A MODELLING METHOD FOR OPTIMISING THE SEATING ARRANGEMENT AT THE ACOUSTICAL DESIGN STAGE OF HALLS

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by
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We have read the thesis entitled "**A MODELLING METHOD FOR OPTIMISING THE SEATING ARRANGEMENT AT THE ACOUSTICAL DESIGN STAGE OF HALLS**" completed by **ÖZGÜL YILMAZ KARAMAN** under supervision of **ASSIST.PROF. DR NESLİHAN GÜZEL** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy.

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ABSTRACT

Although there have been many buildings designed for the performing arts during the history, it is not possible to say that the development of the theatre architecture has ended. Although it is common to built multi-purpose auditoria mostly because of the economical reasons, every kind of performing art requires different characteristics. Drama theatres distinguish from the other spaces for performing arts, for example concert halls, since the both acoustical and visual conditions are equally important to make the spectators enjoy/understand the play. With this idea, it is aimed to examine acoustical and visual properties of drama theatres. By this way, it is aimed to get some results to be used as a design guide at the beginning of a theatre design process. To achieve the evaluation process, eight different rooms are designed to be simulated. Then, the designed rooms are evaluated in terms of both visual and acoustical comfort conditions. Also, by designing different cases it is aimed to evaluate the effect of geometrical design of rooms on the visual and acoustical conditions of rooms.

Keywords: Theatre architecture, sightline design, theatre acoustics.

SALONLARIN AKUSTİK TASARIMINDA OPTİMUM OTURMA DÜZENİNİ SAĞLAYACAK BİR MODELLEME YÖNTEMİ GELİŞTİRİLMESİ

ÖZ

Duyguların ve olayların teatral oyunlarla ifadesi neredeyse insanoğlunun var olduğu ilk dönemlere tarihlenmekte ve antik dönemde inşa edilen ilk tiyatro yapılarından günümüze, çeşitlenen performans türlerine bağlı olarak yapıların mimari ve akustik özellikleri de gelişimini ve değişimini sürdürmektedir. Günümüzde ekonomik koşullar çok amaçlı salonların kullanımını yaygın hale getirmiş olsa da, her performans türü (tiyatro, opera, konser...) farklı akustik özelliklere sahip mekânlar tasarlanmasını gerektirmektedir. Drama tiyatroları, sergilenen oyunun izleyici tarafından algılanabilmesinin hem akustik hem de görsel koşullara bağlı olması bakımından diğer sahne sanatlarından ayrılırlar. Bu noktadan hareketle, tasarlanan sekiz farklı salon tasarımının akustik ve görsel koşullar açısından irdelenmesi ve değerlendirilmesi amaçlanmıştır. Bu değerlendirme sonucunda, mimari tasarımın başlangıç aşamasında kullanılabilecek ipuçları elde edilmesi hedeflenmiştir.

Anahtar sözcükler: Tiyatro mimarisi, görüş açısı tasarımı, tiyatrolarda akustik tasarım

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CHAPTER ONE
INTRODUCTION

"You could just as easily look at paintings in a book, listen to music on CD or explore a world of increasingly bizarre possibilities on the Internet, but beyond the insularizing tendencies of technology, there is still a fundamental need to make an experiential connection with art, performance, space, place and the wider world." (Slessor, 2003). A theatre –it does not matter whether there is a concert or drama being performed inside it– may be the best place where this connection can be achieved in.

Expression of feelings with theatrical or/and musical performances dates back to the ancient times and continues to develop with diversifications till today. Also in course of time, architecture for performing arts continues its development according to the changing needs of the performances; because every kind of performance (music, opera, drama, dance...etc.) needs different acoustic environment as well as stage to audience relationship. With Franklin Hildy's words, "Good theatre spaces facilitate the successful interchange of energy between the actors and the audience, but they also facilitate the generation of energy within the audience itself." (Hildy, 2006) To create such a magical atmosphere in an auditorium is quite a complicated process which includes professionals from different disciplines. Studies show that even non-acoustic phenomena such as the view from the occupied seat, the comfort of the seat itself, the thermal comfort of the environment etc. can also influence the overall judgment. (Cocchi, Farina, Fausti, & Tronchin)

It means that design process is getting more difficult day by day and a performance place is expected to satisfy the spectators in terms of both aural and visual comfort conditions, while the time is getting more limited.

1.1 Aim, Scope and Method of the Study

Although, today, multi-use spaces are becoming more popular because of the economic conditions, every performance needs different conditions as mentioned before. With this idea, in this study, the scope is limited to theatre buildings, especially for drama, where the visual comfort conditions are as important as acoustic requirements. Drama theatres differ from other performing arts buildings with this feature.

These two basic requirements of drama theatres are also emphasized by Appleton:

> Drama productions (also referred as plays) are essentially concerned with the spoken word, but also to a great extent with facial expressions and body language. They are presented by a company of actors within a scenic setting to a script by a playwright and under the interpretation of a director. The performance aims include comprehension of the text, interpretation through dramatic effect and the communication with the audience by the acting and setting. The acoustic aim is to ensure that every member of the audience can hear clearly the spoken word: the visual aim is for the audience to see the facial expressions and physical gestures of the actors. Actors require that they can command the audience while the stage space and scenery neither dwarf nor crowd them. (Appleton, 1996, p. 11)

Although there have been many buildings designed for the performing arts during the history, it is not possible to say that the development of the theatre architecture has ended. Also there is not any book or guide that saying what the ideal design of a performance place is. For this reason, most of the time theatre consultants are introduced during the theatre design process. Because it would be very expensive and/or cause loss of time to modify a completed building according to actual needs.

With this idea, it is aimed to develop a method for evaluating the seating layout of auditoriums according to both visual and acoustical requirements. And also, it is aimed to get some results to be used as a design guide at the beginning of a theatre design process. To achieve this aim, design of different types of rooms as cases is chosen as evaluation method. This kind of work methodology is thought that make possible to compare different types of rooms. Also, by this way it is possible to evaluate each room from the viewpoint of distribution of parameters.

After design of the cases, acoustical and visual evaluations are based on the simulated results of the rooms. During the evaluation process, first, cases are examined from the point of visual and acoustical conditions separately. Mean scores are used to compare room types. On the other hand, each room is evaluated according to results obtained by receiver points. As a final step, it is aimed to examine if there are some correlations between the acoustical parameters and geometrical properties of rooms.

Study includes five main chapters. In the first chapter, after general description of the study, history of theatre and theatre architecture is described briefly. After having a general idea on the history of theatre architecture, design criteria of drama theatres, which are obtained by literature review, are summarised in chapter 2. Also at the end of the chapter 2 some important examples of theatre architecture are examined to get some information for the design process of cases. Properties of the cases, which are designed according to the criteria in chapter 2, are defined in chapter 3. Chapter 4 includes evaluation of the drama theatres and chapter 5 includes conclusions and future remarks.

1.2 History of Theatre and Theatre Architecture

Although the beginning of drama dates back to the 550 BC (Breton, 1989, p. 6), it takes a long period to emergence of Elizabethan and Italian theatres. And till today theatre art continues to develop as well as theatre architecture. The development of theatre architecture also can be defined as a dynamic process, since it consists of appearance, transformation, disappearance and re-emergence of various architectural types (Breton, 1989, p. 6).

Over time, the theatre has assumed many forms, reflecting the successive changes of images and identity that have occurred in the presentation of drama: the strolling player, the great open amphitheatre, the intimate court theatre, the proscenium frame, to contemporary cannibalizations of existing buildings and structures. By the nineteenth century, it had also become a place for staging social rituals, in increasingly lavish promenading spaces. (Slessor, 2003).

1.2.1 Greek Theatre

Around 550 BC first known theatrical/ dramatic events take place in religious ceremonies in honour of Dionysos and there had been four different genres of play "dithyramb, tragedy, comedy and satire" (Breton, 1989). "The birth of the Gods, who represent nature, is celebrated with enthusiasm (Spring), and death is represented with mourning ceremonies (Autumn). In the Hellenistic world, the name of the nature God was Dionysos. During the Peisistratid period (534 BC.) in Athens, festivals were held in the name of Dionysos" (Oz, 2000) and this is accepted as the beginning of theatre art. "Although the temples of the ancient Egyptians may have provided the setting for their dramas, and the theatral area adjoining the palaces at Knossos and Phaistos, Crete (2000-1600 B.C.), may well have served as a place for ritual dances and ceremonies of a dramatic nature. It was in ancient Greece that the Western type of theatre began." (Kayılı, 2002).

Later, theatres were used for the staging of tragedy and comedy, the two divisions of Greek drama, which reached its height under Pericles. Theatres were usually sited on a sloping plot of land, and tiers of seats – wooden at first, but later stone (around 4th century BC) – were backed onto the hillside, while this bowl shape provided a focus for the action. All theatres were open-air, the Theatre of Dionysus at Athens (c. 500 BC) being among the best known (Cole, 2003) , (Breton, 1989).

The geometry of the rows of seats (*cavea*) for the audience was more than half a circle, a fan shape in plan with an angle of more than 180°, to let more people watch the plays, which took place in a flat circular area (*orchestra*). At the beginning the places for storage and actor's were tents and small huts located on the opposite site of orchestra. Later on, cavea had a fixed place, the tents were turned into stone buildings (*skene – stage building*) like theatre at Epidaurus (Barron, 1993) (Oz, 2000). "The *skene* was separated from the auditorium by two open passages (the parodoi), one on each side, which gave access to the orchestra from outside" (Robertson, 1943). "The actors performed on the *loegion* of the *skene* which was later to be supplemented by a *proskenion* and decor was provided by a frontal wall with three doors". (Breton, 1989)

The slope of the seating area was related to the slope of the hill where the lines of the seats placed. But usually Greek theatres had high slope angles which shortens the distance between actors and audience. "All of these provide the advantages of having improved sightlines (...) with the satisfactory distribution of sound. There is no discontinuity between the audience and the performer. This creates the idea of wholeness and the feeling of intimacy" (Saher, 2001).

"This fundamental relationship has changed very little over the centuries, except that the need to shelter the audience and actors in cold climate countries promoted more radical opportunities for seating opportunities." (Phillips, 1993, p. 76).

But Greeks continued to renovate their theatre buildings for accommodating more seats for the audience or needs of changing plays. And also materiel use had been changed as mentioned before. The production of these renovations after the Classic theatre was the Hellenistic. Some characteristics that can be distinguished Hellenistic Theatre from the previous form, (such as the raised stage, and the stage building) were also connected with changes in the methods of playwriting in that period. For example, the introduction of the second and the third actor in tragedies moved the centre of the performance from the orchestra to the stage which was therefore raised. In some cases the cavea was extended with more seating rows, such as in the theatre of Epidaurus, or the orchestra was repositioned, like in the theatre of Dionysus in Athens (Chourmouziadou & Kang, 2008).

"The development of the acoustics of Greek theatre, which spanned more than two centuries, can be seen as equally logical empirical development. A similar trial-and-error process was responsible for the optimization of the proscenium theatre design in more recent times." (Barron, 1993, p. 244)

1.2.2 Roman Theatre

During the Roman Period, theatre architecture continued developing on the bases of Greek Theatre. The geometry of the cavea became semicircle and the theatre building had not to be built on a hill. Theatres were built as independent buildings; Romans used arcs and vaults to build the sloped seating lines.

The passages that made the orchestra accessible before were vaulted during the Roman Period. And these vaulted passages also used for the access from outside to the cavea as well as orchestra. The height of stage wall was increased with the same height as the cavea, and the stage was wide but low in height, projecting much further than the proscenium, namely the front part of the stage building. The shape of the orchestra was reduced to a semicircle and it was not the performance place. The orchestra used for accommodating the aristocratic people of society. The stage height was had to be reduced at this period to make these people able to see the performance on the stage. (Chourmouziadou & Kang, 2008)

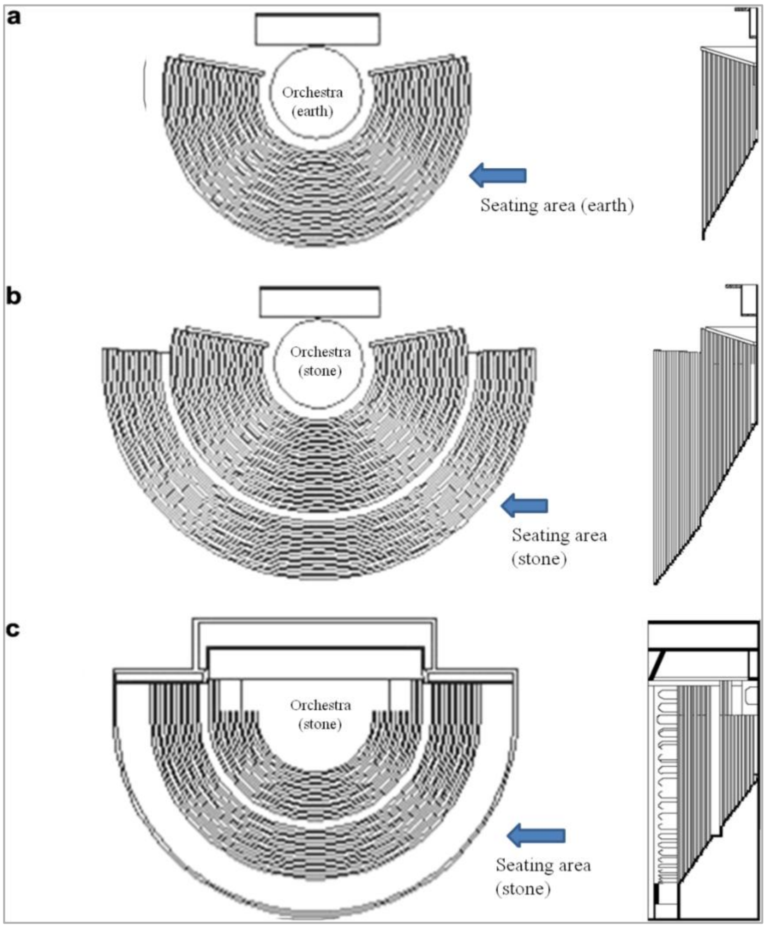

Figure 1.1 Plans and sections of the performance spaces evolved after the 6th century B.C. (Chourmouziadou & Kang, 2008)
(a) Classic Greek theatre (b) Hellenistic theatre (c) Roman theatre.

With these changes, acoustics of the theatres also changed. The orchestra lost its acoustic role as a reflector, since the platform occupied by senators. Also in Roman theatres seating rake increased (30-34°) while size of the theatre became smaller. (Barron, 1993, p. 246)

Finally, in Roman theatres, in particular, a wall behind the performers added to the direct sound, with reflected energy arriving at listeners' ears within a short enough time interval (less than 30 msec) after the direct sound to reinforce both the clarity and loudness of the direct sound. These sound reflecting walls may be thought of as an early first step toward creative room acoustics, with subsequent evolution leading to designing ceiling and wall surfaces of concert halls, opera houses, theatres so that all surfaces contribute constructively to the listening conditions of the people assembled within them. (Cavanaugh & Wilkes, 1999)

Later on, at the ending years of Empire, odeons, smaller and roofed theatres were built in the Greek provinces of Empire as a result of new kind of literary works featuring public declamatory recitals (Breton, 1989).

According to George Izenour, the writer of important reference books on theatre design, the aim of drama had changed and gained the entertaining character and during that time "the artistic aim of theatre became divided into a steadily degraded popular theatre performed outdoors and a more modest elite theatre art performed on a much reduced scale indoors." Also in his opinion "it was within these smaller, more sophisticated, confrontational roofed theatres (odea) that the more traditional, refined theatrical performances took place." These odea were significant examples of Roman architecture and technology. (Izenour, 1990, pp. 71-72)

1.2.3 Mediaeval Theatre

After the Roman Empire, the Church outlaws the theatre and it has taken nearly thousand years to start building new theatres in Europe. The Mediaeval theatre refers the time passed between the fall of Roman Empire and the beginning of Renaissance. Beginning of Mediaeval period drama gained religious character, since the writers (monks and clerics), were inspired from the life of saints and historical legends, while minstrels and jesters performed in streets. (Breton, 1989, p. 7)

But later on, the mediaeval mystery and miracle plays, which began as serious church performances, developed into colourful and theatrical spectacles involving the whole community. At 1200's the theatre moves out the control of church, the plays take place in public places with temporary installations.

One of the most striking props in the plays was the large cart which was often used to transport the actors between locations. The audience would gather at a pre-set meeting point and wait for the first wooden cart to appear. The cart would stop, the players would be perform and then move in the cart to the next location and another cart would arrive to continue the play. (Bellerby, 2008)

1.2.4 Renaissance and Elizabethan Theatres of 16th Century

In 1580, Palladio (1518-1580), commissioned to build a permanent theatre building in Italy. Theatre had a semi-elliptical plan like classical pattern, and the orchestra and proscenium had the same configuration with the Roman theatres. (Figure 1) Theatro Olimpico was designed by the effect of single point perspective art. The theatre had raised stage floor and single point perspective. In 1588 Scamozzi, pupil of Palladio, designs Sabbioneta Theatre. (Figure 1.3) He modifies the semi elliptical shape (the tiers point inwards on a semi-circular plan) and removes the stage wall; also single point perspective backdrop is replaced with multiple point perspectives. (Long, 2006, p. 15)

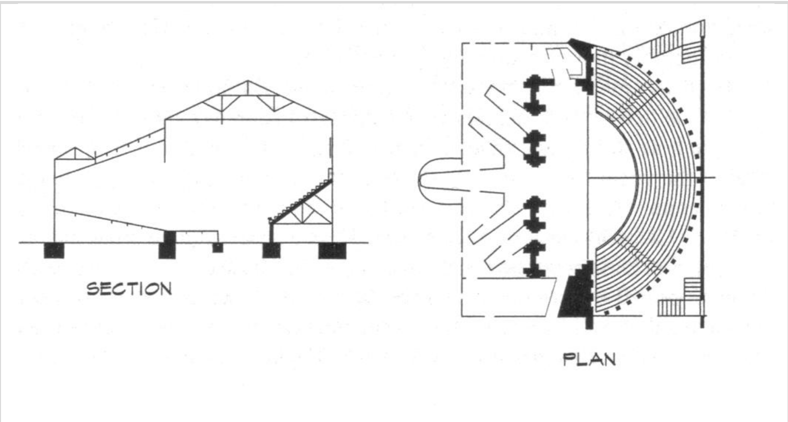

Figure 1.2 Theatro Olimpico, Italy (Long, 2006, p. 15)

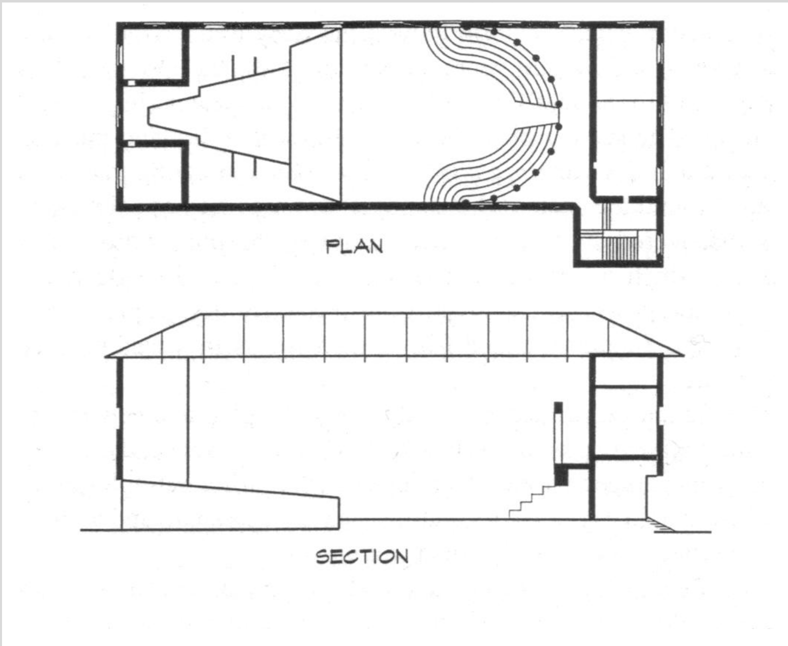

Figure 1.3 Sabbioneta Theatre, Italy (Long, 2006, p. 16)

While these theatres developing in Italy, “in mid 16th century, travelling companies of professional players used to set up their boards in the courtyards of inns; the audience would stand in the yard around the stage or in the galleries that flanked the floors of inn.” (Breton, 1989, p. 8) in England.

First permanent theatres were built in London, in reign of Elizabeth I. They were circular or polygonal timber buildings that have similar layout with temporary original installations. The first one built by James Burbage in 1576. And its style became a model for following examples, including Shakespeare’s Globe Theatre. Theatre designed with three-storied galleries that surround the open stalls. The proscenium stage extended out as apron stage into the middle of the circle. The stage area was partly covered by thatched canopy. Performances were held during the day without a backdrop or curtain. (Breton, 1989)

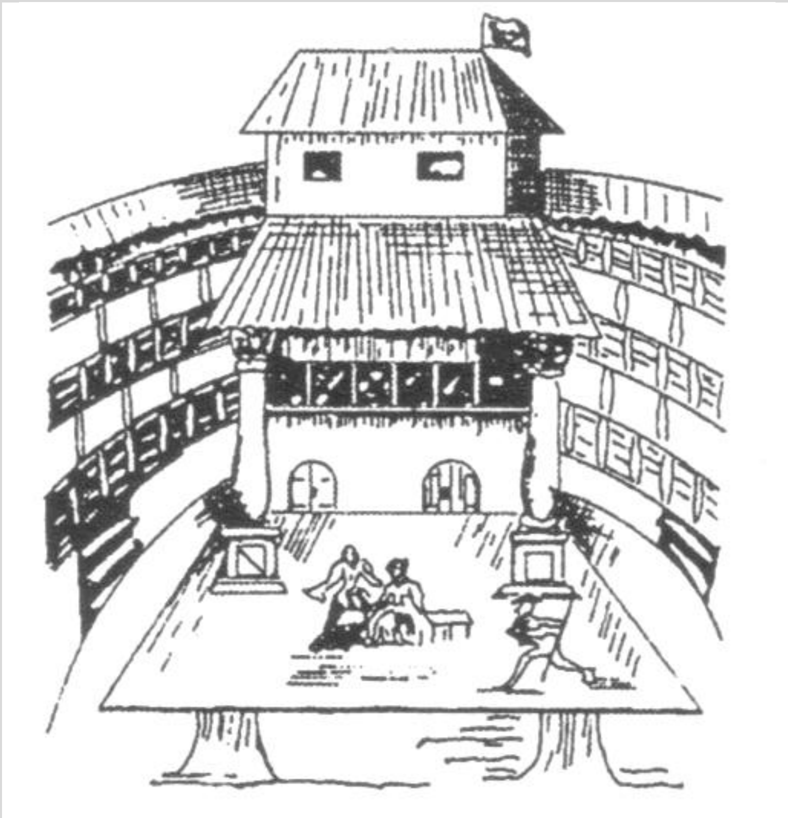

Figure 1.4 The Swan Theatre, London, c. 1600 (Neufert, 2008) (Breton, 1989)

These early theatres were expected to have good acoustics. The side walls provided beneficial early reflections while open-air courtyard reduced reverberation problems. Also, the high walls prevented the theatre from outdoor noise. It is obvious that such simple structures met the need of speech intelligibility that works of Shakespeare required. Otherwise, it would not be possible to understand his long and complicated dialogues for the audience. (Long, 2006)

1.2.5 17th and 18th Century Theatre Architecture in Europe

At the beginning of the 17th century, transformations of the scene design effects the stage as well as the theatre design. At those times new type of a decor, which was created according to the principles of Sabbatini in his Treatise and on Stage and Machinery Construction, was appeared. The use of pictorial decors (using flat frames that centred the perspective by means of successive shots), instead of plastic decors (using angular frames that exaggerated perspective), made possible for actors to enter to the stage without appearing out of scale, and also made possible to change the decor as the various flats slid on rails. The *Theatro Farnese* (Parma, 1628) is evaluated as the first example that had a stage featuring sliding flats. (Figure 1.5) The design of Aleotti produced two results for the theatre morphology; the creation of a stage frame concealing the sliding flats and the reinforcement of the auditorium's longitudinal axis to coincide with the vanishing point of the stage perspective (Breton, 1989, p. 9). The enclosing colonnade behind the seats at Vicenza and Sabbioneta became a two story facade of Venetian windows at the Farnese Theatre. (Forsyth, 1987, p. 12)

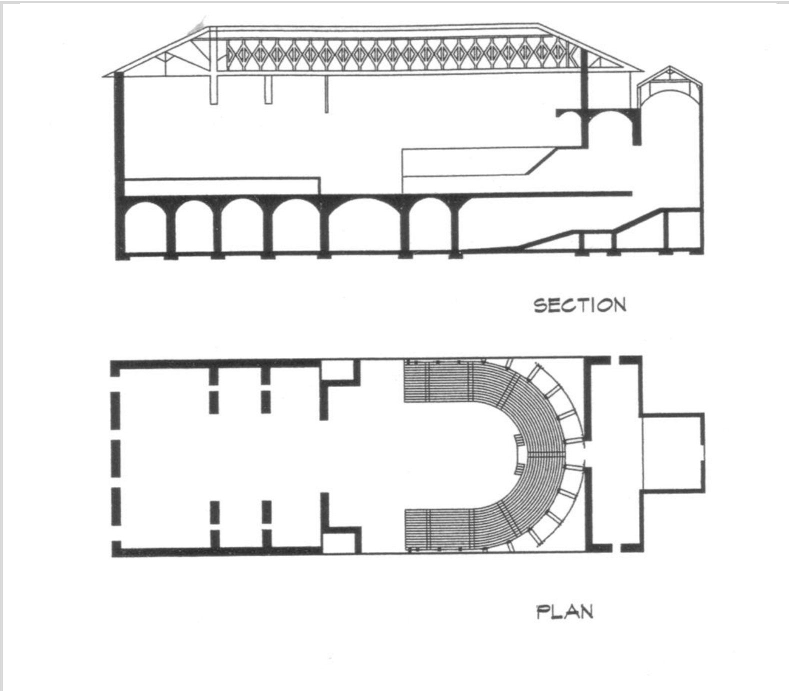

Figure 1.5 Theatro Farnese, Parma, Italy, 1626 (Long, 2006, p. 17)

Later on stage design technology continued its development. In 1641, the use of winches to move scene simultaneously introduced at the *Theatro Novissimo* designed by Giacomo Torelli, in Venice. Also the stage was extended in three directions: the wings were enlarged to allow for the movement of the sliding flats and the stage wall moved further back. (Breton, 1989, p. 9)

It is seen that the characteristics of classical plays also changes during Baroque period. The plays were started to present during the breaks between the musical dances or competitions that were held in the palaces. Academy theatres were not enough to answer the needs of society, which was growing with humanistic thoughts and getting rich. And the kings or feudal lords of the period wanted to build larger theatre buildings to seat more people to watch the plays. (Tuna, 1971, p. 25)

Besides this, some kind of small play (*intermezzo)* which expresses a story with music, dance and especially with songs, becomes popular and starts to be presented in front of the big crowds with its new name "*opera*". (Tuna, 1971, p. 26)

In 1637 Venetian Republic built the first opera house that have a U shape with boxes in place of tiers like the Farnese Theatre. In the auditorium there were differences between people according to their social statues. The stalls behind the orchestra were for commoners while the surrounding tiered boxes were for the use of big families. (Breton, 1989)

In subsequent Italian theatres, the seating layout further evolved into a horseshoe shape to accommodate a larger audience. Splayed fan shape of the side walls also enabled to accommodate ducal boxes at the rear to be seen from side boxes. (Forsyth, 1987) The orchestra, which had first been located at the rear of stage and then in the side balconies, was finally housed beneath the stage as is the practise today. The stage had widened further and now had a fly loft with winches and levers to manipulate the scenery. This became the typical Baroque Italian opera house form, which was adopted by the great opera houses throughout the Europe with little variation for 200 years. (Long, 2006) At its peak point, in the late 18th century, in Italy, opera became commercialised and was henceforth a society venue. People flocked there to see the performances, but above all to be seen. The La Scala in Milan, which is designed by Joseph Piermarini (Breton, 1989), and Fenice in Venice were the most important examples of Italian theatre.

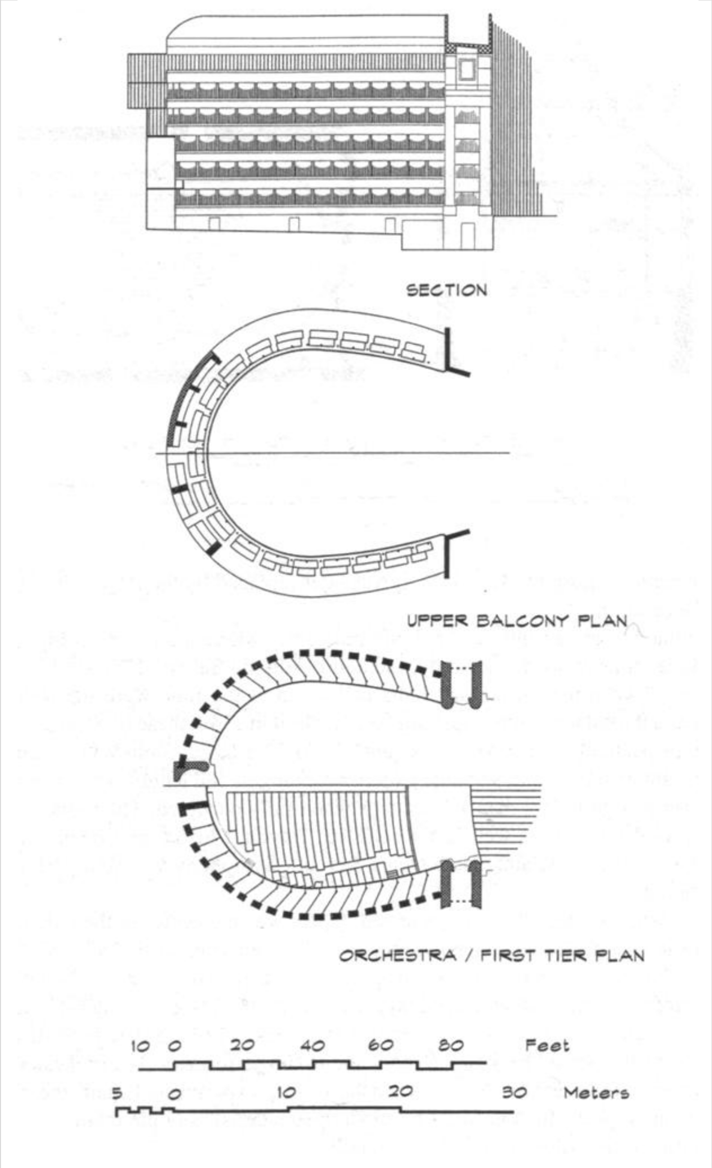

Figure 1.6 Theatro Alla Scalla, Milan, Italy, 1778 (Long, 2006, p. 24)

The development of the theatre in England during the 17th century had some differences. Classical open-air Elizabethan theatres enclosed in this century. They were appeared like baiting yards and cockpits of the period. Inigo Jones built a theatre with the principles of the Palladio’s Teatro Olympico in the Cockpit in Court; however theatre had a curved stage wall.

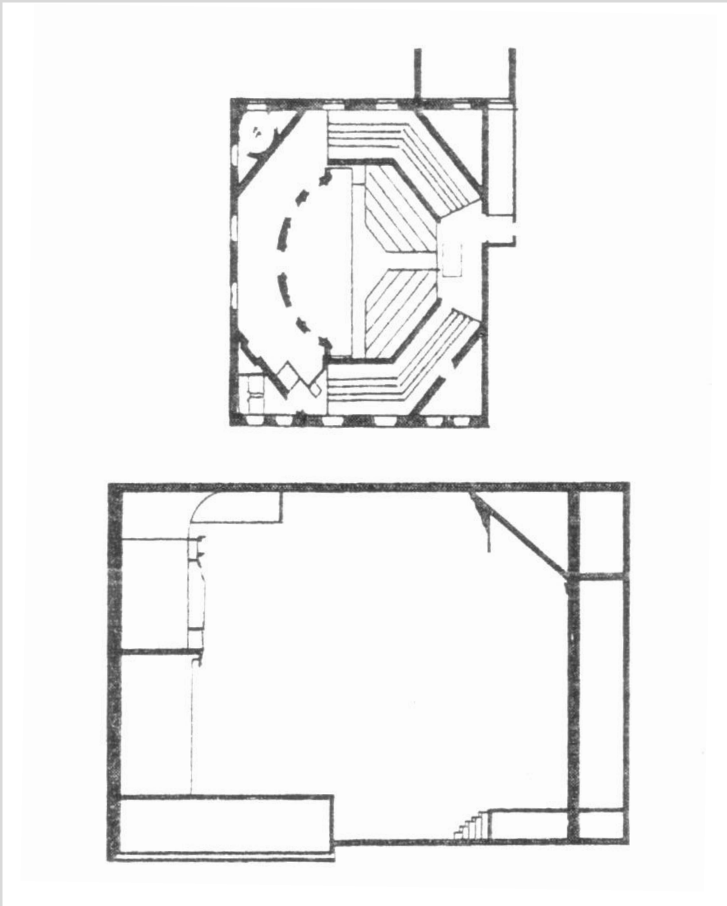

Figure 1.7 Cockpit in Court, architects; Inigo Jones and John Webb, 1630 (Breton, 1989)

In 1642 Parliament outlawed the theatres for 20 years. In 1672, Christopher Wren built the Royal theatre in Drury Lane. Stage design was similar to the Italian examples with sliding scenery, while the auditorium had a different character. Auditorium had a slight fan shape, and two balconies which surmounted the stalls that arranged in curving tiers. Side walls were extended to the proscenium which was extended right into the centre of auditorium. (Breton, 1989) The large undivided balcony of this theatre had become characteristic of nearly all nineteenth century British designs. Between 1661 and 1922, auditorium of Drury Lane theatre had reconstructed many times (no less than seven times) because it was thought as Patent theatre, when theatre numbers were heavily restricted by law. After 1850's, new theatres were started to build again. (Barron, 1993)

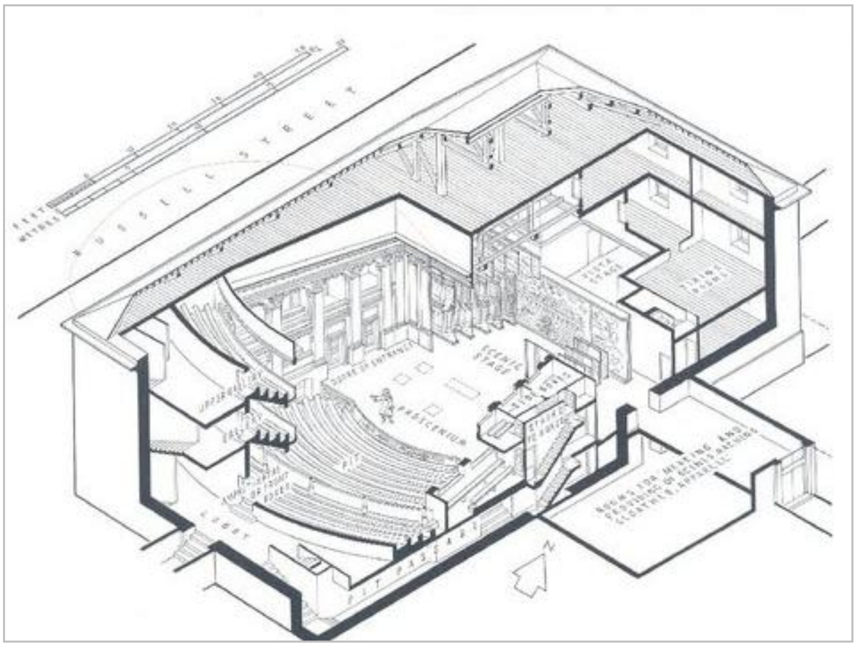

Figure 1.8 Wren's Royal Theatre – Drury Lane, 1672 (http://www.theatrestrust.org.uk/store/assets/0000/0490/H02_DLTR1672_LeacroftDrawing.jpg)

In 17th century theatres in France was affected by the rectangular geometry of tennis courts.[1] In 1645, new theatre design techniques in Italy were introduced by Torelli. But the Italian baroque style and the exposed scenery changes poorly fit to the French classicism. In 1660, a theatre built in Tuileries Palace by Vigarani. Theatre named as "The Hall of Machines" because of the huge depth of the stage.[2] In 1689, Comédie française built by François d'Orbay. Although, the design of theatre was affected by Italian trends, seating layout had national features such as parquet (seats arranged either sides of orchestra), the corbeille (raked tiers to the rear of the stalls) and rows of spectators installed along the side of the stage floor. (Breton, 1989)

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[1] "In the 17th century many indoor tennis courts (constructed for the original royal game), in Paris, London and elsewhere, were converted into theatres when this was found to be a more intensive commercial use for the site". (Forsyth, 1987, p. 12)

[2] "It was here that the French terms 'court' and 'garden' – 'stage left' and 'stage right' – were coined, in reference to the position of the stage relative to the Tuileries." (Breton, 1989, p. 10)

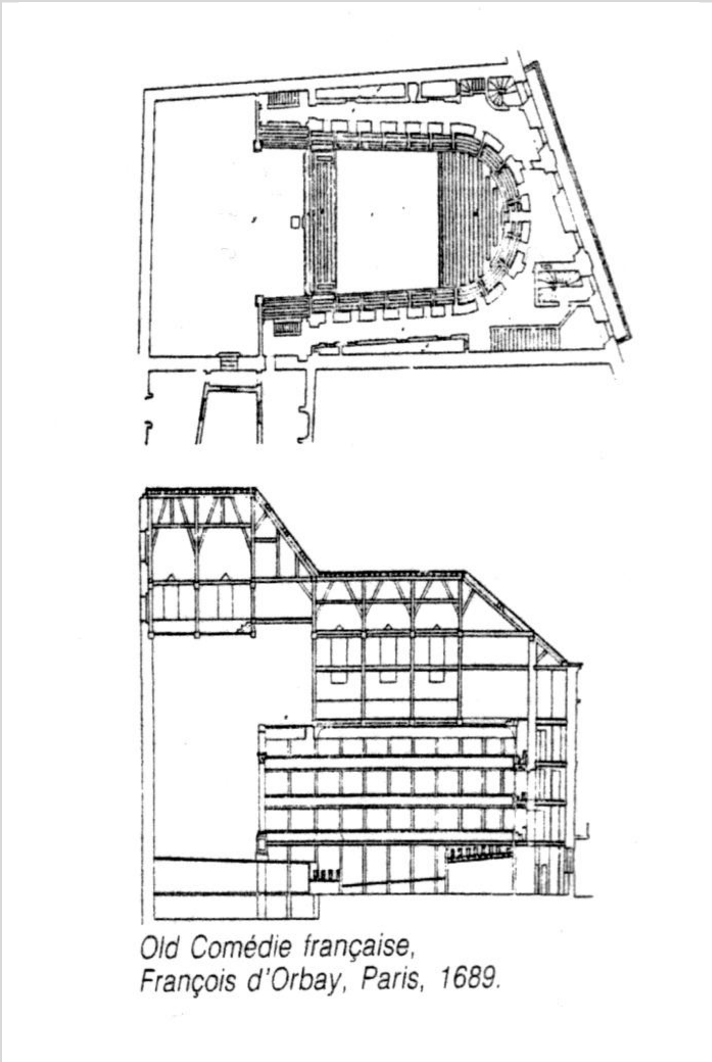


Figure 1.9 Old Comédie française, architect; François d'Orbay, Paris, 1689 (Breton, 1989)

1.2.6 19th Century Theatre Architecture and Wagnerian Revolution

At the end of the 18th century, the subdivision of boxes were started to criticize since they were bad for seeing and hearing as well as immoral. Designers were looking for more egalitarian (*pertaining to equal rights*) seating arrangements which appropriate principles of the French Revolution. With this idea, they returned to classical models for inspiration. However, 100 years later, in 1875, Garnier was still using Baroque form in Paris Opera. This does not mean that architects were not concerning about new design trends. Probably, clients would not accept their new ideas. (Barron, 1993)

Finally, Wagner managed to break traditional rules with his Bayreuth Festspielhaus in 1876 together with the architect Bruckwald. The auditorium designed for the performance of Wagner's operas. He tried to create the features such as the overall harmony and act of participating that Greek theatre had. The stage machinery adopted from the Italian model, while auditorium designed as a fanned amphitheatre to provide same visual and auditory conditions to the audience. (Breton, 1989)

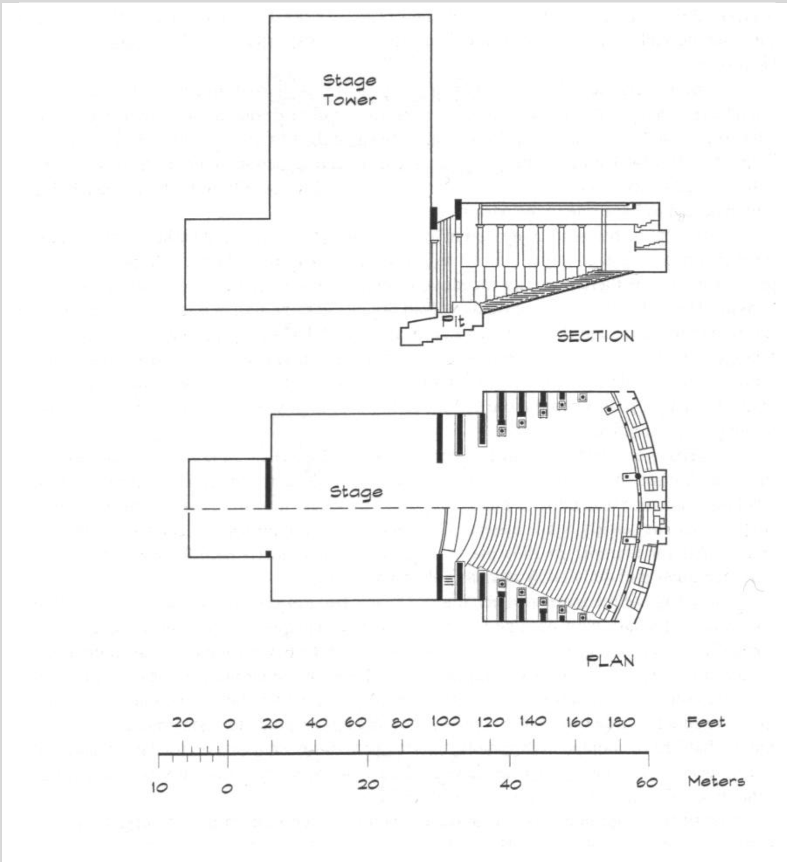


Figure 1.10 Bayreuth Festspielhaus, Germany, 1876 (Long, 2006, p. 26)

Richard Wagner was a revolutionary in politics as well as in music. He wished his orchestra to be invisible, so it was lowered and placed partly below the stage. But those in the boxes could see down into this pit, so he decreed the boxes' removal, an action that also satisfied his social objective of eliminating class snobbery and visual distractions. Finally, in order that the spectator's concentration be complete, Wagner decreed that all seats must face the stage in a single level of stadium – type seating without aisles – the world's first "continental" seating format. (Pilbrow, A Lively Theatre, 2006)

While Wagner introducing his new theatre in Germany, new theatres were started to build in England, at the 1850's and till at the beginning of the 20th century approximately six new British theatres were opening each year. (Barron, 1993)

Steel was introduced as a building material in theatres at the end of 19th century. By using steel, it was possible to built deep, large span galleries that allowed seating more people close to the stage, without needing obstructive columns as in the past, especially in opera houses and concert halls. While steel was changing the auditorium, the development of lighting was changing the stage design. Before the turn of the century, invention of mains electricity made the canvas flats looking unrealistic, as a result, three-dimensional stage design was introduced in 20th century. In parallel, thrust stage was developed and actors started to play at the same space with the audience. Because it is thought that the actors were restricted behind the proscenium arch when the use of limelight and gas lighting had introduced. (Forsyth, 1987)

1.2.7 20th Century Theatre

The development of the drama theatre has been varied during the 20th century. Four types of design trends are described in general:

Auditoria derived from the Italian model or the Wagnerian amphitheatre, where the flexible proscenium toned down the stage/auditorium duality,

Auditoria based on the Elizabethan model integrating stage and auditorium in a common space,

Convertible auditoria in which this relationship was redefined for each performance,

The exodus to places not originally intended for theatre. (Breton, 1989)

The innovations of Richard Wagner in Bayreuth were especially followed by American theatre designers. After about 1910’s vast fan shaped multi-purpose auditoria were started to build to accommodate very large audiences. But such big volumes are considered as less than ideal for virtually everything except perhaps cinema. (Forsyth, 1987)

> One of America's most famous drama companies is housed in the Goodman Theatre in Chicago (1927). It was directly based on Wagner's example. The result was a loss of personal contact between actor and audience that for almost seventy years has hampered actors and directors alike. In the UK the famous Birmingham Rep built a new frontal theatre in the early sixties. Before the first season was over, the actors tried to come out through the proscenium, seeking to rediscover their lost audience. (Pilbrow, 2000)

To break the barrier represented by proscenium arch, many variations of arena and open stages were designed in Europe, Russia and America. One of the first examples of thrust stage (with the audience on three sides) theatre was the Grosses Schauspielhaus designed by Hans Poelzig in Berlin, of 1919-20. This huge building was a former circus originally and converted a theatre. But, it was used for a short period because of bad acoustics. Later on, the thrust stage, modelled upon the Greeks, was adopted by the English theatre director Sir Tyrone Guthrie at a smaller scale. First example was Assembly Hall in Edinburgh. It was built in 1948, and Guthrie wanted to recreate an Elizabethan stage. Following examples were; the Festival Theatre (designed by Routhwaite & Fairfield in 1953-57), Stratford Ontario, the Festival Theatre, Chichester (designed by Powell & Maya in 1961), the Tyrone Guthrie Theatre, Minneapolis (1963), the Crucible Theatre, Sheffield (1971). (Forsyth, 1987) (Pilbrow, 2000)

Although the open stage forms have the advantage of giving the audience sense of involvement in the drama, it can be said that, from the actor’s point of view it is difficult to command the audience over a wide angle. In addition, fire regulations strictly limit the stage/set materials where the stage is not separated from the auditorium by a fire-resistant curtain. And nonetheless, tendency in recent years, even in proscenium type of theatres to reduce the sense of being separated two as auditorium and stage. (Forsyth, 1987)

Developments in theatre architecture show that every stage and auditorium type has its advantages as well as disadvantages. The aim has been to catch the magical atmosphere in theatre, throughout the history. Amongst all the diverseness, the last period of theatre design described by Pilbrow:

> At the end of the 20th century, theatres around the world are returning to the principle of clustering audiences as closely to the stage as possible--not as slavish imitations of the past, for sightlines must be improved to modern standards, but nevertheless bringing audiences into a vivid, lively relationship to each other and the stage. If theatre is to survive and flourish, it must offer audiences some unique quality--and it can: Liveliness, the interaction of live actors and living audience, is the one element that theatre alone possesses in the face of all its multimedia competition. While there is no ideal form of theatre, every type, from proscenium to experimental open-stage studio, will benefit from a dynamic relationship between actor and audience that fosters the work of playwright, composer and performer. (Pilbrow, A Lively Theatre, 2006)

CHAPTER TWO
FACTORS THAT AFFECT THE QUALITY OF THEATRES

"Drama theatres, more than any other building type, must as a matter of functional necessity embody a range of intangible and relatively indefinable architectural qualities such as mood, intimacy, magic and memory." (Forsyth, 1987, p. 125).

Theatre is a three dimensional space, which have quite complicated design process, as it is indicated by Forsyth. This process is mainly expected to create an environment that all audience members should be able to comfortably and clearly see and hear the performance in order to fully experience the event's intended effects, in other words they should have the opportunity for making a connection between actors and themselves.

