük Tiyatro Hall and Opera Hall, are simulated with 3-D models. In these models, the volume and materials are depicted with surfaces. Adequate absorbtion and scattering coefficients are applied to these surfaces and these models are then analysed in the room acoustics software. The analyses will allow quantitative results of acoustical performances of the halls. The results are then evaluated in the next chapter by comparing with those of acoustically good performing renowned examples in the world. These studies will at the end reflect the qualities of case performance halls.

The fifth chapter, Results, will be the part in which some questions will also find answers. The parameters considered in the acoustical evaluation of the halls will be compared to “good” performing halls that have been accepted worldwide. The previous analyses through the images and comparisons mentioned above will reveal whether there are any coincidences and similarities among the parformance halls of the period Early Republic in Turkey and Europe. The reason behind these forms, and influences of or inspirations from foreign performance halls are explained. The quality of recent built performance halls is also criticized in this chapter.

The sixth and the last chapter, Conclusion, will be the section in which the theories are aimed to be proved with the data acquired from the acoustical models. Without these results, it is not appropriate to comment whether the acoustical qualities of these three performance halls are appropriate for their use or not. It can be concluded that the case performance halls are in the same level with contemporary performance hall architecture in Europe, at least in terms of their forms. The reason why Turkey has not been productive as in the Early Republican Period in terms of number and acoustical qualities of performance halls is also enquired.

This study, as it will be concluded in the last chapter, will constitute a reference for the following restoration and renovation activities in these halls. The architectural 3-D models are important documentation for the performance hall architecture of Early Republican Turkey besides being a reference for acoustical evaluation of the period.

# CHAPTER 2

# LITERATURE SURVEY

## 2.1. Historical Development of Performance Space

### 2.1.1. The History of Performance Space

Starting from the earliest periods, performance spaces have substantial significances in social cultural life of the communities. Historical development of performance spaces has shown remarkable developments both in terms of typology and acoustical performance since then. Since Roman and Greek Amphitheaters, various performance spaces encountered in different cultures and have always been one of the indicators of level of societies as well as a manifestation of their architecture and technology. In the course of time, in relation with change and diversity in performance types, art, music, etc., new architecture of performance spaces have also been developed. Starting from the 18th century, opera and symphonic music have been forcing architects to design not only aesthetically and acoustically well designed spaces but also to create point of attraction in urban level i.e. landmarks.

The historical background of music and performance spaces starting from early cultures to twentieth century has become the concern of many publications in the previous century. Concerning this subject, Long (2005) provides a very recent and concise source collecting the information on the subject contributing history of performance space by focusing on their acoustical properties. Based on the detailed explanations of Long, a timeline is prepared with examples of worldly accepted performance halls in Figure 1.

The timeline provided in Figure 1 shows that performance spaces have experienced a great evolution since their existence in the early periods. The initial forms are open circular primitive meeting areas which are followed by amphitheatres of Greeks. Long (2005) emphasizes that the origin of music which began with a primeval song around a campfire has not been dated yet, while it is proved that the existence of the first instruments dates back to

13.000 BC. Based on Long, in the Early Cultures of the Greek and Roman Period (650 bc–ad 400), the existance of performance space started with the necessity of meetings that brought a number of people together for purposes such as military, political or social. Due to the directionality of the human voice, the seating arrangement was naturally shaped according to intelligibility and audibility resulting in the existence of stepped semi circles, i.e. amphitheatres even with a capacity reaching 17.000 as Ancient Theatre at Epidarius, Greece (Long, op.cit.) These explanations continue with the fact that Greek art was developed in music and dance, and acoustic knowledge also dates from that period.

The evolution of performance space continues at the amphitheatres of The Roman and late Hellenistic periods. In this period, they added a stage house, a raised acting area and hang awnings overhead to shade and used arch and vault, and built many indoor theatres in many of the ancient Greek cities. Long illustrates their most impressive work was Colosseum with a capacity of more than 40.000.

The timeline shows the developments in the church design after the acceptance of Christianity. It is known that the early examples of Basilican churches were very reverberant. Other contributions of the period are the rounded arches, domed ceilings and massive structures (until the introduction of the buttresses).Gothic period (1100–1400) on the other hand housed spectacular stone buildings with vaulted naves, many windows, open colonnades and flying buttresses.(ibid.) It is seen in the timeline that theatre performances had also begun to appear in the period. Parallel with the developments in the art, music, commerce and discovery in the Renaissance period, Italy and England housed theater constructions again in the early years of Renaissance. Long states that the stage had orchestra and proscenium, the semi-elliptical form fostered U shape and the stage wall was removed in the small Roman theatres in the late 16$^{th}$ century. In the mid 16$^{th}$ century, however, the theatres were designed with galleries around a central court having good sightlines, a roofed stage, side walls providing early reflections and adequate acoustics. The courtyard was designed as open-air providing decrease in the reverberation. (ibid.)

650 BC Greek Period

Open meeting areas

Outdoor amphitheatre (Greeks)

Indoor Theatre (Greek and Roman odea, 450 BC)

Odeum (Roman Odeon)

Early Christian period (AD 400)

Romanesque Roman Basilican Church

Domed church (Eastern Roman Empire 532-537)

Gothic period begins (1100)

High Gothic Cathedrals

Renaissance Churches and Theatres

Permanent Public Theaters (England, mid 16th century)

Baroque Period begins (1600)

Baroque Churches

Baroque Theatres

Ball Rooms

Beginnings of Opera Houses (Italy, early 1600)

Classical Period begins (1750) and North Europe becomes the center of the gravity of the music

Concert Halls (Halls for nontheatrical musical concerts)

Romantic Period begins (1825)

Paris Opera, Paris, France, 1875 (Horse shoe)

Stadt Casino, Basel, Switzerland, 1776 (Shoebox)

Theatro Alla Scalla, Milan, Italy, 1778 (Horse shoe)

Grosser Musikvereinssaal, Vienna, Austria, 1870 (Shoebox)

Festspielhaus, Bayreuth, Germany, 1876 (Rectangular-Fan Shaped seating)

Metropolitan Opera House, New York, USA 1883

Neues Gewandhaus, Leipzig, Germany, 1884-1944 (Shoebox)

Concertgebouw, Amsterdam, Netherlands, 1888 (Shoebox)

Carnegie Hall, New York, USA 1891(Shoebox)

Boston Symphony Hall, Boston, MA, USA 1900 (Shoebox)

20th century

Philharmonie Halls and Multipurpose Halls

**Figure 1** The chronology of performance space and well-known halls in the world. (The timeline is based on the explanations of Long, 2005.)

In the early seventeenth century, Italy was the place for art and music, and Baroque style (1600–1750) began in the north of the country as shown in the timeline. As its music, architecture of Baroque is also more ornamented and complicated than before. It is the period when a solo singer with single instrument combination was performed and the terms opera, concerto, cantata, sonata, oratorio, etc. were introduced (ibid.). The domes at the artms of the square cross cathedrals resulted in reverberant spaces underneath. It should be noted that the origins of sound theory date back to the Renaissance period, when sound propagation through fluids had been understood. In the late $16^{th}$ century, the theoretical studies on the acoustics field had initiated (ibid.).

It is known that Italian opera houses with U shaped multistory seating arrangement constituted significant step for the development of performance halls. In the early examples such as Venice (1637), the orchestra was placed beneath the wide stage which had a flyloft. The type became a model for the future opera houses during 200 years and in order to overcome the background noise, composers wrote instrumental music (Long, op.cit.). Musical instruments of the period became highly sophisticated during $17^{th}$ and $18^{th}$ centuries. Long notes that the volume of the northern churches was decreased and more seating added for Protestant Music, which resulted in less reverberation time and clarity of speech. As performance rooms grew larger, the instruments became louder. The problem of distributing sound equally to each audience was recognized at the period.

The valuable explanations of Long and the common knowledge on the history of performance spaces acknowledge the significance of Classical Period (1750–1825) for the development of successful performance halls. Classical music was discovered and many concert halls were built around Europe in this period. Altes Gewandhaus in Leipzig, Redoutensaal in Vienna, La Scalla in Milan were significant examples of the halls of the period, in terms of both impressive architecture and acoustics. Vienna became a center of attraction for cultural activities where Salieri, Mozart and Beethoven performed. Long states that Opera became the cultural attraction and successful performance halls were built at the period with efficient seating area, intelligible spaces and low reverberation times. Barron (2009) evaluates the late $18^{th}$ century, In the latter years of the eighteenth century, social forces were beginning to challenge the subdivision into boxes; the Italian Milizia claimed in 1771 for example, that they were bad for seeing and hearing as well as being immoral. More egalitarian seating arrangements were appropriate to the principles of the French Revolution, which made designers return to classical models for inspiration Ledoux's Theatre at Besançon of 1778 is a rare realization of some of these ideals, with open galleries stepping back instead of vertically stacked boxes. But 100 years later Garnier was still using the Baroque form in the Paris Opéra of 1875. That is not to suggest that architects were not considering alternatives, but that clients would not accept them. Only with the single-minded ambition of Wagner was the mould finally broken in his Bayreuth Festspielhaus of 1876.

### 2.1.2. Acoustically Successful Performance Halls in the World

Classical and Romantic period (1825–1900) composers mostly used piano and some other loud instruments. The loudness of the instruments fostered the design of larger concert halls with full orchestras. This is followed by the consideration of the acoustical behavior of the halls. The shapes of the halls changed in time, from Greek theatres to Italian opera and from basilica and shoebox halls to North European concert halls (Long, op.cit.). Many of these performance halls are known worldwide and are considered as the most successful halls in terms of acoustical behavior, however some halls had excessive reverberation time and long delayed reflections.

Based on Barron (2010), during the history of concert halls, mainly two reasons shaped the auditoriums: precedents and science. Successful halls were designed with the evaluation of acoustical performance of previous halls without the knowledge of formulation of acoustics in the late $18^{th}$ and $19^{th}$ century. Architecturally speaking, there were intentional innovations in the design of the halls. They are in shoebox type with high ceilings, walls cladded with diffusing surfaces and low seating capacity. The pit was deepened and partially covered. As given in the timeline in Figure 1, Stadt Casino in Basel (1776) is one of the earliest examples. Neues Gewandhaus in Liepzig (1882), Grosser Musikvereinssaal in Vienna (1870), Concertgebouw in Amsterdam (1888) are the foremost examples of the 19th century.

These performance halls are accepted as significant examples of good acoustics and constituted basis for scientific studies in the 20th century. Generally, the halls of the type have similar features. The plan type is a narrow rectangle (except Concertgebouw), floors are flat, seats are wood, construction is of thick plaster and the high ceiling (approximately 15 m) is heavy wood in these halls. The walls and ceiling are highly ornamented which provides scattering in the space as the chandeliers. In these halls of the period, the capacity is not in modern standards but around 1600-2200. The orchestra is located in the same room with the audience, above the heads of the patrons on a high wooden platform in front of a hard reflective back to support the sound, particularly the bass. The use of thin wood paneling is absent in these inspiring halls with excellent acoustics (ibid.).

Well-known Paris Opera House (1875), Festspielhaus in Bayreuth (1876), etc. are also built at that period. Based on Beranek (1962 and 2004), in addition to Vienna, Leipzig and Amsterdam, the early 20th century Boston Symphony Hall (1900) should also be listed among the most renowned halls of the period in terms of successful acoustical performance.

Table 1 shows the details of these well known halls based on the studies of Beranek as given in Barron, 2009. Their construction dates are between the years 1880-1900 and seat capacity varies from 1680 to 2625. The dimensions are also provided in this table.

**Table 1** Details of the four most renowned classical concert halls after Beranek (1962 and 2004) (Barron, 2009).

| | Concert Hall | | | |
|---|---|---|---|---|
| | Grosser Musikvereins-saal, Vienna | Neues Gewandhaus, Leipzig | Concertgebouw, Amsterdam | Symphony Hall, Boston |
| Date | 1870 | 1884-1944 | 1888 | 1900 |
| Volume ($m^3$) | 15 000 | 10 600 | 18 770 | 18 750 |
| Seat Capacity | 1680 | 1560 | 2037 | 2625 |
| Length (m) | 52.9 | 44.9 | 43.0 | 50.7 |
| Width (m) | 19.8 | 19.2 | 28.4 | 22.9 |
| Height (m) | 17.8 | 15.1 | 17.4 | 18.8 |

The historical development of the performance space since the early period to the late 19th century resulted in four main typologies that were commonly preferred by the designers of the halls: the fan shape, the elliptical or circular form, horse-shoe and shoebox. The alternatives were searched for such as reversed fan shape, rectangular plan with fan shaped or U shaped seating area, etc. Figure 2 shows the four main typologies of performance halls and an illustration based on the explanations of Barron (2010).The most commonly used typology is the shoe box rectangular halls in the 19th century in Europe, however the context has changed in the 20th century. With the beginning of the modern acoustics, technology and scientific reasons determined the acoustical quality of the halls rather than the typology alone.

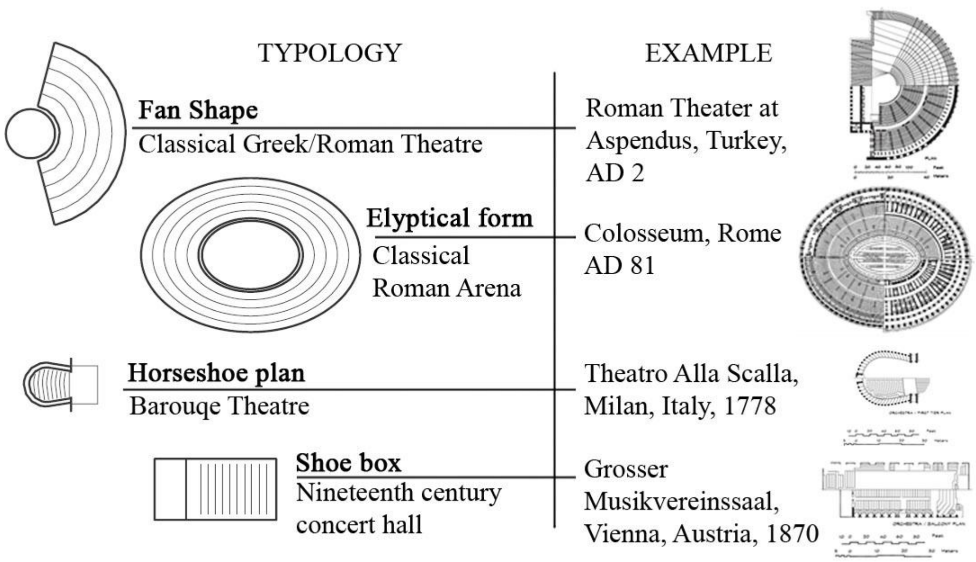



**Figure 2** Development of Major Typologies of Performance Space
(The illustrations are based on Barron, 2010)

The highly ranked successful halls belong to the period 18th and 19th century after the Classic Period begins. The halls reflect the architectural properties of the period not only by plan organization, but also by their classic decoration. Irregular surfaces at the ceiling or the walls are quite common. The balcony paraphet designs are also curved and they have rough texture due to gold latten or other decorative elements. In Figure 3, Beranek (1998) illustrates the classic design of Boston Symphony Hall (1900) emphasizing the stagehouse, irregularities on side walls as niches and deeply coffered ceiling, and balcony design. On the contrary, modern buildings of the 20th century have quite simple flat surfaces that do not have much ornamentation. Moreover, the organization of architectural elements is mostly orthogonal and curved surfaces in the paraphets or in the other parts is not preferred. The surfaces therefore do not scatter the sound as in the classic performance halls.

Long (2009) emphasizes that the prominent feature of the most successful halls is their rectangular shape. The success of this typology has previously been proved by the rankings of concert halls and opera houses through studies of Beranek in the previous years 1962, 1996, and 2004. Long figures out that among the highest ranked halls in the world, the top four halls have a rectangular shape, and the remaining hall has a horse shoe shape. In order to achieve a higher acoustical excellence in modern concert halls, Long suggests that the advantages of rectangular halls should be better understood.

**Figure 3** Boston Symphony Hall (Courtesy Boston Symphony Orchestra) (Beranek, 1998)

The acoustical atmosphere in the classic halls is a reference for many of the contemporary performance hall designs. It is obvious in the recent studies of modern acoustics that the objective criteria and subjective effects in the historic successful buildings are considered and given much importance.

In every successful concert halls, there is a mass use of surface irregularities such as coffers in the ceiling, or the niches and decorations in the wall. Beranek (2003) comments on the sound in famous Philharmonic hall in New York as “glassy, hard and very disturbing”, which he thinks is the result of the absence of surface irregularities, Haan and Fricke (1993) showed that the highest correlation between architectural features in a hall such as length, width, height, their ratios, etc. and subjective acoustical quality is the degree of surface irregularities (Beranek, 2003).

### 2.1.3. Beginnings of Modern Acoustics

The studies on the practical electracoustical devices resulted in the inventions of primitive loudspeakers, telephone, microphone, phonograph and motion picturesat the second half of the 19$^{th}$ century (Long, 2006). In the late 19$^{th}$ and early 20$^{th}$ centuries, the theoretical beginnings of architectural acoustics have started by Sabine. The early studies of acoustics as a science have started after then and many technical books and journals were published expecting to contribute acoustics through broad measurements, observations and mathematical models.

Sabine studied on the reverberation of the auditorium and he determined that the reverberation in an auditorium depends directly on the volume of the room and inversely on the absorbing power of all the surfaces exposed to the action of the sound (Watson, 1917). He also defined the absorbing ability of some common materials which made it possible to correct the acoustical defects of an existing auditorium and to estimate the acoustical behavior of the auditorium before it is constructed.

Prior to Sabine’s work on the Boston Symphony Hall, Architectural Acoustics had been in a lag since there was little to continue as understood from the statement of the designer of the Paris Opera House (1875) (Long, op.cit.). Jean Louis Charles Garnier (1880):

> I gave myself pains to master this bizarre science [of acoustics] but . . . nowhere did I find a positive rule to guide me; on the contrary, nothing but contradictory statements .

> . . I must explain that I have adopted no principle, that my plan has been based on no theory, and that I leave success or failure to chance alone . . . like an acrobat who closes his eyes and clings to the ropes of an ascending balloon.

It is known that in the early twentieth century, Wallace Clement Sabine was asked to solve the acoustical problem in the Fogg Art Museum by President Elliot, which resulted in his experiments on searching the reasons behind difficulties in understanding speech. At the end, he developed the first theory of sound absorption of materials and its relationship with the sound decay in rooms, a formula for the reverberation time and the fact that total absorption and the reverberation time was a constant. Sabine's contribution in the design of Boston Symphony Hall after his studies is considered as a breaking point in the design of concert halls, as in Vienna Musikvereinssaal (Barron, 2000). He followed earlier European examples of performance halls in the shoebox shape, heavy plaster construction and the height. Narrow sides and rear balconies were used to prevent shadow zones. Angled walls and ceiling helped the direction of orchestra sound to the audience. Coffered ceiling and wall niches with statuary resulted in diffusion.

The hall was opened in 1900 and became one of the best concert halls in the world. Starting with that, research on the aspects of room acoustics focused on the relation between the physics of the performance space and the subjective response in the space. In order to assess the relation, the researchers aimed at finding `rules` by performing listening tests with sophisticated methods. In these studies, different measures of acoustic quality were reached such as `Definition`. Similarly, another concentration of the study was on the understanding of the functioning of human hearing. Monaural and binaural listening was noticed as a result of the studies on psychological and physiological acoustics (Bilsen, op.cit.).

In the second half of the 20th century, both performing arts and theatre design became technology-driven with the invention of electronic systems that made television and film industries and computer programs possible. The precision, which is achieved through the electroacoustical developments, raised the expectation of excellence that is difficult to match in a live performance (Long, op.cit.).

The enhancement of acoustical knowledge and technology fostered development in spatial acoustics in the design of halls during the late 20th century. Since mid 20th century, professionals of architectural acoustics have started to investigate acoustical properties systematically. New research topics have been introduced such as formulas and reference ranges for subjective and objective criteria for the room acoustics, production of materials with required acoustical quality, parameters for stage and for the performer as well as the listener, etc. Generally, the most renowned halls of the 19th century constitutes basis for the optimum values for such criteria, which is also supported by the surveys such as subjective rank orderings of Beranek (1996).

The choice of form of the performance space, i.e. plan shape of the performance halls has historically been determined by many different considerations ranging from client expectations to capacity. 1900s, the time when studies on the science of room acoustics began, is a turning point in this respect. Before, the norm was designing according to the precedent necessarily. Italian opera houses and shoebox halls, which were highly decorated, mostly inspired architects of late 18th and 19th century opera houses. By 1900s, the design of concert halls has become a controversial issue about reliance more on scientific developments or precedents. With modernism, use of decoration and detailing minimized and large flat surfaces, new forms rather than developments from existing halls became the common attitude. (Möller, 2011) Barron summarizes some key historical events in determining the performance space typologies in the late 19th and 20th centuries as given in Table 2.

The acoustics of a concert hall contributes to the perception of the quality of the performance. When the acoustical considerations are appropriate for the purpose, as Cox and D'Antonio (2003) emphasizes that the concert hall embellishes the sound and it becomes alive, enveloping and involving the listener in the music making process. Studies on modern acoustics focused on how to provide the audience receive high quality sound. Beranek (1992) also provides a list for the requirements of the acoustical properties that should exist in a concert hall: adequate reverberation time, proper loudness, sufficient amount of early lateral reflections, a short value of initial time delay gap, warmth, diffuse sound field, and a good balance between the early energy within 80ms and that in 2 seconds. In addition to these, similar acoustical atmosphere in every seat of the hall should also be aimed to be achieved in a succesfull performance hall.

**Table 2** Breaking points in the performance space typologies. (Barron, 2000)

| Date | Development | Significant Hall |
|---|---|---|
| 1870-80s | The rectangular (classical) concert hall | Musikvereinssaal, Vienna, etc. |
| 1900 | Sabine's reverberation equation | Boston Symphony Hall |
| 1930s | Cinema: the fan shaped plan | Kleinhans Hall, Buffalo/Salle Pleyel, Paris |
| 1960s | Realisation of the large concert hall problem | Philharmonic Hall, New York |
| 1963 | The terraced concert hall | Philharmonie, Berlin |
| 1972 | Significance of early lateral reflections | Christchurch Town Hall, NewZealand |
| 1989 | Return of the paralel sided hall | McDermott Concert Hall, Dallas |

Regarding the recent studies in the field, Cox and D'Antonio (op.cit.) supported that knowledge from a large number of disciplines exploited in the field of concert hall acoustics in the recent century. Barron (2008) emphasizes that acoustics of concert halls gained more important attention since the search described in *Concert Halls and Opera houses: Music, Acoustics and Architecture* was published (Springer, 2004). A big number of papers on significant findings in the field havebeen published in the recent years andthe publications of previous studies also provided invaluable information.

During the studies on the science in the 20th century, the acoustical terminology has also developed. The appreciation of the musicians as well as listeners and performers was aimed to be based on some objective criteria and soon optimum ranges were defined for these parameters which are explained in the following chapters.

### 2.1.4 20th century developments in the Room Acoustics

Acoustical design should achieve a balance between the architecture and priorities of acoustics. In the previous centuries, the designers were confused with the contradictory statements on acoustics. They had to try and experience the space for achieving good results. "Architectural Acoustics has been described as something of a black art or perhaps more charitably, an arcane science. While not purely an art, at its best it results in structures that are beautiful as well as functional" (Long, 2006).

With the enhancement of acoustical knowledge and technology, spatial hearing, spatial measurement, auralisation and modeling have become the subject for recent studies. Regarding the measurements of spatial sound, the methods have been developed since the studies of Sabine. Essert (1997):

> Sabine used his ears and a stopwatch to measure sound decays. Since then, the vast majority of acoustics measurements on auditoria have been carried out with a single omnidirectional microphone. In the 60s and 70s we began to record and analyse impulse responses, looking at various energy ratios. These, for the most part, still involved single-channel data. Directional information was sometimes investigated with directional microphones and parabolic reflectors.
>
> With the recognition that lateral sound and binaural dissimilarity are important in concert hall acoustics, Barron and others began to measure the lateral fraction, and Ando pushed forward with Interaural Cross Correlation and the binaural room impulse response. The lateral energy fraction at a point has been measured in halls for some years now, although Bradley (1990), Beranek (1996) and others have produced evidence that it is not well correlated with perception.

In 1950s and 1960s, the designers of concert halls discussed the possibility of reducing the reverberation aim such that adequate clarity is provided. Concert hall designers debated the ways to achieve both adequate clarity and reverberation for symphony. "Hall for the twenty-first century" has variable width and variable height adopted the designs done in the late 60s and 70s (Johnson, 1996). The acoustical environment can be changed according to the requirements of the musical performance. Based on Gade (2010), by late 1970's, room acoustic research concentrated on how to design halls to create acoustical environments for the benefit of musicians.

With studies on such issues, the design of the performance halls has gone further. The concert halls have become larger in volume and audience area in time. The reverberation criterion satisfaction in large scale concert halls brought together difficulty of providing accurate clarity and intimacy. This is known as the "large concert hall problem" which has dominated design since 1950s (Barron, 2010). The problem is to provide early reflections for all seating positions despite the large volume, which can be provided by more use of reflecting surfaces around the accurate audience area. Seat capacity has become a major issue of the concert halls especially in the last twenty years. It has become a challenge to balance audience capacity and accurate acoustical conditions.

In the recent decades, the acoustical estimations of well-known concert halls have been done by professionals according to measurable parameters that result in subjective responses in the listeners' ears. In this respect, successful acoustical behavior of the halls depending on the subjective evaluations of the acoustical atmosphere in the halls by professionals constituted a basis for determining referance ranges for the objective criteria. The optimum ranges may show variety among acousticians in time due to the reason that there is not a limit for the science and appreciation of the listeners. What is significant about these criteria is that, the $19^{th}$ century shoebox performance halls mostly obey the recently defined optimum ranges. Barron (ibid.) provides a table given in Table 3 showing the necessity of some features for performance halls for good acoustics.

**Table 3** Some features which distinguish the acoustical design of concert halls, opera houses and drama theatres (Barron, 2010)

| | Concert Hall | Opera House | Drama Theatre |
|---|---|---|---|
| Reverberation Time (s) | 1.8-2.2 | 1.3-1.8 | 0.7-1.0 |
| Scattering | Some | Yes, around stage | Not needed |
| Surfaces to provide early reflections | Yes | Yes, especially for singers | Yes, especially from above |
| Preference for early reflections from side | Yes | Some preference for orchestral sound | No preference |
| Balcony design, vertical agle view | $\theta > 40°$ | $\theta > 30°$ | $\theta > 25°$ |
| Maximum distance of audience from stage | 40 m | 30 m | 20 m |

The recent trend in the field acoustics is evaluating the acoustical performance of a hall according to some objective criteria and supporting it by related subjective quality. In this respect, studies have been held by acousticians via surveys among professionals of music during live performances. Beranek made interviews of leading musicians, music critics and aficionados of music in order to develop a rank ordering of 38 of 66 halls as a continuation of his previous study in 1962. As a result of the study, Barenek grouped the halls into six categories of acoustical quality at the end. (Music and concert hall acoustics, 1996)

Beranek (1996) explains the reasons for making this study by criticizing the similar studies done before. Previous studies of ranking the acoustical quality of concert halls involved recording binaural sound in unoccupied halls and evaluating those recorded signals for judgements of quality. Beranek argues that acoustics of a concert hall can not be judged reliably until the hall is fully occupied since many acoustical parameters such as reverberance, strength, warmth, clarity and even the way the orchestra plays. Table 4 is provided by Beranek on subjective rank ordering of concert halls for which acoustical data are available. “Most halls are the homes of excellent orchestras. Local audiences are, in general, satisfied with their acoustics... No opera houses are included.” (ibid.). According to the survey, Amsterdam Concertgebouw, Boston Symphony Hall and Vienna Gr. Musikvereinssaal constitute the top three halls which are labeled as 'Superior halls'.

**Table 4** Subjective rank orderings of concert halls (Beranek, 1996)

| | City and Name of Concert Hall | No. of seats | Volume in cubic meters | RT Occup. (s) | EDT Unoccup. (s) | BR Occup. |
|---|---|---|---|---|---|---|
| CATEGORY A+, 'Superior' | | | | | | |
| A+ | Amsterdam, Concertgebouw | 2037 | 18 780 | 2.0 | 2.6 | 1.08 |
| A+ | Boston, Symphony Hall | 2625 | 18 750 | 1.85 | 2.4 | 1.03 |
| A+ | Vienna, Gr. Musikvereinssaal | 1680 | 15 000 | 2.0 | 3.0 | 1.11 |

Table 4 continued

| | | | | | | |
|---|---|---|---|---|---|---|
| CATEGORY A, 'Excellent' | | | | | | |
| A | Basel, Stadt-Casino | 1448 | 10 500 | 1.8 | 2.2 | 1.17 |
| A | Berlin, Konzerthaus [Schauspielhaus] | 1575 | 15 000 | 2.05 | 2.4 | 1.23 |
| A | Cardiff, Wales, St. David's Hall | 1955 | 22 000 | 1.95 | 2.1 | 0.96 |
| A | New York, Cernegie Hall | 2804 | 24 270 | 1.8 | - | 1.15 |
| A | Tokyo, Hamarikyo Asahi Hall | 552 | 5 800 | 1.7 | 1.8 | 0.94 |
| A | Zurich, Grosser Tonhallesaal | 1546 | 11 400 | 2.0 | 3.1 | 1.23 |
| **MEDIAN OF CATEGORIES A+ & A** | | **1680** | **15 000** | **1.9** | **Note 1** | **1.11** |
| CATEGORY B+, 'Good to Excellent' | | | | | | |
| B+ | Baltimore, Joseph Meyerhoff Hall* | 2467 | 21 520 | 2.0 | 2.3 | 1.10 |
| B+ | Berlin, Philharmonie Hall | 2335 | 26 000 | 1.95 | 2.1 | 1.01 |
| B+ | Bristol, Colston Hall | 2121 | 13 450 | 1.7 | 1.8 | 1.05 |
| B+ | Christchurch, Townhall | 2662 | 20 500 | 2.1 | 2.0 | 1.01 |
| B+ | Cleveland, Severance Hall | 2101 | 15 690 | 1.6 | 1.7 | 1.12 |
| B+ | Copenhagen, Radiohouset, Studio 1 | 1081 | 11 900 | 1.5 | 2.0 | 1.07 |
| B+ | Costa Mesa, Segerstrom Hall | 2903 | 27 800 | 1.6 | 2.2 | 1.32 |
| B+ | Jerusalem, Binyanei Ha'Oomah | 3142 | 24 700 | 1.75 | 1.85 | 1.20 |
| B+ | Liverpool Philharmonic Hall* | 1824 | 13 560 | 1.5 | 1.8 | 1.00 |
| B+ | London, Royal Festival [Res.On] | 2901 | 21 950 | 1.5 | 1.7 | 1.17 |
| B+ | Munich, Philharmonie am Gasteig | 2487 | 29 800 | 1.95 | 2.1 | 1.00 |
| B+ | New York, Avery Fisher Hall* | 2742 | 20 400 | 1.75 | 1.95 | 0.93 |
| B+ | Paris, Salle Pleyel* | 2386 | 15 500 | 1.5 | 1.8 | 1.23 |
| B+ | Salt Lake, Utah, Symphony Hall | 2812 | 19 500 | 1.7 | 2.1 | 1.00 |

Table 4 continued

| | | | | | | |
|---|---|---|---|---|---|---|
| B+ | Salzburg, Festspielhaus | 2158 | 15 500 | 1.5 | 1.85 | 1.10 |
| B+ | Stuttgart, Liederhalle, Grosser Saal | 2000 | 16 000 | 1.6 | 2.1 | 1.05 |
| B+ | Toronto, Roy Thompson Hall | 2812 | 28 300 | 1.8 | 1.9 | 1.11 |
| B+ | Washington, Kennedy Concert Hall | 2759 | 19 300 | 1.85 | 1.75 | 1.30 |
| B+ | Worcester, MA, Mechanics Hall | 1343 | 10 760 | 1.55 | 2.15 | 1.16 |
| **MEDIAN OF CATEGORIES B+** | | **2467** | **19 300** | **1.7** | **1.9** | **1.07** |
| CATEGORY B, 'Good' | | | | | | |
| B | Chicago, Orchestra Hall* | 2582 | 18 000 | 1.25 | 1.5 | 1.15 |
| B | Edmonton, Alberta Jubilee Aud. | 2731 | 21 500 | 1.4 | 1.4 | 0.96 |
| B | Montreal, Salle Wilfrid-Pelletier | 2982 | 26 500 | 1.65 | 1.9 | 1.11 |
| B | San Francisco, Davies Hall* | 2743 | 24 070 | 1.85 | 2.15 | 1.19 |
| B | Tel Aviv, F.R. Mann Auditorium | 2715 | 21 240 | 1.55 | 1.7 | 0.98 |
| CATEGORY C+, 'Fair to Good' | | | | | | |
| C+ | Bloomington, Indiana U. Auditorium | 2376 | 26 900 | 1.4 | 1.7 | 1.12 |
| C+ | Buffalo, Kleinhans Music Hall* | 2839 | 18 240 | 1.3 | 1.6 | 1.18 |
| C+ | London, Barbican Large Concert Hall* | 2026 | 17 750 | 1.75 | 1.9 | 1.08 |
| **MEDIAN OF CATEGORIES B & C+** | | **2723** | **21 370** | **1.5** | **1.7** | **1.12** |
| CATEGORY C, 'Fair' | | | | | | |
| C | London, Royal Albert Hall | 5080 | 86 650 | 2.4 | 2.65 | 1.13 |
| * Before renovations either recently completed, underway or planning to improve acoustics. | | | | | | |
| Note 1: Seats for several of the halls are unupholstered. Occup: Occupied, Unoccup: Unoccupied | | | | | | |

Beranek (2008) states that hearing each note is not the only measure of acoustical quality in a concert hall. Explaining the comparably good performance of Boston Symphony Hall, he listed a number of criteria that adds to acoustical quality as follows.

First, the reverberation time $T_{60}$ must follow the music to be performed in the hall. 1.9 seconds of Boston is acceptable for symphonic music. Second, the time first reflection is heard after the direct sound, initial time delay gap (ITDG), is another important criteria. ITDG for Boston is in acceptable range, which is around 15 ms. He states that if ITDG is greater than 35 ms, the hall will sound like an arena. Third, the law of the first wavefront is significant. Before about 100 ms, the azimuth location of the source is possible at a seat in the hall. Azimuth location is determined from the first wavefront and is a significant contribution to the acoustical rating. Fourth, during 10 ms period, the sound is broadened by the early reflections, which is called Appaent Source Width (ASW). This value is related with the early energy that arrives through lateral reflections and is measured by the Interaural Cross Correlation coefficient (IACC) (microphones at two ears) or the lateral (energy) faction (LF). Boston Symphony Hall ranks the best among the halls in this respect. Fifth, approximately after 100 ms, the listener is enveloped by the sound. For good sound quality, the Listener Envelopment (LEV) must be high. Additionally, Morimoto (2002) et. al. explains that when LEV is reached, the azimuth direction of the source can not be perceived by the listener. Sixth, as Griesinger (2007) suggested, the energy of the direct sound in the listener's position should not be weaker than -10 dB below the ultimate level for best sound quality. Seventh and the last, texture, the number of early reflections before about 100 ms is an important factor in acoustical quality.

In addition to his study of ranking the performance halls in 1996, Beranek came up with a similar list of 60 halls which are evaluated by conductors and music critics in 2008. Examples taken from the survey are given in Table 5. In this rating of the concert halls, Reverberation Time (T60) and Strength (Total Sound Level, G) is compared. The highly ranked five halls in category 1 have a reverberation value between 1,8-2,0 seconds. Strength values are changing from 3.2 to 6.5 dB in these halls.

**Table 5** Concert Hall Ratings (Beranek, 2008)

| | | T60 (Occup) | Gmid (dB) |
|---|---|---|---|
| Category 1 | | | |
| | Vienna, Grosser Musikvereinssaal | 2.0 | 6.5 |
| | Boston, Symphony Hall | 1.9 | 4.2 |
| | Tokyo Opera City (TOC), Concert Hall | 1.95 | 5.0 |
| | New York, Carnegie Hall | 1.8 | - |
| | Cardiff, Wales, St. David's Hall | 1.95 | 3.2 |
| Special Category (surround Halls) | | | |
| | Berlin, Philharmonie | 1.9 | 3.7 |
| | Los Angeles, Disney Hall | 1.85 | - |
| Category 2 | | | |
| | Cleveland, Severance Hall | 1.6 | 3.5 |
| | Munich, Philharmonie am Gasteig | 1.8 | 1.9 |
| | Washington, D.C., JFK Concert Hall | 1.7 | 2.5 |
| Category 3* | | | |
| | London, Royal Festival Hall | 1.45 | 1.9 |
| | Paris, Salle Pleyel | 1.5 | 3.9 |
| | Montreal, Salle Wilfrid-Pelletier | 1.65 | 0.1 |
| | Buffalo, Kleinhans Music Hall | 1.5 | 2.7 |
| | San Francisco, Davies | 1.85 | 2.2 |
| * The rankings and acoustical data given here precede the renovations that have been made to all of these halls in recent years. | | | |

### 2.1.5. The Development of Performance Spaces in Turkey in the 20th century

The early 20th century, mainly World War I (1914-1918), was the time when Ottoman Empire lost its power. After Republic of Turkey has been founded on its ruins in 1920s, Ankara was chosen as the capital city of the new republic and the country experienced a period of reforms and revolutions. Following the foundation of the Turkish Republic, and setting Ankara as the new capital, the city faced with new construction needs for official, public, governmental buildings for the new Republic, to accompany the development of the society. Beside several new official, public, private buildings some significant performance spaces were built first in Ankara then in İstanbul and İzmir contributing the cultural and social development of the habitants and more general to the cultural development of the young republic. The list of the halls of early 20$^{th}$ century Sarı (2007) provided is expanded:

El Hamra Sineması (by Tahsin Sermet Bey, İzmir, 1922-1926),
Yıldız Sarayı 2. Abdulhamit Salonu (İstanbul), Edirne Türk Ocağı Binası (Edirne Devlet Türk Müziği Topluluğu Salonu, by Dr. Rıfat Osman Bey),
Süreyya Paşa Opera Temsil Salonu (by Auguste and Gustave Perret, İstanbul, 1927),
Türk Ocağı Binası/Resim HeykelMüzesi (by A. Hikmet Koyunoğlu, 1927-1930)
II.Evkaf Apartmanı/Küçük Tiyatro (by Mimar Kemalettin, 1929)
Tayyare sineması (by Arif Hikmet Koyunoğlu, Bursa, 1930-1932)
Sergi Evi/Opera/Büyük Tiyatro (1933, the hall was designed by Paul Bonatz in 1946)

Among many other halls of the period, Süreyya Operası constitutes a significant case in terms of acoustical design in western style. In 1923, Süreyya Paşa decided to build a new opera hall and he visited Paris in order to examine famous buildings. The theatre was designed by Auguste and Gustave Perret brothers who were inspired by the theatre in Champs-Elysees by Gabriel Astruc and some other classic German theatres. The building was opened in 1927 as a cinema and faced with many interruptions which deformed its originality. It was then restorated according to the memories of Süreyya Paşa. The stage was enlarged, orchestra pit and a number of technical rooms were added and frescoes on walls and ceiling in the main hall were restorated. Today, the building is used as Süreyya Paşa Opera Temsil Salonu. (www.kadıkoy.net Access Date: July, 2011)

Turkey was re-acquainted with western style performance and thus performance spaces in the beginning of 20$^{th}$ century. This study provides a comparison between the development of performance spaces in Turkey and in the world after mid 18th century until now. The development, especially in Europe, between 1770 and 1920 was followed by Turkey between 1910 and 1948, which the country lived the most productive period in terms of performance spaces. The effects of late 18th and early 19th century European examples can be seen in Turkey's Early Republic performance halls.

In the Early Republic period, three significant performance halls were built in Ankara, in the old city center, Ulus, in the very first half of the 20th century and they are still in use today. This study concentrates on these three halls for the goals of the study: Resim Heykel Müzesi Multipurpose Hall (Türk Ocağı Binası), Küçük Tiyatro Hall (II.Evkaf Apartmanı) and Opera/Büyük Tiyatro Hall (Ankara Sergi Evi). These performance halls of the capital city prove the most important developments of the period in terms of architectural acoustics since they are the first examples of performance halls in Ankara in western way. Figure 4 shows the location of these halls in the Ulus region.

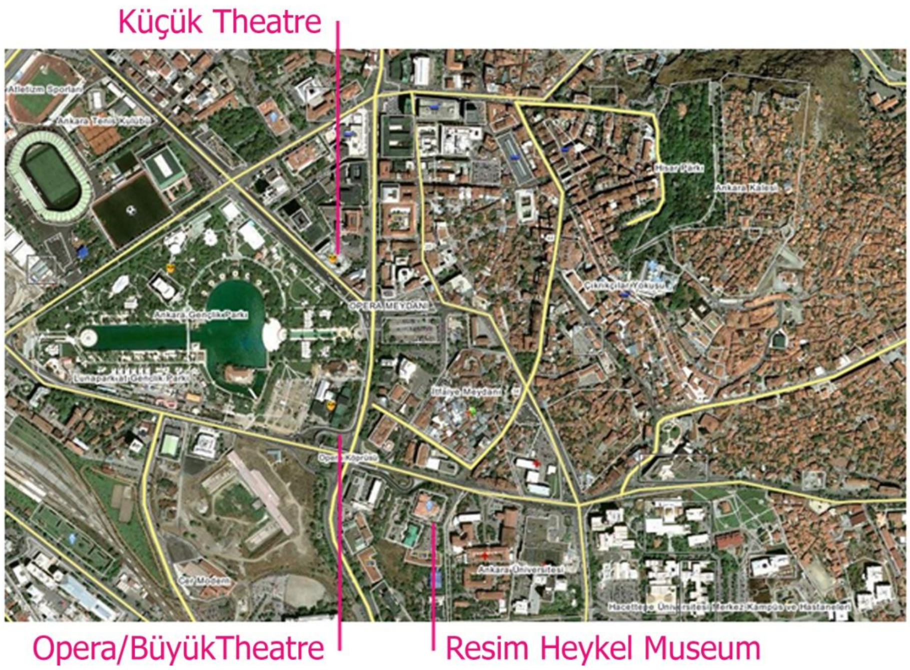



**Figure 4** Location of the case buildings in Ulus district

The case halls are not only historically important but also play an important role in the city due to their active performance. The performance halls that are chosen as cases for this study all belong to Kültür ve Turizm Bakanlığı (Ministry of Culture and Tourism). Resim Heykel Müzesi is a museum of Güzel Sanatlar Genel Müdürlüğü and the performance hall in the building has multipurpose use. Küçük Tiyatro building is used as the headquarter of Devlet Tiyatroları Genel Müdürlüğü (Turkish State Theaters General Directorate) and its hall is used for the drama and musical performances. Opera building is used by Devlet Opera ve Balesi Genel Müdürlüğü (Directorate General of State Opera and Ballet), whereas the performance hall is used for both Devlet Opera ve Balesi Genel Müdürlüğü and Devlet

Tiyatroları Genel Müdürlüğü. Figure 5 shows exterior views of the buildings.

**Figure 5** Resim Heykel Müzesi (www.erhani.com,2006)
Küçük Tiyatro (www.devtiyatro.gov.tr, 2009)
Opera/Büyük Tiyatro (Doğan Hasol)

### 2.1.5.1. Resim Heykel Müzesi Multipurpose Hall

The building was designed as Türk Ocağı Binası by Arif Hikmet Koyunoğlu in 1927-1930 Türk Ocağı Binası is constructed on the Namazgah Hill, near Etnoğrafya Müzesi, which was also designed by the architect (www.guzelsanatlar.gov.tr). Koyunoğlu designed many government buildings in the First National Style. Similar to those buildings of the architect, this building is also symmetric both in the facade and the plan. It consists of a heightened basement floor, ground floor and an upper floor. In the ground floor, there is a hall with marble floor finishes and six marble columns. Behind these columns, gorgeous staircases on two sides lead up to upper floor. *Mihrapçık* motives are used in the balustrade (Kuruyazıcı, 2008). Figure 6 shows the interior view of the hall and the plan of the building, respectively.

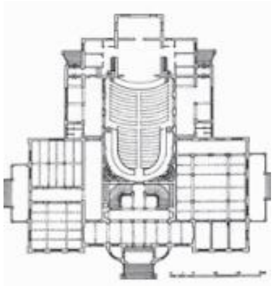


**Figure 6** Resim Heykel Müzesi Multipurpose hall (beykoz-turkocagi.org.tr, 2011)
Resim Heykel Müzesi plan (Aslanoğlu, 2001)

The plan organisation is a multipurpose hall in the middle and other volumes surrounding it. In the front side, these volumes are the entrance and stairs, whereas behind the hall, these volumes are the backstage, foyer, library, museum and meeting rooms. As understood from the restoration projects prepared in 2001(Kültür ve Turizm Bakanlığı Arşivi) the structure of the building is a little bit complex: walls are stone and brick; floors and arches are reinforced concrete. Moreover, some of the columns in the interior are marble. The multipurpose hall audience seats are placed in a "U" shape providing each seat face the stage.

As it is stated, the museum has been included in the present study to evaluate the acoustical performance of the multipurpose hall in the building. The surveys show that the architect Koyunoğlu had a sensitive approach to acoustics while experiencing the space himself during the construction. Kuruyazıcı (2008) quotes:

> Tiyatro salonundaki akustik meselesine çok önem vermiştim. Tanıdığım musiki arkadaşlarımı çağırıyor, çalgı çaldırıyordum. Bir yerden fena akis geliyor mu, ses

> uğulduyor mu diye dikkatli tecrübeler yapıyor, bulduğum kusurları tashih ediyordum. Küçük bir vızıltı veren bir nesne için tam bir ay çalışmıştım. Nihayet onu da bulmuştum. Çelik perdenin vidalarından biri iyi sıkışmadığı için onun rondelası ihtizazla [titreşimle] sallanıyordu. Onu da tamir ettik.

Arif Hikmet Koyunoğlu went to Sanayi-i Nefise Mektebi for education of architecture between the years 1910-1915. Giulio Mongeri was teaching at the academy at that time and he was a model for his students. Karaköy Palas (1920) and Osmanlı Bankası (1926) constitute the most known buildings designed by him. Koyunoğlu designed many buildings in Turkey such as Tayyare Cultural Center (Bursa), Etnografya Müzesi (Ankara), Hariciye Vekaleti (Kültür ve Turizm Bakanlığı), Mithat Alam House (İsrail Büyükelçiliği) and Saint Antoine Church, İstanbul (with Mongeri). (ibid.)

#### 2.1.5.2. Küçük Tiyatro Hall

The building was designed by Mimar Kemalettin Bey in 1929 as II. Evkaf Apartment as a luxurious apartment for Vakıflar Genel Müdürlüğü to derive profit. It consists of a basement floor, a ground floor and 4 typical main floors topped with terrace floor. The structural system is reinforced concrete in this building (Ankara Büyükşehir Belediyesi Arşivi). In the first 20 years, the floors were used as offices and basement levels as storehouse or workshops. Moreover, box and wrestling performances were also held in the building in its early years (www.yapı.com.tr, Access Date: 2008). Figure 7 shows an interior photo of the theatre hall looking at the stage and the plan of the building grond floor.

Mimar Kemalettin Bey was a famous architect of the period and designed many significant buildings. He designed I. and IV. Vakıf Hanı (İstanbul), Ankara Palas, Edirne Station Building, İstanbul University Library, Devlet Demir Yolları Genel Müdürlüğü (Ankara), etc.

In the basement floor of the building that Architect Kemalettin had designed, there had been decor workshops of the conservatory. Additionally, there had been a conference hall and a stage originally in the building. However, due to the economic constrictions of the Second World War, it took long time to turn the hall into a theatre performance hall, i.e. Küçük Tiyatro. In the early 1940s, the President İsmet İnönü pronounced that the Republic needed a new stage. Followingly, it was agreed that the hall at the ground level of Evkaf Apartment in

Ulus district that was built in late 1920s would be adequate for that purpose.

In 1947, soon after Muhsin Ertuğrul was charged in the administration of Tatbikat Sahnesi, the ground level of Ekaf Apartment was re-arranged as a theatre hall. After that, the hall was employed for performances regularly in every evening. Küçük Tiyatro was opened in December 27, 1947 (www.devtiyatro.gov.tr, Access Date: May 2011). Today, on the wall near the entrance of the theatre, it is written that: "Küçük Tiyatro'nun açılmasında hizmeti geçenler: Reşat Şemsettin Sirer, Rüştü Uzel, Halil Vedat Fırat, Tevfik Ararat, Abidin Mortaş, Ahmet Kutsi Tecer. 17.12.1947"

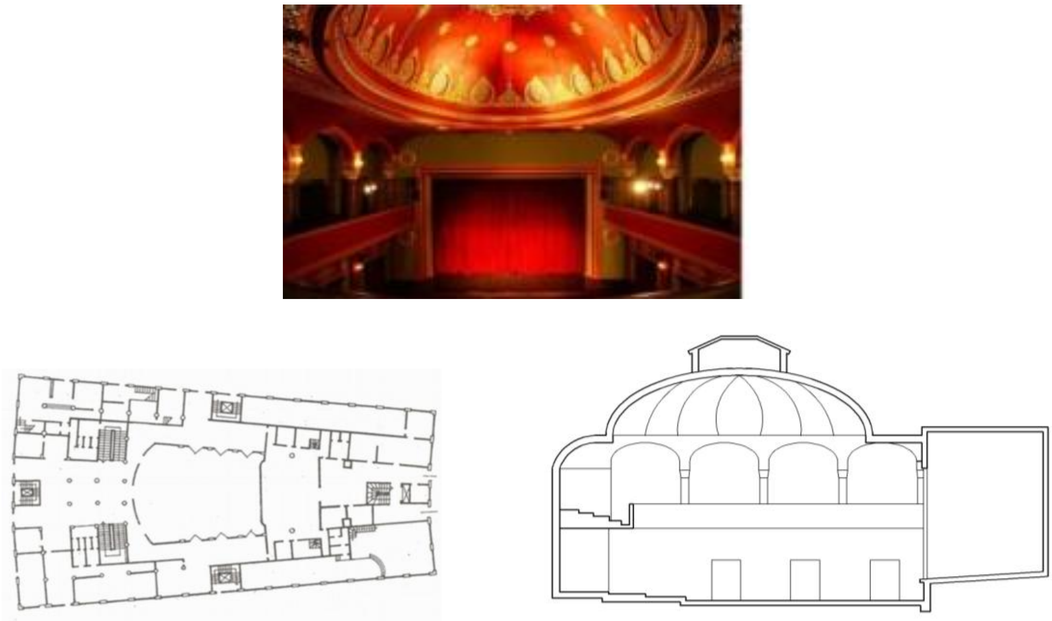


**Figure 7** Küçük Tiyatro Hall interior view (www.devtiyatro.gov.tr, 2010)
The ground level plan of the building (Aslanoğlu, op.cit.)
The section of the building

**2.1.5.3. Opera / Büyük Tiyatro Hall**

Opera building was initially designed and constructed as Ankara Sergi Evi by Şevki Balmumcu in 1933 and its function was altered as an opera house with an additional performance hall in the 1940s. Today it is stil being used for performances, i.e. drama and opera. Figure 8 presents the hall interior photo taken from the stage and a ground level plan of the building.

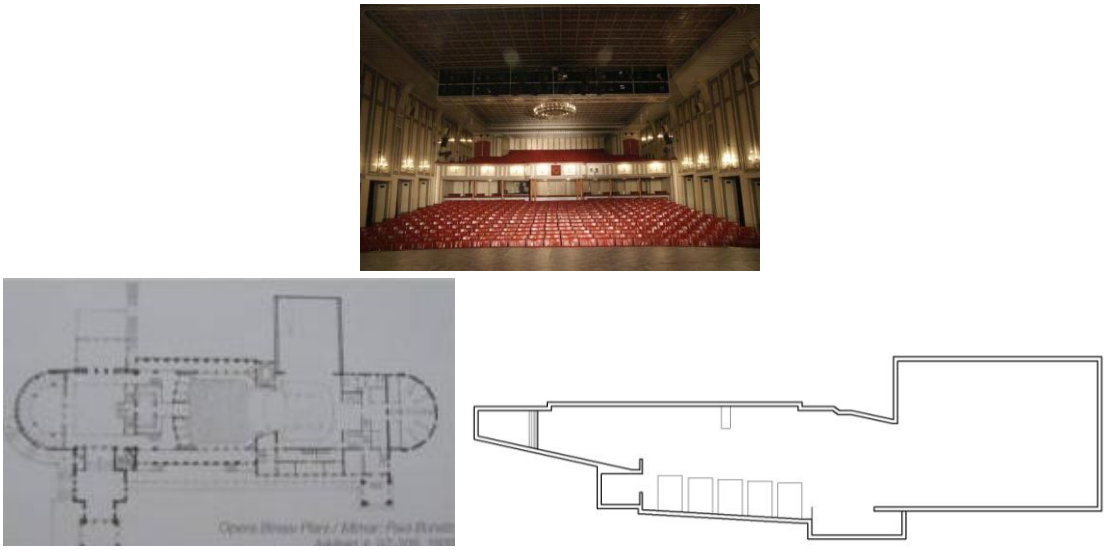


**Figure 8** Opera Hall interior view
The plan of the ground floor of the building (Aslanoğlu, op.cit)
The section of the hall

Before the construction of the Exhibition Building in Ankara, Türk Ocağı Building and some other buildings were chosen for big exhibitions. Together with the rapid development of the capital, new government decided to build an exhibition house so that the Turkish Republic would be able to present its development. 1930s were the years when foreign architects gained popularity in Turkey. The Western influence on the reforms had also started to be seen in the architecture of that decade when an international competition was done for the Exhibition Building among 26 participants.

Among the 16 native participants, Şevki Balmumcu became the winner. The modern reinforced concrete building was built between1933-1934. Şevki Balmumcu designed a modern building, which both provided the requirements of the competition and of a modern exhibition building. He designed the building as a play of vertical and horizontal volumes.
The Exhibition Building was opened in 1934. Firstly, domestic goods were presented by 116 firms. Later, exhibitions on art, industry and design were also held in the following years. During early 1940's, the building continued to house exhibitions.

Due to the reason that Ankara as the capital city did not still has an Opera Building, government searched ways of having an opera. The economic conditions were not sufficient to build a new opera building. This situation resulted in an unexpected solution which is the refurbishment of the Exhibition Building into an Opera House (www.kultur.gov.tr, Access Date: July, 2010). In order to re-design the building as an opera, the German Architect Paul Bonatz was charged with the task. Bonatz also designed Saraçoğlu Memur Evleri (Ankara), Ankara Teknik Öğretim Müsteşarlığı Technical Office and Stuttgart Hauptbahnhoff.

Bonatz refurbished the building in a more decorative way. The most significant change, definitely, was the addition of a multipurpose performance hall, which had an orchestra pit in front of the stage. The main function, which was exhibition, would then serve as a performance, either opera or theatre. As an opposition to decorative design of the façade and the interior by Paul Bonatz, the performance hall was not designed with that much decorative detail. The hall was enough to meet the needs of the capital city at the time as an opera. The matter here is, whether such an intervention to an existing building could result in an acoustically successful performance hall or not. In this respect, the volume as well as the applications of appropriate materials to proper places plays a significant role. The building as a whole, is an important heritage from 1930's and as an opera and theatre building today, it still has a very significant role in the cultural prosperity of Ankara.

### 2.2.1. Modern Room Acoustics and the Importance of Impulse Diagram

Acoustics, which has been a part of science for many years, plays an important role for room acoustic approaches. Perception of a sound by the listener includes the source signal and the reflections of the sound, which is the impulse response. Impulse Response Diagram gives the information about sound for a specific source and receiver position. The acoustic impression is formed by the objective properties of the sound field. A sound is propagated from the source in particular direction which vibrates the particles of the medium that surrounds the source. The sound waves travels in the same direction as the vibration of the particles in longitudinal direction. The pattern of changes in the pressure of these particles are squeezed and then pulled out.

Figure 9 shows the frequency ranges of various instruments based on Pierce (1983). As seen in the image, human voice ranges from the frequencies 63 Hz to 1k approximately. 500Hz-1000Hz are generally considered as mid frequencies for the calculations of objective parameters, which is important for the acoustical evaluation of the performance spaces.

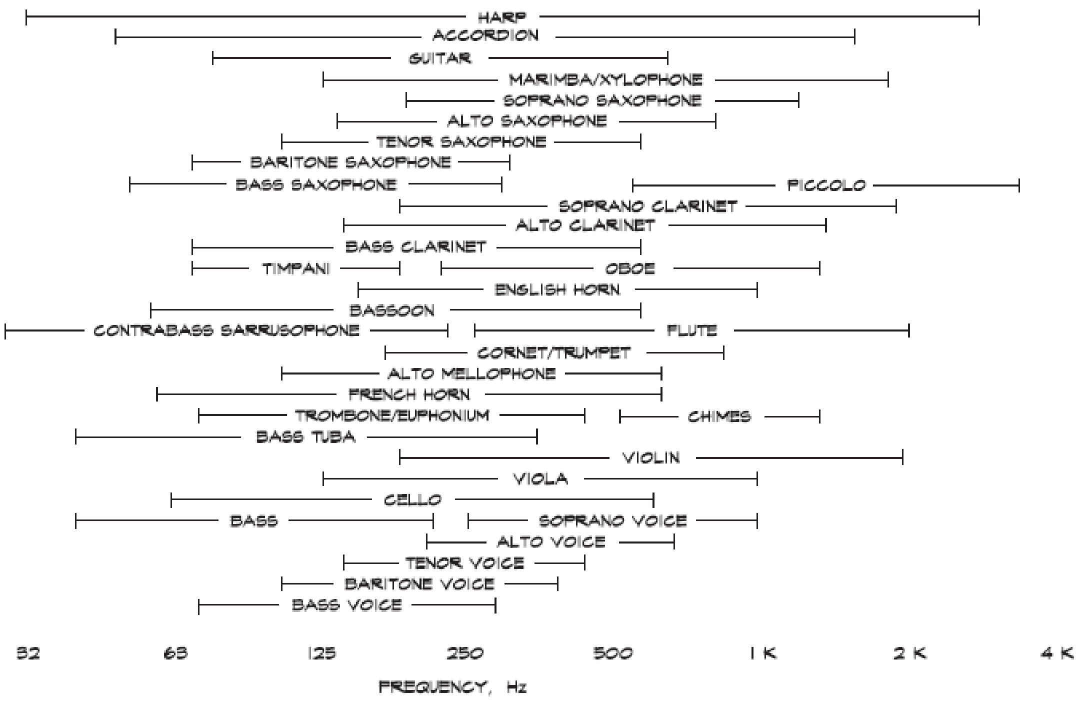



**Figure 9** Frequency ranges of various instruments (Pierce,1983)

Impulse response is the pressure response recorded at the receiver position of the interest at the time when a pulse is produced at the relevant source position. The pulse is very short but intense. The impulse response describes transmission between two points, which is an omni-directional measure (Barron, 2009). The pressure impulse response has both positive and negative values, while acoustic energy is related to pressure squared ($p^2$) and is positive.

The impulse diagram, which shows the impulse response of a room, determines many of the objective criteria. The diagram consists of time and sound pressure relationship of a sound impulse until the reverberation is minimized. Early Sound is the direct sound and reflections before 80 miliseconds (Barron, 2006). Late Sound is the sound arriving more than 80 miliseconds after the arrival of the direct sound (J.S.Bradley, 2000). Late sound is related with distance, volume and reverberation. The existence of unwanted echoes, time delays and duration of reverberation can also be understood from the impulse diagram of a sound in a room. Figure 10 is an example of impulse response diagram showing early and late sounds.

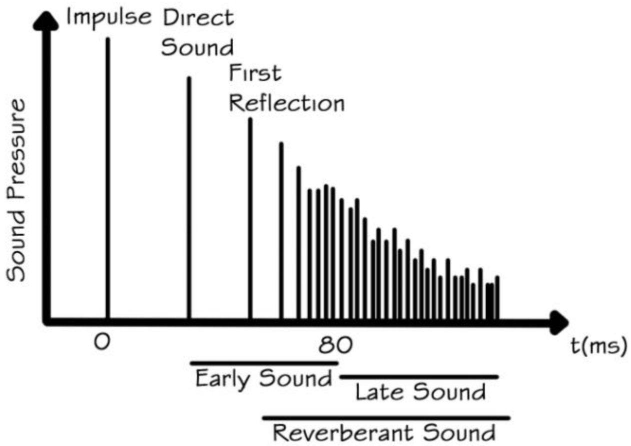



**Figure 10** A sample impulse response diagram

Figure 11 provides another sample impulse response of the concert hall shown on the left. The early reflections from overhead supports the direct sound and thus provides a clear sound, the reflections from the side walls results in a spacious and enveloping sound, and the extended reverberation time creates fullness of the sound. These subjective responses are the results of objective factors of the impulse and the hall.

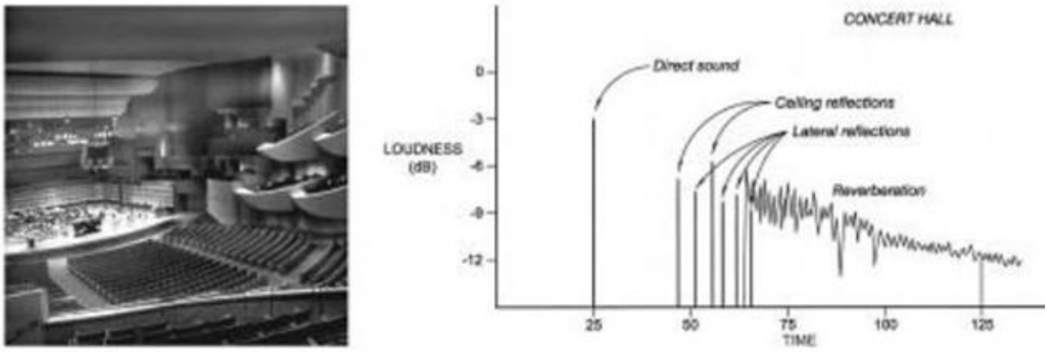



**Figure 11** Impulse response of a concert hall. (Acoustics: Principles and Practice, 2010)

### 2.2.2. Parameters of Room Acoustics

The study in this part aims to provide general aspects of room acoustics. Room acoustics is defined as the science of radiation, propogation and transmission of sound waves within the enclosed space. It is an objective phenomenon and consists of several qualitative and quantitative parameters which are known as subjective and objective factors.

At the beginning of the 21$^{st}$ century, there has been a consensus on the set of five parameters that is also stated in ISO 3382 (Skàlevik, 2011). The objective parameters were defined as reverberation time (seconds), early decay time (seconds), early-to-late sound index (dB), early lateral energy fraction and total sond level (strength, dB). The developing studies on the subject resulted in the definition of many other parameters. The invention of objective and subjective parameters led to further studies on concert halls. There have been valuable studies on subjective musical responses and their reasoning acoustical factors such as rank orderings of Beranek on 58 concert halls and that of Hidaka and Beranek on 23 opera houses. The rank orderings of Beranek will be provided in the following chapters.

#### 2.2.2.1. Objective Parameters

In the early 20$^{th}$ century, Reverberation Time (RT) is considered to be the key determinant of the acoustical performance of a concert hall, however further studies in the field showed that there are other significant criteria. These are known as "objective parameters" which results in "subjective" effects on listeners.

Objective measures of parameters constitute an intermediate definition between the design elements and their subjective effects. The design decides the behavior of the sound in the room and this sound field is experienced both by listeners and performers. By calculating the objective measures, it is possible to evaluate the behavior of the room and the sound field created.

Each quantity of objective parameters are measured in a series of octave frequency bands at several seat positions, however the results are given as averages. There are international standards for these quantities, ISO 3382, in which the accurate measurement methods are described (Barron, 2009). Due to the reason that studies on the subject are still developing, optimum ranges might change in time.

Among many other parameters, Early Decay Time (EDT) and reverberation is considered as significant factors that are correlated with many other objective criteria, thus resulting in many subjective responses. In addition to this, Cederlöf emphasizes that the highest ranked halls in the recent studies have high clarity, definition and short reverberation time. Barron (1993) suggests that the recommended characteristics for reverberation time show that for low frequencies the reverberation time should not be lower than for middle frequencies. On the other hand, Hidaka and Beranek (2000) suggest the most important of the objective acoustical parameters for determining acoustical quality in opera houses as reverberation time RT (or EDT), strength of the sound throughout the house $G_M$, intimacy ITDG, spaciousness [1-IACCE3] and bass ratio BR.

In large concert halls, it is a challange to provide adequate Sound Strength (G), whereas in a small concert hall (capacity<800 seats), it is difficult to control the loudness. Generally, in small concert halls mean G values are found to be in the range of +6 to +12 dB and high values of early lateral energy. Statistically, EDT, G, C (Clarity) and LG (Late Lateral Sound Level) are dependent of RT, source-receiver distance and hall volume. (http://www.akutek.info/index_files/www_acoustics.htm, Access Date: March, 2011)

As seen in the explanations above, there are many components of acoustics of a room. Similarly, the studies still continue resulting in a mass of information on the subject. The same situation is also valid for the subjective parameters. Therefore, a concise table is prepared in this study in order to collect the data on acoustical parameters and will be provided in the Case Study Chapter.

#### 2.2.2.2. Subjective Parameters

Subjective parameters are the resulting effects of objective factors in the listener's or performer's ears, as stated before. In recent decades, the studies more focused on the subjective and objective factors in concert halls. Beranek (1962) defined 18 significant subjective matters from intimacy to warmth. In 1996, the author also related musical factors and their reasoning acoustical factors. According to his illustration given in Figure 12, the subjectice factors can be listed as fullness of tone, clarity, intimacy, spaciousness, timbre and tone color, envelopment, ensemble and dynamic range. The acoustical factors for these responses vary from objective parameters like reverberation time to architecturel properties of the hall such as the irregularities in the wall. Indeed, the room properties and physical conditions in the room create objective parameters thus resulting in subjective factors.

The major dimensions of concert hall acoustics based on Barron (2010) are that the clarity should be appropriate for the appreciation of musical details, that the reverberance in the room should be adequate, that the impression of the space should be provided, that the listener should feel the intimate acoustic atmosphere and adequate loudness in the room. Gade (2010) emphasizes that early reflections support ensemble, while late reflections foster support and reverberance. Similarly, Kaiser (2009) provided time intervals of the impulse response and their corresponding possible effects that Griesinger (1997) suggested. Based on his suggestion, the time scale of reflections and expected response is:

0-10ms: affection of loudness, broadening of source image, change in timbre
10-50ms: cause room impression in terms of the size of the room
50-150ms: reduction of intelligibility and sensation of envelopment
150-end: reverberation

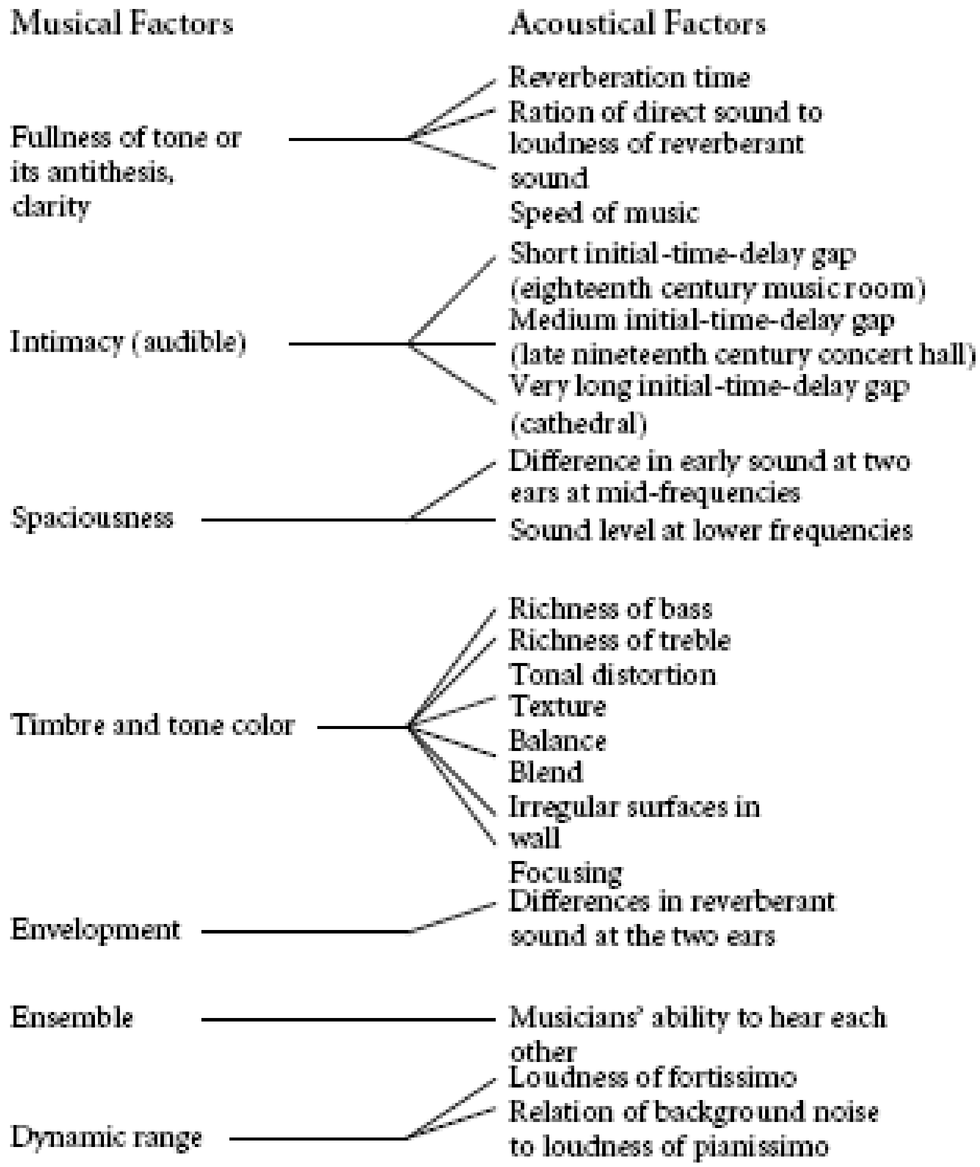



**Figure 12** The main subjective criteria and their reasoning acoustical factors (Beranek, 1996)

Based on Barron (op.cit.), clarity and received sound level for the listener are significant concerns for music. For clarity and intelligibility, the energy of direct sound should be combined with the early reflections. Clarity is defined by the author as the ability to hear musical detail and intimacy as the feeling of involvement in the performance.

In concert halls, spaciousness is created when the correlation of the left and right ear signal resulting from early lateral reflections is decreased. Early reflections arrive at the listener no later than 80 ms after the direct sound. Marshall (1967) suggested the importance of early lateral reflections in creating spaciousness. His claim was followed by many authors. In his systematic subjective observations in this field, Barron (1971) approved that it is not necessary to have numerous early reflections to create spaciousness. A specious sound field can be created by adding just one lateral reflection to the direct sound. Similarly, Ando (1985) suggests that after only four reflections, the speciousness rapidly decreases to the final value. (Bilsen, op.cit.)

Barron (2010) provides the information of the two spatial affects occurring in a performance hall that is first proved by Morimoto and Maekawa (1989). These spatial issues are that the early reflections provide a sense of the source becoming broader, while late sound results on the feeling of being enveloped by the sound. Further definitions of subjective factors are also provided in the following chapters as well as in the Glossary of Terms.

# CHAPTER 3

# MATERIALS AND METHODOLOGY

In this study, acoustical analysis of these significant halls is done through acoustical modeling and calculations through room acoustic software. Room acoustic modeling software calculates acoustical behavior through surfaces rather than curvelinear forms or lines. Therefore, the abstraction of the materials that refer to the interior architectural spatial features of case performance halls is a crucial step in the architectural 3-D modelling. Curved surfaces are divided into smaller planar sections, and each section was modeled as a surface. This division should be done such that both curvelinear form is still maintained and number of surfaces is not aggravated. The increased number of surfaces in an acoustical model will result in the longer calculation time.

Computer simulations are done through the room acoustic software Odeon 9.2 Auditorium version in this study. The program uses ray tracing method with image-source method for calculations. Prepared 3-D architectural CAD model is imported to the program and each surface is listed automatically. Layers in the file are matched with proper materials in the acoustical modeling stage. In the selection of adequate material properties for the layers, the porousity, existence of air gap, montage method, etc. are significant criteria that should be taken into consideration. If no material of the list corresponds with the properties of the layer, new material is introduced with adequate absorption coefficients at required frequency ranges. The model at this step is checked whether there are missing parts or breaks in the concections. The following step is assigning proper transmission and scattering coefficients to materials. Scattering coefficient ranges from 0-1 and is assigned for the roughness or smoothness of the surface. Higher values are given for heavily rough surfaces. To illustrate, 0,6 is given for the audience in this study.

According to the setup information given in Table 6, the lambert scattering method is chosen in the acoustical modeling. Fractional surface type is preferred due to the existence of curved forms in the model. Survey method is selected for this study. The scattering is reflection based and appropriate values are given to the surfaces in the models. Angular absorption is not chosen since the rooms are not highly absorptive. For the noise stemming from the HVAC systems, Noise Criteria 20 is assumed. For the receiver (audience) positions, 0,7m distance and 1,20m height is assigned.

Next step is the positioning of source and receivers in the models. The receiver and reflective surfaces are also defined. Followingly, room settings are done in terms of background noise, scattering methods to be used, angular absorption, temperature, humidity, etc. as given in Table 6. After all the settings are completed, the program is ready to calculate the quantitative results. The propogation of sound in case halls and acoustical behavior of these rooms will be explicated in the Case Study chapter more in detail.

**Table 6** Setup Information for the Acoustical Modeling of the case performance halls regarding the settings of ODEON 9.2 Aditorium

| | TITLE | TERM/ VALUE | DEFINITION/ EXPLANATION | ACCEPTED VALUE |
|---|---|---|---|---|
| ROOM SETUP INFORMATION | SCATTERING METHOD | **Scattering method: None/ Lambert/ Full Scatter** | None: Scattering is not taken into account<br>Full Scatter: 100 % scattering is applied to all surfaces.<br>Lambert: All directions of late reflections are calculated using the scattering coefficients assigned to the surfaces. Lambert scattering is preferred for realistic results. | Lambert |
| | | **Oblique Lambert** | In the ray-tracing process, secondary sources are generated at the collision points between walls and rays traced. The directivity pattern applied to these sources is Lambert (the cosine directivity which is a model for diffuse area radiation). The oblique lambert method allows including frequency dependent scattering in late reflections of point response calculations. | Oblique lambert |
| | | **Fractional Surface Type** | In some cases Reflection Based Scattering Coefficient may overestimate the scattering in small surfaces. In order to prevent this problem in small faces that forms a curved surface, the surface type is chosen as Fractional. The reason behind is that these small surfaces do not provide any significant edge diffraction. | Fractional Surface Type is chosen in small faces that forms a curved surface. |
| | | **Point Response Parameters: Survey/ Engineering/ Precision** | Survey: Angular absorption disabled,<br>Engineering: Angular absorption in soft materials only, Recommended number of rays<br>Precision: Angular absorption in soft materials only, Number of rays and later reflection density is very high. | Survey method |
| | | **Number of Rays** | Number of rays reflected can be changed with this option. | Recommended number of rays |
| | | **Reflection based scatter** | Scattering coefficient is used in order to describe surface scattering due to roughness of material and diffraction caused by limited surface size. Scattering due to diffraction is distance and angle dependent.<br>Normally, different scattering coefficients should be applied to surfaces with same material, because the size and position differs in each surface. However, in reflection based scattering method, each reflection is unique. Even if same scattering coefficient is applied to all surfaces, each surface scatters differently due to the difference in sizes.<br>Reflection based scattering method combines scattering due to diffraction due to typical surface dimensions, angle of incidence, distance to surface edges and Ip. ("Odeon's Reflection Based Scattering Method," video by OdeonDK, uploaded 18.06.2010, web address: http://www.youtube.com/user/OdeonDK#p/a/u/1/_bymZkisMWM, access date: 15.04.2011) | Appropriate scattering coefficients are given to the surfaces. |
| | GENERAL SETTINGS | **Angular Absorption: Disabled/ All Materials/ Soft Materials Only** | Angular absorption can be disabled or applied either to all materials or to soft materials, only. In this context „soft materials' means cases with a statistical absorption coefficient > 0.5. This is the recommended default, as there is negligible effect of applying the angular absorption to cases with lower absorption; so some calculation time can be saved. | Angular absorption is disabled due to the reason that selected halls are not extremely absorptive spaces. |
| | | **Back ground noise levels** | They are used in the calculations of the Speech Transmission Index (STI) | Background noise is considered as NC 20. |
| | AIR CONDITIONS, BK. NOISE, , etc. | **Temperature & Relative humidity** | Temperature and relative humidity of the air in the room may be set. These parameters affect the speed of sound and the sound attenuation in the air. | Temperature: 20 °C<br>Relative Humidity: 50 % |
| | | **Model Check Max. Accepted Warp and Wall Overlap** | Acceptable Warp is the maximum accepted warp of surfaces accepted. Acceptable wall overlap is the maximum wall overlap accepted . Large warps or overlaps of walls leads to many lost rays and imprecise results. | Maximum accepted warp: 0.010m<br>Maximum wall overlap: 0.050m |
| | | **NC Curve** | Noise Criteria is the noise generated from the HVAC systems within the room. NC20 is recommended for describing background sound in concert halls, opera houses, large auditoriums, etc. ("Noise Criteria for Rooms," Acoustical Solutions Inc., www.acousticalsolutions.com) and (Barron, 2009) | NC 20 |
| | CALCULATION PARAMETERS | **Impulse response length** | This value should cover at least 2/3 of the reverberation curve; roughly 2000 ms should be sufficient. | 2/3 of RT is used. |
| GENERAL INFORMATION | 3D INVESTIGATE RAYS | **3d investigate ray tracing** | The *3D Investigate Ray-tracing* Display can be used for testing the model for water tightness, that is if rays are disappearing out of the model. The rays may disappear due to missing surfaces, warped surfaces, overlapping surfaces, surfaces being assigned transparent materials | Models are tested. |
| | | **Maximum Damping** | Vibratory motions of the structure | It is not taken into account. |

Table 6 continued

| | | | | |
|---|---|---|---|---|
| | | **Grid** | A grid is defined by selecting a number of surfaces above which the receivers are to be positioned and specifying the distance between receivers and receiver's height above the surfaces. | Grid is defined. |
| | | **Late reflection density** | Determines the reflection density, which ODEON will attempt to achieve in the late portion of the decay for Grid response calculations. The higher the value in the late reflections, the lower is the chance to see undesired isolated peaks. For grid calculations 100 reflections /ms is suggested as a compromise between calculation speed and reliability of the results. | 100 reflections /ms |
| | | **Distance Between Receivers** | The distance between receiver (audience) positions. | 0.70 m |
| | | **Receivers height above surfaces** | The height of the receiver (eye level) from the ground. | 1.20 m |
| | | **Calculation of Stage Parameters** | The stage parameters can only be calculated if the job only contains one active source, the active source is a point source or the distance between receiver and source is approximately 1 meter (0.9 to 1.1 meter) | The stage parameters are calculated. |
| | **GRID** | **Curved Surfaces** | All surfaces in the model must be plane, so curves have to be approximated by dividing them into plane sections. Subdivisions about every 10° to 30° will probably be adequate to reproduce focusing trends, without excessive numbers of surfaces | Curved surfaces are created by dividing the surface into smaller plane sections. |
| | | **Single point response** | Offers detailed calculation and auralisation options for one selected receiver. | It is calculated. |
| | | **Grid Response** | Offers a calculated grid map of room acoustical parameters, if a grid has been specified. | Grid is defined. |
| | | **Multi Point Response** | Offers Room Acoustical Parameters for all the receivers defined in the Receiver List. | It is calculated. |
| | | **3d direct sound** | *3D Direct Sound* is for calculation and visualization of direct SPL | It is calculated. |
| | **JOB LIST** | **Streaming convolution** | Creates almost real time effect in auralisation. Streaming Convlution is the listening to the room immediately after an impulse response has been calculated. | It is checked. |
| | | **Key diffraction frequency** | Default is 707 Hz in order to obtain the best result in the mid frequency range for music and speech. This is the frequency at which diffraction is calculated for the ray-tracing part of calculations. All other parts of point response calculations take into account frequency dependent scattering. This frequency should only be changed in special cases where the focus is on another frequency range. | 707 Hz |
| | | **Transition Order/ Reflection order** | The TO applies only to point sources. Below the transition order, calculations are carried out using the "Image Source Method," above TO a special ray-tracing algorithm is used. Transition Order of 2 is generally suggested. Rays will detect image sources until the selected Transition Order, and above this order, they will detect secondary sources. | 2 |
| | | **Quick Estimate/ Global Estimate** | **Quick Estimate**: This method estimates a mean absorption coefficient inserted in the Sabine, Eyring and Arau-Puchades formulas and assumes diffuse field conditions. Diffuse field can not be assumed if the room absorption is unevenly distributed or the room contains de-coupling effects such as niches or connected corridors.<br>**Global Estimate:** Is a more precise method that does not make assumptions about diffuse field conditions and that calculates reflection paths and global reverberation time more precisely. The method uses Schröder formulas, the room volume and mean free path, and generates estimates of decay curves. | The RT is checked through Quick Estimate and global RT is calculated by Global Estimate method. |
| | | **Reflector Coverage** | Reflector Coverage display allows fast evaluation of the receiver area covered by a number of reflectors for a selected source position. | Not applicable |
| | | **Reflectogram** | Reflectograms are only used for point sources. If Transition Order is 0, the reflectogram will contain one `reflection` which is the direct sound. | Direct sound is used |
| | | **BRIR** | Binaural Room Impulse Response. In the auralisation facility, binaural listening is also possible. BRIR gives a clue how the room sounds and allows evaluate the quality of the calculated point response. The number of rays and reflection density may be necessarily increased as a result of BRIR. | BRIR is checked. |
| | | **Calculation Method** | The calculation method (Sabine, Eyring, etc.) is selected according to the overall α (absorption) value in the hall.<br>Sabine equation applies quite well to rooms whose dimensions are larger than the sound wavelength and whose absorption is well distributed throughout the room. For rooms with one or more very absorbing surfaces the Norris-Eyring equation usually gives a better RT value. (Handbook of Acoustics, 2007) | The method is used appropriately. |
| | | **HAAS effect** | When a sound is reflected off a flat solid surface, the returning sound wave can be perceived as an echo. If the delay time between the initial sound and a second sound is decreased, the echo eventually disappears, because the reflected sound finally fell below the level/delay treshold of perceptibility. This is the Haas effect. (Long, 2006)<br>Haas effect is related with the integration of early sound and delays.<br>Haas effect may change C80 and D50 values. (“HAAS effect function in Odeon,” video, http://www.youtube.com/watch?v=oSZ_zGLGGQg, access date: 15.04.2011) | In additional sound systems, HAAS can be used. |

# CHAPTER 4

# CASE STUDY

## 4.1. Acoustical Analysis of Three Case Halls

In this study, the acoustical evaluation of Resim Heykel Müzesi Multipurpose Hall, Küçük Tiyatro Hall and Opera Hall is studied. One significant contribution of this study is that the evaluations will provide a valuable reference for further studies on these buildings. Another issue is that these halls have been important performance apaces since they were built. Despite these, acoustical analyse of these halls were disregarded and they faced with many renovations during their history. It is known that these three halls have benefited the social life in the capital city, Ankara. The halls are still being used for a big number of performances every year. The comparison of these case halls with their acoustically well-known contemporaries is also done in this study. The recent studies on room acoustical parameters are summarized in a concise table in order to better evaluate the calculation results of acoustical modeling.

More than 40 years have passed since the famous paper on computer simulations in room acoustics by Krokstad, Strøm and Sørsdal was published. Since then, a growing number of programs have been developed on various algorithms for the purpose of education, survey and consulting (Vorländer, 1995). Advanced programs surpassed scale models and pushed forward the auralisation facility. The precision of these programs have have been studied since 1990s in order to be able to create realistic evaluations by beter software. Benefits of 3D acoustical modeling can be listed as:

1. The possibility of better understanding the propagation of sound in space and in time.
2. The ability to visualise, animation and auralisation
3. The ability to get impulse response data according to specific position or time

In order to fulfill the goals of the study, the three case performance halls are examined in detail and modeled within the framework of architectural acoustics. It is aimed with this attitude that the acoustical performance of these performance halls is simulated as original. The model setup details are provided in the previous chapter. 3-D Models of case performance halls are shown in Figure 13, 14 and 15.

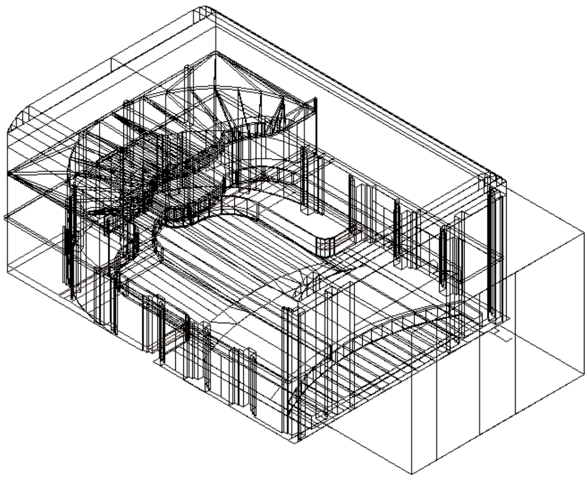


**Figure 13** Resim Heykel Müzesi Multipurpose Hall - Axonometric view

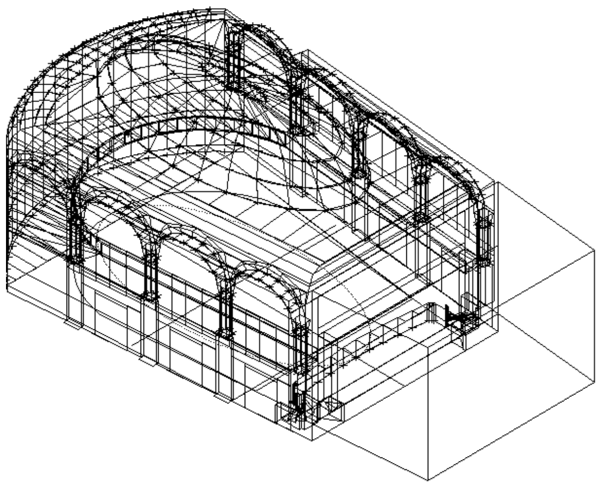


**Figure 14** Küçük Tiyatro Hall - Axonometric view

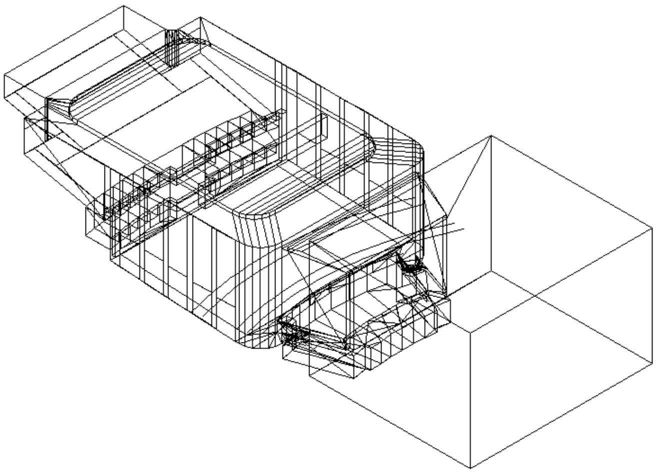


**Figure 15** Opera/ Büyük Tiyatro Hall - Axonometric view

Table 7 contains basic details of the three studied halls: Resim Heykel Müzesi Multipurpose Hall, Küçük Tiyatro Hall and Opera/Büyük Tiyatro Hall. The architects of the buildings and their typologies, current uses, interventions to the halls, basic architectural characteristics such as the decorations and volumetric properties, existence of balcony, orchestra pit and lodge in these halls, number of renovations, capacity and area of these halls are given in the table. As provided in the table, the typology of the case halls is shoebox. The use of gold latten motives is another common property in these halls. They have been renovated many times since they were built. Floor finish and audience seat materials differ in these halls. Their capacities are between 420 and 730.

**Table 7** Basic details of the studied halls: Resim Heykel Müzesi Multipurpose Hall, Küçük Tiyatro Hall, Opera / Büyük Tiyatro Hall

| **Performance Hall (Architect) $\text{Date}_{\text{building}}$ / $\text{Date}_{\text{hall}}$** | **Typology** | **Current Use** | **Basic architectural characteristics of the hall** | **Balcony Lodge Orchestra pit** | **Renovations** | **Seats** | **Area/ Total Volume** |
|---|---|---|---|---|---|---|---|
| Resim Heykel Müzesi (Arif Hikmet Koyunoğlu) 1927-1930 / same | Shoebox, U shaped hall with curved corners at the ceiling | Operet Concert Congress Panel Conference Musical | Heavily ornamented gold latten motive decoration on walls, paraphets and ceiling, plastered walls, wooden seats, marble floor (The floor was originally cladded with carpet.) | Rear (1) and U shaped (1) balcony Side lodges Orchestra pit | Yes. More than 5 | 426: Current 468: Original (Kuruyazıcı, 2008) | 532 $m^2$/ 5582 $m^3$ |
| Küçük Tiyatro (Mimar Kemalettin Bey) 1929 / 1947 | Shoebox with an elyptical dome and curved rear side | Drama Musical | Heavily ornamented ceiling with dome and altin varak decoration, columns with muqarnas and arches, medium upholstered wooden seats, plastered walls and parquet floor. | U shaped (1) balcony | Yes. More than 5 | 467 | 472 $m^2$/ 4680 $m^3$ |
| Opera / Büyük Tiyatro (Şevki Balmumcu: building) (Paul Bonatz: hall) 1933 / 1946-1948 | Shoebox | Opera Ballet Drama | Wood cladding with air gap behind at ceiling and walls, leather upholstered seats, parquet floor. | Two levels Lodge Orchestra pit | Yes. | 698:Current 730: Original Approximately | 760 $m^2$/ 5434 $m^3$ |

### 4.2. Case Study

Three pioneer performance halls of Early Republic period in Ankara are chosen as case halls for this study. These halls are used greatly during their history and are still housing significant performances from opera to drama today. The selected halls are all considered as “small” halls due to their capacity smaller than 800 (Möller and Hyde, 2006). During restoration of these halls, some details have been changed or renewed, which probably altered the acoustical performance of original design. Considering this aspect, the halls are modeled as original. In order to get the original data, the files from official archives were examined and some interviews were done with performers and officers. In this chapter, the architectural features of the performance halls are scrutuinized in detail so that original status of the spaces are modelled. In order to achieve this, the drawings and photographs and archive documents are searched to collect the original materials and their uses in the halls.

Table 8, Table 9 and Table 10 contains the information material properties of case halls each material having a different layer and the material code that is assigned in the room acoustic modeling software (ODEON 9.2 Auditorium). The views from these layers are also provided in the tables. The scattering coefficients assigned to the surfaces as well as the absorption values at different frequency ranges are listed in these tables.

**Table 8** Material and layer information of the model of Resim Heykel Müzesi Multipurpose Hall

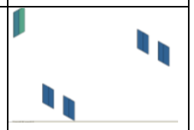
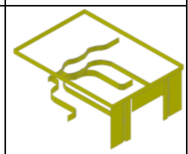
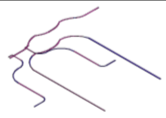
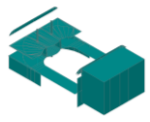
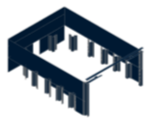
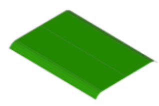
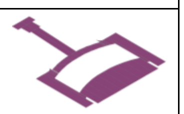
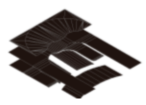
| **RESİM HEYKEL MÜZESİ MULTIPURPOSE HALL** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **PART** | **LAYER NAME** | **MATERIAL DEFINITION** | **ODEON 9.2 REF. NO** | **SCATTERING** | **ABSORPTION COEFFICIENT** | | | | | | | | **SURFACE** |
| | | | | | **63 Hz** | **125 Hz** | **250 Hz** | **500 Hz** | **1000 Hz** | **2000 Hz** | **4000 Hz** | **8000 Hz** | |
| INNER WALLS  | VELVET CURTAIN | heavy velour velvet curtain hang in front of door with 5-10cm behind | 2013 | 0,05 | 0,14 | 0,14 | 0,35 | 0,55 | 0,72 | 0,70 | 0,65 | 0,65 |  |
| | GOLD LATTEN | altın varak texture on large smooth plastered painted concrete surface | 2283 | 0,3 | 0,01 | 0,01 | 0,02 | 0,02 | 0,02 | 0,03 | 0,03 | 0,03 |  |
| | RED PAINT ON | large smooth plastered painted concrete surface | 2283 | 0,05 | 0,01 | 0,01 | 0,02 | 0,02 | 0,02 | 0,03 | 0,03 | 0,03 |  |
| | VELVET | heavy velour velvet curtain hang in front of door with 5-10cm behind | 2013 | 0,05 | 0,14 | 0,14 | 0,35 | 0,55 | 0,72 | 0,70 | 0,65 | 0,65 |  |
| | BLUE PAINT ON PLASTER | large smooth plastered painted concrete surface (inner walls and balcony ceilings) | 2283 | 0,05 | 0,01 | 0,01 | 0,02 | 0,02 | 0,02 | 0,03 | 0,03 | 0,03 |  |
| | WOODEN DOOR | Wooden door in the balcony lodgia | 603 | 0,09 | 0,14 | 0,14 | 0,10 | 0,06 | 0,08 | 0,10 | 0,10 | 0,10 |  |
| | PAINT | large smooth plastered painted concrete surface | 2283 | 0,05 | 0,01 | 0,01 | 0,02 | 0,02 | 0,02 | 0,03 | 0,03 | 0,03 |  |
| CEILING  | CEILING | gold latten (altın varak) painted decorated rough hard plastered surface | 2283 | 0,2 | 0,01 | 0,01 | 0,02 | 0,02 | 0,02 | 0,03 | 0,03 | 0,03 |  |
| FLOOR  | MARBLE | marble on concrete floor (current) | 401 | 0,05 | 0,01 | 0,01 | 0,01 | 0,01 | 0,01 | 0,02 | 0,02 | 0,02 |  |
| | | Soft heavy carpet on concrete floor (original) | 2291 | 0,05 | 0,09 | 0,09 | 0,08 | 0,21 | 0,26 | 0,27 | 0,37 | 0,37 | |
| | AUDIENCE | audience on wooden seats | 904 | 0,6 | 0,24 | 0,24 | 0,40 | 0,78 | 0,98 | 0,96 | 0,87 | 0,87 |  |

Table 8 continued

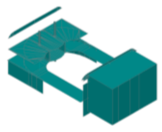
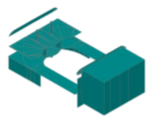
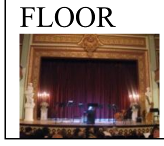
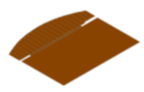
| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| STAGE WALLS | BLUE PAINT ON PLASTER | large smooth plastered painted concrete surface (iner walls and balcony ceilings) | 2283 | 0,05 | 0,01 | 0,01 | 0,02 | 0,02 | 0,02 | 0,03 | 0,03 | 0,03 |  |
| | COTTON AND GOLD LATTEN | partial rough texture on cotton upholstered on wood with air gap behind | 2310 | 0,2 | 0,28 | 0,28 | 0,12 | 0,10 | 0,17 | 0,13 | 0,09 | 0,09 |  |
| | STEEL HANGING | Stage wall on side with steel elements | 2131 | 0,3 | 0,59 | 0,59 | 0,59 | 0,81 | 0,64 | 0,26 | 0,17 | 0,17 |  |
| STAGE CEILING | BLUE PAINT ON PLASTER | large smooth plastered painted concrete surface with steel elements (iner walls and balcony ceilings) | 605 | 0,3 | 0,60 | 0,60 | 0,60 | 0,60 | 0,60 | 0,60 | 0,60 | 0,60 |  |
| STAGE FLOOR  | PARQUET | parquet on joists on concrete floor | 2388 | 0,05 | 0,4 | 0,4 | 0,3 | 0,2 | 0,17 | 0,15 | 0,10 | 0,10 |  |

**Table 9** Material and layer information of the model of Küçük Tiyatro Hall

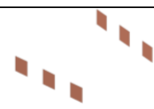
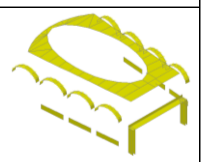
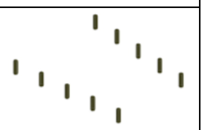
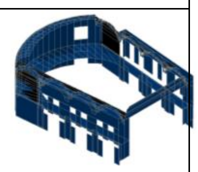
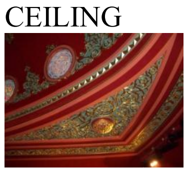
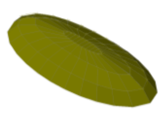
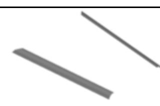
| KÜÇÜK TİYATRO HALL | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **PART** | **LAYER NAME** | **MATERIAL DEFINITION** | **ODEON 9.2 REF. NO** | **SCATTERING** | **ABSORPTION COEFFICIENT** | | | | | | | | **SURFACE** |
| | | | | | **63 Hz** | **125 Hz** | **250 Hz** | **500 Hz** | **1000 Hz** | **2000 Hz** | **4000 Hz** | **8000 Hz** | |
| MAIN HALL WALLS  | VELVET CURTAIN | heavy velour velvet curtain hang in front of door with 5-10cm behind | 2013 | 0,05 | 0,14 | 0,14 | 0,35 | 0,55 | 0,72 | 0,70 | 0,65 | 0,65 |  |
| | WOODEN DOOR | solid wooden door | 603 | 0,09 | 0,14 | 0,14 | 0,10 | 0,06 | 0,08 | 0,10 | 0,10 | 0,10 |  |
| | BALCONY PARAPHET | convex, rough textured (altın varak) plastered painted concrete surface | 2352 | 0,3 | 0,3 | 0,3 | 0,2 | 0,15 | 0,13 | 0,10 | 0,08 | 0,08 |  |
| | GOLD LATTEN | rough textured (altın varak) plastered painted concrete surface | 302 | 0,1 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |  |
| | WINDOW | smooth double glass window | 600 | 0,05 | 0,08 | 0,08 | 0,04 | 0,03 | 0,03 | 0,02 | 0,02 | 0,02 |  |
| | MARBLE | large, smooth, hard marble column | 2318 | 0,05 | 0,01 | 0,01 | 0,01 | 0,01 | 0,01 | 0,02 | 0,02 | 0,02 |  |
| | MUQARNAS | rough textured polygon surfaces on painted, plastered concrete (muqarnas) | 302 | 0,2 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |  |
| | INNER MAIN WALLS | large smooth plastered painted hard concrete surface | 2283 | 0,05 | 0,01 | 0,01 | 0,02 | 0,02 | 0,02 | 0,03 | 0,03 | 0,03 |  |
| CEILING  | ELYPTICAL DOME | medium decorated plastered curved surface (dome) | 302 | 0,1 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |  |
| | FLAT CEILING | decorated rough hard plastered surface | 302 | 0,1 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |  |

Table 9 continued

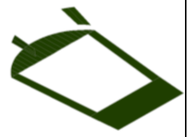
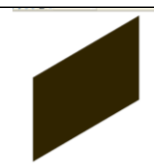
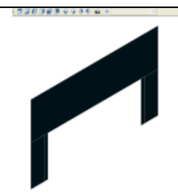
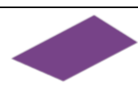
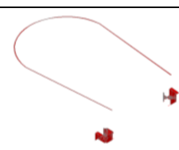
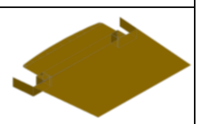
| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FLOOR  | PARQUET | parquet on concrete floor | 2340 | 0,05 | 0,04 | 0,04 | 0,04 | 0,07 | 0,06 | 0,06 | 0,07 | 0,07 |  |
| | AUDIENCE | audience on medium velvet upholstered wooden seats | 908 | 0,6 | 0,62 | 0,62 | 0,72 | 0,80 | 0,83 | 0,84 | 0,85 | 0,85 |  |
| STAGE  | STAGE FRONT PARAPHET | plywood panels | 2352 | 0,05 | 0,30 | 0,30 | 0,20 | 0,15 | 0,13 | 0,10 | 0,08 | 0,08 |  |
| | STAGE PAINTED WALL | large smooth plastered painted hard concrete surface | 302 | 0,05 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |  |
| | STAGE WALL (BACK) | large smooth plastered painted hard concrete surface | 302 | 0,05 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |  |
| | STAGE WALL (FRONT) | large smooth plastered painted hard concrete surface | 302 | 0,05 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |  |
| | STAGE CEILING | concrete surface with steel catwalks, hangings, etc. | 605 | 0,05 | 0,6 | 0,6 | 0,6 | 0,6 | 0,6 | 0,6 | 0,6 | 0,6 |  |
| | WOODEN STAIRS | parquet on joists on concrete stairs and balcony paraphet top | 502 | 0,1 | 0,20 | 0,20 | 0,15 | 0,10 | 0,10 | 0,05 | 0,10 | 0,10 |  |
| | STAGE FLOOR | parquet on concrete floor | 502 | 0,05 | 0,20 | 0,20 | 0,15 | 0,10 | 0,10 | 0,05 | 0,10 | 0,10 |  |
| | | Hollow wooden podium | 2388 | 0,05 | 0,4 | 0,4 | 0,3 | 0,2 | 0,17 | 0,15 | 0,10 | 0,10 | |

**Table 10** Material and layer information of the model of Opera Hall

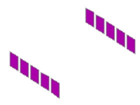
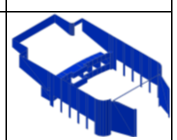
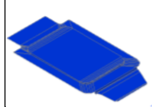
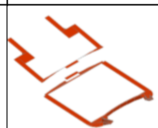
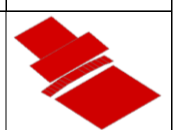
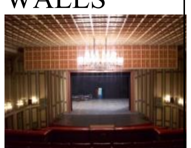
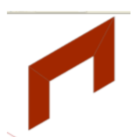
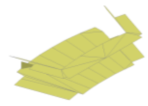
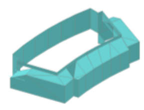
| OPERA / BÜYÜK TİYATRO HALL | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **PART** | **LAYER NAME** | **MATERIAL DEFINITION** | **ODEON 9.2 REF. NO** | **SCATTERING** | **ABSORPTION COEFFICIENT** | | | | | | | | **SURFACE** |
| | | | | | **63 Hz** | **125 Hz** | **250 Hz** | **500 Hz** | **1000 Hz** | **2000 Hz** | **4000 Hz** | **8000 Hz** | |
| INNER WALLS  | LEATHER CLADDED DOOR | Heavily quilted leather on heavy wooden door | 603 | 0,05 | 0,14 | 0,14 | 0,10 | 0, 06 | 0,08 | 0,10 | 0,10 | 0,10 |  |
| | CURTAIN 1 | heavy velour velvet curtain hang in front of door with 5-10cm behind | 2013 | 0,05 | 0,14 | 0,14 | 0,35 | 0,55 | 0,72 | 0,70 | 0,65 | 0,65 |  |
| | WALL CLADDING | painted wood cladding on concrete walls with air gap behind | 2353 | 0,1 | 0,42 | 0,42 | 0,21 | 0,10 | 0,08 | 0,06 | 0,06 | 0,06 |  |
| CEILING  | LIGHT MASS | smooth large painted plastered hard concrete surface with lighting instruments | 302 | 0,3 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |  |
| | CEILING | painted wood cladding on concrete ceiling with air gap in between. There are rough gridal decorative motives on the surface | 302 | 0,1 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |  |
| FLOOR  | PARQUET | parquet on concrete floor | 502 | 0,2 | 0,20 | 0,15 | 0,10 | 0,10 | 0,10 | 0,05 | 0,10 | 0,10 |  |
| | AUDIENCE | heavily leather upholstered audience seats and audience | 908 | 0,6 | 0,62 | 0,62 | 0,72 | 0,80 | 0,83 | 0,84 | 0,85 | 0,85 |  |
| STAGE WALLS  | BACK WALL | large smooth plastered painted hard concrete surface | 302 | 0,05 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |  |
| | STEEL CURTAIN | vertical steel guy elements in front of large smooth plastered painted concrete surface | 2131 | 0,3 | 0,59 | 0,59 | 0,59 | 0,81 | 0,64 | 0,26 | 0,17 | 0,17 |  |
| | FRONT WALL | large smooth plastered painted hard concrete surface | 302 | 0,05 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |  |

Table 10 continued

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| STAGE CEILING | STAGE FLOOR | parquet on concrete floor, air gap behind | 2388 | 0,05 | 0,4 | 0,4 | 0,3 | 0,2 | 0,17 | 0,15 | 0,10 | 0,10 |  |
| | STAGE CEILING | concrete surface with steel catwalks, hangings, etc. | 605 | 0,1 | 0,6 | 0,6 | 0,6 | 0,6 | 0,6 | 0,6 | 0,6 | 0,6 |  |
| STAGE FLOOR | ORCHESTRA FLOOR | parquet on joists on concrete floor, orchestra with instruments on wooden chairs | 900 | 0,6 | 0,27 | 0,27 | 0,53 | 0,67 | 0,93 | 0,87 | 0,80 | 0,80 |  |
| ORCHESTRA | ORCHESTRA WALLS | plywood cladding on walls | 2352 | 0,05 | 0,30 | 0,30 | 0,20 | 0,15 | 0,13 | 0,10 | 0,08 | 0,08 |  |

In the acoustical modeling step, the positioning of the receivers is a significant task in order to be able to understand the acoustical condition in every point. A number of receivers are placed in all of the critical positions in reality in the hall.

In Resim Heykel Müzesi Multipurpose Hall, as seen in Figure 16, 20 receivers are positioned. In Küçük Tiyatro Hall, 19 receivers are placed, which is shown in Figure 17. Finally, in Opera Hall, 26 receivers are positioned in the critical points that are illustrated in Figure 18. According to the complexity of the room, the positions of the receivers are decided.

The room acoustic modeling program provides the results for both multipoint response and grid response. The positioning of receivers in the critical locations in the rooms makes it possible to calculate the acoustical parameters at that points. This data can be used for the determination of problematic positions that might have undesirable acoustical conditions in that hall. The results of each receiver is provided in Appendix A in detil.