Obtaining unobstructed sight lines from all seats to the stage to be able to allow full view of performers and scenic elements, as well as unobstructed and direct sound propagation are main design considerations during the theatre design process. In addition, to design a theatre with these abilities some criteria must be taken in consideration such as type of production that is put on the stage, building codes that limits the density of seating or requests safety curtain, visual limits of human eye, decision of seating capacity, and so on. But on the other hand, it is not possible to mention about a design guide explaining all the needs and giving absolute solutions such as the best form or best volume...etc. This complexity is also explained by Hugh Hardy very clearly:

> "Whatever the audience-performer relationship, auditorium design begins with the organization of the seating levels. These must be arranged to give the best possible sight lines for the audience with the shortest distance to the stage. Many relationships between audience and performer are possible, some formal and fixed, others informal and flexible. Choosing the right configuration is an exercise in three dimensions (....) In short, there is no right or wrong relationship between audience and performer. Each has its virtues, each its limitations. Each must be considered in relation to the programmed capacity, production style, and scale of

intended presentation. For instance, a wide proscenium may be ideal for spectacle, but the resulting seating configuration will hinder intimate drama. A thrust stage may be perfect for the presentation of plays, but it is awkward for the opera. Whatever the production approach, the hope is to strike a balance between distance from the stage and angle of viewing so that the individual members of the audience feel themselves part of a whole. The goal is to insure audience members are aware of each other, sensing they are gathered to witness an event together." (Hardy, Hugh; Hardy Holzman Pfeiffer Associates, 2000, s. 18-19)

So, in this chapter, it is aimed to have a general idea about design parameters of a theatre.

2.1 Type and Scale of Production

Although, there are several approaches for theatre design in different countries – for instance, European countries usually have different production traditions as well as building dimensions from theatres of Unites States– design of a theatre should be start with defining the type of production, since it affects the capacity, stage design, acoustical and visual requirements of venue.

Different performances have different scales. Ballet involves group of dancers and needs wide-open spaces, while grand opera needs big sets, voices and casts. Some plays, like the Greek Classics or Shakespeare, have an epic scope while intimate kitchen dramas contain handful of characters (Dachs, 2006). All these different productions have different involvement degrees between audience and play, and need different scale of stage and auditorium space in addition to different visual and acoustical requirements. To have a more clear idea, the scales of production types, which are possibly provided in a theatre, are listed below:

Drama: The average straight play seldom has a cast of more than 12, but it can be from 2 to 20. On the other hand, some plays, such as the Shakespeare histories, have large casts with many extras.

Grand Opera, full-scale ballet, musicals, and pantomime: These activities often involve singers, dancers and chorus. The style of production and scenery is usually spectacular and generally implies a proscenium stage form.

Chamber opera, chamber ballet, music hall and variety, cabaret, plays with music: The cast is not likely to be more numerous than for straight drama, but proper arrangements must be made for musicians (The Association of British Theatre Technicians, ABTT, 1972).

2.2 Seating Capacity

One of the most important issues of an early design stage of a theatre to decide the number of seats required. The capacity should be determined by the acoustical and visual needs of the production type (Aural and visual limitations, sightlines, acoustics, circulation and seating density, size and the shape of the stage... etc.). Seating capacity is also in relation with the economics of theatre building. Simply, more seats mean more money. But usually the problem is not so easy to solve, because the attention of people against the play is not a certain issue. Sometimes all the seats may not be sold while sometimes demand can be more than capacity.

Table 2.1. Limits of seating capacity according to production type (Dachs, 2006)

Production type	**Seating capacity**
Small community or experimental theatres	150-200
Regional drama theatre	400-700
Drama theatres in a major community	600-900
Small scale dance or opera	500-1500
Large-scale opera, ballet and multipurpose theatres for touring musicals	1800-2500

The capacity changes of auditoria according to production type are described in table 2.1. And also, theatre buildings are classified as small, medium, large according to their capacities (table 2.2). It is possible to see some differences for seating capacity of different kind of theatres in different references. But their main aspects are very similar. The capacity of a theatre also depends on population of the city or town where the building serves (table 2.3).

Table 2.2. Definition of room size according to the seating capacity (ABTT, 1972)

Definition of theatre size	**Seating capacity**
Very Large	1500 or more seats
Large	900-1500
Medium	500-900
Small	Under 500 seats

Table 2.3. Seating capacities by category of building (Appleton, 1996)

Metropolitan centre	
Dance theatre	1200-1500
Drama theatre / Commercial theatre	750-900 with proscenium format
	500-1200 with open stage formats
Small and medium scale drama	150-350, 350-500
Regional centre	
Touring theatre	900-1400
Drama theatre	750-900 with proscenium format
	500-1200 with open stage formats
Small and medium scale drama	150-350, 350-500
Town centre	
Community theatre	150-350
Amateur theatre	150-350

It is not recommended to provide some more seats, for example, for Saturday nights, if the seats remain empty in other nights, because the empty seats have negative effect both on audience and actors. A Full house and difficulty in getting tickets are considered as the best possible advertisement and are an incentive for the public to go on the less popular days. (The Association of British Theatre Technicians, ABTT, 1972). It is also recommended to extend performances over a longer period rather than increasing the capacity over a short duration. (Appleton, 1996, p. 132)

2.3 Stage Design

One of the most important criteria for designing a theatre is stage design. Besides physical dimensions, the form of the stage is very important since the theatre form is developed and also classified mostly according to the type of stage. The open stage and proscenium or picture frame types are used for drama theatres.

As mentioned before, there are different types of stages that affect the audience-actor relationship directly. Although proscenium or picture-frame stage has been very common in recent past, open stages are designed to improve the degree of relationship between audience and play. The open stage can be described as an arrangement that the performance and spectators share the same space. (Appleton, 1996) There are different types of open stages and they usually differ with the encirclement degree of the stage by the audience.

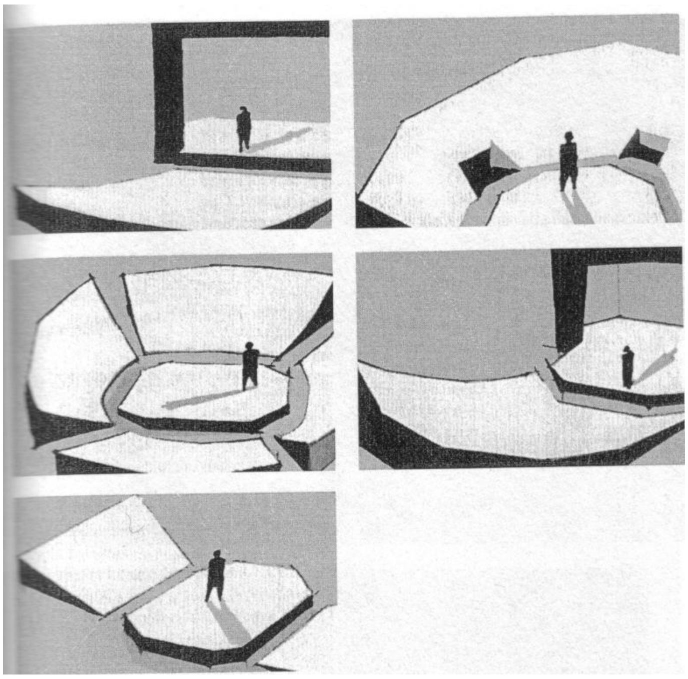
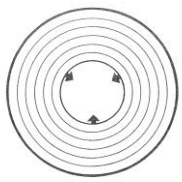
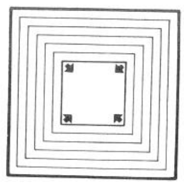
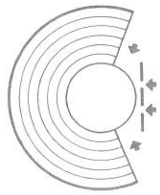
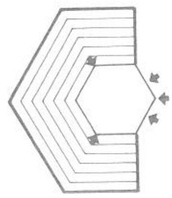
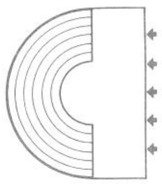
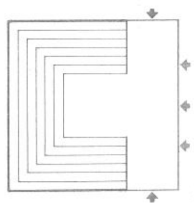
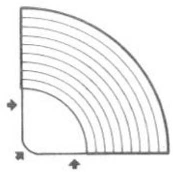
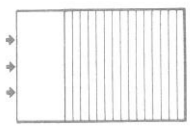
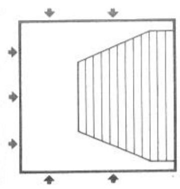
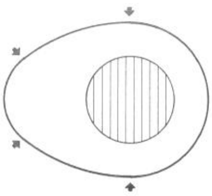


Figure 2.1 different stage types- drawings by Ming Cho Lee
(Pilbrow, An auditorium and Stage Design Guide, 2006)

2.3.1 *Open Stage Forms According to Encirclement Degree by the Audience*

360° Encirclement; the audience surrounds the stage completely. Other names of this type of stage are theatre-in-the-round, island stage, arena stage and centre stage. (The Association of British Theatre Technicians, ABTT, 1972) (Pilbrow, 2006)

Table 2.4 Open stage forms (The Association of British Theatre Technicians, ABTT, 1972)

360 ° encirclement - arena stage	210° encirclement – Greek theatre
 	 
180 ° encirclement – thrust stage	90° encirclement
 	
Zero encirclement – end stage	Space stage
	 

210° - 220° Encirclement; The classical Greek and Hellenistic theatres were examples of this type, where the main acting area is at the focus of seating. (The Association of British Theatre Technicians, ABTT, 1972)

180° Encirclement; Roman theatres were examples of this type and later on Renaissance theatres followed the pattern. The emphasis moved towards the back wall, which now forms the boundary of acting area. More recent forms of this type are named as thrust, three-sided or peninsular stage. On the other hand, modern examples vary the degree of encirclement and they differ from the older examples.

(The Association of British Theatre Technicians, ABTT, 1972) *Courtyard Theatres* are also usually included in this type. The rectangular auditorium surrounded by two or three balconies is thought as modern version of the Elizabethan, Restoration and Georgian theatres of England. (Pilbrow, An auditorium and Stage Design Guide, 2006)

90° Encirclement; this type is a wide-fan arrangement that has similarities with the proscenium stage in point of performance technique. This arrangement allows most of the performance to be seen against stage walls or scenic background instead of spectators. (The Association of British Theatre Technicians, ABTT, 1972)

Zero Encirclement; with its usual name *end stage* is simply a proscenium theatre without a proscenium arch and without the working areas needed to deploy scenery. In this type of open stage as much as the acting area and the audience are placed in the same space. (The Association of British Theatre Technicians, ABTT, 1972)

Space Stage; in this type, audience is surrounded completely or partly by the stage. It is also called as wrap-round stage or calliper stage. (The Association of British Theatre Technicians, ABTT, 1972)

2.3.2 Proscenium stage

The term ‘proscenium’ means *before the scene* and at the beginning the acting area was the forestage in front of the proscenium. In 19th century, with the changes of lighting and scenic demands and growing number of seats, plays started to be performed behind the proscenium opening. Finally proscenium type stage has become a partially or fully separated acting area from the audience by a wall with an opening, through which the performance is seen. But in recent years, it is discovered that the intimacy, which is desirable for a theatre, is not obtained only with an open stage, also, it can be obtained by seating the audience in a three-dimensional space. (Pilbrow, An auditorium and Stage Design Guide, 2006) This type of stage allows making elaborate scenic effects and transformations that can be concealed from the audience. (The Association of British Theatre Technicians, ABTT, 1972)

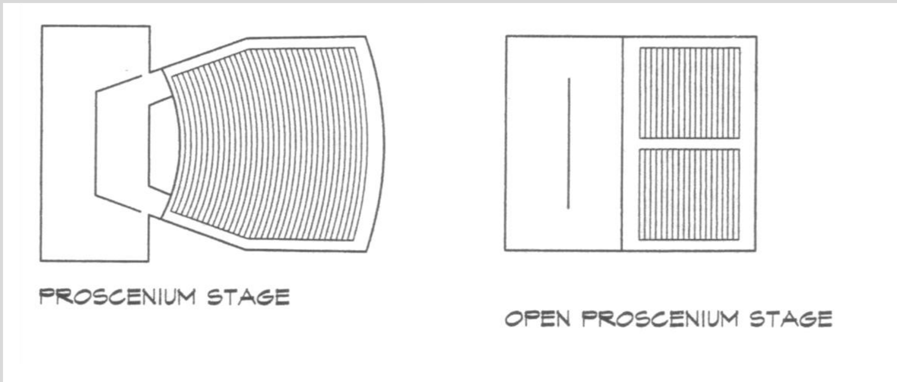


Figure 2.2 Proscenium stage (Long, 2006)

To be able to perform the play at least partially in the same space with the audience, usually *Forestage or Apron Stage* is designed. Forestage is described as the part of the stage between setting line and stage riser, or edge of the stage if there is no riser. When it is extended into the auditorium, it is named as an apron stage and it can make an open stage effect. (The Association of British Theatre Technicians, ABTT, 1972)

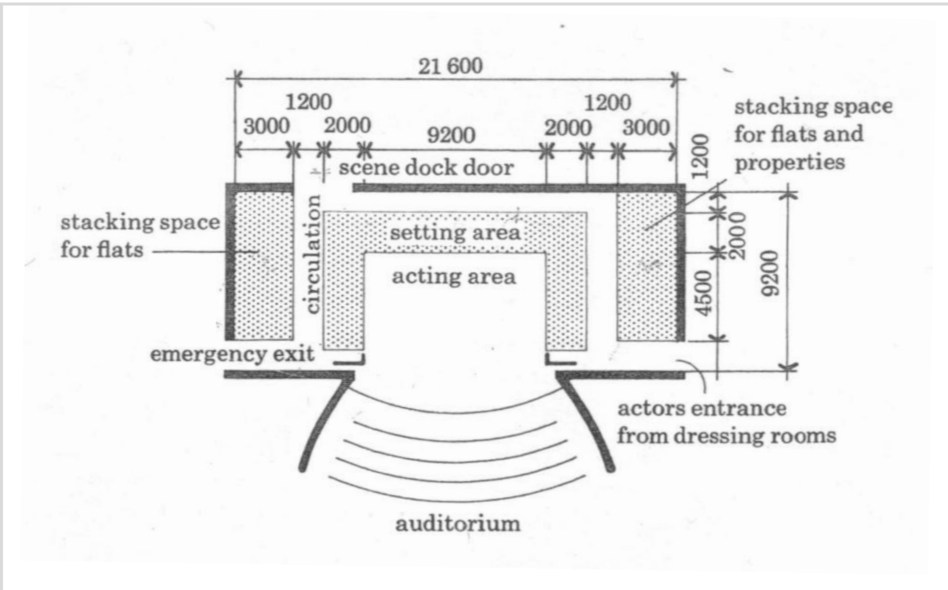


Figure 2.3 Recommended minimum dimensions for proscenium stage for medium size theatre (Appleton, 1996) (The Association of British Theatre Technicians, ABTT, 1972)

There is a wide spectrum of modern proscenium theatres. These range from the small drama theatre to the largest opera house. They may or may not have an orchestra pit or a forestage, often of variable size. Some proscenium dimensions are shown in table 2.4. (Pilbrow, An auditorium and Stage Design Guide, 2006)

Table 2.4 Dimensions of proscenium opening (Pilbrow, 2006)

	Proscenium width (ft)	**Proscenium height (ft)**
Drama theatre	30-36 in Europe (40-45 in the U.S.)	24-32
Opera house	45-55	30-45 or more

2.4 Auditorium Design

While designing the auditorium (the container for the audience) there are many factors that must be taken into consideration. The requirements of the auditorium change according to performance type and scale, stage form and dimensions, seating capacity. After deciding them, auditorium can be shaped by considering visual and aural limits, sightlines and acoustical requirements.

2.4.1 Form and Volume of Auditorium Space

In fact, all the design criteria, which are explained in this chapter, more or less affect the other ones. Aural and visual characteristics of the space are shaped according to the type of production, and these characteristics affect the shape and dimensions of auditorium. Whatever the purpose of the auditoria, the main concern is to seat as much as possible audience having good acoustical and visual conditions. In his book, Forsyth also emphasizes that the most important factor for theatres is its ambience that should encourage actor-audience relationship. “A theatre’s success undoubtedly relates to its three dimensional form, and a performance which is successful in one theatre will not necessarily be equally so in another.” (Forsyth, 1987, p. 125)

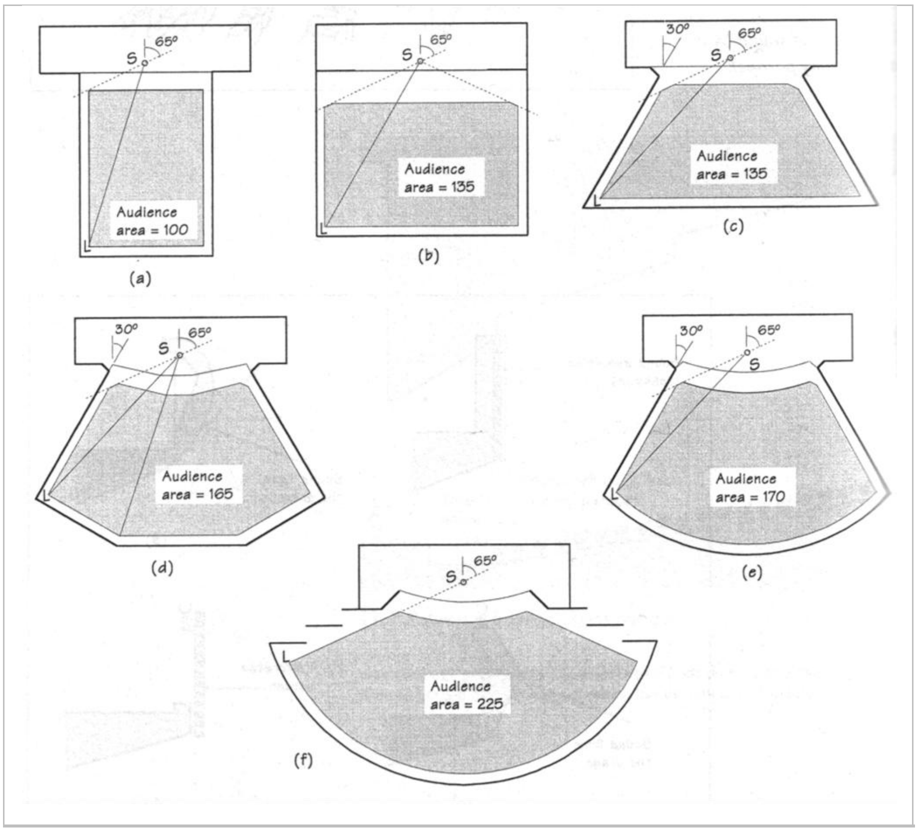


Figure 2.4 Relative audience areas of rectangular and fan shaped halls. All areas are normalized with respect to (a), which has been assumed to have an audience area of 100 units. The maximum speaker- listener distance, as represented by line SL, is the same in all shapes. (Mehta, Johnson, & Rocafort, 1999)

And as mentioned in previous chapters, most of the time design of auditoria has been influenced by the designs of the older examples. Considering the history of theatre architecture, earliest examples that we know are Greek and Roman open-air theatres. Later on, similar forms had been covered with a roof during the renaissance. In Baroque period, big opera houses with horseshoe plans and side boxes became popular. During 19th Century, best concert halls were built in shoebox form while fan shape was becoming one of the most popular shapes for the theatre design, because it allows accommodating more seats close to the stage by comparing the rectangular form. Especially since the second part of 20th Century, theatre designers have been looking for better relations between actors and audience. But it is quite a hard job to achieve, since there are endless possibilities of room shape selection. Briefly, theatre architecture has been developing by searching new forms for the best actor-audience relationship. According to Richard Pilbrow (Theatre Project Consultants) "...Almost every variation of the actor-audience relationship has been explored in the twentieth century, and each has its own value.” (Pilbrow, An auditorium and Stage Design Guide, 2006)

One of the most important factors that defining the quality of theatre space, is dimensions in other words volume of the hall. Auditorium volume is important especially, for the good acoustical design, since it affects the acoustical characteristics of the room, with the effect of shape. Effects of the shape and dimensions on the acoustical properties of a theatre will be discussed more detailed in title of acoustics for speech.

2.4.2 Design of the Seating Layout

Design of the seating layout is an important part of auditorium design and mainly depends on the selected stage format in other words, the stage-audience relationship as well as aural and visual limitations, number of levels and sightlines. After these decisions, seating layout is shaped by the design of an individual seat, seating density and geometry. Also building codes for safety affect the seating layout design, which is very important in terms of both visual and acoustical design.

2.4.2.1 Design of Seat

At the heart of any auditorium is the seat itself: its dimensions, spacing and construction. Comfort is clearly a high priority. Audience members everywhere, with each generation, seem to be getting physically larger. But architect should find a balanced design. Live theatre requires an alert, participated audience, contrary to the relaxed and passive experience of cinema. To achieve this, seats must be as close together and as upright as comfort allows. The smaller the comfortable seat can be, the more people can be seated close to the actor and the greater the chance of an exciting theatre experience. (Pilbrow, An auditorium and Stage Design Guide, 2006)

The design aim is to provide an appropriate standard of comfort during a performance. The range of human body dimensions wide and also tolerance levels vary between generations and indeed between performing arts: the young can tolerate simple seating found less comfortable by older age groups, whereas those attending concerts of classical music appear to expect a level of comfort higher than those at a drama performance. The dimensions of a seat are generally based on a median characteristic of the anticipated users, which varies by age and also by nationality. (Appleton, 1996)

2.4.2.2 Seating Geometry

While designing seating geometry, one of the most important criteria is making the seating area focused towards the performance. Most common types are straight and curved row forms. Further forms are the angled row, the straight row with curved change of direction. Curved rows are thought as more efficient in terms of numbers within a given area but may increase construction costs.

2.4.2.3 Seating density

Seating density depends on the dimensions and features of the selected seat format. After the seat selection the distance between the rows should be considered as well as the number of seats in a row and gangways. In addition, building codes, especially fire safety regulations limit the number of seats in a row and regulates the distances between rows and widths of gangways.

Number of seats in a row

With traditional seating the maximum number in a row is limited to 22 if there are gangways at both ends of the row, and 11 if a gangway is on one side only. Continental seating[1] refers to rows of seats with more than 22 seats extending to the side gateways and more exits than traditional seating. Continental seating is more

[1]The term continental seating is generally used to describe seating in which each row extends virtually the full width of the auditorium without any intersecting gangways. (The Association of British Theatre Technicians, ABTT, 1972)

appropriate with the proscenium format to achieve side wall to side wall rows of seats. With formats where the audience surrounds the platform/stage it is less applicable and gangways within the seating become inevitable. (Appleton, 1996) The great advantage of continental seating is that none of the best viewing positions are lost to gangways, and from the actor's point of view the audience is undivided. (The Association of British Theatre Technicians, ABTT, 1972)

Row to row spacing

Spacing is conditioned by the distance between the leading edge of the seat (in upright position, if tippable) and the rear of the back of the seat in front. The critical dimension is the vertical clearway which enables people to pass along the row. For traditional seating the minimum is 300 mm and this dimension increases with the number of seats in a row. For continental seating the clearway is to be not less than 400 mm and not more than 500 mm. Legislation also dictates the minimum row to row dimension at 760 mm: this is usually not adequate and the minimum should be 850 mm for traditional seating. (Appleton, 1996)

Gangways

The widths of gangways within seating layouts at each level within an auditorium are determined by their role as escape routes and the number of seats served. The minimum width is 1100 mm. The gangways can be ramped up to a ratio 1.10 and 1.12 if used by persons in wheelchairs. Steeper slopes must have regular steps extending the full gangway width. (Appleton, 1996)

2.4.2.4 Seating rake

To make the stage visible for the all spectators, designing a sloped floor is one of the most effective solutions. Designing a raked seating area also affects the amount of direct sound that reaches the listener. For this reason, this subject will be explained more detailed in following sections.

2.5 Design Considerations for Good Visual Conditions

It has been said that 87 percent of our perception is based on sight (fhwa). Henceforth the good visual conditions for the spectators in a theatre space to be able to understand and to be involved in the play is one of the main considerations. Another research is showing the relation between seeing and hearing and also emphasizes the importance of having good visual conditions. The research on sound localization demonstrated that blindfolding of normally sighted subjects results in deficits in accuracy in horizontal plane sound localization. (Abel & Paik, 2003, p. 230) The mentioned juxtaposition between our eyes and ears is considered as Mother Nature's way to help coordinate our hearing with seeing. (Mehta, Johnson, & Rocafort, 1999)

The relation between good hearing condition and good vision of speaker (or the stage) is also underlined with a dictum: "If one can see the speaker well, one is likely to hear the speaker well." (Mehta, Johnson, & Rocafort, 1999)

On the other hand, it is not possible to say that if all the seats have perfect sight lines the result will be the best auditorium. Besides this it is accepted that all seats may not have equal visual conditions. Sometimes seats with bad sight lines by comparing to other ones can be included to keep the sense of envelopment that has created within the auditorium.

2.5.1 Limits and Properties of Human Vision

To be able to decide what is necessary for designing good view from occupied seat, it could be useful to understand the properties of human vision. Although human vision depends on many factors, most important ones for theatre design are distance between the actor and spectator and horizontal and vertical visual field of eyes (limits of sight).

2.5.1.1 Visual Acuity and Distance

Visual acuity is the spatial resolving capacity of the visual system. This may be thought of as the ability of the eye to see fine detail. Visual acuity is limited by diffraction, aberrations and photoreceptor density in the eye. Also visual acuity depends on different factors such as refractive error, illumination, contrast and the location of the retina being stimulated as well as the distance which is important for the spectators in drama theatres to be able to see the facial expressions of actors on stage. (Kalloniatis & Luu, 1996)

The eye has a visual acuity threshold below which an object will go undetected. This threshold varies from person to person, but as an example, the case of a person with normal 20/20 vision can be considered. The standard definition of normal visual acuity (20/20 vision) is the ability to resolve a spatial pattern separated by a visual angle of one minute of arc. (Larson, 2001-2008)

To be able to obtain a general idea it can be useful to understand sensitivity of human eye. It is found that when visually inspecting an object for a defect such as a crack, the distance (d) might be around 30 cm. This would be a comfortable viewing distance. At 30 cm, the normal visual acuity of the human eye is 0,0088646 cm. According to the visual acuity tests it is accepted that if one can read the letters on the 9^{th} row, which are approximately 9 mm high, from the distance of 6 meters, his eye is accepted as healthy. (Larson, 2001-2008)

When considering theatre design, the limit of the seeing the facial expressions of actors is important. This issue is also emphasized by an actor, Jane Alexander: “Ideally, every member of the audience should be able to see the actors’ eyes. Eyes are ‘the windows of the soul’, and expression and emotion are paramount in an actor’s delineation of a role.” (Alexander, 2000, p. 52)

There are some small differences in different references for acceptable values for the maximum distance between stage and furthest seat. According to the Long, “if the subtle facial expressions of theatrical performance are to be appreciated, the furthest patron should be seated no more than about 80 feet (approx. 24 m) away" (Long, 2006, p. 698). Similarly, according to the Neufert the distance between last row and stage should not exceed 24 m. (Neufert, 2008, p. 461) On the other hand, most references accept that maximum distance should not exceed 20 meters (approx. 65 ft) (Appleton, 1996, p. 109), (Pilbrow, An auditorium and Stage Design Guide, 2006, p. 36), (Mehta, Johnson, & Rocafort, 1999, p. 231) to see small gestures.

2.5.1.2 Visual Field in Vertical Plane

The visual field is defined as "part of a space measured in angular magnitude that can be seen when the head and the eye are absolutely still." In normal viewing conditions human eye has limited angle of sight without head movement. The standard line of sight is not horizontal and it is 10° below the horizontal while standing, and 15° while sitting. The magnitude of the optimum viewing zone for displaying materials is accepted as 30° below the standard line of sight. (Panero & Zelnik, 1979)

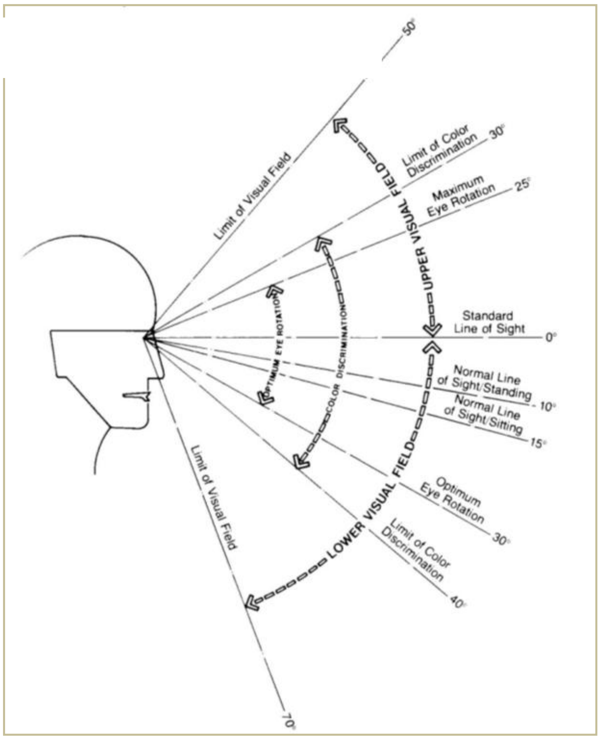


Figure 2.5 Vertical visual field of human eye (Panero & Zelnik, 1979)

2.5.1.3 Visual Field in Horizontal Plane

Similar to the vertical sight line, human eye has limited horizontal angle of sight without head movement. The visual limit of the individual eye is termed “monocular vision” and in this field objects appear unclear and diffused. When an object is observed by both eyes simultaneously, the visual fields of each eye overlaps by creating a central field and is termed as “binocular vision”. Within this field, which is 60° in each direction, sharp images can be transmitted to the brain, depth perception occurs and colour discrimination is possible. Depending on the particular colour, it begins to disappear between 30° and 60° of the line of sight. (Panero & Zelnik, 1979)

According to the Neufert, good visual condition can be achieved at 30° horizontal angle with a little eye movement. If there is a little eye and head movement together, the horizontal viewing angle will be 60°. Maximum viewing angle without head movement is 110° and for the greater angles, objects start to be blurred and this situation causes the sense of insecurity. (Neufert, 2008)

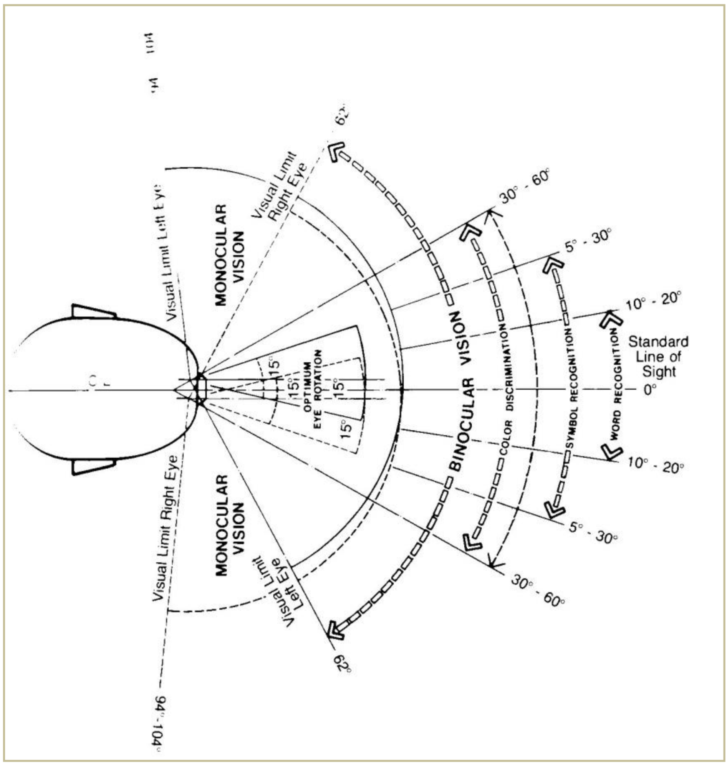


Figure 2.6 Horizontal visual field (Panero & Zelnik, 1979)

Without head movement the arc to view the whole of the performance area on plan is remarked as 40° from the eye in some references. And acceptable head movement degree is debatable, for example, for side galleries where the spectators should turn their heads to see the performance. (Appleton, 1996) (Saher, 2001)

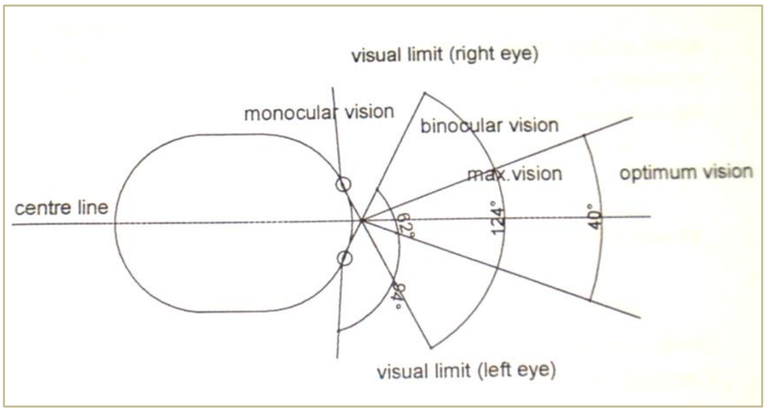


Figure 2.7 Horizontal vision (Saher, 2001)

2.5.2 Factors that Affect the Sightline Design

Decisions that made during the design process, affect the visibility of the stage, actors and scenic elements by the spectators. Visual quality of auditorium mainly depends on three factors; seating rake, width of the stage opening and viewing distance. (Neufert, 2008) In addition to these factors other dimensions and type of stage, form of the auditorium space, and staggered seating design when the rake is not enough can be considered as other factors.

2.5.2.1 Anthropometry

The sightline calculations based on anthropometric studies since the height of the eye above the ground while sitting and the height of the top of the head above the eyes are considered during the sight line analysis. On the other hand, extreme situations like a large person sitting in front of the small one are very hard to consider mathematically.

2.5.2.2 Vertical Sightlines and Seating Rake

To be able to have unobstructed sightlines, it is important to evaluate the section(s) of auditorium. For this reason, in theatres raked seating areas preferred on condition that keeping the rake under the safety limits. In live theatre, the spectator is generally looking down on the stage while in cinema he looks up and naturally takes a more reclining position.

After making decisions about seat dimensions, row spacing and seating layout, vertical sightlines are usually worked graphically. First, the lowest and nearest point which the whole audience should be able to see must be decided. Then, the longitudinal cross section of the hall should be studied to find out sight line of each seated person. According to theoretical approach to find the floor slope, beginning should be made from the first row, which is usually at elevation zero. The elevation of the second row is established by drawing a line from the top of the head of the person in the first row to the focal point and extending it to the second row. The head of the person is assumed to be 100 mm above the eye height. The elevations of further rows are determined by the same graphical method. By using this graphical method floor slope increases with the distance from the stage. If the aisle floor is not ramped the step heights will not be equal. But according to building codes, it is not permitted to build unequal steps because of the safety reasons. (Mehta, Johnson, & Rocafort, 1999) (The Association of British Theatre Technicians, ABTT, 1972)

It is remarked that the vertical sightline design is affected by the following factors (The Association of British Theatre Technicians, ABTT, 1972);

- The distance of farthest seat to the performance
- Depth of acting area and the vertical height above it should be considered according to the type of performance
- Nearest and lowest part of the stage which must be seen by all spectators
- Highest point of acting area which also must be seen by the farthest spectators.

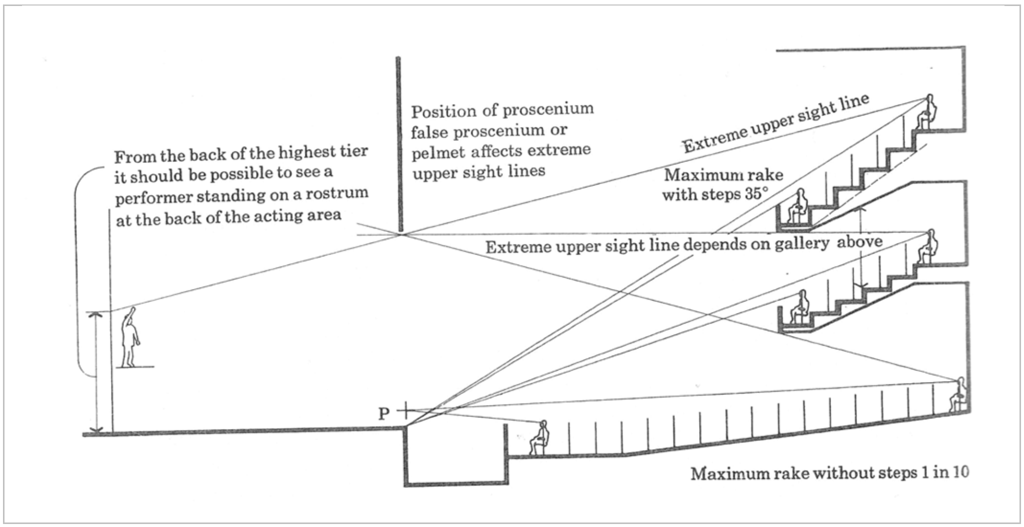


Figure 2.8 Vertical Sightlines (The Association of British Theatre Technicians, ABTT, 1972)

It is also important the vertical sightlines if there is a balcony(s) within the auditorium, because it must be checked if the front of the stage is visible for spectators sitting in the balcony. Especially if there is a forestage the solution can be quite difficult.

2.5.2.3 Horizontal Sightlines and Staggered Seating

Horizontal sightlines an important factor for especially theatres with proscenium stage since they limit the width of the seating area in the auditorium. Also, sightlines from the side seats restrict the amount of the stage that can be used as acting area. (Appleton, 1996) (The Association of British Theatre Technicians, ABTT, 1972)

Although the theoretically raked floor, which is described above, gives the opportunity for unobstructed sightlines for every row, it is not always possible. For such a situation, staggering the rows of seat is considered as a solution. By this method, it is possible to calculate sightlines based on each spectator seeing over the head of person two rows in front. But staggered seating still may cause obstructions while watching the performance. (The Association of British Theatre Technicians, ABTT, 1972)

2.5.2.4 Stage - Spectator distance

The distance to stage is very important for spectators especially while watching a drama, since the speech intelligibility also depend on how well the listener is able to see the facial expressions, gestures, body movements and sometimes even the lip movements of actor. For this reason, the distance between the stage and furthest seat should be taken into consideration. And it is limited to 20-24 meters for drama theatres as explained before. Usually front point of the stage is considered while calculating the distance and installation of seating layout (seat dimensions, geometry and density) affects the subjected distance.

Also further information can be found in references about the distance between spectators and stage (actor). Table 2.5 shows speech supporting elements and the maximum distances of their visibility.

Table 2.5 Speech supporting elements and the maximum distances of their visibility. (Mehta, Johnson, & Rocafort, 1999, p. 231)

Visibility of Speech Supporting Element	**Max. Distance (m)**
Facial Expressions	12
Gestures	20
Large Body Movements	30

2.5.2.5 Form and Size of Auditorium

Sightlines differ by the form of auditorium, since it affects the shape of seating layout and the viewing distance of occupied seat. First examples of theatres were semi-circular shape as mentioned before, and this form shortened the distance between stage and spectator. Similarly, fan shape is very common for theatre design, because it allows more audience sitting close to the stage by comparing the rectangular forms.

2.5.2.6 Size and shape of stage

Sightlines vary for each stage and form of theatre since the relation between the stage and audience vary in each type, as mentioned before. And it is quite a hard job to be sure that every seat has the perfect view of the stage. During the sightline design process it should be decided which part(s) of the stage must be seen. The choice can be one of or all of the followings; whole width of the stage, the whole height of the proscenium, the forestage, all the scenery on the stage.

2.6 Acoustic Design of Theatre

Performance type also affects the acoustic design of an auditorium. The characteristic of a dramatic play can be described as an intimate exchange between actors and audience. The architectural/ constructional design of theatre is very important to obtain desired acoustic quality within the theatre since, most of the time play is performed without electronic amplification. Drama theatres are expected to have mostly the features of rooms for speech, although some plays involve musical parts. Thus, it is suggested that many of the acoustical requirements for a speech auditorium apply to a theatre also. Architecturally, the most important difference between a drama theatre and a speech auditorium is the provision of a stage enclosure in a theatre. The most commonly used stage type is a proscenium stage, which is described in previous chapters. The stage enclosure consists of a tall shaft – a fly gallery – for hanging and storing the scenery sets. (Mehta, Johnson, & Rocafort, 1999, pp. 289-290)

To investigate the most important criteria for the theatre acoustics, Barron conducted a questionnaire survey in three public theatres. The questionnaire was included scales of speech intelligibility and ease of listening in addition to the one used for music. The results showed that listeners were responding consistently on three attributes; *intelligibility*, *intimacy* and *reverberance*. And it was found that only intelligibility was rated as significant for judgement of the acoustics overall. Listeners were able to assess acoustic intimacy and reverberance but they were indifferent to the degree of these attributes. As a result, this survey suggests that, speech intelligibility is prime concern, at least for theatres, where intelligible speech cannot be guaranteed. (Barron, 1993, p. 228)

In the light of these previous researches, drama theatres are evaluated as rooms for speech more than music within the thesis and acoustic criteria for rooms for speech are main concern.

2.6.1 Acoustics for Speech

It is said that good acoustics for music and speech are generally incompatible. And it is thought that designing for speech is a quite simpler. Because, if speech intelligible and background noise is not intrusive, the result will be satisfactory. However, some recent theatres are evaluated as poor in term of speech intelligibility. (Barron, 1993)

Shortly it can be said that the main factors affect the intelligibility are power and clarity (Moore, 1988). So, it must be considered to optimize conditions for loudness and clarity at the design stage of theatres. Fundamental requirements to be considered while designing rooms for speech are also defined as (Long, 2006, p. 579):

- There must be adequate loudness.
- The sound level must be relatively uniform.
- The reverberation characteristics of the room must be appropriate.
- There must be a high signal-to-noise ratio.
- Background noise levels must be low enough to interfere with the listening environment.
- The room must be free from acoustical defects such as long delayed reflections, flutter echoes, focusing and resonance.

2.6.2 Design Considerations for Acoustics

As explained before, the strength of the direct sound, distribution of the early sound energy, and the duration of reverberation processes are important factors that shape the acoustical characteristics of an auditorium. And these properties of the room depend on constructional data, such as;

- speaker-listener distance,
- seating layout (number of seats and their arrangement) and rake
- shape and volume of the room,
- stage type
- finishes (materials of walls, ceiling, floor, seats, etc.)
- reflectors
- balcony overhangs
- acoustical defects

While the reverberation time is determined by room volume and finishing materials, the latter influences strongly the number, directions, delays and strengths of the early reflections received at a given position or seat. The strength of the direct sound depends on the distances to be covered, and also on the arrangement of the audience. (Kuttruff, 2001)

2.6.2.1 Speaker –Listener Distance

Distance between actor and spectator affects the amount of direct sound that reaches to the seat. And most of the time the direct sound signal arriving from the sound source to a listener along a straight line is not influenced at all by the walls or the ceiling of a room. Nevertheless, its strength depends on the geometrical data of the hall, namely on the (average) length of paths which it has to travel, and on the height at which it propagates over the audience until it reaches a particular listener. (Kuttruff, 2001)

To minimize the distance between speaker and listener some design arrangements such as economy in seat and row spacing, economy in number and width of gangways within the seating area, optimum shape of seating area and introduction of gallery(s), should be taken into consideration. (Moore, 1988)

Actually, maximum acceptable distance between stage and furthest seats in acoustical design of drama theatres very similar with the sightline design limitations. For drama performances, the maximum distance from the stage front to any seat limited to 20m, especially if there is no electronic amplification (Gade, 2007, p. 335).

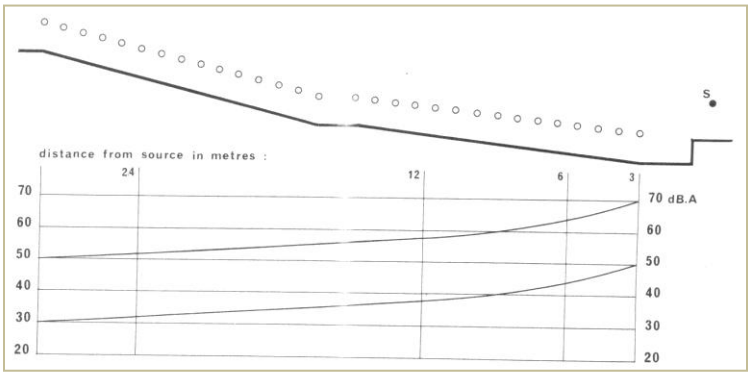


Figure 2.9 Decrease of the human voice by distance (Moore, 1988, p. 142)

Also, in some sources, there are some approximate measures for the distance between the source and listener. These values can be useful to have a more clear idea. (Moore, 1988) (Templeton, 1993)

- Up to 15 m → Relaxed listening
- 15 m to 20 m → Good intelligibility
- 20 m to 25 m → Satisfactory
- 30 m → Limit of acceptability without electronic amplification.

2.6.2.2 Seating rake and layout

The rake of seating is as important for sound as it is for sight. When sound passes at a low angle of incidence over an audience, it is strongly attenuated because of the highly absorptive properties of the audience. (The Association of British Theatre

Technicians, ABTT, 1972) This absorption is cumulative and is chiefly responsible for the difficulty experienced in hearing at the rear of the hall with a level floor. This phenomenon causes a reduction in sound level in addition to the reduction due to distance. (Moore, 1988)

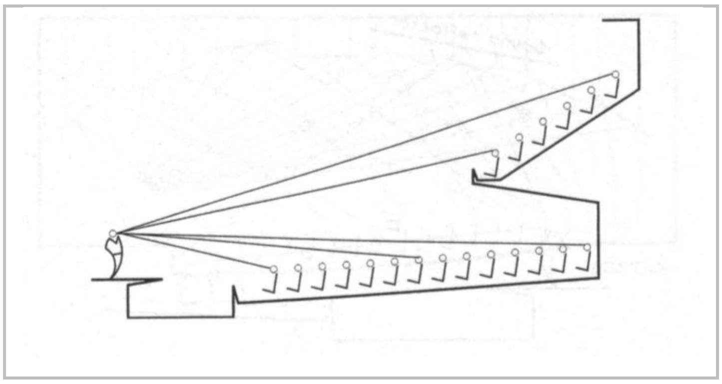


Figure 2.10 Good sightlines yields good direct sound (Long, 2006, p. 583)

2.6.2.3 Shape and Volume of Auditorium

As explained before, the smaller the average distance between the audience and the actor the better the acoustical results for normal drama, although for music or musical shows this is not necessarily true. And plan shape of auditorium affects the seating layout and as a result the speaker-listener distance. For an accepted maximum speaker-listener distance, increasing the side-wall splay increases the audience capacity.

Auditorium volume is a very important factor since it is affecting the acoustic character of the auditorium. And minimizing the room volume is critical while designing an auditorium for speech. Because, “The smaller the volume per seat, the greater the sound energy is available to each listener. A smaller volume also means that a smaller amount of absorption is needed to obtain a given reverberation time, since the reverberation time is directly proportional to the room volume.” (Mehta, Johnson, & Rocafort, 1999, p. 238) As mentioned before, dedicated drama theatres are seldom built with a seat count higher than 500–1000, because visual as well as acoustic intimacy, including close view of facial expressions and freedom from artificial amplification, are given high priority. (Gade, 2007)

2.6.2.4 Stage Type

Because of the reduced average distance between stage and the audience, open-stage theatres might be acoustically satisfactory with rather larger audiences. On the other hand, it must be remembered that the human voice has pronounced directional properties and at the higher sound frequencies, which are extremely important for speech intelligibility, the sound behind the speaker's head is at least 10 dB less than directly in front of his mouth. In proscenium theatres the stage house is considered as an acoustical disadvantage because it represents a volume of enclosed space in which the sound can be lost. (The Association of British Theatre Technicians, ABTT, 1972)

2.6.2.5 Balcony Overhangs

It is inevitable to introduction a balcony while designing a theatre with an audience exceeding 800 to limit the speaker-listener distance and create the sense of intimacy. But deep balconies can cause shadow effect for the audience that sitting under it. As a rough guide, the depth of balcony overhang should be no more than two times the height of balcony opening. (Mehta, Johnson, & Rocafort, 1999) (The Association of British Theatre Technicians, ABTT, 1972)

2.6.2.6 Finishes

In auditorium most of the sound absorption is provided by the audience. As explained before, if the volume of the room increases the need of the sound absorbing surfaces will increase, depending on the desired reverberation time. For theatres, in generally, surfaces that close to the stage should be reflective. The sound absorbing materials should be placed in the rear parts of the hall, if necessary. To prevent delayed reflections from rear wall, it can be treated with a sound absorbing material or can be diffusively reflective. (Mehta, Johnson, & Rocafort, 1999) (Long, 2006)

2.6.2.7 Sound Distribution by Reflections

In auditoriums where unamplified speech is important, sound energy can be increased by physically placing hard surfaces in appropriate positions so that they can distribute sound to the audience. Reflector size is important for scattering at the interested frequencies and to limit the delay time, which is related to the distance between source and reflector, less than 30 to 50 msec. (Long, 2006)

Reflective surfaces within the auditorium should be designed so that the reflections are concentrated more on the most distant seats. Also, in designing reflectors it is necessary to decide on the positions of the sound sources, which will vary, particularly in a theatre with an adjustable stage. (The Association of British Theatre Technicians, ABTT, 1972)

> When a room is to be used for speech, the direct sound should be supported by as many strong reflections as possible with delay times not exceeding about 50 ms. Reflecting areas (wall portions, screens) placed very close to the sound source are especially favourable, since they can collect a great deal of the emitted sound energy and reflect it in the direction of the audience. For this reason it is wrong to have heavy curtains of fabric behind the speaker. On the contrary, the speaker should be surrounded by hard and properly orientated surfaces, which can even be in the form of portable screens, for instance. Similarly, reflecting surfaces above the speaker have a favourable effect. If the ceiling over the speaker is too high to produce strong and early reflections, the installation of suspended and suitably tilted reflectors should be taken into consideration. (Kuttruff, 2001)

2.6.2.8 Acoustical Defects

The presence of acoustical defects causes to poor speech intelligibility in addition to general discomfort within the room. In most references these defects are described as well as the ways for preventing them. Some of the most important defects that affect the quality of speech in a room are shown in figure 2.11.

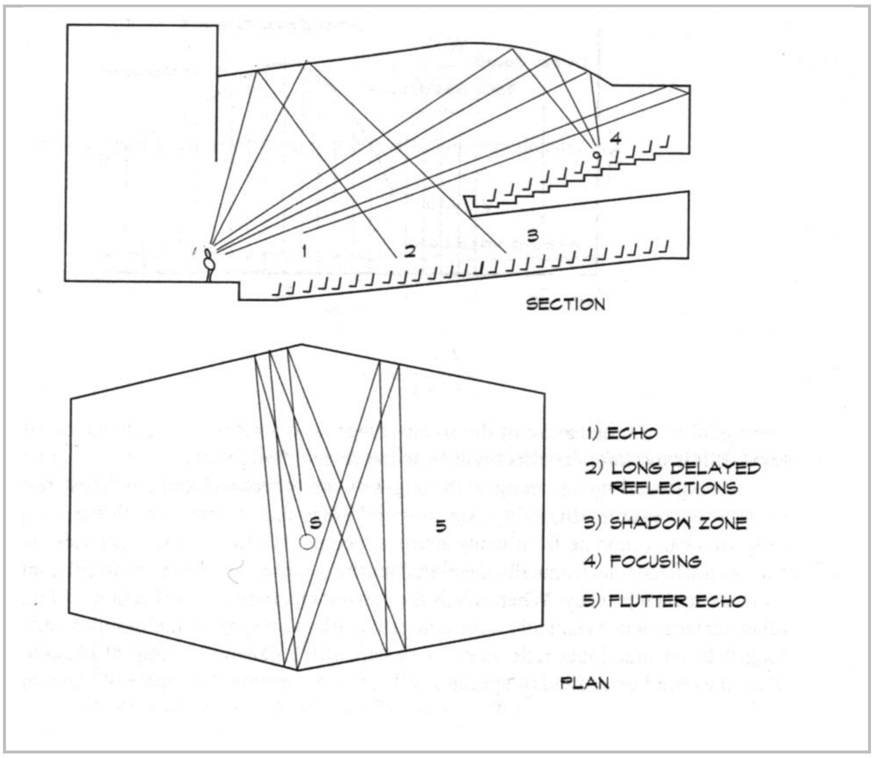


Figure 2.11 Examples of acoustical defects (Long, 2006)

2.6.2.8.1. Echoes. Echo is defined as a repetition of the original sound that is distinctly perceptible. As a rule, if the delay is greater than 1/25 sec (14m) for speech and 1/12 sec (34m) for music then that reflection will be a problem. *Flutter echoes* are sounds that persists locally due to multiple reflections between parallel planes, concave or chevroned surfaces. *Long delayed reflections* are like echoes, but have a somewhat shorter delay time. They are not perceived as separate sounds, but blur the understanding of the original sound. (Long, 2006)

2.6.2.8.2. Sound Concentration (Focusing). Sometime referred to as 'hot-spots', these are caused by focussed reflections off concave surfaces. The intensity of the sound at the focus point is unnaturally high and occurs at the expense of other listening areas. (Marsh, 1999)

2.6.2.8.3. Sound Shadowing. Sound shadowing is basically defined as the situation where a significant portion of the reflected sound is blocked by a protrusion that itself doesn't contribute to the reflected component. In general, it is recommended to avoid balconies with a depth exceeding twice their height, since they will cause problems for the rear-most seats beneath them. (Marsh, 1999)

2.6.2.8.4. Distortions. As a result of wildly varying absorption coefficients at different frequencies, an undesirable change in the quality and tone colouration (of frequency distortions) of sound occurs within the enclosure. As a solution, balance should be obtained between the absorption coefficients of acoustical finishes over the whole audible range. (Marsh, 1999)

2.6.2.8.5. Coupled Spaces. It is common for two spaces to be coupled to each other through an opening between them. When an auditorium is connected to an adjacent space which has a substantially different RT, the two rooms will form an acoustically coupled space. Most commonly occurring coupled rooms are a hall and a stage coupled through the proscenium opening, or a hall coupled to a deep balcony. As long as the airflow is unrestricted between the two spaces, and when the RTs of the rooms are unequal, the decay of the most reverberant space will be noticeable within the least reverberant. If the reverberation times of both rooms are the same, there will be no energy exchange between rooms during the decay process. (Mehta, Johnson, & Rocafort, 1999, p. 220) (Marsh, 1999).

2.6.3 Acoustical Parameters: Measuring and Evaluating Acoustical Quality of Theatres

As mentioned before, the goal of good acoustical design for drama theatres is to make possible clear, accurate and relaxed speech communication like rooms for speech, such as classrooms or meeting rooms. Listeners (in theatre spectators) should be able to understand all of the words that are being spoken to them without having to strain. As an additional difficulty, actors on the stage usually do not speak at the same level during the play, they can shout or they can whisper.

It is accepted that good acoustical design requires one to maximise the signal-to-noise ratio and to provide optimum room acoustics conditions. It is common experience that speech communication is difficult in many rooms, and almost all reported noise levels in rooms exceed recommendations, indicating that there still remain problems to be solved. The situation is complicated by the fact that speech and noise levels are greatly influenced by room acoustics and one cannot consider the two elements in isolation. (Bradley J. , 2003)

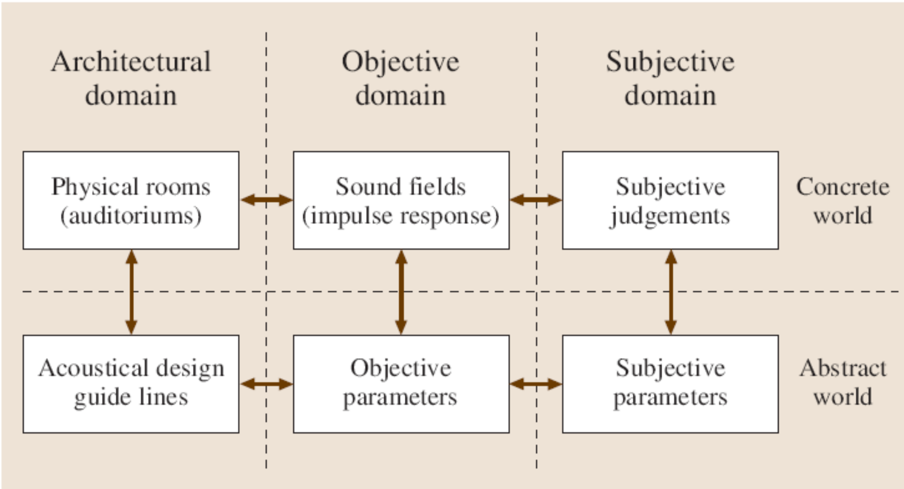


Figure 2.12 Overview of concepts related to room acoustics (Gade, 2007)

When we criticize the acoustic character of an auditorium, we usually use subjective judgements or expressions. But these subjective impressions need to be expressed or converted to objective parameters so that they can be measured or evaluated more accurately. This is a quite hard job. Gade has described the issue briefly with a simple scheme (Figure 2.12). And with his words the scheme "illustrates the universe of architectural acoustics".

In the upper half of the figure, we have the phenomena experienced in the real world. Going from left to right, we have the auditoria, in which we can experience objective sound fields causing subjective impressions of the acoustic conditions. In all of these three domains, we find a huge number of degrees of freedom: halls can differ in a myriad of ways (from overall dimensions to detailed shaping of small details like door handles), the sound fields which we describe by the impulse response concept – as explained in a moment – contain a wealth of individual sound components (reflections), each being a function of time, level, direction and frequency. Also, every individual may have his/her own way of expressing what the room does to the sound heard. In other words, like in many other aspects of life, the real world is so complex that we need to simplify the problem – reduce the degrees of freedom – through definition of abstract, well-formulated and meaningful concepts and parameters in all three domains (the lower row of boxes).

These parameters differ by the purpose of the auditorium since the different performance types need different acoustical environments. For this reason, acoustical parameters for drama theatres are defined in this section.

The subjected theatre building can be built already or the evaluations can be made by using scale model or computer simulation. Recently, programs allow the simulation of a number of acoustical parameters using a reconstruction of the hall in a CAD format. This kind of simulation is of great interest because it models the acoustical impact of possible changes of the hall before the building it or actual modifications of existing one. After having measured and/or computed the values of several parameters it is possible to compare them with optimum values to evaluate the acoustical characteristics of the room.

2.6.3.1 Acoustic background (noise control)

Clarity of speech in a theatre is also affected by the noise level of the auditorium. Possible noise sources for a theatre can be listed as external noise (noise coming from the outside the hall), mechanical plant noise such as air conditioning noise and noise generated by the audience such as footsteps. To be able to keep the noise level below the recommended values, theatre must be protected from all external noise and must have mechanical plant designed so that the background noise level does not exceed certain criteria. (Mehta, Johnson, & Rocafort, 1999) (Moore, 1988) Background noise levels in lecture halls should be designed to an NC 30 (35 dBA) while larger auditoria to an NC 25 (30 dBA). The difference is due to the greater loss of loudness in a larger space. (Long, 2006, p. 587)

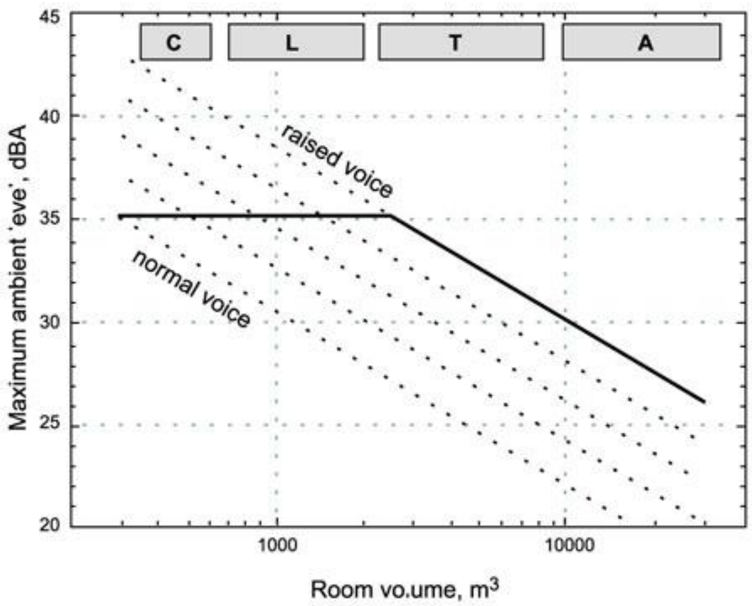


Figure 2.13 Maximum ambient noise level goals (solid line) (C=classrooms, L=lecture halls, T=theatres, A=large auditoriums) (Bradley J. , 2002)

2.6.3.2 Signal-To-Noise Ratio

The louder speech sounds are relative to interfering noises, then the greater the intelligibility of the speech. Some researches shows that the received level be at least 25 dB higher than the background noise level for adequate intelligibility (Long, 2006, p. 587). But Bradley suggests that 15 dB margin is acceptable. According to his research, there are many kind of speech intelligibility tests and most of the studies, which are based on different tests, have indicated that a signal-to-noise ratio (S/N) of ≥ +15 dBA provides conditions in which 100% intelligibility scores are possible. (Bradley, 2003)

2.6.3.3 Impulse Response

When a sound is generated by a single source on the stage, as shown in Fig. 2.14 a spherical wave propagates away from the source in all directions and the sound first heard in the listener position originates from that part of the wave that has propagated directly from the source to the receiver, called the direct sound. This is shown on the left in the lower part of Fig. 2.14, which shows the received signal versus time at a given position in the room. The direct sound is soon followed by individual early reflections. The sound wave continues to be reflected and to pass the receiver position until all the energy has been absorbed by the boundaries/objects or by the air. The density of these later reflections increases with time (proportional to t^2), but the attenuation due to absorption at the room boundaries ensures that eventually all sound dies out. This decay is often heard as reverberation in the room, as Sabine did, when he carried out his famous experiment in the Fogg Art Museum more than 100 years ago. (Gade, 2007, p. 304)

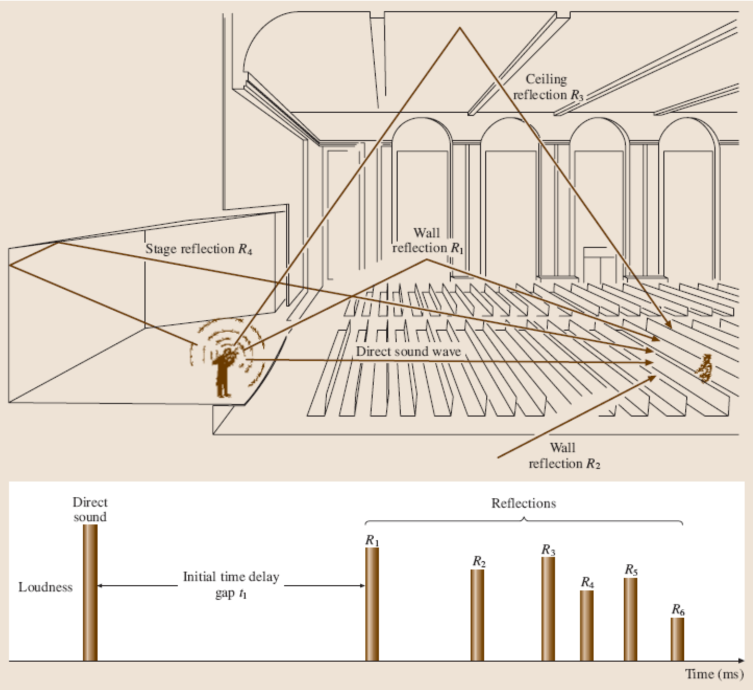


Figure 2.14. Diagram illustrating the generation of an impulse response in a room (Gade, 2007, p. 304)

The diagram in Figure 2.14 shows an example of impulse response pattern. In practice, the pattern can be more complicated, since the divisions cannot be so distinct. The time between the arrival of the direct sound and the first major reflection is called the *initial delay gap*. If this gap is short enough, early reflections can contribute to increased intelligibility. If it is too long, its effect will be to decrease intelligibility (Long, 2006, p. 589).

Although it is possible to measure speech intelligibility in an existing room, it can be useful to predict it before room is constructed. Since, impulse response is one of the basic sources of information regarding the audible properties of the sound field in a room; some speech intelligibility measures based on room's impulse response. In other words it is possible "to predict the result of introducing an arbitrary forcing function (speech) by convolving (integrating) the input with the room's impulse response" (Long, 2006, p. 590).

2.6.3.4 Reverberation Time (RT)

Reverberance can be defined as the best known of all subjective room acoustic aspects. The reverberation time T which is the traditional objective measure of this quality, was invented 100 years ago by W.C. Sabine. T is defined as the time it takes for the sound level in the room to decrease by 60 dB after a continuous sound source has been shut off. (Gade, 2007, p. 306)

In practice, the evaluation is limited to a smaller interval of the decay curve, from −5dB to −35 dB (or −5dB to −25 dB) below the start value; but still relating to a 60 dB decay (Figure 2.13). That is because of the difficulty to produce a noise level that is 60 dB above the background noise in practice. RT is obtained by measuring the time over 30 dB decay and doubling it. (Mehta, Johnson, & Rocafort, 1999, p. 213)

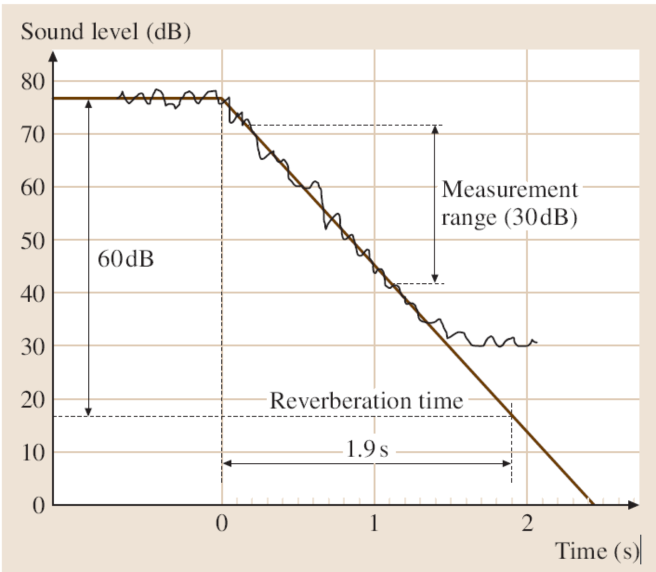


Figure 2.14 Definition of Reverberation time (Gade, 2007)

2.6.3.4.1 Reverberation Time and Speech Intelligibility. Reverberation affects verbal-communication quality by affecting the early- and late-arriving energies. When the sound energy that does not reinforce the direct sound it becomes a masking sound for speech and reduces speech intelligibility. The negative effect of long reverberation time on speech intelligibility is well known to anyone who has tried to speak a large stair hall, a gymnasium, or a highly reverberant auditorium. While, the early energy[2] supplements the direct sound and compensates for background noise, increasing speech intelligibility, the late energy masks the direct sound, effectively increasing the background noise, and decreasing speech intelligibility. (Hodgson, 2004) (Mehta, Johnson, & Rocafort, 1999, p. 215)

From this point, it can be said that the shorter the reverberation time, the more intelligible the speech. But making such a conclusion is not true, since speech intelligibility decreases markedly as the listener moves away from the speaker in an open space, where there is no reverberation. Thus, the optimum reverberation time for a hall meant for speech is a compromise between the loss of intelligibility due to excessive reverberation, and a loss of sound level due to inadequate reverberation (Mehta, Johnson, & Rocafort, 1999, p. 216)

2.6.3.5 Early Decay Time

The earlier studies of sound decay, especially the original one by Sabine, assumed that the entire 60 dB decay of sound is smooth and uniform. But, measurements in actual halls have revealed that the 60 dB decay may not be uniform. Due to masking, the entire decay process is only perceivable during breaks in the speech or music. During running music or speech, the later, weaker part of the reverberation will be masked by the next syllable or musical note. Therefore an alternative measure, early decay time (EDT) has turned out to be better correlated with the reverberance perceived during running speech and music. EDT is defined as the time it takes the sound energy to decay from zero to -10 dB, multiplied by 6. Multiplying by 6 is

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[2] The early and late energies are defined as the total energies radiated by the speech source which arrive at a receiver position at times less than and greater than 50 ms after the arrival of the direct sound, respectively. (Hodgson, 2004)

preferred to establish a comparison with reverberation time (RT) (Mehta, Johnson, & Rocafort, 1999, p. 262) (Gade, 2007).

In spite of the fact that EDT is a better descriptor of reverberance than T, T is still regarded the basic and most important objective parameter. This is mainly due to the general relationship between T and many of the other room acoustic parameters and because a lot of room acoustic theory relates to this concept, not least diffuses field theory, which is the basis for measurements of sound power, sound absorption, and sound insulation. T is also important by being referred to in legislation regarding room acoustic conditions in buildings. (Gade, 2007)

2.6.3.6 Distinctness (Deutlichkeit) (D)

As mentioned before, in a room, listeners hear the direct sound of the talker followed by many delayed reflections of the speech. Although we typically hear the combined effect of many thousands of reflections, all reflections are not equal, and they do not all affect us in the same way. Early-arriving reflections within about 50 ms after the direct sound are particularly important because our hearing system integrates them with the direct sound, making it seem louder. Thus increased early-reflection energy is expected to increase intelligibility as it is discussed in title reverberation time and speech intelligibility.

It is emphasized that, although the importance of early-arriving reflections is not widely appreciated, it is not a new concept and Joseph Henry explained the key points in the 1850s. In their study, which is titled as “On the importance of early reflections for speech in rooms” Bradley, Sato and Picard find out the effect of the early reflections in rooms for speech. According to the paper; “The speech intelligibility test results confirm the importance of early reflections for achieving good conditions for speech in rooms. The addition of early reflections increased the effective signal-to-noise ratio and related speech intelligibility scores for both impaired and non-impaired listeners.” Also they found that “the new results show that for common conditions where the direct sound is reduced, it is only possible to understand speech because of the presence of early reflections. Analyses of measured impulse responses in rooms intended for speech show that early reflections can increase the effective signal-to-noise ratio by up to 9 dB" (Bradley, Sato, & Picard, 2003).

The concept that the ratio of early-arriving to late-arriving speech sounds would relate to speech intelligibility developed from work by Thiele in the 1950s. It was proposed as a measure of Clarity (Bradley, 2003). Distinctness (Deutlichkeit – Early Energy Fraction) is defined as "ratio of the early sound energy in the first 50ms after the arrival of the direct sound to the total sound energy". D is one of the oldest measures, which has the advantage that it can be used as a predictive tool. (Barron, 1993, p. 229)

$$D = \frac{\int_0^{0.05} p^2(t)dt}{\int_0^{\infty} p^2(t)dt}$$

Equation of Distinctness (Barron, 1993, p. 229)

2.6.3.7 Speech Intelligibility Metrics

Most of the objective parameters are mainly relevant in larger auditoria intended for performance of music. Since, in auditoria used for speech the influence of the acoustics on intelligibility is a major issue, the measure of the speech intelligibility is necessary. And there are several metrics currently in use for the prediction of the intelligibility of speech in rooms: the Articulation Index (AI), the Articulation Loss of Consonants (AL_{cons}), the Speech Transmission Index (STI), the Useful to Detrimental Sound Ratio (Uτ) and the Useful to Late Energy Ratio (Cτ) (Long, 2006). But the development of these measures has not ended yet. Acousticians are still trying to find the measure, which is most related to speech intelligibility.

Traditionally, acoustic measures of speech intelligibility have concentrated on one of two concerns: either the signal-to-noise ratio or the impulse response. In any practical situation both should be considered, though from an analytic point of view they can be measured independently (Barron, 1993).

Articulation Index is based on signal-to-noise ratio and originally developed in Bell Telephone Laboratories. This is a very important tool for predicting privacy in buildings and open plan offices but it is not found to be appropriate for calculating speech intelligibility in rooms. Since reflections from the internal surfaces of the rooms need to be considered. (Barron, 1993)

Turning to the impulse response measures, one of the most preferred measure is *early energy fraction* (Deutlichkeit of Thiele), which is based on a subdivision between useful and detrimental energy as defined in previous title. In the case of early energy fraction, the division occurs at 50 ms after the direct sound. (Barron, 1993)

Lochner and Burger developed the concept of useful-to-detrimental sound ratios, where ‘useful’ is the combination of the direct and early-reflected sound and ‘detrimental’ is the sum of the late-arriving speech sounds plus the ambient noise. They introduced a weighing factor for the early energy and they accepted that detrimental energy arrives after 95 ms. The Lochner and Burger ratio is expressed in decibels derived from the ratio of useful to detrimental sound. (Bradley, 2003)

But as mentioned before, an ideal speech intelligibility measure is supposed to combine both the signal-to-noise ratio and impulse response aspects. In 1986 Bradley introduced such a ratio. He has investigated useful-to-detrimental ratios including the effect of background noise. In the formula, D is the early energy fraction and n/s is the noise-to-signal ratio. The subscript 50 of U refers to the 50 ms time limit for the early energy fraction. (Barron, 1993) (Bradley J. , 1986)

The Speech Transmission Index (STI) is a more recent measure that combines both room acoustics and S/N aspects into a single measure. Although the STI measure is quite complex and appears to be very different than the useful-to-detrimental sound ratio, the two measures are actually very closely related. (Bradley J. , 2003)

This measure is based on the idea that speech can be regarded as an amplitude modulated signal in which the degree of modulation carries the speech information. If the transmission path adds noise or reverberation to the signal, the degree of modulation in the signal will be reduced, resulting in reduced intelligibility. The modulation transfer is tested by emitting noise in seven octave bands, each modulated with 14 different modulation frequencies and then calculating the ratio between the original and the received degree of modulation, the modulation reduction factor, in each of these 98 combinations. A weighted average of the modulation reduction factor then results in a number between 0 and 1, corresponding to very poor and excellent conditions respectively. A faster measurement method using only two carrier bands of noises and four plus five modulation frequencies is called rapid STI (RASTI). The STI/RASTI method is described in an International Electro technical Commission (IEC) standard: IEC 286-16. Although the original method of STI or RASTI measurement employs modulated noise signals, it is also possible to calculate the modulation reduction factor from the impulse response. Thus, the modulation reduction factor versus modulation frequency F, which is called the modulation transfer function (MTF), can be found as the Fourier transform of the squared impulse response normalized by the total impulse response energy. (Gade, 2007)

2.7 Examples of Theatre Architecture

Looking at the past still can be a very useful way to find answers some questions during design process of any kind of building. Before starting a design of a new building, most of the time architects evaluate the past examples. This approach can also be effective for both architectural and acoustical design of a theatre. In Beranek's words; "…Before these tools were available (modern evaluation techniques in acoustics), the designer of a hall in which music was to be played could learn about acoustics only by observing other halls…" (Beranek L. L., 1962). This idea also emphasized by Pilbrow; "The past shows a way ahead. Before electricity and amplification, theatres simply had to be intimate. The opera houses of Europe and the theatres of London's West End and New York City's Broadway were the product of four hundred years of evolution." (Pilbrow, An auditorium and Stage Design Guide, 2006)

It is also thought as a useful way to explore successful theatres of the past to learn what made a successful theatre, according to Professor Franklin Hildy: "There are numerous lessons to be learned from the study of historic theatre buildings. I like to refer to this work as 'applied theatre history' because of its implications for modern theatre." (Hildy, 2006)

With this idea, following examples of theatres are divided into two sections. In first part, most of the selected theatre buildings, which are also exemplified by reference books, are mostly historic buildings. In the second part, to have an idea about the recent examples, drama theatres that built at the end of 1990's and in 21st century are selected.

2.7.1. Examples of Drama Theatres

There are many examples of theatres for different types of productions and they have their own positive or/and negative features. Examining these features (shape, volume, capacity, stage design, acoustics...etc.) of similar theatres, which are evaluated as satisfactory in terms of theatrical requirements, fastens the design process. With this idea, some theatre examples are going to compare to verify design criteria that will be used for design of case studies (models).

Most of the theatre examples are from England, since the most important examples are built in there. They are successful and living representatives of theatre buildings. Also there are some examples that designed by famous architects, such as Mario Botta, Kouis Kahn, and Alvar Aalto.

2.7.1.1 Theatre Royal, 1766

Bristol, England

Performance Type: Drama

Architect: Thomas Patey

Seating Capacity: 638

The auditorium is defined as a remarkable survival of an eighteenth century city theatre, designed by Thomas Patey, with similar dimensions to the contemporary Theatre Royal, Drury Lane. Whereas it is thought that Drury Lane may have had a slightly fan-shaped auditorium with tiers facing the stage on a shallow curve, the balconies at Bristol are fully semi-circular in the centre, and very nearly parallel at the sides. Stage-boxes are framed between giant Corinthian pilasters. The stage originally projected as far as the outer pilasters, but has long been cut back to the inner pair, and the crucial Georgian proscenium doors removed. During the history, the building had some modifications. One of them was addition of a second tier with a deep gallery in the centre in about 1800. (The Theatres Trust)

> In 1972 the whole structure of the 18th century stage house with its splendid Victorian machinery was demolished, an incredibly destructive act, and rebuilt with an inappropriately flat stage instead of the raked stage that the form and sightlines of the auditorium demand. Surprisingly, the opportunity to restore the original apron and proscenium arch doors was not taken. A sad memorial, a model of the stage machinery was put on display in the theatre foyer in 1981. In 1972 W Skinner's mediocre 1903 entrance front was also demolished and replaced by a new studio theatre by Peter Moro, the New Vic, itself now of interest as an important work of its time. A new entrance was made through the adjacent imposing mid eighteenth century façade of the former Coopers' Hall. (The Theatres Trust)

The building is listed Grade I. The theatre has been closed since 2007 because of the financial problems and refurbishment works and expected to reopen at the end of 2009. (The Theatres Trust)

Figure 2.15 View of first floor of theatre from stage (Photo: Ian Grundy 2001 (The Theatres Trust))

From an acoustic standpoint, the theatre accepted as a good example with flat frequency characteristics and short reverberation time (0.8 s). Although some acoustical defects such as focusing had been detected especially in rear stalls, it is thought that “in buildings with such a rich history, such defects always seem to be acceptable”. (Barron, 1993, p. 257)

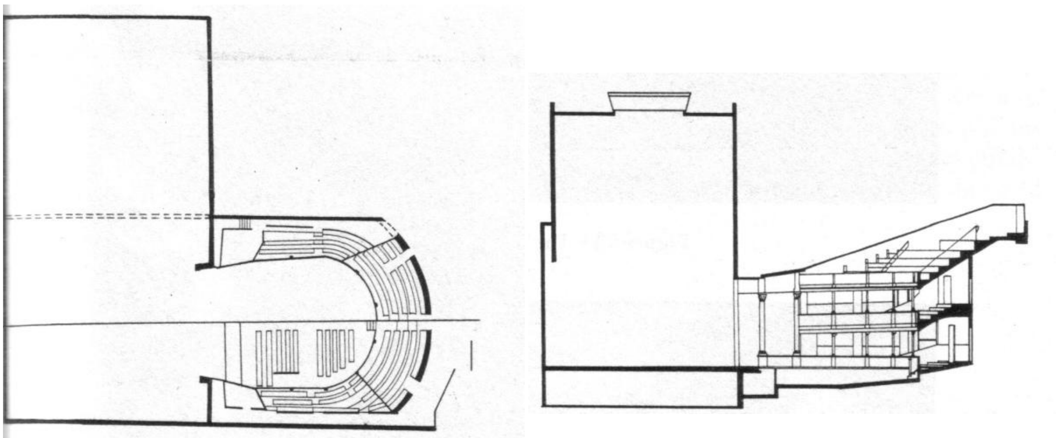


Figure 2.16 Plan and section of Theatre Royal, Bristol (Barron, 1993)

Figure 2.17 View of auditorium – photo: Ian Grundy 2001 (The Theatres Trust)

Figure 2.18 View of stage (The Theatres Trust))

2.7.1.2 Wyndham's Theatre, 1899

London

Performance Type: Drama

Architect: W.G.R. Sprague

Seating Capacity: 765

Wyndham's Theatre was built in 1899 and designed by architect W.G.R. Sprague with Portland stone facing, concealed roof. Theatre has fine and very little altered auditorium with very elegant "Louis XVI" plasterwork to balconies of horseshoe dress and upper circles, steeply raked gallery, ornate stage boxes and richly gilded architectural frame to proscenium arch. The theatre was Grade II* listed by English Heritage in September 1960. (English Heritage, 2007)

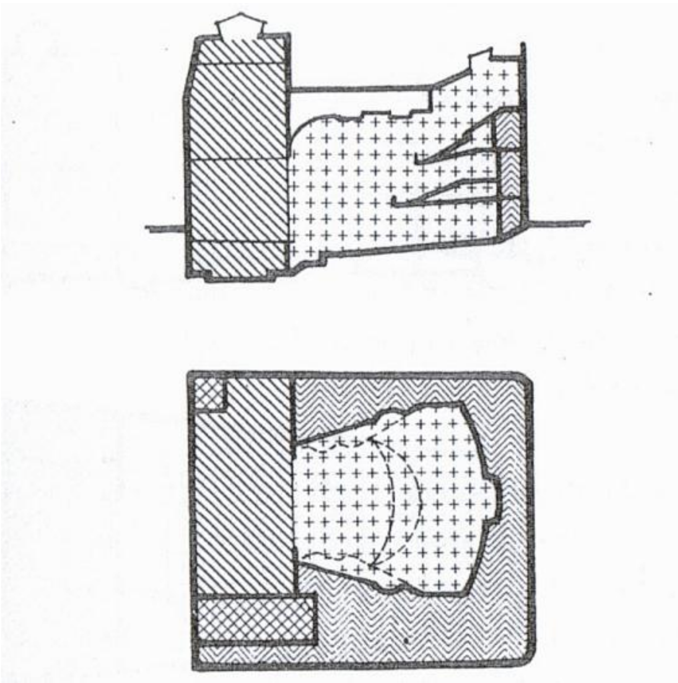


Figure 2.19 Simplified plan and section of theatre (The Association of British Theatre Technicians, ABTT, 1972)

The auditorium is one of Sprague's most delightful and best preserved inventions. The gallery is the rearward extension of the upper tier. Boxes with bowed fronts in three storeys (the lowest at dress circle level) paired, with semicircular arches at the two upper levels and set between pilasters carried on massive brackets. The proscenium was designed as a complete picture frame of the kind originated by Squire Bancroft at the Haymarket nearly 20 years earlier. It has an elegantly enriched architrave, above which is a composition of allegorical winged figures in full relief, carrying festoons and supporting framed portraits. The elaborate festooned house curtain was replaced in the 1970s by the Alberys, the last in the long family succession at this theatre, with a new curtain which faithfully reproduced the original design, a rare and costly gesture. Magnificent circular ceiling painted in the manner of Boucher, restored with other paintings about the same time. The saloon and public foyers, etc are in complementary style. Despite the tight planning, this has to be regarded as one of London's finest theatres. (The Theatres Trust)

In 2008 the auditorium and washrooms of Delfont Mackintosh's Wyndham's Theatre were completely refurbished and all common areas redecorated. Two new gantry levels were installed over the stage together with structural steelwork to strengthen the fly system. New lighting and sound systems were installed connected to a new lighting control room by way of a discreet cornice. The stone façade of the theatre was cleaned and renovated and signage lighting replaced. (Vivid Interiors)

Figure 2.20 Auditorium of Wyndham's Theatre, London. (Vivid Interiors)

Figure 2.21 Stage view from balcony (Vivid Interiors)

2.7.1.3 Apollo Theatre, 1901

Shaftesbury Avenue, Westminster, London, England

Performance Type: Drama,

Architect: Lewen Sharpe

Seat Count: 827

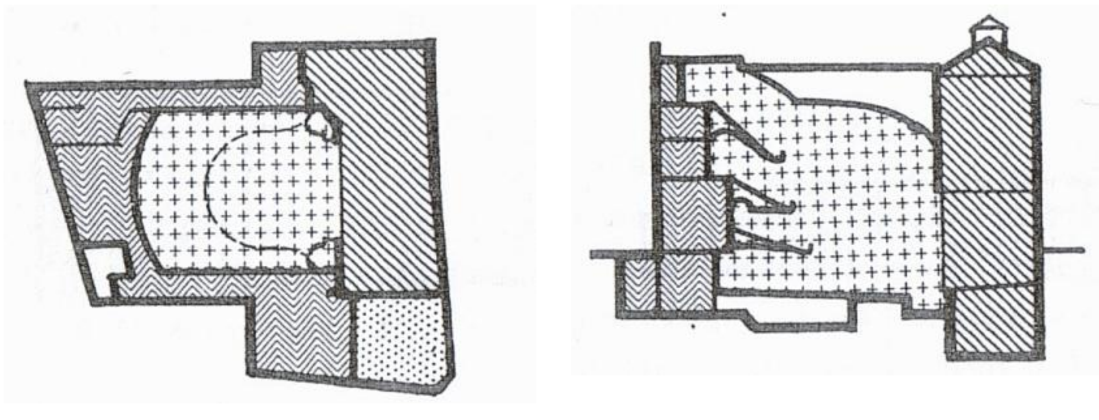


Figure 2.22 Simplified plan and section of Apollo theatre (The Association of British Theatre Technicians, ABTT, 1972)

The Apollo Theatre was built in 1901 by architect Lewen Sharp with sculptured work by T. Simpson. It is a stone faced, plain brick building to Rupert Street and Denmark Street. This was Sharp's only complete theatre (he made major alterations to Camberwell Palace in 1908) and it is externally quite unlike any other theatre of its time in London. Together with the Lyric, the Gielgud and the Queens, all grouped on the north side of Shaftesbury Avenue, the Apollo contributes to one of London's most important theatre streetscapes. The main façade is in a free Renaissance style with a distinct Art Nouveau flavour; stone, in three main storeys with a tall attic above the cornice; three major bays, the outer two treated as pavilions with flat canted fronts around which the main cornice breaks. Lively auditorium with splendid plaster enrichment in what was described as Louis XIV manner, somewhat interfered with by Shaufelberg in 1932. Three cantilever balconies (arguably one too many, producing sightline problems at several levels) terminating in elaborately modelled serpentine-fronted boxes. The angle of view from the upper balcony is said to be steepest in London. The theatre was Grade II* listed by English Heritage in June 1972 (English Heritage, 2007) (The Theatres Trust)

Figure 2.23 Stage of Apollo theatre (Photos of Apollo Theatre Figures 2.23-2.25 copyright holder: English heritage.NMR (The Theatres Trust)

Figure 2.24 Auditorium from stage (The Theatres Trust)

Figure 2.25 Balconies and stage (The Theatres Trust)

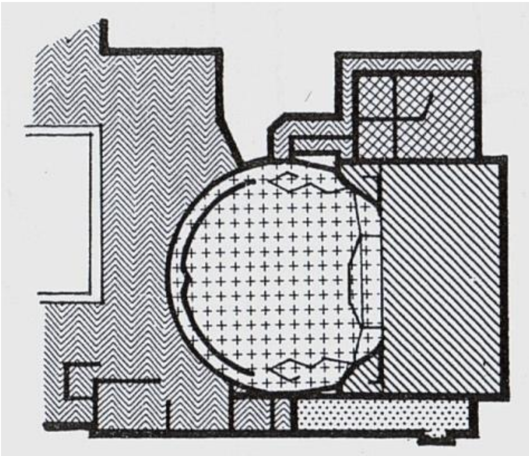
2.7.1.4 Forum Theatre, 1968

Billingham, Cleveland, England

Performance Type: Drama

Architect: Elder Lester &Partners

Seating capacity : 637



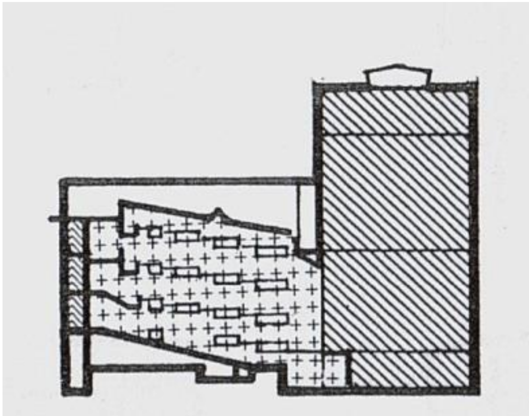


Figure 2.26 Simplified plan and section of Apollo theatre (The Association of British Theatre Technicians, ABTT, 1972)

The Forum Theatre was an integral part of the whole complex, which was England's first example of a comprehensive community recreation centre, with facilities for sport and the arts grouped together, sharing the common entrance foyer, restaurants, bars and toilets. It was designed in 1964-5 by Elder, Lester and Partners with A J Ward as the architect in charge. It was essentially designed for a family night out and the boxes that figure so prominently in the design are for this purpose. Seating is in fan shaped stalls in three blocks with the capacity of 643 people and the auditorium walls are 'papered with people' with shallow balconies creating a series of boxes on three levels designed with high quality slatted timber fronts. It is considered as an exceptional modern auditorium, extraordinarily warm and intimate, since no seat is more than 60ft from the stage. The upper balcony provides the lighting gallery with access to the control and projection room at the rear of the second balcony. The first 20ft of the auditorium floor is constructed in sections which can be manually removed to create an orchestra pit of 33ft x 9ft. The theatre can also be converted into a conference centre or a cinema complete with projection room and screen. Above the proscenium opening is an acoustic hood that can be adjusted for variations in performance. There is no proscenium frame. The theatre is fully equipped with workshops, dressing rooms, scene dock and prop stores which are located beneath the stage. Late in 2000 the local authority suggested that the Forum Complex should be demolished to make way for a superstore. A new site would be provided for the sporting activities but no site was indicated for a new theatre, which was also not costed. However, this is an outstanding and novel theatre of architectural and historic interest and was Statutory Listed in October 2004. The Forum Theatre is now physically separated from the rest of the complex but remains very popular with a good management hosting a range of shows. The Forum Theatre is now closed for major refurbishment and expected to be reopen in December 2010. (The Theatres Trust) (UK Theatres Online)

Figure 2.27 Auditorium of Forum theatre (Mexico75, 2009)

2.7.1.5 Thorndike Theatre, 1969

Leatherhead

Performance Type: Drama

Architect: Roderick Ham

Seating capacity : 530

There had been a cinema building before the theatre was built, and the architect, Roderick Ham draw up a scheme utilising the outside walls and roof of the old cinema. These can still be seen today. The side walls, roof trusses and part of the original stage were retained. The cinema boiler room was enlarged and office space added to the East Wing. The vision for the building was that it would be a complete cultural centre, not just a theatre. An art gallery, coffee bar, restaurant, bar and youth theatre were all components of this. Actress Dame Sybil Thorndike and her husband, Sir Lewis Casson kindly agreed to give their support to the theatre and took a keen interest from the outset. (The Leatherhead Theatre)

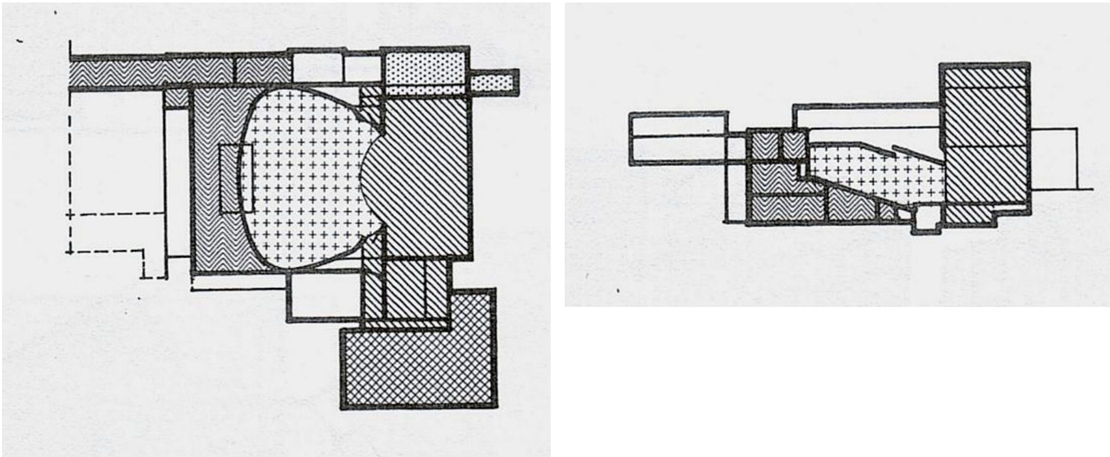


Figure 2.28 Simplified plan and section of Thorndike theatre (The Association of British Theatre Technicians, ABTT, 1972)

Working closely with the management team, Roderick devised an innovative design with open foyers rising around the bulk of the auditorium. It was a successful design that “It was the product of an ideal pairing of architect and client: an architect fascinated by theatre, Roderick Ham, and an experienced director who knew what her company needed, Hazel Vincent Wallace.” Theatre was opened in 1969, and its design won an award from the Royal Institute of British Architects. (Calder, 2004)

Although seating 530, 200 more than the old theatre, no one would be as far from the stage as in the former building, because of the steeply raked auditorium, which reflects widespread trends in modernist theatre architecture. It is a proscenium theatre, but the proscenium arch is made almost invisible by its dark colour, uniting the audience and actor in a single room. To give a sense of enclosure, and to avoid the long back rows common to most fan-shaped auditoria, the rear wall is brought round in a wide curve, embracing the audience. Thorndike Theatre is defined as one of the most intimate and architecturally accomplished proscenium theatres of British modernism, with its thoughtful design and its relatively small number of seats. After many years of success, regional theatre has struggled for funding and closed from 1997-2001, it is now open again as a part-time theatre and a community centre, as well as a religious meeting-place. It is listed Grade II. (The Leatherhead Theatre) (Calder, 2004)

Figure 2.29 Auditorium of Thorndike theatre (Calder, 2004)

2.7.1.6 Belgrade Theatre, 1958

Belgrade Square, Coventry, England

Performance Type: Drama
Architect: Arthur Ling, Coventry City Arch.
Seating capacity: (Original) 910 - Current: 866

The Belgrade was the first civic producing theatre to be built after the Second World War. It was designed by Arthur Ling (City of Coventry Architects Dept). Although based on traditional late nineteenth century theatre design the Belgrade adapts this to a 'fifties' culture. Built as part of the Coventry City centre regeneration programme the theatre has a flank to Corporation Street and a principal elevation facing Belgrade Square which, when lit at night, is particularly impressive. This latter façade exhibits a wholly glazed metal-frame double-height foyer which contains mosaics by Martin Froy and fine hanging lamps by Bernard Schottlander. (The Theatres Trust)

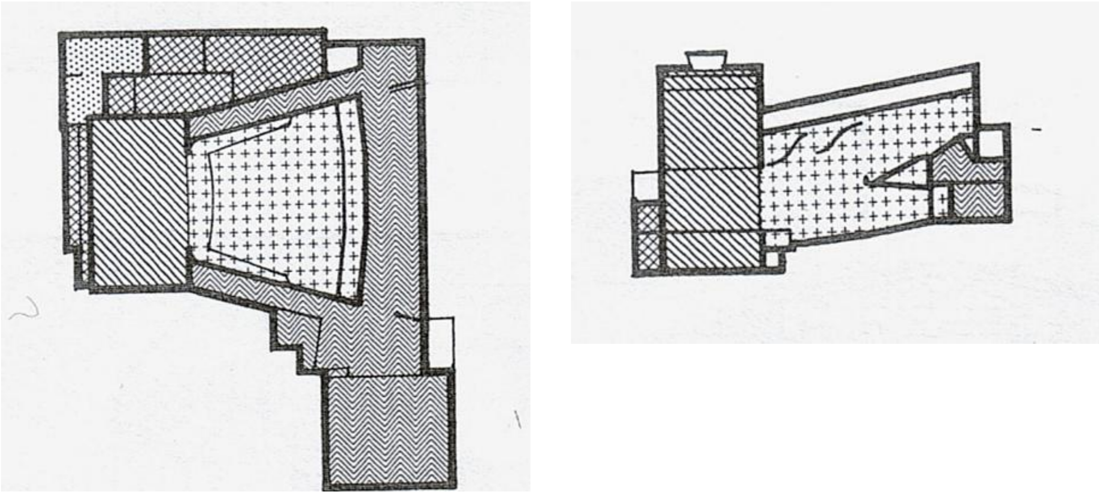


Figure 2.30 Simplified plan and section of Belgrade theatre (The Association of British Theatre Technicians, ABTT, 1972)

Figure 2.31 Colour photograph showing the auditorium. Taken from the stage looking out into the wood-lined auditorium, it shows the raked stalls, a single end balcony and the ceiling with four stepped, projecting boxes (two at stalls level and two at the balcony level) at either side. The front of the stage dominates the foreground at the bottom of the photograph (Photo and comment by Ian Grundy (The Theatres Trust)

The auditorium, with stalls, circle and boxes, is panelled in wood. The stalls, a centre block with two gangways, originally had two boxes at the rear on each side. These have been consolidated into one box each side with the technical boxes between them. The front of the slightly curved circle of 10 rows of seats with a central gangway gives a slight feeling of separation between the two parts of the theatre, but the two tiers of stepped stage boxes, not dissimilar in concept from the Royal Festival Hall, provide a good visual link between the circle and the proscenium. Originally there were sixteen boxes, but when the forestage was extended the front four were removed. The proscenium stage has an extendable forestage over the orchestra pit (accommodating 12 musicians). The stage was refitted in 1998. And also the building was listed Grade II in 1998. During 2006 the theatre closed for a major refurbishment, by providing extra facilities in a significant extension: a second auditorium, B2; rehearsal room; new dressing rooms, wardrobe and technical rooms; and extra foyer and front-of-house facilities. The new studio and the refurbished theatre, designed by architect Stanton Williams, re-opened in 2007. (The Theatres Trust)

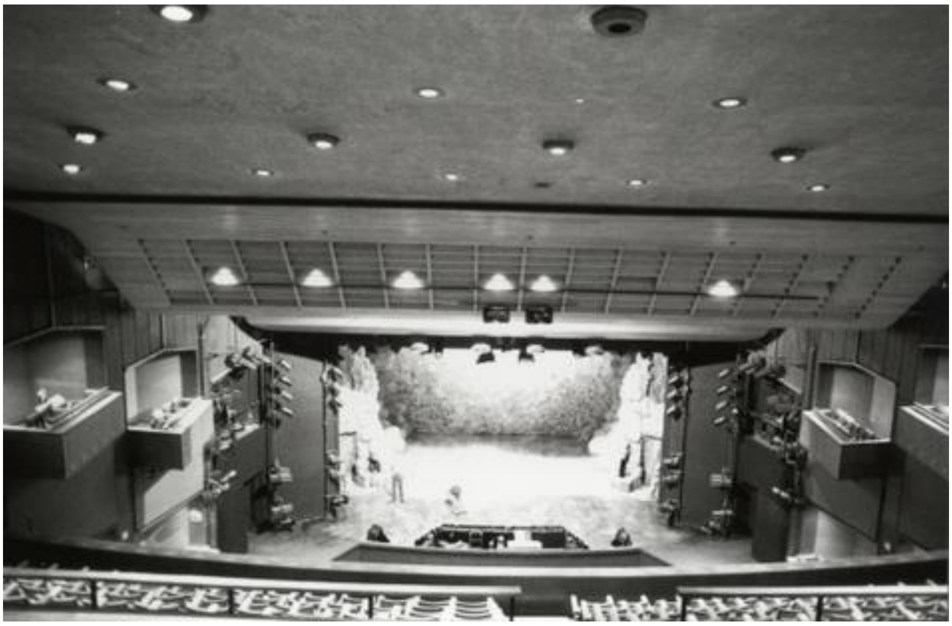


Figure 2.32 Black and white photograph, taken from high up on the balcony, it shows the stage and proscenium, the ceiling above and two stepped, projecting boxes either side at balcony level. It is a deep stage with some scenery visible. The front of the balcony is in shot at the bottom of the photograph. (Photo and comment by Ian Grundy (The Theatres Trust)

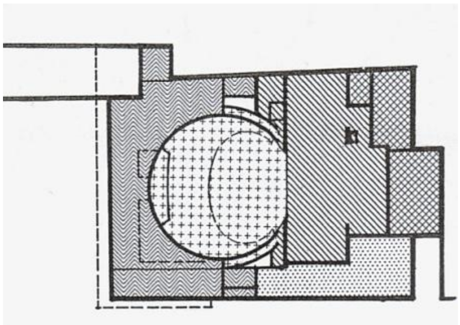
2.7.1.7 Playhouse, 1963

Nottingham, England

Architect: Peter Moro& Partners

Seating capacity: 756

The Nottingham Playhouse is designed by award-winning architect Peter Moro in the early 1960s. It became Grade II listed in July 1994 in recognition of its place in modern theatre architecture and design. In the auditorium there are approximately 750 seats. Arguably the best views can be found at the back of the stalls and especially row 'M'. (BBC Nottingham)



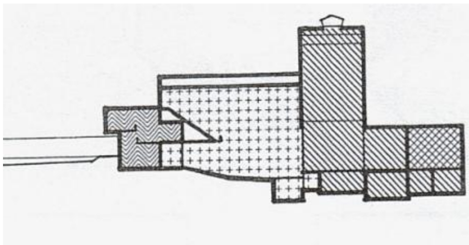


Figure 2.33 Simplified plan and section of Belgrade theatre (The Association of British Theatre Technicians, ABTT, 1972)

This reinforced concrete building has a square plan with a 2-storey foyer to Wellington Circus. The circular auditorium with stalls and a single circle rises within this square body and behind it there is a higher fly tower. Proscenium-arch stage is adaptable as apron or thrust stage which can be raised over the orchestra pit and the front stalls; the surrounding row of seats can be adjusted round this altered form; a novelty in 1963. A circular grid serves this apron stage whilst contributing to the architectural form of the interior. The Nottingham Playhouse is considered as an important example, since it was the first theatre in England to break away from the conventional proscenium stage. It is accepted that the theatre marks the beginning of a new and extremely successful period for the British theatre. (English Heritage, 2007)

Figure 2.34 The original Robin Day seats at Nottingham Playhouse have been remade with extra padding and safety mechanisms. (Harwood, 2009) Photo: (Gilbert, 2009)

2.7.1.8 Sydney Opera House Drama Theatre, 1973

Sydney, Australia

Architect: Jørn Utzon

Constrution: 1957-1973

Seat Count: 544

Sydney Opera House (1957 - 1973) is a masterpiece of late modern architecture. It is admired internationally and proudly treasured by the people of Australia. It was designed by Jørn Utzon. He is believed to give Australia a challenging, graceful piece of urban sculpture in patterned tiles, glistening in the sunlight and invitingly aglow at night. Sydney Opera House was inscribed in the World Heritage List in June 2007. The expert evaluation report to the World Heritage Committee stated that: "…it stands by itself as one of the indisputable masterpieces of human creativity, not only in the 20th century but in the history of humankind."