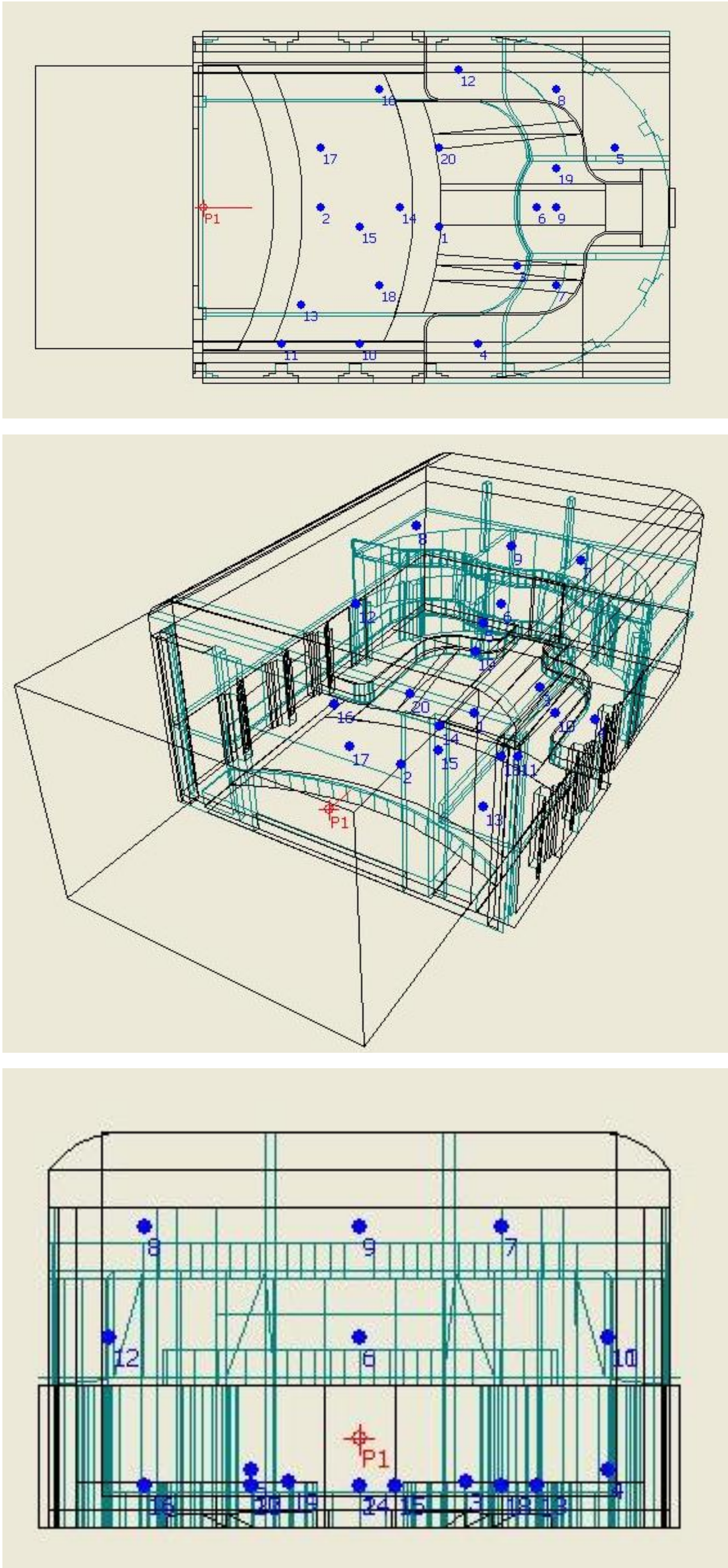



**Figure 16** Resim Heykel Museum Multipurpose Hall Receiver Positions Top, Axonometric and Back views respectively.

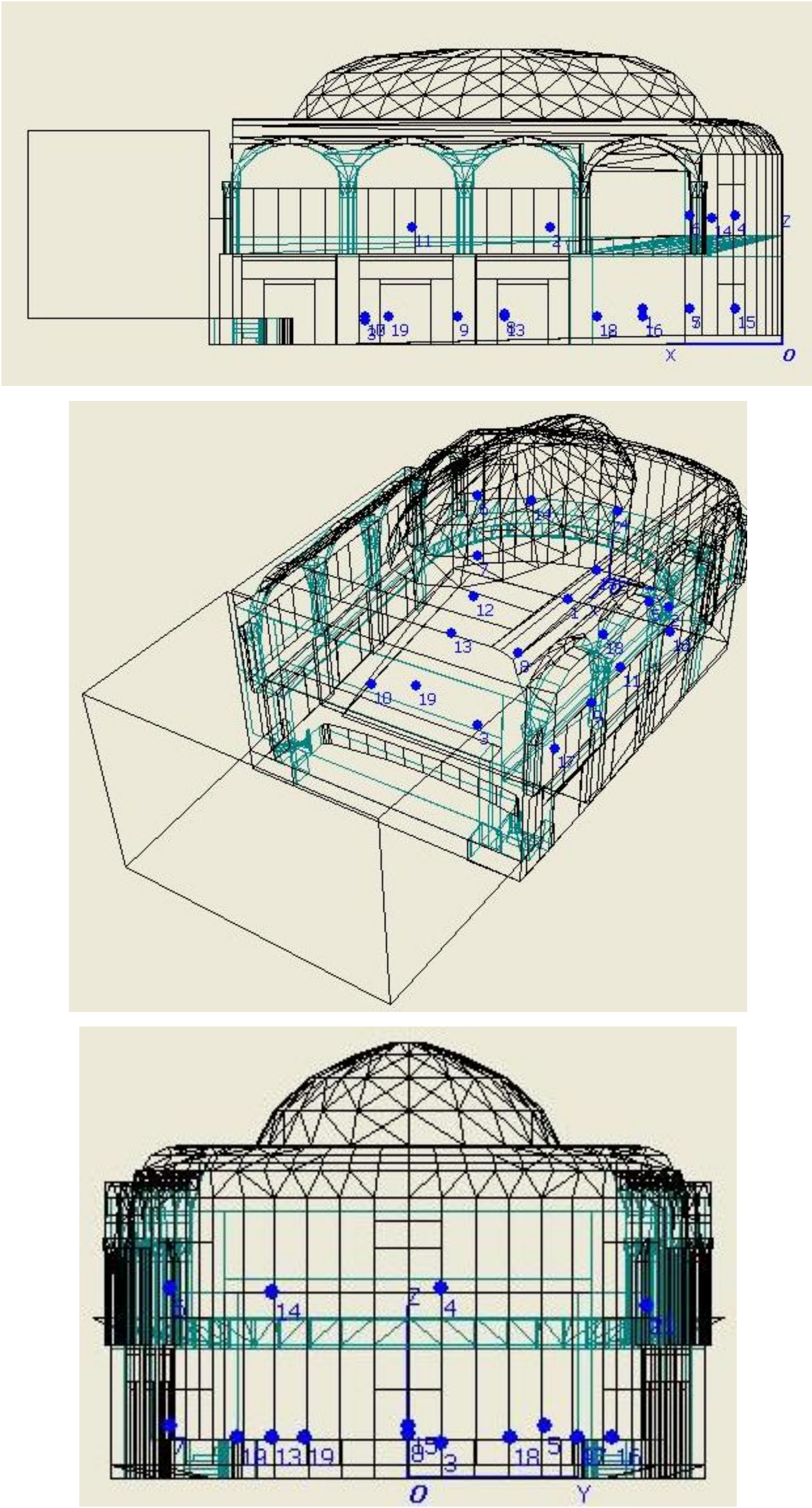



**Figure 17** Küçük Tiyatro Hall Receiver Positions

Side, Axonometric and Back views respectively.

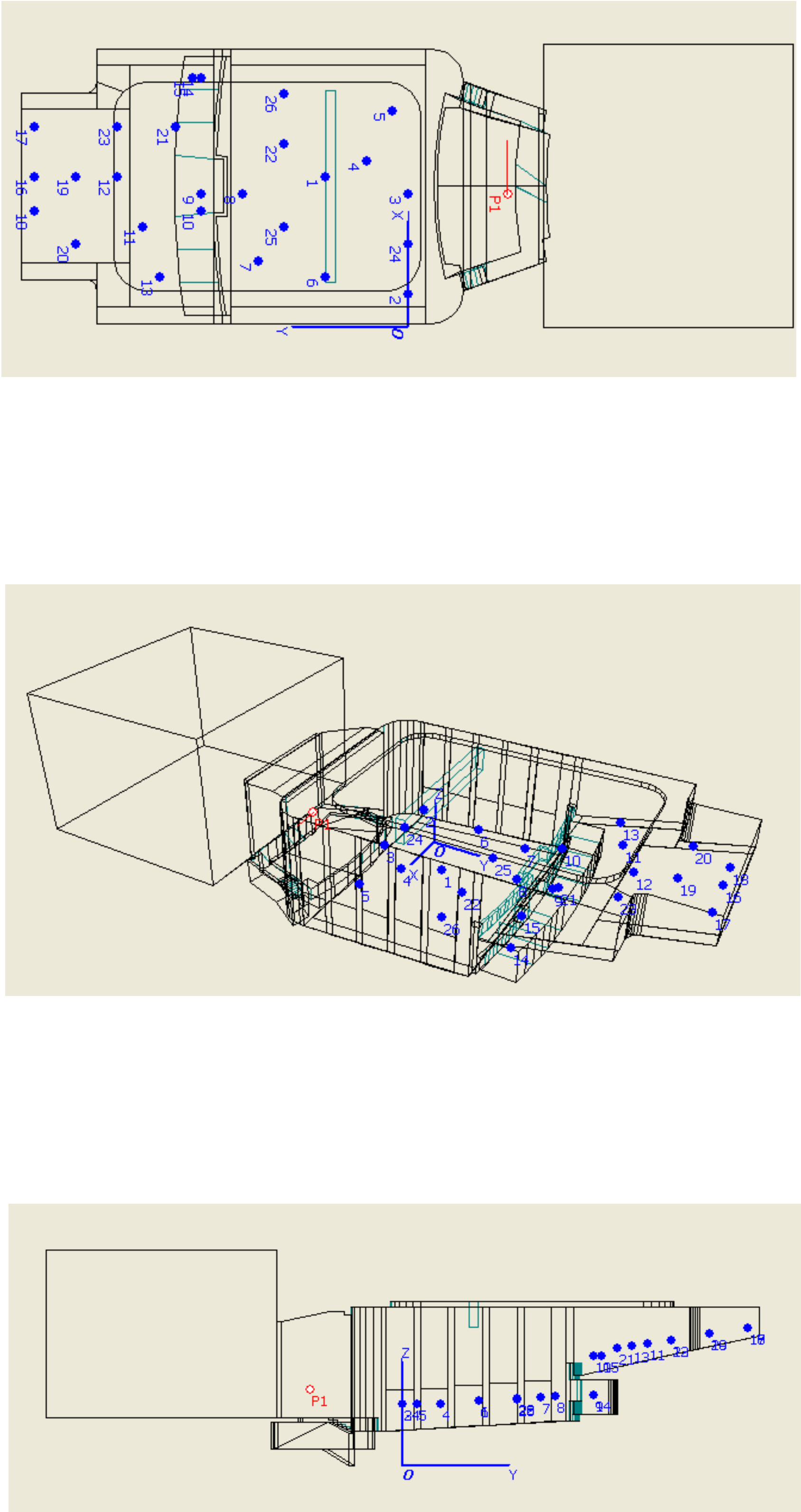



**Figure 18** Opera Receiver Positions

Top, Axonometric and Side views respectively.

# CHAPTER 5

# RESULTS

3D model of a performance hall having the surfaces defined with appropriate material definitions is done before acoustical calculations through room acoustic modeling software are started. The three models prepared for this study are shown in Figure 13, Figure 14 and Figure 15. These models are then imported to the software. During the acoustical modeling, first matching materials are assigned to the layers of the surfaces with adequate scattering and absorption coefficients as in the Table 7, Table 8 and Table 9. Second, receiver and source locations and properties are defined, which is illustrated in Figure 16, Figure 17 and Figure 18. Third, room setup is done according to the information given in Table 6. In the following steps, calculations are set up and initiated. The results of these calculations is provided in this chapter in the following pages. The graphs prepared according to the results is provided in the Appendices. In Appendix A, EDT, T30, SPL, C80, D50, Ts, LF80, SPL(A), LG80 and STI values at the frequencies 500 Hz and 1000 Hz are given in bar charts. In Appendix B, grid responses of case performance halls are provided.

According to the information provided in Table 8, Table 9 and Table 10 showing the detailed information on the surfaces and layers, materials are matched with the surfaces. The absorptivity characteristics of the selected materials, the scattering properties of the surfaces and the volume determines the acoustical behavior of the room.

## 5.1. Evaluation Criteria

Table 11 is prepared to match the Objective Parameters and their corresponding subjective quality. The table is significant due to being a summary of recent studies on the acoustical parameters. Reference values as well as the value at acoustically well-known performance halls in the world and their discovery are also provided in this table.

**Table 11** Objective Parameters and corresponding subjective quality

| Acoustical Quality (Objective) | Definition | Reference Value | The value in acoustically well-known performance halls | Corresponding quality (Subjective) | Discovery of the parameter (Lacatis, 2008) |
|---|---|---|---|---|---|
| ITDG in ms | Initial Time Delay Gap is the interval between the arrival of the direct sound and the first reflection at the listener. ITDG should be short to provide early reflections before 80ms to support early sound. If ITDG value is short, this means that energies of the earliest reflections are added to the direct sound, which is an attractive acoustical quality of a performance hall.<br>If ITDG<20 ms, intimacy can be achieved. (Egan, 1988) | <25 (Beranek,1996)<br>≤ 20 (Hidaka,2004)<br>Lack of intimacy if >35ms (Beranek, 2008) | Boston, Symphony Hall: 15 ms<br>(Beranek, 2008) | Intimacy (Sound reflections that arrive shortly after the direct sound)<br>Clarity (Ability to distinguish indivudial sound) (Lee) | 1974, Schroeder, Ando |
| RT in s | Reverberation Time, Tmid, is the time required for the reverberant sound level to decay 60 dB below the maximum. RT varies little throughout a well-designed auditorium. It affects C80, EDT and G. (Barron, 2006) It tends to be constant throughout the hall. (Barron, 2009)<br>$T_{10}$, $T_{20}$, $T_{30}$ reverberation times can be measured. | Conference<br>0.85<Tmid<1.30 (Riberio, 2002)<br>Music<br>1.30<Tmid<1.83 (Riberio, 2002)<br>Concert Halls<br>1.8 ≤ RT ≤ 2.2 (Barron, 2005)<br>Speech 0.7-1.0 (Barron,1993 for 500 Hz)<br>Opera 1.3-1.8 (Barron,1993 for 500 Hz)<br>Drama Theatres 0.7-1.0 (Barron, 2010) | Amsterdam, Concertgebouw: 2.0<br>Boston, Symphony Hall: 1.85<br>Vienna, Gr. Musikvereinssaal: 2.0<br>London, Royal Festival [Res.On]: 1.5<br>Cardiff, Wales, St. David's Hall: 1.95<br>New York, Cernegie Hall: 1.8<br>(Beranek, 1996) (Occupied)<br>Boston Symphony Hall: 1.9<br>London, Royal Festival Hall: 1.45<br>(Beranek, 2008) (Occupied) | Clarity<br>Liveness<br>Brilliance | 1922, Sabine<br>1930, Eyring, Norris<br>1988, Arau |
| T30 in s | Reverberation Time. 30 dB decay of the sound level is measured between -5 and -35 dB and then doubled. (Long. 2006) | 1.5 - 2.2 s (Çalışkan, 2002)<br>1.7 – 2.3 (ODEON 7.0) | | Clarity<br>Liveness<br>Brilliance | |
| EDT in s | Early Decay Time. The initial rate of sound decay in the first 10 dB of drop after the initial burst. It differs according to the position of the listener.<br>EDT=(1.1) RT±0.2 (Barron)<br>There are high correlations among RT, EDT and $C_{80}$. EDT is the most useful of three in comparisons with subjective judgements. (Beranek, 2003)<br>±%10xT (Gimenez, 1988) | Conference<br>0.648<EDTmid≤0.81 (Riberio, 2002)<br>Music<br>1.04<EDTmid ≤ 1.56 (Riberio, 2002)<br>1.8-2.6 (Jordan,1981)<br>1.5-2.0 (Cremer,1982)<br>1.6 (Gade,1989)<br>1.8-2.2 (Barron, 1993)<br>1.8-2.1 (Hyde,1994)<br>1-3 (ISO 3382-1) | Amsterdam, Concertgebouw: 2.6<br>Boston, Symphony Hall: 2.4<br>Vienna, Gr. Musikvereinssaal: 3.0<br>London, Royal Festival [Res.On]: 1.7<br>Cardiff, Wales, St. David's Hall: 2.1<br>(Beranek, 1996) (Unoccupied) | Liveness<br>Clarity<br>Reverberance | 1970, Jordan |
| $T_s$ in ms | Central Time is the time of the centre of gravity of the squared impulse response. The parameter is considered to be highly correlated with the Early Decay Time. The higher the Ts is, the more spatial is the acoustic impression at the listener's position. (Ahnert and Schmidt, EASERA Manual)<br>Ts=RT/0.0138 (Kurtulan,2009)<br>Ts is also correlated with D50 and C80. | <140 (Cremer, 1988)<br>Music<br>70-150 (1000 Hz)<br>Speech<br>60-80 (500 Hz - 4000 Hz)<br>(Ahnert and Schmidt, EASERA Manual Appendix)<br>60-260 (ISO 3382-1) | | Clarity<br>Liveness<br>Intelligibility<br>Spaciousness | 1971, Kürer, R., Cremer |

Table 11 continued

| | | | | | |
|---|---|---|---|---|---|
| D50 in % | Definition/ The distinctness of the speech. The ratio of early reflections energy to total energy within 50 miliseconds. There is a high negative correlation between Reverberation Time and Definition. (Schroeder, 1979) | 0.34 (Cremer,1982)<br>0.56 (Bradley,1986)<br>0.4 - 0.6 (Gimenez, 1988)<br>0.45-0.55 (Hilbert,1982)<br>Conference ≥0.65 (Riberio, 2002)<br>Music 0.45<D≤ 0.60 (Riberio, 2002) | | Intelligibility<br>Intimacy<br>(Hyde, 2005) | 1953, Thiele |
| C80 in dB | Clarity/Early to late sound index is the difference of the sound energy received at a listener in the first 80 milliseconds minus the (late) reverberant sound energy | -4<C80<4 (Gade)<br>0 (Cremer, 1982)<br>-4 - 0 (Beranek, 1996)<br>-2 - +2 (Barron, 1993)<br>-1 - +1 (Hyde, 1994)<br>Symphony<br>-1-+2 (Hyde, 2006)<br>-2- +4 (Çalışkan, 2002)<br>-5 - +5 (ISO 3382-1) | Milan Teatro Alla Scala: 3.6<br>Paris Opera Garnier: 4.6<br>*London Royal Opera House: 4.5<br>*Steel shutter behind main stage closed<br>(Hidaka, Beranek, 1999) | Clarity | 1974, Abdel Alim (C80: clarity for music,<br>C50 : clarity for speech |
| $LF_{80}$ in % | Lateral Fraction, Objective Source Broadening. It is the ratio of Early Lateral Energy to the Early sum of the energy, or the ratio of lateral to omni-directional energy.<br>LF-octave freuency range:<br>125 Hz ≥ LF ≥ 500 Hz: Envelopment<br>500 Hz ≥ LF ≥ 4000 Hz: Source Broadening<br>LF > 4000 Hz: Image shifting<br>(Ahnert and Schmidt, EASERA Manual) and (Barron and Marshall)<br>Low frequency LF is correlated with mid-frequency BQI. (Beranek, 2008) | 0.1≤ LF≤0.35 (Barron, 2006)<br>$LF_{80}$>0.25 (ODEON 7.0) | Boston: 0.20<br>Amsterdam: 0.18<br>Vienna: 0.17<br>Paris Salle Pleyel: 0.15<br>Munich: 0.13<br>(Hidaka et al., Beranek, Okano, 1996) ($LF_{E4}$ unoccupied) | Envelopment<br>Spaciousness<br>Source broadening<br>Image Shifting | 1971, Barron, Marshall |
| G in dB | Strength or Total Sound Level. Total level relative to the direct sound level at 10m from the source (Barron, 2006)<br>The sound strength *G should be planned* to decrease with the distance from the stage as in the Boston Symphony Hall. (Beranek, 2008)<br>The judgement of the loudness of an orchestra is same in remote seats with the front ones even though G decreases with the distance from the source. (Ibid.)<br>High G values show that the room is filled with a strong energy, however Intelligibility and Clarity is diminished. (Weselak, 2007) | G>0 (Riberio, 2002)<br>3-5 (Beranek, 1996)<br>0.3-0.35 (Hilbert, 1982)<br>0-2.5 (Hyde, 1994)<br>-3-5 (Nagata, 1990)<br>+3<G<+5 (large symphony) (Möller and Hyde, 2006) | Vienna, Grosser Musikvereinsaal: 6.5<br>Boston Symphony Hall: 4.2<br>London, Royal Festival Hall: 1.9<br>(Beranek, 2008) | Level of sound<br>Intimacy | 1976, Lehmann |
| SII | Speech Intelligibility Index | SII < 0.45 (Poor)<br>SII > 0.75 (Good)<br>(Herman J.M. Steeneken, 2002 and ANSI Standard) | | Intelligibility | |
| STI | Speech Transmission Index | 0.00 - 0.30 (Bad)<br>0.30 – 0.45 (Poor)<br>0.45 – 0.60 (Fair)<br>0.60 – 0.75 (Good)<br>0.75 – 1.00 (Excellent)<br>(ODEON Manual) | | Intelligibility | 1980, Steeneken, Houtgast |
| SPL in dB | Sum of sound pressure level (eight bands) | | | | |
| $SPL_A$ | Sum of a weighted sound pressure level (eight bands) | | | | |

Table 11 continued

| | | | | | |
|---|---|---|---|---|---|
| $ST_{early}$, $ST_{late}$, $ST_{total}$ | Support for early, late and total energy. It is related with the amount of the reflected energy on the stage and measured from 1m distance from the source. Later reflections are also considered. (Gade, 2007) | Chamber Music<br>$ST_{early}$: -10<br>Symphony<br>$ST_{early}$: -14 (Gade, 2007) | | | |
| LG80 in dB | Sum of Late lateral sound pressure levels (125Hz to 1000Hz band - four bands) | (-7) – 3 dB<br>(ISO 3382-1)<br>(-14)-1 Db (Till, 2010) | Vienna, Gr. Musikvereinssaal: -3 (Skålevik, 2008) | Envelopment | |
| RASTI in % | Room Acoustic Speech Transmission Index | >75 (Riberio, 2002)<br><0.30 (Bad)<br>0.30 – 0.45 (Poor)<br>0.45 – 0.60 (Fair)<br>0.60 – 0.75 (Good)<br>0.75 < (Excellent)<br>(Gade,2007) | | Intelligibility | 1985, Steenek, Houtgast |
| RR | Terminal Reverberation: Room Response | (-0.5) <RR< (+0.5)<br>(Maekawa, 1994) | | Liveness | 1960, Dresden School |
| BRIR | Binaural Room Impulse Response. It is a set of two impulse responses (reverberant sound within first 80 ms after the direct sound) detected at the left and right ear when an impulse is emitted. | | | | |
| IACC | Inter-aural Cross-correlation. It is defined for the initial 80 ms of the impulse response at both ears as the average of 500 Hz, 1kHz and 2kHz. Parallel walls and strong lateral reverberance supports Spaciousness. IACC measures the similarity of early sound at the two ears. A small value of IACC contributes to spaciousness. (Handbook of Acoustics, 2007) | If the sound comes from the front, IACC=1.0 (Beranek, 2008)<br>IACC < 0.50 (Lee) | 0.3<Vienna, Boston <0.4<br>0.4<Amsterdam<0.5<br>$IACC_{E3}$ Average to three bands, 500 to 2kHz<br>(Hidaka et al., Beranek, Okano, 1996) ($LF_{E4}$ unoccupied) | Envelopment<br>Spaciousness | 1974, Ando |
| BQI | Binaural Quality Index<br>BQI=1-IACC<br>BQI and $LF_{E4}$ are highly correlated for BQI<0.65 (Beranek,2008)<br>It is almost the same whether the hall is occupied or unoccupied and it affects the overall acoustical quality. (Beranek, 2003) | 0.6 (Chamber Music)<br>0.7 (Symphony Hall)<br>(Gade, 2007) | Berlin, Philharmonie (1-IACC): 0.46 (Beranek, 1996)<br>Vienna: 0.71<br>Boston: 0.65<br>Amsterdam: 0.62<br>Berlin: 0.46<br>(Hidaka et al., Beranek, Okano, 1996) ($LF_{E4}$ unoccupied) | Envelopment<br>Spaciousness<br>Overall acoustical quality | 1968, Keet |
| SDI | Surface Diffusivity Index. It is the visual means for rating surface irregularity on side walls and ceiling on a scale from 0 to 1.0. (Beranek, 2003) | 0.8-1.0 The highest<br>0.5-0.8 The middle<br>0.3-0.6 The lowest range<br>(Beranek, 2003) | Vienna: 1<br>Boston: 1<br>Amsterdam: 1<br>(Beranek, 2003) | | 1960, Haan, Fricke |
| ST1 in dB | Stage Support Factor measures the degree to which a lone musician’s sound is reflected by surfaces around the stage back to him/her. (Beranek,2003) | -14,4<ST1<-12<br>-15<ST1<-12 (Gade, 1989) | Amsterdam, Concertgebouw: -18<br>Cardiff St. David’s Hall: <-15<br>(Beranek,2003) | Hearing other musicians | 1989, Gade |
| TR | Treble Ratio. Ratio of sum of 2000 Hz and 4000 Hz to mid-frequency late arriving sound levels at 500 Hz and 1000 Hz | | Berlin, Philharmonic Hall: 2.1 (Lee) | Brilliance (Persistance of sound at high frequencies) (Lee) | |

Table 11 continued

| | | | | | |
|---|---|---|---|---|---|
| SI in % | (Effective) Spatial Impression (ESI). Möller and Hyde states that spatial impression (SI) is generally consists of two basic perceptual components: auditory source width (ASW), a function of the “early” sound field, and listener envelpment (LEV), a function of the “late” sound field.<br>SI is also correlated with D50. | %20- %25 (adequate for full orchestras if $G_{total}$ is in the +5dB range. ESI can be higher in smaller ensembles only if source power does not create loudness saturation) (Möller and Hyde) | Vienna, Grosser Musikvereinsaal: 21%<br>Boston Symphony Hall: 23 % (Approximately) (Möller and Hyde) | The subjective response to the image broadening aspect of SI is proposed as being a factor of both LF and $G_e$.(Möller and Hyde) | 1960, Barron, Marshall |
| BR | Bass Ratio is the low frequency responsiveness of a room. Ratio of low frequency ones (125 and 250 Hz) to mid frequency reverberation times (500 and 1000 Hz).<br>It depends on the material characteristics of the walls, seats, ceiling, openings or fixtures. (Beranek, 2006) | 1.2 < BR (Egan, 1988)<br>Music: 1-1.3<br>Speech: less than 0.9-1 (Ahnert and Schmidt, EASERA Manual)<br>1.40 (Beranek, 1996) | Amsterdam, Concertgebouw: 1.08<br>Boston, Symphony Hall: 1.03<br>Vienna, Gr. Musikvereinssaal: 1.11<br>London, Royal Festival [Res.On]: 1.17<br>Cardiff, Wales, St. David's Hall: 0.96<br>New York, Cernegie Hall: 1.15<br>(Beranek, 1996) (Occupied)<br>Berlin, Philharmonic Hall: 1.01 (Lee) | Warmth (Persistance of sound at low frequencies) (Lee)<br>Fullness of bass tone<br>BR is not related to subjective acoustical quality. (Bradley and Soulodre) | 1962, Beranek |
| SS | Source Strength. It is a function of the source level and a factor of LF and $G_{early}$. | | | | |
| ASW in degrees | Apparent Source Width. Enlargement of the sound source with early reflections and is related with early lateral reflections. Stereo effect. As LF increases, source broadens and music gains body and fullness. (Hidaka, 1996)<br>(1-IACC) relates to ASW. (Beranek, 1996) | | | Broadening of sound source<br>Fullness<br>Spaciousness<br>Envelopment | 1967, Marshall |
| LEV | Listener Envelopment. Surround Source/Room Impression. The value of LEV must be large enough for good sound quality. Wakuda (2003) proved that not only the lateral level, but also late sounds from above and behind affect LEV significantly. | | Vienna, Musikvereinssaal: 2.0<br>Amsterdam, Concertgebouw: 1.4<br>Berlin, Konzerthaus: 1.2<br>Boston, Symphony Hall: 0.3<br>Berlin Philharmonie Hall: -0.2<br>(Beranek, 2008) | Sound quality<br>Envelopment | 1995, Bradley, Soloudre |
| LEGEND | | | | | |
| Parameters based on time | | | | | |
| Parameters based on sound energy or other factors than time | | | | | |

### 5.2. Evaluation of the Results

Table 12 shows the calculation results of the models in the frequencies 500Hz and 1000 Hz and Minimum, Average and Maximum values in the rooms are also provided in this table. These results of the selected parameters and their evaluations are given below.

**T30:** T30 is the reverberation time calculated for 30dB decay of the sound level. The value is calculated for different frequencies and plays an important role on the overall clarity, liveness and brilliance of the room. The parameter depends on the volume of the hall, massive doors, openings and absorption coefficients of the materials in the room.

The three models for the multipurpose hall at the museum are produced in order to observe and compare the outcomes of different interruptions in the hall. RHM symbolizes the original design with carpet floor cladding, RHM(M) model has marble floor cladding instead of carpet, which is the current use. RHM(O) stands for the hall with orchestra pit open.

Resim Heykel Müzesi Multipurpose Hall is used for different performances such as operet, conference, concerts, etc. One important issue is that each performance type requires different acoustical atmosphere. Speech dominant performances need more Definition but less Reverberation in the room, however opera requires more reverberant and live space. The evaluation of the hall is inevitably dependent on the type of the performance. Another significant issue for the evaluation of the hall is that the floor cladding of the room has been changed into marble from heavy carpet.

Resim Heykel Müzesi Multipurpose Hall (RHM) seems to have an acceptable average value for the reverberation time at 500 Hz, however at 1000 Hz, the average value is below the preferable ranges for the operet. The minimum and maximum T30 values at 500 Hz show big difference, however the average is acceptable for the purpose of use. The average T30, 1,35s, is an in-between value for conference and opera performances in the room. For the lower frequencies, the hall has a perceptible high T30 value reaching 3s. This might be due to the reason that thick plaster supports the bass.

**Table 12** Minimum, average and maximum values of parameters for case halls at frequencies 500 Hz and 1000 Hz.

RHM: Resim Heykel Museum Multipurpose Hall with its original design
RHM (M): Current situation with marble floor
RHM (O): Current situation with orchestra pit open
KT: Küçük Tiyatro Hall
O: Opera/Büyük Tiyatro Hall

| Parameter | | T30 | | EDT | | Ts | | D50 | | C80 | | LF80 | | STI | SPL | | $SPL_A$ | LG80 | BR | TR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Recommended range | | 1.5 - 2.2 s | | 1.8 - 2.2 s | | 60 - 150 ms | | 45 - 60 % | | (-4) – (4)dB | | 0.1 - 0.35 % | | >0,45 | | | | (-14)-1 dB | 1.2< | |
| Frequency (Hz) | | 500 | 1000 | 500 | 1000 | 500 | 1000 | 500 | 1000 | 500 | 1000 | 500 | 1000 | | 500 | 1000 | | | | |
| **RHM** | **Min** | 1,14 | 0,87 | 1,04 | 0,75 | 65 | 49 | 0,35 | 0,44 | 1,0 | 2,2 | 0,133 | 0,131 | 0,50 | 62,5 | 60,2 | 67,3 | 57,2 | 2,04 | 0,8 |
| | **Ave** | 1,54 | 1,16 | 1,26 | 1,03 | 85 | 68 | 0,48 | 0,56 | 2,4 | 4 | 0,253 | 0,246 | 0,55 | 65 | 63,7 | 70,5 | 60,1 | | |
| | **Max** | 3,43 | 1,45 | 1,57 | 1,35 | 109 | 90 | 0,66 | 0,74 | 4,7 | 6,7 | 0,393 | 0,390 | 0,61 | 67,8 | 67,2 | 73,9 | 61,5 | | |
| **RHM (M)** | **Min** | 1,27 | 1,0 | 1,07 | 0,93 | 54 | 53 | 0,35 | 0,39 | 0,0 | 1,2 | 0,143 | 0,142 | 0,50 | 62,6 | 60,5 | 67,5 | 57,7 | 1,0 | 0,9 |
| | **Ave** | 1,40 | 1,25 | 1,33 | 1,10 | 74 | 73 | 0,46 | 0,53 | 2,0 | 3,4 | 0,255 | 0,249 | 0,54 | 65,3 | 64 | 70,8 | 60,3 | | |
| | **Max** | 1,65 | 1,78 | 1,57 | 1,45 | 99 | 99 | 0,64 | 0,71 | 3,8 | 5,5 | 0,394 | 0,393 | 0,58 | 68,1 | 67,5 | 74,2 | 61,6 | | |
| **RHM (O)** | **Min** | 1,10 | 0,95 | 1,05 | 0,88 | 70 | 54 | 0,27 | 0,34 | -0,5 | 0,5 | 0,136 | 0,136 | 0,46 | 61,6 | 59,4 | 66,4 | 58 | 1,9 | 0,8 |
| | **Ave** | 1,41 | 1,18 | 1,39 | 1,14 | 92 | 76 | 0,45 | 0,51 | 1,7 | 3,1 | 0,252 | 0,246 | 0,53 | 65,0 | 63,7 | 70,5 | 60 | | |
| | **Max** | 1,58 | 1,58 | 1,60 | 1,41 | 118 | 99 | 0,63 | 0,71 | 3,7 | 5,4 | 0,428 | 0,438 | 0,57 | 67,9 | 67,3 | 74 | 61,6 | | |
| **KT** | **Min** | 1,32 | 1,26 | 1,49 | 1,32 | 97 | 91 | 0,18 | 0,19 | -2,3 | -1,8 | 0,132 | 0,126 | 0,45 | 64,3 | 64,0 | 70,2 | 57,4 | 1,2 | 0,9 |
| | **Ave** | 1,52 | 1,47 | 1,73 | 1,66 | 121 | 116 | 0,33 | 0,34 | -0,4 | -0,1 | 0,249 | 0,246 | 0,50 | 66,3 | 65,9 | 72,0 | 59,6 | | |
| | **Max** | 1,73 | 1,76 | 1,98 | 1,90 | 137 | 131 | 0,49 | 0,51 | 1,8 | 2,1 | 0,385 | 0,405 | 0,55 | 68,0 | 67,8 | 74,1 | 60,7 | | |
| **O** | **Min** | 0,95 | 0,93 | 0,79 | 0,74 | 49 | 45 | 0,36 | 0,38 | 0,5 | 0,8 | 0,172 | 0,174 | 0,53 | 62,4 | 61,8 | 67,9 | 50,7 | 1,0 | 1,1 |
| | **Ave** | 1,40 | 1,41 | 1,17 | 1,17 | 74 | 71 | 0,56 | 0,58 | 3,4 | 3,7 | 0,279 | 0,278 | 0,61 | 64,8 | 64,2 | 70,6 | 54,2 | | |
| | **Max** | 1,67 | 1,88 | 1,53 | 1,47 | 99 | 95 | 0,73 | 0,77 | 5,4 | 6,2 | 0,439 | 0,448 | 0,69 | 68,7 | 68,3 | 75,0 | 56,8 | | |

The hall with marble floor RHM(M) has a higher minimum value of T30, however the average mid frequency reverberation is not much different from RHM. The hall with open orchestra pit RHM(O) has a slightly lower minimum T30 value than RHM (M). The overall average mid frequency T30 does not show great difference. The value is approximately 1.30s which is considered as low for operet performances but adequate for drama or concerts.

Küçük Tiyatro Hall has proper average Reverberation Time T30 for drama performance. The minimum values are also good for speech activity, however the average and maximum T30 seems to be a little high for the performance. T30 maximum values are over 1,7s which is preferable for opera or concert performances rather than drama.

Opera Hall has a low minimum T30 value due to the excessive use of wooden wall cladding with air gap behind. Not only the walls but also the ceiling is cladded with the material in the room. The cladding is more absorptive in the lower frequencies and this results in a short reverberation time lower than 1 s. On the other hand, the maximum values in mid frequencies are appropriate for the opera performance. This hall, as Resim Heykel Müzesi Hall, is used for both opera and drama performances which requires different ranges for T30. Average value for mid frequencies is low for opera but proper for drama performances.

The three halls of the Early Republic Period capital city, Resim Heykel Müzesi Multipurpose hall, Küçük Tiyatro Hall and Opera Hall has an average mid frequency T30 range of 1,30s - 1,50s. The ceiling helps in the direction of orchestra sound to the audience. Narrow sides and rear balconies helps to prevent shadow zones.

**EDT:** Early Decay Time is defined as the initial rate of sound decay in the first 10 dB of drop after the initial burst. EDT values may vary according to the position it is measured in the room. There are high correlations among RT, EDT and $C_{80}$. Beranek (2003) suggests that EDT is the most useful criteria among these in terms of similarity to subjective judgements. Barron relates EDT with RT as EDT=(1.1) RT±0.2. In order to evaluate the acoustical quality of the halls, it seems that EDT, a measure of unoccupied hall, is a better choice than RT measured in occupied halls (Beranek, 2008). RT and EDT decays are expected to be identical in a highly diffuse space. Yet, recent studies show that early decay time is more related with the subjective judgment of reverberance than reverberation time (Barron, 2009). EDT is affective in the Liveness, Clarity and Reverberance in the room and EDT may inversely affect the Intimacy.

Average mid frequency values of EDT at Resim Heykel Müzesi Multipurpose Hall are less than optimum ranges. This shows that reverberation in the room is low and this results in a dead room. The use of marble instead of carpet floor cladding resulted in a slightly more reverberant space. Similarly, orchestra pit provided a longer EDT and a more live performance room.

Küçük Tiyatro Hall has a higher EDT than Resim Heykel Müzesi Multipurpose hall. The reverberation in the theater hall is convenient for musical and drama performances. Reverberation is not required to be long in this hall due to the reason that it is not used for opera.

Opera Hall average EDT values are quite lower than the expected range at mid frequencies. The maximum values are appropriate for opera function. Average EDT in the room is more convenient for the other type of performance, drama. A critical problem of the hall is the low reverberation at frequencies below 500 Hz due to the absorptive wall cladding. This is not preferred for the bass sound.

**Ts:** Center Time is the time of the centre of gravity of the squared impulse response. The parameter is considered to be correlated with the Early Decay Time, D50 and C80. Center Time is a significant determinant of many acoustical data about the room. The higher the Ts is, the more spatial is the acoustic impression at the listener's position. Shorter Ts shows a lower Initial Time Delay Gap, which results in intimacy and clarity in the room. Center Time is preferred to be below 20-25ms in a performance hall in order to support the direct sound. Free path distribution of an impulse gives information about the parameter whether it is short or long.

In Resim Heykel Müzesi Multipurpose Hall, minimum mid frequency Ts values are slightly below 60ms, however the average and maximum Center Time values are in the optimum range. The values are appropriate for speech activities. The multipurpose hall with marble floor also behaves similarly and RHM (O) has a higher value of average Ts. These values show that the hall has a short Initial Time Delay Gap and thus Clarity and Intimacy in the hall.

Center Time values at Küçük Tiyatro Hall in the mid frequencies are in optimum ranges. The hall is more spatial than Resim Heykel Müzesi Multipurpose Hall. Both halls are clear and intimate, i.e. the music sounds as though it is played in a small room (Beranek, 1962). The use of hard surfaces, the size of the rom and scattered surfaces well contributed to Intimacy.

Opera Hall has critical minimum values of Ts, however the average is between optimum ranges. Among the three halls, Küçük Tiyatro Hall has the most preferable Center Time values. The three case halls have Intimacy and Spatiousness.

**D50:** Definition is the ability to distinguish the speech. Schroeder (1979) suggests that Definition and Reverberation Time are negatively correlated. Definition is a significant factor for Intelligibility in the room for the speech activities. Hyde (2005) provided a list for the acoustical parameters supporting Intimacy which showed D50 is also a supporting factor.

In Resim Heykel Müzesi Multipurpose Hall, the variations such as the difference in the floor cladding and the existence of the orchestra pit do not alter the values of D50 much. The three types have the same problem of low minimum Definition values. The average D50 are in the optimum range which means there is Intelligibility in the room.

In Küçük Tiyatro Hall, only the maximum values of D50 are in the optimum range. The minimum and average mid frequency values are very low to support Intelligibility in the hall. On the other hand, the hall of Opera has similar D50 values as the multipurpose hall. The minimum values are low, however the average and maximum D50 are within the preferred range.

**C80:** Early to Late Sound Index is the factor that provides Clarity in a room. Clarity is the ability to distinguish and articulate individual sounds or the sounds of different instruments. Surfaces near source and massive materials foster clarity in a room. The comments on the front and rare wall C80 values may vary according to the authors. Positive values of the parameter mean that a sound energy received in a position in the first 80ms is greater than the received late reverberant sound energy.

The hall at Resim Heykel Museum is not a very muddy room, however C80 values in all types reached values beyond the limits of the optimum range which is +4 dB. High C80 values mean existance of high early reflections. The overall average C80 values in the hall are within the optimum range.

C80 values are all in the optimum range in Küçük Tiyatro Hall showing that there is preferred Clarity in the room. Maximum mid frequency values of Opera Hall are above the optimum range diminishing the Clarity in the room in some receivers' points. The hall average C80 values showed a clear room in general.

**LF80:** The relative amount of sound arriving from the side of a listener results in the subjective response: Envelopment. Strong lateral reflections, i.e. Lateral Fraction, are expected in narrow halls and from hard surfaces to obtain Envelopment.

Lateral Fraction average in Resim Heykel Müzesi Multipurpose Hall is in the optimum range and Envelopment is felt in RHM, RHM (M) and RHM (O). The maximum values are above the range especially when the orchestra pit is open. Other case halls, KT and O, behave similar with RHM in the average, minimum and maximum values at mid frequencies.

**STI:** Speech Transmission Index is a significant determinant of Intelligibility in a room. The expected STI is over 0,45 and higher values means more intelligible acoustical atmosphere.

Resim Heykel Müzesi Multipupose Hall has a fair intelligibility in the room like the two other case performance halls. The average STI is similar in these halls, however Opera Hall has the highest average value of the parameter.

**SPL:** Sound Pressure Levels in three case halls are in the range of 64-66dB and do not exceed these values. The halls behave similar in terms of pressure levels.

**$SPL_A$**: A weighted Sound Pressure Level at eight frequency ranges is 2dB higher in the average value in Küçük Tiyatro Hall than other case performance halls. The other halls behaves similarly in terms of the parameter.

**LG80:** Late Lateral Sound Level is a measure of the subjective response Envelopment through late lateral energy. Wakuda (2003) proved that not only the lateral level, but also late sounds from above and behind affect LEV significantly. Based on, Furuya et. al. (2005), it can be concluded that late energy from behind constitutes approximately 60 %, while late vertical energy forms 40% of the lateral energy. Depending on these recent findings and

Beranek (2008), it can be concluded that LEV (Listener Envelopment) provides a better evaluation of Envelopment in a room than LG80, however the latter is used in this study.

The average mid frequency LG80 value of the three case halls RHM, KT and O are in 55-62 range and theyare all considered as small rooms. Small volume fosters Envelopment subjective response. Among these case halls, Opera Hall shows slightly lower values of Late Lateral Sound Level which does not change the subjective response much.

**BR:** Bass Ratio is related with the acoustical behavior of the room in low frequencies. It is the ratio of reverberation at 125 Hz and 250 Hz to the value 500 Hz and 1000 Hz. The parameter is the measure of Warmth and fullness of bass tone. In the calculation of BR, T30 values are used. T30 is measured between -5 and -35 dB of the sound decay curve and is critical for reverberation, Clarity and Liveness.

In Resim Heykel Müzesi, the use of marble floor affected Bass Ratio positively. That is, in RHM and RHM (O) cases, BR values are around 2, while the ratio at RHM (M) is 1. The expected Bass Ratio is below 1,2 and Opera Hall and Küçük Tiyatro Hall also have optimum values of BR. Ideal BR means that the low frequency reverberation is not considerably higher than mid frequency one. The Warmth, i.e. the persistance of sound at low frequencies in Küçük Tiyatro Hall is more successful than RHM (O). In order to evaluate Warmth in Opera Hall, the poor reverberation at low freuqencies should also be considered.

**TR:** Treble Ratio which is the ratio of reverberation at high frequencies to that at mid frequencies and gives the information about the acoustical behavior of the room in high frequencies. The TR values of the case halls RHM, RHM (M), RHM (O) and KT are in the 0,8-0,9 range, while the ratio in Opera hall is a bit above the average of other halls. This means that Brilliance, i.e. persistance of sound at high frequencies, in Opera hall is more than the other case halls.

The resulting data of the acoustical modeling which are provided in the Appendices as grid and multipoint responses showed the acoustical behavior of the rooms. The results of the values at 500 Hz and 1000 Hz are evaluated, which is an accepted common attitude in acoustical evaluations. The overall results can be summarized in terms of the behavior of the halls at speech and musical activities.

Küçük Tiyatro Hall is mostly used for theatre performances, so the speech performance is expected to be better than that of the Opera House. In the latter hall, the main activity is opera, ballet and drama which are the performances of both music and speech. This requires that the acoustical performance for musical activities at Opera Hall should be better than the former hall. On the contrary, Küçük Tiyatro Hall seems to present better musical performance than Opera Hall due to higher Reverberation Time, Early Decay Time and Central Time values and lower Definition, Clarity Index and Speech Transmission Index. Clarity is lowest at the theatre hall, while highest at Opera Hall.

Resim Heykel Müzesi Multipurpose Hall seems to have better acoustical conditions for speech performances due to lower Reverberation Time, Early Decay Time and Central Time values, while the hall has higher Clarity Index and Definition values. Speech Transmission Index is better than Küçük Tiyatro Hall while worse than Opera Hall. Opera Hall presented the most optimum values of speech intelligibility among the case halls with positive values of Clarity Index and highest Definition.

In the overall positions of Resim Heykel Multipurpose hall, Reverberation Time is calculated around 1.3 seconds. In the balcony levels and ground level lodgias, T30 gets the highest values in the room. Sound pressure levels are higher at the front positions, but low at the second level balcony. Clarity gets positive values in the receiver positions. Definition values are low at the second level balcony, however the average is acceptable. Lateral Fraction is high at the back side in the ground level. Sound Pressure Level is low at the second balcony. The Late Lateral Fraction and Speech Transmission Index values are homogenious in the room. The STI values should be higher for speech activities.

In Küçük Tiyatro Hall, the ground level back positions have higher Reverberation time but lower Early Decay Time. Sound Pressure Level is higher in the ground level but lower in the balcony positions. Definition is low at the back side of the room. Lateral Fractşon and Late Lateral Levels are lower in the side balcony, while Speech Transmission Index is homogenious in the room.

These graphs show that, in the balcony of te Opera hall, the Definition is lower than other position. Central Time gets the highest values, however Definition and Clarity gets the lowest values in the front rows of the balcony. In the lodgia, Definition is slightly better than the balcony positions. Due to paralel walls, the receiver positions close to side walls get higher Lateral Fraction. Late Lateral Levels are low in the positions far from the stage, but high in the front positions. Speech Transmission Index is homogenous in the hall around the acceptable value of 0.6.

# CHAPTER 6

# CONCLUSION

The advances in the field of acoustics since the early 20$^{th}$ century in parallel with advances in electronics, communication, design media and psychology enable designers/researchers/practitioners to consider acoustics as an integral part of the design and application processes. Among several branches of acoustics, architectural acoustics in terms of noise control and acoustical qualities expected to be experienced in the buildings and thus in the built environment has still been one of major concerns of designers. In this context performance halls with all their complexities in the architectural program, and their potentials of being landmarks of where they belong, highly effecting the cultural life still deserves to be studied more.

Historical development of performance halls regarding their design and acoustical qualities has been studied extensively by many researchers resulting in broad literature on acoustics in general. Several studies evaluating world wide acknowledged performance halls have been published. The field has a mass of subject to be surveyed and valuable studies have continued on the modern acoustics for over a century. The publications show that studies on the history of performance halls and acoustics have been done mainly in Europe, Japan and America. The acoustical success of the historic halls of Europe and USA such as Amsterdam Concertgebouw, Boston Symphony Hall, Paris Opera House, Leipzig Neues Gewandhaus, Berlin Konzerthaus, and Vienna Musikvereinssaal is worldly accepted.

The acoustics of contemporary performance halls in Turkey has also been studied in the recent years. Yet there is still much to do for the acoustical evaluation of Early Republic period performance halls. This study aims to provide first detailed computational models of three important performance hall in Ankara belonging to that era namely Resim Heykel Müzesi Multipurpose Hall, Küçük Tiyatro Hall and Opera Hall, enabling further studies on these buildings (structural performance, thermal performance and etc), their detailed acoustical analysis and evaluations regarding their contemporaries and finally providing data for future renovations. The documentation provided in this study delivers detailed reference for future studies on these performance halls. In addition, the tables summarizing a very broad literature on acoustics aim to provide a concise guide and reference for future studies.

The results of the present study can be summarized as:

- Resim Heykel Müzesi Multipurpose Hall is used for a wide range of activities of speech and music like musical comedy, operet, conference and musical dance performances. On the other hand, Küçük Tiyatro is used mostly for drama performances while Opera Hall is used for both music and drama performances such as operas and ballets. The musical performance of the latter hall was expected to be better than the former hall. According to the data obtained from acoustical simulation analysis, Küçük Tiyatro seemed to present better musical performance than the Opera Hall due to higher EDT, RT values and lower D50, C80 and STI values. This meant that Küçük Tiyatro Hall has better acoustical performance for musical performances than Opera Hall that is not enough compatible with their present functions.

- Resim Heykel Müzesi Multipurpose Hall seemed to have good acoustical behavior for speech activities due to lower RT and higher C80 and D values. STI values are much better than those of Küçük Tyatro Hall. However, both halls are clear and intimate, and the acoustic data of the hall at Resim Heykel Müzesi supports speech performances.

- Resim Heykel Müzesi Multipurpose Hall, Küçük Tiyatro Hall and Opera Halls are dead rooms in general, in other words the EDT values are lower than worldly accepted halls of the period. Similarly, due to the low T30 values, the three rooms are all spaciouss and appropriate for speech performances but not adequate for musical activities such as opera or musical. When compared to successful halls of the period in terms of such properties, Early Republic period halls are less reverberant and thus not preferrable for symphonic or other musical activities.

- The performance halls studied in this thesis faced with a number of renovations in years. These interventions have potentials to change the acoustical behavior of the halls and result in a different perception of the sound field compared with their initial state. Such interventions mostly affect the absorptivity of the materials negatively thus changing the reverberation time, clarity, etc.

- Resim Heykel Müzesi Multipurpose Hall, Küçük Tiyatro Hall and Opera Hall are all in rectangular plan. There are similarities among Early Republic performance halls and highly ranked successful halls of the period in form and in architecture. The widespread typology, i.e. shoebox plan of the period that exists in prosperous halls is also seen in case halls.

- The materials and methods are other commonly used properties in the halls of the period. Additionally, the decorations with gold latten, curved balcony parapets, motives, ornamented and coffered ceilings and articulations in the walls are also mutual properties. Opera Hall has less textured surfaces at the cladded ceiling, in parapets and in the walls.

- The design of balconies, lodges and ceiling of case halls show similarity with the worldly accepted halls. The relationship between lodges and balconies with the overall volume and the stagehouse at case halls is parallel with successful ones. To illustrate, U-shaped balcony at Resim Heykel Müzesi and Küçük Tiyatro Hall, rear balconies at Opera and Resim Heykel Müzesi Multipurpose Hall, the huge dome at the decorated ceiling of Küçük Tiyatro Hall are similar properties with the forerunners of the period in the world.

- Even though architectural properties show similarity between famous successful halls and case halls as stated above, there are differences in terms of the capacity, area and volume. In other words, the performance halls of the period show difference in terms of scale. The seat capacity of worldly accepted halls is around 1500-2600, whereas case halls are accepted as „small' due to the capacity lower than 800 as stated before.

- Despite scale differences, the great similarity between the architecture of the halls of the period shows the interaction of their architects at the period. This might stem from the similarity of the architectural education or the influences during the visits of the architects abroad. Architects of the case halls, Arif Hikmet Koyunoğlu, Kemalettin, Paul Bonatz had a chance to visit and stay in Europe or they had foreign teachers in the Sanayi-i Nefise Mektebi thus experimented a similar education with western architects. This has a potential to result in such similarity between the designs of these halls.

- The architectural similarities between Early Republic performance halls and their acoustically well known contemporaries did not resulted in big resemblances in terms of acoustical performance. The case halls are less reverberant than forerunners of the period. Essert (1997) argues that a low ceiling tends to promote low reverberance, lack of envelopment, and a generally inadequate increase in loudness. However, this does not result in unpleasant acoustical atmosphere in these halls due to the reason that performances based on speech requires less reverberence than musical performances as in highly ranked halls. The evaluations of parameters rather than reverberance differ among case halls.

The acoustical conditions of the three case halls, in fact, can be improved for achieving better performances of musical and speech activities. Further studies are needed to develop some suggestions for the acoustical improvement in such halls by providing well-designed renovation programs.

This study constitutes a condensed examination of acoustical behavior of Early Republic performance halls with reference to worldly accepted halls of the period. The studies in this subject needs to be continued in the future. Additional contributions on the subject will provide to highlight and thus develop the acoustical performance of significant historic buildings.

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## APPENDIX A

### RESULTS: MULTI POINT RESPONSES OF THE HALLS

(EDT, T30, SPL, C80, D50, Ts, LF80, SPL(A), LG80, STI values at the frequencies 500 Hz and 1000 Hz)

RHM: Resim Heykel Museum Multipurpose Hall with its original design

RHM (M): Current situation with marble floor

RHM (O): Current situation with orchestra pit open

KT: Küçük Tiyatro Hall

O: Opera/Büyük Tiyatro Hall

### RESİM HEYKEL MÜZESİ MULTIPURPOSE HALL

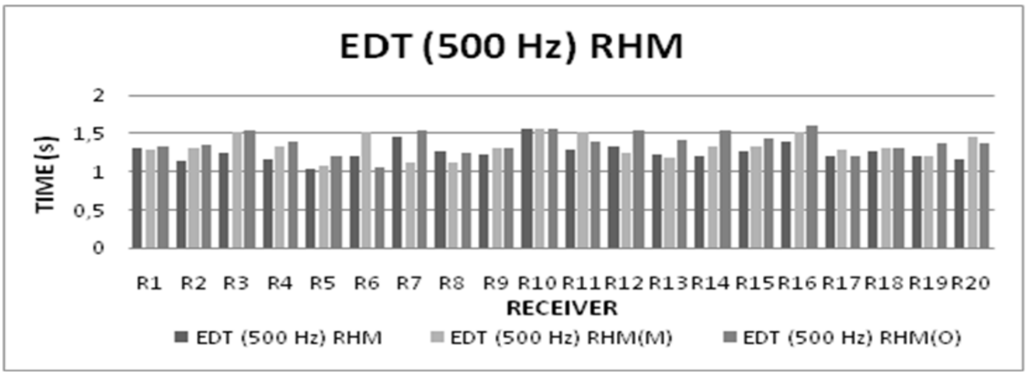


**Figure 19** EDT at 500 Hz in RHM, RHM(M) and RHM(O)

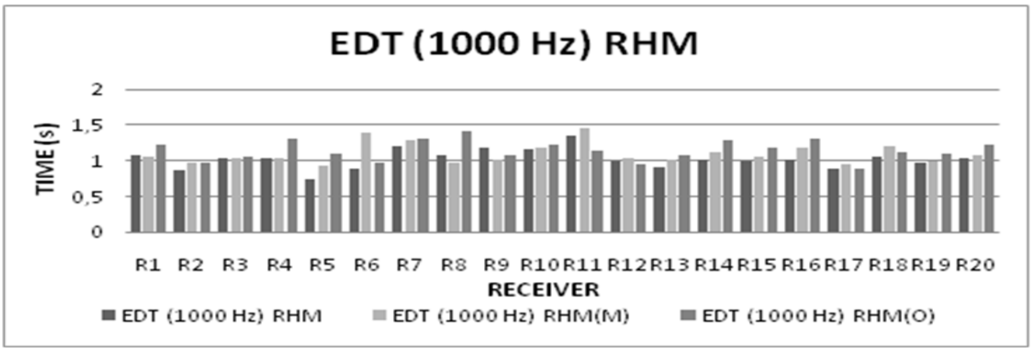


**Figure 20** EDT at 1000 Hz in RHM, RHM(M) and RHM(O)

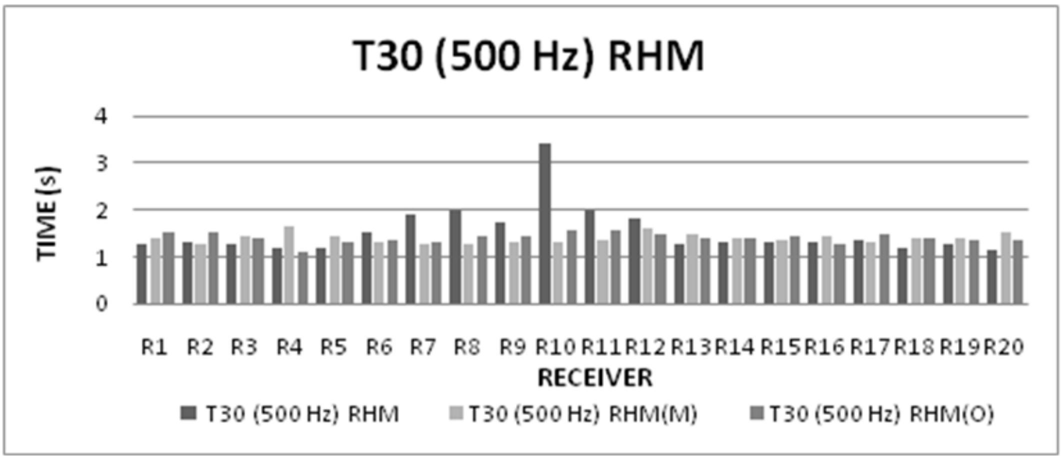


**Figure 21** T30 at 500 Hz in RHM, RHM(M) and RHM(O)

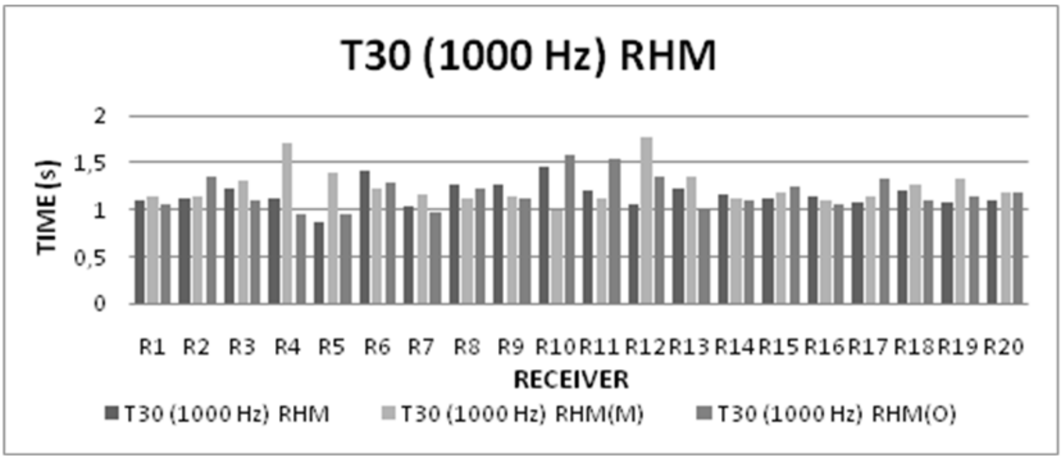


**Figure 22** T30 at 1000 Hz in RHM, RHM(M) and RHM(O)

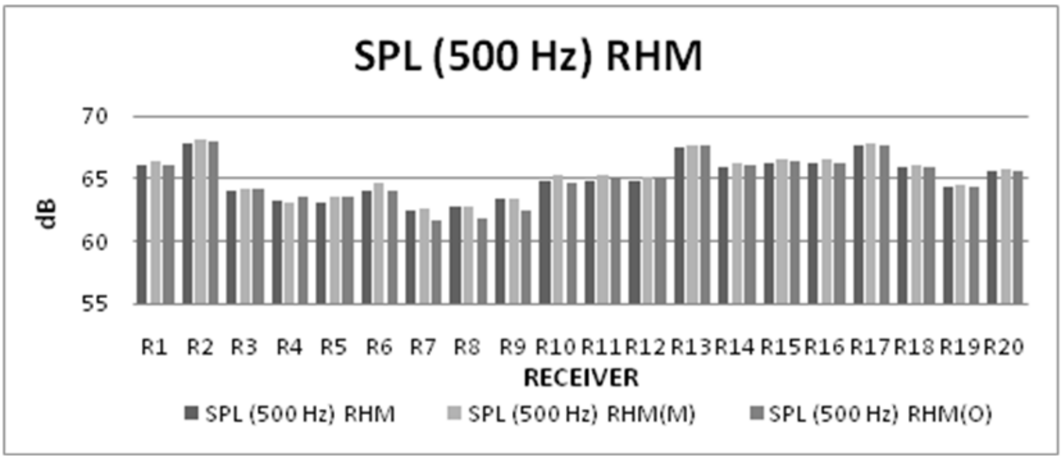


**Figure 23** SPL at 500 Hz in RHM, RHM(M) and RHM(O)

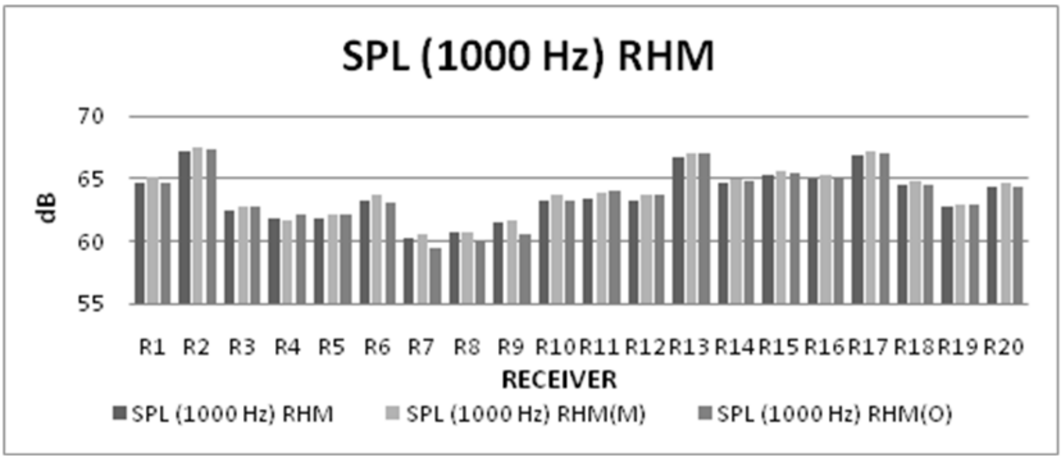


**Figure 24** SPL at 1000 Hz in RHM, RHM(M) and RHM(O)

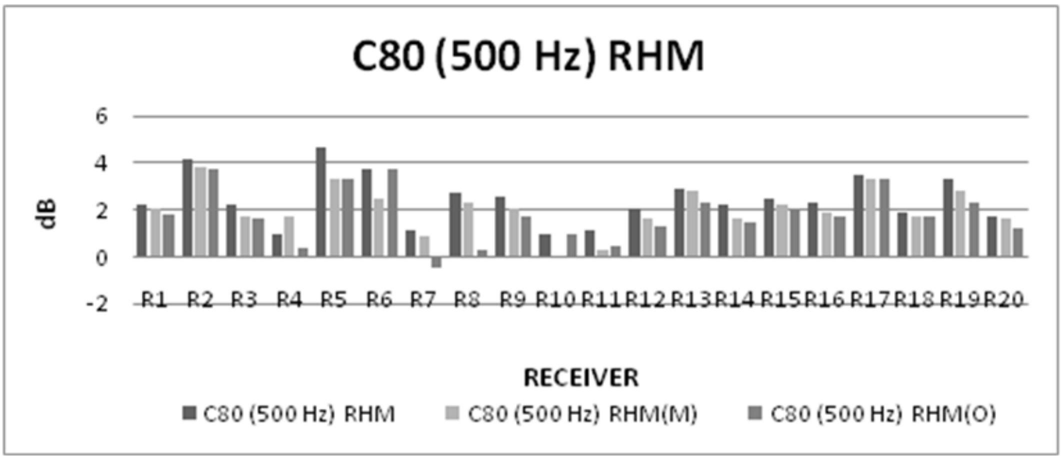


**Figure 25** C80 at 500 Hz in RHM, RHM(M) and RHM(O)

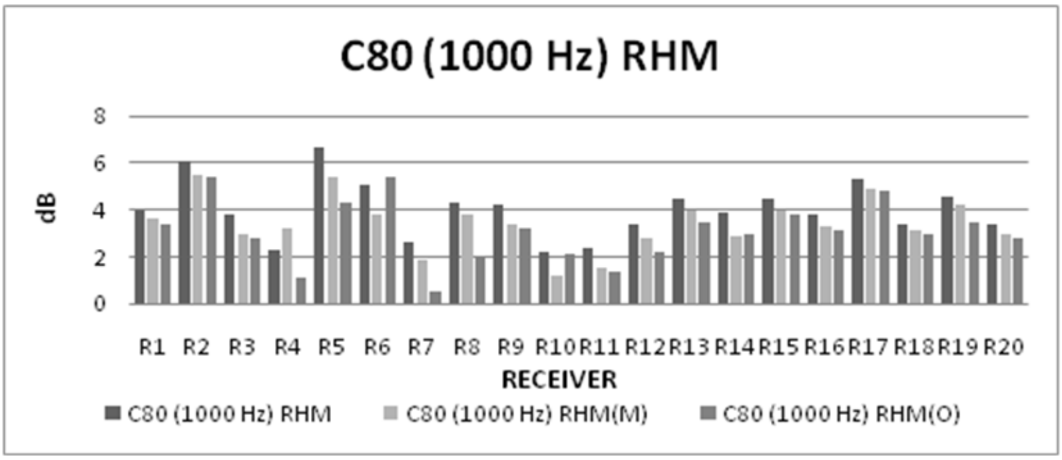


**Figure 26** C80 at 1000 Hz in RHM, RHM(M) and RHM(O)

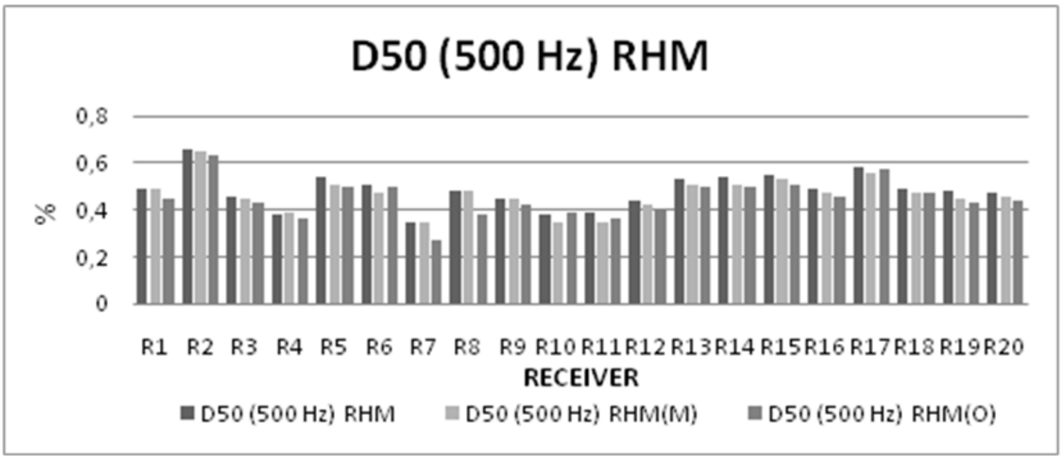


**Figure 27** D50 at 500 Hz in RHM, RHM(M) and RHM(O)

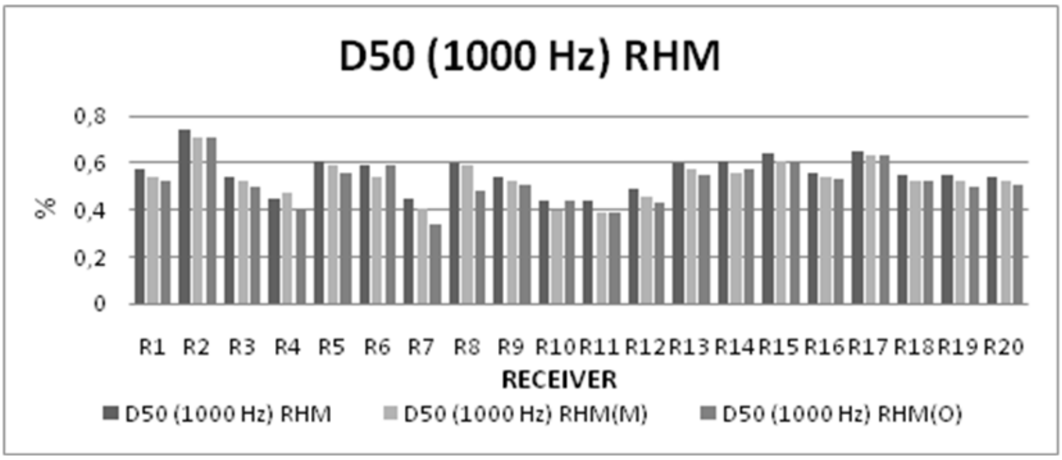


**Figure 28** D50 at 1000 Hz in RHM, RHM(M) and RHM(O)

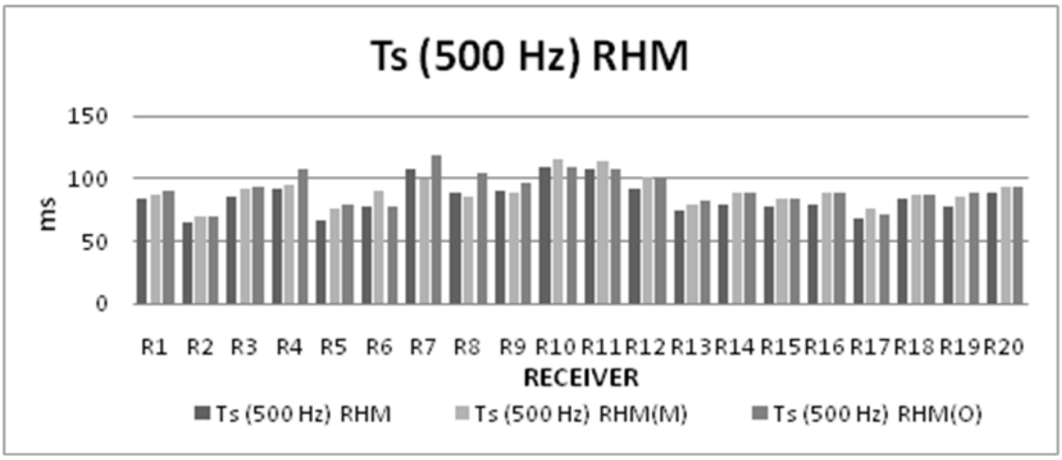


**Figure 29** Ts at 500 Hz in RHM, RHM(M) and RHM(O)

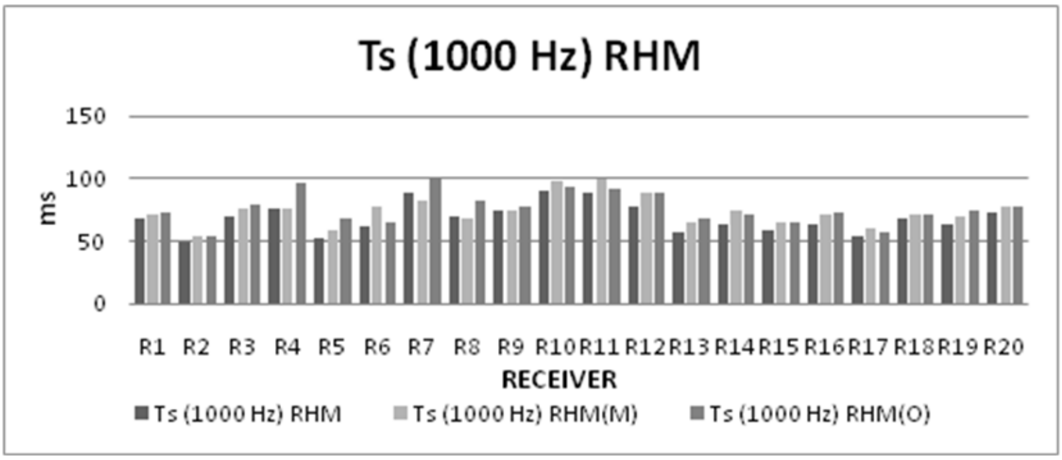


**Figure 30** Ts at 1000 Hz in RHM, RHM(M) and RHM(O)

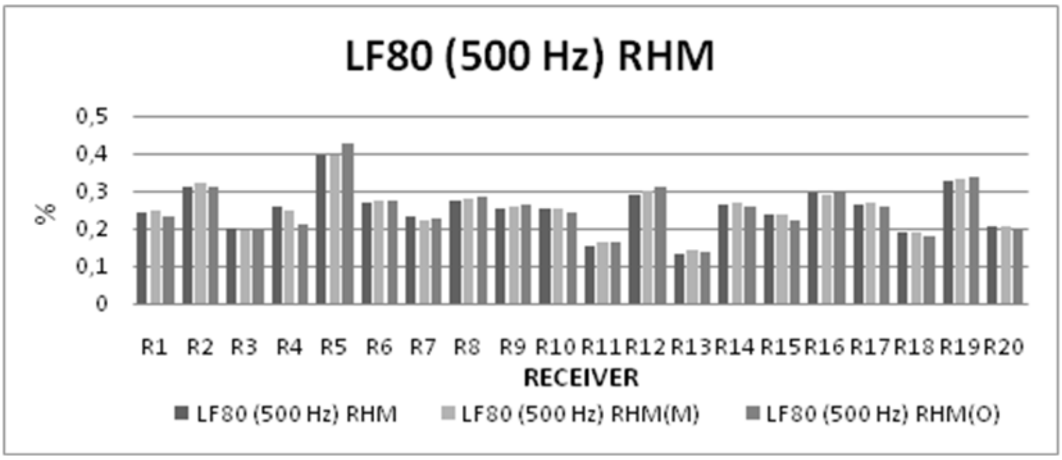


**Figure 31** LF80 at 500 Hz in RHM, RHM(M) and RHM(O)

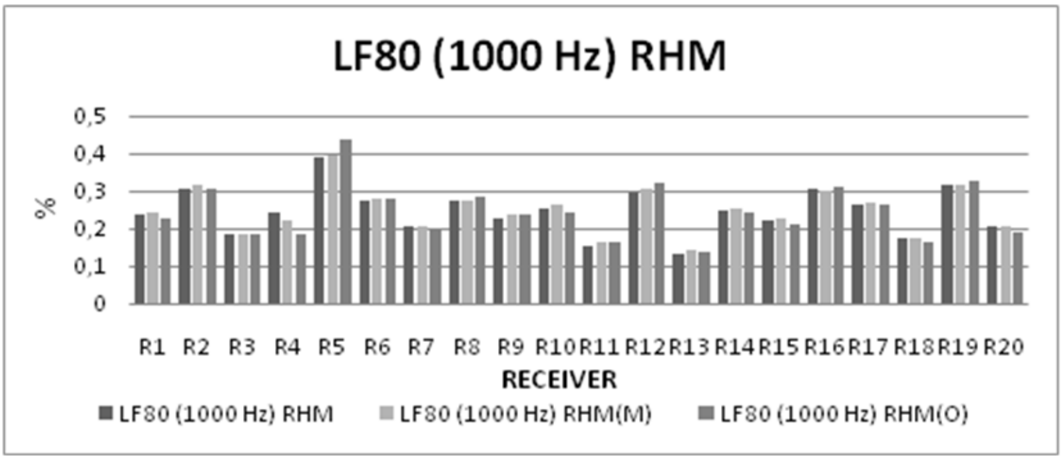


**Figure 32** LF80 at 1000 Hz in RHM, RHM(M) and RHM(O)

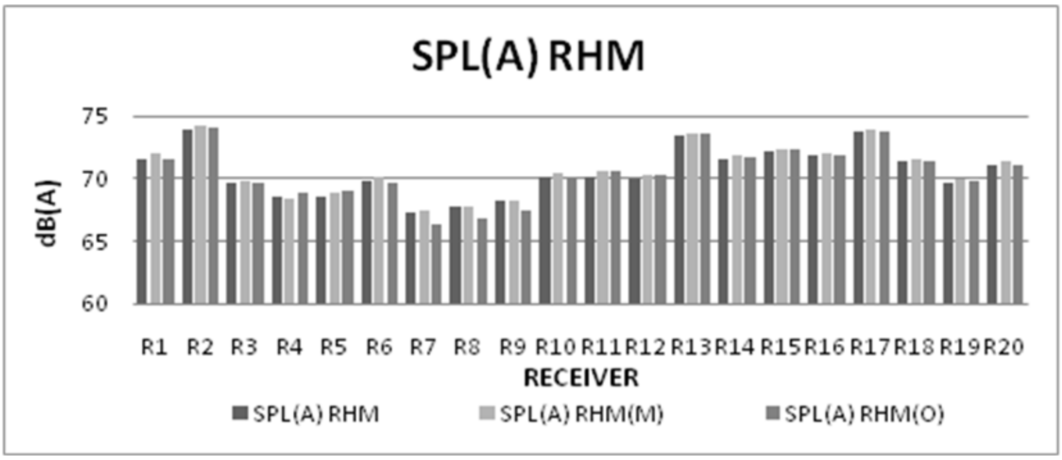


**Figure 33** SPL(A) in RHM, RHM(M) and RHM(O)

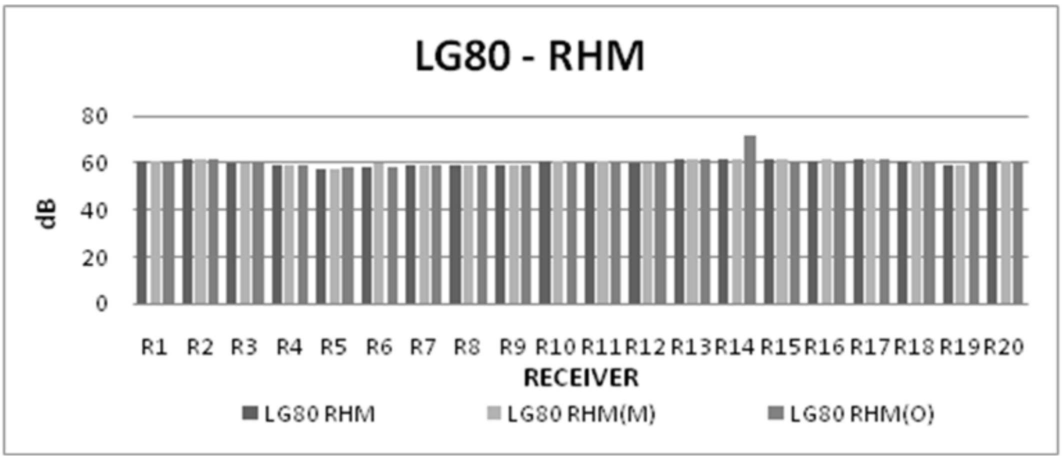


**Figure 34** LG80 in RHM, RHM(M) and RHM(O)

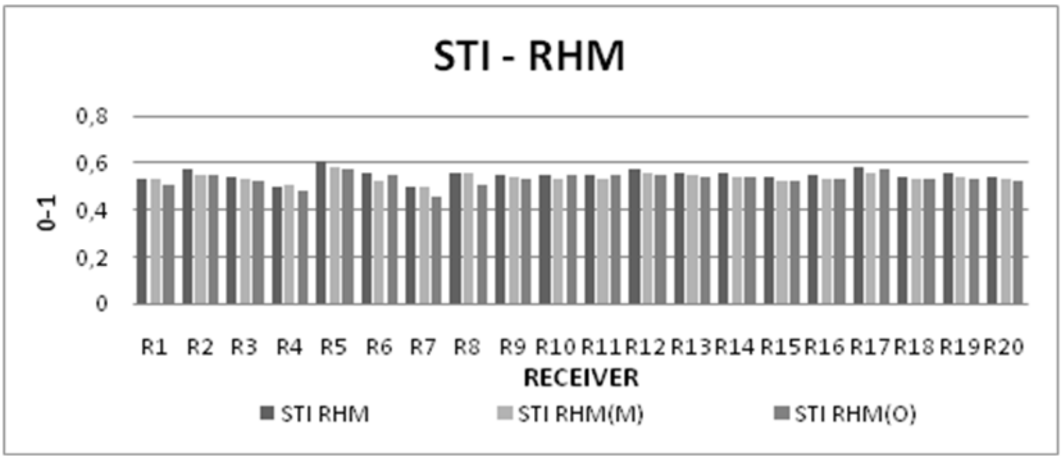


**Figure 35** STI in RHM, RHM(M) and RHM(O)

## KÜÇÜK TİYATRO HALL

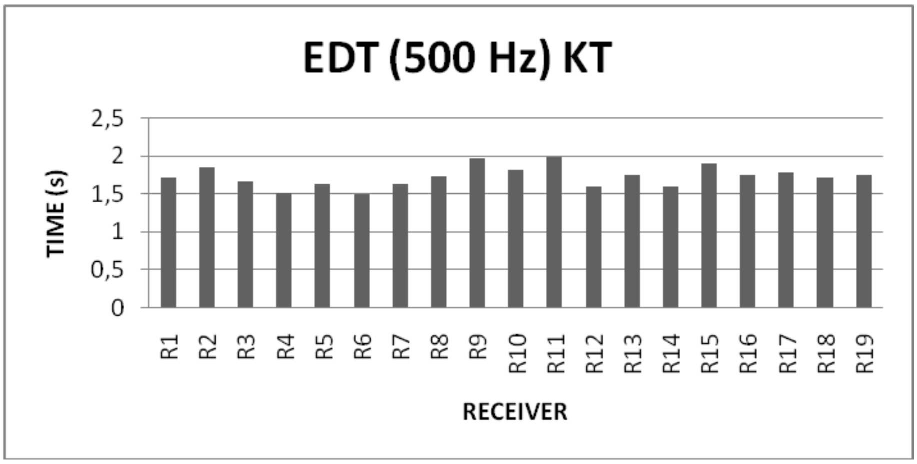


**Figure 36** EDT at 500 Hz in KT

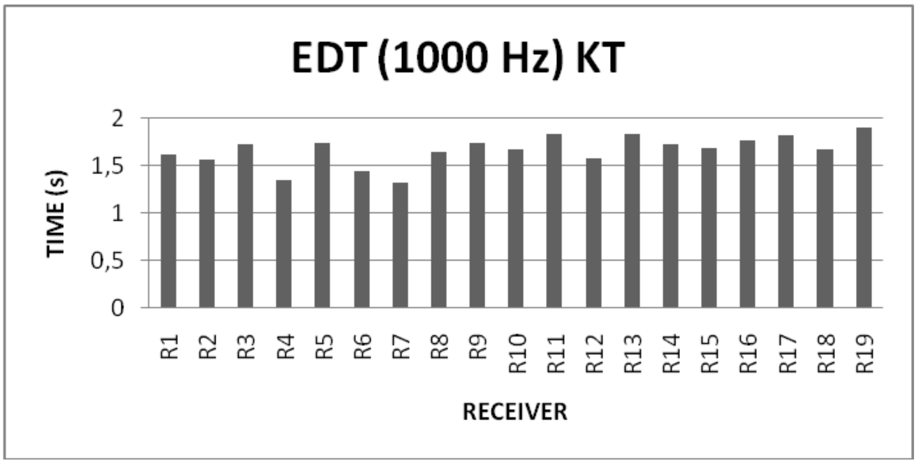


**Figure 37** EDT at 1000 Hz in KT

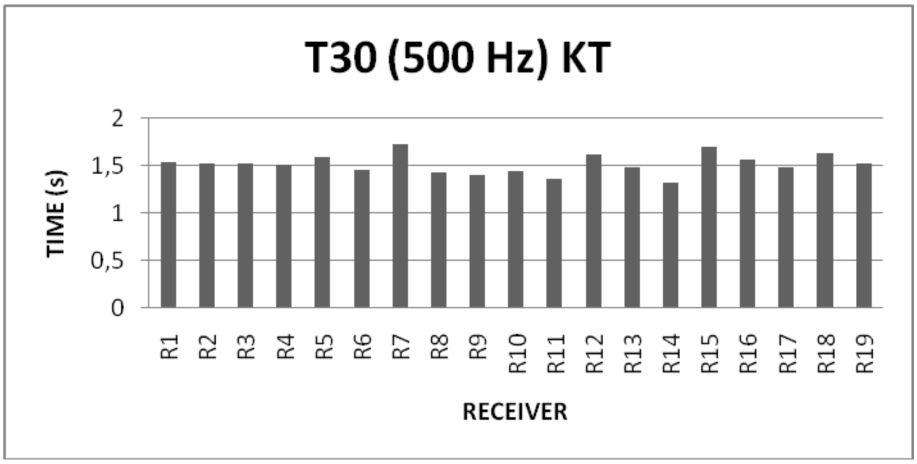


**Figure 38** T30 at 500 Hz in KT

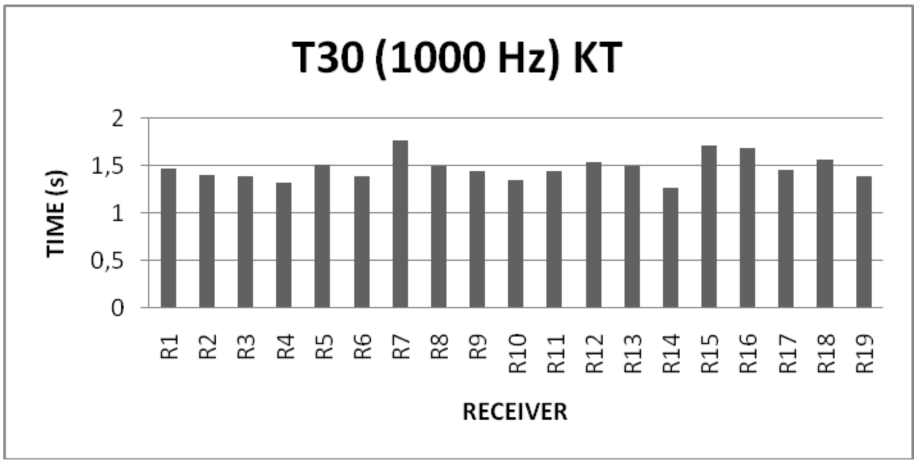


**Figure 39** T30 at 1000 Hz in KT

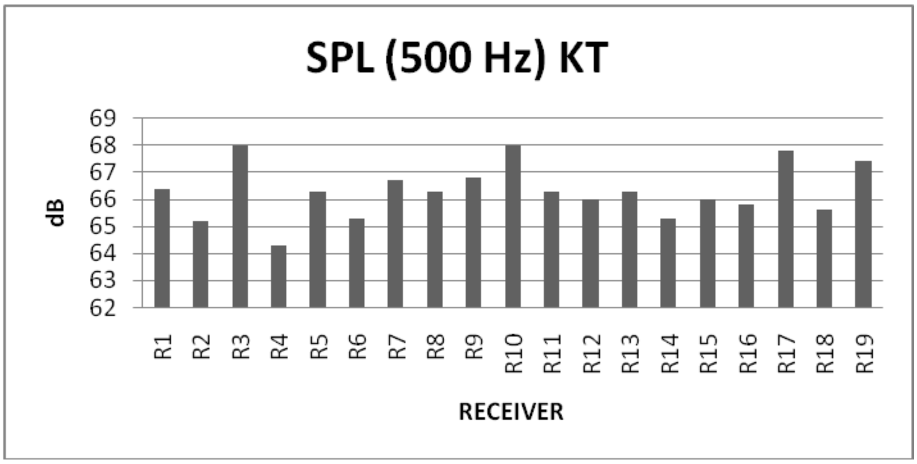


**Figure 40** SPL at 500 Hz in KT

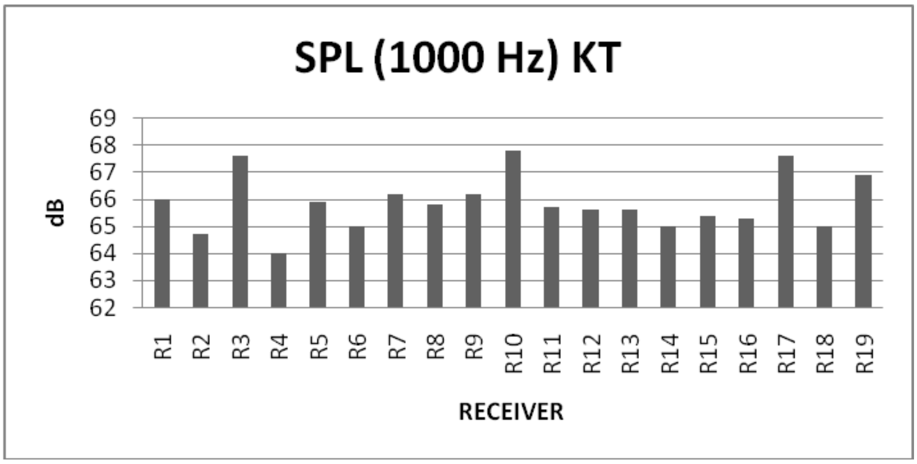


**Figure 41** SPL at 1000 Hz in KT

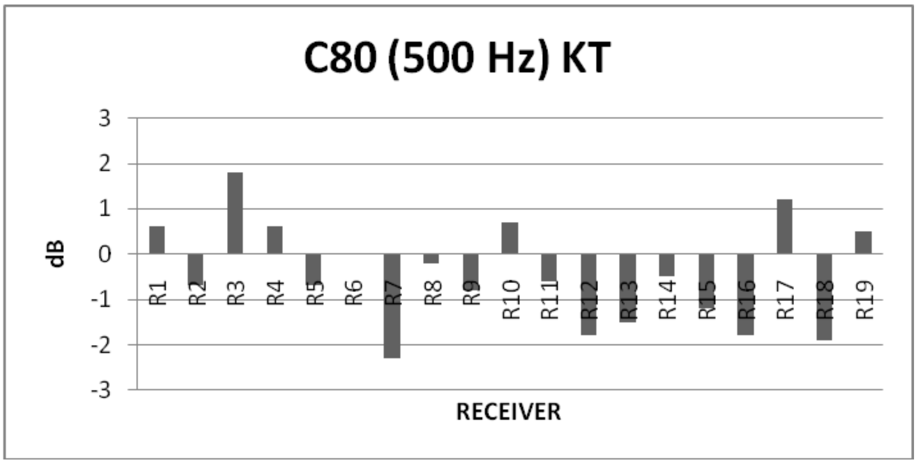


**Figure 42** C80 at 500 Hz in KT

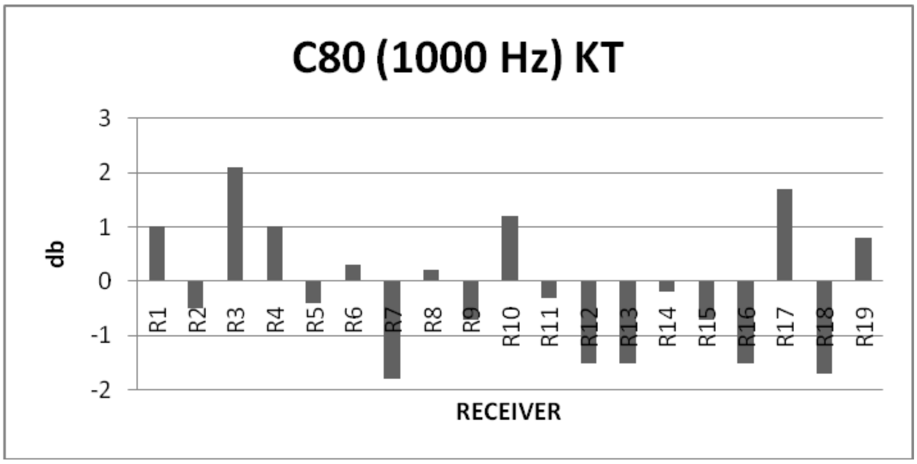


**Figure 43** C80 at 1000 Hz in KT

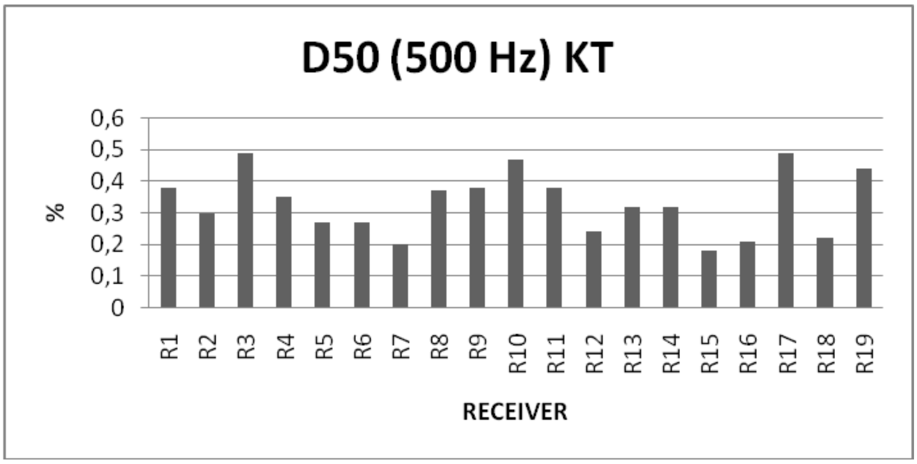


**Figure 44** D50 at 500 Hz in KT

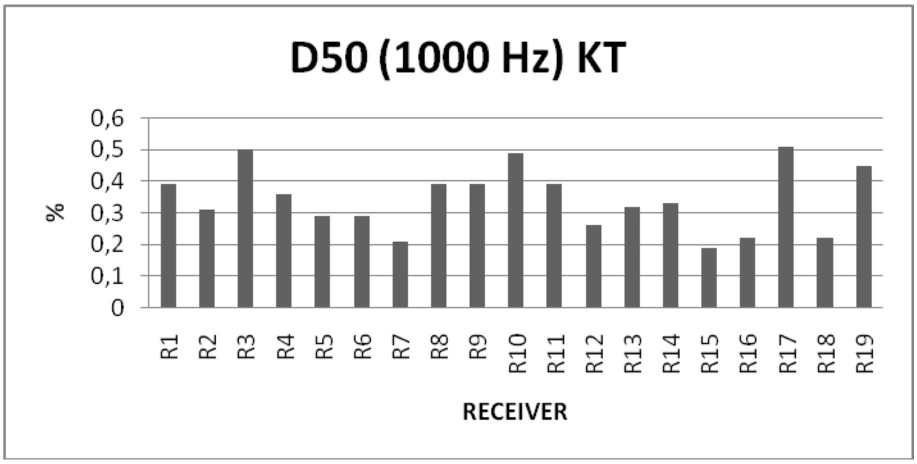


**Figure 45** D50 at 1000 Hz in KT

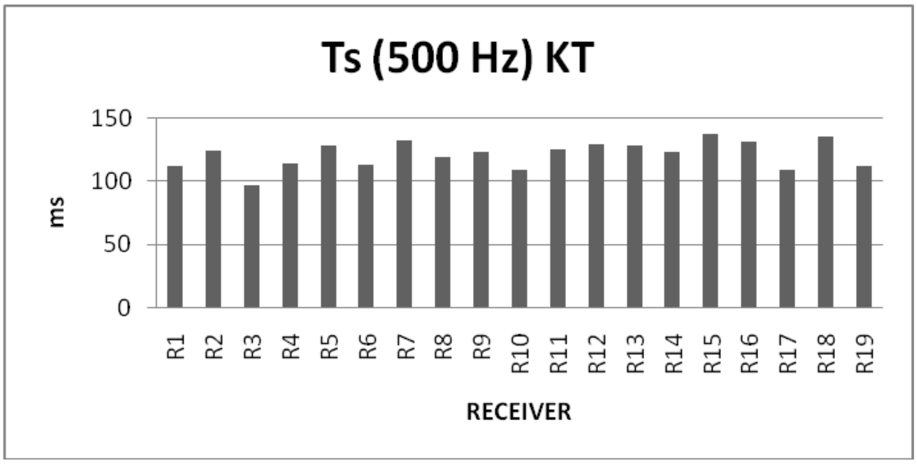


**Figure 46** Ts at 500 Hz in KT

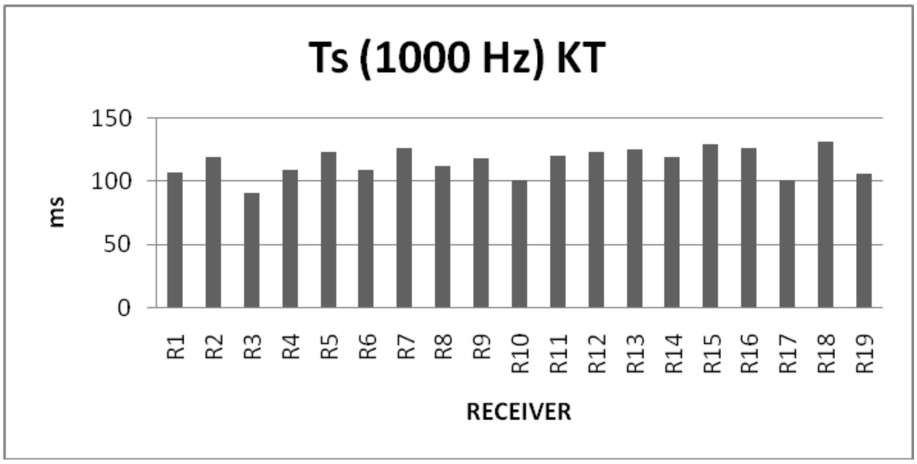


**Figure 47** Ts at 1000 Hz in KT

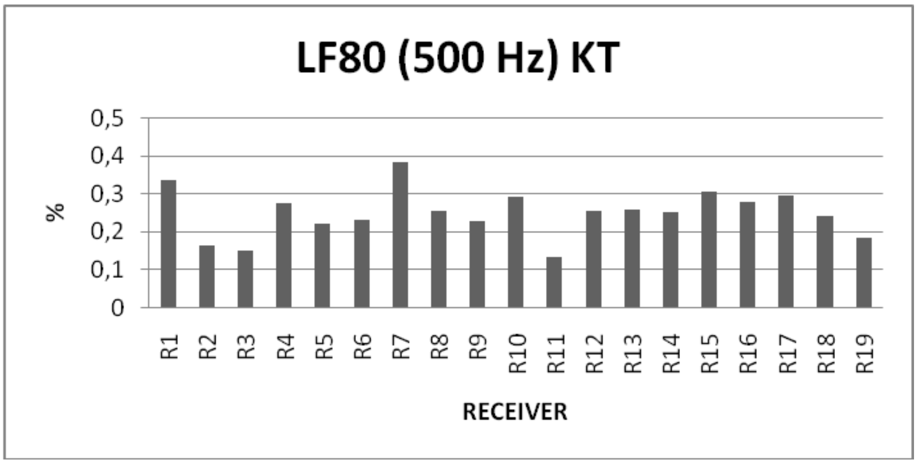