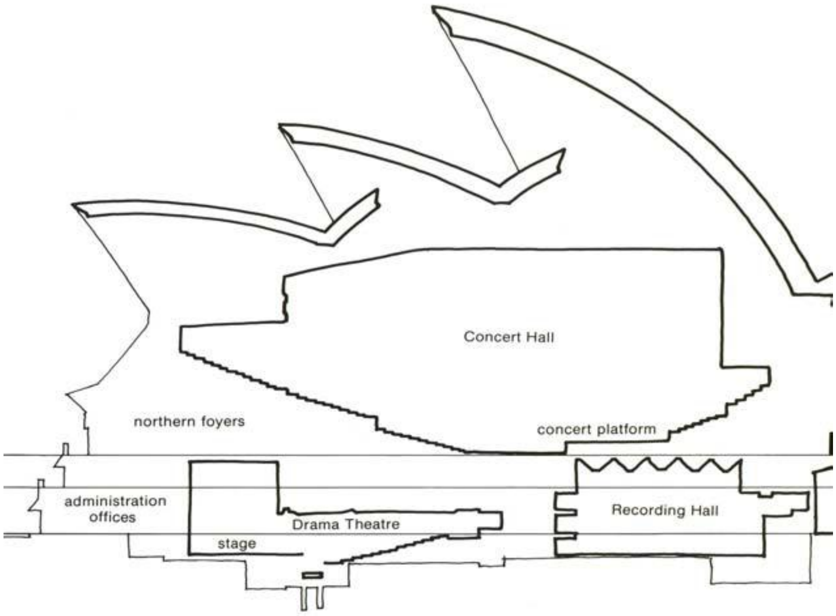


Figure 2.35 Section of Sydney Opera House (LÖKÇE, 2003)

Within this unique building, a wide range of venues and facilities live; a concert hall, an opera theatre, a drama theatre, Utzon Room, a playhouse, a studio theatre, a forecourt and a recording studio. In the context of thesis, drama theatre, which is a medium sized proscenium arch theatre, is focused.

The drama theatre is used by several performing companies; Sydney Theatre Company, Bangarra Dance Theatre, Sydney Festival, Sydney Opera House and Bell Shakespeare. The maximum seating capacity is 544 in 19 rows. The auditorium is raked from the fourth row, ensuring good sightlines from all seats. The walls and ceiling are painted black and the floor is covered with blue carpet. The seats are made of white birch timber and are upholstered in tangerine woollen fabric. With these features, it is found that auditorium is most suitable for drama, dance and small scale musical productions as well as spoken word presentations. The Drama Theatre is equipped with a computerised flying system and twin concentric stage revolves (centre and ring). The maximum proscenium opening is 13.5m wide by 4.8m high. The height to the grid is limited to 10.4m. The stage is 14m deep upstage of the safety curtain with a forestage of 2m. (Sydney Opera House)

Figure 2.36 Sydney Opera House (Tourism Australia/ Adam Bruzzone, 1992-2009)

Figure 2.36 Sydney Opera House Drama Theatre – Auditorium (Sydney Opera House)

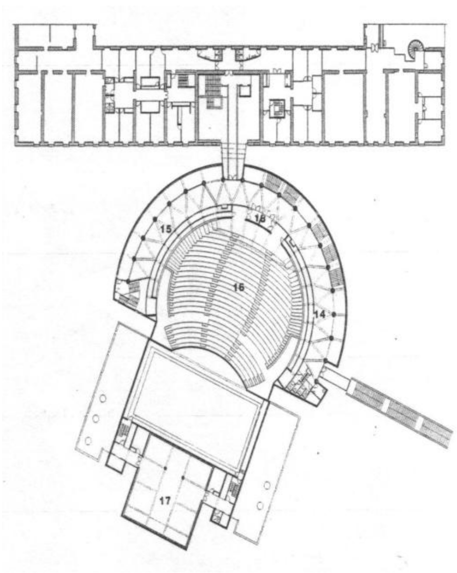
2.7.1.9 Andre Malraux Theatre and Cultural Centre, 1987

Chambery, France

Architect: Mario Botta

Project 1982 (competition project 1° prize)	Seat count(s): 950 seats – theatre 150 seats - cinema
Construction: 1983-1987	

The Andre Malraux cultural centre includes two buildings; the east wing of the former barracks (main lobby, cultural activities, offices), and new theatre divided into two areas (public space/ theatre production space). The auditorium is a fixed amphitheatre with a proscenium that can be converted into an orchestra pit. It is bounded by a narrow technical gallery that traces a long horizontal fissure along the curving wall and acts as a sound trap. The lower side of this concrete sheet is striated by layers of wood in a "diamond point" arrangement (absorbent rock wool lined perforated wood on the rear wall, reflecting fireproof plywood on the side walls); the upper side is covered with adjustable plywood acoustic panels. (Breton, 1989, pp. 92-94)



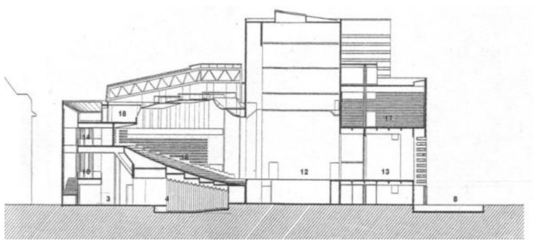


Figure 2.37 Plan level 2 and Longitudinal section of Andre Malraux Theatre (Breton, 1989, p. 93)

Figure 2.38 Interior and exterior views of Andre Malraux cultural centre, 1987 (Official web site of Mario Botta)

2.7.1.10 Jyvaskyla Theatre, 1982

Jyvaskyla, Finland

Client: City of Jyvaskyla

Architect: Alvar Aalto

Acoustics: Mauri Parjo Ltd.

Seat count: 551

Within the project of administrative and cultural centre of Jyväskylä, in 1964 Aalto had designed a theatre house to be placed on the northeast side (at the corner of Kilpisenkatu and Vapaudenkatu) of the ceremonial square alongside the town hall block. The drawings completed in 1966 show a theatre with 500 seats in an asymmetrical auditorium, its irregular facade turned towards the square, whereas the stage is on the Kilpisenkatu side in the east. In conjunction with construction of the police headquarters on the adjacent plot, Aalto produced a partly reworked plan for the theatre, with larger facilities but a considerably simplified roof design. In 1972, while working on plans for enlarging the town hall, Aalto again completely redesigned the theatre and turned the axis of the stage and auditorium so as to move the building's main facade to the Vapaudenkatu side. The asymmetrical cavea in this plan seats an audience of 620. The auditorium of theatre integrates the opposite characteristics that it derives from the twin spaces with which it is associated on one hand, the stability and symmetry of the stage (the prior conditions for any theatrical creation) and, on the other, the dynamism and asymmetry of the foyers. In this duality, it fulfils the role of a shell protecting the spectators from outside disturbance and focusing their attention on the show. The decision to build the theatre was taken only after Aalto's death, and the working drawings were drawn up between 1977 and 1982 by Elissa Aalto. (Breton, 1989) (Alvar Aalto Foundation, 2005-2009)

Figure 2.39 Exterior view of Jyvaskyla Theatre (Alvar Aalto Foundation, 2005-2009)

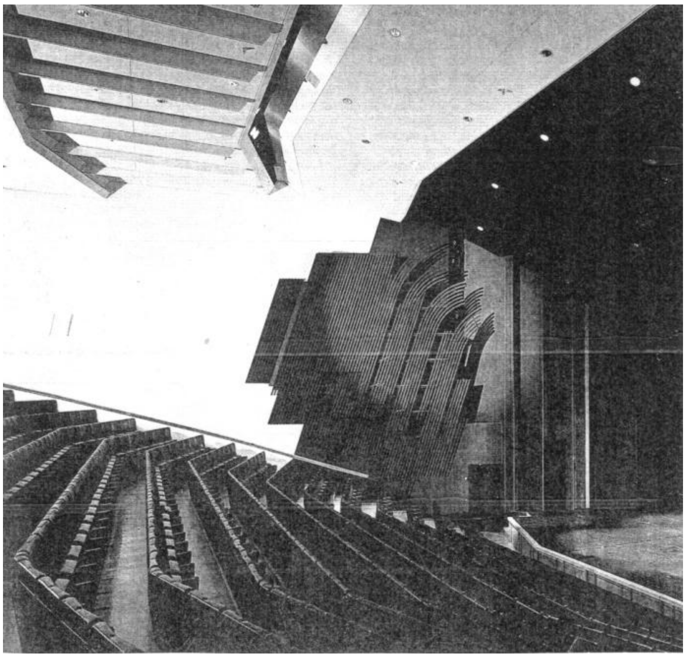


Figure 2.40 Auditorium of Jyvaskyla Theatre (Breton, 1989)

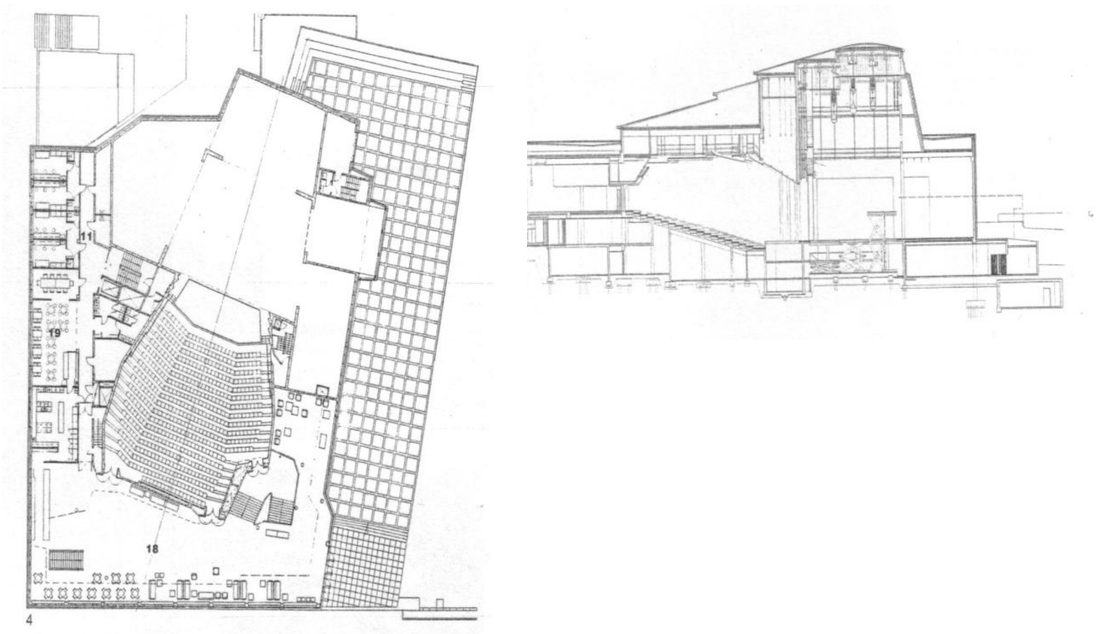


Figure 2.41 Plan and section of theatre (Breton, 1989)

2.7.1.11 Theatre of Dramatic Art, 1973

Fort Wayne, Indiana, United States

Architect: Louis I. Kahn

Theatre design: George C. Izenour

Acoustics: Syril M. Harris

Client: Fort Wayne Fine Art Foundation

Seat count: 669

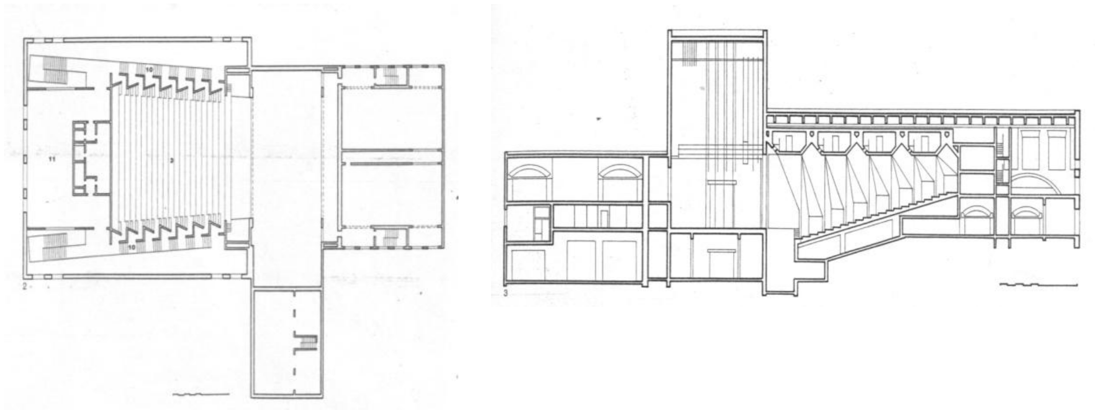


Figure 2.42 Plan and section of Fort Wayne theatre (Breton, 1989)

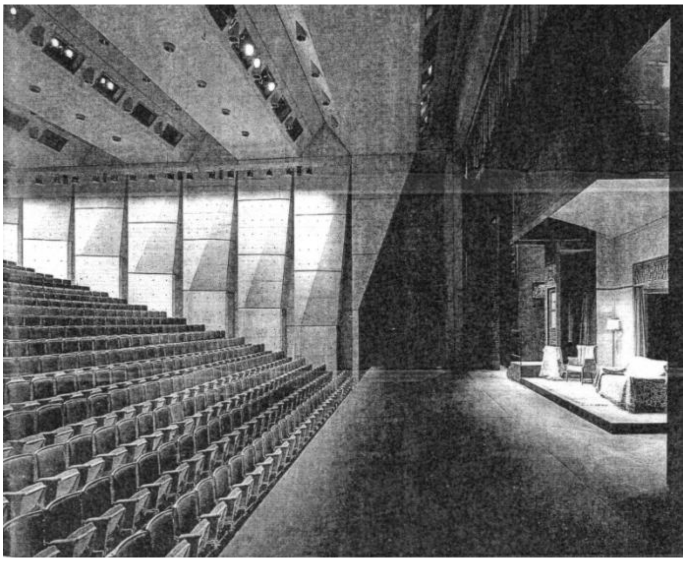


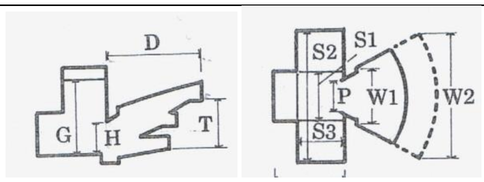
Figure 2.43 Auditorium of Fort Wayne theatre (Breton, 1989)

While designing Fort Wayne, it is said that Louis Kahn evoked the image of a violin in its case. He uses two different constructional orders; brick (the flatness of the wall) and concrete (the plasticity of the envelope). The brick wall (violin case) is the skin that complies with urban conditions whereas the concrete envelope (the violin itself) is the skin that satisfies the demands of theatrical activity. Between these two skins, Kahn has established a distance and located a reversible space – the foyer. The theatre was planned as part of a cultural complex, occupying two blocks that were – with architect's words – "responsible" for each other. Although it had not been designed as an isolated object, finally only the theatre was built. The parts of the theatre are logically arranged on either side of the stage – served laterally by a technical wing; there are public spaces to the front and to the rear, what Kahn called the "actors' house". The envelope of the auditorium – walls and ceiling – is in concrete, because it is poured, this material can assume folded or pliable surfaces like the wood of a violin. (Breton, 1989, pp. 100-104)

2.7.1.12 Comparison of Examples

Some basic dimensions of drama theatre examples are compared in table 2.6.

Table 2.6 Comparison of examples in the context of seating capacity, room and stage dimensions



P – Proscenium width
H – Proscenium height
S1, S2 – Stage width
S3,S4 – Stage Depth

G – Stage Height
W1-W2 – Auditorium width
D – Auditorium depth

Theatres	**Date**	**Seat counts**	**P**	**H**	**S1 (S2)**	**G**	**W1 (W2)**	**D**
Wyndham's	1899	765	8,20	7,90	19,20	14,90	10,70 (18,80)	18,30
Apollo	1901	827	9,10	8,80	21,30	18,30	13,70	20,40
Forum	1968	637	13,40	7,00	21,30	17,10	20,70	20,70
Thorndike	1969	530	9,70	4,90	18,90	14,00	12,20 (23,50)	17,40
Belgrade	1958	910	11,00	5,50	18,30	12,50	14,60 (21,90)	19,80
Playhouse	1963	756	9,70	6,50	29,00	18,30	21,90	20,40
Sydney	1973	544	10,72 (13,74)	4,72	-	10,20	-	-
A. Malraux	1987	950	23,00	9,00	29,00	12,00	36,00 (max.)	26,00 (max.)
Jyvaskyla	1982	551	13,00	6,00	19,00	11,00	23,00 (max.)	20,00 (max.)
Dramatic Art	1973	669	16,00	7,50	30,00	10,00	20,00 (max.)	21,00 (max.)
Theatre Royal	1766	638	7,40	6,00	-	-	-	-

2.7.2 Contemporary Examples of Drama Theatres

The examples that collected under this title are built after 1990’s and the aim was to get a quick idea of contemporary examples of proscenium type of drama theatres more than getting detailed information on them. Some of the projects are renovation of old buildings and mostly renovation process includes both stage and auditorium facilities. For the stage, the renovation of machinery or setting system as well as the places for actors is very common. In the auditorium, most of the time seating layout is needed to be renewed according to the new legislations and/or building codes. For both renovation projects and new constructions, the fan shaped or horse-shoe plans seem quite common as well as the balconies.

The selection of the examples* is quite a hard job since there are many examples of drama theatres. While deciding the examples, it is considered to choose the examples of theatres that built specifically for drama plays. And also, they are tried to be selected from different countries to have a wider opinion.

2.7.2.1 American Conservatory Theatre (1996)
San Francisco, California, USA

Architect	: Gensler and Associates
Owner/ Users	: American Conservatory Theatre
Acoustician	: Paoletti Associates
Theatre Type(s)	: Drama Theatre
Seat Count(s)	:1,000
Construction Type	: Renovation

* The examples that listed below have a common feature that Theatre Project Consultants which is an important theatre consultancy firm, had added some contribution to them, so most of the time the firm is cited in the text. The firm declares that they have contributed in more than 1,200 projects ranges from studio theatres to performing arts centres in over 70 countries. For that reason some how they are related to most of the recent projects, and they have quite a large archive of theatre projects.

The historic 1,000-seat Geary Theatre was constructed in the aftermath of the 1906 San Francisco earthquake, opened in 1910, and operated continuously until severely damaged in the Loma Prieta earthquake of 1989. The effort to stabilize and restore the building was completed in 1996 and brought the theatre into compliance with modern codes and contemporary expectations for patron comfort and amenities. The stage house was rebuilt with a unique tilting stage floor. (Theatre Projects Consultants, Inc.)

Figure 2.x Renovation process of theatre (1994) (Sherman Takata/Gensler and Associates Architects , 2009)

Figure 2.x American Conservatory Theatre (1996) (Theatre Projects Consultants, Inc.)

2.7.2.2 San Jose Repertory Theatre, Sobrato Auditorium (1997)
San Jose, California, USA

Architect	: Holt Hinshaw
Owner / Users	: San Jose Repertory Theatre
Acoustician	: Charles M. Salter Associates
Theatre Type(s)	: Drama Theatre
Seat Count(s)	: 565
Construction Type	: New Construction

It is a 565-seat flexible proscenium theatre that is accepted offering modern theatrical technology and a classic playhouse form in a contemporary mix. The auditorium features orchestra, parterre, and balcony seating areas with side seating boxes extending down toward apron stage. (Theatre Projects Consultants, Inc.) The design of the theatre won the “Honour Award” of United States Institute for Theatre Technology (USITT) in 1998.

Figure 2. San Jose Repertory Theatre, Sobrato Auditorium (1997) (Theatre Projects Consultants, Inc.)

2.7.2.3 Aksra Theatre, King Power Complex (2007)

Bangkok, Thailand

Architect	: Architects A49
Owner	: King Power Foundation
Users	: Touring performances
Acoustician	: Theatre Projects
Theatre Type(s)	: Drama Theatre
Seat Count(s)	: 579
Construction Type	: New Construction

Aksra Theatre is located in King Power Complex, in Bangkok. The theatre is situated above a shopping mall, which presented several challenges in designing the theatre space and supporting accommodation to be functional. Specifically, the backstage areas needed to be carefully planned so that props and scenery could be brought into the building without disrupting the activities in the shopping mall below. The Aksra Theatre is designed to be luxurious, employing gold leaf in the wall bass-relief decorations and elegant furnishings in the public areas. The theatre itself is a single tiered 'horse-shoe' style auditorium, presenting traditional Thai performances and King Power Sakorn Puppet performances. The stage supports over 200 performers. (Theatre Projects Consultants, Inc.)

Figure 2. Exterior view of Complex (photo from architect’s web site)

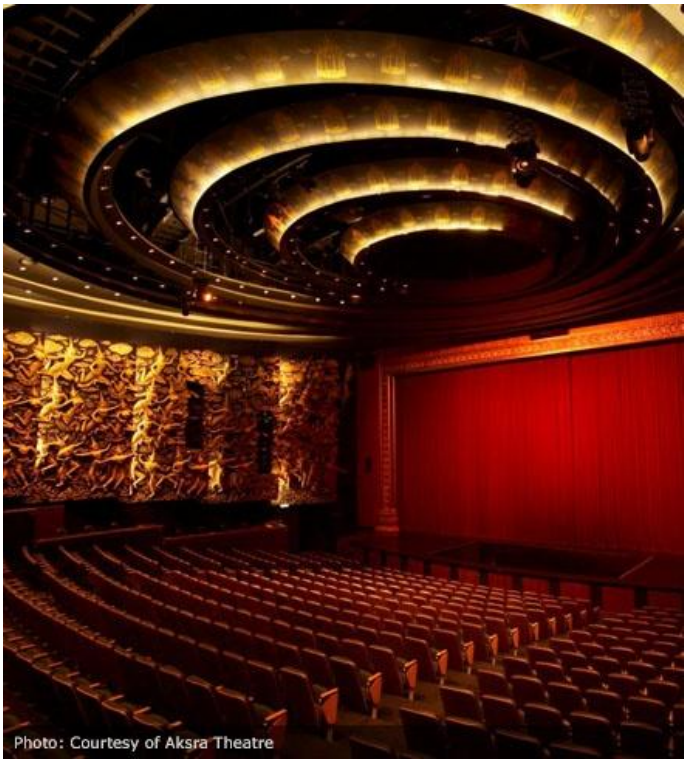


Figure 2. Aksra Theatre, King Power Complex (2007)
(Theatre Projects Consultants, Inc.)

2.7.2.4 Le Quai Theatre (2006)

Angers, France

Architect: Architecture-Studio

Owner: Ville d'Angers

Users: Open-Arts, National Centre of Contemporary Dance, National Dramatic Centre, and local and regional groups

Acoustician: Acoustique Vivié & associés

Theatre Type(s): Drama Theatre, Flexible Theatre

Seat Count(s): 900 - 400

A collaborative work have been done by Theatre Projects and Architecture-Studio for designing two auditoria at new cultural centre, which aims to enhance the work of some of France's most prestigious artistic groups. The main auditorium is a 900-seat proscenium theatre, which adapts to a 600 seats for drama and music events. The centre also includes a flexible studio theatre seating 300-400 people, depending on configuration. Additionally the complex has dance studios, a rehearsal space, a large foyer that can be used for street performances, and other ancillary spaces. (Theatre Projects Consultants, Inc.)

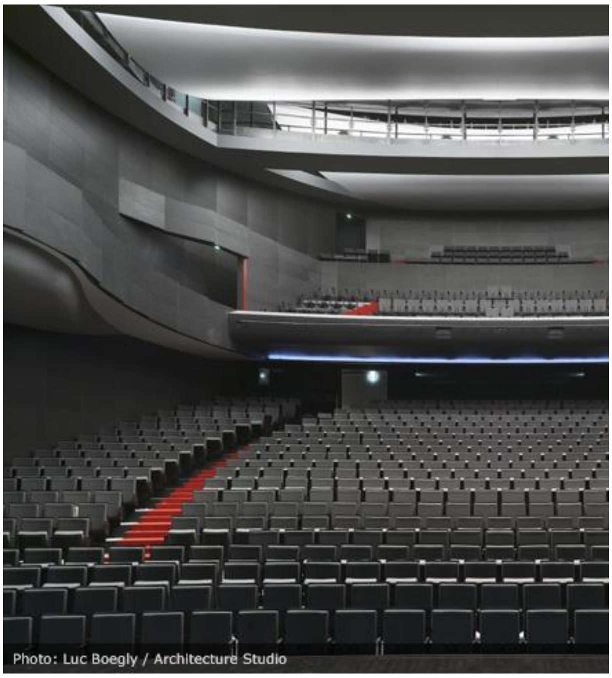


Figure 2. Le Quai – Drama theatre (Theatre Projects Consultants, Inc.)

2.7.2.5 Philadelphia Theatre Company, Suzanne Roberts Theatre (2007)
Philadelphia, Pennsylvania, USA

Architect: Kieran Timberlake Associates
Owner: Philadelphia Theatre Company
Users: Philadelphia Theatre Company and local arts groups
Acoustician: Akustiks
Theatre Type(s): Drama Theatre and Flexible Theatre
Seat Count(s): 365
Construction Type: New Construction

Part of a mixed-use development on the Avenue of the Arts, this new 32,000 square foot home for the Philadelphia Theatre Company features two performance spaces. A 365-seat drama theatre is the company's main stage space, and a flexible theatre is used for workshops, readings, and more intimate performances. (Theatre Projects Consultants, Inc.)

Figure 2. Philadelphia Theatre Company, Suzanne Roberts Theatre (Theatre Projects Consultants, Inc.)

2.7.2.6 University of Notre Dame, Marie P. Debartolo Center for the Performing Arts (2002)

South Bend, Indiana, USA

Architect: Hardy Holzman Pfeiffer Associates

Owner: University of Notre Dame

Users: University of Notre Dame academic programs and touring performances

Acoustician: McKay Conant Brook

Theatre Type(s): Arts Centre

Educational

Concert Hall

Drama Theatre – 350 seats

Flexible Theatre

Recital Hall

This arts centre provides a major focal point on the Notre Dame campus. The 122,000 square foot complex features a 900-seat concert hall, 350-seat main stage proscenium theatre, 100-seat studio theatre, 200-seat cinema, and a 100-seat organ/choral hall. The extensive support facilities include rehearsal spaces, dressing rooms, green room, storage, offices, and classrooms. (Theatre Projects Consultants, Inc.)

Figure 2. University of Notre Dame, Marie P. Debartolo Center for the Performing Arts

2.7.2.7 Vassar College, Vogelstein Center for Drama & Film (2003)

Poughkeepsie, New York, USA

Architect: Cesar Pelli & Associates

Owner: Vassar College

Users: Vassar College

Acoustician: Acentech

Theatre Type(s):

Educational

Drama Theatre – 330 seats

Outdoor Venue

In 1997 Theatre Projects worked with Cesar Pelli & Associates to create a master plan for the renovation of the historic Avery Hall on the Vassar campus. The project continued in 2000 with plans for new drama and film spaces to be built behind the preserved facade of Avery Hall. The new 54,000 square foot building includes a drama theatre, flexible theatre, cinema, and extensive instructional and craft spaces. On the north side, the Centre opens onto the Frances Daly Fergusson Quadrangle, used by the drama department for outdoor productions and by the college for concerts and other campus events. (Theatre Projects Consultants, Inc.)

Vassar College, Vogelstein Center for Drama & Film

2.7.2.8 Steppenwolf Theatre, (1991)

Chicago, Illinois, USA

Theatre Type:	Drama Theatre
Theatre Form:	Proscenium
Seat Count:	500
Project Type:	New Construction
Architect:	James, Morris & Kutyla- Chicago, IL
Acoustician:	The Talaske Group

Steppenwolf theatre is designed for Steppenwolf Theatre Company by the architectural office James, Morris & Kutyla- Chicago, IL. The Steppenwolf Theatre includes a main stage, a studio theatre, and a full size rehearsal room and offices. The Auditorium looks like classic American Playhouses, with its balcony and side boxes stepping down toward the apron stage. The curved balcony front and precisely positioned box seats frame the stage apron in steel and rough concrete, in contrast to the rich colour and texture of the draperies and seats. (Morris Architects Planners, 1999-2006) (Theatre Projects Consultants, Inc.)

Figure 2. Steppenwolf theatre

Figure 2. View of Steppenwolf theatre when occupied

CHAPTER THREE
DEFINITION OF THE DESIGNED CASES

As explained in the first chapter, design of some theatre examples (cases) and making evaluations according to them is chosen as method of the study. For that reason, eight different types of drama theatres with the same volume are designed. But it is quite a hard job, since design of a theatre building (like any other rooms) depends on many factors which has been tried to be described in previous chapters. For example, it is clear that an architect can design endless forms or dimensions for different requirements. On the other hand, even the dimensions of a single seat can affect the design of whole auditoria, in detail. In this chapter, the basic acceptances that are made for the design of these theatre examples are going to be explained as well as properties of the designed theatre volumes. Design phases that are followed during the design process of cases are summarized in the chart below (Figure 3.1).

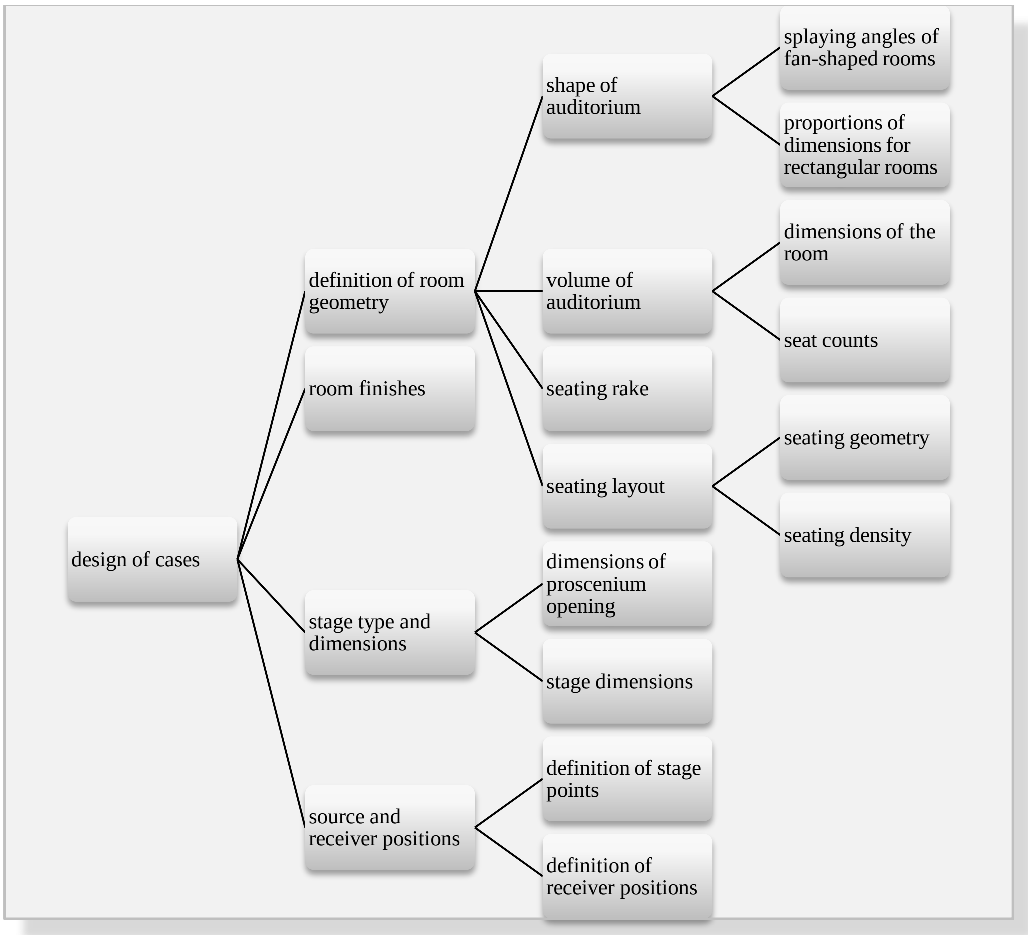


Figure 3.1 Design Phases of the Case Studies

3.1 Properties Related to Room Geometry

The decisions that are made during the design process can affect both acoustics and sightline design of an auditorium. These criteria can be listed as room shape and dimensions, seating layout and rake, stage specifications.

3.1.1 Room Shape

In this study, as explained before, most common plan type of drama theatres, fan-shape is aimed to be studied from the viewpoint of both acoustic and sightline conditions. Also, in the end of the previous chapter, by comparing the examples of drama theatres, it is found that most of them have fan or circular shape auditoria with balconies. To be able to make some comparisons there are 3 types of fan shaped auditoria designed with same volume, they are different from each other with their splaying angles in plan. The aim of this kind of change is to be able to see the effect of changes of splaying angles on the auditoria. The decisions about the some design criteria are made according to the design requirements and also the examples of theatres that explained in chapter 2. In most references 30^0 is defined as the limit of the splaying angle of the side walls, since, for the greater angles, the loss of early reflections and the loss of sightlines can became a problem, because of the width of the auditorium. In this context three fan-shaped auditoria with 15^0, $22{,}5^0$and 30^0 splaying angles have designed to see the effect of the change of angles of same volume.

In addition to these three auditoria with fan shape, a rectangular one is designed with the same volume, to make a comparison between the different forms that are used for the same purpose. For the rectangular auditoria, it is important to choose the proportions of side dimensions (width, length and height) to prevent the coinciding modal frequencies. For this reason there are offered suggestions on preferred room dimensions in some references. These are usually given in terms of the ratios of the lengths of the sides of a rectangular room. (Long, 2006)

Researches show that some of the suggested ratios are more appropriate for the rooms for speech; the ratios of Knudsen and European. (Yüğrük, 1995) Within the study, European ratio is used for the design of Rectangular room.

Table 3.1 Preferred Ratios for the Rectangular Rooms (Sahin, 2007)

Name of the Ratio	**height x width x length**	**floor area/ height**
Venn O.Knudsen	1 x 1.88 x 2.5	4.7
European	**1 x 1.67 x 2.67**	**4.45**
John E. Volkman	1 x 1.6 x 2.5	4.0
Golden Section	1 x 1.62 x 2.62	4.0
P.E.Sabine	1 x 1.5 x 2.5	3.75

And finally, to see the effect of balcony within the auditorium, a balcony added to four theatres (3 fan-shaped and 1 rectangular) while the volume is kept same. The designed cases and their geometrical features are described below. The cases are named according to their splaying (opening) angles and the existence of balcony in the room.

3.1.2 Room Volume

There are two main factors that define the volume of the auditoria, dimensions of the room and seat count. But besides the number of seats and required volume for them, the volume of the auditoria are decided by keeping in mind that there are no electronic amplification and human eye have limitations. To minimize the changing factors between the cases, and also to be able to compare selected criteria the volumes of the auditoria is kept approximately same while the plan forms are changed.

Finally volumes of auditoria tried to be kept between 2500 - 3000 m^3 and maximum distance between stage and the furthest seat is considered as about 20 meters. To obtain the equal volumes of fan-shaped auditoria, the lengths of rooms are decreased, since the widths of the rooms increase by the increase of splaying angles.

3.1.3 Seating Layout

The seat counts of the designed auditoria have been defined by using the design criteria that described in chapter 2. The rows of seats are shaped as circular for fan-shaped auditoria while for the rectangular room they are designed as straight rows, parallel to the stage. The lines of rows are designed as perpendicular to the side walls. The row to row distance is defined as 0,95 m.

3.1.4 Volume per Seat

Since the area of spectators has an important effect on the acoustics of the auditoria, it is recommended to limit the number of spectators according to the room volume. And there is an equation, which is defined below, for calculating the maximum number of spectators (N_{max}) by depending on the room volume (V).

$N_{max} = 1{,}54\ V^{0{,}75}$ (Yuksel Can, 2007)

Also, there is another criterion, volume per seat, which is used for determining the appropriate volume for specific purposes. There are different values in different references for the optimum volume per seat (occupant) in drama theatres and some of them are shown in Table 3.2.

Table 3.2 Optimum Volumes for Drama Theatres (m^3/occupant)

Reference	**Minimum**	**Recommended**	**Maximum**
(Mehta, Johnson, & Rocafort, 1999)	2	...	5
(Maekawa)	4	...	6
(Abdülrahimov, 1998)	4	...	6

By using the N_{max} equation, total seat counts are checked if they are under the limit of N_{max} value or not. As an example, for the volume of 2780 m^3 the maximum number of seats is found 591. And the value of volume per seat is kept between 4-6 m^3.

3.1.5 Seating Rake

After making decisions about seat dimensions, row spacing and seating layout, the rake of the seating area, which is important for both acoustic and sightline design, has been worked graphically for each auditorium. Height of the point, which the whole audience should be able to see, is defined as 0.60 m and it is located at the end of apron stage. Then, the longitudinal cross section of the hall is studied to find out sight line of each seated person. The eye level is accepted as 1.20 m above the floor. According to theoretical approach to find the floor slope, first row is accepted at elevation zero. The elevation of the second row is established by drawing a line from the top of the head of the person in the first row to the focal point and extending it to the second row. The head of the person is assumed to be 120 mm above the eye height. The elevations of further rows are determined by the same graphical method.

3.1.6 Individual Properties of Designed Cases

As explained before eight different types of auditoria have been designed; three fan shaped room and a rectangular shaped room, and their balcony added versions. They are described below, in titles that are describing room type.

3.1.6.1 Fan-Shaped Room with 15^0 Splaying Angle (F 15)

There are 509 seats in this room. The minimum width is 13,20 m. and the maximum width is 23,60 m. The maximum length of the room, from proscenium wall to the rear wall (in the middle axis) is 20,90 m.

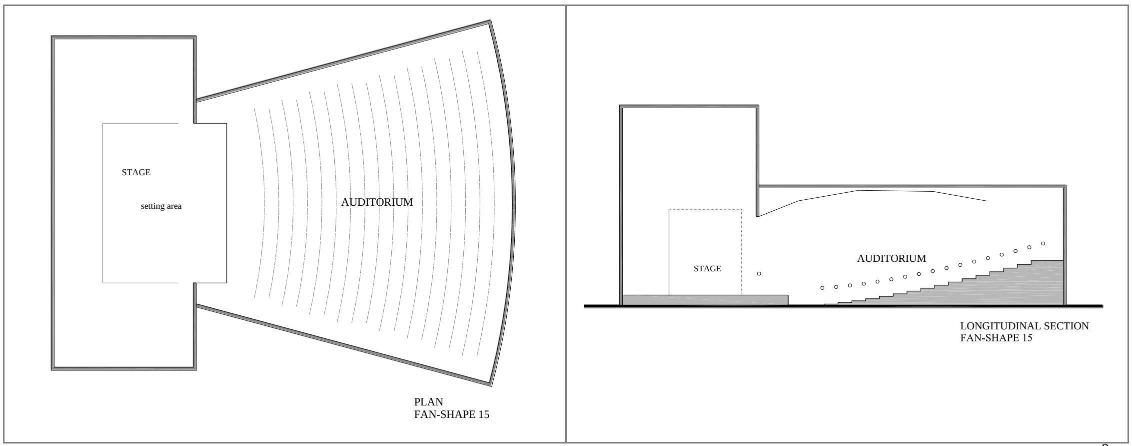


Figure 3.2 Plan and longitudinal section of the Fan-Shaped Auditorium (F 15) – Splaying angle is 15^0

3.1.6.2 Fan-Shaped Room with 15^0 Splaying Angle and Balcony (F15 B)

There are 532 seats in this room. The minimum width is 13,20 m. and the maximum width is 22,20 m. The maximum length of the room, from proscenium wall to the rear wall (in the middle axis) is 18,00 m.

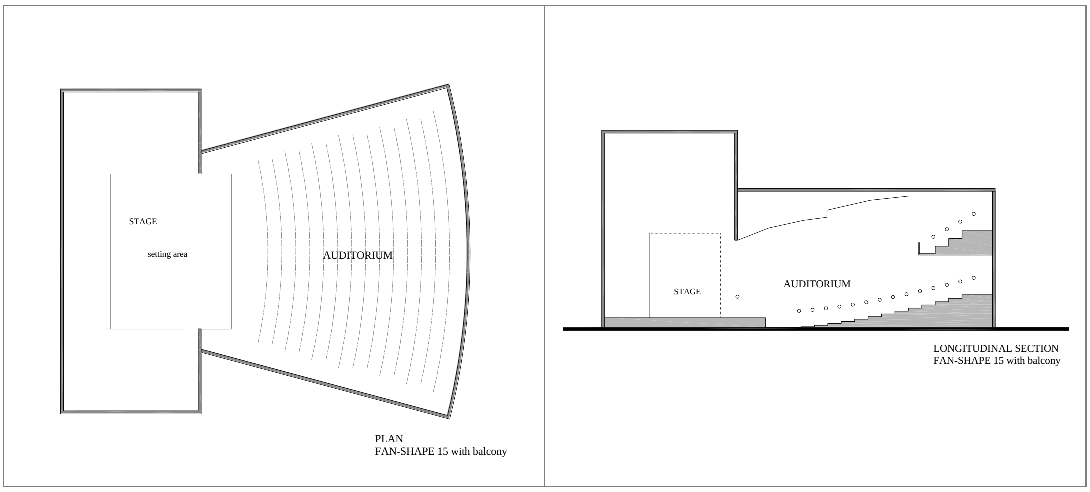


Figure 3.3 Plan and longitudinal section of the Fan-Shaped Auditorium with balcony (F15 B) – Splaying angle is 15^0

3.1.6.3 Fan-Shaped Room with $22,5^0$ Splaying Angle (F 22)

There are 505 seats in this room. The minimum width is 13,20 m. and the maximum width is 26,75 m. The maximum length of the room, from proscenium wall to the rear wall (in the middle axis) is 19,00 m.