**Figure 48** LF80 at 500 Hz in KT

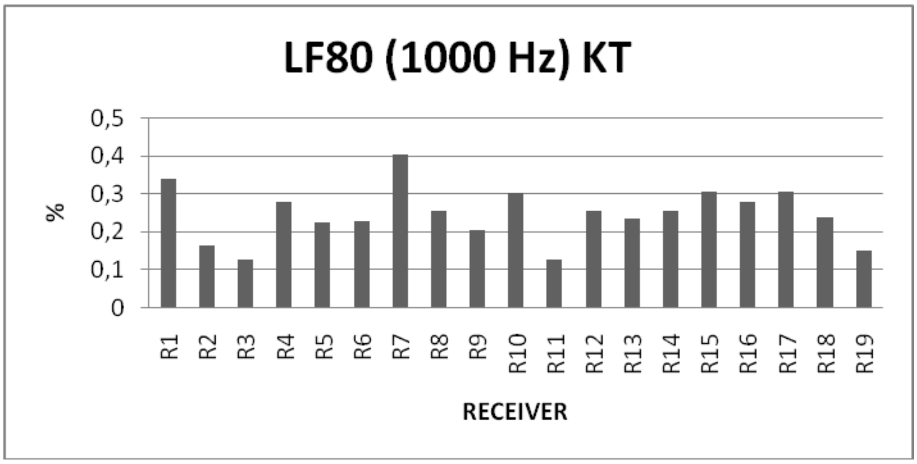


**Figure 49** LF80 at 1000 Hz in KT

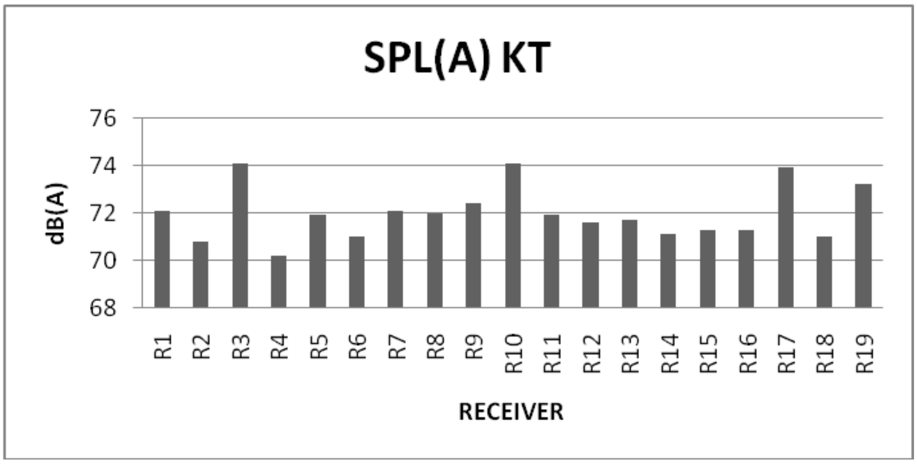


**Figure 50** SPL(A) in KT

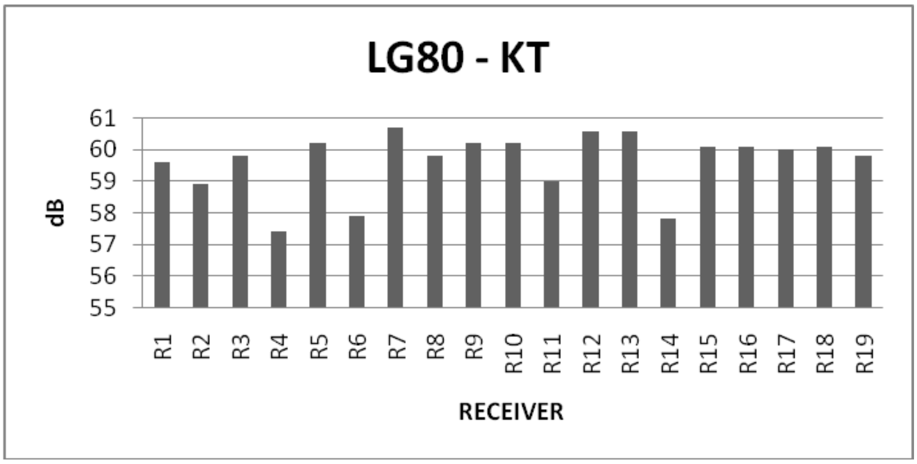


**Figure 51** LG80 in KT

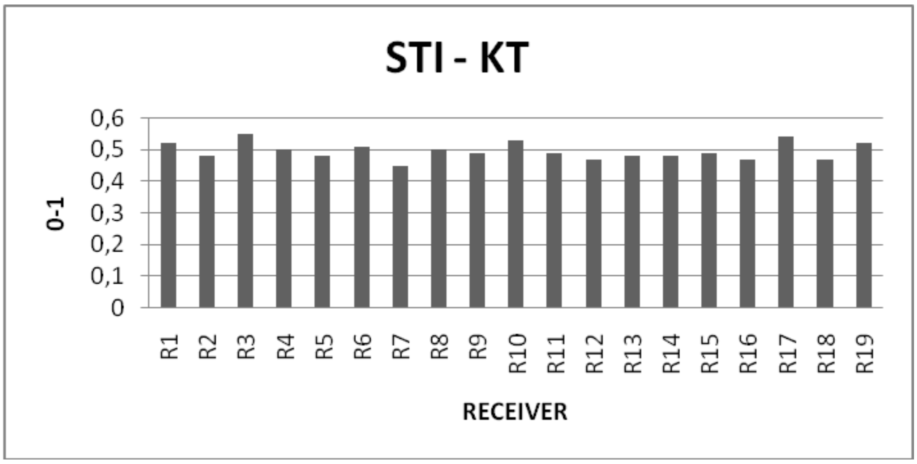


**Figure 52** STI in KT

**OPERA HALL**

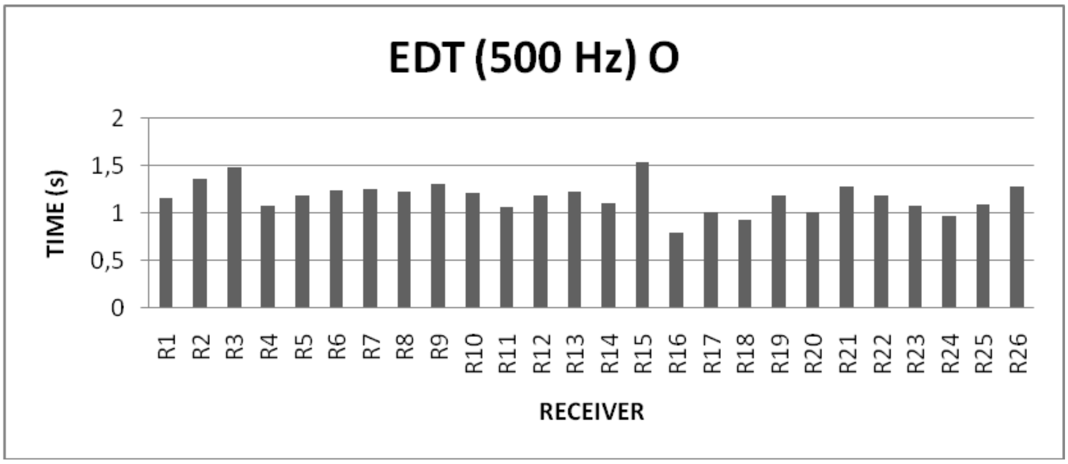


**Figure 53** EDT at 500 Hz in O

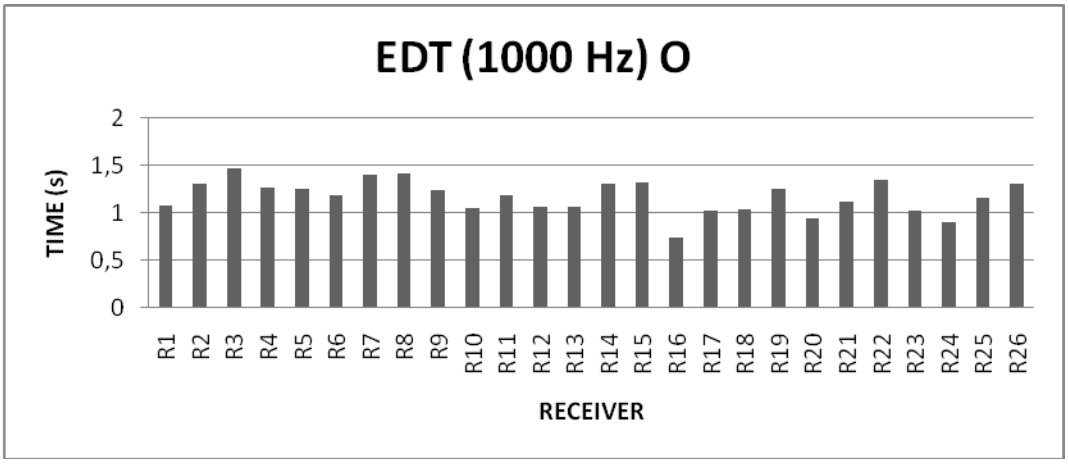


**Figure 54** EDT at 1000 Hz in O

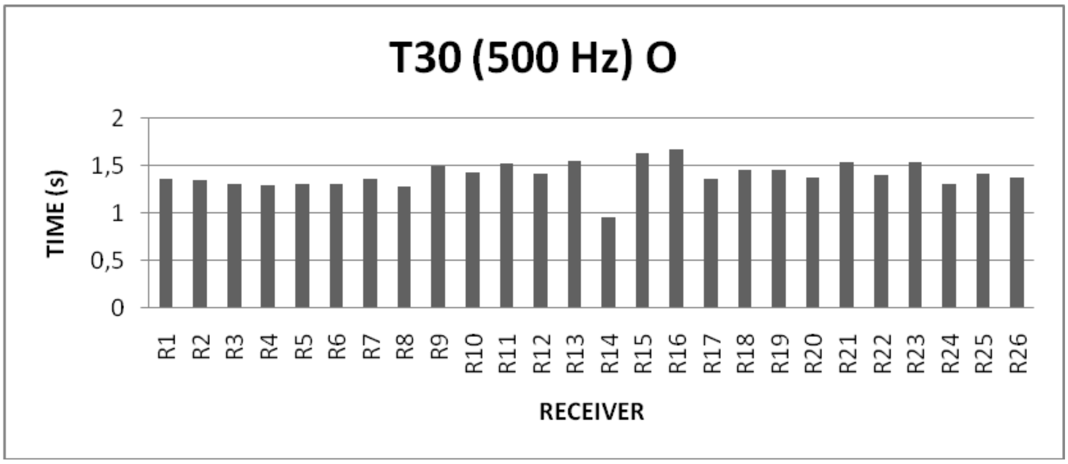


**Figure 55** T30 at 500 Hz in O

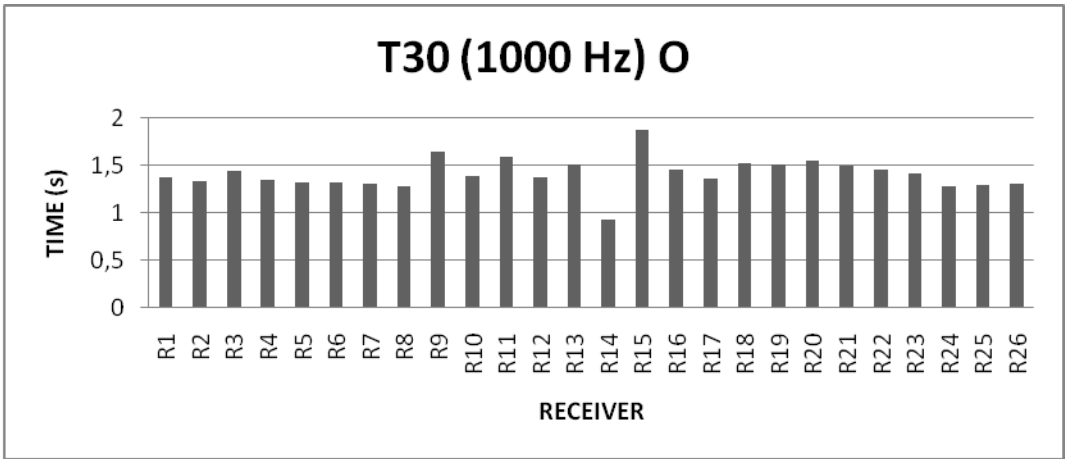


**Figure 56** T30 at 1000 Hz in O

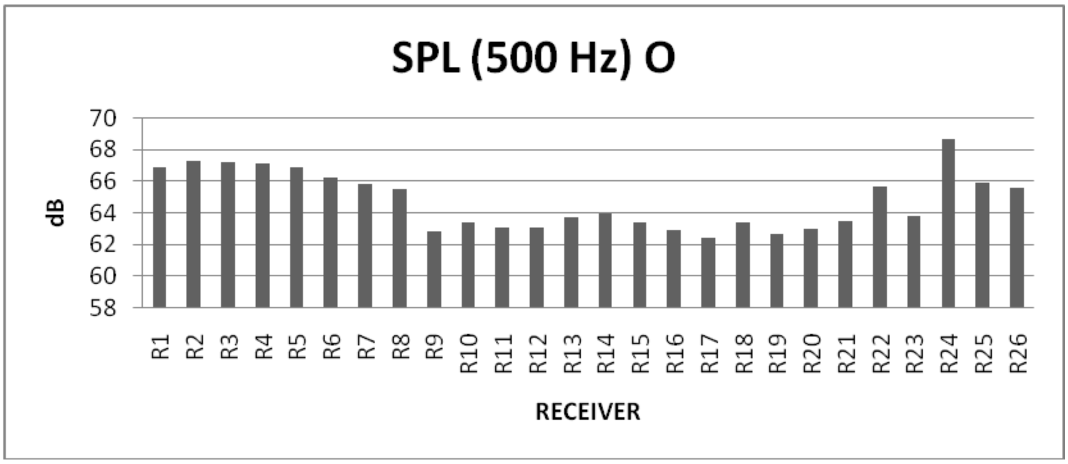


**Figure 57** SPL at 500 Hz in O

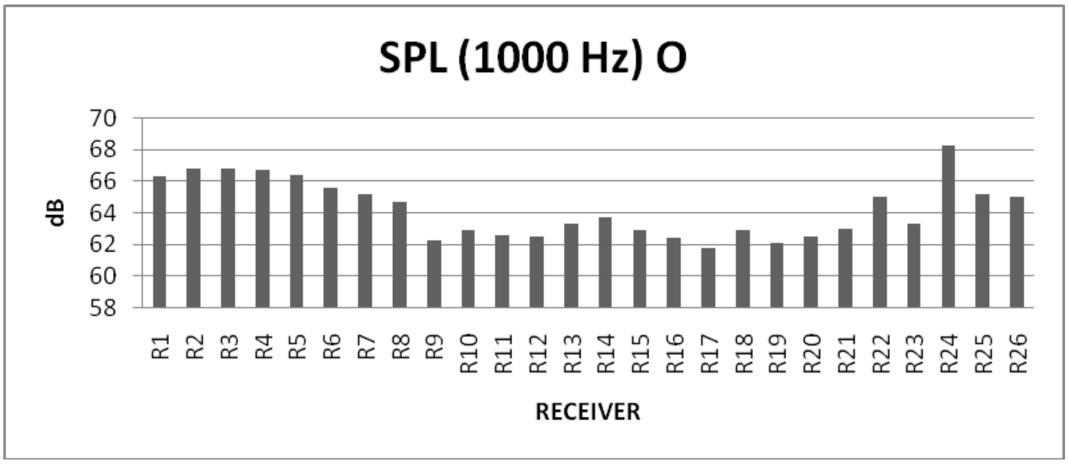


**Figure 58** SPL at 1000 Hz in O

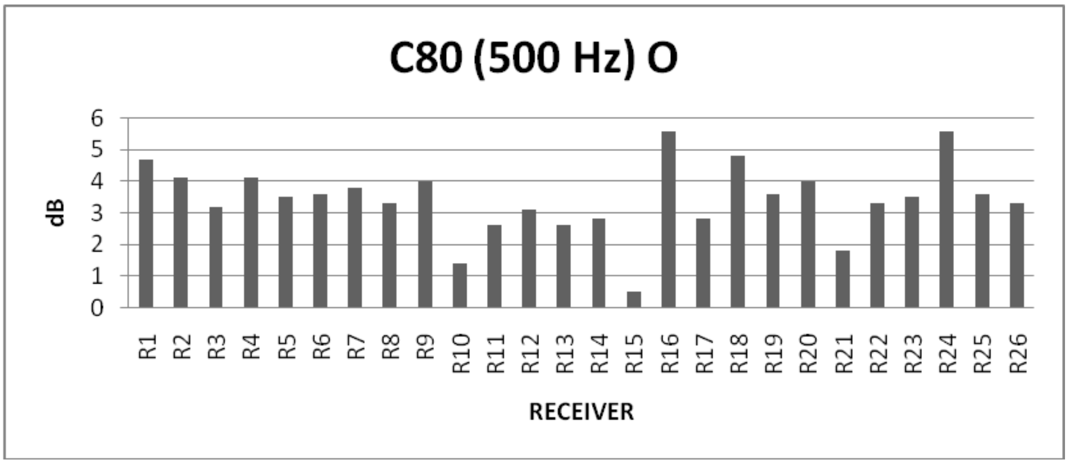


**Figure 59** C80 at 500 Hz in O

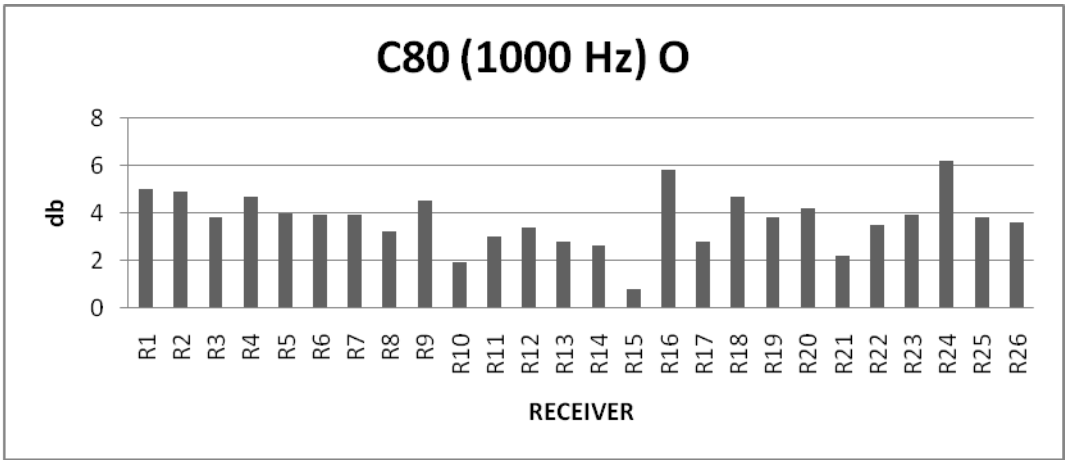


**Figure 60** C80 at 1000 Hz in O

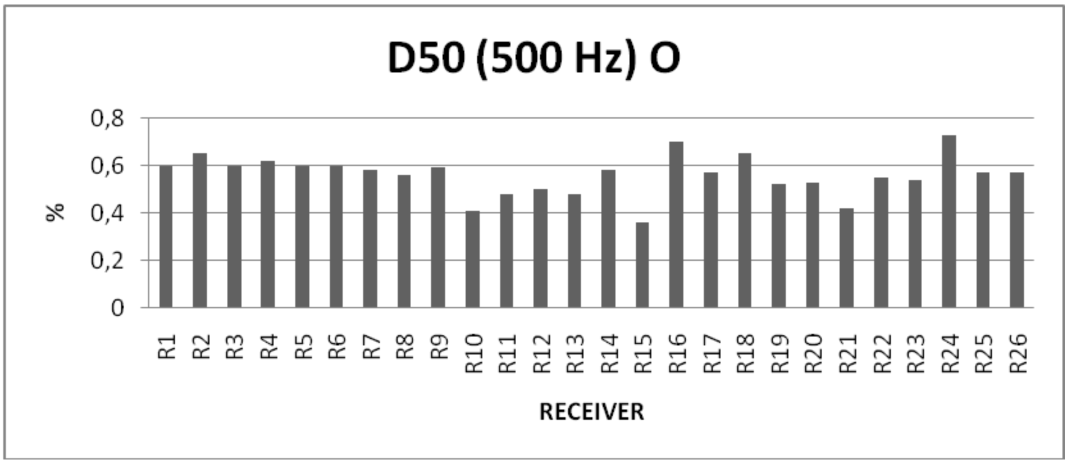


**Figure 61** D50 at 500 Hz in O

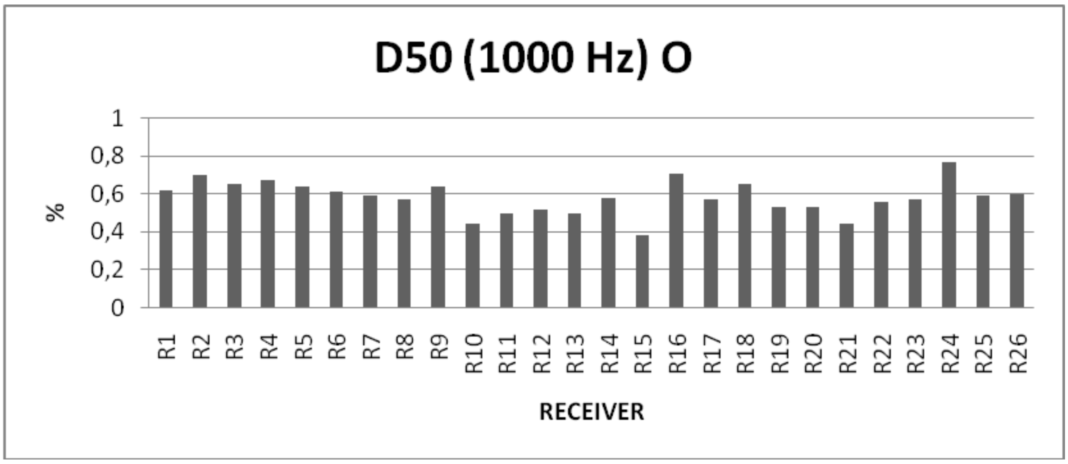


**Figure 62** D50 at 1000 Hz in O

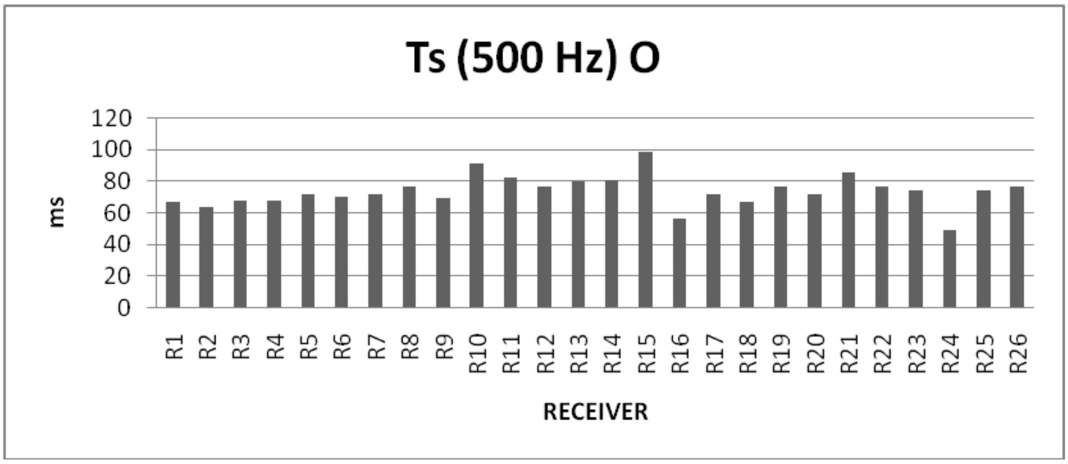


**Figure 63** Ts at 500 Hz in O

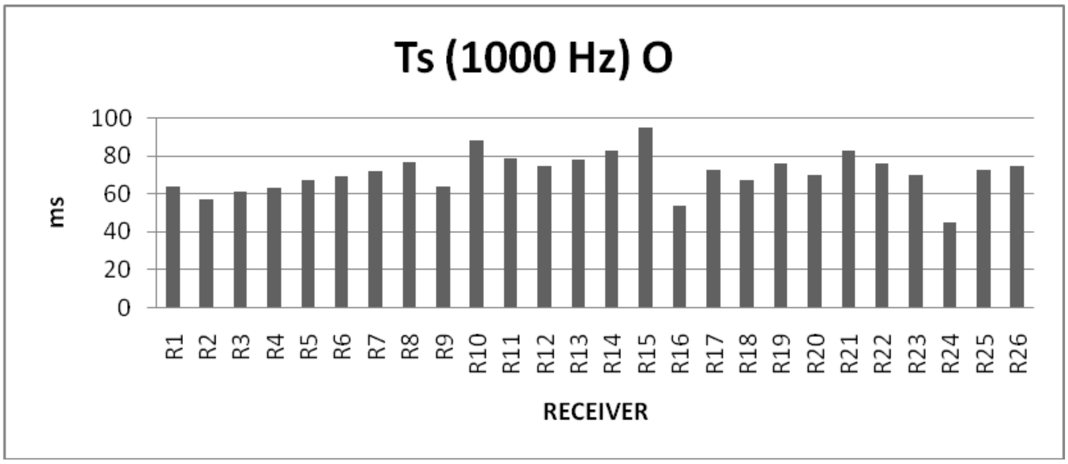


**Figure 64** Ts at 1000 Hz in O

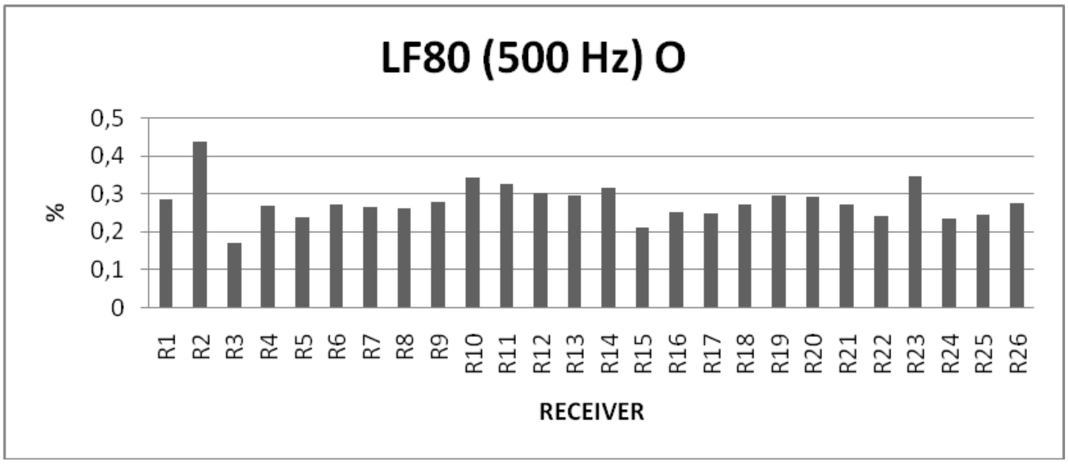


**Figure 65** LF80 at 500 Hz in O

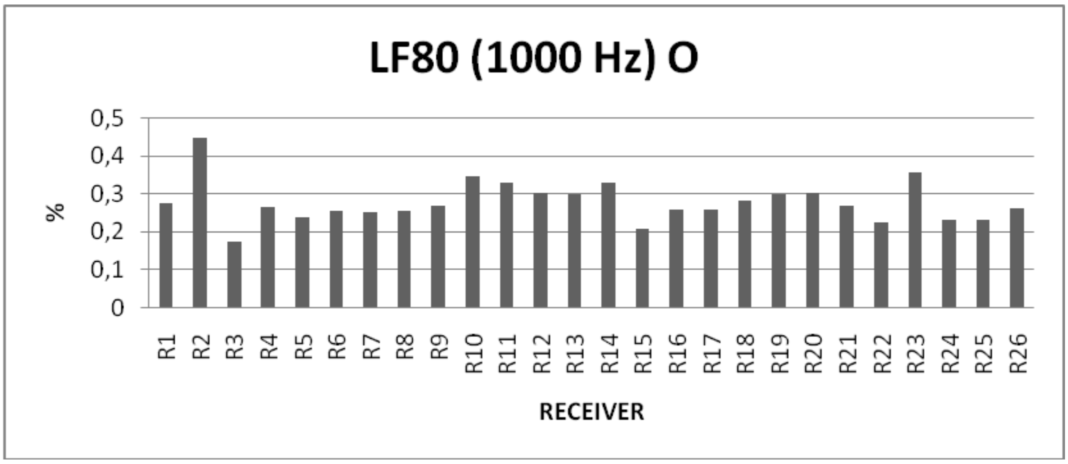


**Figure 66** LF80 at 1000 Hz in O

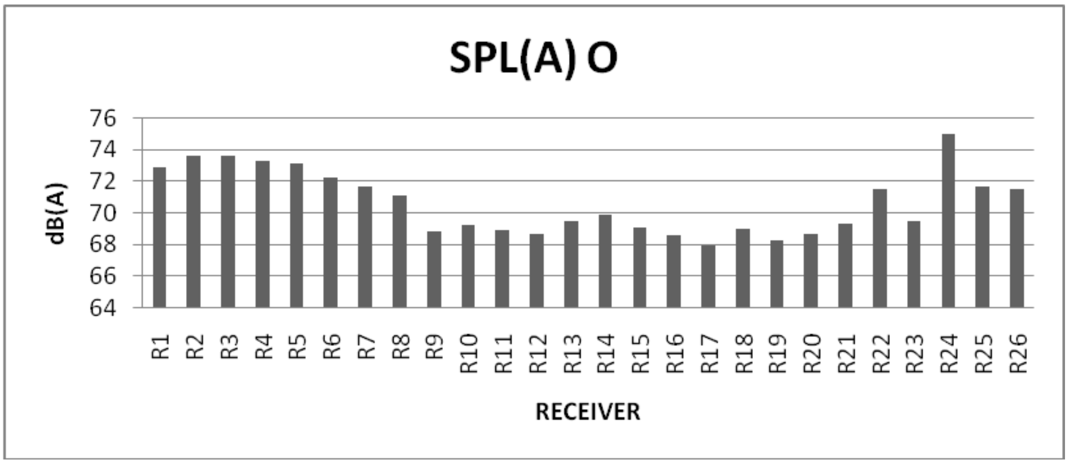


**Figure 67** SPL(A) in O

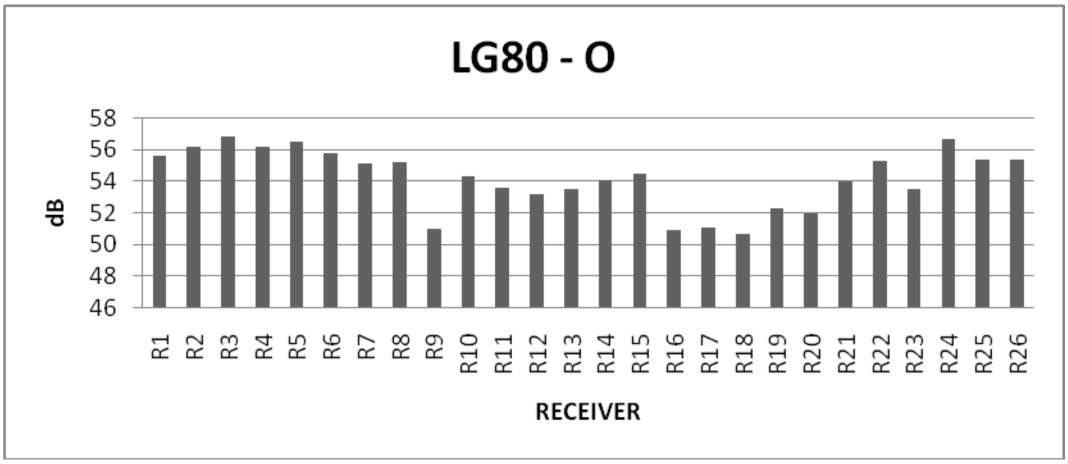


**Figure 68** LG80 in O

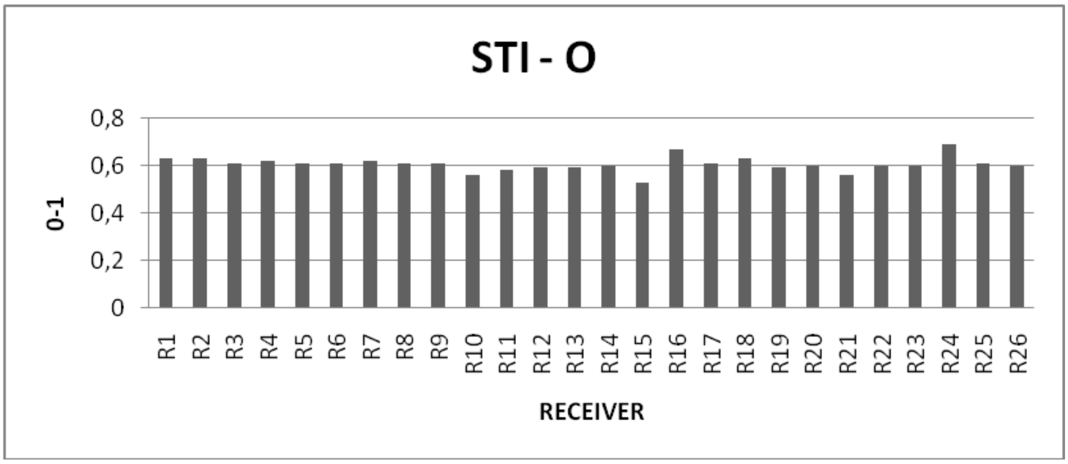


**Figure 69** STI in O

## APPENDIX B

## RESULTS: GRID RESPONSES OF CASE PERFORMANCE HALLS

RHM: Resim Heykel Museum Multipurpose Hall with its original design

RHM (M): Current situation with marble floor

RHM (O): Current situation with orchestra pit open

KT: Küçük Tiyatro Hall
O: Opera/Büyük Tiyatro Hall

### RESİM HEYKEL MÜZESİ MULTIPURPOSE HALL

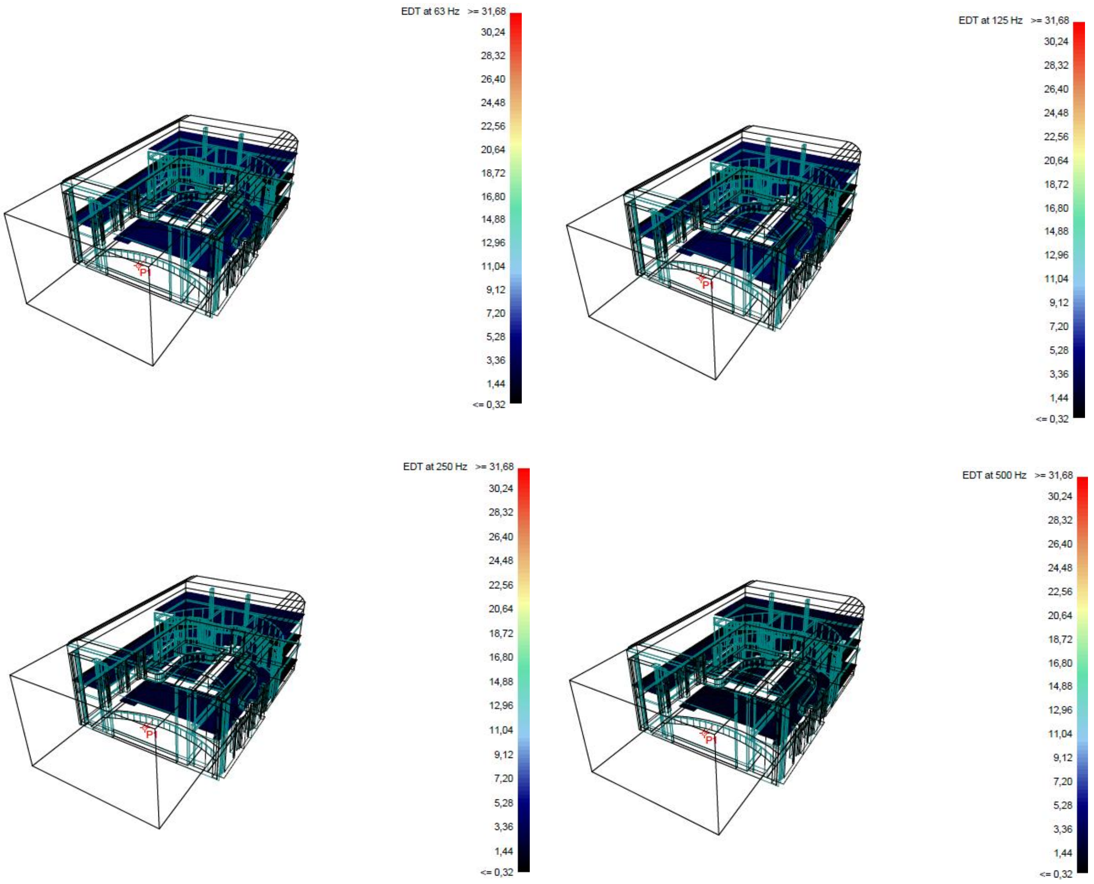


**Figure 70** EDT at 63 Hz, 125 Hz, 250 Hz and 500 Hz (RHM)

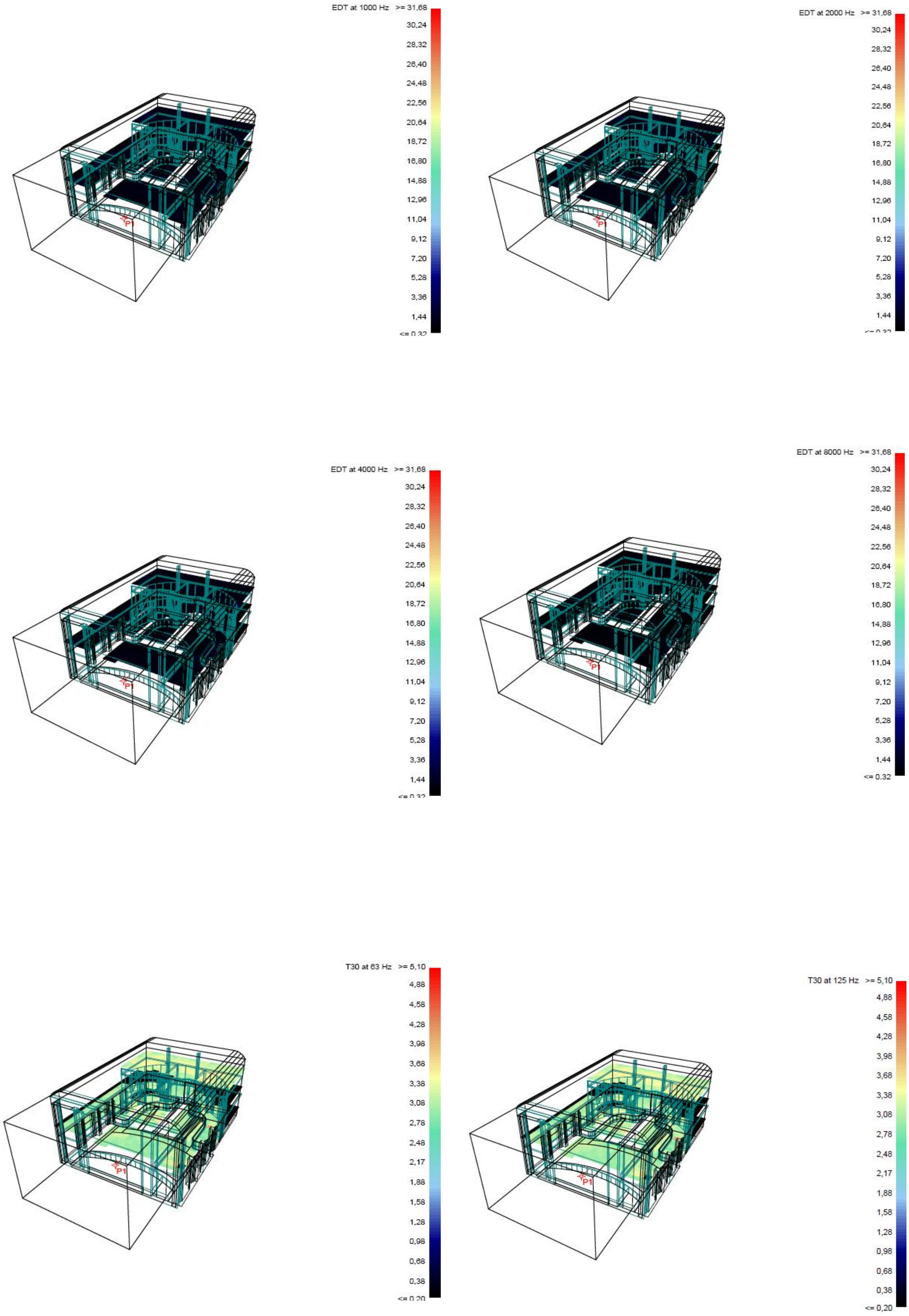


**Figure 71** EDT at 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz
T30 at 63 Hz and 125 Hz (RHM)

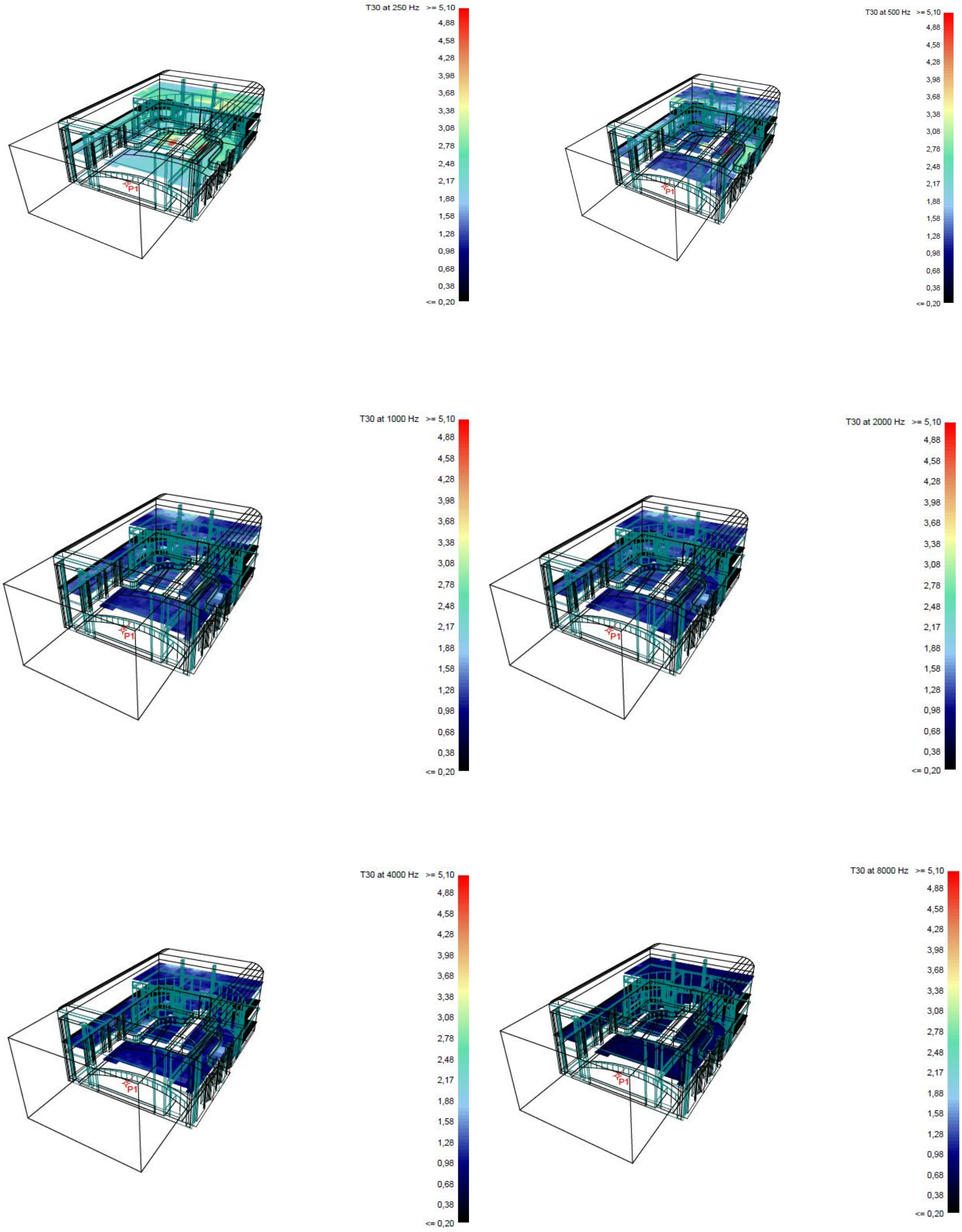


**Figure 72** T30 at 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz (RHM)

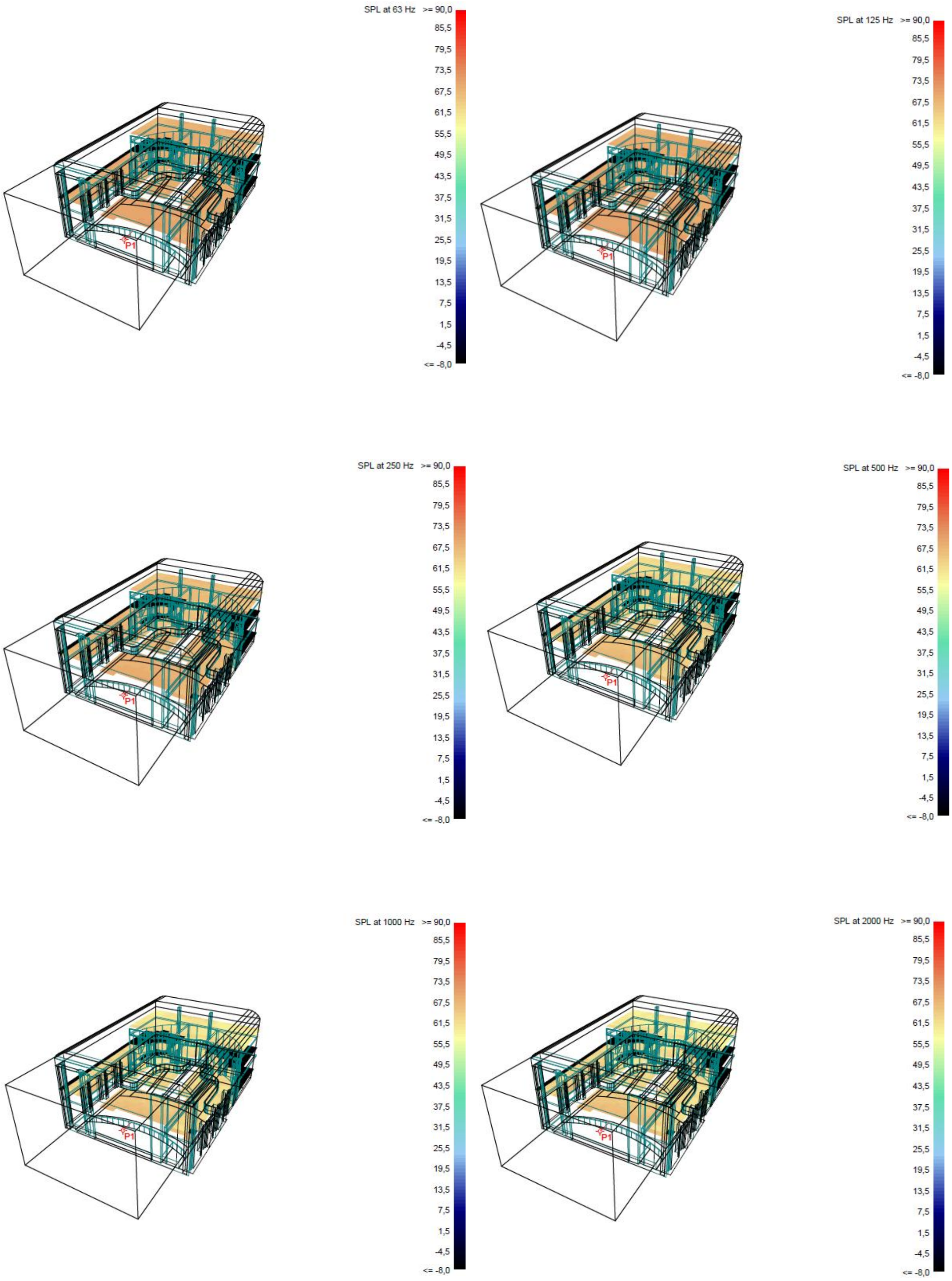


**Figure 73** SPL at 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz and 2000 Hz (RHM)

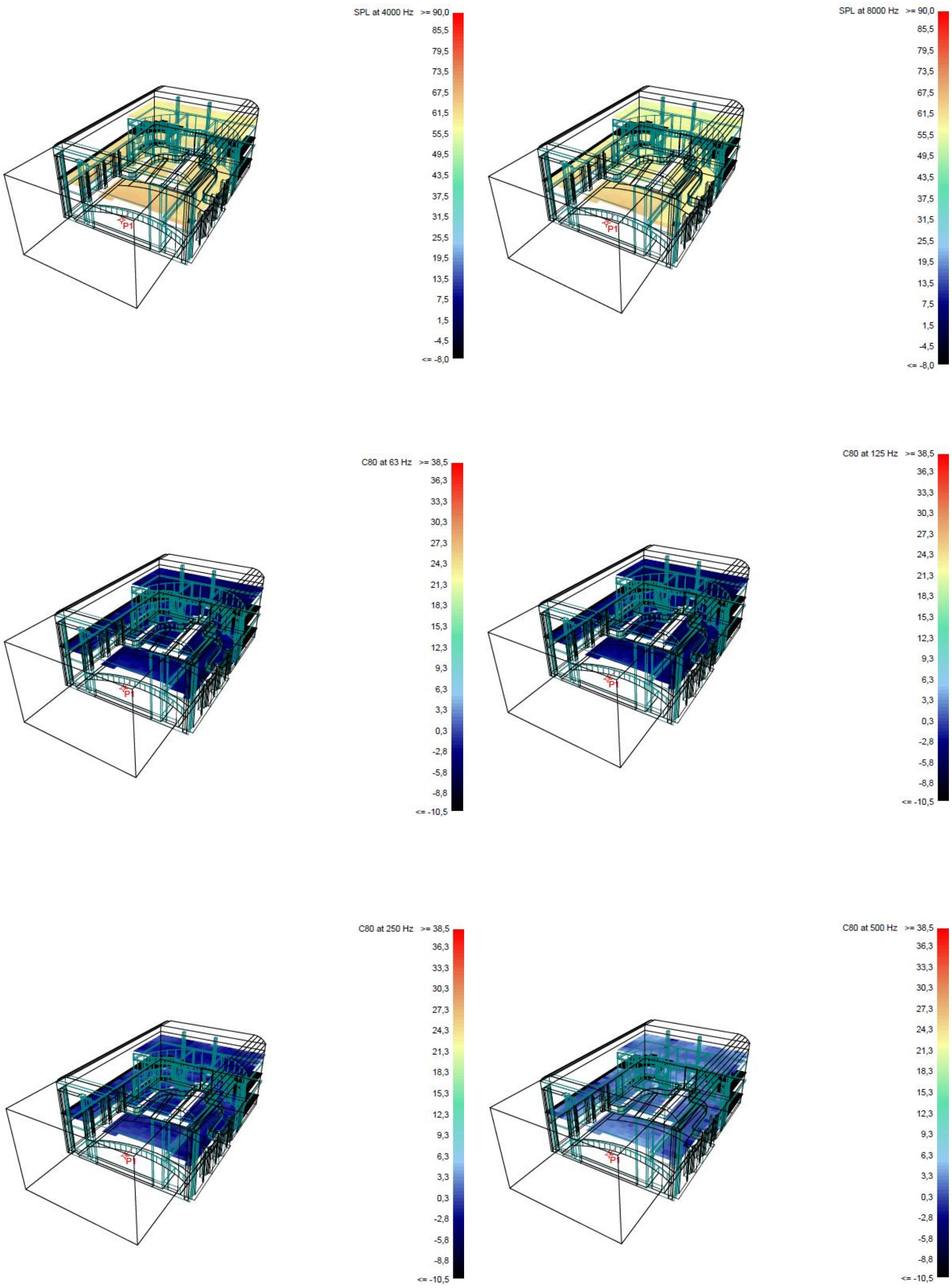


**Figure 74** SPL at 4000 Hz, 8000 Hz
C80 at 63 Hz, 125 Hz, 250 Hz and 500 Hz (RHM)

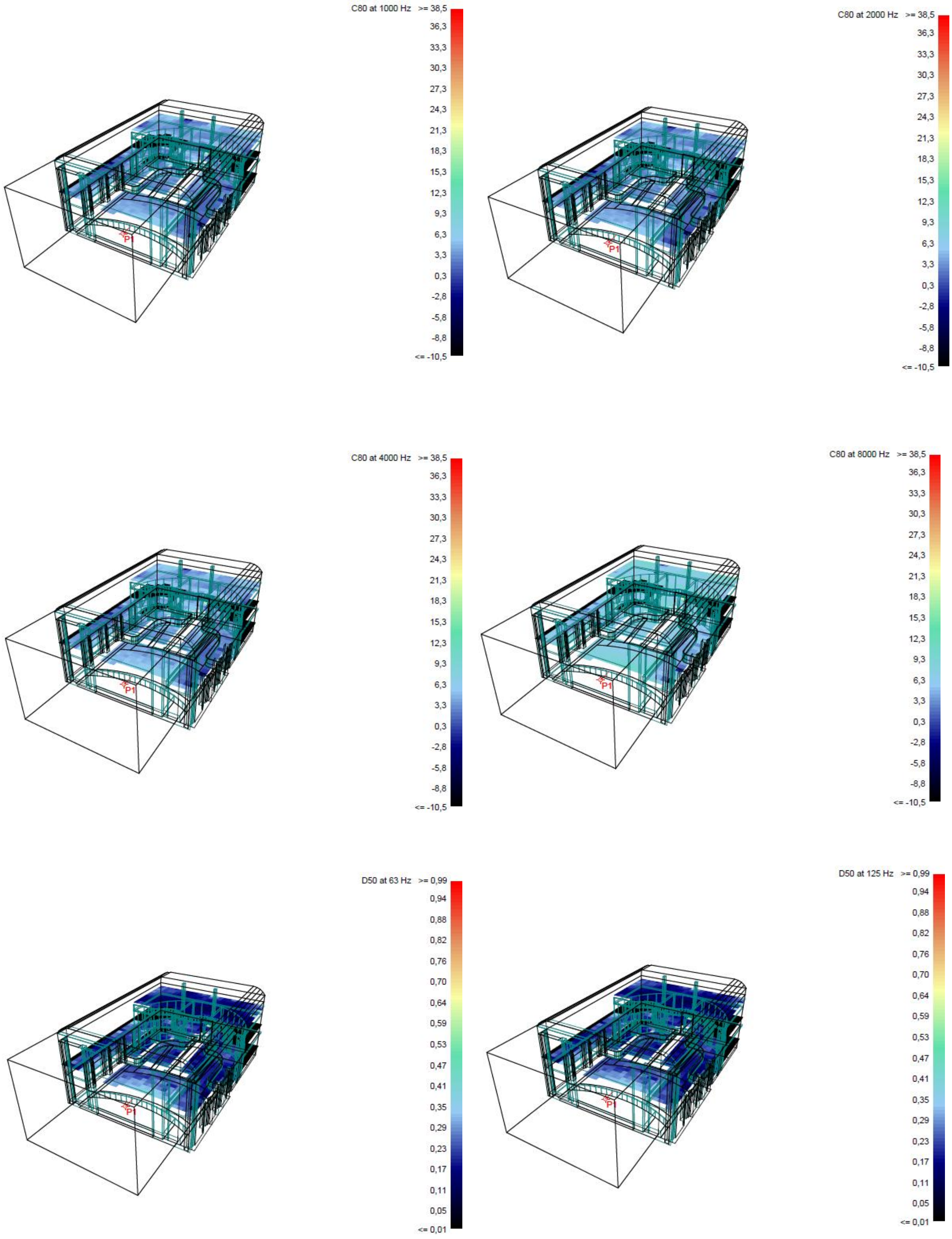


**Figure 75** C80 at 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz

D50 at 63 Hz and 125 Hz (RHM)

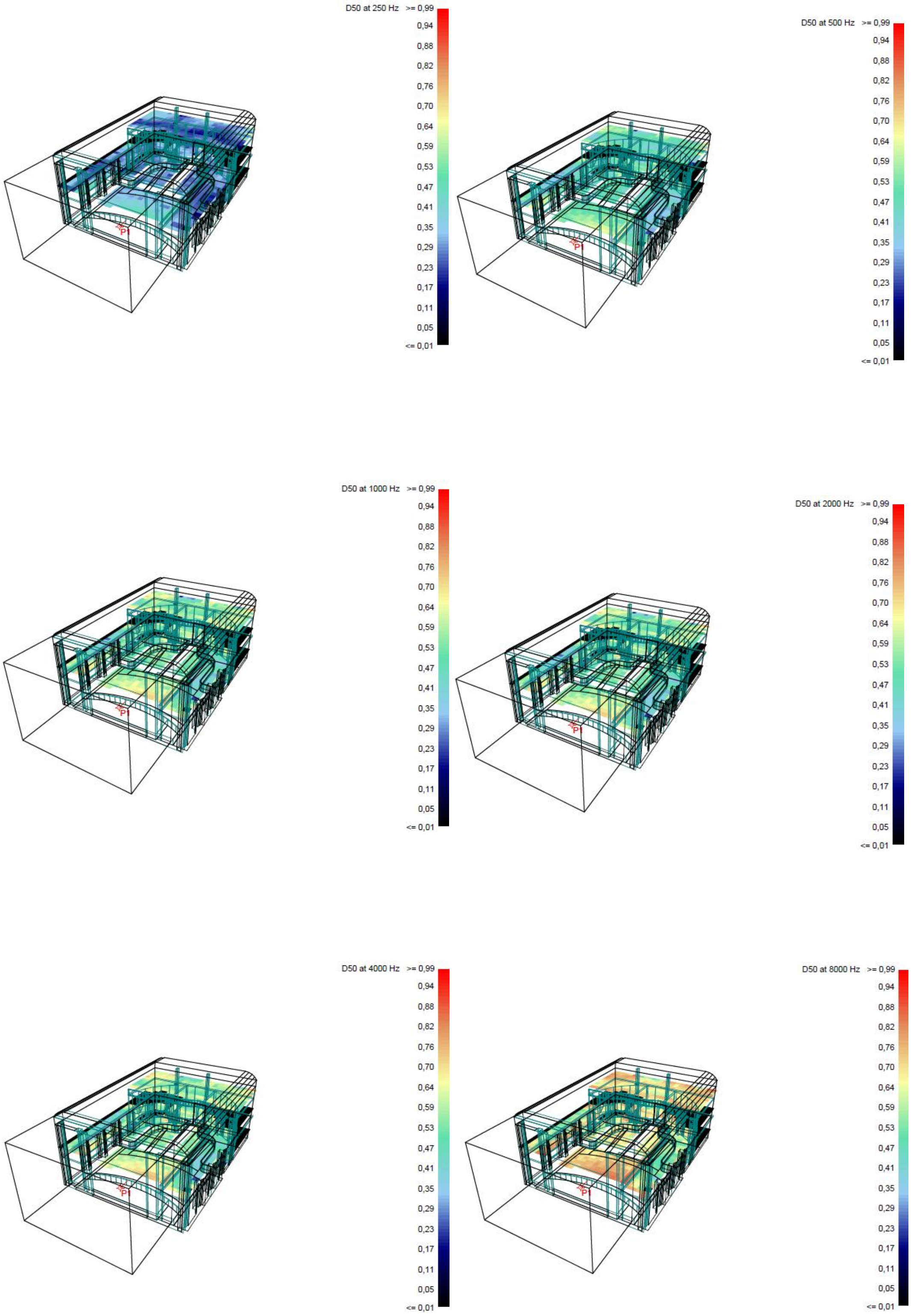


**Figure 76** D50 at 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz (RHM)

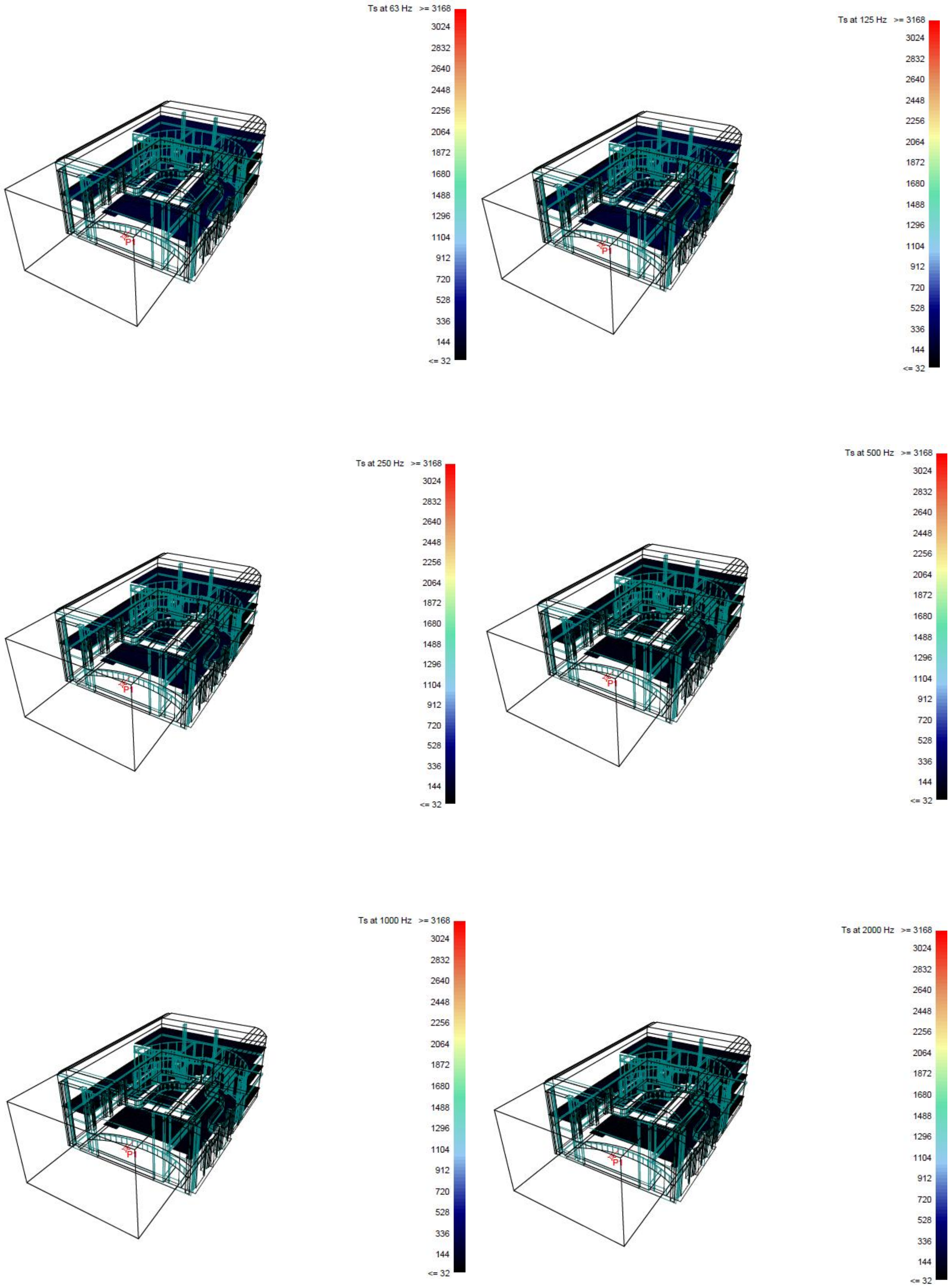


**Figure 77** Ts at 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz and 2000 Hz (RHM)

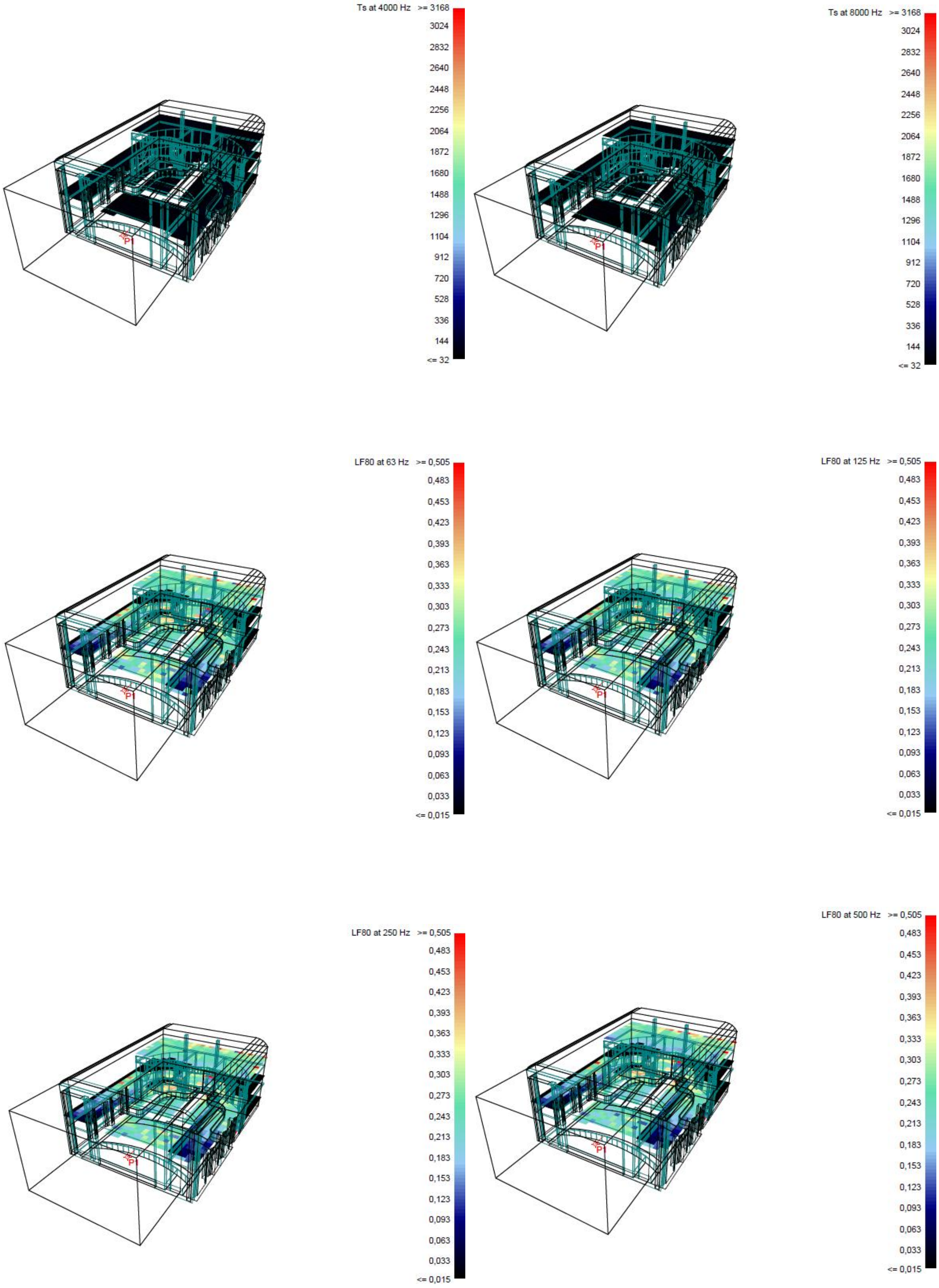


**Figure 78** Ts at 4000 Hz, 8000 Hz

LF80 at 63 Hz, 125 Hz, 250 Hz and 500 Hz (RHM)

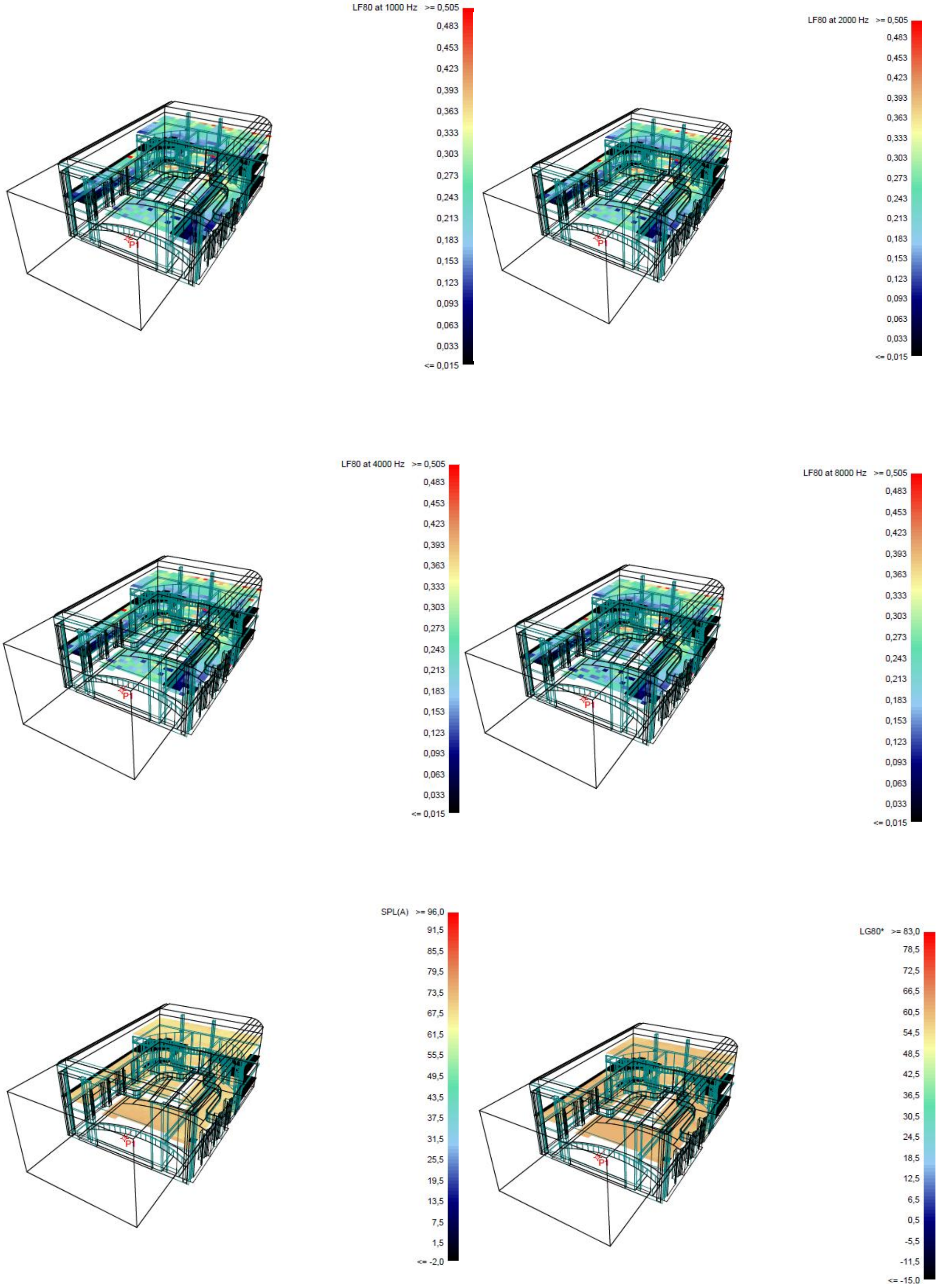


**Figure 79** LF80 at 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz
SPL (A) and LG80 (RHM)

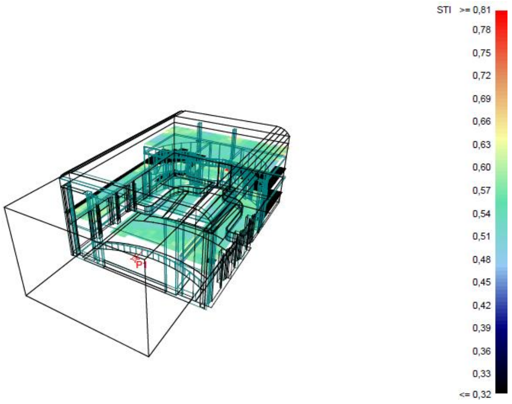


**Figure 80** STI (RHM)

**RHM (M)**

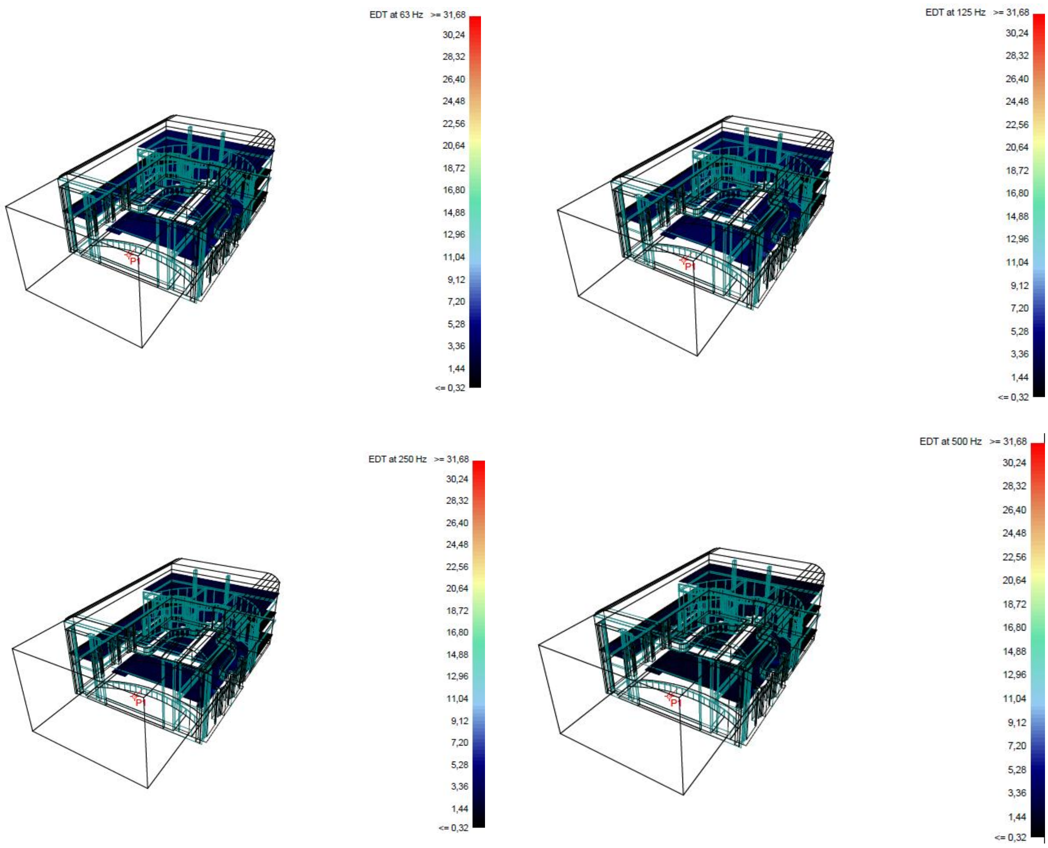


**Figure 81** EDT at 63 Hz, 125 Hz, 250 Hz and 500 Hz (RHM (M))

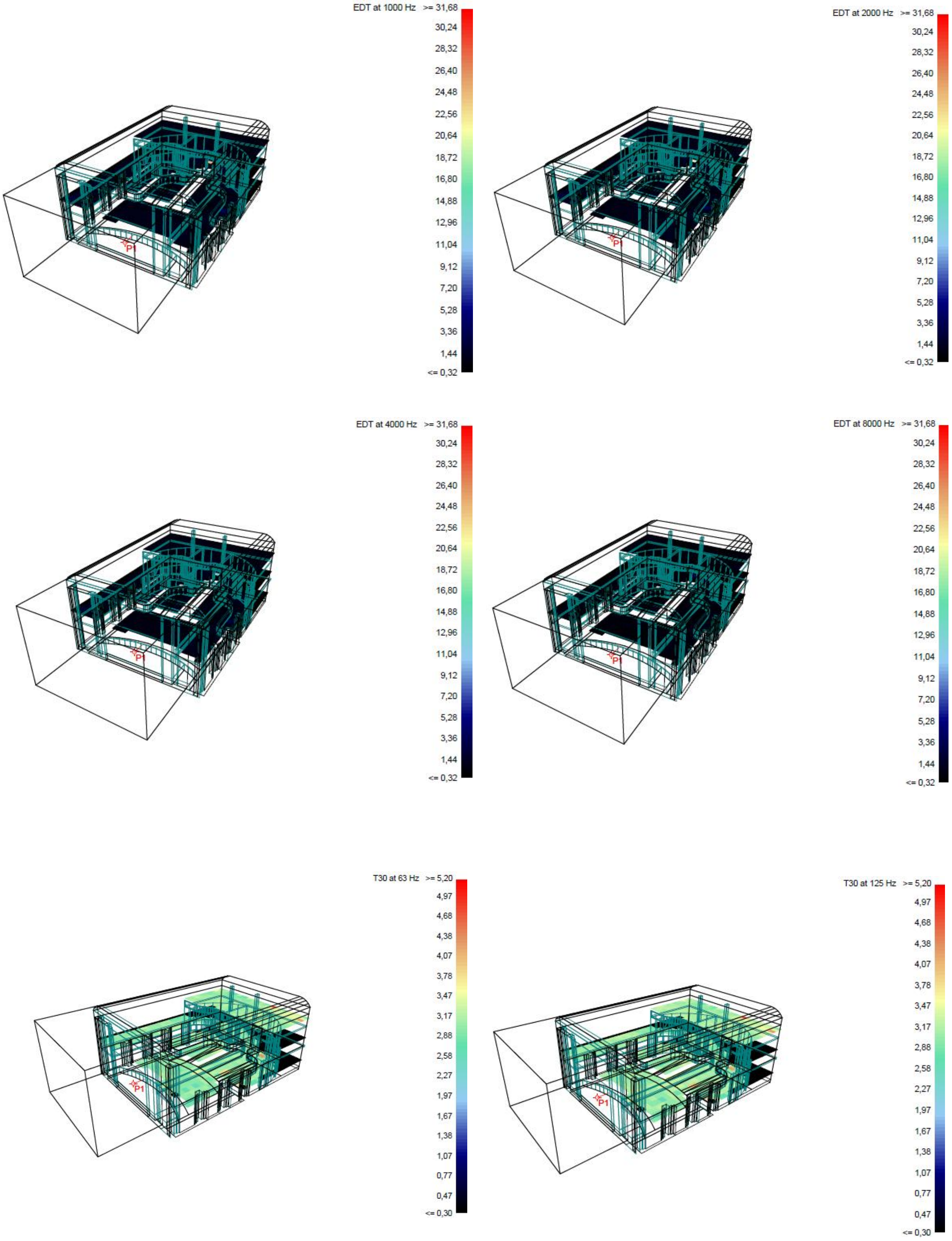


**Figure 82** EDT at 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz
T30 at 63 Hz and 125 Hz (RHM (M))

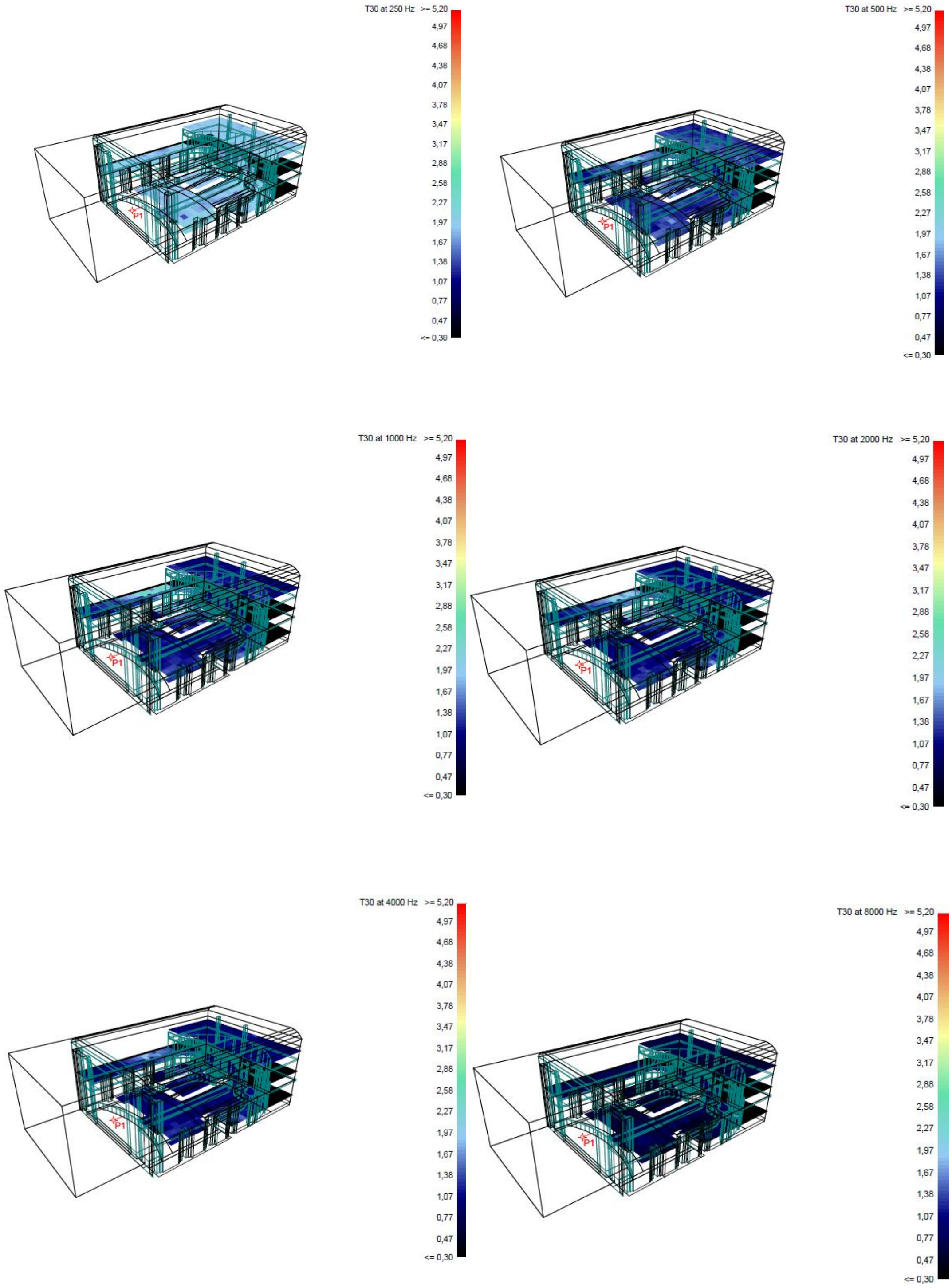


**Figure 83** T30 at 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz (RHM (M))

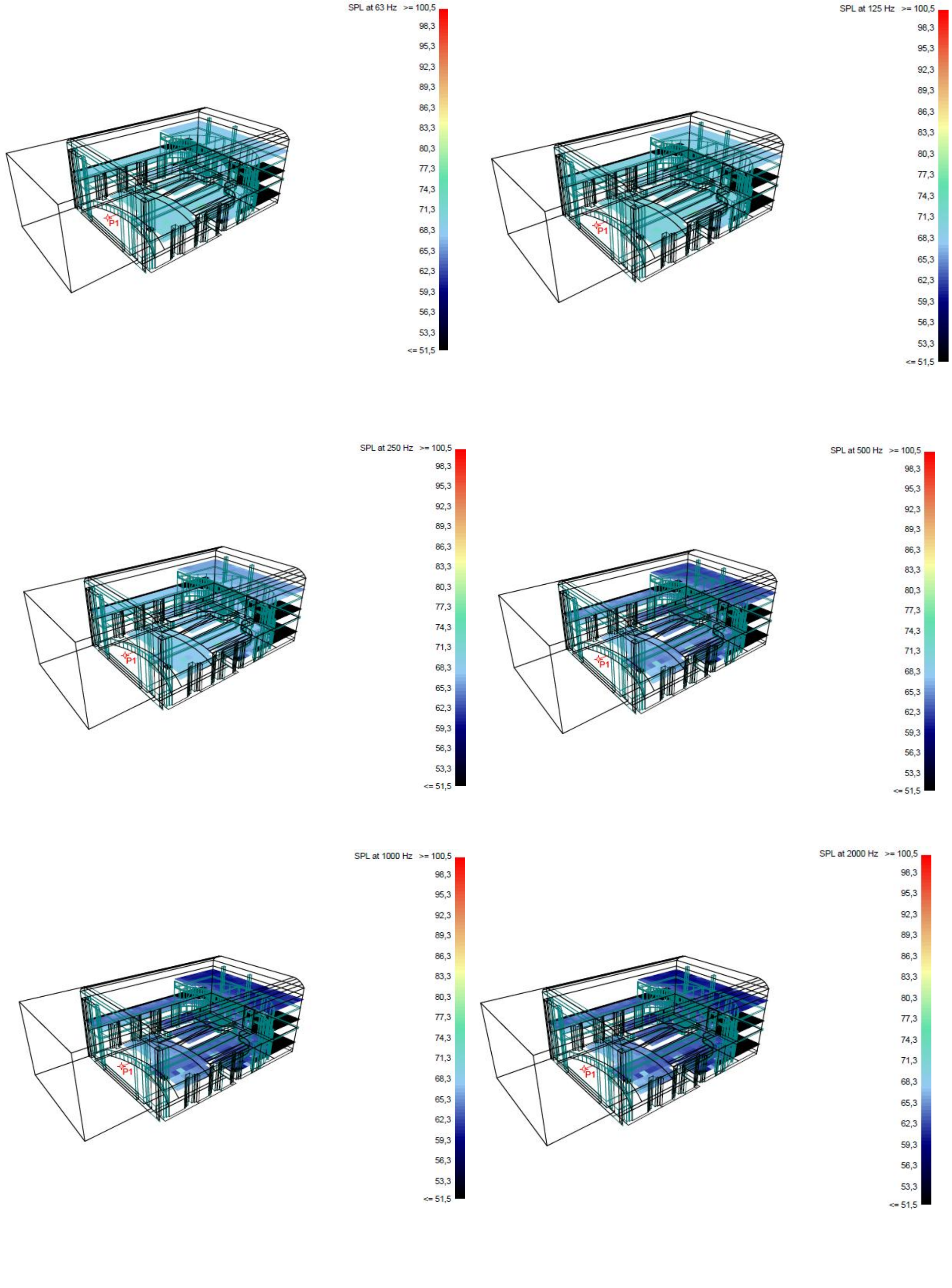


**Figure 84** SPL at 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz and 2000 Hz (RHM (M))

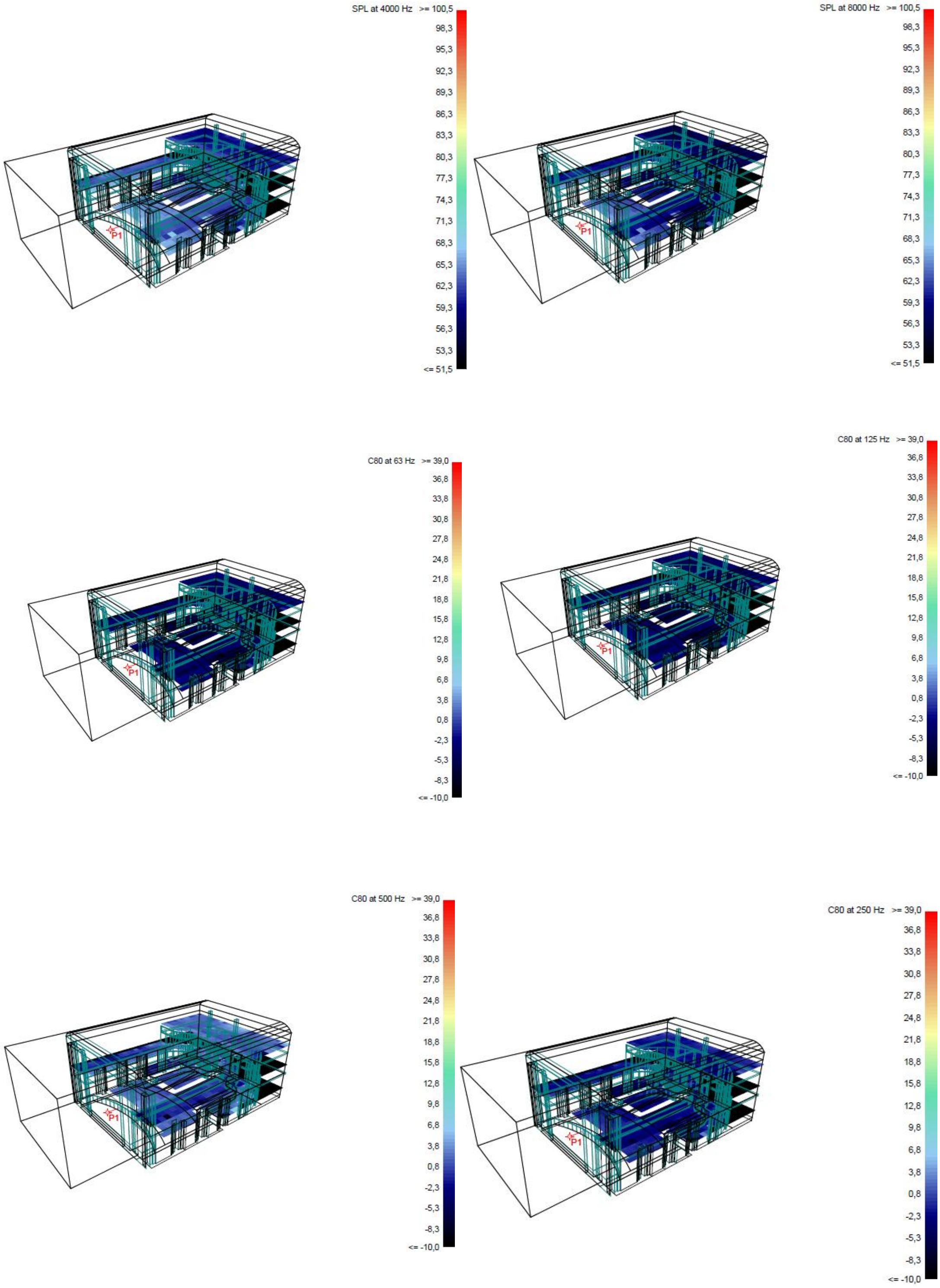


**Figure 85** SPL at 4000 Hz and 8000 Hz
C80 at 63 Hz, 125 Hz, 250 Hz and 500 Hz (RHM (M))

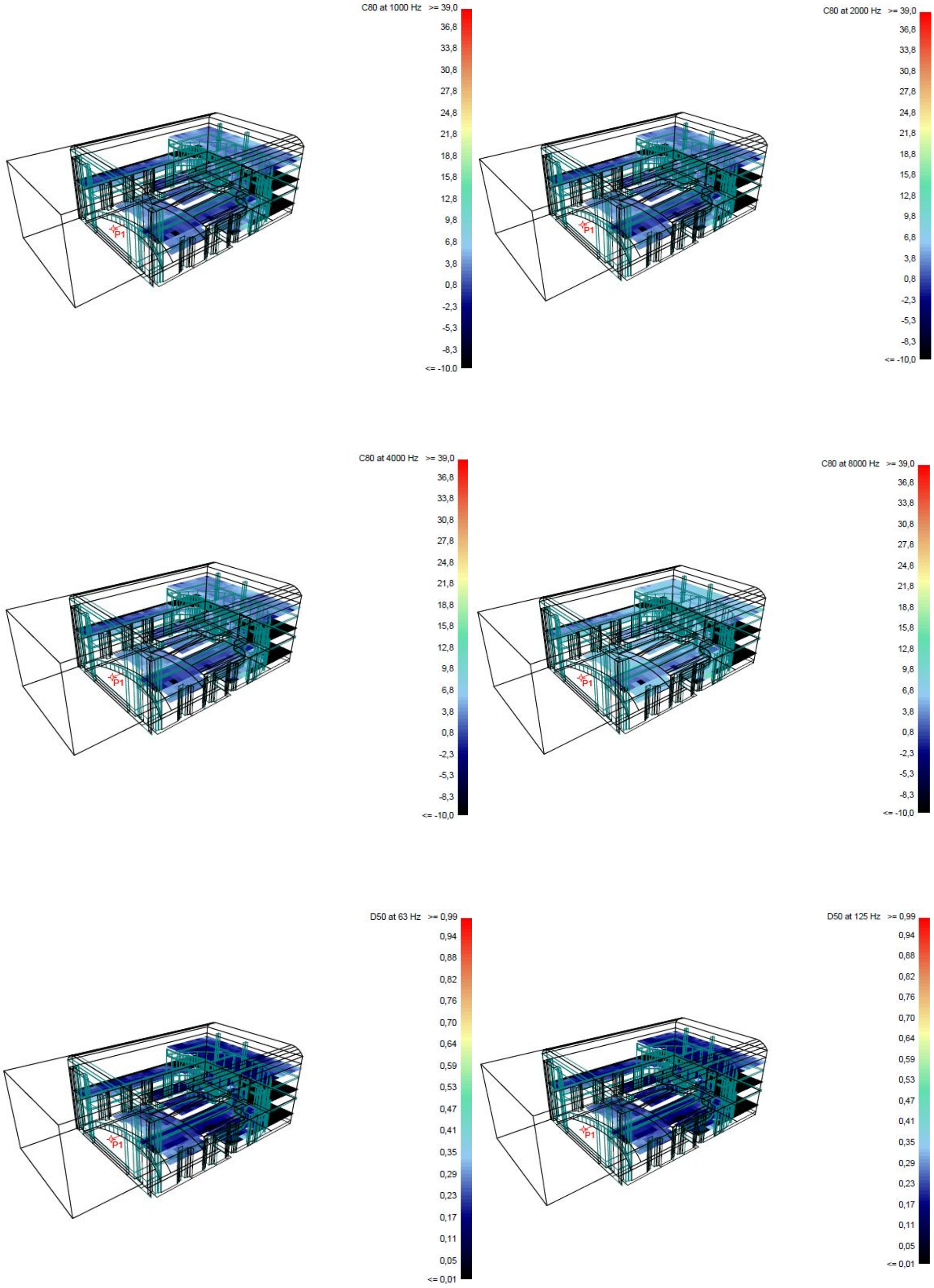


**Figure 86** C80 at 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz

D50 at 63 Hz and D50 at 125 Hz (RHM (M))

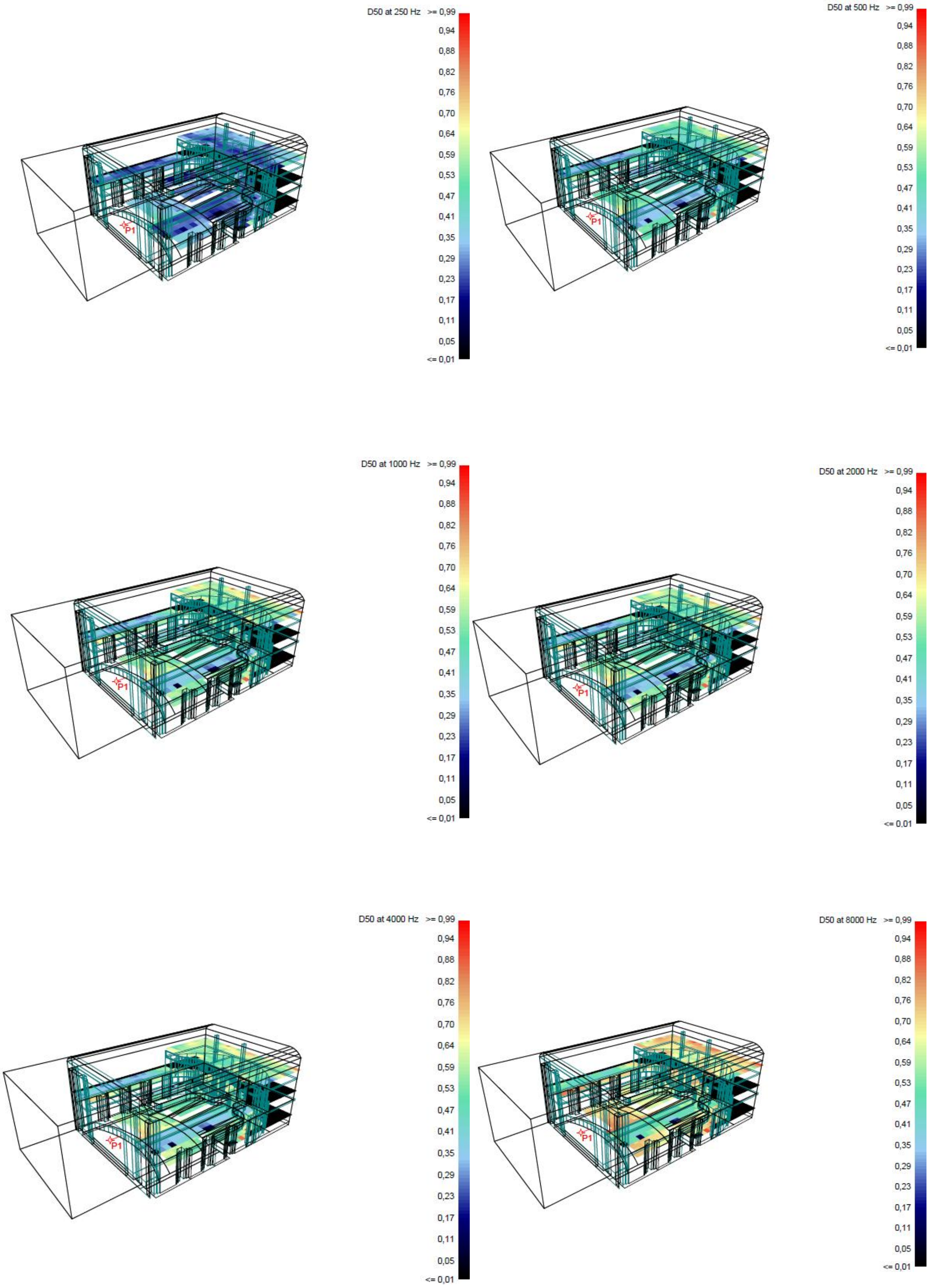


**Figure 87** D50 at 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz (RHM (M))

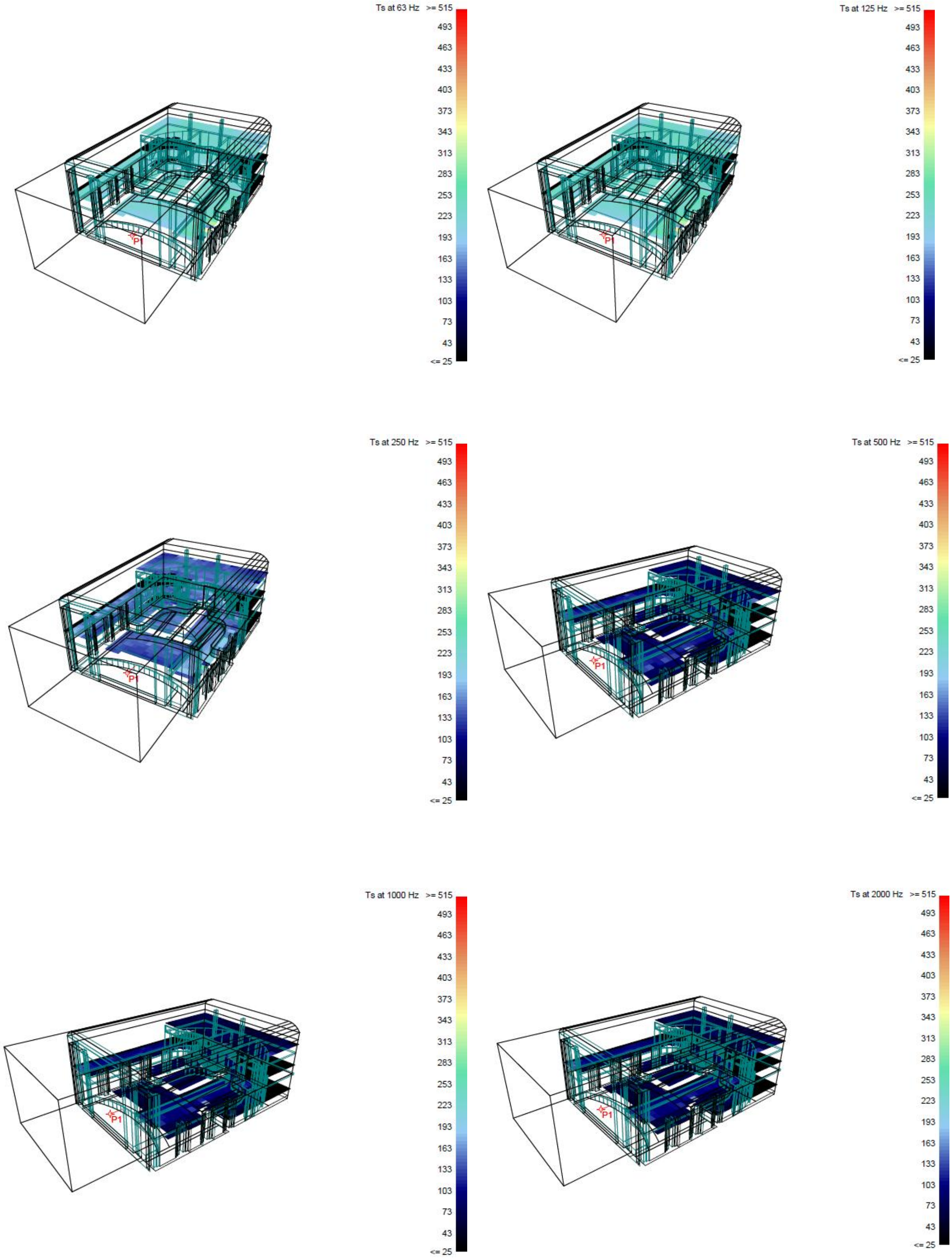


**Figure 88** Ts at 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz (RHM (M))

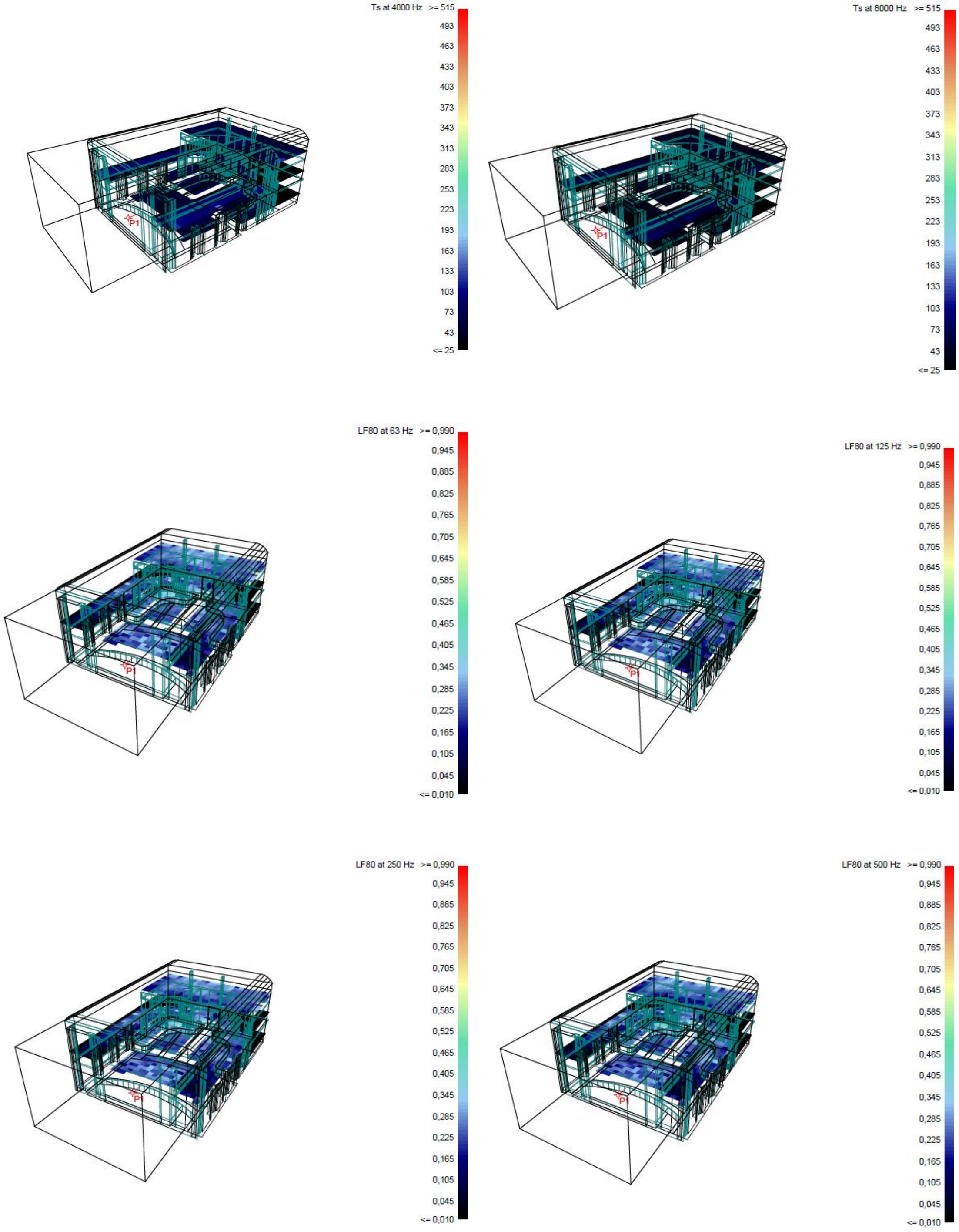


**Figure 89** Ts at 4000 Hz and 8000 Hz
LF80 at 63 Hz, 125 Hz, 250 Hz and 500 Hz (RHM (M))

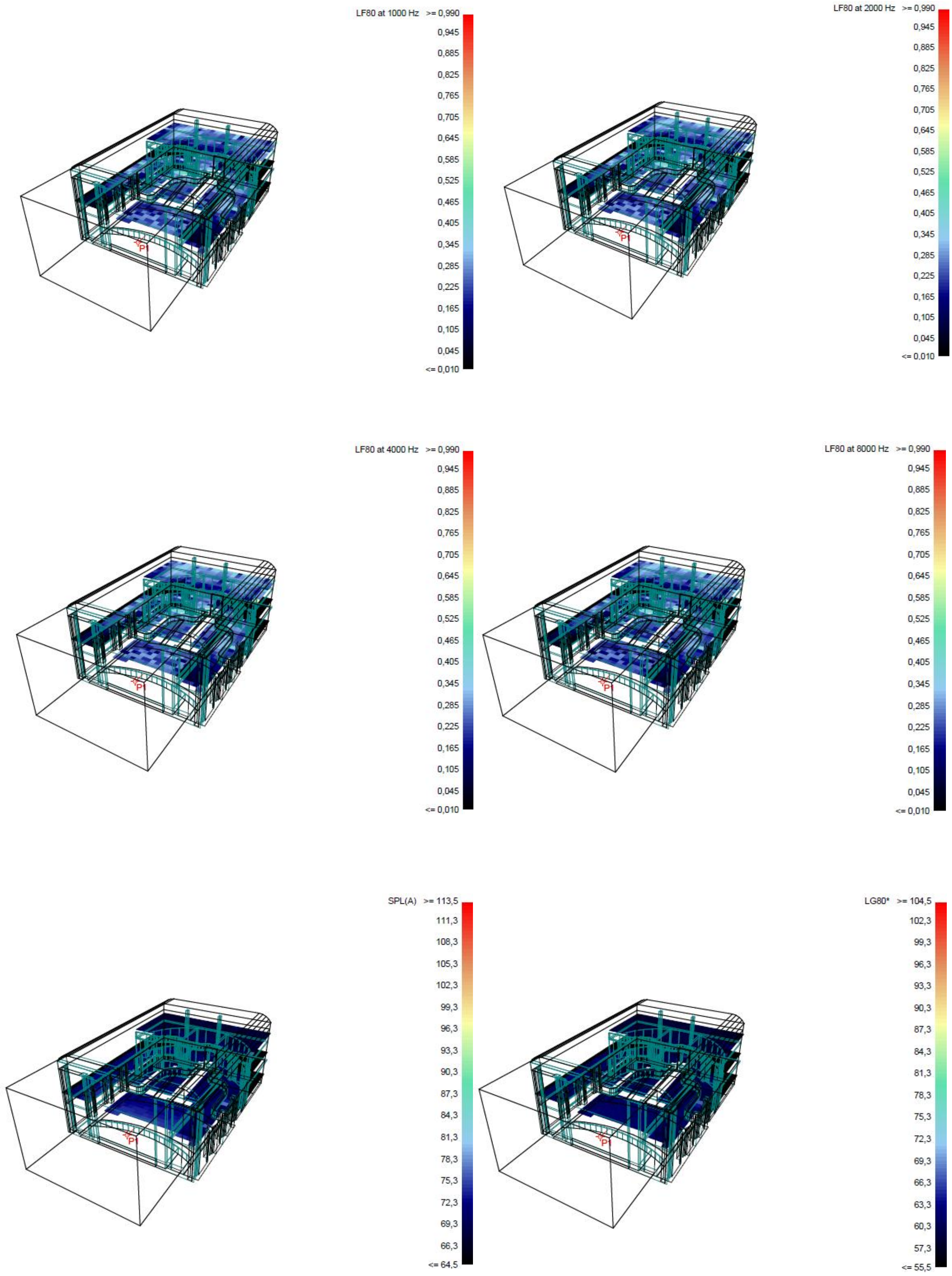


**Figure 90** LF80 at 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz
SPL(A), LG80 (RHM (M))

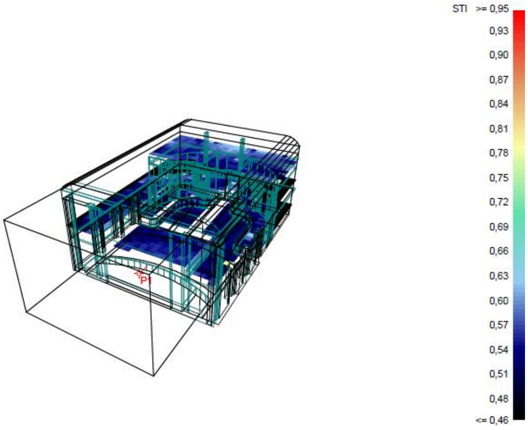


**Figure 91** STI (RHM (M))

**RHM (O)**

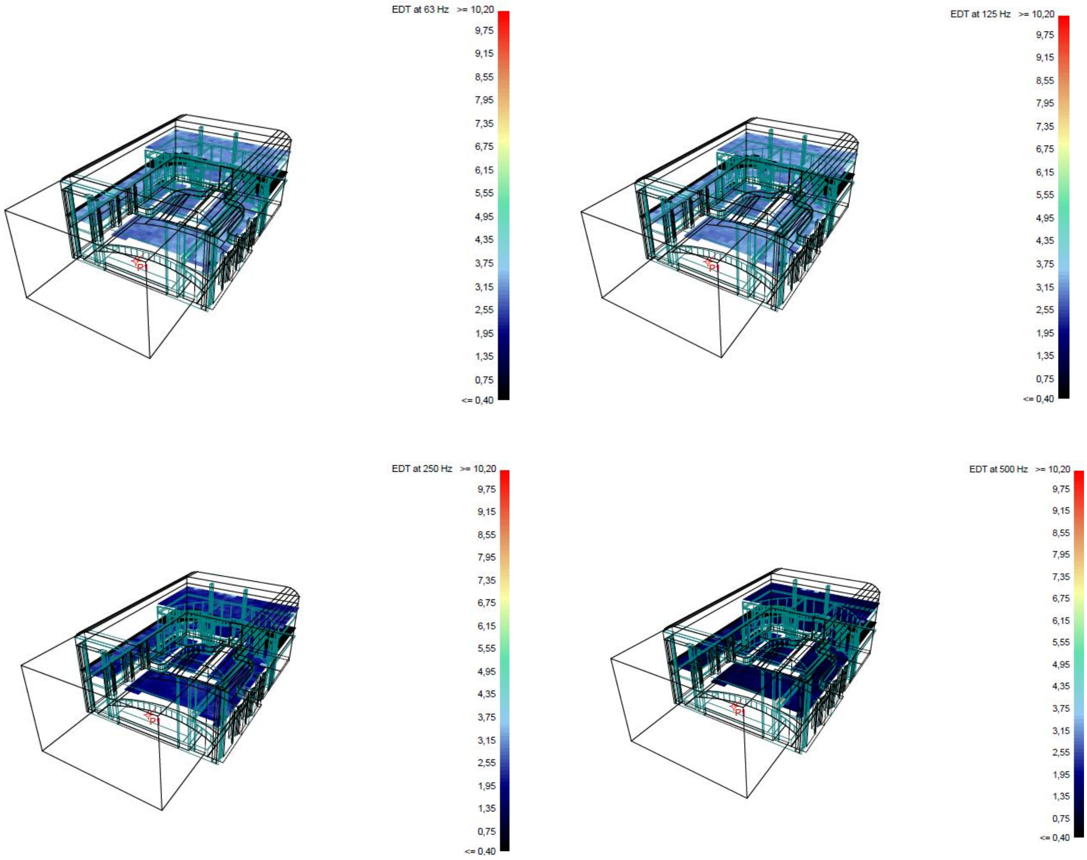


**Figure 92** EDT at 63 Hz, 125 Hz, 250 Hz and 500 Hz (RHM (O))

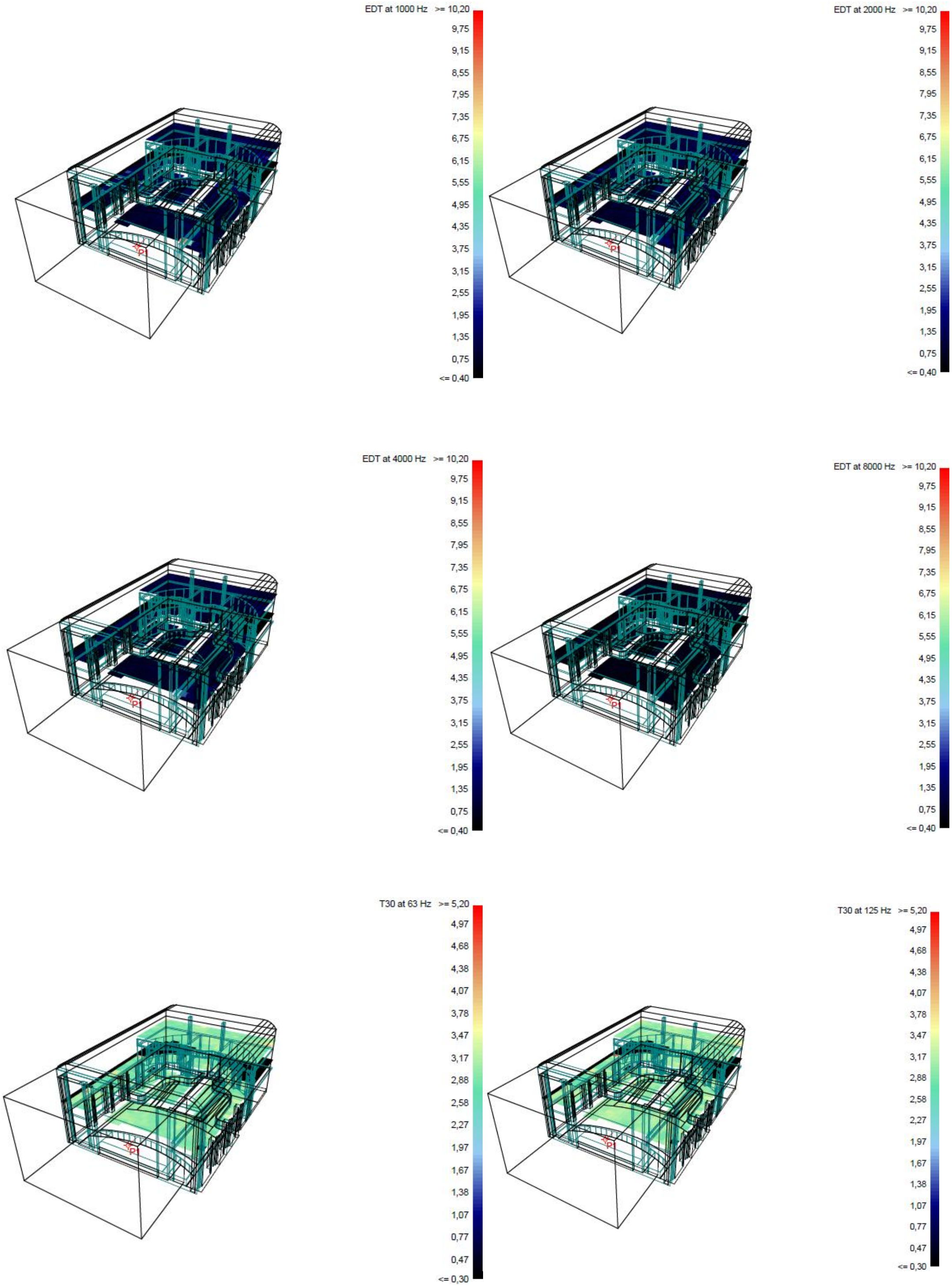


**Figure 93** EDT at 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz

T30 at 63 Hz and 125 Hz (RHM (O))