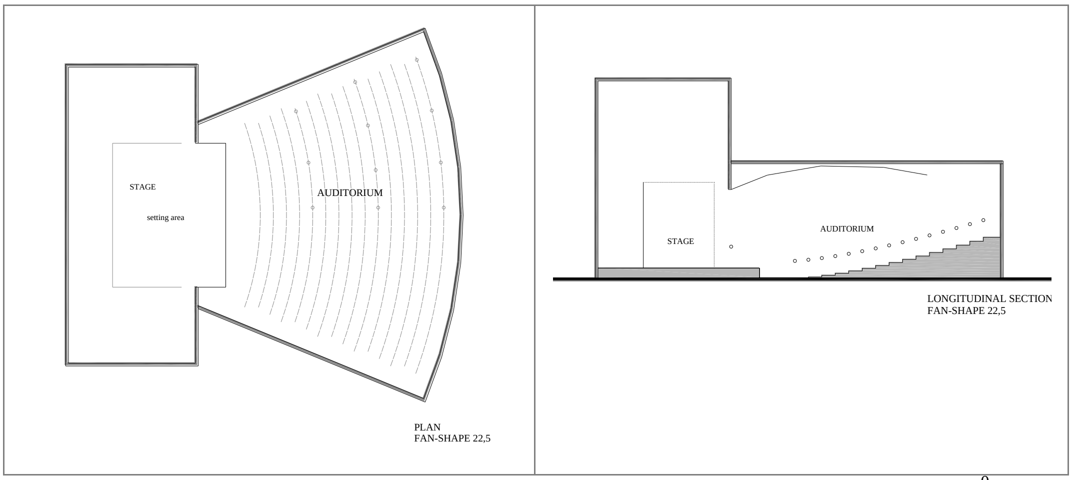


Figure 3.4 Plan and longitudinal section of the Auditorium (F22) – Splaying angle is $22,5^0$

3.1.6.4 Fan-Shaped Room with $22,5^0$ Splaying Angle and Balcony (F 22 B)

There are 575 seats in this room. The minimum width is 13,20 m. and the maximum width is 25,20 m. The maximum length of the room, from proscenium wall to the rear wall (in the middle axis) is 17,10 m.

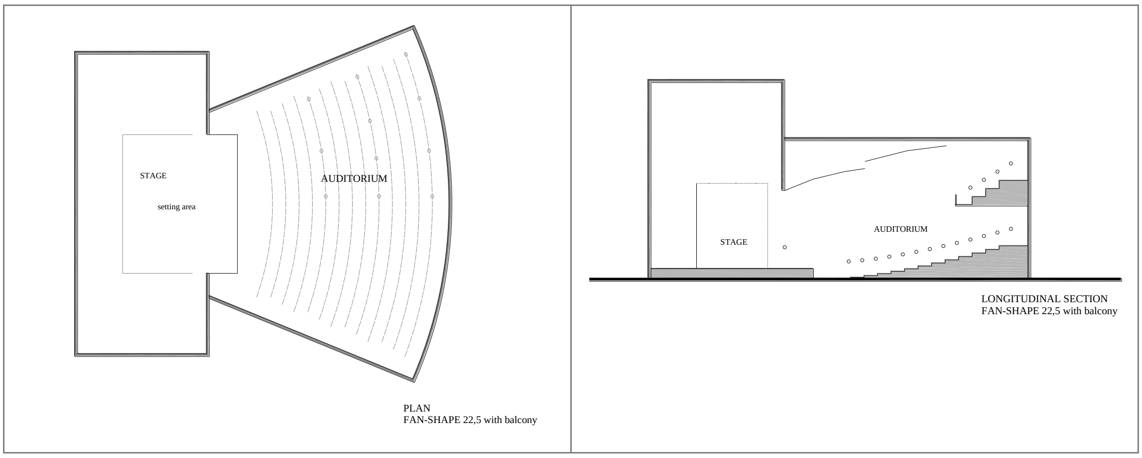


Figure 3.5 Plan and longitudinal section of the Auditorium with balcony (F22 B) – Splaying angle is $22,5^0$

3.1.6.5 Fan-Shaped Room with 30^0 Splaying Angle (F 30)

There are 518 seats in this room. The minimum width is 13,20 m. and the maximum width is 29,60 m. The maximum length of the room, from proscenium wall to the rear wall (in the middle axis) is 18,00 m.

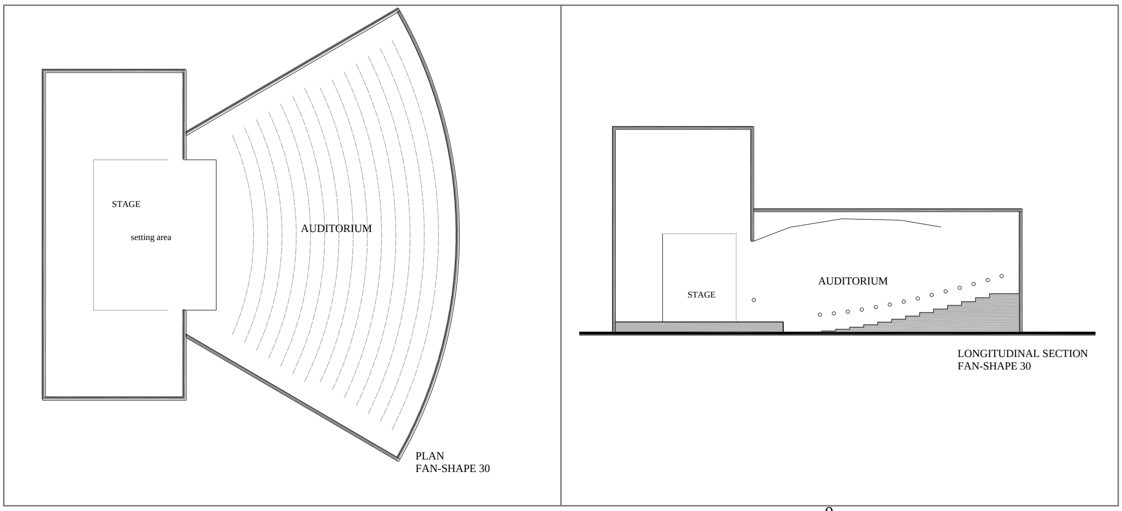


Figure 3.6 Plan and section of the Auditorium (F30) – Splaying angle is 30^0

3.1.6.6 Fan-Shaped Room with 30^0 Splaying Angle and Balcony (F 30 B)

There are 590 seats in this room. The minimum width is 13,20 m. and the maximum width is 27,70 m. The maximum length of the room, from proscenium wall to the rear wall (in the middle axis) is 16,20 m.

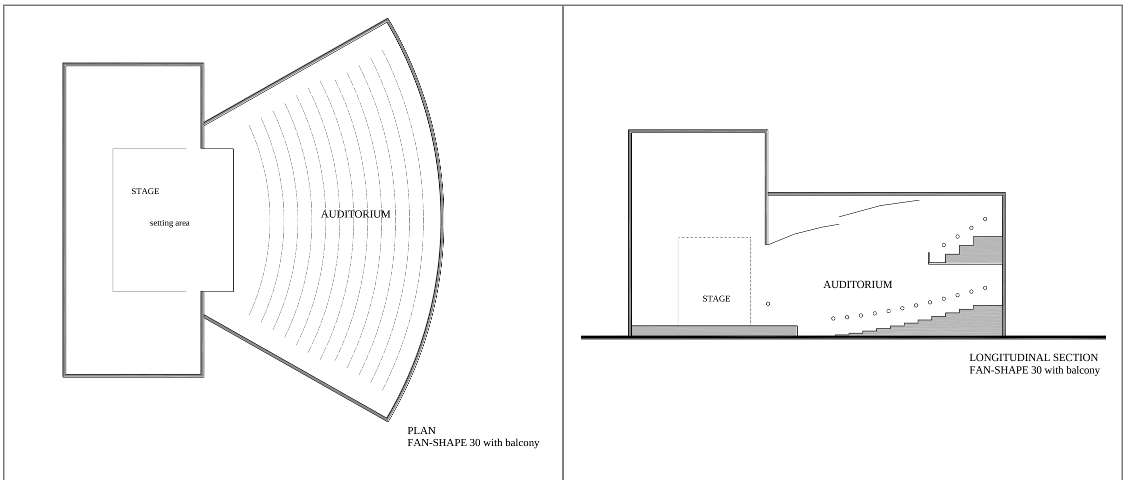


Figure 3.7 Plan and section of the Auditorium with balcony (F30) – Splaying angle is 30^0

3.1.6.7 Rectangular Room (REC)

There are 399 seats in this room. The width is 14,20 m. The length of the room, from proscenium wall to the rear wall (in the middle axis) is 22,70 m.

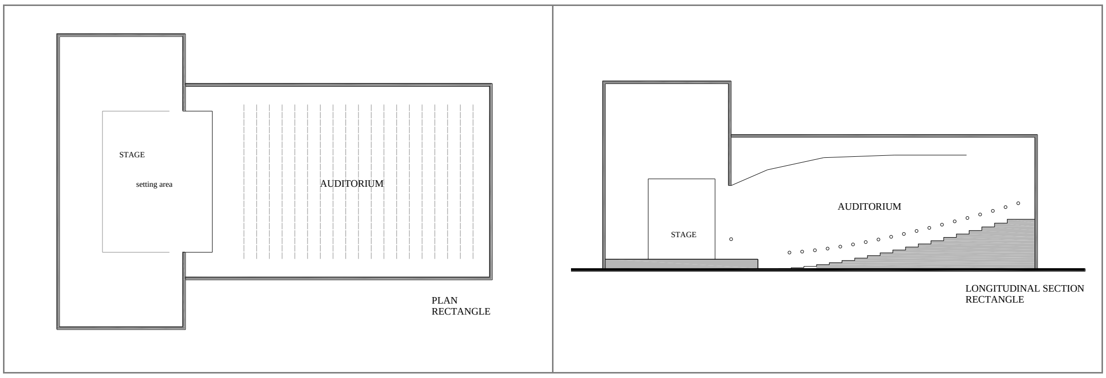


Figure 3.8 Rectangular Auditorium (REC)

3.1.6.8 Rectangular Room with Balcony (REC B)

There are 441 seats in this room. The width is 14,20 m. The length of the room, from proscenium wall to the rear wall (in the middle axis) is 20,80 m.

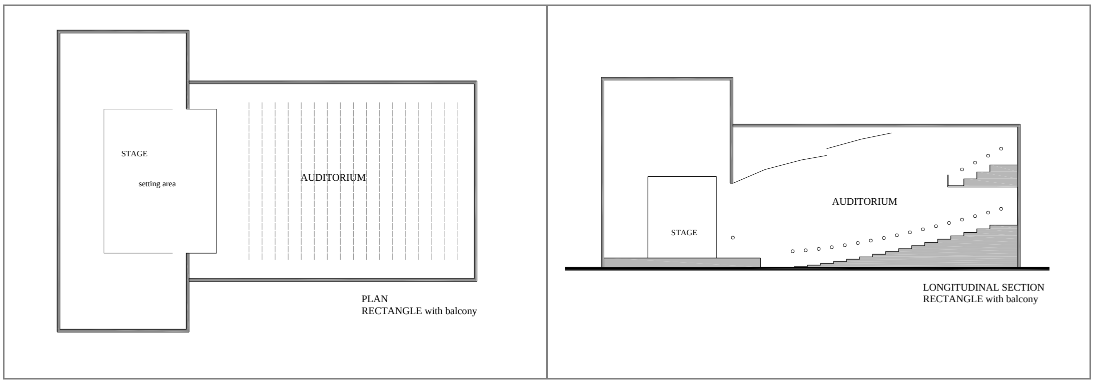


Figure 3.9 (R-B) Rectangular Auditorium with balcony

3.1.6.9 Comparison of the Room Properties

In table 3.3 some of the features (such as volume, the seat count) of the designed auditoria are compared. While volumes of the rooms are very similar, it is seen that seat counts are varying by the shape.

Table 3.3 Volumes, seats counts, and according to them, volumes per occupant in auditoria. (Numbers in the brackets show the values for the floor and the balcony separately)

Auditoria Type	**Volume (m^3)**	**Number of Rows**	**Seating Capacity**	**Volume per seat (m^3/ seat)**
Fan 15	2710	17	509	5,32
Fan 22,5	2740	15	505	5,42
Fan 30	2790	14	518	5,38
Rectangle	2705	19	399	6,77
Fan 15 B	2710	(14+4) 18	(400+132) 532	5,09
Fan 22,5 B	2790	(13+4) 17	(421+154) 575	4,85
Fan 30 B	2780	(12+4) 16	(422+168) 590	4,7
Rectangle B	2635	(17+4) 21	(357+84) 441	5,97

3.2 Stage Type and Dimensions

For all the cases, dimensions and form of the stage is same. A proscenium stage with fly tower is designed according to minimum requirements and also by considering the dimensions of examples of drama theatres that explained in previous chapters. Some dimensions of the stage are listed below.

- Width of the proscenium opening: 10.50 m
- Height of the proscenium opening: 5.50 m
- Total Stage width: 22.00 m
- Total Stage Depth: 9.60 m
- Fly Tower Height: 13.10 m
- Width of apron stage: 10.50 m
- Depth of apron stage: 2.00 m

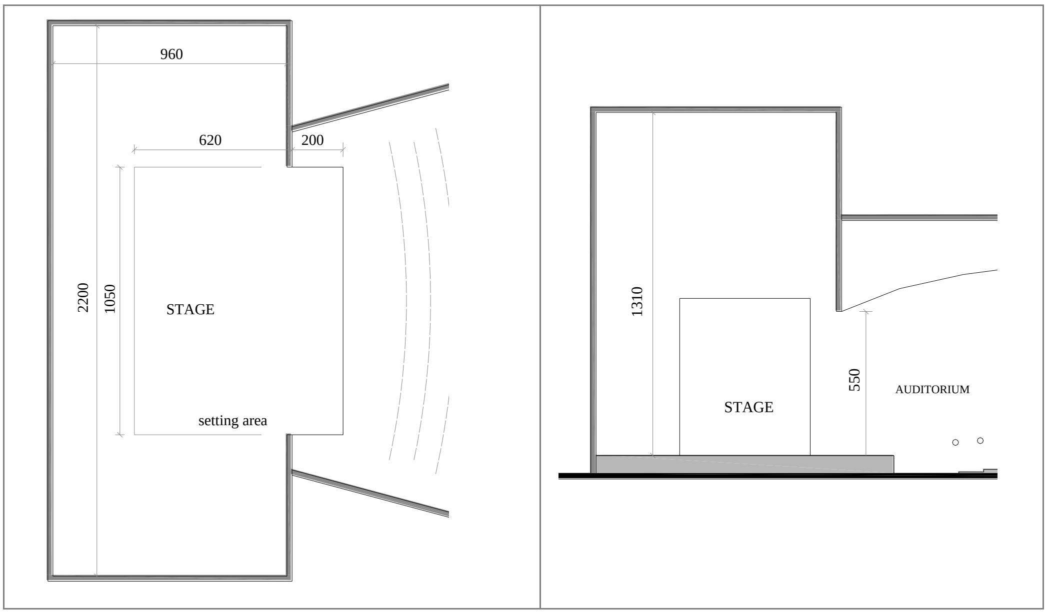


Figure 3.10 Plan and section of designed proscenium stage

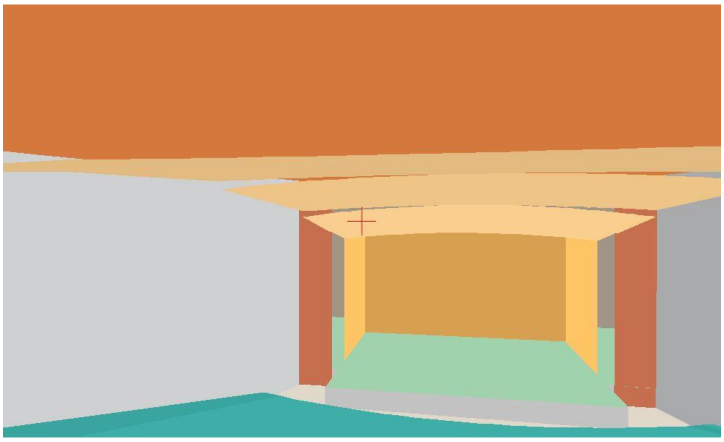


Figure 3.11 View of the designed stage (from 3D drawings)

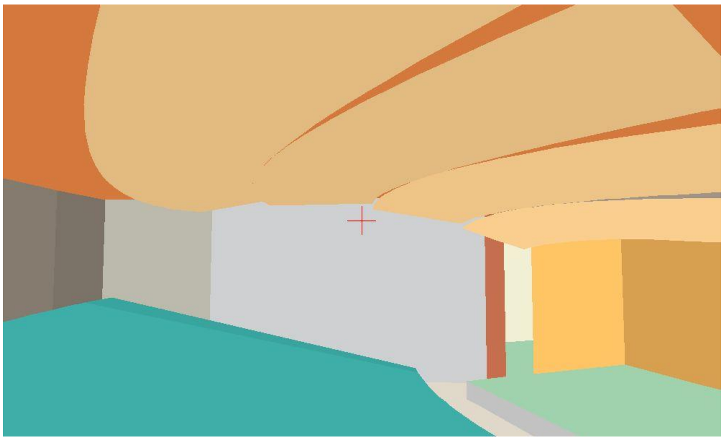


Figure 3.12 View of the designed stage and auditorium

3.3 Comparison of the Designed Cases with Theatre Examples

In chapter 2, important examples of drama theatres, which are collected from reference books related to acoustics, have been examined and also they are compared. Similar comparison is done in this section between the examples and designed auditoria and it is seen that, dimensions of the designed auditoria are between the maximum and minimum values of examples.

Table 3.4 Comparison of the stage dimensions. (Barron, 1993) (Breton, 1989) (The Association of British Theatre Technicians, ABTT, 1972)

Theatres	Proscenium Dimensions (m)		Stage Dimensions (m)		
	Width	**Height***	**Width**	**Depth**	**Height to Grid**
Designed Auditoria	10,50	5,50	22,00	9,60	13,10
Wyndham's	8,20	7,90	19,20	8,80	14,90
Apollo	9,10	8,80	21,30	8,50	18,30
Forum	13,40	7,00	21,30	11,90	17,10
Thorndike	9,70	4,90	18,90	10,10	14,00
Belgrade	11,00	5,50	18,30	8,80	12,50
Playhouse	9,70	6,50	29,00	15,20	18,30
Sydney	10,72 (13,74)	4,72	-	-	10,20
A. Malraux	23,00	9,00	29,00	15+5	12,00
Jyvaskyla	13,00	6,00	19,00	14+10	11,00
Dramatic Art	16,00	7,50	30,00	12+3	10,00
Theatre Royal	7,40	6,00	-	-	-

* Height above stage.

Table 3.5 Comparison of the auditoria dimensions. (Breton, 1989) (The Association of British Theatre Technicians, ABTT, 1972)

Theatres	Seat counts	Number of tiers	Width* of Auditorium	Length ** of Auditorium	Height of Auditorium	
					a	**b**
F15	509	1	13,20 (23,60)	20,90	8,20	2,40
F 22,5	505	1	13,20 (26,75)	19,00	8,20	2,15
F 30	518	1	13,20 (29,60)	18,00	8,20	1,95
Rectangle	399	1	14,20	22,70	9,80	3,00
F 15 B	532	2	13,20 (22,20)	18,00	9,70	6,20
F 22,5 B	575	2	13,20 (25,20)	17,10	9,70	6,20
F 30 B	590	2	13,20 (27,70)	16,20	9,55	6,05
Rectangle B	441	2	14,2	20,80	10,35	6,85
Wyndham's	765	3	10,70 (18,80)	18,30	-	11,90
Apollo	827	4	13,70	20,40	-	15,20
Forum	637	3	20,70	20,70	-	7,90
Thorndike	530	1	12,20 (23,50)	17,40	-	4,60
Belgrade	910	2	14,60 (21,90)	19,80	-	-
Playhouse	756	2	21,90	20,40	-	9,10
A. Malraux	950	1	36,00 (max.)	26,00 (max.)	12,00	
Jyvaskyla	551	1	23,00 (max.)	20,00 (max.)	10,00	
Dramatic Art	669	1	20,00 (max.)	21,00 (max.)	8,00	

* Values in brackets are the maximum width (for fan shape)

** The length of auditorium, from proscenium opening to the farthest point on the rear wall.

a – Maximum height of auditorium b - Height above stage of top most seat (floor).

3.4 Finishes of the Auditoria

The materials that cover the room surfaces are very important, since, different materials have different absorption characteristics, which affect the acoustical characteristics of the rooms. Because of the possibility of making endless variations/combinations of materials it is required to make some acceptances. Also it is possible to compare the different absorption values of same volumes but this issue is not considered within this study.

Basic principles that described in chapter 2 are applied to case studies and selected surface materials are same for all types. The rear walls of the rooms and balcony fronts are designed as absorptive surfaces. Plaster and paint are selected for the side wall covering, to obtain some reflections. But rear pars of the side walls are designed as absorptive surfaces. Since the early reflections are very important for the rooms for speech, the ceiling reflectors are added. More details about the absorption characteristics of the materials will be explained in chapter 4, in the acoustical evaluation process.

3.5 Source and Receiver Positions

The number and location of the receiver points within the auditoria as well as the source numbers and locations on the stage are very important during the simulation process. The defined stage points (source positions) and seats (receiver positions) are used for both acoustical and visual evaluation process.

3.5.1 Definition of the Required Number and Positions of Receivers (Seats)

The most important issue for defining receiver positions is to distribute them within the room so that they can reflect the characteristics of critical points. With this idea, receivers are located in three main groups according to distance to the stage. In first group, receivers are in the fifth row, to simulate the situation of front rows. Receivers in the second group are placed in the 9^{th} or 10^{th} row depending on the total number of rows in the designed case to simulate the characteristics of middle rows. And the third group of receivers are located in the last row in the auditorium. For the cases with balcony, the first and the last rows in the balcony are chosen.

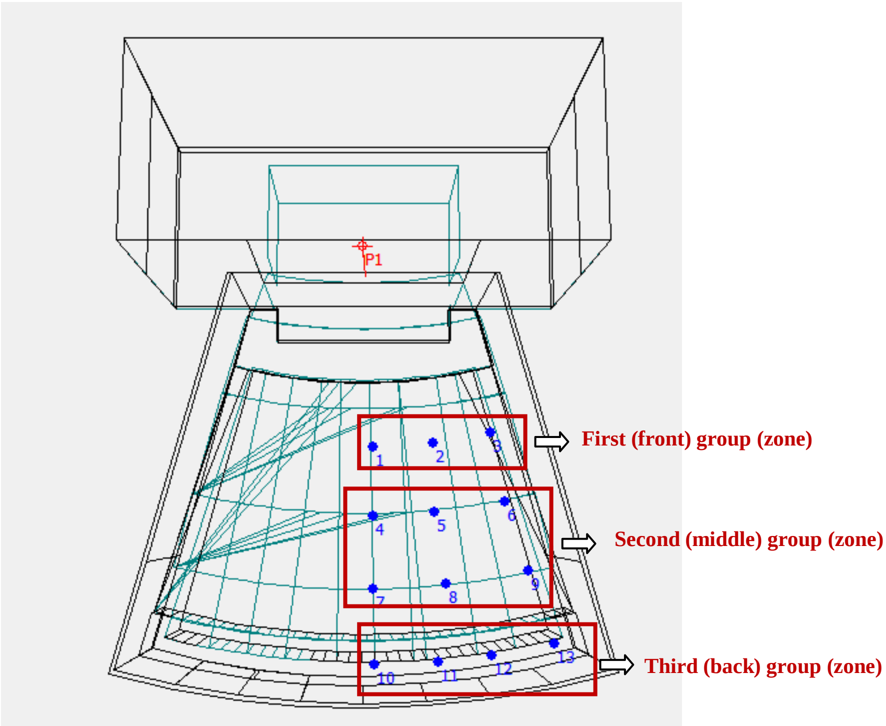


Figure 3.13 Receiver positions in F 15

Since the designed cases are symmetrical, the receivers (seats) are located in one side of the plan. And this method is quite common for in such studies. To be able to get reliable results from the acoustical measurements ISO standards define the (minimum) required numbers of receivers (Table 3.6) (ISO 3382, 1997)

Table 3.6 Number of receiver points according to seating capacity (ISO 3382, 1997)

Seating Capacity	**Number of Receivers**
500	6
1000	8
2000	10

Also the height of the receiver points is defined as 1.20 m to represent the height of ear. In table 3.5 the seating capacities and the number of receivers within the designed auditoria are shown. The number of sources and positions are same for all types.

Table 3.7 Defined number of receivers within the auditoria.

Auditorium type	Number of seats	Number of receiver points
F 15	509	13
F 22,5	505	11
F 30	518	13
R	399	12
F 15 B	(400+132) 532	(10+7) 17
F 22,5 B	(421+154) 575	(11+8) 19
F 30 B	(422+168) 590	(13+9) 22
R B	(357+84) 441	(9+6) 15

In all rooms, there are more receiver points than what recommended in ISO standards to obtain more data for comparison. In figures 3.14-3.20 receiver positions of all the designed auditoria are shown.

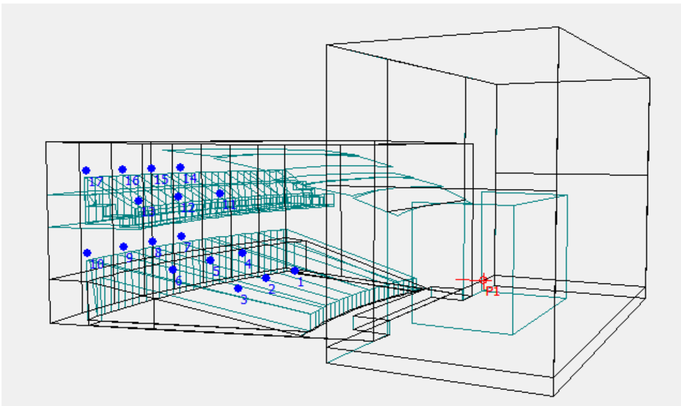


Figure 3.14 Receiver positions in F 15 B

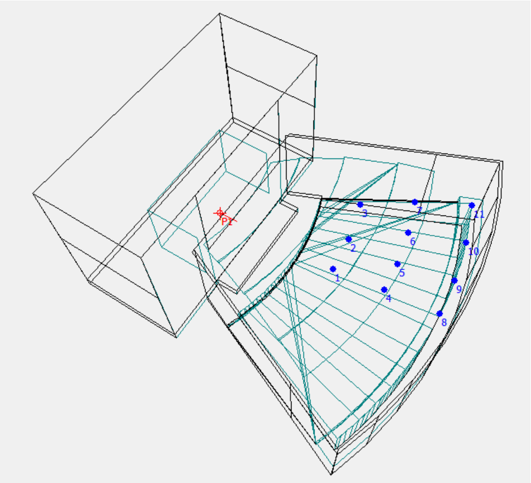


Figure 3.15 Receiver positions in F 22,5

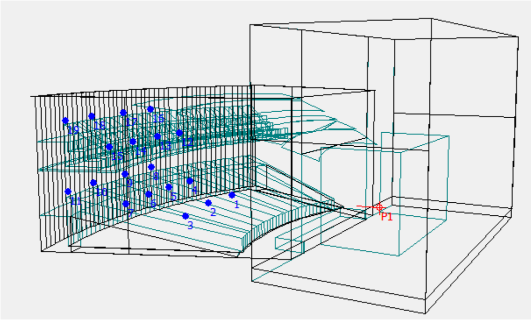


Figure 3.16 Receiver positions in F 22,5 B

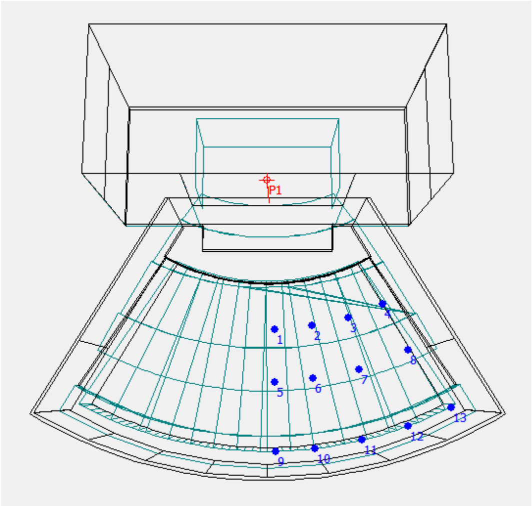


Figure 3.17 Receiver positions in F 30

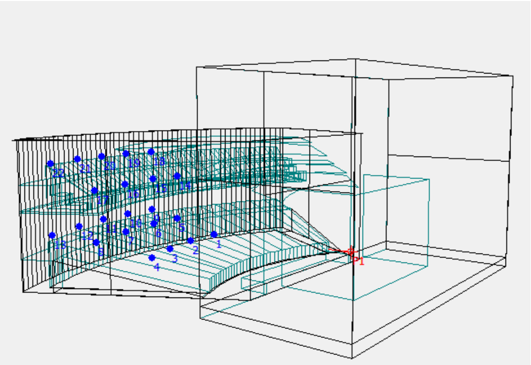


Figure 3.18 Receiver positions in F 30 B

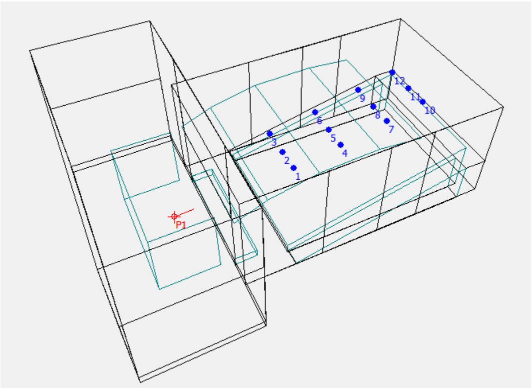


Figure 3.19 Receiver positions in rectangular room

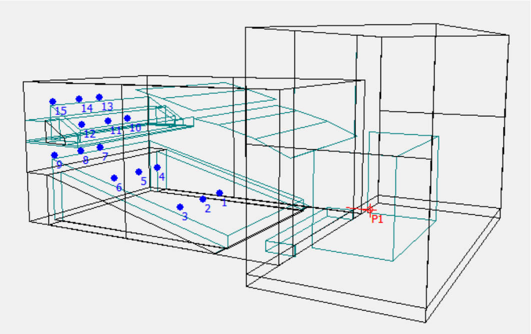


Figure 3.20 Receiver positions in rectangular room with balcony

3.5.2 Definition of Source Numbers and Positions

It is considered that the change of source location affect the acoustic environment of the room since, the stage has a fly tower. So there are three source points on the stage, one of them is located in fly tower (P1), second one is located at the intersection of stage and auditorium (P2) while the third one (P3) is located on the apron stage, within the auditorium space. The height of the source points are defined as 1.50 m, which is recommended height of source by ISO standard. In figures 3.21 and 3.22 source positions on the stage are shown.

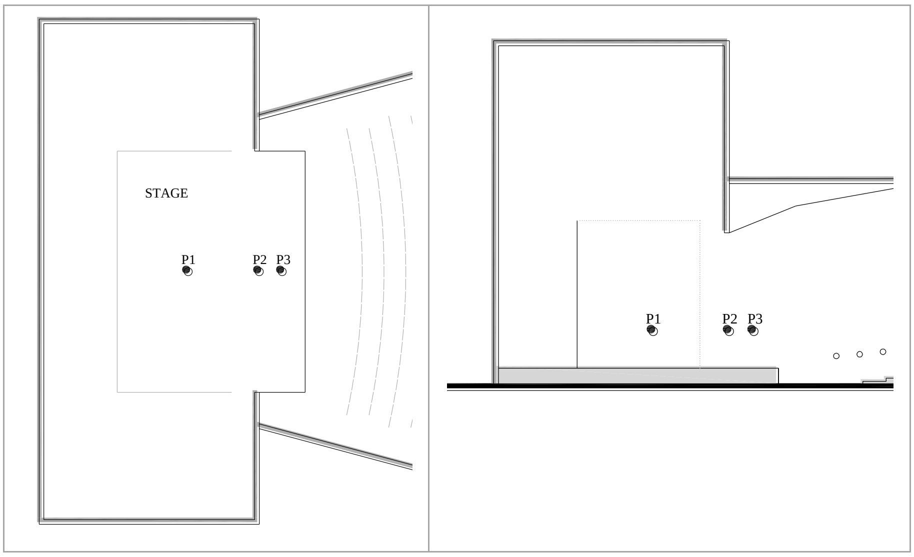


Figure 3.21 Source positions on plan and section (P1 – P2 – P3)

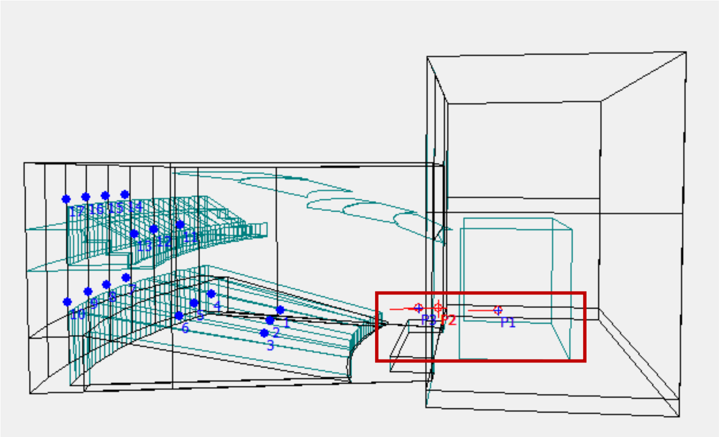


Figure 3.22 Source positions in 3D view (P1 – P2 – P3)

CHAPTER FOUR

EVALUATION OF THE DESIGNED CASES

As explained in previous chapters, examining seating layout of drama theatres from the point of two important factors; acoustic and sightline design, constitutes the main aim of this study. By this way, it is expected to obtain some useful results which can help to accelerate the theatre design process and to optimize the conditions for spectators within the auditorium.

Since it is aimed to evaluate both sightlines and acoustics of auditoria in this study, evaluation stage consists of two steps. The first step of the evaluation consists of two sections; first, evaluation of the designed auditoria from the viewpoint of visual comfort conditions then evaluation of them from the viewpoint of acoustics. In the second step, it is aimed to compare the results to be able to understand if there is a relation between sightlines and acoustics. Steps that are followed during the evaluation process are summarised in the chart below (Figure 4.1).

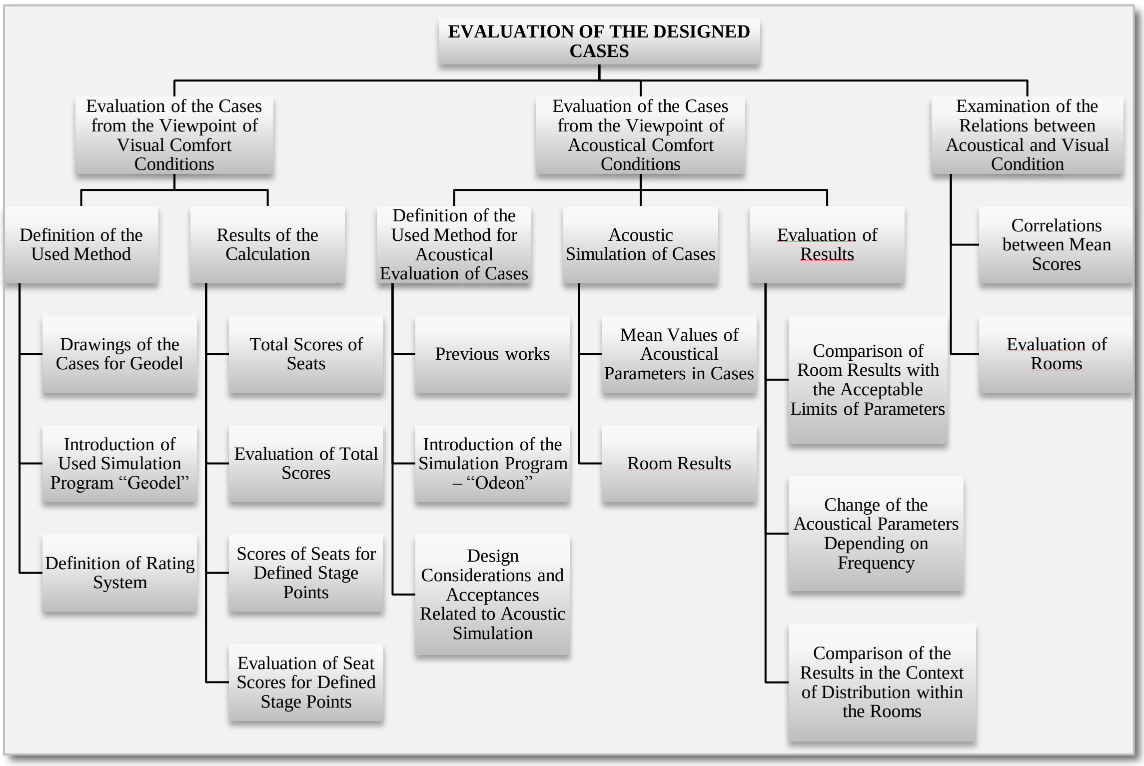


Figure 4.1 Evaluation process of the designed cases

4.1 Evaluation of the Cases from the Viewpoint of Visual Comfort Conditions

In a drama theatre it is important to see the small gestures of actors as well as to hear them. For this reason understanding the changes of visual comfort conditions within the auditorium is one of the main issues of this research.

Dealing with the sightlines is not a new issue. Most of the times after designing of a theatre by an architect, the sightlines of the critical seats are checked by the acoustic or theatre consultant. Such a consultant may use 3D drawings or special software to make the sightline analysis to check the critical seats within the auditorium in terms of viewing conditions. In this case, the external influence is viewing quality in a theatre house and the driven design is the form of the theatre seating (seating layout). But common software to perform a sightline analysis has not been found, at least during the literature search of this study. In other words, if a person wants to check the sightlines of the seats in any auditorium, he/she probably has to get some professional help.

With similar concerns, an evaluation study for proscenium type of auditoria had been done by Konca Şaher, in her M.Sc. thesis. In the thesis a program was developed for calculation of vertical and horizontal viewing angles by using visual basic. Then, the program was used to evaluate the METU auditorium. (Saher, 2001) But the effect of distance was ignored in the study, and it was concentrated on only the sightline design.

Therefore, the effect of distance has been taken into consideration in this thesis as an addition to previous works. And instead of evaluating a specific auditorium, to have at least a general idea by examining the different shapes of auditoriums and to use this result as general design criteria for drama theatres, constitutes one of the aims of this study.

4.1.1 Definition of the Used Method

In this context, the cases defined in chapter 3 are evaluated from the viewpoint of sightlines. To be able to make this evaluation, lisp based software, “Geodel”, has been used. Although the program is not developed for specifically for sightline design of rooms, it is flexible software that drawing files can be inserted.

The calculation of the stage visibility is based on two main factors,

- The horizontal viewing angle from the occupied seat and
- The distance between the seat and selected stage point.

Vertical angle of view is ignored in the calculation process, since the rake of the seating is designed according to rules of graphical method and it is accepted that seats have unobstructed sightlines in section. Followed steps to make the calculation can be listed basically as;

- Preparation of 2D drawing of the auditorium with seats and stage,
- Definition of formula, which calculate the scores of the seats,
- Importing the drawing file (in dxf format) to the program, and definition of the formula, seats and stage area within Geodel,
- And getting the results, according to defined formulas.

4.1.1.1 Introduction of Used Simulation Program “Geodel”

“Geodel” (**GEO**metry **DE**riving **L**anguage) has been developed by **A. Vefa Orhon,** in Dokuz Eylul University Faculty of Architecture, as a parametric design and analysis tool, which is needed in geometrical design studies. The program is used in lectures that are held in the architectural faculty as a supplementary tool. This design interface uses lisp based language named as “GeoLisp”. For this reason, while entering the equations into the program, it is necessary to write them in lisp language. The use of Geodel accelerates the calculation process, since there are many seats in the cases, as well as many stage points. Also, the necessary information such as distance between source and receiver positions and the horizontal viewing angle is obtained by using Geodel instead of calculating them from drawings one by one.

4.1.1.2 Drawings of the Cases for Geodel

To make the sightline calculations, plan drawings of auditoria are necessary. In the drawing, seats must be drawn by lines, and stage area should be defined with points. If there is proscenium frame, the walls of the frame should be drawn as poly lines so that they can be defined in Geodel. The setting area is accepted as the stage area that should be visible, in the plan. Calculations are based on how much of this area is seen by the selected seat, according to the defined limitations by formula. To simplify the calculation process, the area is defined with points. For this reason, it is necessary to draw the stage area with points. Designed stage for the cases, have a rectangular plan and setting area, where the play takes place, is defined with 357 points with 0.50 m distance between them (stage points).

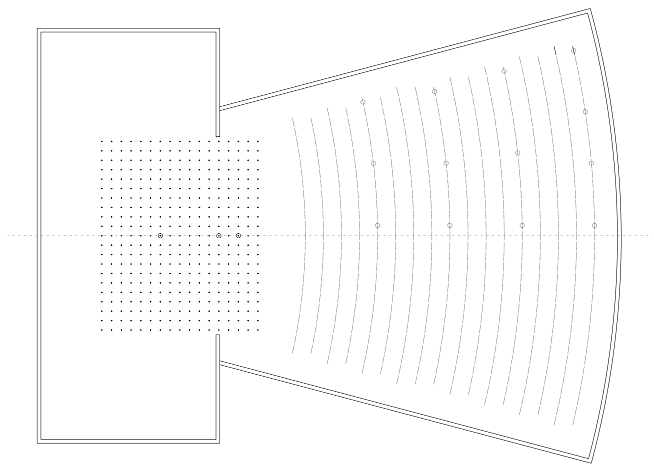


Figure 4.1 Example of a 2D drawing for inserting to Geodel.

4.1.1.3 Definition of Rating System – (Calculation Equations)

To be able to make comparisons between different types of rooms as well as between defined receiver points, it is necessary to obtain numerical results by using the information related to visual conditions. For that reason, some equations are developed to get numerical values (scores) by using the viewing angle and distance.

Horizontal viewing angle and distance between stage and receiver points are calculated by Odeon and by using defined equations; program also calculates the scores for each seat in the auditorium. The calculation process includes two main steps; calculation of the seen part of the stage (setting area) and distance between the seat and stage. As tried to be explained in chapter two, human eye have limitations for horizontal view. This limit of the horizontal viewing angle, also limits the visible part of the stage, especially for the seats placed near the side walls. Besides the limits of the horizontal viewing angle, distance is an important factor since it affects the visual acuity.

Accepted limit for the horizontal viewing angle is 60^0 (30+30) within the study, as a result of literature review in chapter 2. The head movement is ignored, since it is accepted as an uncomfortable situation for the spectators. But it is possible to extend the limits of viewing angle by changing the value in the command line. The program, first calculates the approximate place of the human eye, and the normal line of the seat, since most of the time seats are not parallel to the stage. Then, it calculates the angle between the normal line and the stage point. The calculation is made for all the stage points and for all seats. The angle is checked if it is more than 30^0 or not. If so, the score of the seat will be zero, since it is accepted that it is not comfortable for a spectator to move his head during the whole play.

Calculating the horizontal viewing angle or distance is the first part of calculation process. To be able to make comparisons between seats or/and auditoria it is decided that these values should be converted to a kind of "rating system". So, by using the angle and distance information, the score of a seat is calculated by defined equations in the command line. The effect of viewing angle and distance are combined by multiplying the results of the equations, since adding up two results can be misleading.

For the calculation of the score of horizontal viewing angle a simple equation is used:

$$Sc_a = 1- (a / 30)$$

Sc_a is “score” of the seat and “**a**” denotes the angle of horizontal view (the angle between the normal line and stage point), which is calculated by the program. Also, the command line includes two conditions,

- If “a” value is greater than 30^0 then the value of “a” will be accepted as if it is 30^0, and in this case, according to equation the score will be “0”,
- If $0<a<30$ then the value will be a number between 1 and 0. For example, if horizontal viewing angle is 15^0, the score will be 0,5 for the seat, for the selected stage point. By using the program, it is possible to calculate total score (sum of the scores for all stage points) for a seat.

Similarly, for the calculation of the score according to the distance, the equation below is used:

$Sc_d = 600 / d$

Sc_d is “score” of the seat and “**d**” denotes the distance between stage point and seat, which is calculated by the program. The accepted limit value of 600 (6 meters) is decided according to the limit that is used in “Snellen Chart”, which is a table for examining the visual acuity of eye and used by medical doctors. According to the tests based on Snellen chart, it is accepted that if one can read the 9 mm height signs (letters) from the distance of 6 meters, his eye is accepted as healthy. Since the height of the target sign is the same as human eye, the same distance is accepted as a limit value in the equation. This issue has been explained more detailed in title “2.5.1.1 Visual Acuity and Distance” in chapter 2. Also, the command line includes two conditions,

- If “d” value is smaller than 6 meters then the value of “d” will be accepted as if it is 6 meters, and in this case, according to equation the score will be “1”, the maximum.
- If $d>6$ m then the value will be smaller than 1. For example, if the distance is 9 meters between the seat and stage point, the score will be 0,67 for the seat, for the selected stage point. By using the program, it is possible to calculate total score (sum of the scores for all stage points) for a seat.

Final score of the seat will be depending on both scores and obtained by multiplying them to be able to see the effects of both distance and horizontal viewing angle.

$$Sc = [1- (a / 30)]\ [600 / d]$$

4.1.2 Results of the Calculation

The results of the calculations are divided into two categories. First, the total scores of seats are calculated. This means that the scores are the total score of the all stage points and give the idea of how much of the stage is visible from the selected seat. And another evaluation is based on the specific stage points, which are the same with the places of sources in the acoustic simulation. But instead of listing all the results here, the scores of the selected seats are shown.

4.1.2.1 Total Scores of Seats

Total scores of selected seats for each auditorium are listed in the titles of auditorium type.

4.1.2.1.1 Fan Shape 15. Sightline scores of 509 seats in the auditorium have been calculated. The scores range between **49,53** (minimum) and **106,65** (maximum) within the room. The visualization of the scores can be seen in figure 4.2. And total scores of the defined receiver positions are shown in Table 4.1 below the figure.

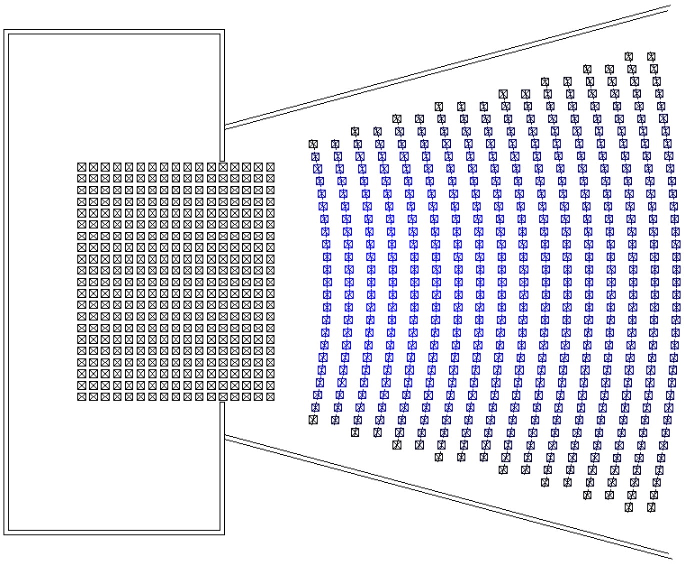


Figure 4.2 Visualization of seating area according to the results (light blue defines high scores, the colour is getting darker when the score decreases)

Table 4.1 Total Scores of the defined seats in F15

Seat number	Total score for seat
1	105,59
2	95,87
3	50,19
4	96,85
5	88,14
6	56,19
7	85,66
8	79,04
9	53,37
10	75,62
11	72,55
12	65,24
13	49,89

4.1.2.1.2 Fan Shape 15 with Balcony. Sightline scores of 532 seats (400 in floor and 132 in balcony) in the auditorium have been calculated. The scores range between **50,19** (minimum) and **106,65** (maximum) in floor level, and range between **46,7** and **84,48** in balcony. The visualization of the scores can be seen in figure 4.3. And total scores of the defined receiver positions are shown in Table 4.2 below.

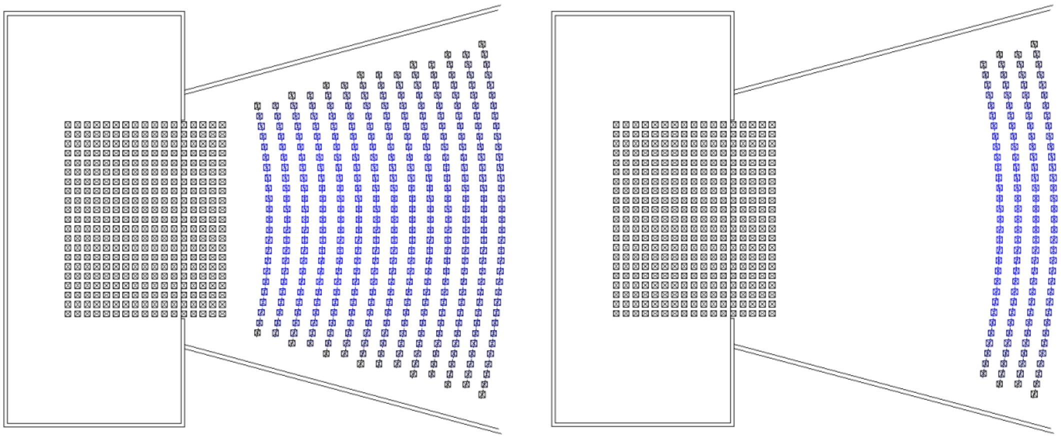


Figure 4.3 Visualization of seating area of Fan Shape 15 with balcony according to the results – on the left floor level, on the right balcony level(light blue defines high scores, the color is getting darker when the score decreases)

Table 4.2 Total Scores of the defined seats in F15 B

	Seat number	Total score for seat
Floor level	1	105,59
	2	95,87
	3	50,18
	4	96,85
	5	88,14
	6	56,19
	7	82,99
	8	79,79
	9	71,47
	10	50,67
Balcony	11	84,31
	12	76,07
	13	50,56
	14	76,08
	15	73,18
	16	65,65
	17	46,70

4.1.2.1.3 Fan Shape 22,5. Sightline scores of 505 seats in the auditorium have been calculated. The scores range between **44,38** (minimum) and **106,66** (maximum) within the room. The visualization of the scores can be seen in figure 4.4. And total scores of the defined receiver positions are shown in Table 4.3 below.

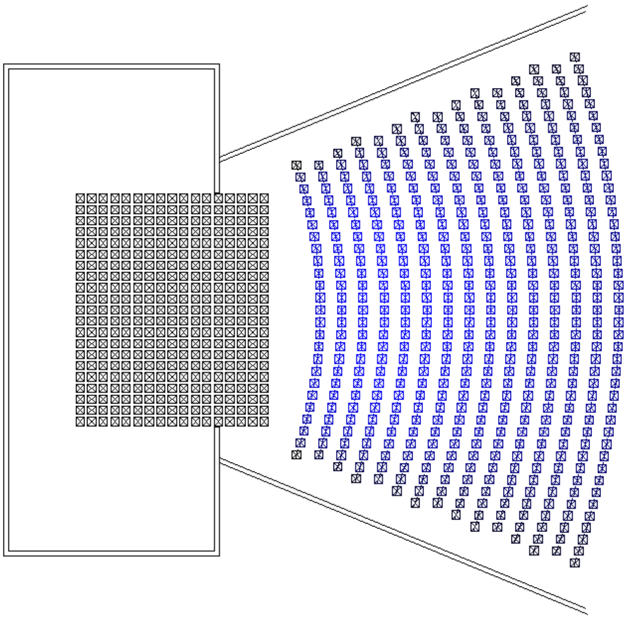


Figure 4.4 Visualization of seating area according to the results (light blue defines high scores, the colour is getting darker when the score decreases)

Table 4.3 Total Scores of the defined seats in F22

Seat number	Total score for seat
1	105,60
2	100,85
3	58,73
4	94,09
5	90,90
6	78,53
7	52,27
8	80,43
9	78,22
10	68,76
11	51,06

4.1.2.1.4 Fan Shape 22,5 with Balcony. Sightline scores of 575 seats (421 in floor and 154 in balcony) in the auditorium have been calculated. The scores range between **44,37** (minimum) and **106,65** (maximum) in floor level, and range between **46,99** and **86,41** in balcony. The visualization of the scores can be seen in figure 4.5. And total scores of the defined receiver positions are shown in Table 4.4 below.

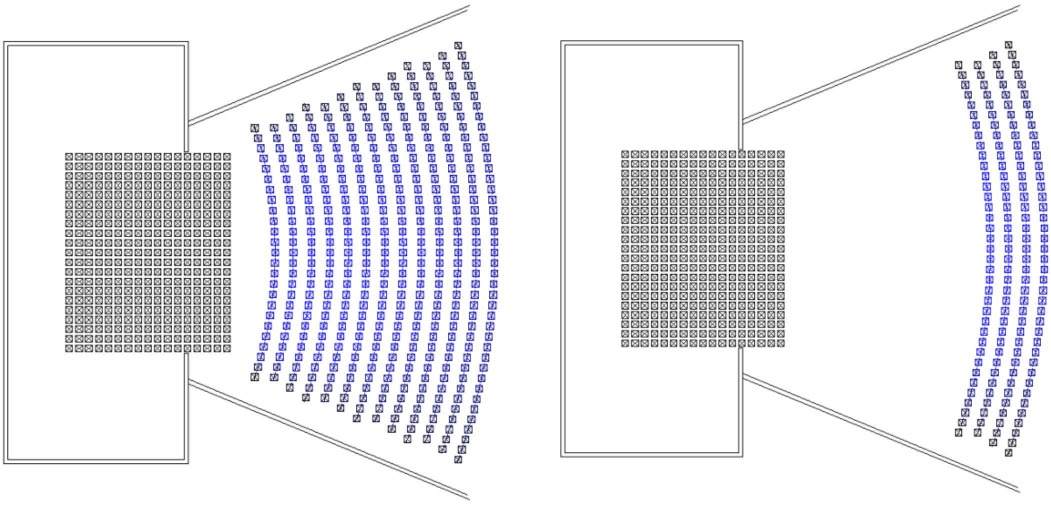


Figure 4.5 Visualization of seating area of Fan Shape 22,5 with balcony according to the results – on the left floor level, on the right balcony level (light blue defines high scores, the colour is getting darker when the score decreases)

Table 4.4 Total Scores of the defined seats in F22 B

	Seat number	Total score for seat
Floor level	1	105,60
	2	100,85
	3	58,74
	4	96,88
	5	93,31
	6	82,95
	7	53,95
	8	85,67
	9	82,76
	10	70,26
	11	51,38
Balcony	12	86,22
	13	83,30
	14	72,05
	15	48,19
	16	77,80
	17	75,20
	18	63,96
	19	46,99

4.1.2.1.5 Fan Shape 30. Sightline scores of 518 seats in the auditorium have been calculated. The scores range between **50,83** (minimum) and **106,65** (maximum) within the room. The visualization of the scores can be seen in figure 4.6. And total scores of the defined receiver positions are shown in Table 4.5 below.

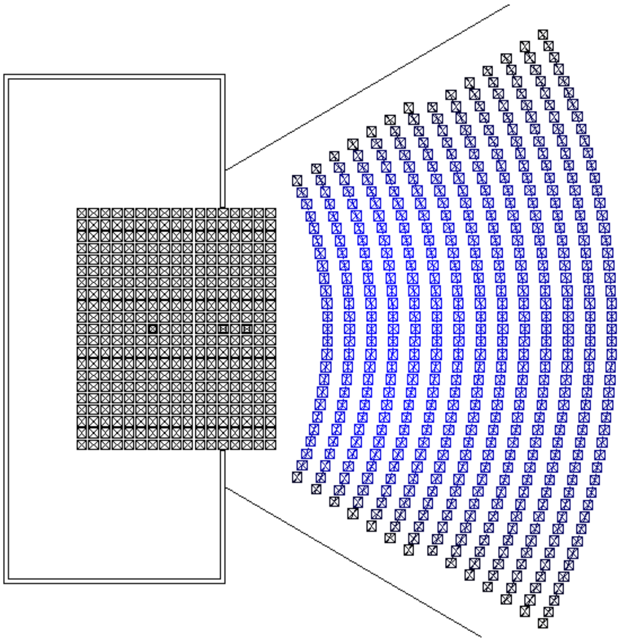


Figure 4.6 Visualization of seating area of fan shape 30 according to the results (light blue defines high scores)

Table 4.5 Total Scores of the defined seats in F30

Seat number	Total score for seat
1	105,64
2	104,70
3	93,85
4	53,35
5	96,95
6	94,89
7	85,70
8	55,23
9	83,05
10	81,97
11	77,04
12	66,19
13	50,80

4.1.2.1.6 Fan Shape 30 with Balcony. Sightline scores of 590 seats (422 in floor and 168 in balcony) in the auditorium have been calculated. The scores range between **52,03** (minimum) and **106,65** (maximum) in floor level, and range between **47,87** and **88,34** in balcony. The visualization of the scores can be seen in figure 4.7. And total scores of the defined receiver positions are shown in Table 4.6 below.

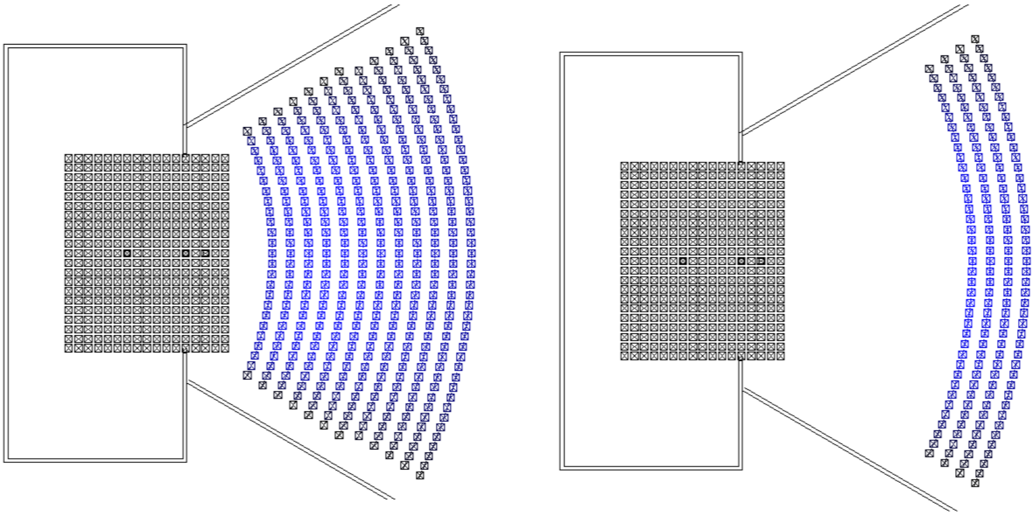


Figure 4.7 Visualization of seating area of Fan Shape 30 with balcony according to the results – on the left floor level, on the right balcony level (light blue defines high scores, the colour is getting darker when the score decreases)

Table 4.6 Total Scores of the defined seats in F30 B

	Seat number	Total score for seat
Floor level	1	105,64
	2	104,70
	3	93,85
	4	53,35
	5	96,95
	6	94,89
	7	85,70
	8	55,23
	9	88,49
	10	87,08
	11	82,81
	12	71,60
	13	52,64
Balcony	14	88,35
	15	86,45
	16	78,10
	17	50,67
	18	79,81
	19	78,55
	20	74,75
	21	64,74
	22	47,87

4.1.2.1.7 Rectangular Shaped Room. Sightline scores of 399 seats in the auditorium have been calculated. The scores range between **37,92** (minimum) and **106,55** (maximum) within the room. And total scores of the defined receiver positions are shown in Table 4.7 below.

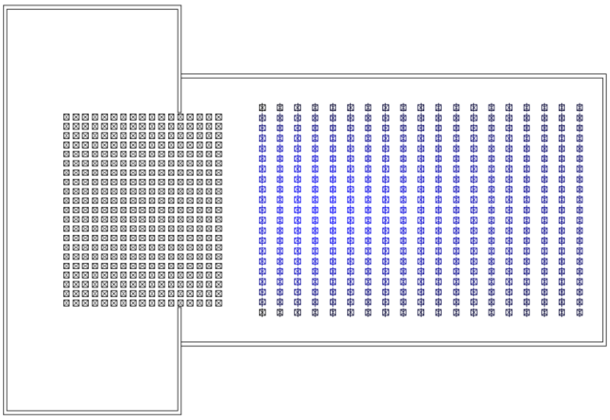


Figure 4.8 Visualization of seating area of rectangular room according to the results (light blue defines high scores)

Table 4.7 Total Scores of the defined seats in Rec

Seat number	Total score for seat
1	105,56
2	93,41
3	49,47
4	94,18
5	82,75
6	51,23
7	80,59
8	73,33
9	51,54
10	71,40
11	66,19
12	50,33

4.1.2.1.8. Rectangular Shaped Room with Balcony. Sightline scores of 441 seats (357 in floor and 84 in balcony) in the auditorium have been calculated. The scores range between **37,92** (minimum) and **106,55** (maximum) in floor level, and range between **44,41** and **77,73** in balcony. The visualization of the scores can be seen in figure 4.9. And total scores of the defined receiver positions are shown in Table 4.8 below.

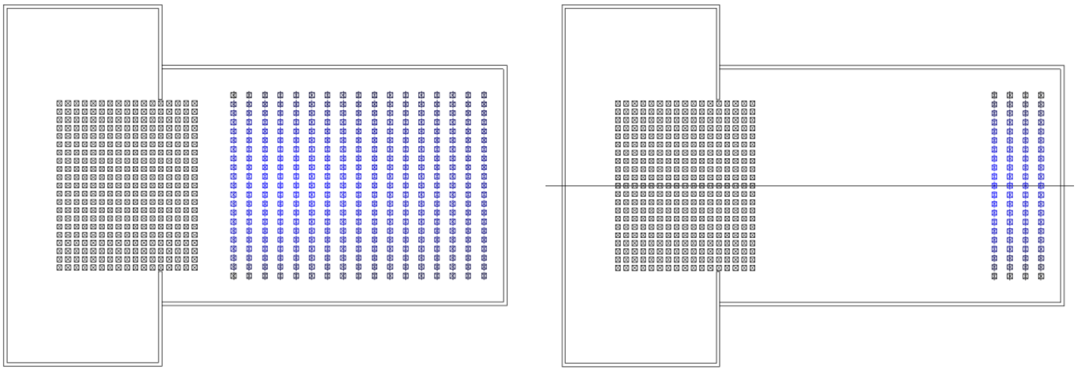


Figure 4.9 Visualization of seating area of rectangular room with balcony according to the results – on the left floor level, on the right balcony level (light blue defines high scores, the colour is getting darker when the score decreases)

Table 4.8 Total Scores of the defined seats in Rec B

	Seat number	Total score for seat
Floor level	1	105,56
	2	93,41
	3	49,47
	4	91,37
	5	80,84
	6	51,43
	7	75,78
	8	69,66
	9	51,11
Balcony	10	77,41
	11	70,05
	12	48,21
	13	70,08
	14	64,47
	15	47,41

4.1.2.2 Evaluation of Total Scores

By examining the results, (table 4.9) it is seen that the best scores are almost same for all types of the auditoria. The seats that have the best score are placed in the 4th row and in two sides of the seat in the middle. By comparing the mean values of the rooms the maximum value is calculated in Fan 30. Also, F 30 has the highest score among the designed auditoria for the seat with minimum score. Without considering acoustical parameters, Fan Shape with 30^0 splaying angle seems as best choice.

Table 4.9 Comparison of the total scores of rooms

Room Type	Min. Score in the room	Max. Score in the room	Mean score of the room
Fan 15	49,53	106,65	80,39
Fan 22	44,38	106,65	83,08
Fan 30	**50,83**	106,65	**85,02**
Rectangle	37,92	106,55	76,75
Fan 15 B	50,19 (46,7)	106,65	80,08
Fan 22 B	44,37 (46,9)	106,65	81,51
Fan 30 B	52,03 (47,9)	106,65	83,55
Rectangle B	37,92 (44,4)	106,55	75,54

Another important criterion is homogeneous distribution of the scores within the rooms, since it means that seats have equal conditions. To evaluate the homogeneity of the seat scores within the rooms, the “coefficient of variation” of the scores is calculated. This value is the ratio of standard deviation divided by the mean for a given sample used to measure spread. The coefficient of variation is a quite common value for comparison of the results of different groups. (Triola, 2004)

$CV = 100\ (SD / Mean)$ (Triola, 2004)

CV: Coefficient of Variation (%)

SD: Standard Deviation

The small value means small variation. And the smallest score is derived from the fan-shape 30 and the largest coefficient of variation is derived from the rectangular room with balcony (Table 4.11).

Table 4.11 Descriptive statistics of the rooms

Variable	Mean	StDev	CoefVar	Minimum	Maximum
F15	80,39	15,092	18,77	49,53	106,655
F15 B	80,086	15,136	18,9	46,698	106,655
F 22	83,087	15,16	18,25	44,376	106,658
F 22 B	81,512	15,429	18,93	44,371	106,658
F30	85,016	15,127	**17,79**	50,825	106,654
F 30 B	83,557	15,277	18,28	47,896	106,654
Rec	76,758	16,15	21,04	37,919	106,559
Rec B	75,543	16,113	21,33	37,919	106,559

In addition, the number of the seats with high scores and low scores within all the seats are considered. The number of seats, which have the scores lower than 55, and the number of seats, which have the scores larger than 80, are compared. The aim of this comparison is to see the distribution of the seat scores within the room. The maximum score within all the rooms is about 106,50. And if the score of a seat is calculated as 55, it means that its score is equal to half of the best one. For that reason, having the score less than 55 is accepted as quite negative. Similarly, if the score of a seat is calculated as 80, it means that its score is equal to 75 percent of the best seat, and it can be accepted as a good score.

Table 4.10 Seat numbers with minimum and maximum scores

Room Type	Total Seats	No of seats Sc<55	% (Sc<55)	No of seats Sc>80	% (Sc>80)
F15	509	32	6	265	52
F22	505	26	5	311	62
F30	518	22	4	350	68
Rectangle	399	40	10	171	43
F15 B	532	38	7	278	52
F22 B	575	38	7	326	57
F30 B	590	34	6	368	62
Rectangle B	441	50	11	171	39

More detailed examination of the calculation results confirms that fan-shaped auditorium with 30^0 splaying angle has the best scores. The worst situation is for the rectangular shaped auditorium with balcony, since it occupies the largest number of seats with the scores lower than 55 and the fewest number of seats with the scores more than 80. For all types of the auditoria, seat scores in balcony level are lower than in first floor due to the fact that by the increase of the height, the distance between the seat and stage increases. In spite of negative effect of lower scores of the seats in balcony level, fan 30 with balcony has quite good conditions as well as fan 22,5.

4.1.2.3 Scores of Seats for Defined Stage Points

Scores of selected seats according to defined stage points for each auditorium are showed in graphics below, and they are titled according to auditorium type. The aim of this calculation is to show that in some situations, one of the factors (angle and distance) can be dominant factor. And it is also aimed to compare the change of acoustic results according to three source points (P1-P2-P3), which are shown in different colours in graphs, with the changes of sightline scores.

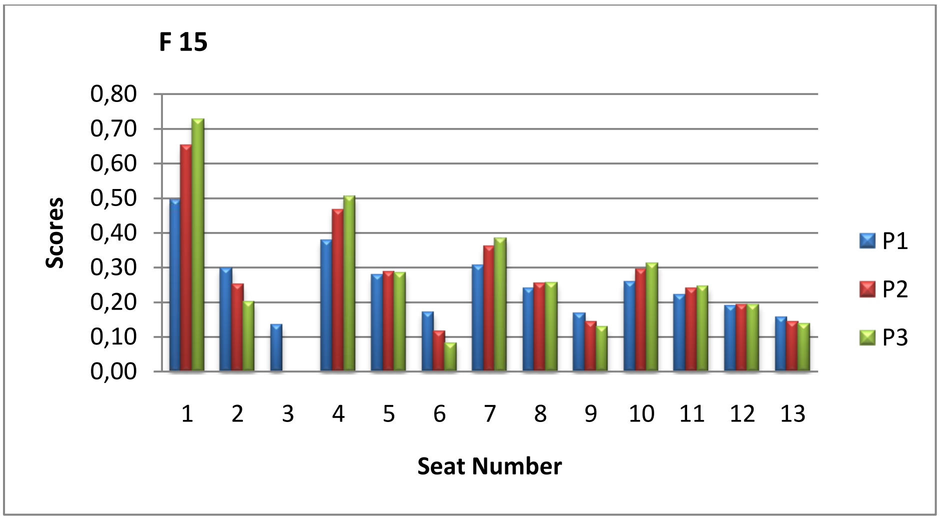


Figure 4.10 Calculated seat scores according to stage points for F15

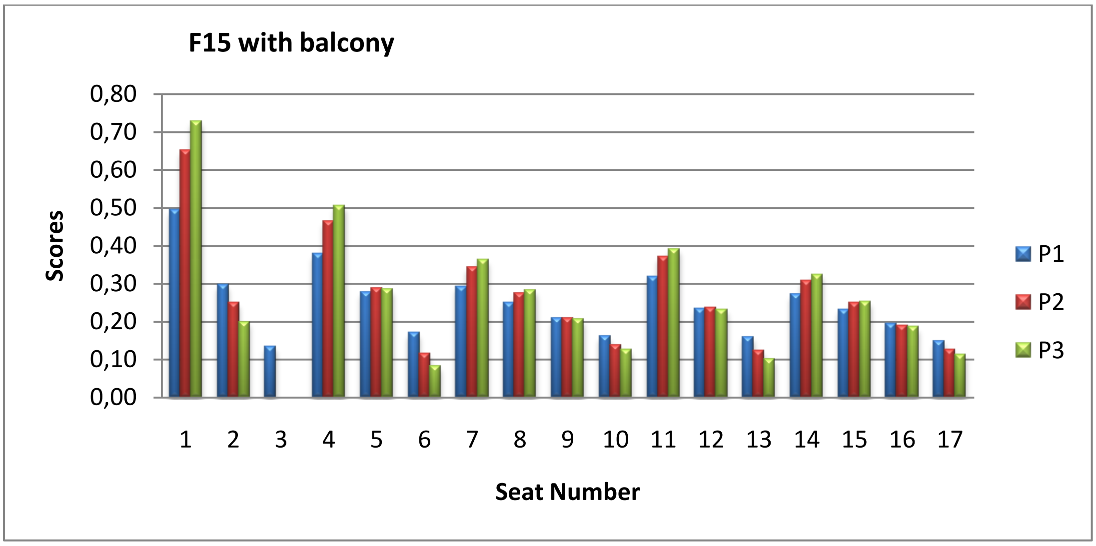


Figure 4.11 Calculated seat scores according to stage points for F15 B

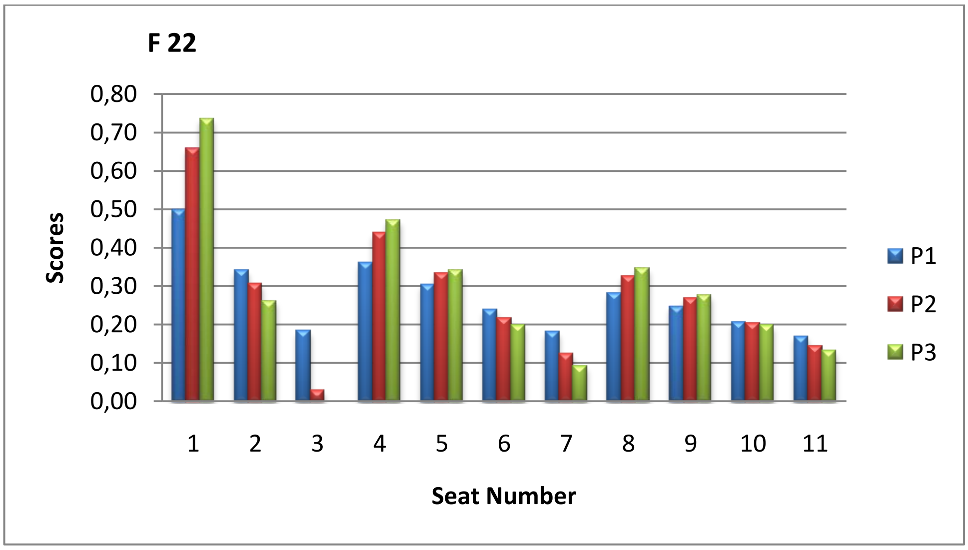


Figure 4.12 Calculated seat scores according to stage points for F22

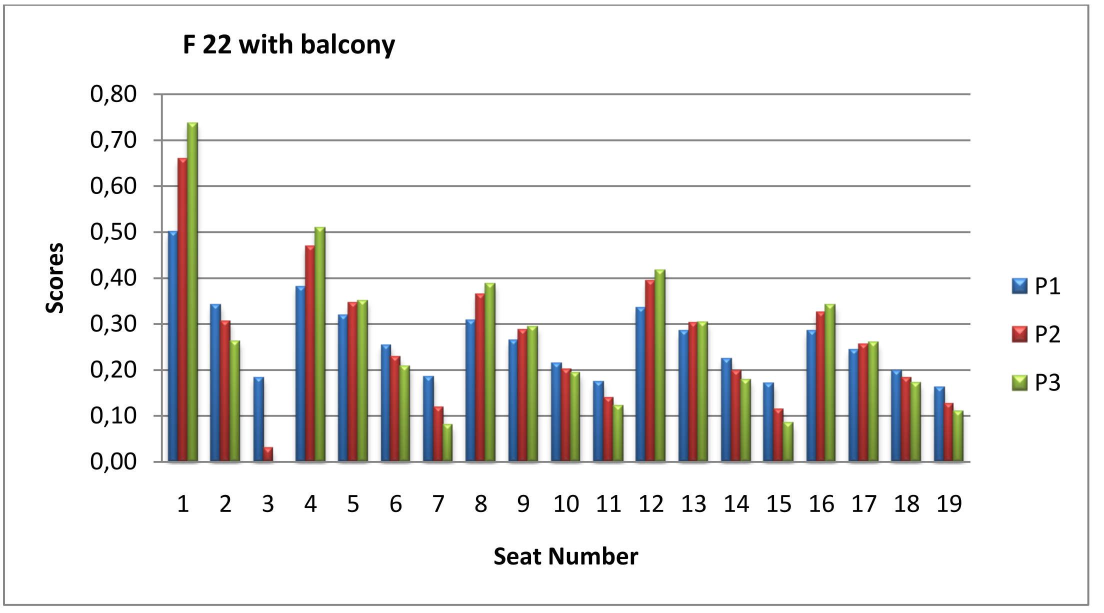


Figure 4.13 Calculated seat scores according to stage points for F22 B

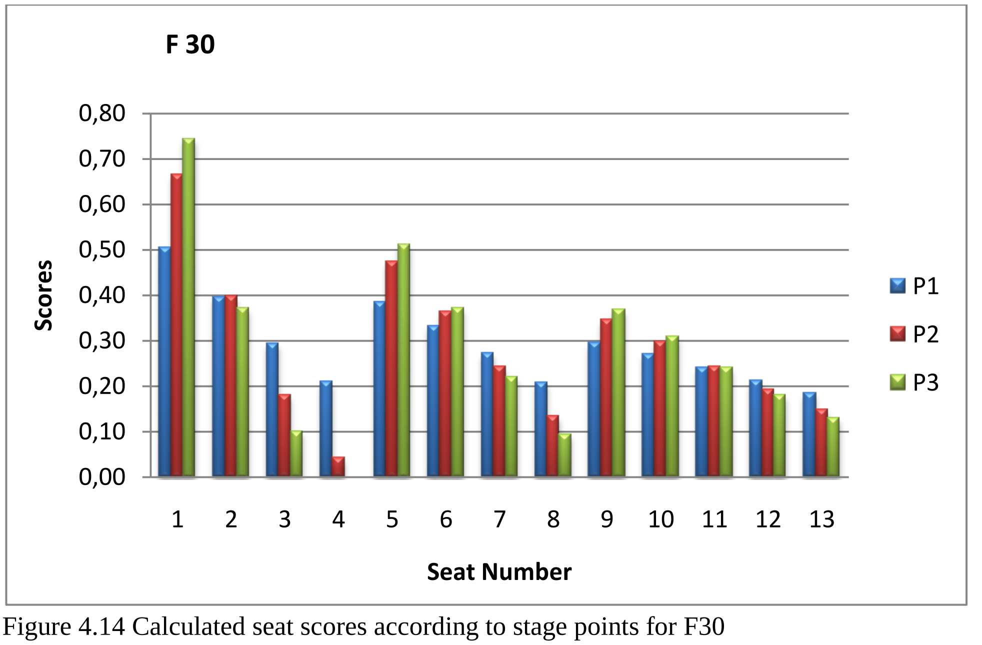


Figure 4.14 Calculated seat scores according to stage points for F30

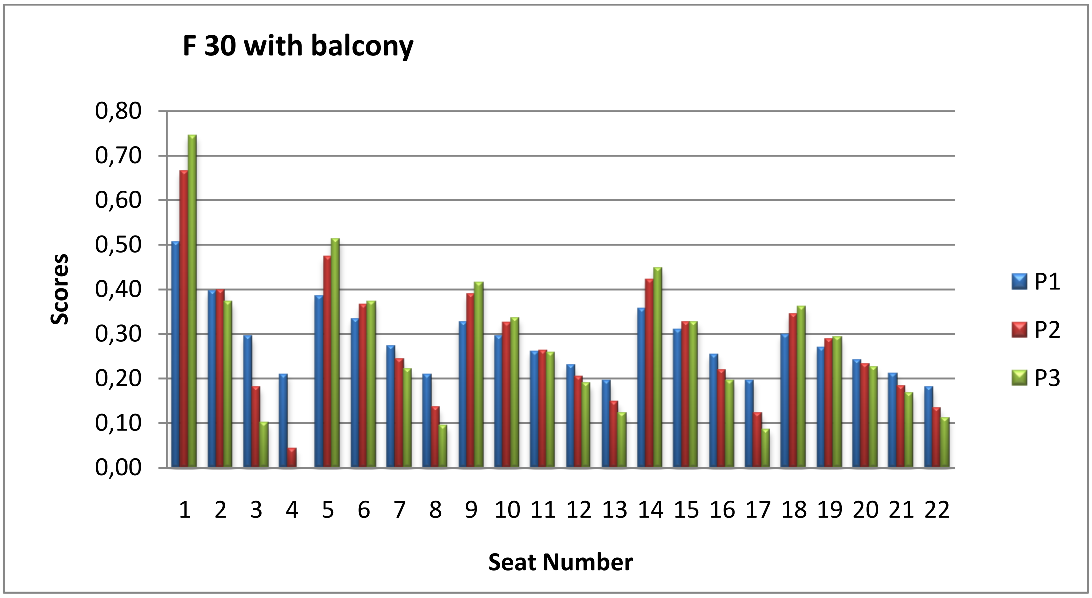


Figure 4.15 Calculated seat scores according to stage points for F30 B

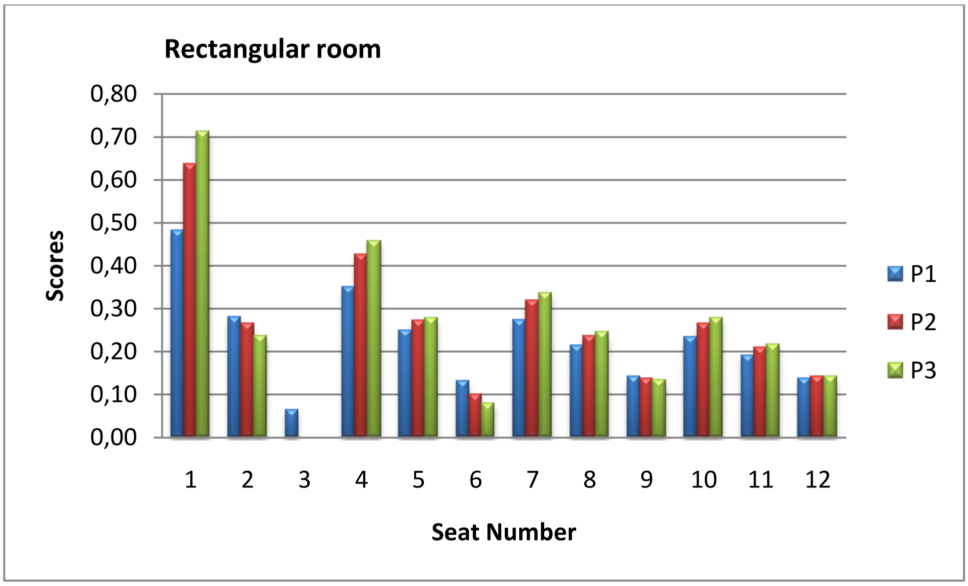


Figure 4.16 Calculated seat scores according to stage points for rectangular room.

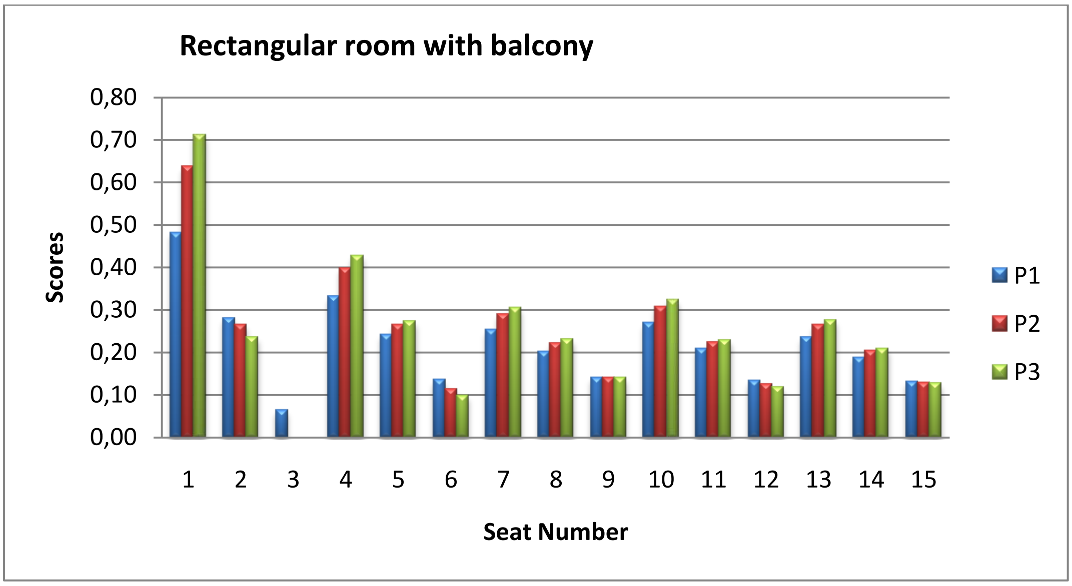


Figure 4.17 Calculated seat scores according to stage points for rectangular room with balcony

4.1.2.4 Evaluation of Seat Scores for Defined Stage Points

With a quick review of results in Figures 4.10 – 4.17, it is seen that for all of the cases, if an actor stands at P2 or P3 a spectator sitting in the fifth row and seat number 3 cannot see him, since the score of the seat with that stage points are 0. The reason of the score is in that seating point, to see the stage spectator should move his head. Scores are varying according to the horizontal viewing angle and distance changes. For fan shaped rooms with splaying angles 22,5 and 30^0 P2 is visible without head movement, but the score is quite small.

Also, in graphs (Figures 4.10-4.17) it is seen that, if there was no effect of distance, the seats in the last rows would have the best visual conditions. But by the effect of distance the scores are decreasing through the back rows. For the seats near the middle axis of the rooms the scores of the P3 are higher (because P3 is the nearest stage point to the seating area) but for the seats near the side walls, (because of the viewing angle) the difference between the scores of stage points is decreasing.

4.2 Evaluation of the Cases from the Viewpoint of Acoustical Comfort Conditions

Today, to accelerate the design process and by this way to save time as well as money is very important and for this reason the use of computers during the architectural design is inevitable. 3D simulations and drawings in the electronic media make it easy to modify the design at any phase of the process. Similarly, during the design process of rooms it is very common to use simulation programs instead of scale models to evaluate the auditorium's acoustical features and to make any necessary change or/and additions before the construction process. By this way, it is possible to prevent unwanted effects that occur within the room volume. In the light of this issue, designed rooms are simulated acoustically and acoustic parameters are measured.

4.2.1 Definition of the Used Method

In this study, it is accepted that none of the designed rooms needs electronic amplification and there is no inconvenient situation like excessive noise levels. With a basic description, the acoustic evaluation is based on the simulation of the designed auditoria and analysis of the results. The steps of the evaluation are;

- Definition of the design considerations related to the acoustics of the auditoria.
- Inserting the room information into the simulation program and processing the acoustical simulation.
- Definition of the studied acoustical parameters and their acceptable values for the drama theatres.
- Analysis of the simulation results. Analysis consists of two main steps; first one is the evaluation and comparison of the mean results of parameters. The second step focuses on the distribution of the parameters within each room.

4.2.1.1 *Previous works related to the distribution of acoustical parameters and the works considering the effect of room design on the acoustical parameters within rooms*

There have been many studies, which are held by professionals, dealing with the acoustics of rooms (especially rooms for music), growing numbers of parameters for evaluation and the distribution of them within a room. Surveys are held by using/evaluating measurements in existing theatres or by using acoustic simulation of existing or experimental buildings. Studies of important acousticians such as J.S. Bradley and M. Barron are cited in the study several times, since they have made researches on especially rooms for speech.

But among all data, which is sometimes quite complicated or is not easy to apply, it would be useful to have some guidelines to accelerate the architectural design process. With similar concerns, some important studies have been done also in our country and in here it is aimed to focus on these previous works that have similar concerns or use similar techniques with this study. Their methods and some results are explained briefly below.

One of the important studies related to distribution of acoustical parameters in rooms, had been done by Ayşe E. Aknesil in Yıldız Technical University. It is quite an extensive study that 96 types of rooms (combinations of three basic shape with 3000 or 9000 m^3 volumes, and also having different absorption characteristics) are evaluated. One of the results of the survey showed that the effect of the room shape on distribution of acoustical parameters is distinctive especially in smaller rooms with 3000 m^3 volume. (Erdem Aknesil, 1997) It is an important result also for this study, since the different shaped auditoriums with volumes quite close 3000 m^3 are subjects of it.

Another research was held by Nurgün Tamer Bayazıt in İstanbul Technical University. To discover the effect of design criteria on acoustics of rooms for music, she had studied on 27 rectangular shaped auditoria that were designed by combination of 3 different side dimensions. By using some statistical methods it was tried to find some equations that could be used by architects while designing rectangular shaped auditoria. At the end of the study, it is suggested that the method can be used for auditoria with different shape and different use. (Bayazıt, 1999)

In both studies, Odeon software is used for acoustical simulation and results were evaluated by using statistical methods and comparing the graphics. But, both studies are not concentrated on acoustics for speech, for that reason, this study differs from them by considering mainly acoustics for speech.

Recently, a research had been completed in Yıldız Technical University by Özge Şahin. The aim of the study was to understand the effect of change of source positions in rooms for speech. Odeon had been used as acoustical simulation tool and three basic shapes (rectangle, square and fan) of auditoria had been taken into consideration. Although it seems similar to this thesis since they are both dealing with acoustics for speech, in her study there were not a fly tower on the stage and the change of source position was on the x axis. But in this study the change of source position is on the y axis because of the fly tower.

4.2.1.2 Introduction of the Simulation Program – "Odeon"

There are some programs that are developed by universities or companies for acoustic simulation of the enclosed spaces, such as ODEON, CATT Acoustic, DIVA, CARA, DIRAC, ACOUSTIC X. (Öziş, 2007) Odeon is one of the most preferred acoustic simulation software, which was developed by Denmark Technical University (DTU) and Auditorium version of the program is used in this study. By the definition of the official web site of Odeon "it is software for simulating the interior acoustics of buildings. From geometry and surface-properties acoustics can be predicted, illustrated and listened to. Sound reinforcement is easily integrated in the acoustic predictions. Odeon uses image-source method combined with ray tracing." (Odeon Room Acoustics Software)

Odeon software is accepted as a quite reliable tool for predicting the acoustical properties of rooms. It has been used in many researches and projects related to room acoustics and recommended by many important acousticians. For example, according to Prof. Dr. Mehmet Çalışkan from Middle East Technical University " Odeon has proven to be a viable research tool due to its flexibility and efficiency in modelling and analysis" also according to Çalışkan, Odeon is an effective tool for also educational and research purposes. It has been used in METU since 2003. (Odeon Room Acoustics Software)

4.2.1.3 Design Considerations and Acceptances Related to Acoustic Simulation

General design considerations and acceptances of cases have been tried to be described in chapter 3. But some of the specifications of the rooms affect the acoustical conditions directly, such as design of ceiling reflectors, sound absorption characteristics of room surfaces. For that reason they will be explained in this section.

Source and receiver positions and specifications of room volumes (dimensions, seat counts etc.) have already been defined in chapter 3, since they are also inputs of sightline analysis. But it can be necessary to give additional information about the features of sound source and receivers.

4.2.1.3.1 Ceiling Reflectors. The ceiling reflector profile is determined on the bases of geometrical acoustics and reflectors are tried to be designed as increasingly greater amount of sound energy is directed to the rear part of the room. They are designed by drawing ray diagrams for each room, while considering mainly the longitudinal section. The reflectors are thought as suspended panels, since they are usually preferred for both being aesthetically pleasant and functional. They allow easy access for lighting, air conditioning and other services located in the ceiling. In Figures 4.18 and 4.19 two examples of designed reflectors and their coverage of seating area are shown.

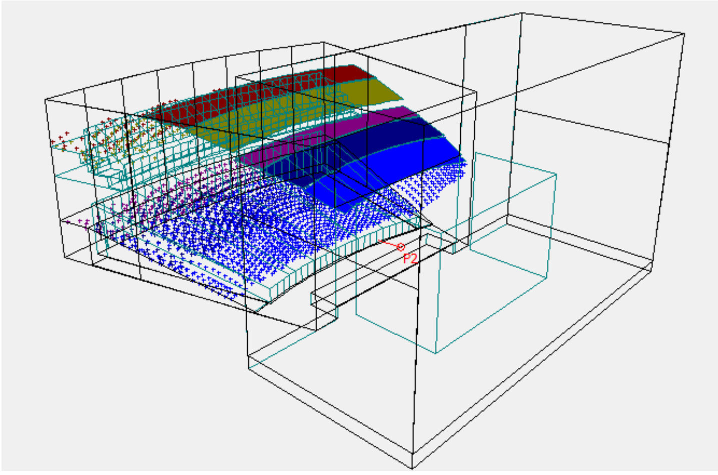


Figure 4.18 Ceiling reflectors and their coverage of seating area (as an example – fan shape 15 with balcony)

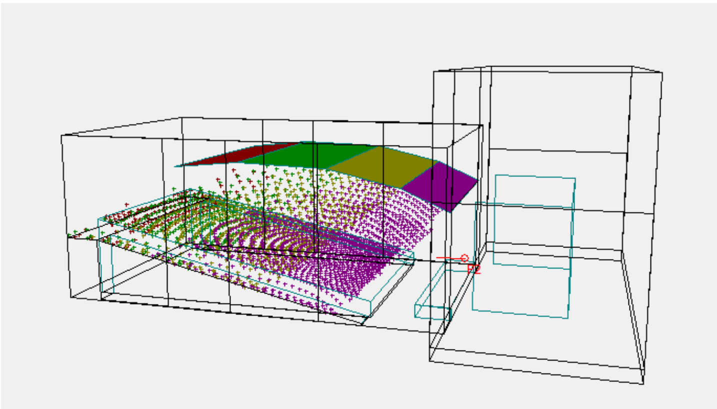


Figure 4.19 Ceiling reflectors and their coverage of seating area (as an example – rectangular room)

4.2.1.3.2 Source and Receivers. Although numbers and positions of source and receiver have been described in chapter three, some additional information related to acoustic simulation process are explained here. It is recommended in the manual of the software that, for a typical concert hall a source-receiver distance less than 10 metres should be avoided to get good predictions of reverberation time by using Odeon. For this reason, the closest receivers are located on the fifth row.

As explained before, to see the effect of change of source position on y axis there are three point sources placed on the stage. The type of used source is

"BB93_RAISED_NATURAL.SO8" and it is selected since it has similarities with the human talking. Detailed properties of the source are seen in Figure 4.20.

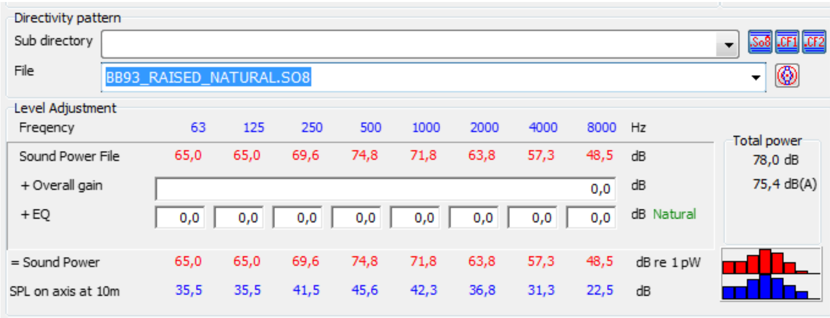


Figure 4.20 Properties of the sound source

4.2.1.3.3 Room Finishes. Materials are selected from the Odeon library, and in this process, it is tried to obtain the reverberation time values between 0,8-1,0 seconds (Sirel, 1981) and to keep it nearly same for all frequencies to prevent negative effect of distortion. To achieve this step, quick estimation tool of the simulation program is used. The minimum and maximum values of the reverberation time are defined by considering the suggested values of reverberation times in references. The selected materials are same for all the rooms.

Table 4.10 Room finishes and their absorption coefficients depending on frequency (Odeon Library).

Code	**Material**	**Room/ Stage Surface**	**Absorption Coefficients of Materials Frequency (Hz)**					
			125	250	500	1000	2000	4000
3001	Wooden panelling	Ceiling reflectors	0,1	0,07	0,05	0,06	0,06	0,06
3005	Parquet	Stage floor	0,2	0,15	0,1	0,1	0,05	0,1
3063	Thin plywood panelling	Scenery Panels	0,42	0,21	0,1	0,08	0,06	0,06
4036	Plaster gypsum or lime	Side walls of the room	0,14	0,1	0,06	0,04	0,04	0,03
4045	Gypsum board two layers total (32 mm)	Side walls of the stage	0,28	0,12	0,1	0,17	0,13	0,09
7001	6mm pile carpet bonded to closed-cell foam underlay	Auditorium floor	0,03	0,09	0,25	0,31	0,33	0,44
10008	Canvas covering	Rear wall of the stage	0,9	0,7	0,5	0,35	0,25	0,15
11057	Medium upholstered chairs, average	Seating area	0,35	0,45	0,57	0,61	0,59	0,55
12100	Rockfon	Stage and room ceiling – rear wall	0,45	0,5	0,55	0,65	0,7	0,65

The selection of the materials of stage was quite a hard job, since it has a fly tower and it has a coupling effect. To prevent such an unwanted situation, several materials had been tried and finally the materials that cause minimum changes of reverberation time by the change of frequency are decided. Materials have a code number in the Odeon library, and used materials and their absorption characteristics are listed in table 4.10.

4.2.2 Acoustic Simulation of Cases

There are three sources and minimum 11 receiver points in each room. The mean values of the acoustical parameters are measured according to each source; this means there are three different results of acoustic parameter measurements. The selected parameters to evaluate the acoustics of the cases are reverberation time (T30), early decay time (EDT), distinctness (D50), sound pressure level (SPL) and speech transmission index (STI).

4.2.2.1 Mean Values of Acoustical Parameters in Cases

To have an idea on acoustical characteristics of rooms, mean values of acoustical parameters are given in titles of parameters for all cases and for all sound sources. Detailed results are listed in Appendix B.

4.2.2.1.1 Early Decay Time. For all room types, EDT values are lower than reverberation times. EDT values are decreasing at high frequencies, and the situation is similar for all source positions. In tables 4.11-4.13 simulated mean EDT values are shown.

Table 4.11 Average EDT values of receiver points when sound source 1 is open.

EDT, average – Source position 1 (P1)						
Room type	**Frequency (Hz)**					
	125	**250**	**500**	**1000**	**2000**	**4000**
Fan 15	0,69	0,62	0,55	0,48	0,44	0,45
Fan 22	0,78	0,71	0,59	0,56	0,5	0,5
Fan 30	0,82	0,75	0,6	0,52	0,47	0,45
Rec	0,89	0,74	0,63	0,59	0,42	0,38
Fan 15 B	0,6	0,56	0,49	0,45	0,32	0,3
Fan 22 B	0,6	0,62	0,57	0,51	0,41	0,39
Fan 30 B	0,53	0,59	0,53	0,53	0,43	0,34
Rec B	0,63	0,58	0,52	0,5	0,35	0,34

Table 4.12 Average EDT values of receiver points when sound source 2 is open.