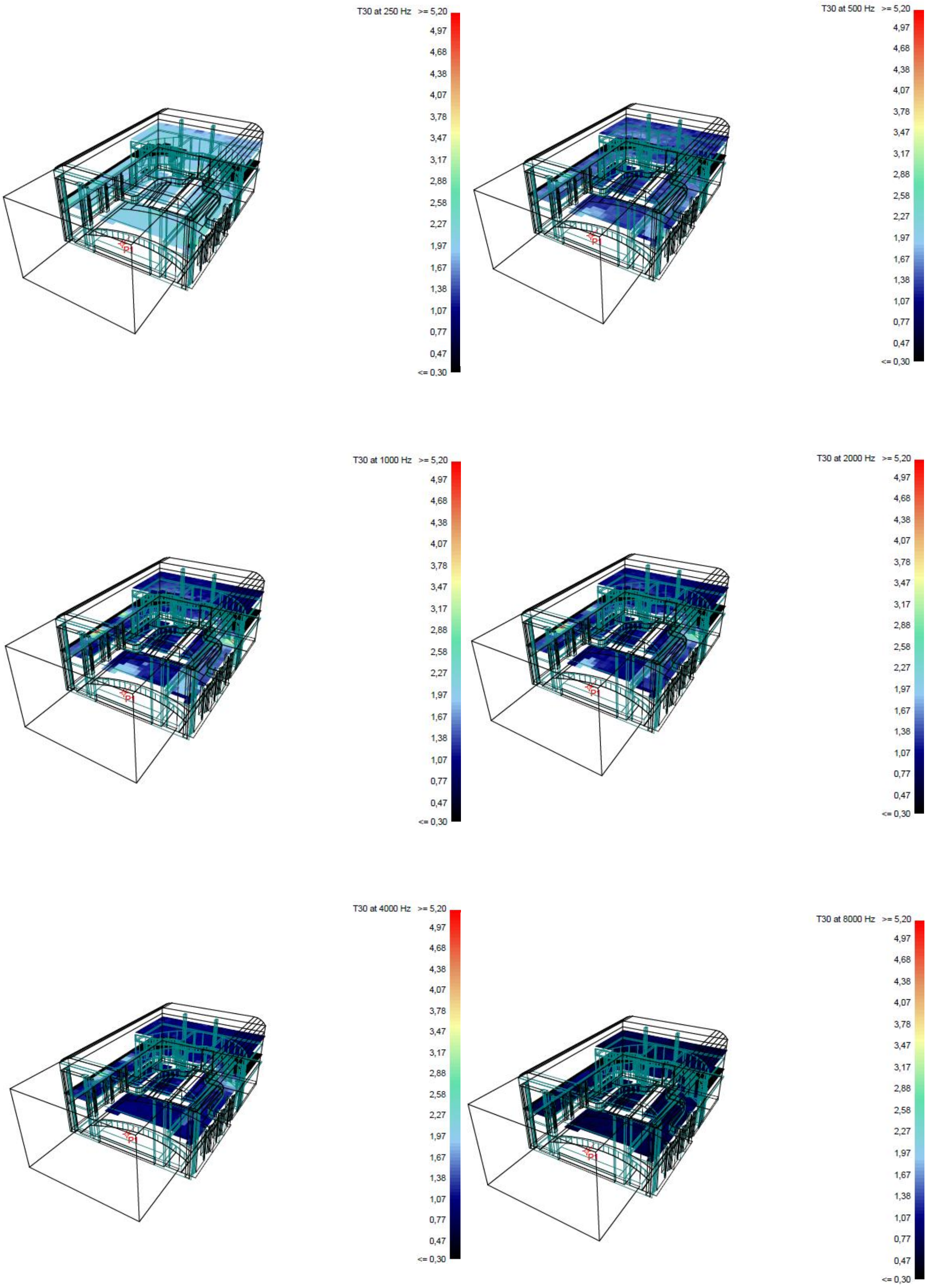


**Figure 94** T30 at 250Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz (RHM (O))

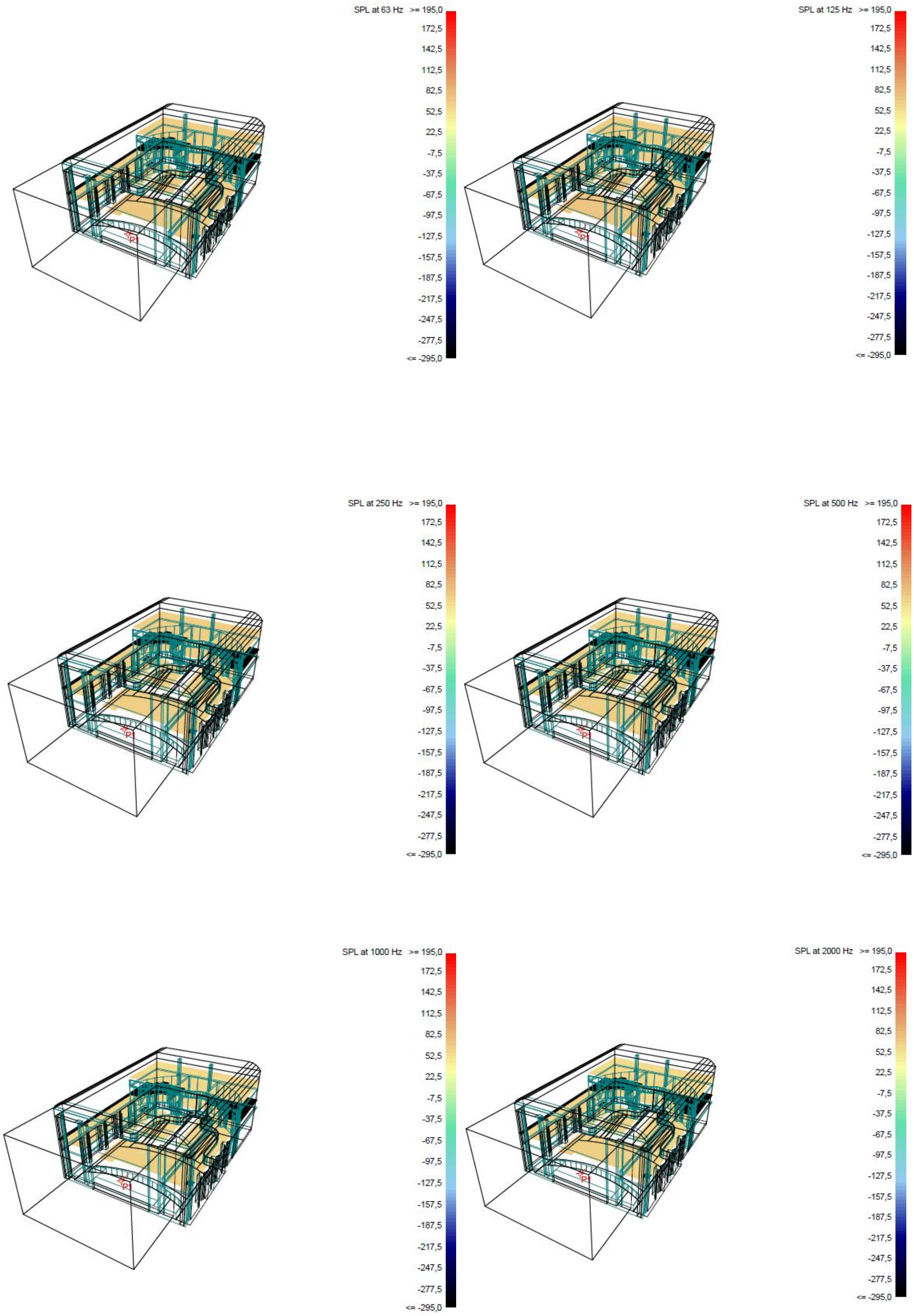


**Figure 95** SPL at 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz and 2000 Hz (RHM (O))

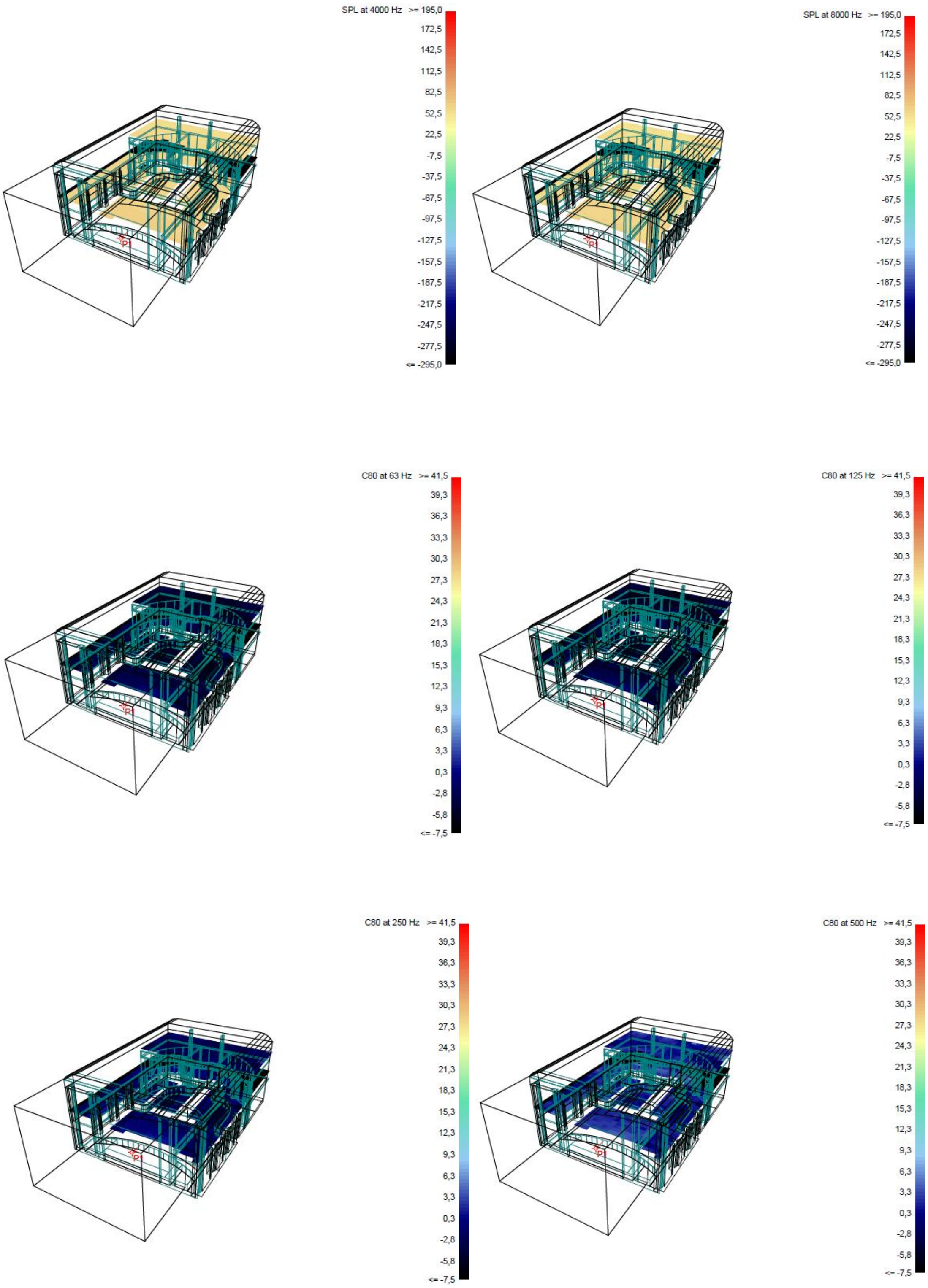


**Figure 96** SPL at 4000 Hz and 8000 Hz

C80 at 63 Hz, 125 Hz, 250 Hz and 500 Hz (RHM (O))

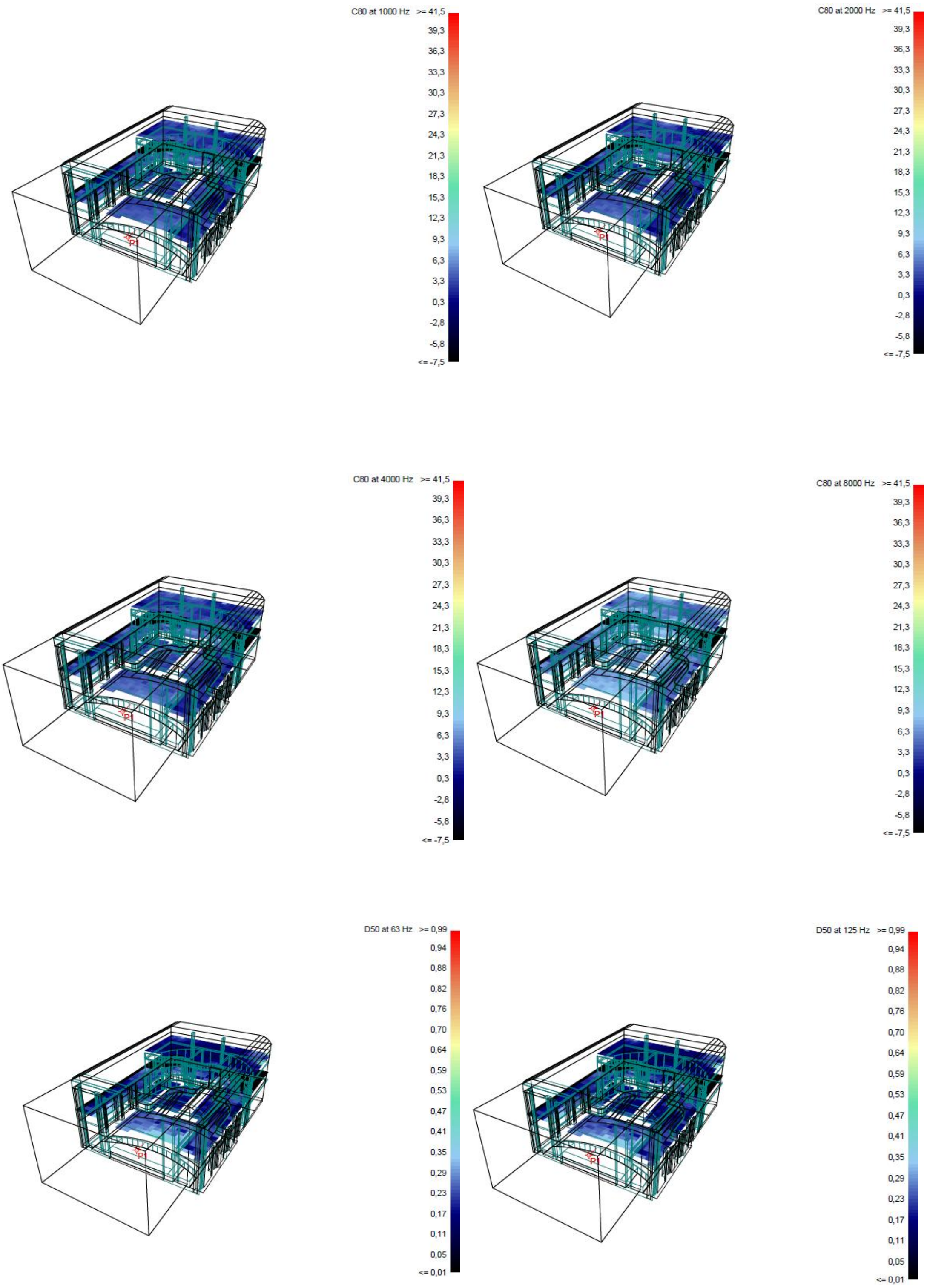


**Figure 97** C80 at 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz
D50 at 63 Hz and D50 at 125 Hz (RHM (O))

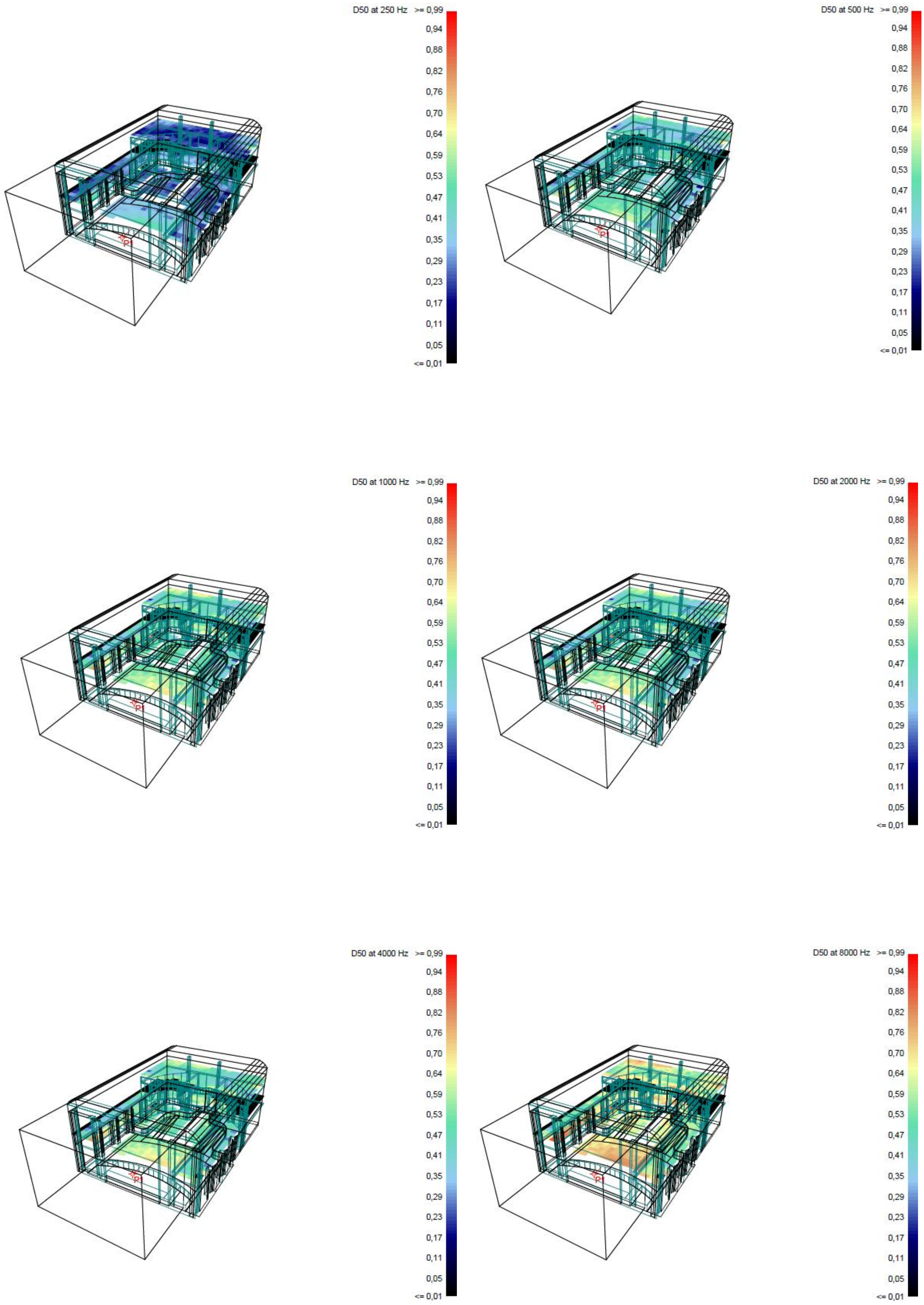


**Figure 98** D50 at 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz (RHM (O))

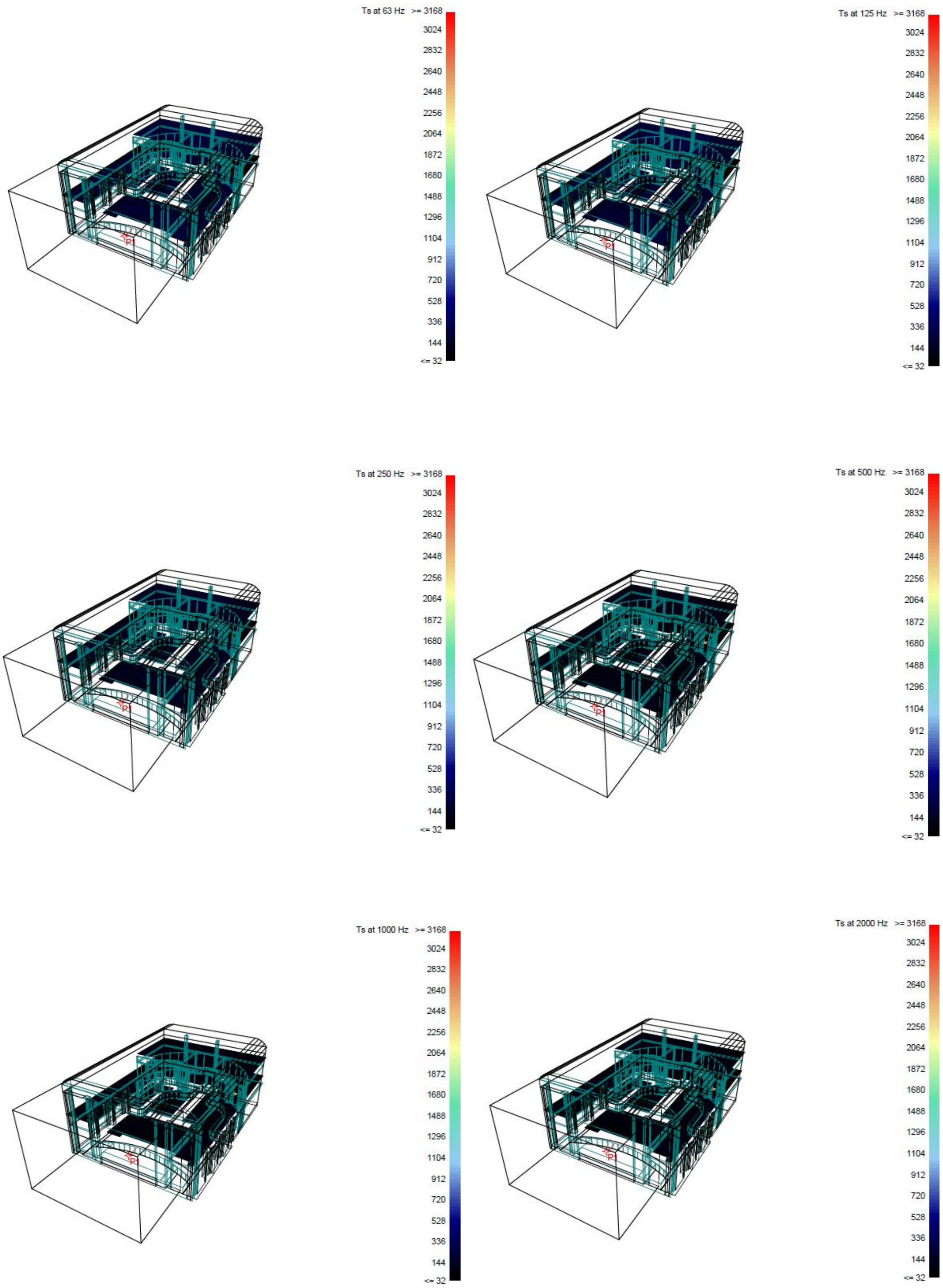


**Figure 99** Ts at 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz and 2000 Hz (RHM (O))

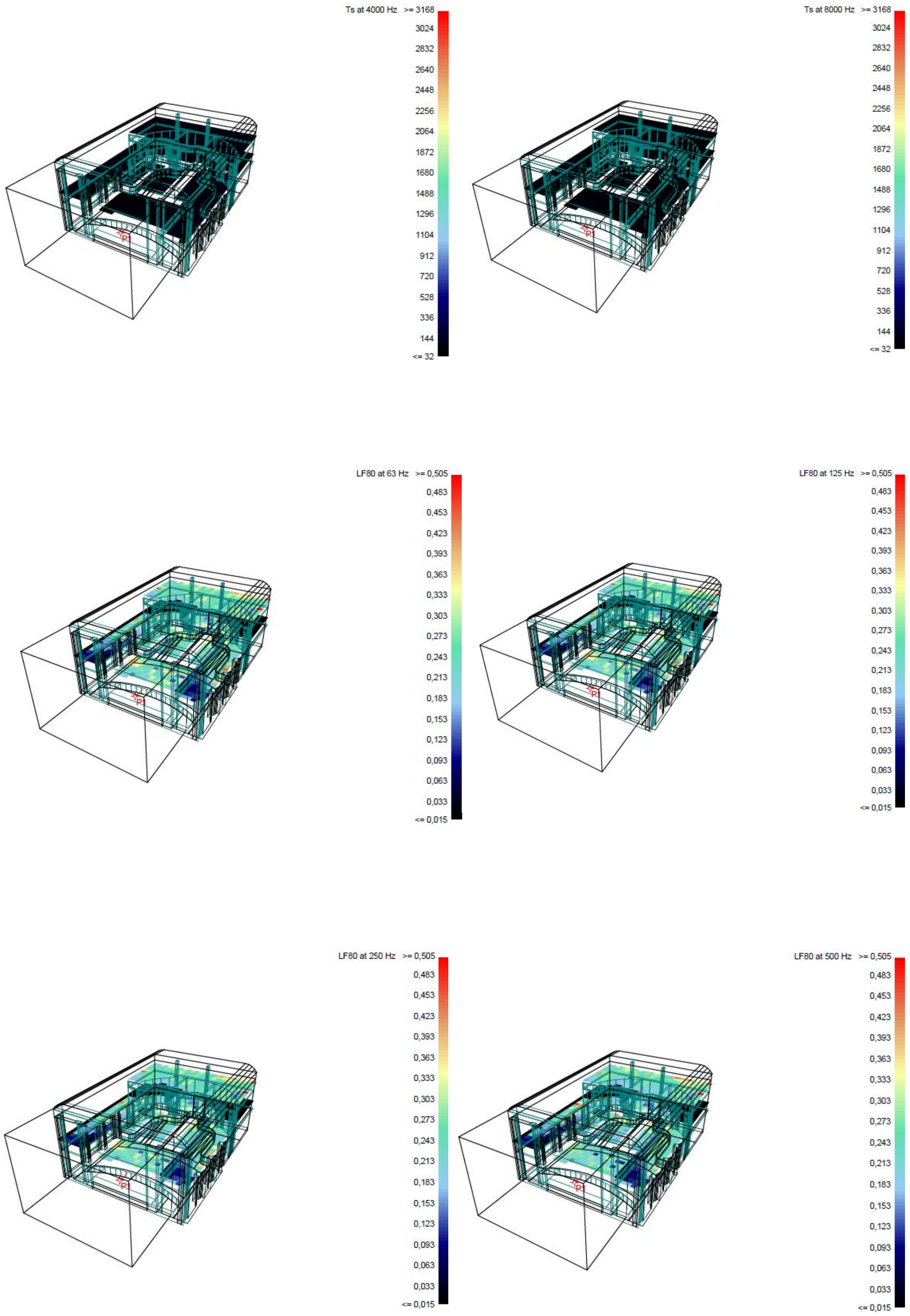


**Figure 100** Ts at 4000 Hz and 8000 Hz

LF80 at 63 Hz, 125 Hz, 250 Hz and 500 Hz (RHM (O))

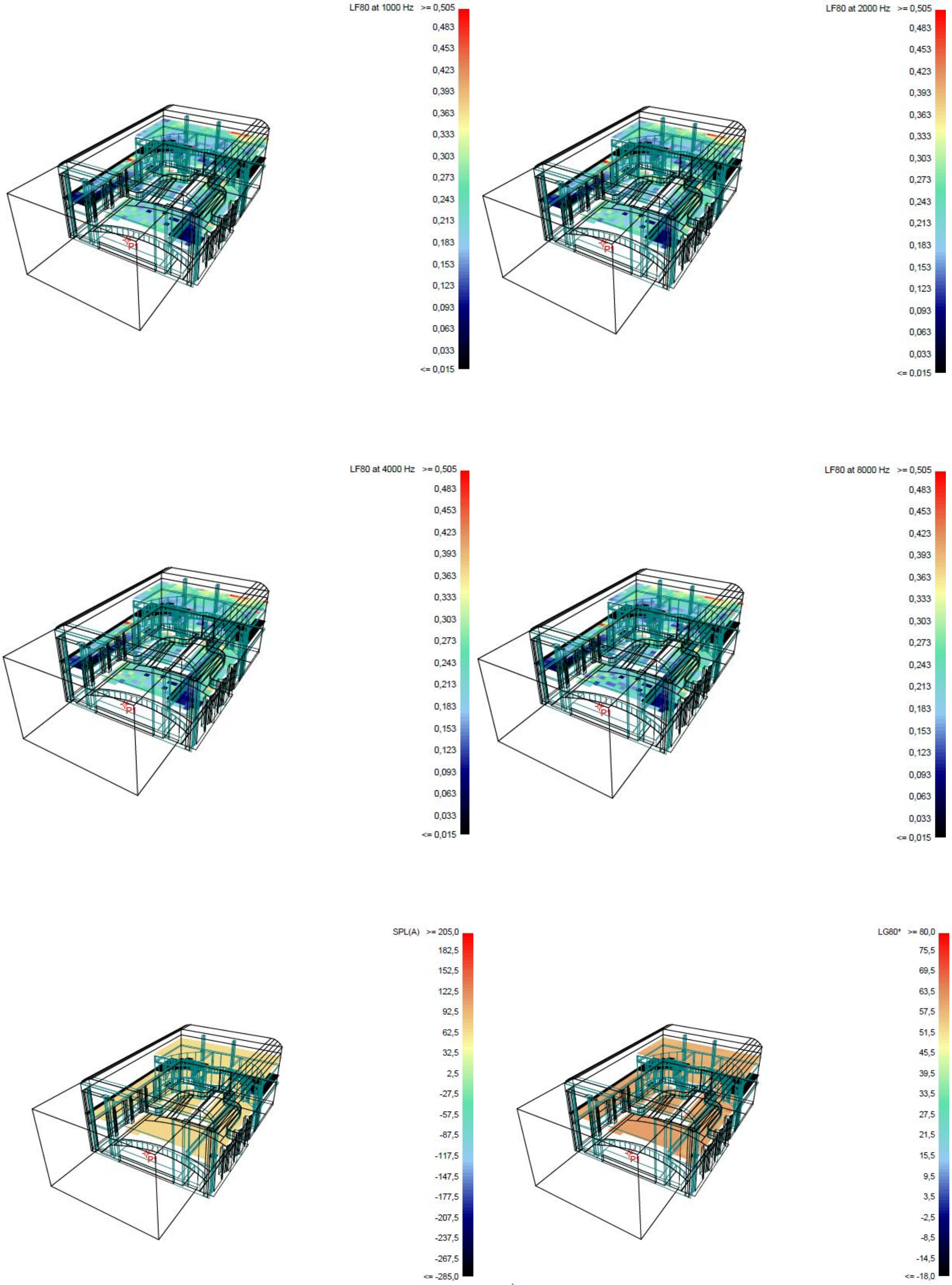


**Figure 101** LF80 at 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz

SPL(A), LG80 (RHM (O))

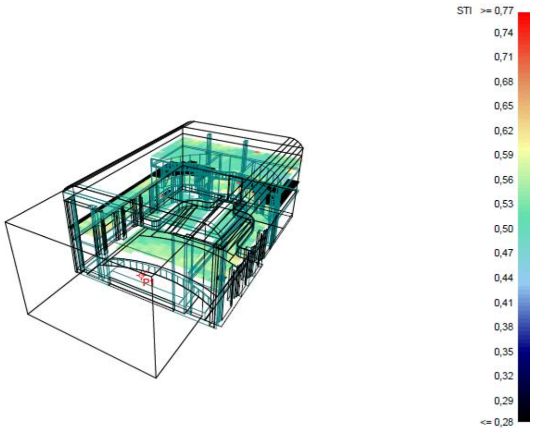


**Figure 102** STI (RHM (O))

## KÜÇÜK TİYATRO

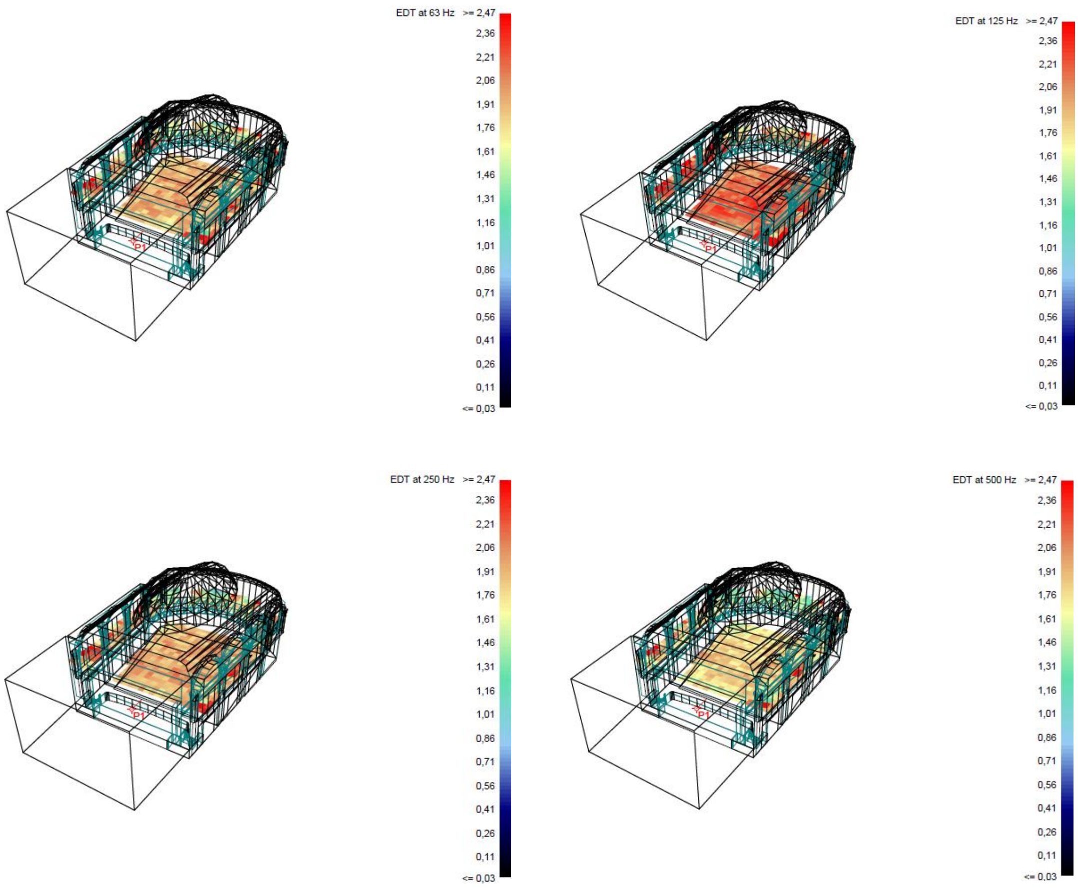


**Figure 103** EDT at 63 Hz, 125 Hz, 250 Hz and 500 Hz (KT)

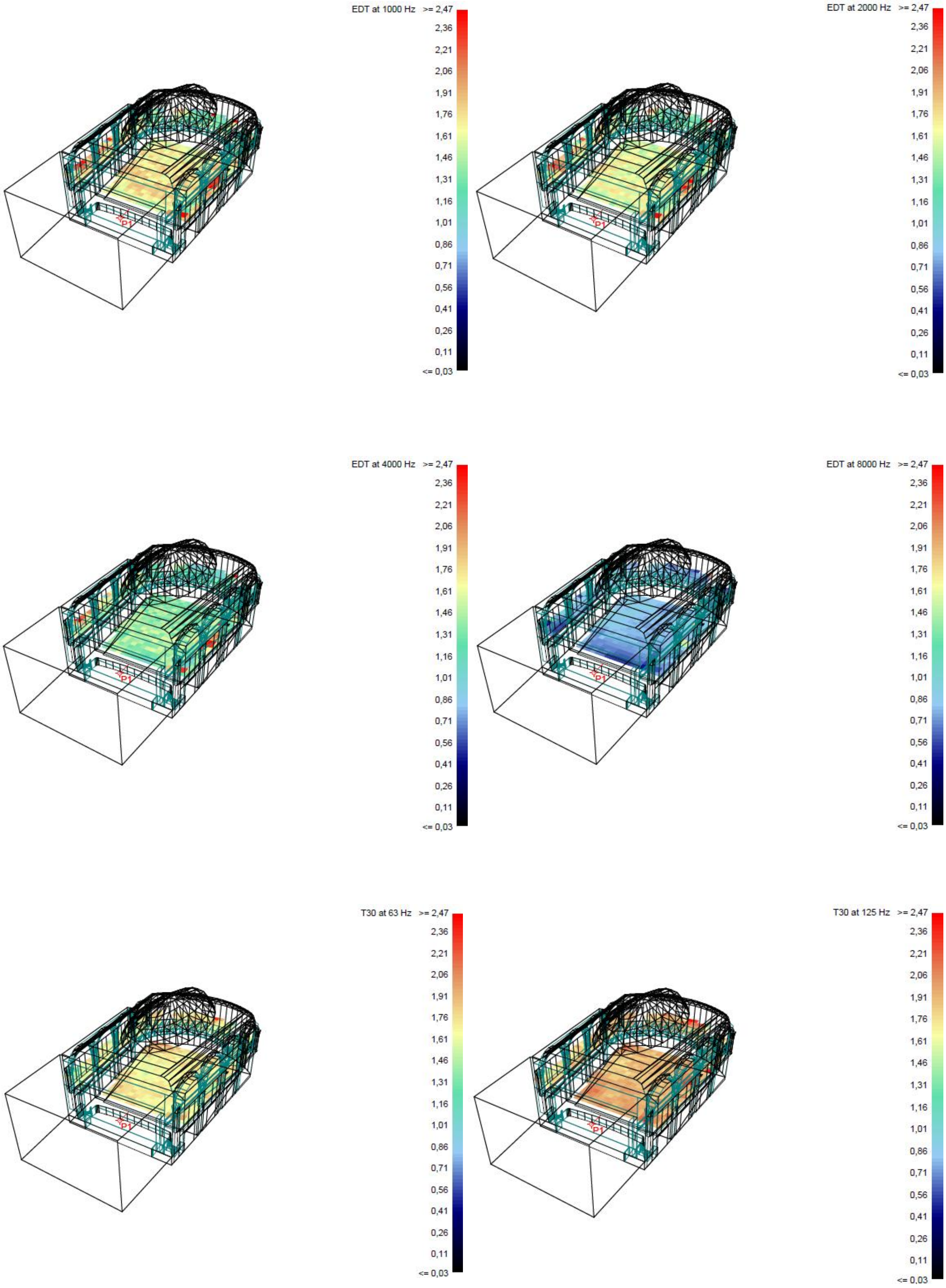


**Figure 104** EDT at 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz
T30 at 63 Hz, 125 Hz (KT)

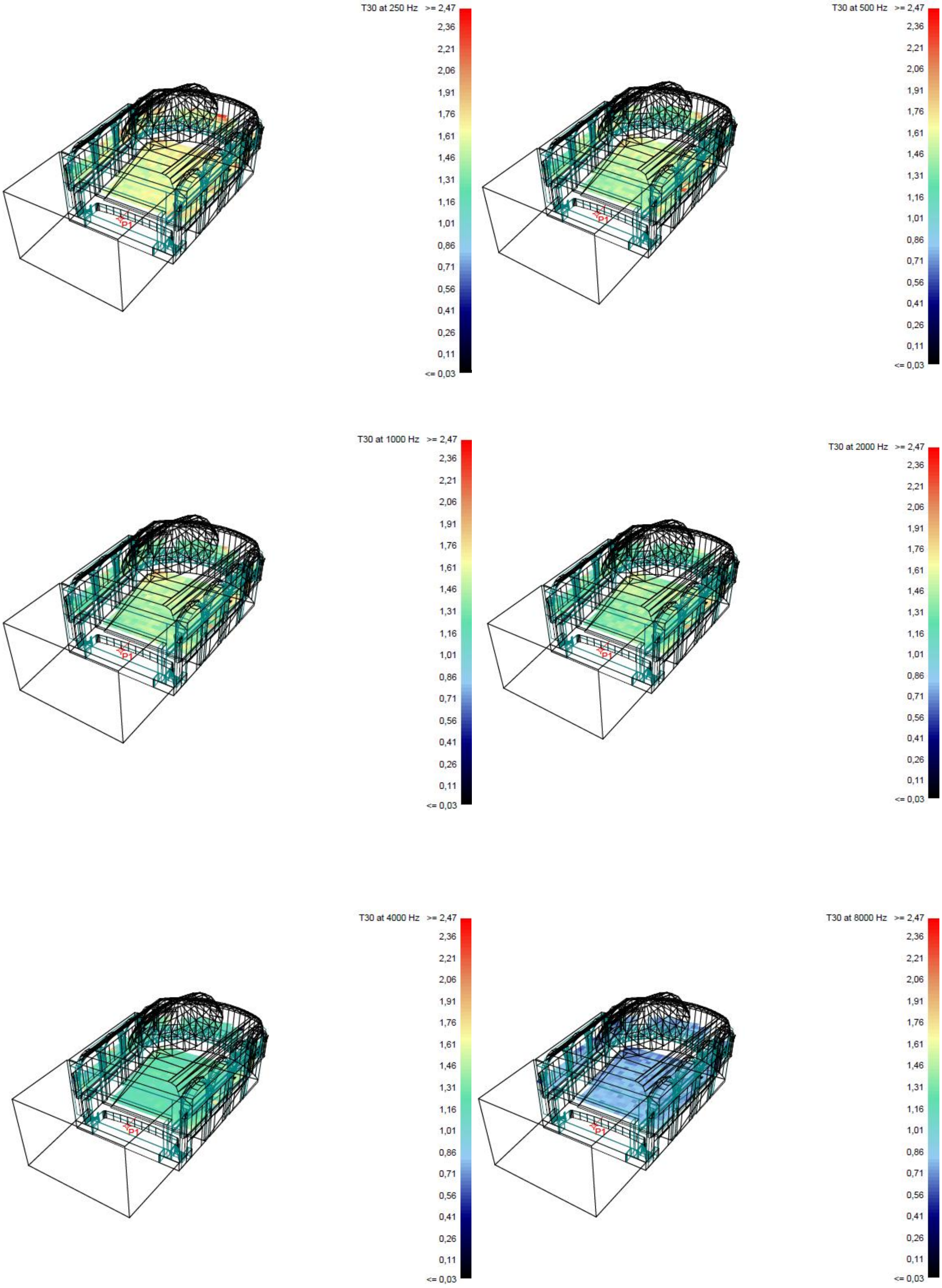


**Figure 105** T30 at 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz (KT)

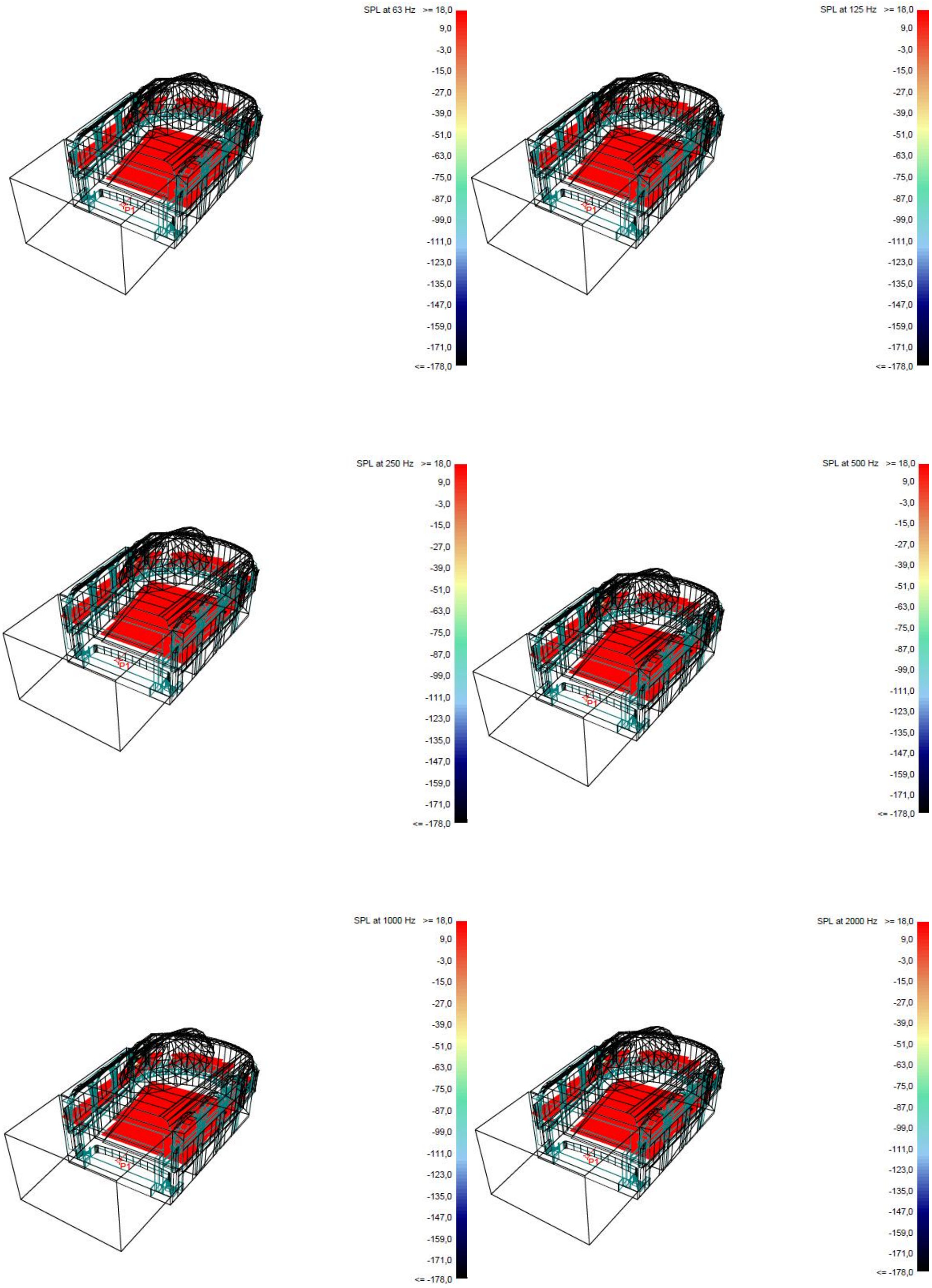


**Figure 106** SPL at 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz and 2000 Hz (KT)

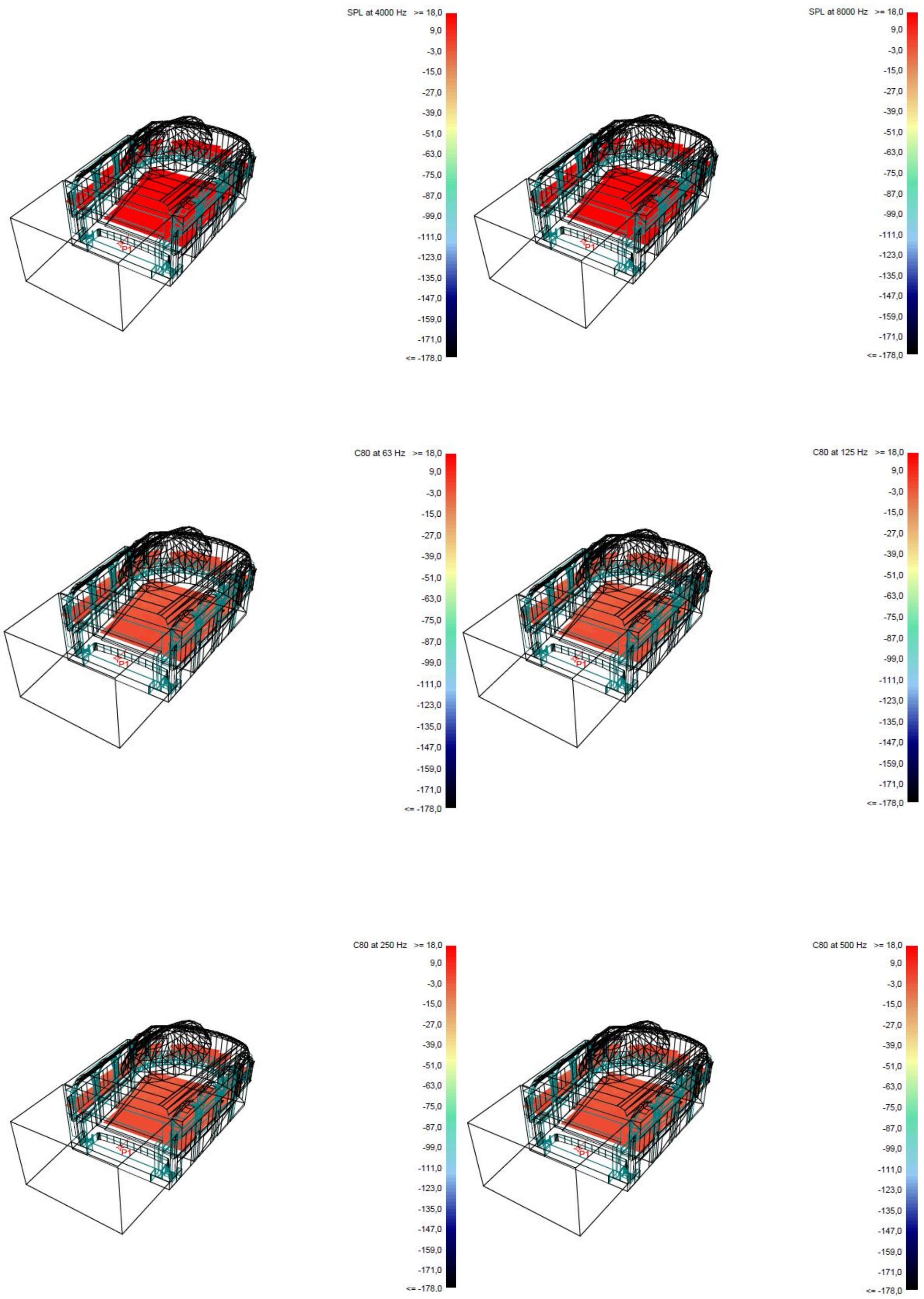


**Figure 107** SPL at 4000 Hz and 8000 Hz
C80 at 63 Hz, 125 Hz, 250 Hz and 500 Hz (KT)

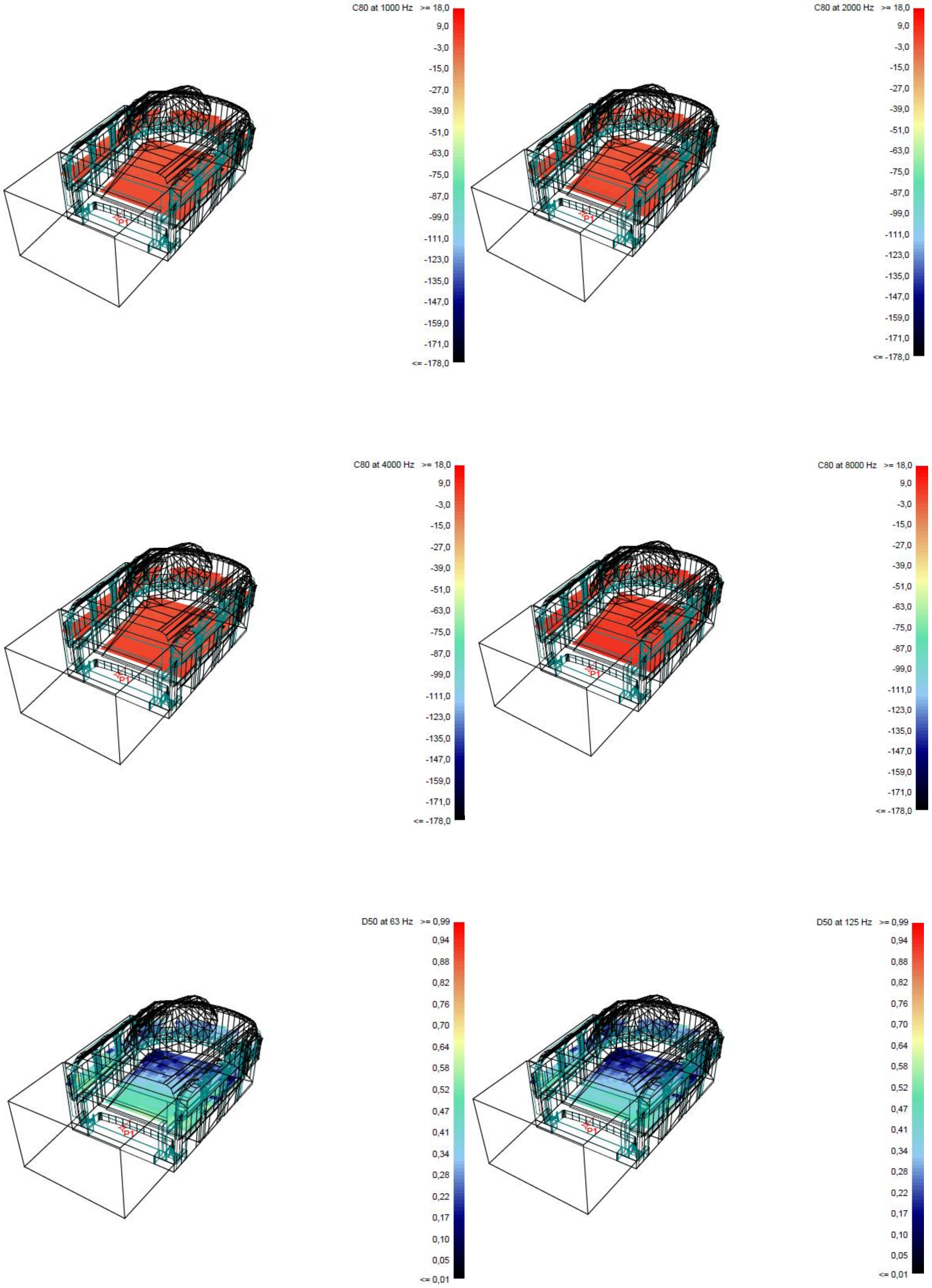


**Figure 108** C80 at 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz

D50 at 63 Hz and 125 Hz (KT)