EDT, average – Source position 2 (P2)						
Room type	**Frequency (Hz)**					
	125	**250**	**500**	**1000**	**2000**	**4000**
Fan 15	0,64	0,56	0,47	0,39	0,3	0,27
Fan 22	0,59	0,56	0,42	0,34	0,25	0,22
Fan 30	0,62	0,5	0,43	0,31	0,23	0,22
Rec	0,76	0,58	0,52	0,45	0,39	0,38
Fan 15 B	0,43	0,4	0,33	0,29	0,23	0,22
Fan 22 B	0,43	0,4	0,35	0,3	0,22	0,2
Fan 30 B	0,39	0,36	0,34	0,28	0,21	0,19
Rec B	0,63	0,61	0,5	0,5	0,38	0,34

Table 4.13 Average EDT values of receiver points when sound source 3 is open.

EDT, average – Source position 3 (P3)						
Room type	**Frequency (Hz)**					
	125	**250**	**500**	**1000**	**2000**	**4000**
Fan 15	0,63	0,59	0,44	0,39	0,33	0,3
Fan 22	0,62	0,52	0,43	0,34	0,27	0,24
Fan 30	0,61	0,5	0,42	0,32	0,25	0,23
Rec	0,75	0,62	0,56	0,51	0,43	0,39
Fan 15 B	0,51	0,44	0,39	0,33	0,27	0,25
Fan 22 B	0,48	0,43	0,4	0,33	0,26	0,24
Fan 30 B	0,46	0,43	0,37	0,34	0,24	0,22
Rec B	0,64	0,52	0,49	0,48	0,34	0,34

4.2.2.1.2 Reverberation Time. Mean values of reverberation times of receiver points are shown in tables 4.14-4.16.

Table 4.14 Average T30 values of receiver points when sound source 1 is open.

T 30, average – Source position 1 (P1)						
Room type	**Frequency (Hz)**					
	125	**250**	**500**	**1000**	**2000**	**4000**
Fan 15	0,95	0,89	0,89	0,91	0,97	0,97
Fan 22	0,92	0,86	0,85	0,84	0,93	1,06
Fan 30	0,91	0,83	0,83	0,85	0,94	0,9
Rec	1,06	0,97	0,95	0,93	1,02	1,07
Fan 15 B	0,82	0,79	0,9	0,95	1,06	1,16
Fan 22 B	0,73	0,73	0,82	0,91	0,99	1,06
Fan 30 B	0,73	0,71	0,81	0,89	0,99	1
Rec B	0,94	0,91	0,96	1,02	1,03	1,05

Table 4.15 Average T30 values of receiver points when sound source 2 is open.

T 30, average – Source position 2 (P2)						
Room type	**Frequency (Hz)**					
	125	**250**	**500**	**1000**	**2000**	**4000**
Fan 15	0,93	0,89	0,9	0,93	0,96	0,94
Fan 22	0,92	0,87	0,92	0,91	0,96	0,96
Fan 30	0,88	0,82	0,84	0,85	0,93	0,95
Rec	0,94	0,86	0,82	0,84	0,9	0,88
Fan 15 B	0,85	0,82	0,85	0,87	0,91	0,92
Fan 22 B	0,72	0,71	0,83	0,91	0,96	0,97
Fan 30 B	0,72	0,69	0,75	0,8	0,87	0,89
Rec B	0,91	0,88	0,97	1	0,97	0,92

Table 4.16 Average T30 values of receiver points when sound source 3 is open.

T 30, average – Source position 3 (P3)						
Room Type	**Frequency (Hz)**					
	125	**250**	**500**	**1000**	**2000**	**4000**
Fan 15	0,97	0,91	0,86	0,82	0,86	0,84
Fan 22	0,92	0,8	0,75	0,74	0,8	0,83
Fan 30	0,89	0,82	0,79	0,8	0,83	0,83
Rec	0,97	0,91	1,13	1,1	1,14	0,97
Fan 15 B	0,81	0,77	0,8	0,78	0,83	0,83
Fan 22 B	0,73	0,68	0,73	0,74	0,81	0,83
Fan 30 B	0,71	0,66	0,73	0,79	0,91	0,92
Rec B	1,02	0,96	1	1,07	1,02	0,98

4.2.2.1.3 Distinctness. Mean D50 values of receiver points are listed in tables 4.17 – 4.19.

Table 4.17 Average D50 values of receiver points when sound source 1 is open.

D 50, average – Source position 1 (P1)						
Room Type	**Frequency (Hz)**					
	125	**250**	**500**	**1000**	**2000**	**4000**
Fan 15	0,67	0,74	0,79	0,83	0,89	0,9
Fan 22	0,68	0,74	0,78	0,81	0,88	0,89
Fan 30	0,7	0,75	0,8	0,83	0,89	0,91
Rec	0,69	0,76	0,81	0,83	0,89	0,9
Fan 15 B	0,8	0,82	0,84	0,85	0,91	0,92
Fan 22 B	0,8	0,81	0,82	0,84	0,9	0,91
Fan 30 B	0,83	0,83	0,84	0,85	0,9	0,91
Rec B	0,76	0,8	0,83	0,84	0,9	0,91

Table 4.18 Average D50 values of receiver points when sound source 2 is open.

D 50, average – Source position 2 (P2)						
Room type	**Frequency (Hz)**					
	125	**250**	**500**	**1000**	**2000**	**4000**
Fan 15	0,7	0,77	0,83	0,87	0,91	0,92
Fan 22	0,74	0,8	0,86	0,9	0,93	0,94
Fan 30	0,74	0,8	0,86	0,9	0,93	0,94
Rec	0,66	0,73	0,77	0,8	0,87	0,87
Fan 15 B	0,83	0,86	0,89	0,91	0,94	0,94
Fan 22 B	0,84	0,86	0,88	0,9	0,93	0,94
Fan 30 B	0,86	0,87	0,89	0,91	0,93	0,94
Rec B	0,71	0,76	0,79	0,81	0,88	0,88

Table 4.19 Average D50 values of receiver points when sound source 3 is open.

D 50, average – Source position 3 (P3)						
Room type	**Frequency (Hz)**					
	125	**250**	**500**	**1000**	**2000**	**4000**
Fan 15	0,68	0,75	0,8	0,83	0,89	0,9
Fan 22	0,69	0,77	0,83	0,88	0,92	0,93
Fan 30	0,71	0,78	0,84	0,89	0,93	0,93
Rec	0,64	0,71	0,75	0,77	0,85	0,86
Fan 15 B	0,78	0,82	0,85	0,87	0,92	0,93
Fan 22 B	0,8	0,83	0,85	0,89	0,92	0,93
Fan 30 B	0,82	0,85	0,87	0,89	0,92	0,93
Rec B	0,7	0,76	0,78	0,81	0,88	0,89

4.2.2.1.4 Sound Pressure Level. Mean Results of receiver points are listed in tables 4.20-4.22.

Table 4.20 Average SPL values of receiver points when sound source 1 is open.

SPL, average – Source position 1 (P1)						
Room type	**Frequency (Hz)**					
	125	**250**	**500**	**1000**	**2000**	**4000**
Fan 15	47,1	51,6	56,4	52,8	45,3	38,8
Fan 22	40,2	44,9	50	46,1	38,9	32,4
Fan 30	39,8	44,5	49,6	45,7	38,6	32,1
Rec	41,7	46,6	51,7	47,5	40,4	33,7
Fan 15 B	39,6	44,5	49,8	45,8	38,9	32,2
Fan 22 B	38,4	43,5	48,8	44,9	37,9	31,4
Fan 30 B	38,1	43,1	48,5	44,7	37,6	31,1
Rec B	41,4	46	50,9	46,6	39,6	32,9

Table 4.21 Average SPL values of receiver points when sound source 2 is open.

SPL, average – Source position 2 (P2)						
Room type	**frequency**					
	125	**250**	**500**	**1000**	**2000**	**4000**
Fan 15	42,6	47	51,8	48,2	40,6	34,1
Fan 22	42,4	46,7	51,5	48	40,5	34
Fan 30	42	46,3	51	47,6	40,1	33,7
Rec	43,6	48,1	52,7	48,9	41,5	34,8
Fan 15 B	41,2	45,6	50,4	46,9	39,4	32,9
Fan 22 B	40,3	44,9	49,9	46,4	39	32,6
Fan 30 B	39,7	44,3	49,3	45,8	38,3	31,9
Rec B	42,7	46,9	51,4	47,3	39,8	33,1

Table 4.22 Average SPL values of receiver points when sound source 3 is open.

SPL, average – Source position 3 (P3)						
Room type	**Frequency (Hz)**					
	125	**250**	**500**	**1000**	**2000**	**4000**
Fan 15	43,2	47,5	52	48,6	40,9	34,4
Fan 22	42,8	47	51,5	48,1	40,5	34
Fan 30	42,2	46,5	51	47,6	40,1	33,7
Rec	44,1	48,5	52,9	49,2	41,8	35,1
Fan 15 B	41,5	45,9	50,5	47,1	39,5	33
Fan 22 B	40,6	45,1	49,8	46,5	39,1	32,6
Fan 30 B	40	44,6	49,3	45,9	38,3	32
Rec B	43,1	47,3	51,6	48	40,6	33,8

4.2.2.1.5 Speech Transmission Index. Mean values of STI is listed in table 4.23.

Table 4.23 Average STI values of receiver points.

Room type	**STI, average**		
	P1	**P2**	**P3**
Fan 15	0,78	0,79	0,78
Fan 22	0,77	0,81	0,79
Fan 30	0,78	0,81	0,8
Rec	0,77	0,76	0,75
Fan 15 B	0,81	0,82	0,8
Fan 22 B	0,8	0,82	0,8
Fan 30 B	0,8	0,83	0,82
Rec B	0,79	0,77	0,77

4.2.3 Evaluation of the Results

Examination of acoustical conditions has two phases. First, it is aimed to compare the rooms. And as a second step, it is aimed to look at each room and to examine if the acoustical parameters are same for all of the receiver points, in other words if the acoustical parameters are distributed uniformly.

All simulation results are obtained for 8 octave bands in Odeon. But within the evaluation process it is quite common to use the values at 500 Hz or the mean values of mid frequencies, since this range of sound includes the frequencies that are most important for speech (Bradley, 2002). For that reason, mid frequency values of the acoustical parameters are evaluated within the study. On the other hand, the change of the acoustical parameters by frequency is examined in a separate title. Mid values are calculated as follows (Cerda, Gimenez, Romero, Cibrian, & Miralles, 2009) (Mehta, Johnson, & Rocafort, 1999):

$$T30_{mid} = ½\,(T30^{500Hz} + T30^{1kHz})$$

$$EDT_{mid} = ½\,(EDT^{500Hz} + EDT^{1kHz})$$

In the evaluation process, first the results are grouped in tables or/and graphs than they are examined and compared to find out differences. To find out the degree of variations, which are derived from different receiver points or different rooms, standard deviations and coefficients of variation are calculated and compared.

The Standard Deviation of a set of sample/population is defined as: "a measure of variation of values about the mean. It is a type of average deviation of values from the mean and one of the most important measures of variation. The value of the standard deviation (SD) is usually positive. It is zero only when all of the data values are the same number. Also larger amounts of s indicate greater amounts of variation and it can increase dramatically with the inclusion of data values that are very far away from all of the others. When it is necessary comparing variation in different populations the coefficient of variation is used. The coefficient of variation (CV) for a set of sample or population data describes the standard deviation relative to the mean and expressed as a percent. (Triola, 2004, pp. 75-79)

To find out relations between different parameters, correlation analysis is applied to results. To make correlation analysis and calculations common statistical analysis software "Minitab 15" and/or "Microsoft Excel" is used.

4.2.3.1 Comparison of Room Results with the Acceptable Limits of Parameters

As explained before, simulated results of five main acoustical parameters are used in the study to evaluate the acoustical conditions of cases. Although the examination of the variations between and within the cases is one of the most important aims of the study, the designed cases are also examined in point of suitability degree of recommended values of acoustic parameters.

4.2.3.1.1 Reverberation Time (RT). From the viewpoint of reverberation time, it is seen that the results (table 4.24) can vary by the room type, since the used materials are same. By considering the recommended values from different references (table

4.25), it can be said that all rooms have quite appropriate T30 values for all the source positions.

Also the change of the source position affects the measured reverberation time. For fan shaped rooms, when the sound source is on apron stage (P3) the value of reverberation time decreases. For rectangular shaped rooms the situation is just opposite. For F30 and Rec. B type of rooms, the changes of T30 values by change of source position are not as distinct as other types.

Table 4.24 Mean T30 values of rooms for 3 different source positions

Room Type	**T30** (values of mid frequency), (s)		
	P1	**P2**	**P3**
Fan 15	0,90	0,92	0,84
Fan 22	0,85	0,92	0,75
Fan 30	0,84	0,85	0,80
Rec	0,94	0,83	1,12
Fan 15 B	0,93	0,86	0,79
Fan 22 B	0,87	0,87	0,74
Fan 30 B	0,85	0,78	0,76
Rec B	0,99	0,99	1,04

Table 4.25 Optimum reverberation time values for mid frequencies

Reference	**Activity**	**RT (s)**
(Sirel, 1981)	Speech Auditoria	0,8 – 1,05
(Templeton, 1993, p. 66)	Drama (Theatres)	0,9 – **1,4**
(Barron, 1993)	Speech auditoria	**0,7** – 1,0
(Mehta, Johnson, & Rocafort, 1999)	Speech auditoria	0,8 (± 0,2) – 1,2 (± 0,2)
(Kinsler, Frey, Coppens, & Sanders, 2000, p. 334)	Speech auditoria	0,84 $(T=RV^{1/3})$

4.2.3.1.2 Early Decay Time (EDT). Reverberation time is one of the most common and important acoustical measures but recent studies indicate that in actual speech and music only the first or initial portions of the reverberation process in rooms is actually heard by people. As a result, the acoustical measure early decay time is developed (Cavanaugh & Wilkes, 1999, p. 237). Although some equations have been developed for the optimum values of EDT in concert halls, values or limits for EDT values of rooms for speech are not so definite. For most of the concert halls it is found that EDT values are nearly %10 higher than reverberation time (Mehta, Johnson, & Rocafort, 1999, p. 264). But for the rooms for speech situation is quite different since longer EDT causes masking effect on speech and this issue is shown in figure 4.21 and 4.22.

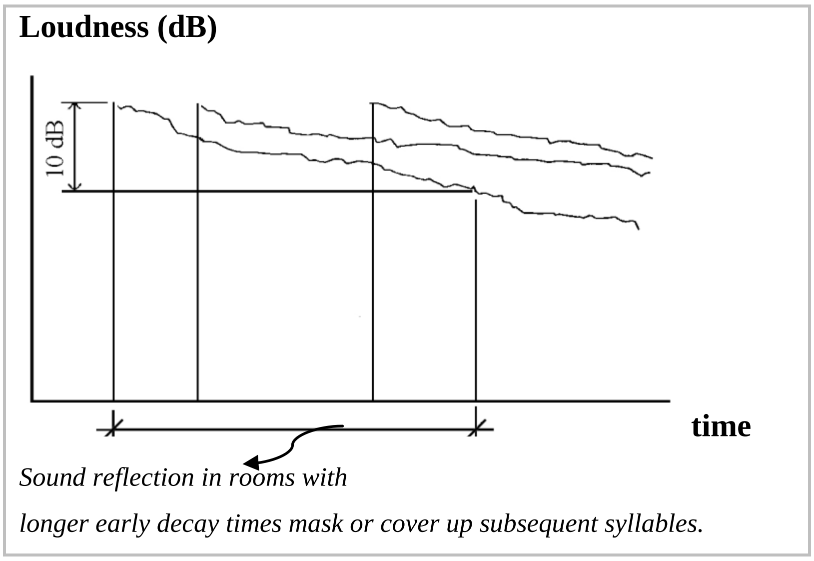


Figure 4.21 Graph of long EDT (Cavanaugh & Wilkes, 1999, p. 237)

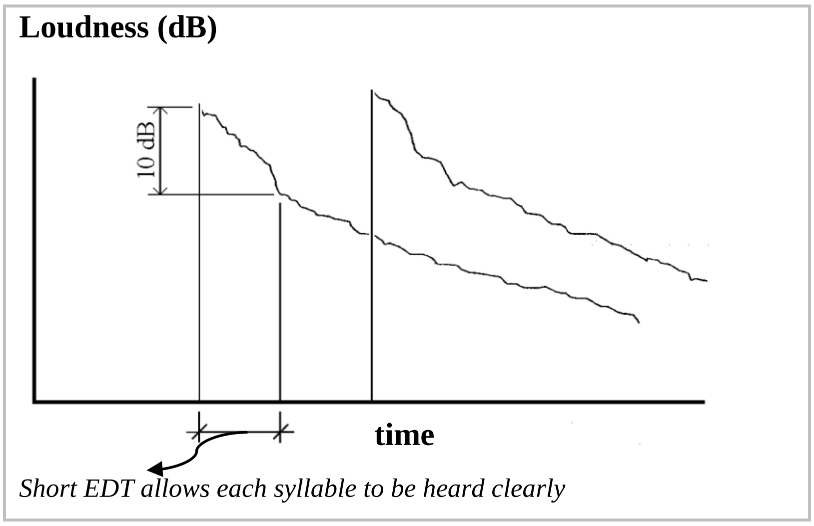


Figure 4.22 Graph of short EDT (Cavanaugh & Wilkes, 1999, p. 237)

The closer values of EDT and RT show that the sound energy is uniformly distributed within the room. In this case, the entire decay of sound is smooth and uniform and earlier studies are based on this theory. But recent surveys and measurements in actual halls revealed that the decay outline of some halls may not be uniform. When the results of the designed cases are considered, it is seen that all the rooms have two-slope decay outliners, with shorter EDT and longer RT.

In some of the designed cases values of the EDT are quite low, but by the decrease of the EDT it is seen that values of D50, which is one of the most important parameters in rooms for speech, is increasing for all the designed rooms. For all the rooms, linear correlation coefficient between EDT and D50 values are nearly “-1”, which means one of them is increasing while the other parameter is decreasing (Table 4.26).

Similar strong linear correlation is obtained between EDT – T30 and T30 – D50 for fan shaped rooms. Especially for fan shaped rooms with balcony, values are around 0,9. But for rectangular shaped rooms such a correlation does not exist.

Table 4.26 Linear correlation between parameters – Source Position 2

Room type	**Correlation between EDT-T30**	**Correlation between EDT-D50**	**Correlation between T30-D50**	**D50**	**STI**
Fan 15	-0,62	-0,99	0,52	0,85	0,79
Fan 22	-0,78	-0,98	0,64	0,88	0,81
Fan 30	-0,62	-0,99	0,56	0,88	0,81
Rec	0,42	-0,98	-0,25	0,79	0,76
Fan 15 B	-0,90	-0,99	0,85	0,90	0,82
Fan 22 B	-0,97	-1,00	0,97	0,89	0,82
Fan 30 B	-0,97	-0,99	0,97	0,90	0,83
Rec B	-0,41	-0,97	0,40	0,80	0,77

4.2.3.1.3 Distinctness (D50). Acceptable limit value for distinctness (D50) is defined as 0,50, since it is found that for values of D50 that are greater than 0,50 90% of intelligibility can be obtained. (Kurtulan, 2009) (Kuttruff, 2001) (Barron,

1993) The results of the cases are greater than 0,50 and most of the mean values of rooms are greater than 0,80. For that reason, they can be evaluated as quite good. By increase of D50 it is observed that STI values are getting higher (Table 4.26).

4.2.3.1.4 Speech Transmission Index (STI). As explained before, also STI is one of the most used parameters of speech intelligibility and acceptable limits are described below (Long, 2006, p. 598);

$0 < STI < 0,3$	*Bad*
$0,3 \leq STI < 0,45$	*Poor*
$0,45 \leq STI < 0,6$	*Fair*
$0,6 \leq STI < 0,75$	*Good*
$0,75 \leq STI < 1,00$	*Excellent*

If the results of rooms are considered, all rooms have excellent mean values of STI (Table 4.26).

4.2.3.1.5 Sound Pressure Level (SPL) and Total Speech Level. Sound pressure level in the auditorium is one of the most important measures. According to Barron, there are two main criteria that should be considered for theatre buildings, the early energy fraction (Distinctness) and the total speech level. The evaluations are made for D50 in previous title. And total speech level is determined by the SPL at the receiver points. Total speech level is described as the sound level at an individual seat for an actor placed at a particular position and orientation on stage, relative to the average direct sound level at 10m. (Barron, 1993, p. 428)

For comparison of the results it is necessary to find out the minimum acceptable value for speech sound level. The sound levels at 10 m. relative to the frequency are given by the Odeon. For the selected sound source, the mean value of the direct sound at 10 m is calculated as about 44 dB for the mid frequencies. To determine the minimum acceptable level, the method described by Barron is used. (Barron, 1993, p. 428) It is accepted that, actual sound level at a seat is *44 + S* dB SPL, and S symbolizes the *speech sound level*.

A typical acceptable background noise level in theatres is NC25 and the mean value of NC25 at mid frequencies is 29 dB SPL. And as explained before, in chapter two, an acceptable signal-to-noise ratio in a theatre is 15 dB. Thus, the criterion for intelligible speech transmission is obtained as;

$44 + S > 29+15$ or

$S > 0$

When considering the mean values of rooms at mid frequencies, in table 4.27 for all the cases it is seen that the minimum acceptable speech sound level (S) is achieved.

Table 4.27 Calculated S values in rooms

Room type	S values according to source positions (dB)		
	P1	**P2**	**P3**
Fan 15	10,60	6,00	6,30
Fan 22	4,05	5,75	5,80
Fan 30	3,65	5,30	5,30
Rec	5,60	6,80	7,05
Fan 15 B	3,80	4,65	4,80
Fan 22 B	2,85	4,15	4,15
Fan 30 B	2,60	3,55	3,60
Rec B	4,75	5,35	5,80

As a small conclusion, after evaluation of the mean values of acoustical parameters, it can be said that all the designed auditoria meet the acoustical requirements for drama theatres.

4.2.3.2 Change of the Acoustical Parameters Depending on Frequency

Values of the acoustical parameters vary depending on the frequency. Keeping this change at minimum level is important for the intelligibility of speech, especially for the reverberation time. For that reason, calculated mean values of the acoustical parameters in simulated rooms are compared. To determine the degree of change depending on frequency (in 6 octave bands), coefficient of variation of each parameter in each room is calculated. Since there are three source positions (P1, P2, P3) used in the study, three different results obtained.

The graphs in Figures 4.23 – 4.26 are showing the values of parameters relative to the frequency for the source position 2. In general, T30 and D50 values are increasing at high frequencies, while EDT values are decreasing by increase of frequency.

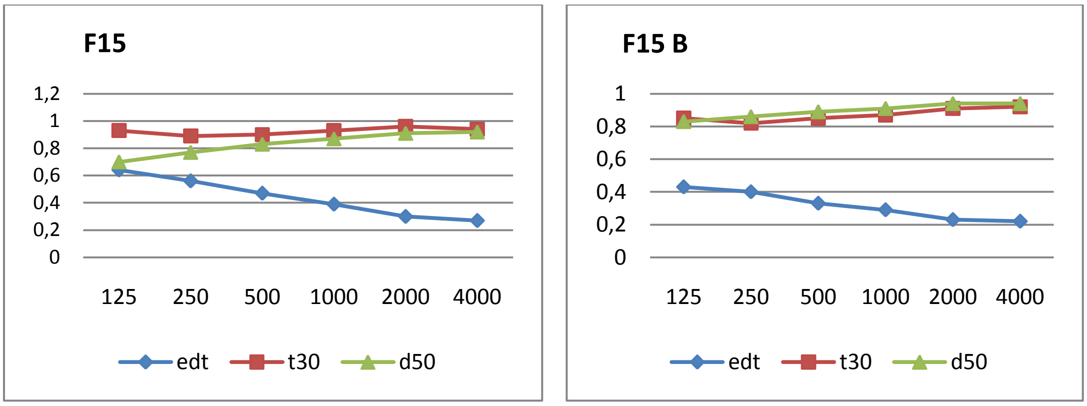


Figure 4.23 Acoustical parameters for F15 and F15 B

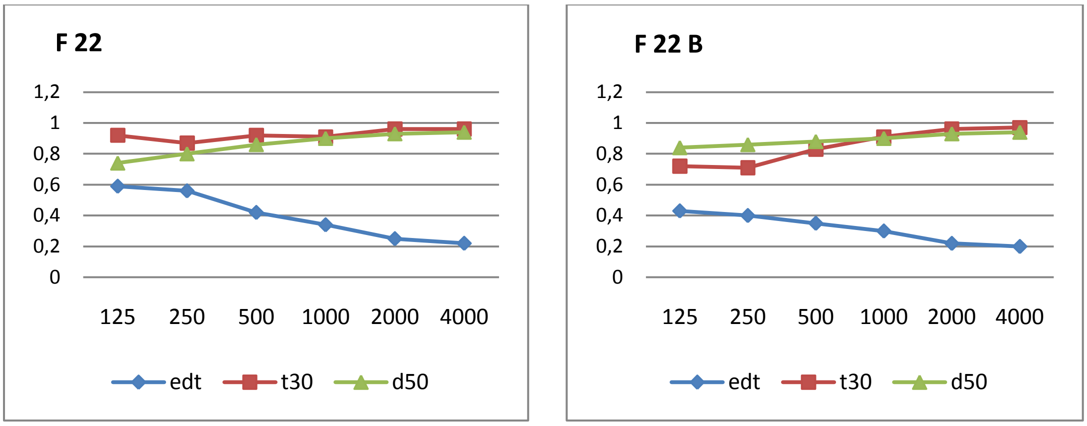


Figure 4.24 Acoustical parameters for F22 and F22 B

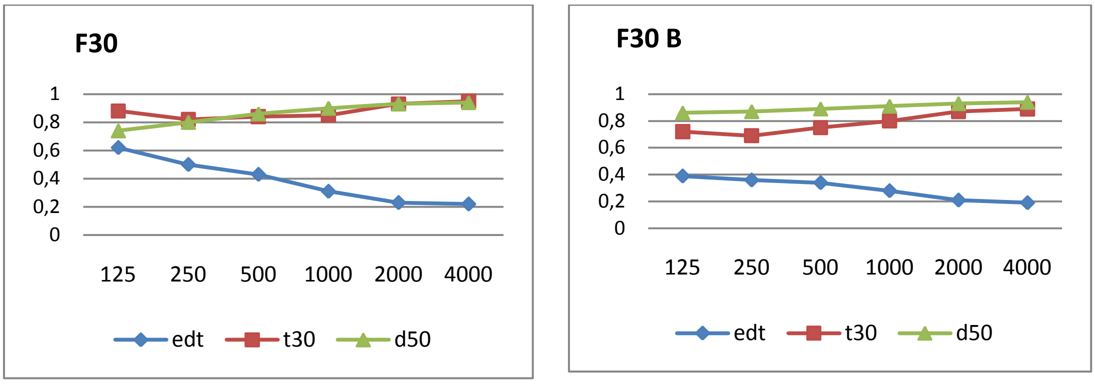


Figure 4.25 Acoustical parameters for F30 and F30 B

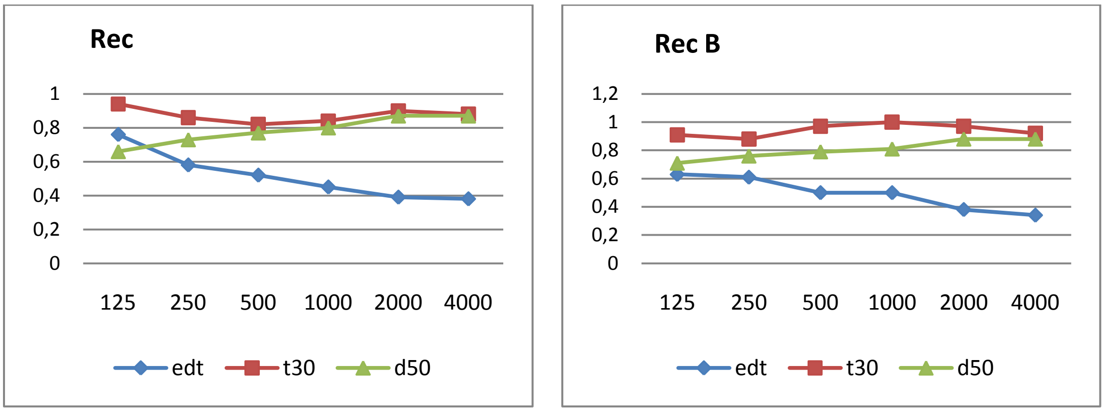


Figure 4.26 Acoustical parameters for REC and REC B

More detailed comparison and evaluation of the results are made below, under the title of each parameter.

4.2.3.2.1 Early Decay Time (EDT). When the results are examined (Table 4.28), it is seen that change of EDT values by frequency is quite distinct. Also, it is seen that change of source position effects degree of this variation within the room. Maximum variation is derived in rectangular shaped room for source position 1 (P1). For source positions 2 and 3, maximum variation by frequency is seen in fan shaped room with 30^0 splaying angle (F30).

In the graph below (Figure 4.27), it is seen that the variation of EDT values by frequency is similar for source positions 2 and 3. When the sound source 1 is open, in other words, if the actor stands on P1 change of the EDT values by frequency is quite different. That is probably because of the effect of fly tower. As a result, it can be said that EDT parameter is quite affected by the change of source position.

Table 4.28 Coefficients of variation of measured EDT values by frequency in designed cases

Room Type	**Mean Values of EDT (s)**			**Standard Deviation**			**Coefficient of Variation (%)**		
	P1	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
F15	0,54	0,44	0,45	0,10	0,15	0,14	18,70	33,26	30,46
F22	0,61	0,40	0,40	0,11	0,16	0,15	18,93	39,14	36,73
F30	0,60	0,39	0,39	0,15	0,16	0,15	25,39	41,45	38,45
REC	0,61	0,51	0,54	0,19	0,14	0,13	31,63	27,87	24,18
F15 B	0,45	0,32	0,37	0,12	0,09	0,10	27,11	27,36	27,60
F22 B	0,52	0,32	0,36	0,10	0,09	0,10	18,95	29,67	26,93
F30 B	0,49	0,30	0,34	0,09	0,08	0,10	18,39	27,85	28,46
REC B	0,49	0,49	0,47	0,12	0,12	0,11	24,44	23,77	24,47

* Green filling shows minimum values while purple filling shows maximum values.

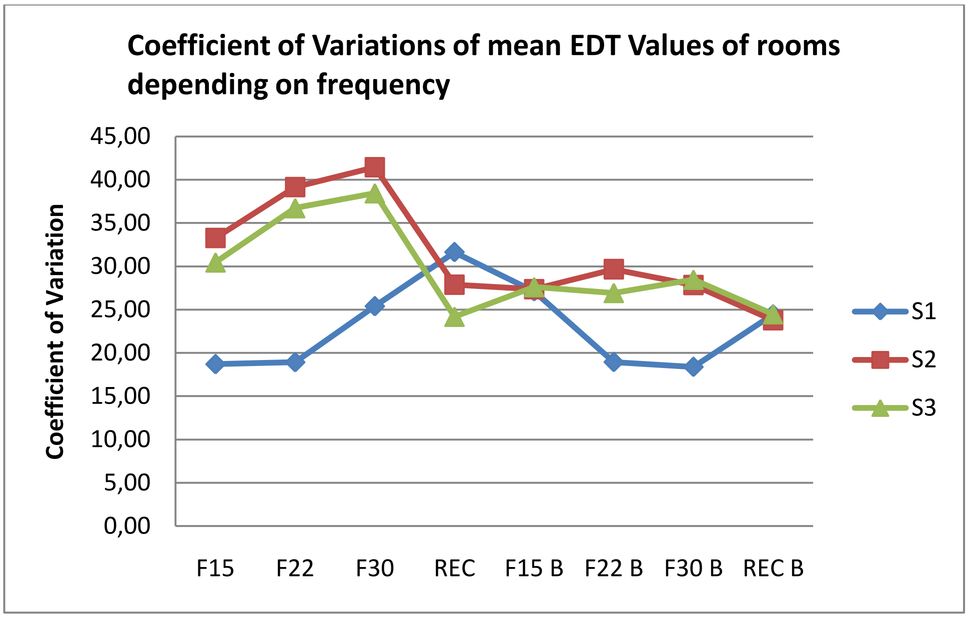


Figure 4.27 Coefficient of variation graph - EDT

4.2.3.2.2 Reverberation Time (T 30). In table 4.29, it is seen that the variation of reverberation time by the frequency is quite low and it is quite a good condition.

Table 4.29 Coefficients of variation of measured T30 values by frequency in designed cases

Room Type	Standard Deviation			Mean Values of T 30 (s)			Coefficient of Variation (%)		
	P1	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
F15	0,04	0,03	0,05	0,93	0,93	0,88	4,08	2,80	6,23
F22	0,08	0,03	0,07	0,91	0,92	0,81	9,06	3,67	8,06
F30	0,05	0,05	0,04	0,88	0,88	0,83	5,29	5,91	4,24
REC	0,06	0,04	0,10	1,00	0,87	1,04	5,87	4,95	9,48
F15 B	0,14	0,04	0,03	0,95	0,87	0,80	15,02	4,42	3,12
F22 B	0,14	0,12	0,06	0,87	0,85	0,75	15,68	13,62	7,45
F30 B	0,13	0,08	0,11	0,86	0,79	0,79	14,72	10,32	13,71
REC B	0,06	0,05	0,04	0,99	0,94	1,01	5,70	4,82	3,79

* Green filling shows minimum values while purple filling shows maximum values.

In the graph below (Figure 4.28), it is seen more clearly that, for F 22 and F 30 with balcony, the variation of reverberation time by frequency is more distinct than other room for all source positions. Although it is an unwanted situation for speech auditoria to change of RT by frequency, values can be evaluated as acceptable for F22 and F30.

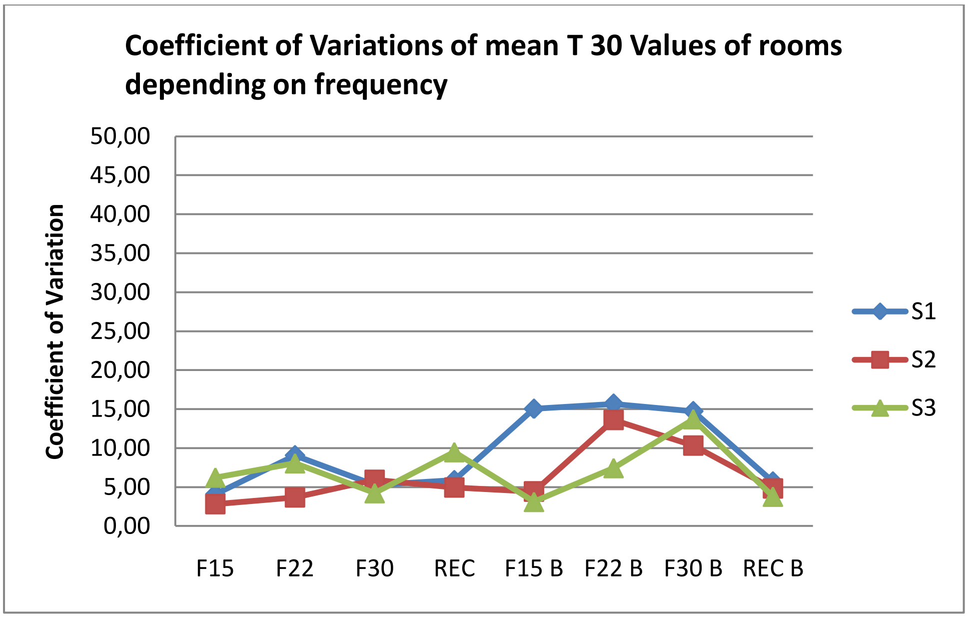


Figure 4.28 Coefficient of variation graph – T30

4.2.3.2.3 Distinctness (D 50). By considering the mean D50 values of rooms, the minimum variations are seen in fan-shaped rooms with balcony, just opposite of the situation for reverberation time (Table 4.30 and Figure 4.29). And the variation degree of parameter by frequency is not dependent on the source position, since the results are nearly same for all source positions.

Table 4.30 Coefficients of variation of measured D50 values by frequency in designed cases

Room Type	**Standard Deviation**			**Mean Values of D 50**			**Coefficient of Variation (%)**		
	P1	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
F15	0,09	0,09	0,08	0,80	0,83	0,81	11,07	10,26	10,42
F22	0,08	0,08	0,09	0,80	0,86	0,84	10,19	9,12	11,15
F30	0,08	0,08	0,09	0,81	0,86	0,85	9,92	9,12	10,42
REC	0,08	0,08	0,08	0,81	0,78	0,76	9,79	10,45	10,98
F15 B	0,05	0,04	0,06	0,86	0,90	0,86	5,65	4,93	6,70
F22 B	0,05	0,04	0,05	0,85	0,89	0,87	5,57	4,40	5,95
F30 B	0,04	0,03	0,04	0,86	0,90	0,88	4,16	3,58	4,77
REC B	0,06	0,07	0,07	0,84	0,81	0,80	6,86	8,34	9,07

* Green filling shows minimum values while purple filling shows maximum values.

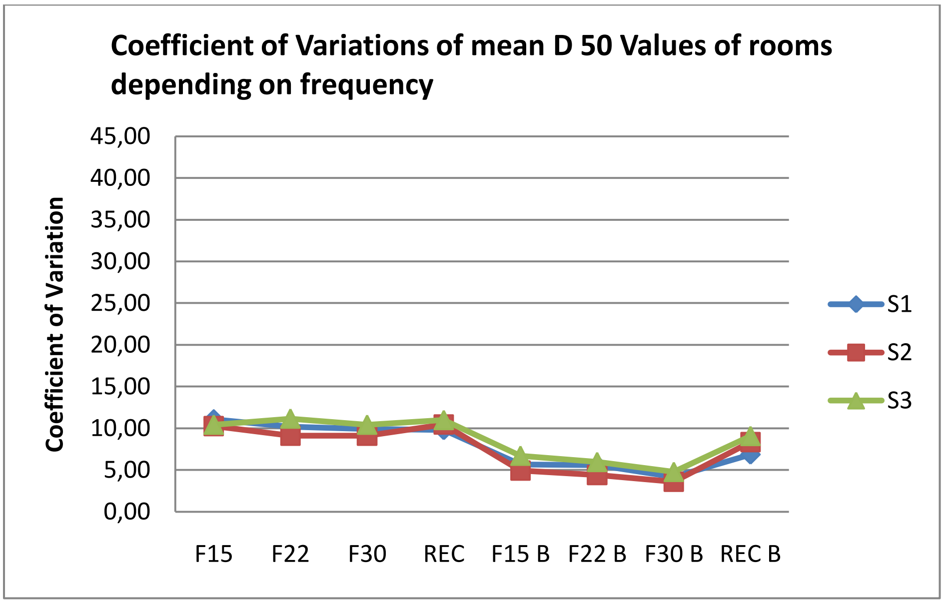


Figure 4.29 Coefficient of variation graph – D50

4.2.3.2.4Sound Pressure Level (SPL). It is seen that the variation degree of sound pressure level by frequency is nearly same in all rooms for all source positions. (Table 4.31 and Figure 4.30)

Table 4.31 Coefficients of variation of measured SPL values by frequency in designed cases

Room Type	**Standard Deviation**			**Mean Values of SPL**			**Coefficient of Variation (%)**		
	P1	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
F15	6,27	6,31	6,30	48,67	44,05	44,43	12,89	14,32	14,19
F22	6,23	6,23	6,26	42,08	43,85	43,98	14,81	14,21	14,23
F30	6,19	6,18	6,19	41,72	43,45	43,52	14,84	14,21	14,22
REC	6,35	6,36	6,34	43,60	44,93	45,27	14,57	14,16	14,00
F15 B	6,21	6,24	6,26	41,80	42,73	42,92	14,85	14,60	14,59
F22 B	6,17	6,17	6,15	40,82	42,18	42,28	15,13	14,62	14,54
F30 B	6,18	6,21	6,20	40,52	41,55	41,68	15,25	14,94	14,88
REC B	6,33	6,49	6,34	42,90	43,53	44,07	14,76	14,92	14,39

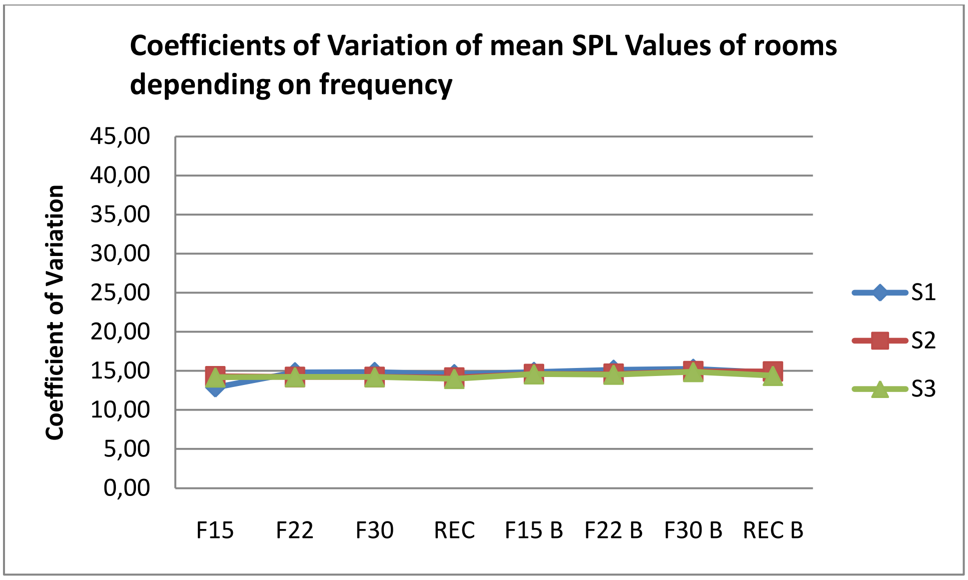


Figure 4.30 Coefficient of variation graph – SPL

4.2.3.3 Comparison of the Results in the Context of Distribution within the Rooms (Comparison of Receiver Points in Each Room)

In this part of the study, the acoustical properties of room are evaluated by examining the acoustical parameters of defined receiver points. Thus, Each room is evaluated under a separate title and evaluations are made for five acoustical parameters (EDT, RT, D50, STI and SPL). Mean values of the acoustical parameters for each receiver points are shown in graphs instead of tables to see the changes easily. In addition, all simulation results of the receiver points are listed in appendix B. In graphs, numbers on the x axis define the number of receiver points. To define different rows, dashed lines are used in the graphs.

4.2.3.3.1 Fan Shape 15 (F15). There are 13 numbers of defined receiver points in the room. By considering EDT values at defined receiver points, when the source 1 (P1) is opened, the values of the seats in 5th row are quite high. Except these 3 seats, for all the source positions, EDT values of receiver points range between 0,28 – 0,64 seconds (Figure 4.31). If these values are evaluated alone, it is possible to say that they are quite low by comparing the T30 values.

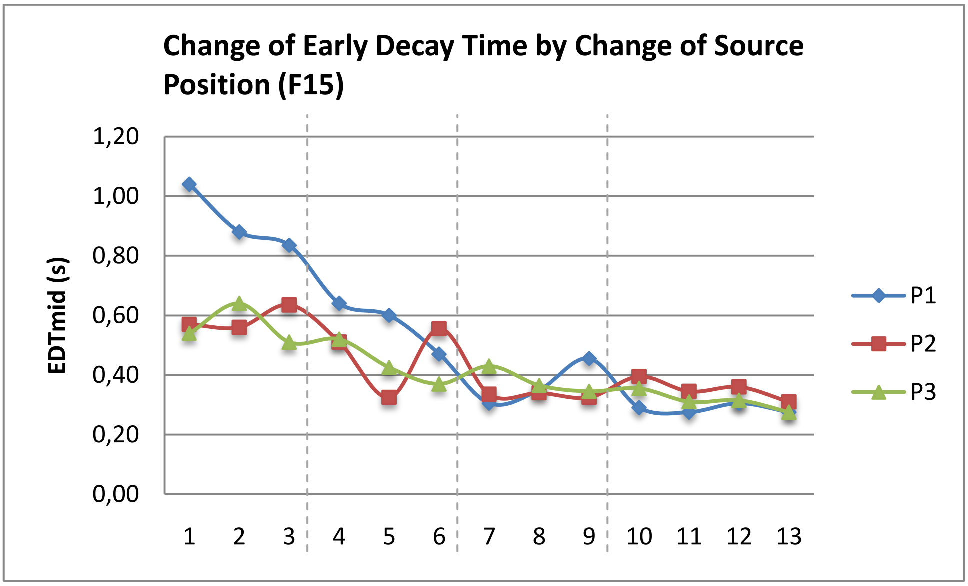


Figure 4.31 EDT values of receiver points in F 15

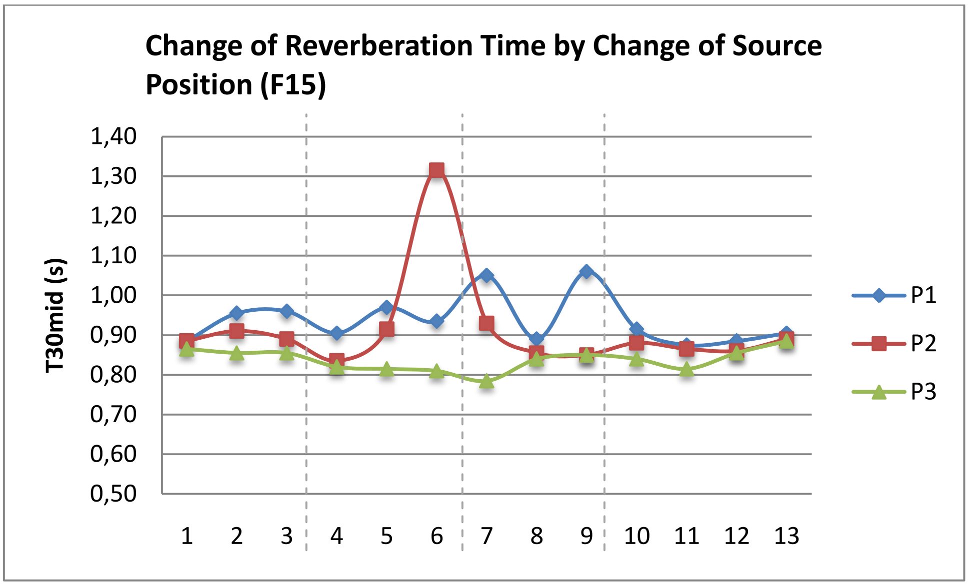


Figure 4.32 T30 values of receiver points in F 15

Most distinctive change of reverberation time occurs at 6th receiver point, which is located at 9th row and near the side wall of the room, when the source two is opened (Figure 4.32). Although the T30 value of 1,32 seconds at that point is a little higher than recommended maximum limit for theatres, values of D50 and STI are quite good.