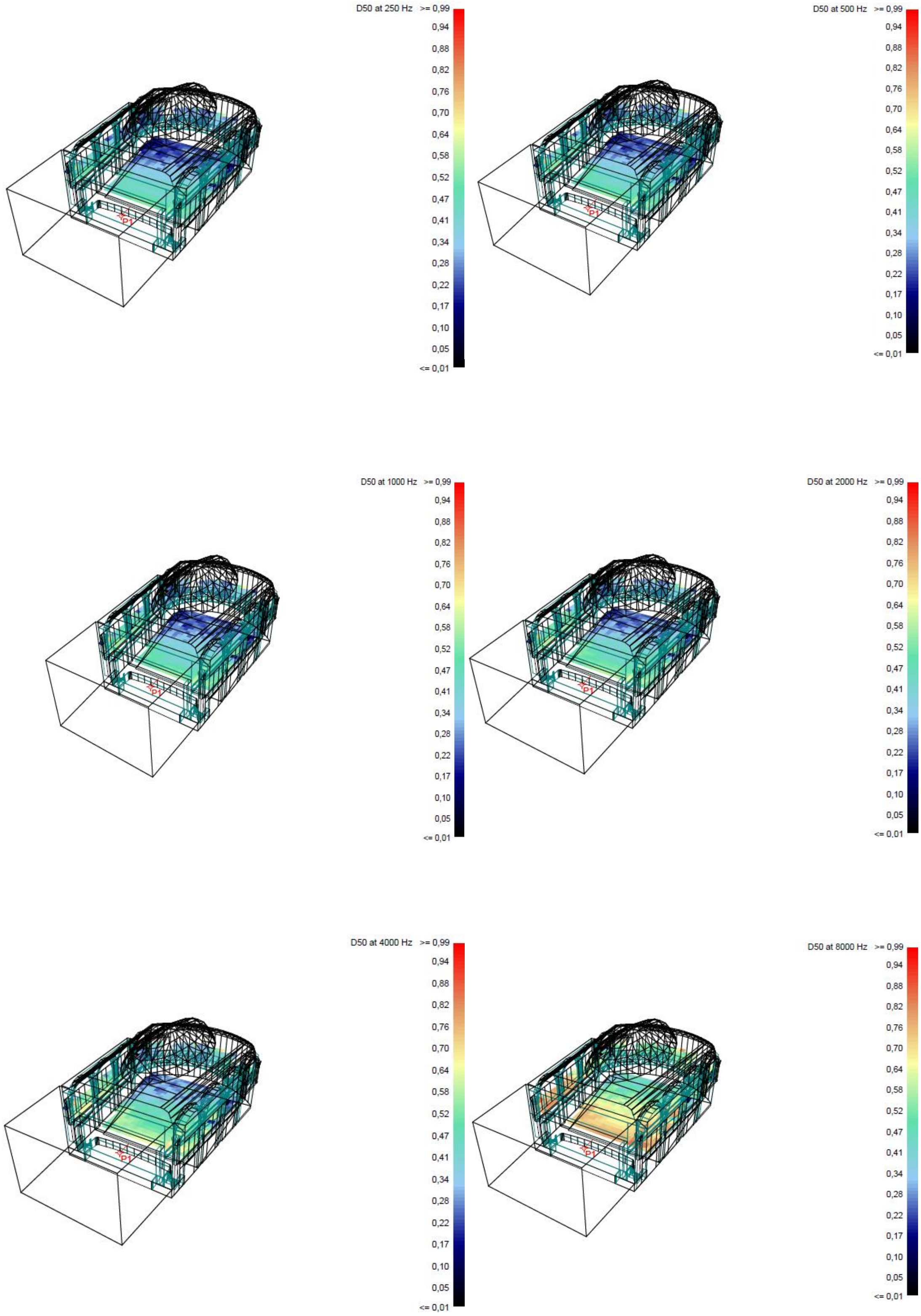


**Figure 109** D50 at 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz (KT)

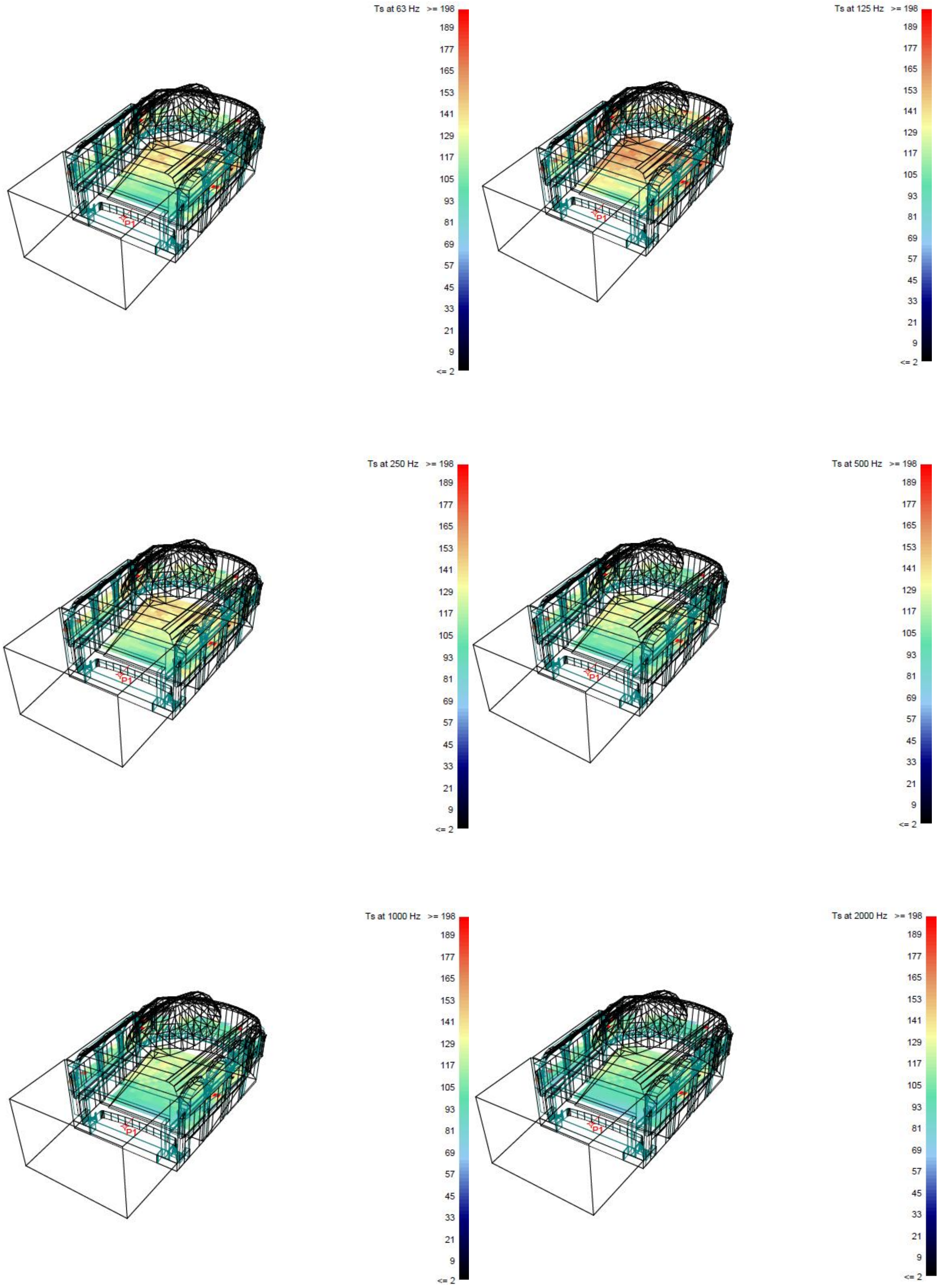


**Figure 110** Ts at 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz and 2000 Hz (KT)

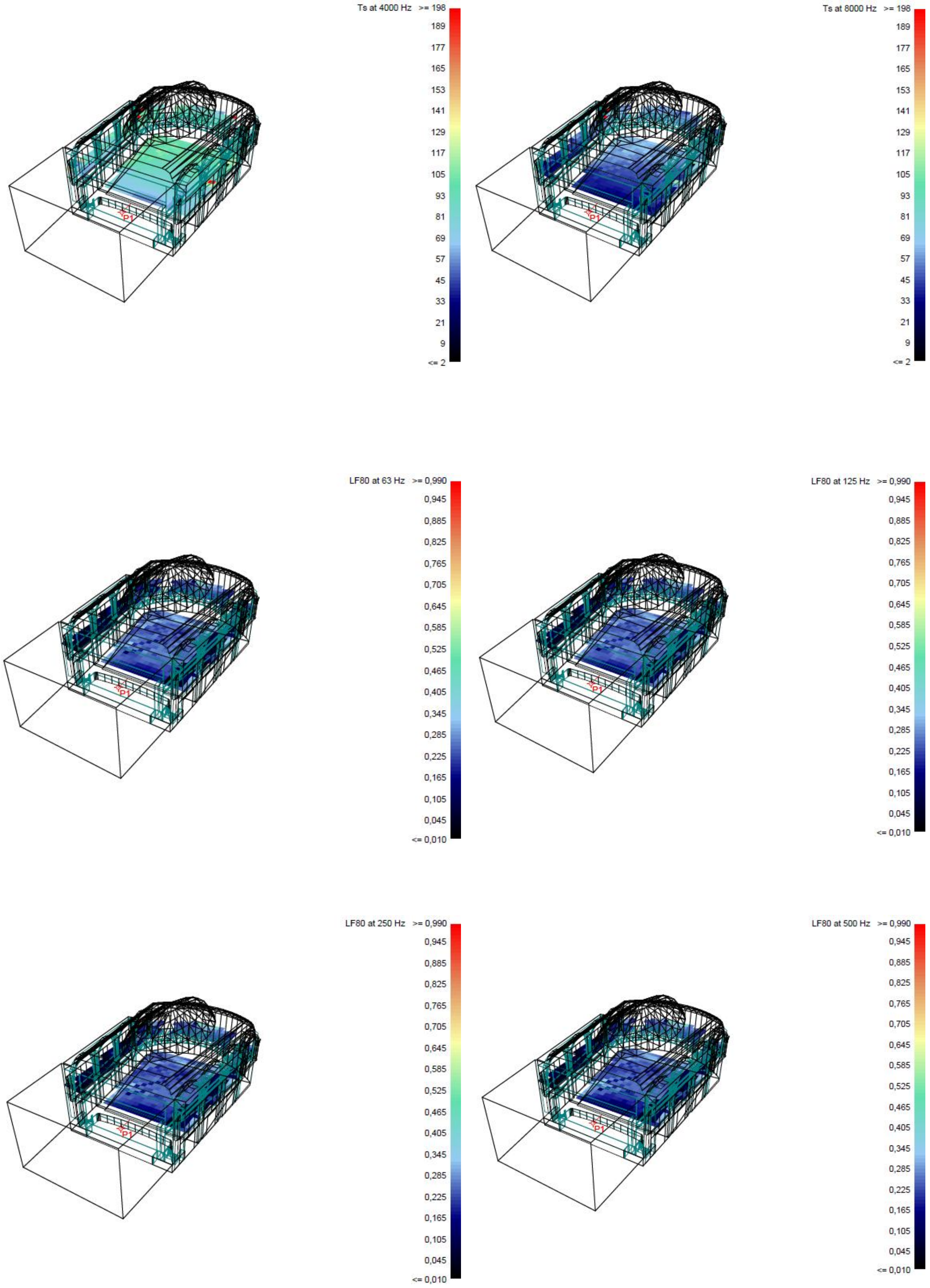


**Figure 111** Ts at 4000 Hz and 8000 Hz
LF80 at 63 Hz, 125 Hz, 250 Hz and 500 Hz (KT)

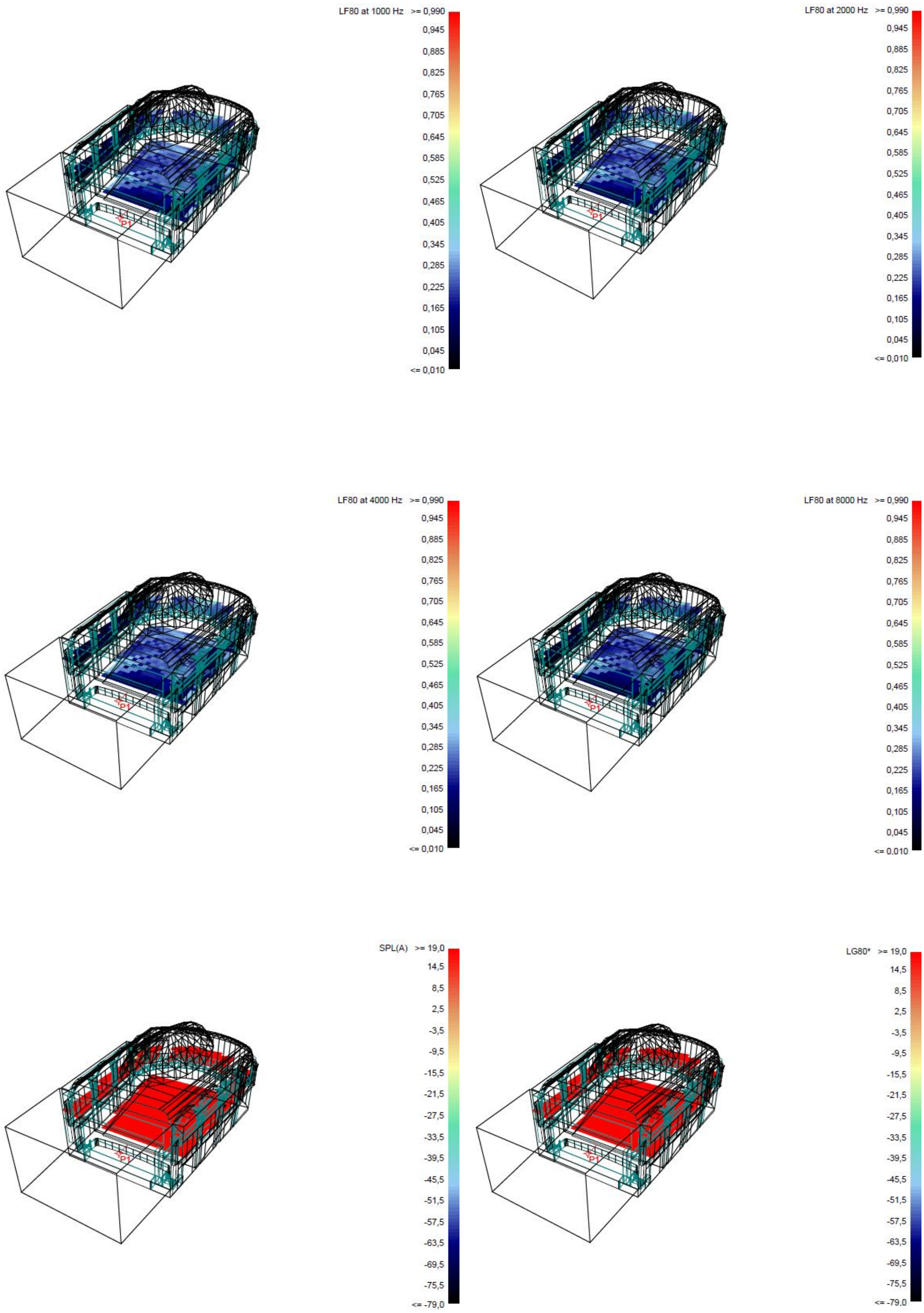


**Figure 112** LF80 at 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz
SPL(A) and LG80 (KT)

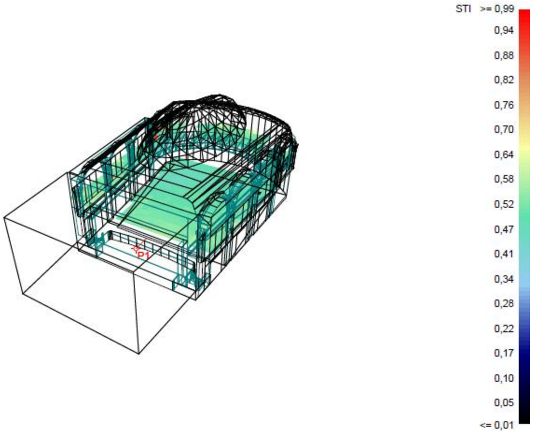


**Figure 113** STI (KT)

## OPERA

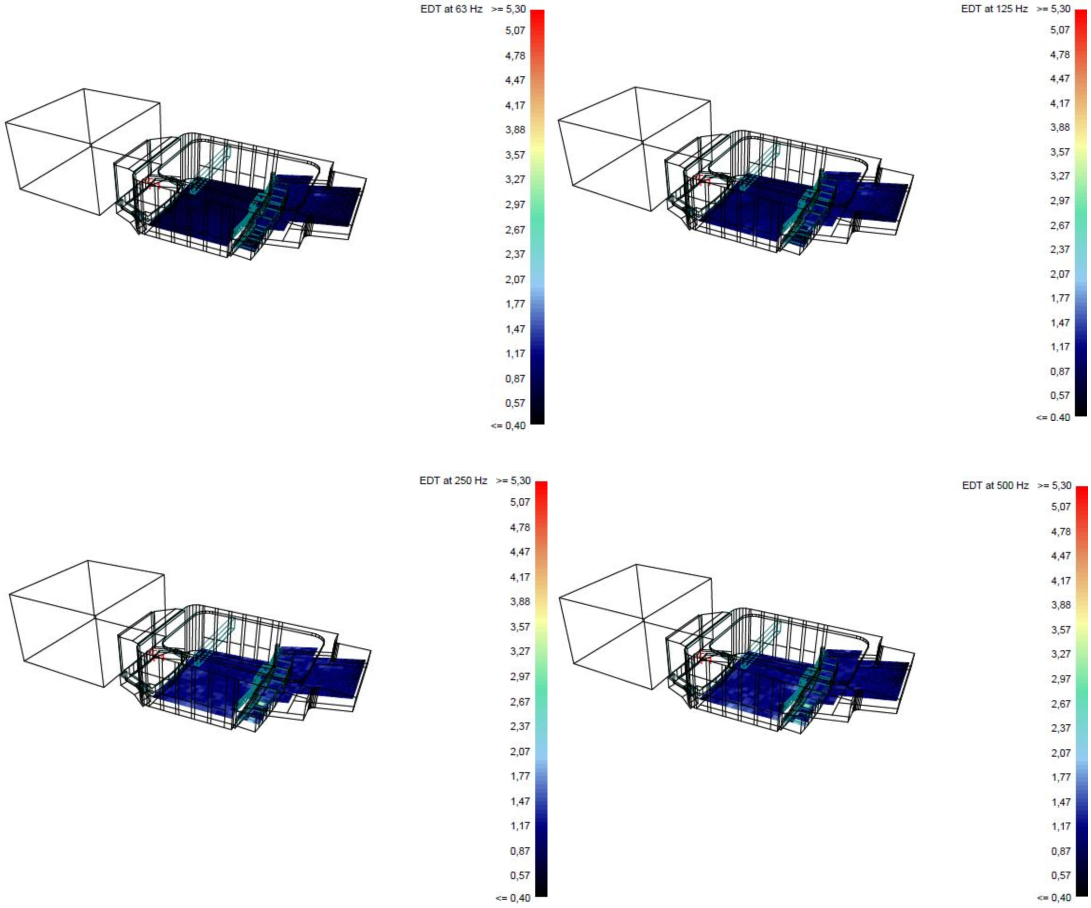


**Figure 114** EDT at 63 Hz, 125 Hz, 250 Hz and 500 Hz (O)

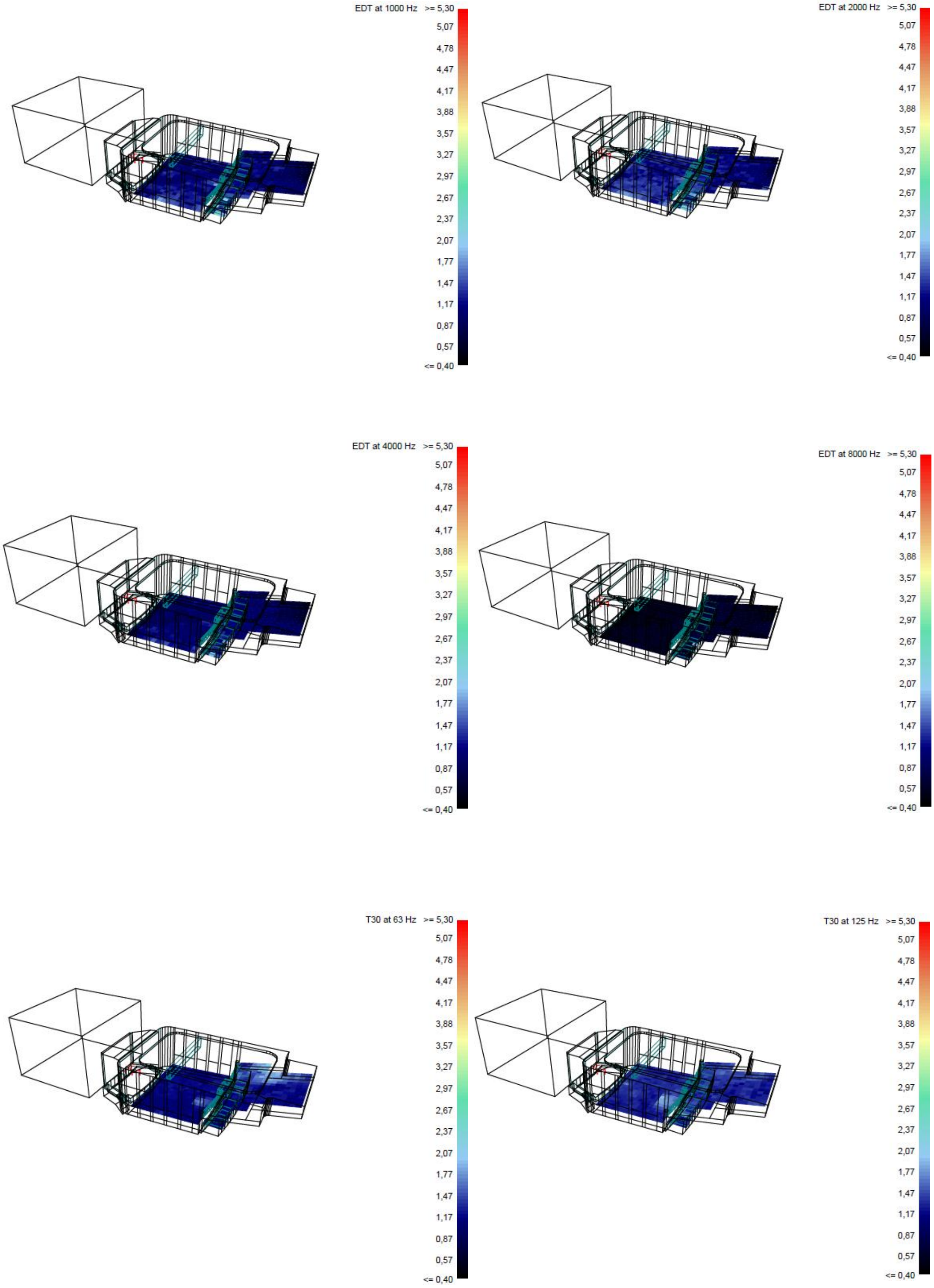


**Figure 115** EDT at 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz
T30 at 63 Hz and T30 at 125 Hz (O)

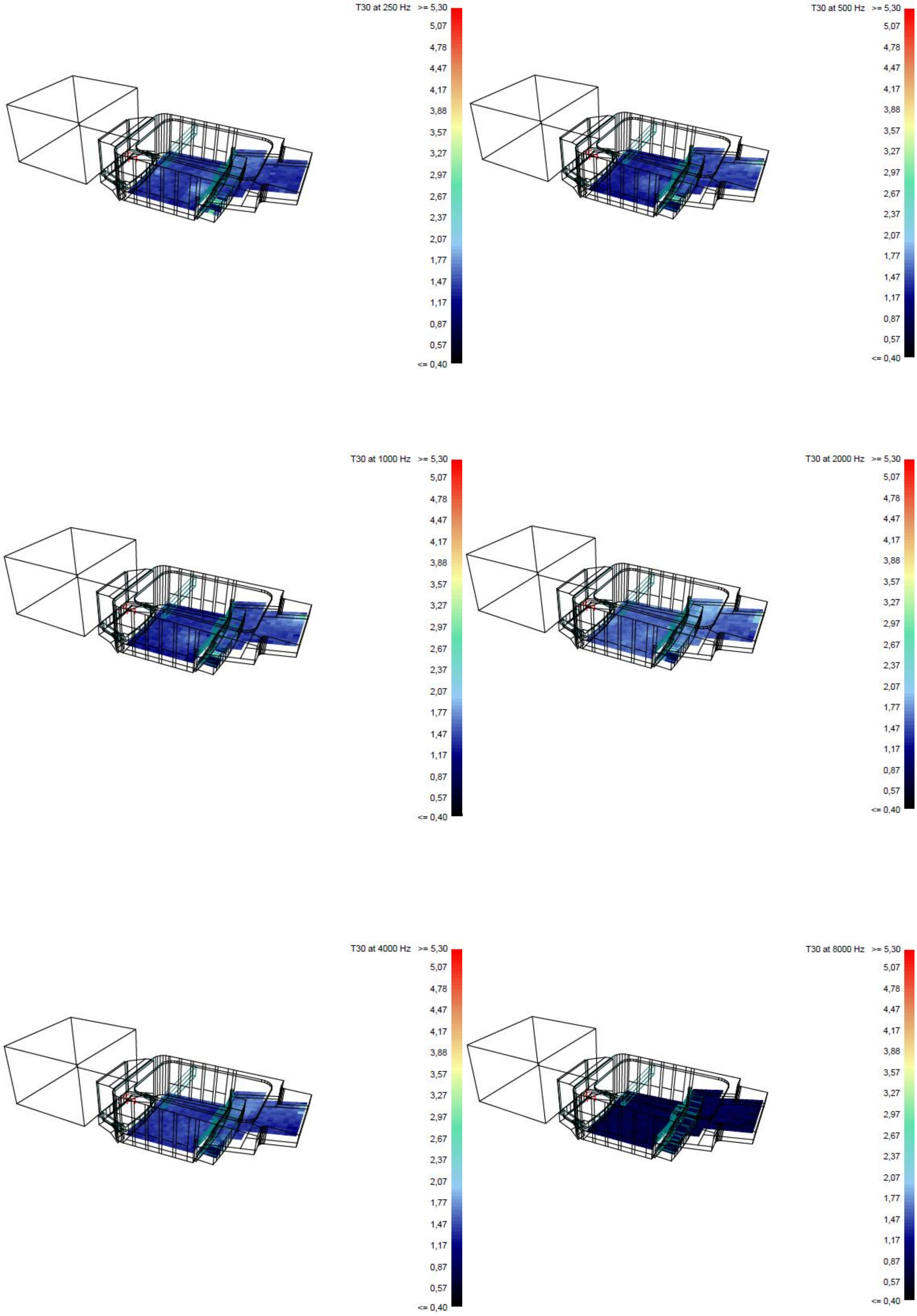


**Figure 116** T30 at 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz (O)

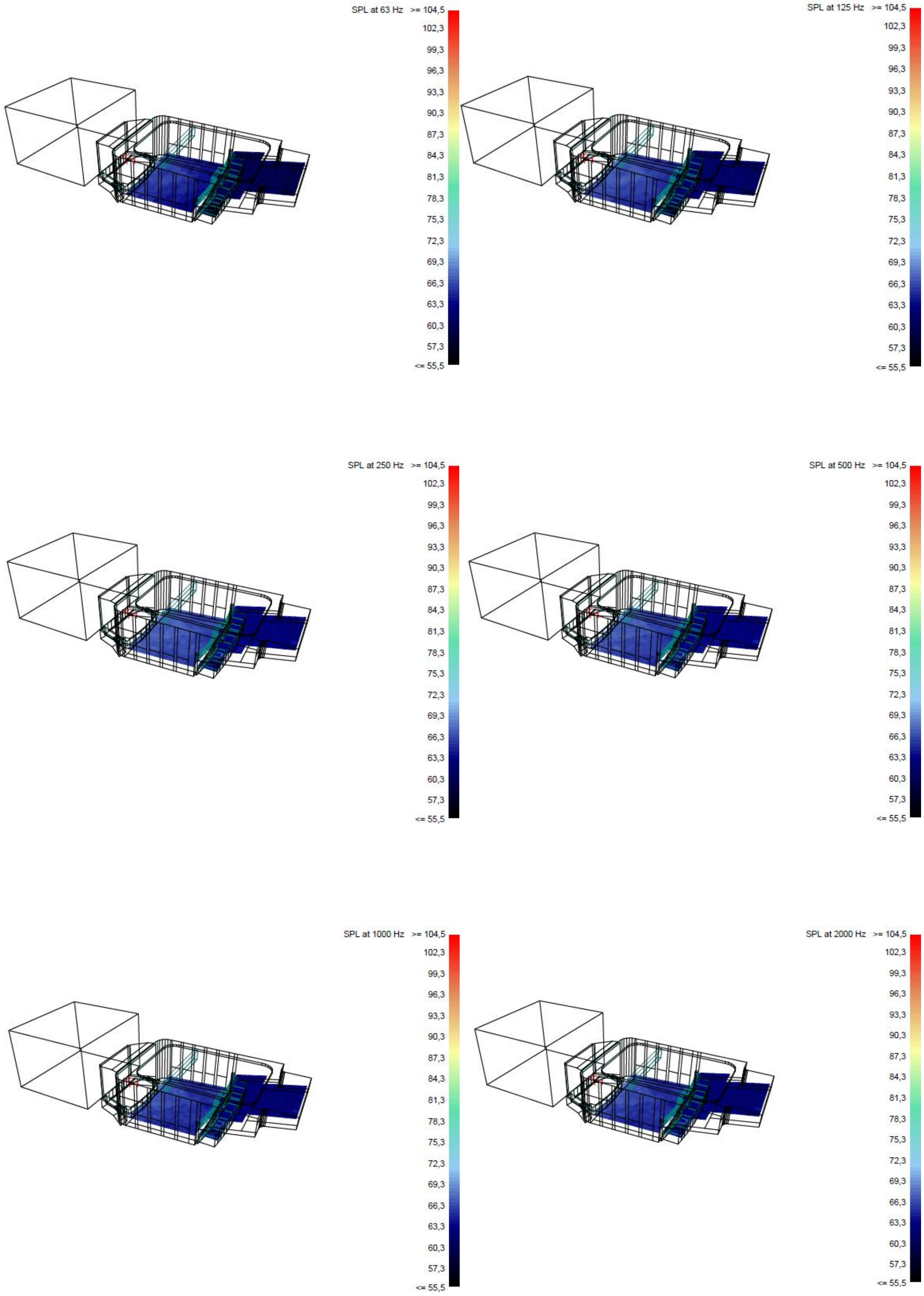


**Figure 117** SPL at 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz and 2000 Hz (O)

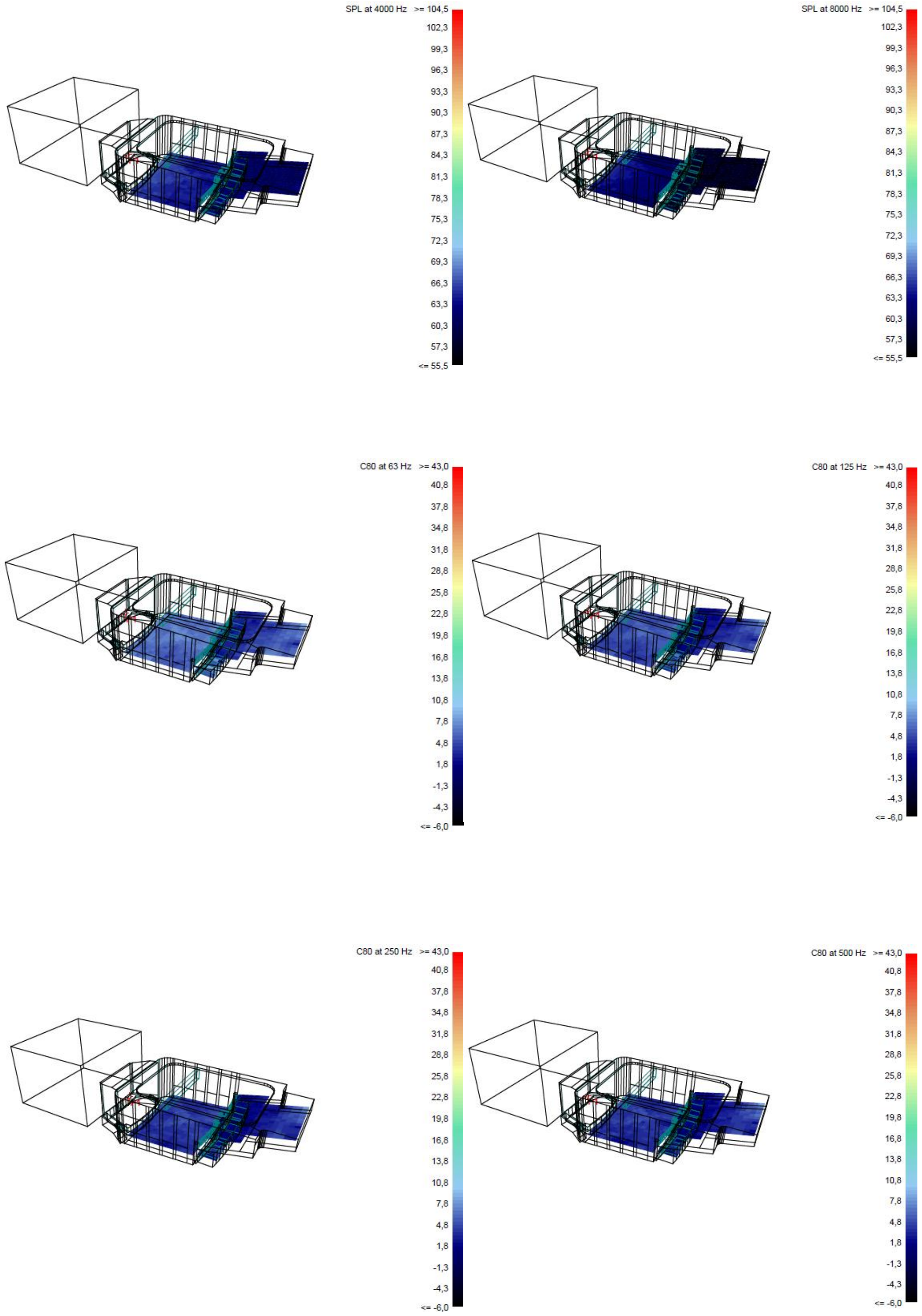


**Figure 118** SPL at 4000 Hz and 8000 Hz

C80 at 63 Hz, 125 Hz, 250 Hz and 500 Hz (O)

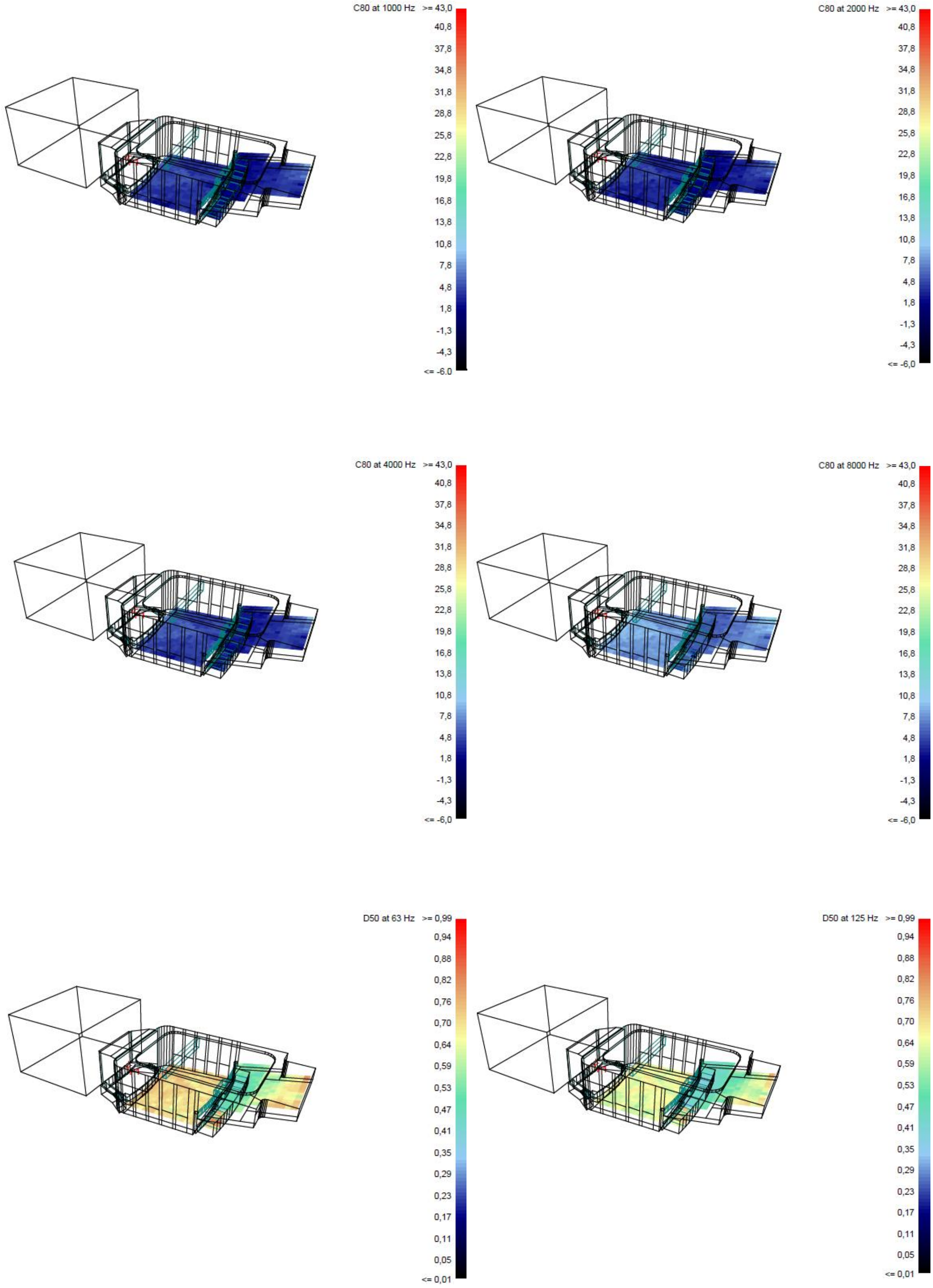


**Figure 119** C80 at 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz
D50 at 63 Hz and 125 Hz (O)

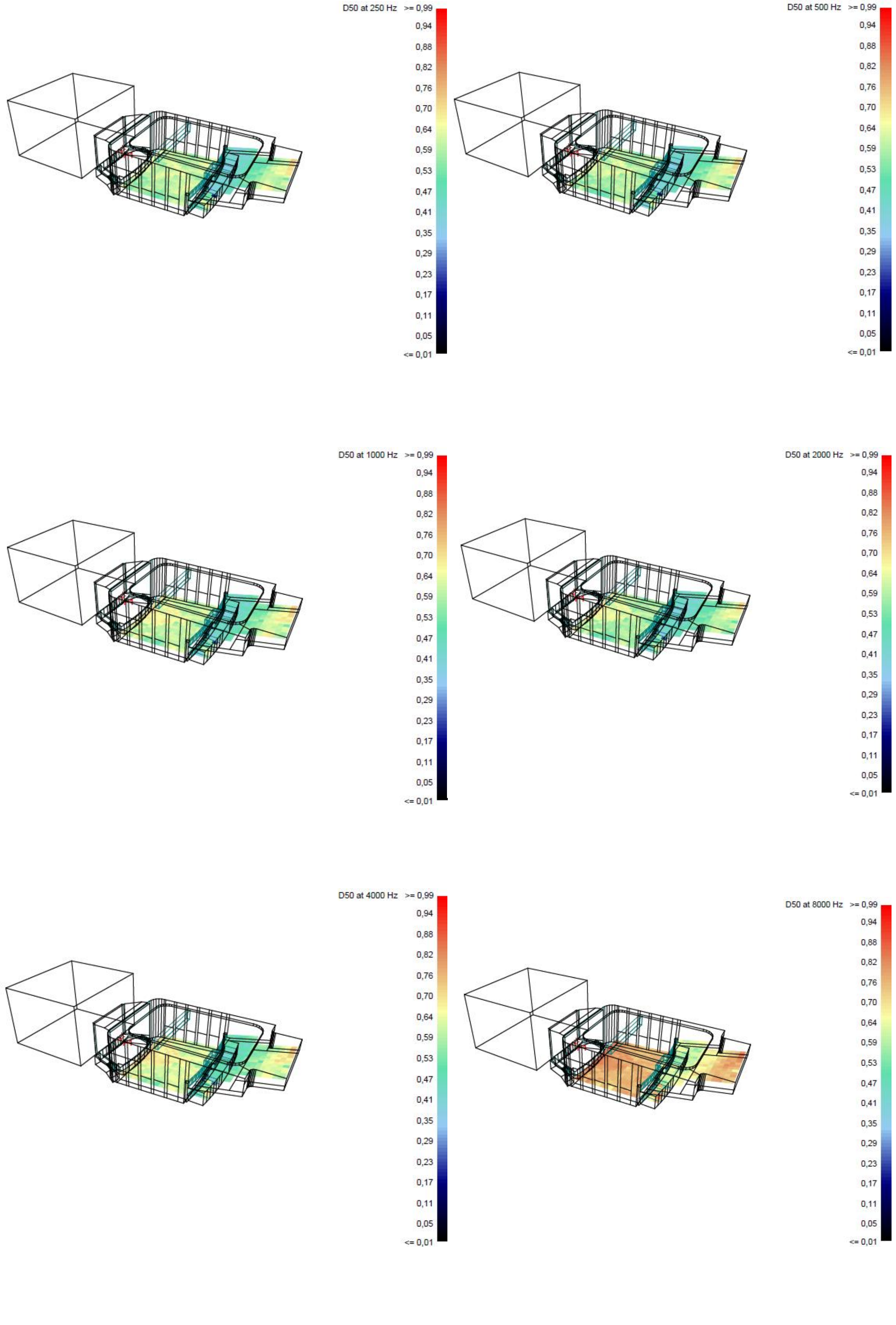


**Figure 120** D50 at 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz (O)

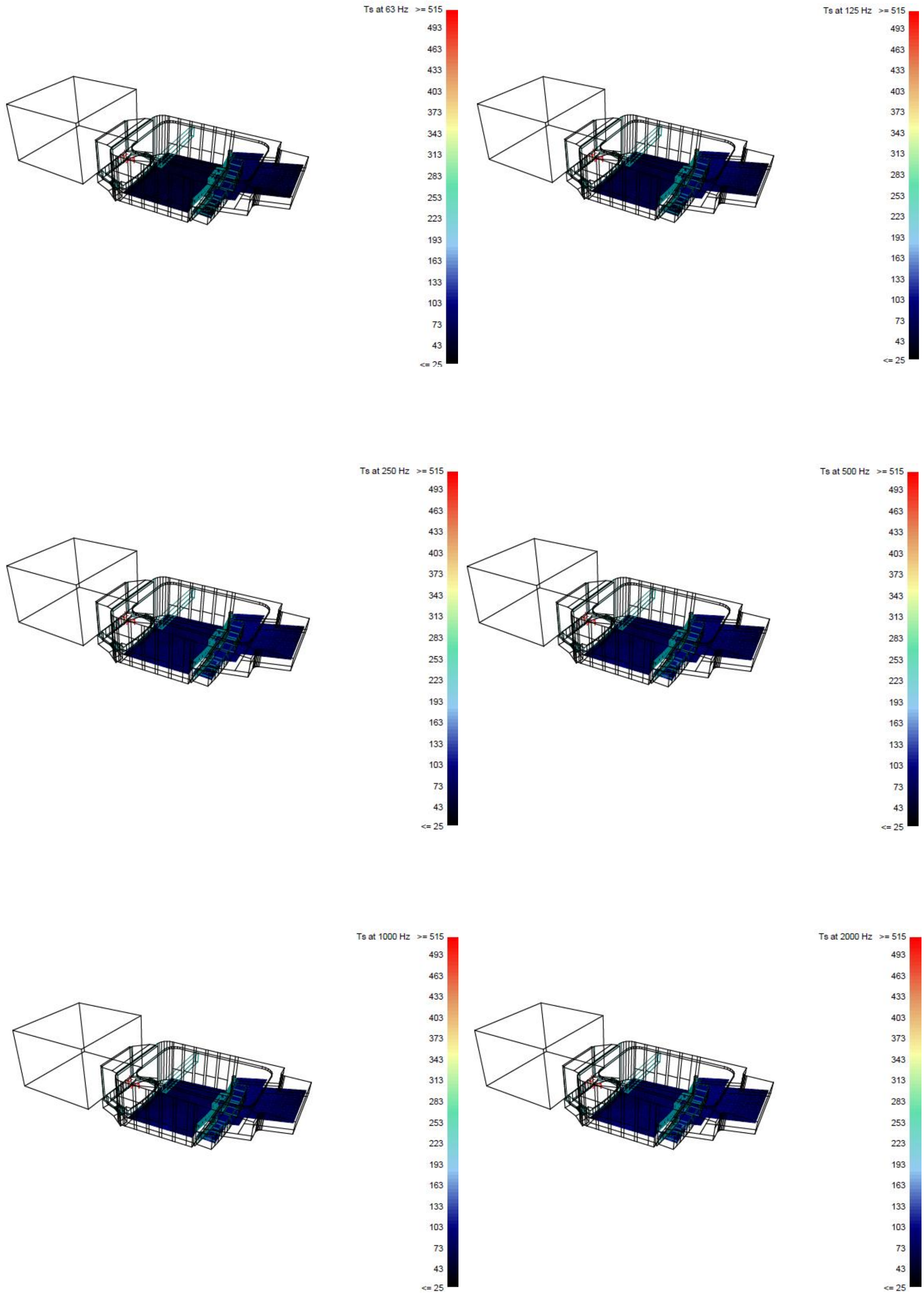


**Figure 121** Ts at 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz and 2000 Hz (O)

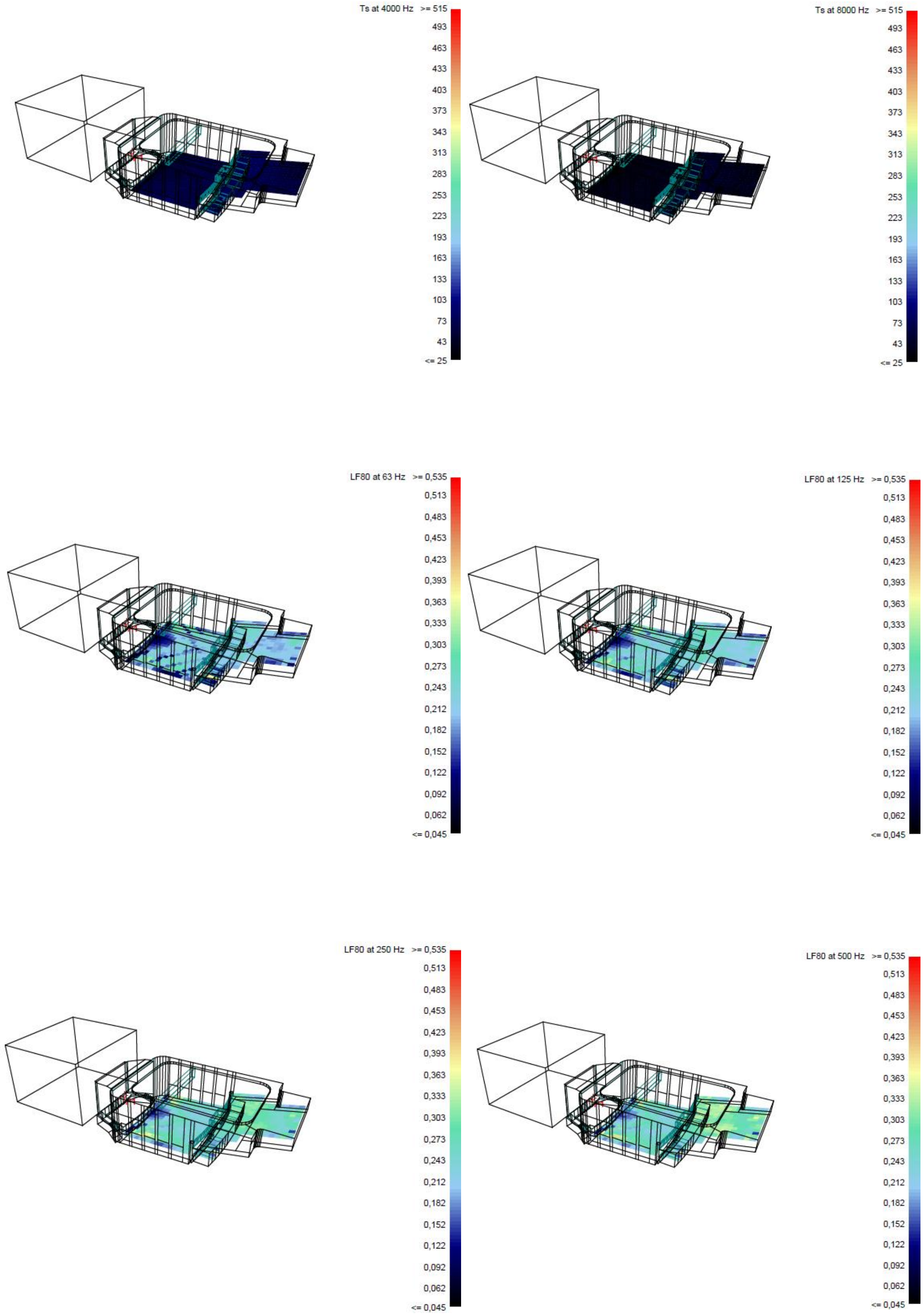


**Figure 122** Ts at 4000 Hz and 8000 Hz

LF80 at 63 Hz, 125 Hz, 250 Hz and 500 Hz (O)

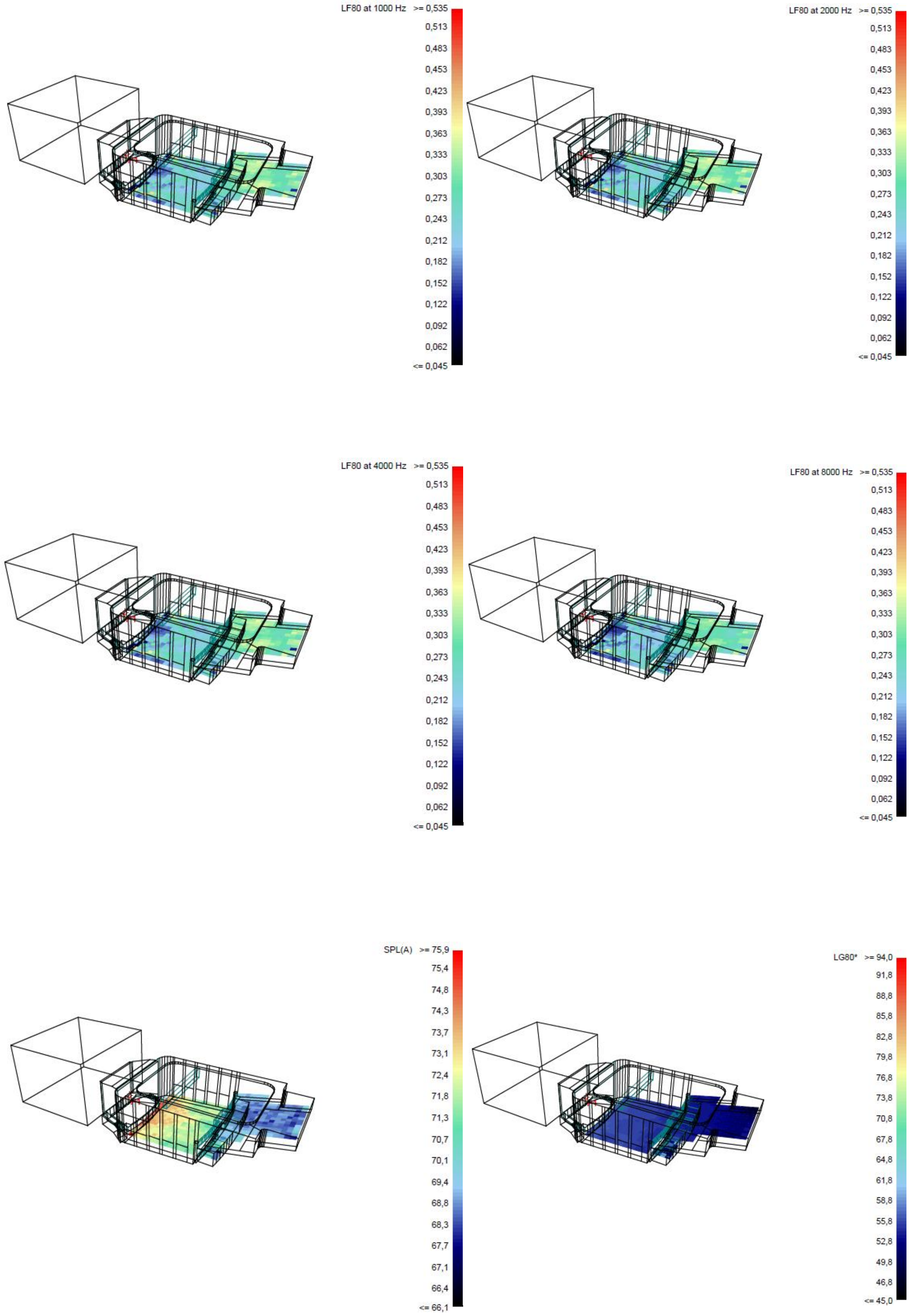


**Figure 123** LF80 at 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz
SPL(A) and LG80 (O)

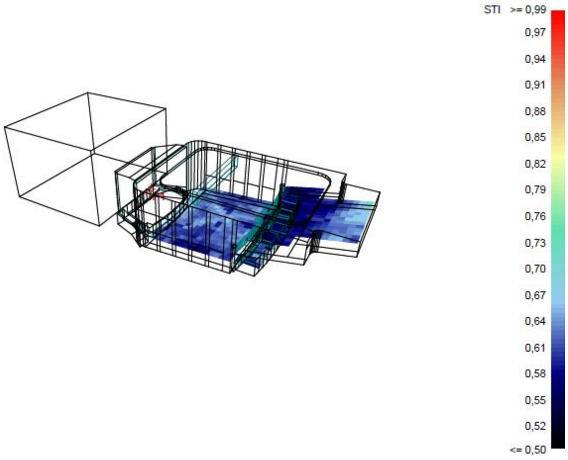


**Figure 124** STI (O)

## APPENDIX C

## GLOSSARY OF TERMS

**Apparent Source Width (ASW):** ASW is the apparent auditory width of the sound field created by a performer as perceived by an audience. Barron and Marshall (1981) have defined ASW as the `*subjective sensation* associated with early lateral reflections`. When the lateral reflection level rises, the source broadens and the music gains fullness and body. (Hidaka, 1996)

**BR:** Ratio of mid frequency reverberation times to low frequency ones. Beranek noticed that Bass Ratio measured at occupied halls did not reflect the subjective ratings of those halls. It was found that bass sound strength that is perceived was related with both the early and late arriving sound levels rather than reverberation times. This emphasized the significance of the early reflection period. (Cavanaugh, 2009 p.140)

**BRIR:** is a set of two impulse responses detected at the left and right entrance of the ear channels of a dummy head (or indeed at blocked entrenches of the ear channels of a (living) person residing in a room, when a sound source has (or some sound sources have) emitted an impulse. The BRIR should include all the (necessary) information on receiver position and orientation, source(s), position(s) and orientations, room geometry, surface materials and the listeners geometry

**Clarity (C80):** Clarity in dB is the ratio of the "useful energy" which is received in the first 50-80 ms of the Impulse Response and the "detrimental energy" which is received after that. (Fausti and Farina)

The early to late index is developed from the Deutlicheit (distinctness) proposal made by Thiele (1953). 50 ms time interval is used initially, which is often used for speech now. For music performances, 80 ms period is preferred as proposed by Reichardt et al (1975).

**D50 in %:** The ratio of early reflections energy to total energy within 50 miliseconds.

**Early Decay Time (EDT):** A measure of reverberation, EDT is the time that it takes for the reverberant energy in a room to decrease by 10 dB from its steady-state value. Early Decay Time is a measure of reverberation in a different way from Reverberation Time. Reverberation Time is the time required for 60 dB decay of a sound, whereas the Early Decay Time is the time for the first 10 dB decay. It is multiplied by 6 to extrapolate the result to a similar 60 dB decay of Reverberation Time. Although some researchers have suggested early decay times depending on the 15 dB or 20 dB decay of sound level ($EDT_{15}$ or $EDT_{20}$), most commonly accepted Early Decay Time is related with 10 dB decay.

Jordan proposed the term EDT depending on the previous studies suggesting that "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 10 dB." (Lothar Cremer, Helmut A. Müler, 1982) (Cavanaugh,2009)

**Ensemble:** Halls with high ceilings and no canopy results in the difficulty for the orchestra to play in good ensemble. (Beranek, 2003)

**IACC:** Dissimilarity of the sounds arriving left and right ears IACC positively affects spaciousness and total acoustical quality of concert halls. and LF
(Hidaka, 1997 Music and concert hall acoustics p.315)

IACC and LF are assumed to be objective parameters affecting the spaciousness in concert halls. IACC should be measured for the initial 80 ms of the impulse response as the average for three bands, 500 Hz, 1 kHz and 2 kHz. This contributes to the evaluation of the ASW. Judgments of ASW for various sound fields show that $IACC_{E3}$ is superior to LF. Moreover, it is approved that IACC $_{E3}$ contributes not only to the spaciousness but also to total acoustical quality of concert halls. (Hidaka, Beranek, Okano, 1996)

**Intelligibility:** The degree to which speech can be understood. With specific reference to speech communication system specification and testing, intelligibility denotes the extent to which trained listeners can identify words or phrases that are spoken by trained talkers and transmitted to the listeners via the communication system.

**G in dB:** Total level relative to the direct sound level at 10m from the source (Barron, 2006)

**LF in %:** Early Lateral Energy Fraction is the ration between the sound which arrives from the side within the 80 ms after the direct sound. This is a linear measure of source broadening, later called as spatial impression. (Barron and Marshall, 1981)

Marshall (1967) and Barron (1971) showed that early lateral energy fraction (LF) is a significant measure of source broadening where LF is the ratio of the sum of the early lateral energy to the sum of the early total energy. When loudness is low in a hall, LF should be higher in order to obtain adequate spatial impression. (Möller and Hyde, 2006)

**Reverberation:** Reverberation is the persistence of sound in an enclosed space after the original excitation sound has ceased. It consists of a series of very closely spaced reflections, or echoes, whose strength decreases over time due to boundary absorption and air losses.

**Reverberation Time:** Reverberation Time (RT) The time required for the sound in an enclosure to decay 60 dB, the time required for the time average of the sound energy density, initially in a steady state, to decrease, after the source is stopped, to one-millionth of its initial value. The unit is the second and RT depends mainly on two factors: Room volume and total surface absorption.

**RT 60:** "RT60 is the amount of time it takes for the reverberant energy in an enclosed space to drop by 60 dB from its initial, steady-state value after the original sound has ceased." (http://www.meyersound.com, Access Date: May 2011)

**Speech Transission Index (STI):** Developed in the early 1970's, the Speech Transmission Index (STI) is an machine measure of intelligibility whose value varies from 0 (completely unintelligible) to 1 (perfect intelligibility).

**SDI:** SDI is the surface diffusivity index grading the archtitectural irregularities on side walls and ceiling in a performance hall. Beranek (2003) supports the findings of Haan and Fricke that the highest correlation between architectural features in a hall and subjective acoustical quality is the degree of surface irregularities. They rated surface irregularity on a scale from 0 to 1. The highest rated halls in the study of acoustical measurement of fifty eight concert halls that Beranek surveyed, the highest rated concert halls have many irregularities on ceiling and the side walls. Surface diffusivity index gets greater than 0.8 in highly rated halls and 0.3-0.6 in the lowest rated halls.

**$ST_{early}$ (also $ST_{late}$, $ST_{total}$):** STearly (Gade, 1989) is a measure for performers and depends on acoustic energy. It is measured on stage, 1m from the source.

**T30 in s:** Reverberation time of 30 dB decay of the sound level

**Texture**: It is the appearance of reflectograms in the first 80-100 ms after arrival of the direct sound. (Hidaka and Beranek, 2000)

**TR:** Ratio of 4000 Hz to mid-frequency late arriving sound levels. (Cavanaugh, 2009)
The ratio of high frequency (2–4kHz) reverberation time to mid-frequency (500–1000Hz) reverberation time

**Ts in ms:** The Centre Time is the centre of gravity along the time axis of the squared impulse response. The quantity was suggested by Cremer and Müller (1982). The parameter is considered to be highly correlated with the Early Decay Time (typical correlation coefficient= 0.975), which resulted in that it has lost favor for concert halls. (Barron, 2009)

**Warmth:** Meyer (1996) suggested that the warmth of the orchestral sound is generated by relatively strong low frequency components. In other words, warmth depends on the frequency characteristic of the reverberation time. Similarly, good sound radiation of the low instruments and good low frequency reflections from the surfaces close to the instruments provide warmth of the orchestral sound. For better feeling of warmth, the strength of the bass group may be varied. (Meyer, 1996)