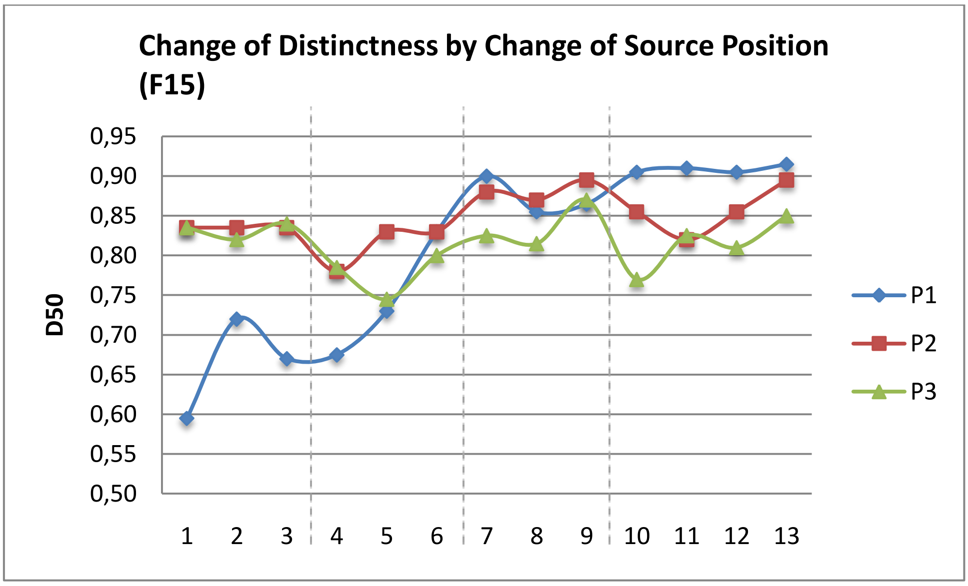


Figure 4.33 D50 values of receiver points in F 15

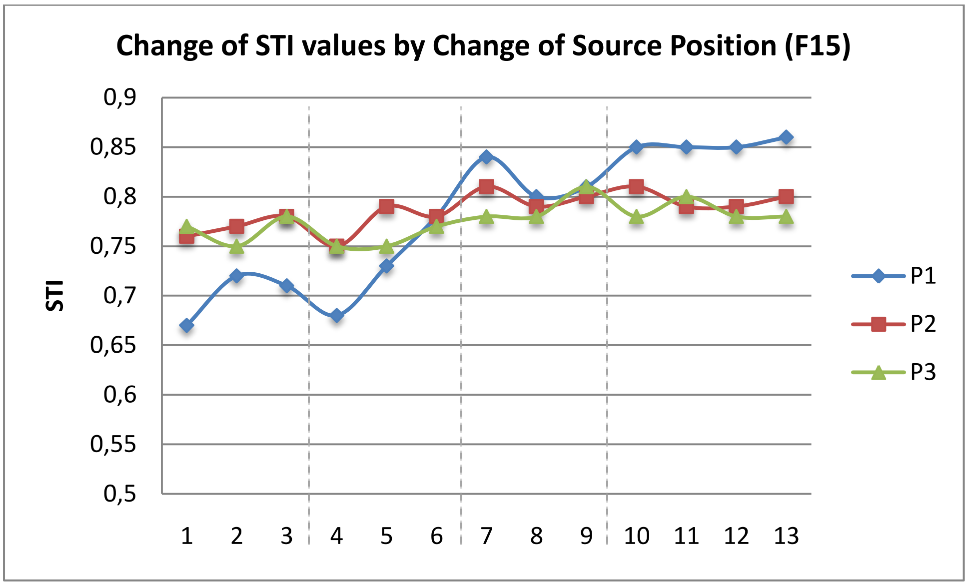


Figure 4.34 STI values of receiver points in F 15

When source 1 is opened probably by the effect of relatively high EDT values, STI values of seat 1, 2, 3, 4 and 5 go under 0,75 like D50 values (Figure 4.33 – 4.34). Since the acceptable minimum limit for D50 is 0,5 it is not a bad condition but in point of STI, values under 0,75 are evaluated as “good” instead of “excellent”. Although values of the front seats are decreasing when source is located at point 1, they are still acceptable.

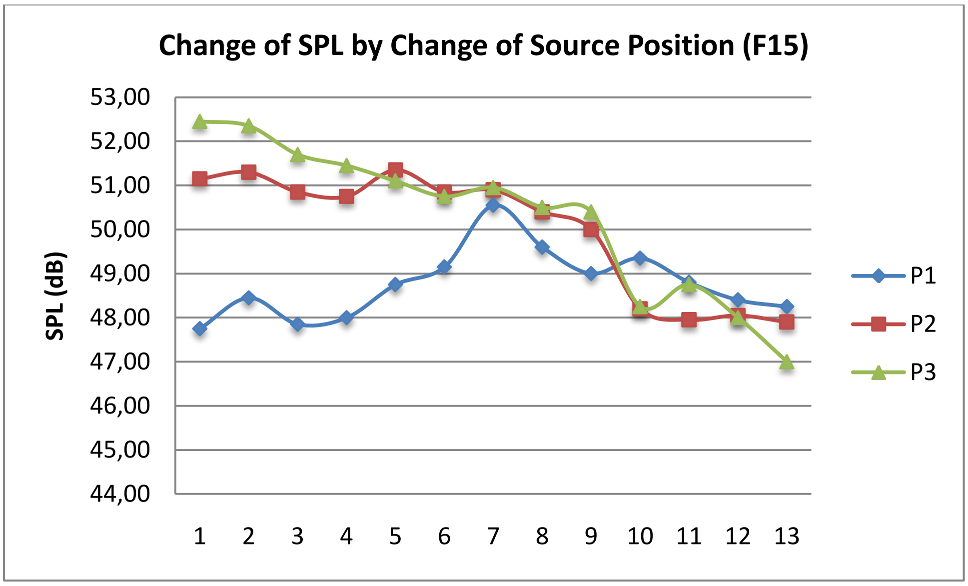


Figure 4.35 SPL values of receiver points in F 15

By considering speech sound levels, all the receivers are in good condition, since the S values of the seats are more than calculated acceptable limit “0”. But the effect of fly tower is seen in graph above (Figure 4.35) for the change of SPL values. For P2 and P3 sound pressure levels of the seats at the back of auditorium decrease by the effect of distance. But for source position 1, also the seats in the front rows have relatively low values of SPL. As a result, it can be said that seats in the front are more affected by the change of source position.

The explained variations between receiver points according to source position are also described as coefficient of variations in table 4.32 below. While calculating the standard deviation, it is preferred to include the extreme (minimum and maximum) values of parameters to see the difference between results.

Table 4.32 Descriptive statistics of receiver points in F 15. (Numbers next to the Parameters indicate the source position)

Parameters	Number of seats	Mean Value	Standard Deviation	Coefficient of Variation	Minimum Value	Maximum Value	Range
EDT 1	13	0,52	0,26	50,60	0,28	1,04	0,77
T30 1	13	0,94	0,06	6,45	0,88	1,06	0,19
SPL 1	13	48,76	0,78	1,61	47,75	50,55	2,80
D50 1	13	0,81	0,11	13,92	0,60	0,92	0,32
STI 1	13	0,78	0,07	8,99	0,67	0,86	0,19
EDT 2	13	0,43	0,12	27,59	0,31	0,64	0,33
T30 2	13	0,91	0,12	13,53	0,84	1,32	0,48
SPL 2	13	49,97	1,40	2,80	47,90	51,35	3,45
D50 2	13	0,85	0,03	3,82	0,78	0,90	0,12
STI 2	13	0,79	0,02	2,30	0,75	0,81	0,06
EDT 3	13	0,42	0,11	26,03	0,28	0,64	0,37
T30 3	13	0,84	0,03	3,26	0,79	0,89	0,10
SPL 3	13	50,28	1,74	3,45	47,00	52,45	5,45
D50 3	13	0,81	0,03	4,13	0,75	0,87	0,13
STI 3	13	0,78	0,02	2,33	0,75	0,81	0,06

4.2.3.3.2 Fan Shape 15 with Balcony (F15 B). By considering EDT values at defined receiver points, when the source 1 is opened, the values of the seats in 5th row are quite high, like F 15. Also, for the seat no 5 and 11 the EDT value is around 0,60 and relatively high. For source positions 2 and 3 the EDT values range between 0,27 – 0, 47 seconds (Figure 4.36).

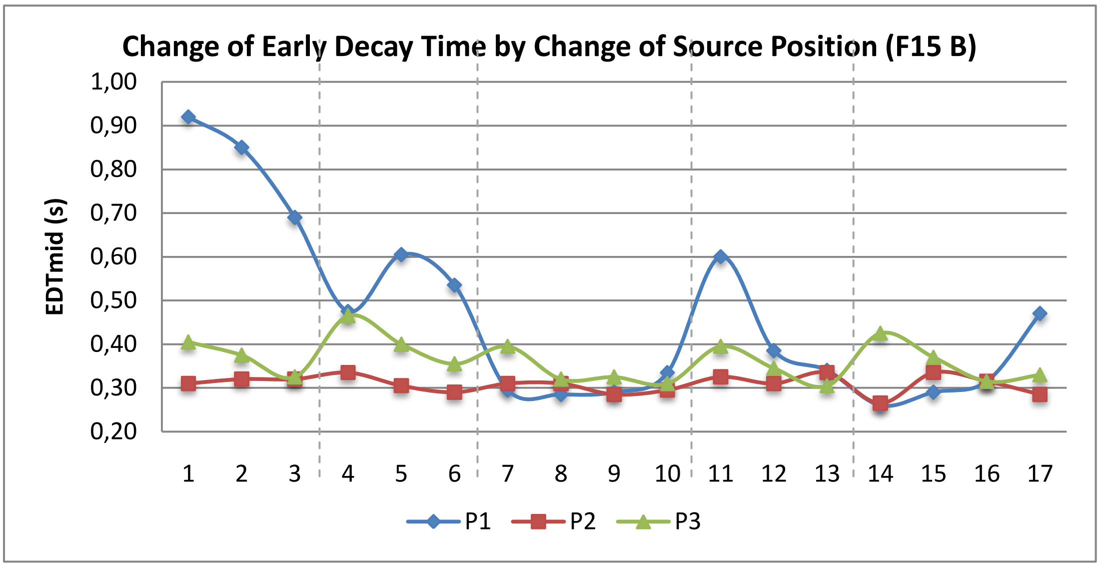


Figure 4.36 EDT values of receiver points in F 15 B

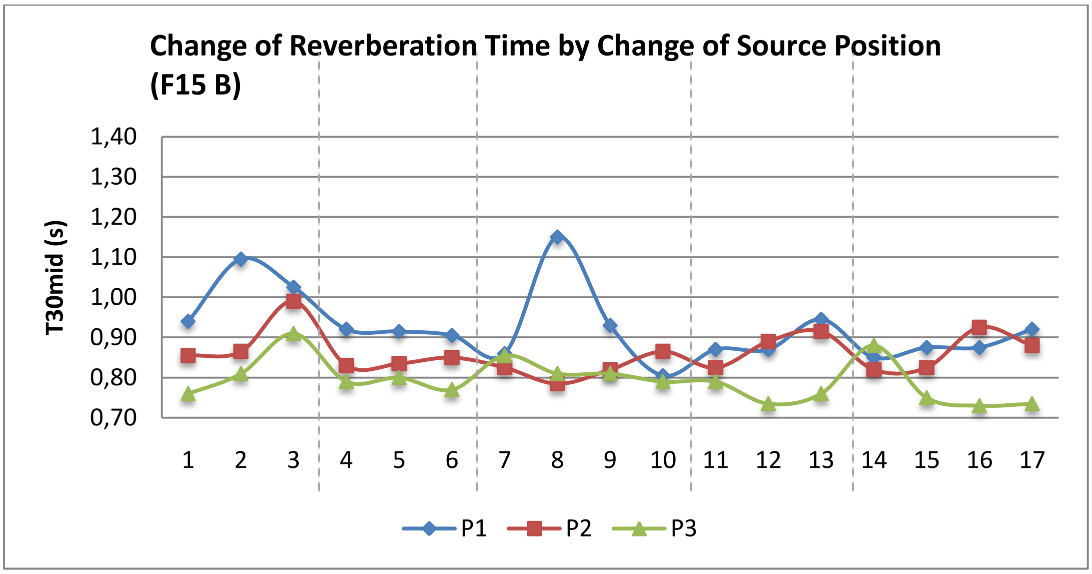


Figure 4.37 T30 values of receiver points in F 15 B

Most distinctive change of reverberation time occurs at 8th receiver, which is located at 14th row under the balcony, when the source 1 is opened. The T30 value of

1,15 seconds at that point is still an acceptable value. In this room, T30 values of the seats located in the front and middle parts of auditorium are under 0,80 seconds like the seats located in first row of balcony (Figure 4.37).

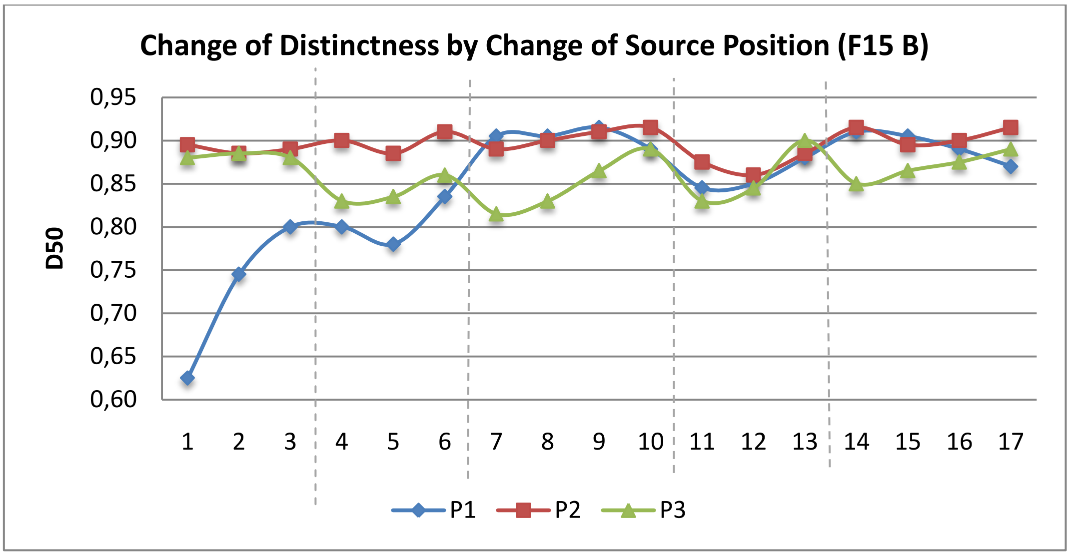


Figure 4.38 D50 values of receiver points in F 15 B

When source 1 is opened seats 1 and 4 have STI values under 0,75. And for the seat number 1 D50 value is relatively low. The situation is quite similar with F 15. In the room, for all the sources, seats located in first row of balcony have relatively low values of STI and D50 (Figure 4.38 – 4.39).

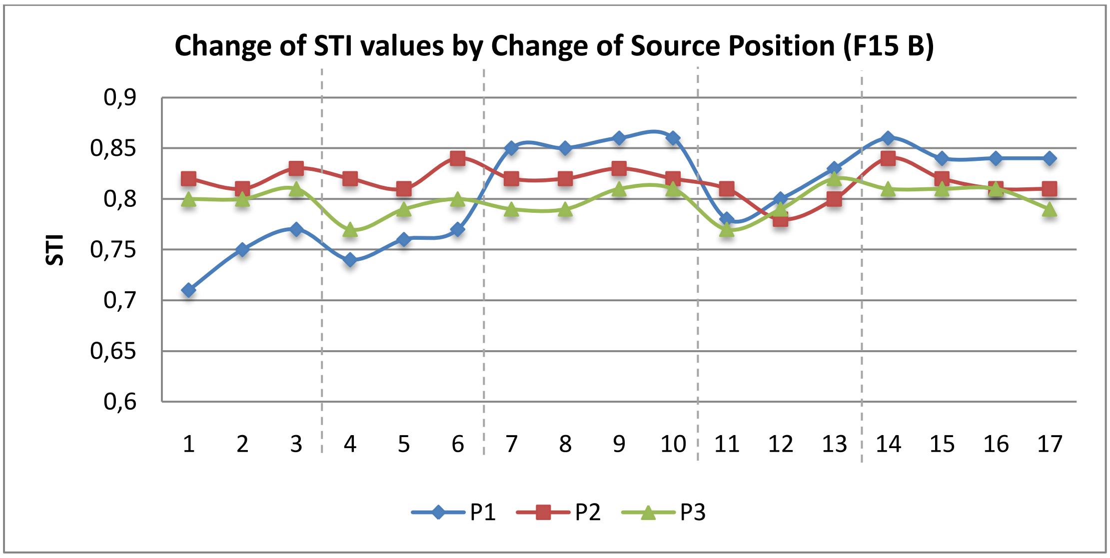


Figure 4.39 STI values of receiver points in F 15 B

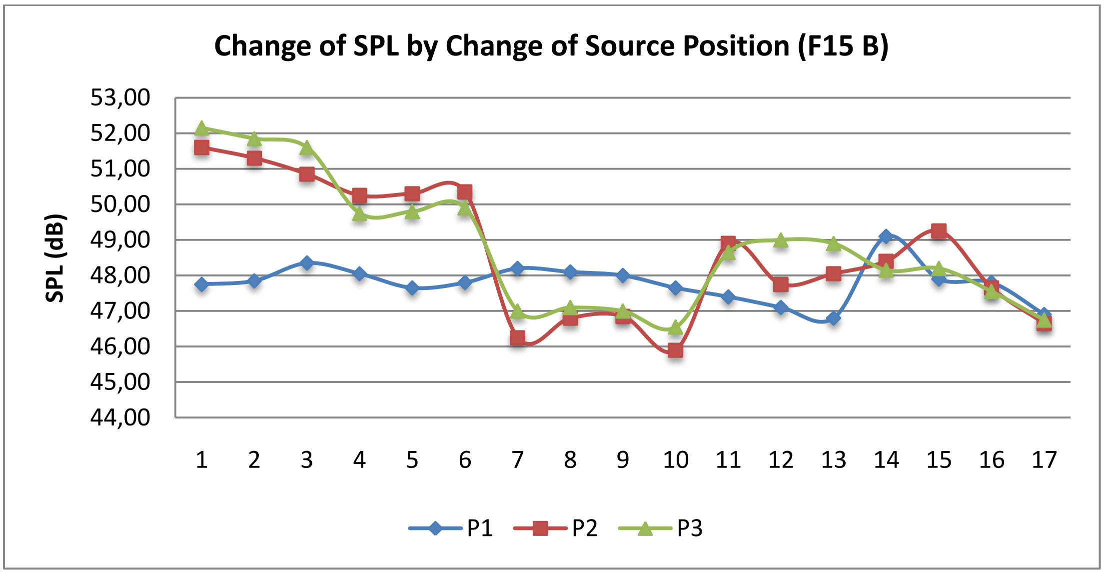


Figure 4.40 SPL values of receiver points in F 15 B

By considering speech sound levels, all the receivers are in good condition, since the S values of the seats are more than calculated acceptable limit “0”. But the effect of balcony is seen in graph above (Figure 4.40) for the change of SPL values. For P2 and P3 sound pressure levels of the seats under the balcony decrease. But as explained their values are still acceptable.

The explained variations between receiver points according to source position are also described as coefficient of variations in table 4.33 below. While calculating the standard deviation, it is preferred to include the extreme (minimum and maximum) values of parameters to see the difference between results. According to the results in the table, minimum variations of parameters are seen when the sound source 2 is opened.

Table 4.33 Descriptive statistics of receiver points in F 15 B. (Numbers next to the Parameters indicate the source position)

Parameters	Number of seats	Mean Value	Standard Deviation	Coefficient of Variation	Minimum Value	Maximum Value	Range
EDT 1	17	0,47	0,21	43,97	0,26	0,92	0,66
T30 1	17	0,93	0,09	9,58	0,81	1,15	0,35
SPL 1	17	0,84	0,08	9,01	46,80	49,10	0,29
D50 1	17	0,81	0,05	6,11	0,71	0,86	0,15
STI 1	17	47,79	0,55	1,15	0,63	0,92	2,30
EDT 2	17	0,31	0,02	6,39	0,27	0,34	0,07
T30 2	17	0,86	0,05	5,79	0,79	0,99	0,21
SPL 2	17	48,65	1,86	3,82	45,90	51,60	5,70
D50 2	17	0,90	0,02	1,70	0,86	0,92	0,06
STI 2	17	0,82	0,01	1,77	0,78	0,84	0,06
EDT 3	17	0,36	0,05	12,78	0,31	0,47	0,16
T30 3	17	0,79	0,05	6,40	0,73	0,91	0,18
SPL 3	17	48,82	1,81	3,71	46,55	52,15	5,60
D50 3	17	0,86	0,03	3,02	0,82	0,90	0,09
STI 3	17	0,80	0,01	1,78	0,77	0,82	0,05

4.2.3.3.3 Fan Shape 22 (F 22).

There are 11 defined receiver points in the room. By considering the graphs for F22 (Figures 4.41 – 4.45) it is seen that 3 seats in the 5th row have relatively long EDT values, while having relatively low D50, STI and SPL values when the sound source 1 is opened. For sound source 2, the T30 value of the 8th receiver is peak. The value is 1,17 seconds and although it is an acceptable value, quite different from the other receiver points. When the source 3 is opened, all the receiver points have quite low T30 values. At the 6th receiver, T30 value measured lower than 0,70 seconds (the minimum acceptable value of reverberation time). From the point of view T30, minimum variation is seen when the sound source 1 is opened.

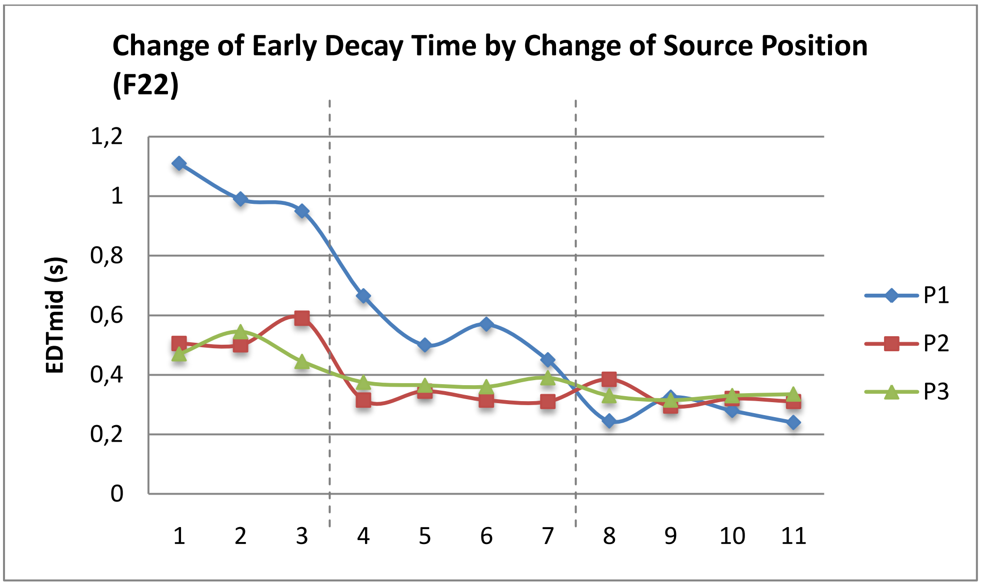


Figure 4.41 EDT values of receiver points in F 22

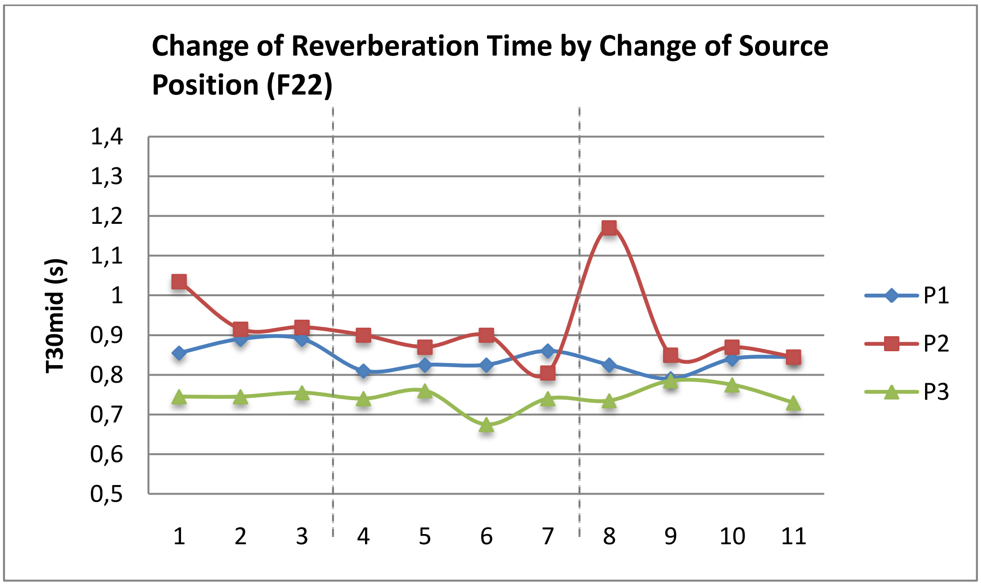


Figure 4.42 T 30 values of receiver points in F 22

From the point of view D50, it is seen that values are higher than 0,80 when the sound source 2 or 3 is activated, while STI scores of the seats are excellent. SPL levels of the seats located at the back of the auditorium decrease by the effect of distance. When the sound source 1 opened, it is seen that STI and D50 values of the first 4 receiver points are relatively low and SPL values of all the receiver points are quite similar.

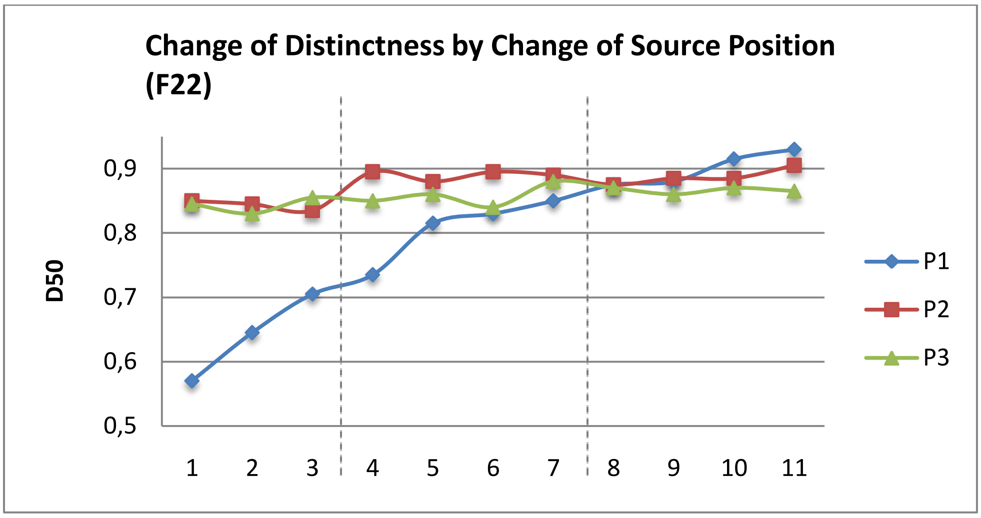


Figure 4.43 D50 values of receiver points in F 22

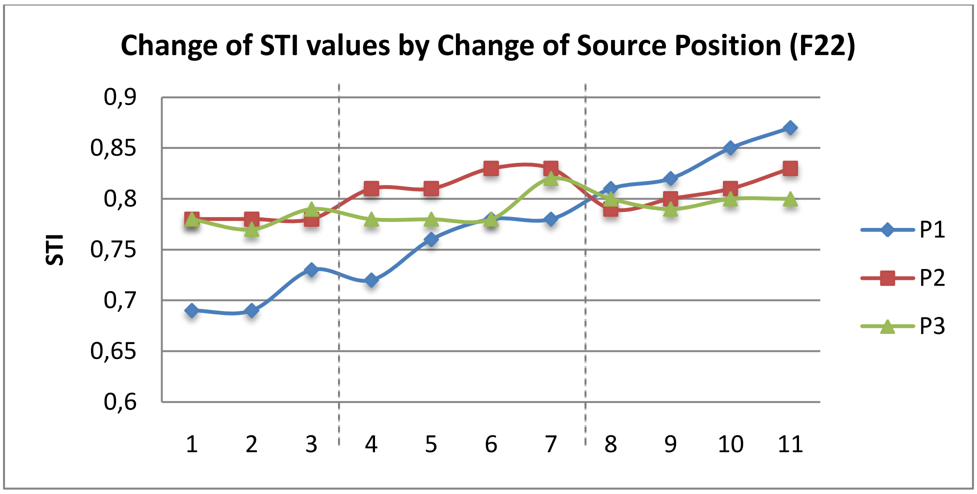


Figure 4.44 STI values of receiver points in F 22

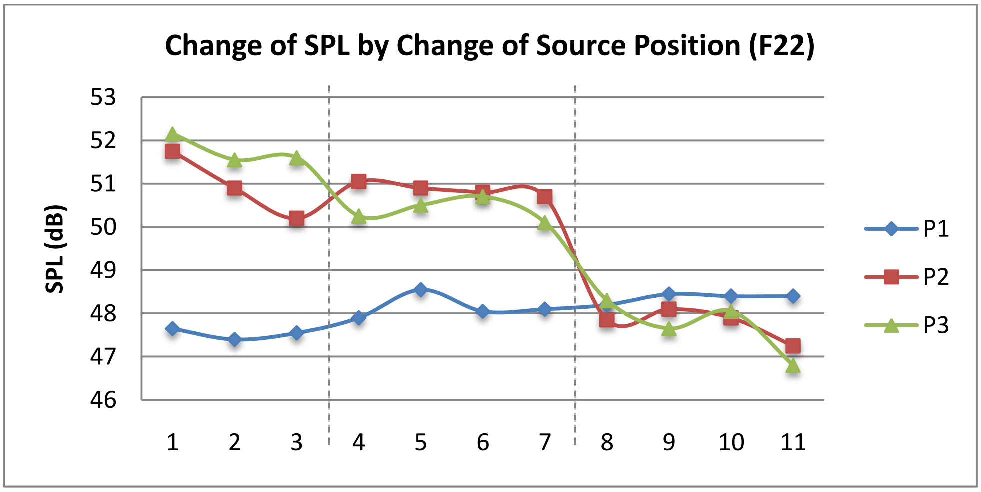


Figure 4.45 SPL values of receiver points in F 22

A summary of the results in graphs above can be seen in table 4.34.

Table 4.34 Descriptive statistics of receiver points in F 22. (Numbers next to the Parameters indicate the source position)

Parameters	Number of seats	Mean Value	Standard Deviation	Coefficient of Variation	Minimum Value	Maximum Value	Range
EDT 1	11	0,58	0,32	54,97	0,24	1,11	0,87
T30 1	11	0,84	0,03	3,70	0,79	0,89	0,10
SPL 1	11	48,06	0,39	0,81	47,40	48,55	1,15
D50 1	11	0,80	0,12	14,65	0,57	0,93	0,36
STI 1	11	0,77	0,06	7,94	0,69	0,87	0,18
EDT 2	11	0,38	0,10	26,83	0,30	0,59	0,30
T30 2	11	0,92	0,10	11,19	0,81	1,17	0,37
SPL 2	11	49,76	1,63	3,27	47,25	51,75	4,50
D50 2	11	0,88	0,02	2,62	0,84	0,91	0,07
STI 2	11	0,80	0,02	2,51	0,78	0,83	0,05
EDT 3	11	0,39	0,07	18,43	0,32	0,55	0,23
T30 3	11	0,74	0,03	3,82	0,68	0,79	0,11
SPL 3	11	49,79	1,80	3,61	46,80	52,15	5,35
D50 3	11	0,86	0,01	1,72	0,83	0,88	0,05
STI 3	11	0,79	0,01	1,79	0,77	0,82	0,05

4.2.3.3.4 Fan Shape 22 with Balcony (F 22 B). There are 19 defined receiver points in the room and 8 of them are located in the balcony. The increase of the EDT values of seats in the first row is seen also at the seats located in the first row of balcony, when P1 is activated. When other sources are activated EDT values range between 0,20 - 0,50 seconds (Figure 4. 46).

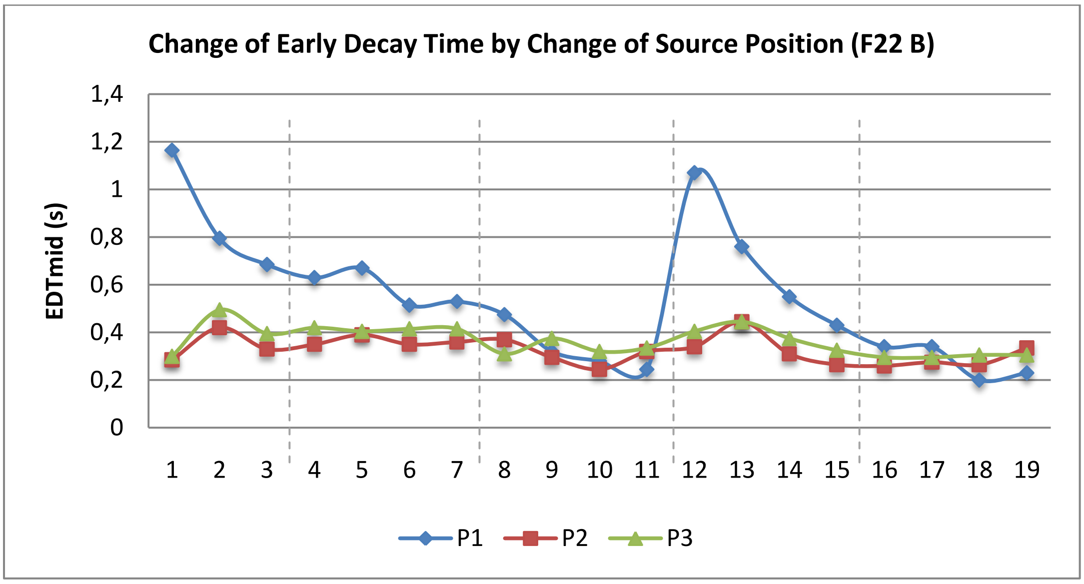


Figure 4.46 EDT values of receiver points in F 22 B

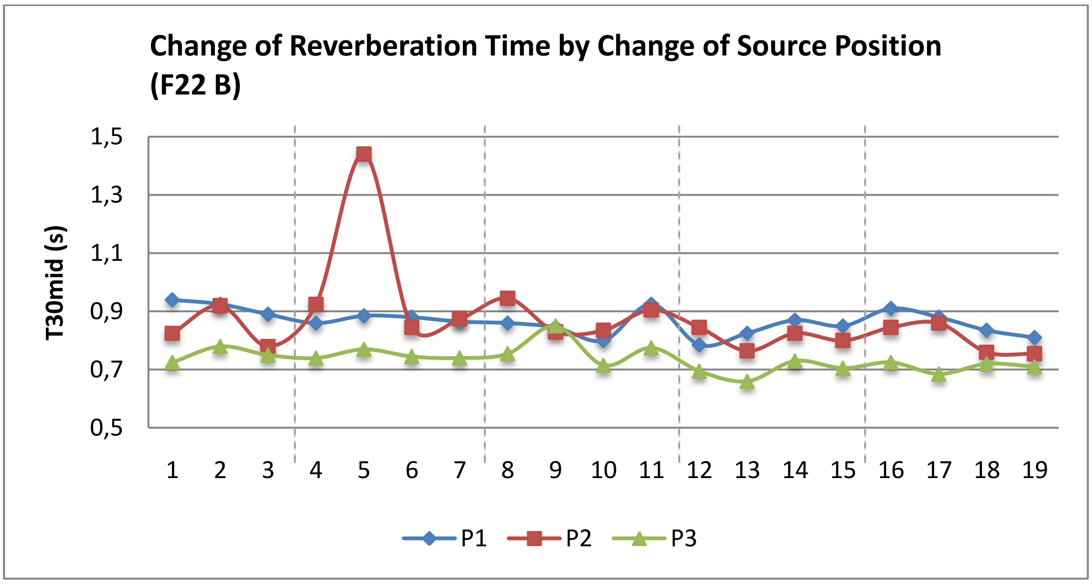


Figure 4.47 T 30 values of receiver points in F 22 B

When T30 graph is examined (Figure 4.47), it is seen that values range between about 0,70 – 0,90 seconds, except the peak at 5th receiver. When P2 is activated the T30 value is measured as 1,44 seconds, which exceeds the limits defined before.

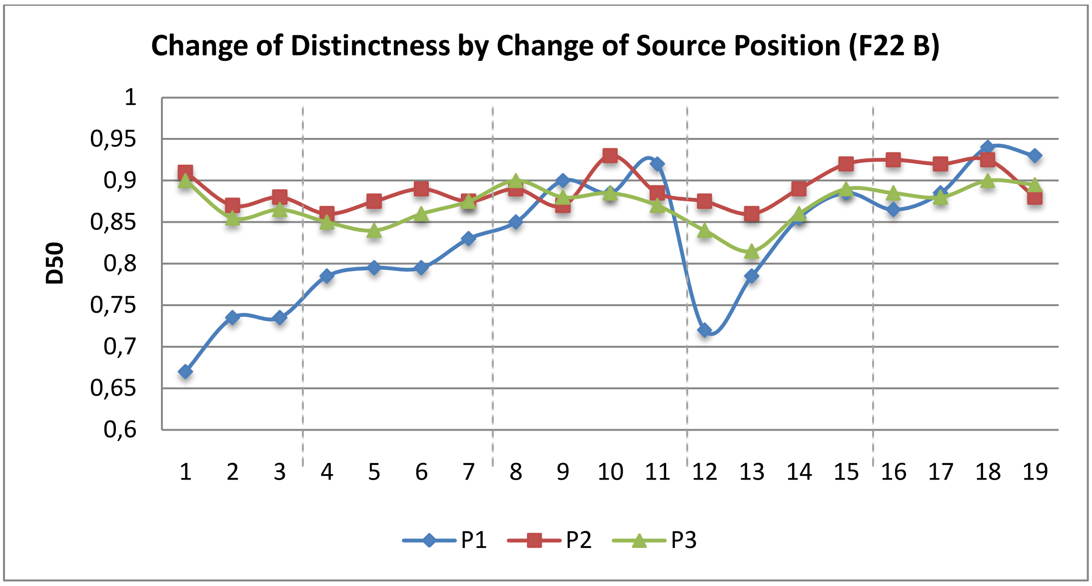


Figure 4.48 D50 values of receiver points in F 22 B

D50 and STI values of the receiver points are quite good when P2 or P3 is active and variation degree of parameters by receiver points is quite low (Figure 4.48 – 4.49).

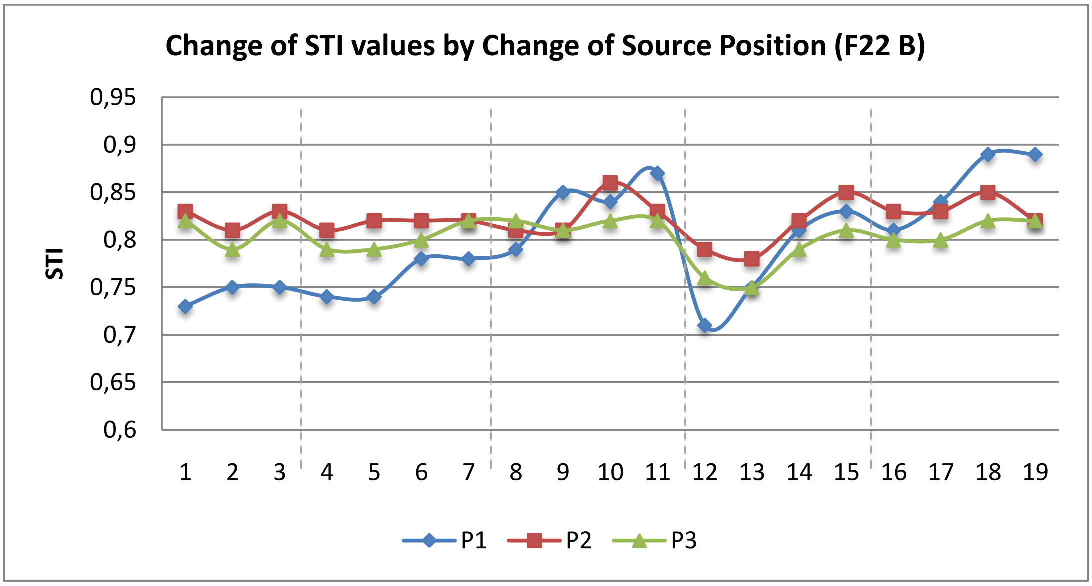


Figure 4.49 STI values of receiver points in F 22 B

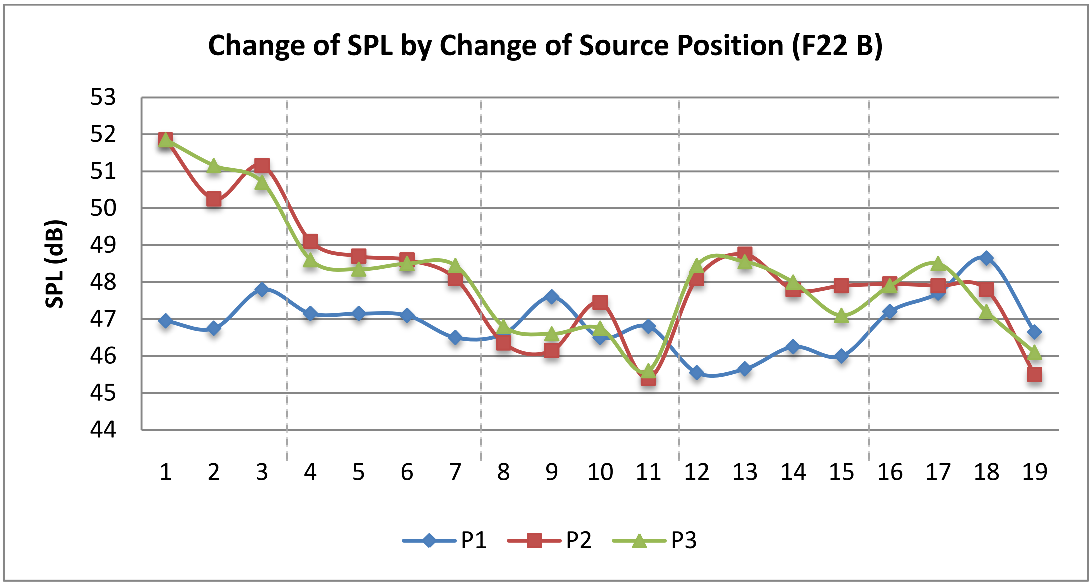


Figure 4.50 SPL values of receiver points in F 22 B

SPL values are decreasing by the effect of distance and also the effect of balcony overhang is seen as decrease of SPL (Figure 4.50). Except the 19th seat SPL values of the seats located in balcony are higher than seats located under the balcony.

Table 4.35 Descriptive statistics of receiver points in F 22 B. (Numbers next to the Parameters indicate the source position)

Parameters	Number of seats	Mean Value	Standard Deviation	Coefficient of Variation	Minimum Value	Maximum Value	Range
EDT 1	19	0,54	0,27	50,73	0,20	1,17	0,97
T30 1	19	0,87	0,04	4,96	0,79	0,94	0,16
SPL 1	19	46,87	0,76	1,62	45,55	48,65	3,10
D50 1	19	0,83	0,08	9,36	0,67	0,94	0,27
STI 1	19	0,80	0,06	7,02	0,71	0,89	0,18
EDT 2	19	0,33	0,06	16,99	0,25	0,45	0,20
T30 2	19	0,87	0,15	16,98	0,76	1,44	0,69
SPL 2	19	48,15	1,69	3,52	45,40	51,85	6,45
D50 2	19	0,89	0,02	2,61	0,86	0,93	0,07
STI 2	19	0,82	0,02	2,35	0,78	0,86	0,08
EDT 3	19	0,37	0,06	16,39	0,30	0,50	0,20
T30 3	19	0,74	0,04	5,64	0,66	0,85	0,19
SPL 3	19	48,17	1,65	3,43	45,60	51,85	6,25
D50 3	19	0,87	0,02	2,72	0,82	0,90	0,09
STI 3	19	0,80	0,02	2,59	0,75	0,82	0,07

4.2.3.3.5 Fan Shape 30 (F 30). There are 13 defined receiver points in the room. Similar to other rooms that are examined before, EDT values of the seats in the front (5th) row are higher than T30 values when P1 is activated (Figure 4.51).

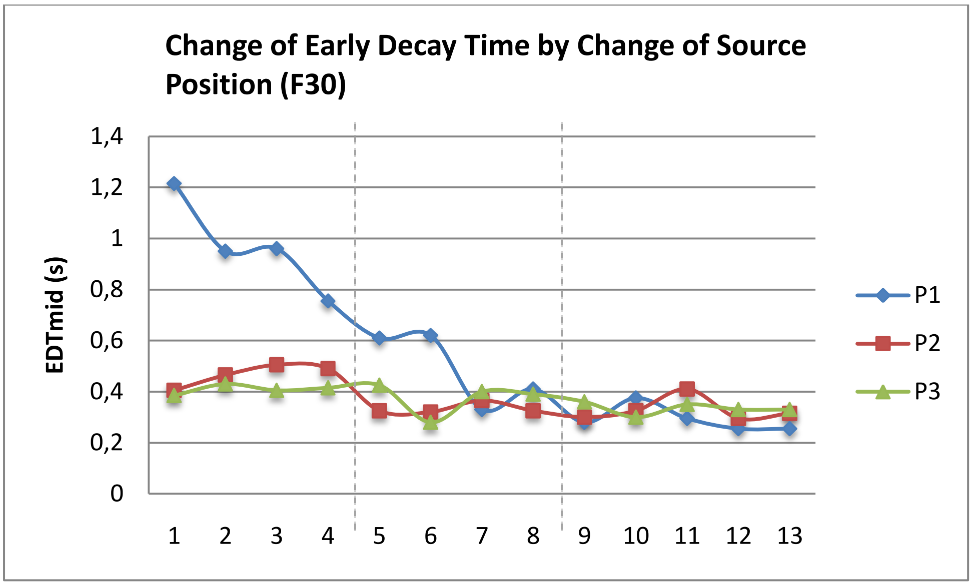


Figure 4.51 EDT values of receiver points in F 30

T30 values of the receiver points are quite close and they are all between the defined minimum and maximum limits, for all the sound source positions (Figure 4.52).

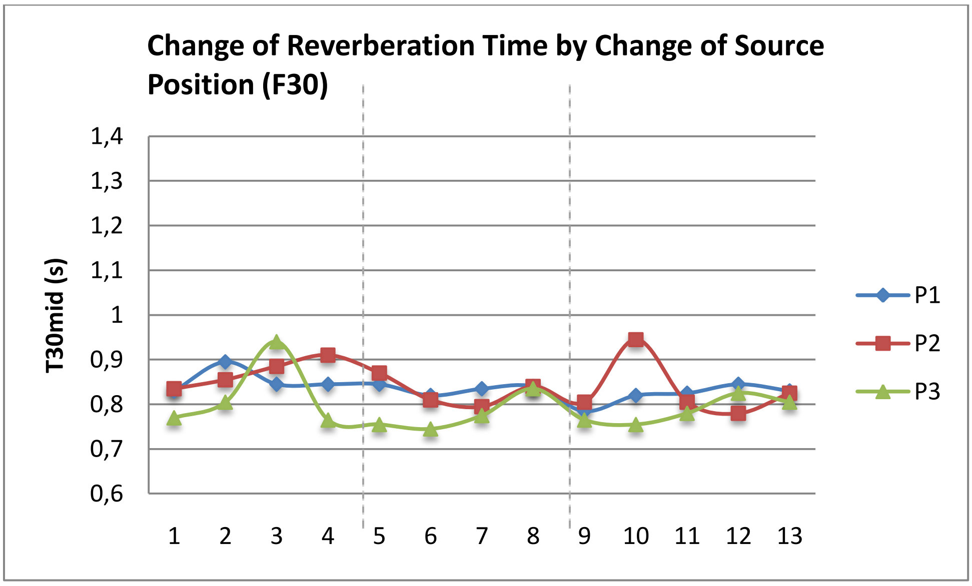


Figure 4.52 T 30 values of receiver points in F 30

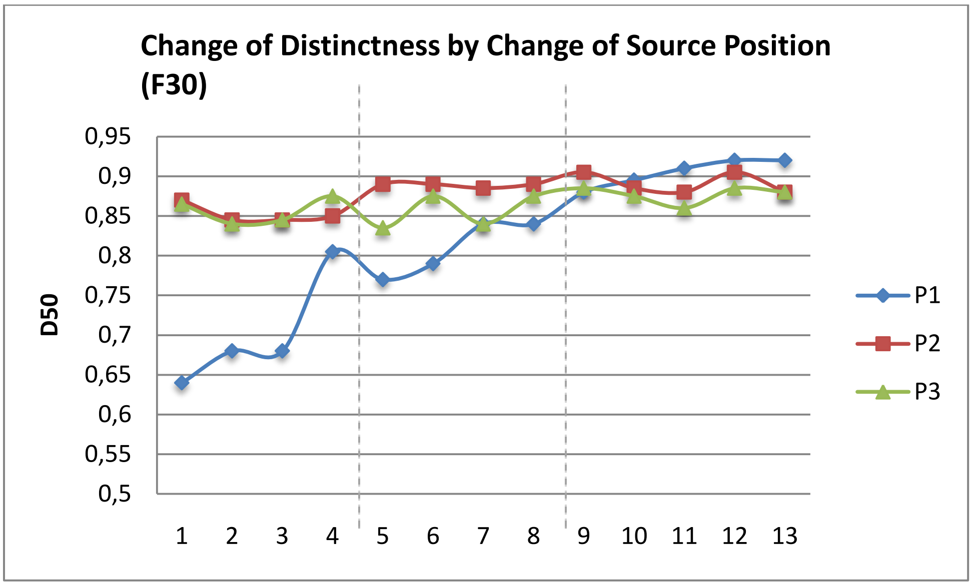


Figure 4.53 D50 values of receiver points in F 30

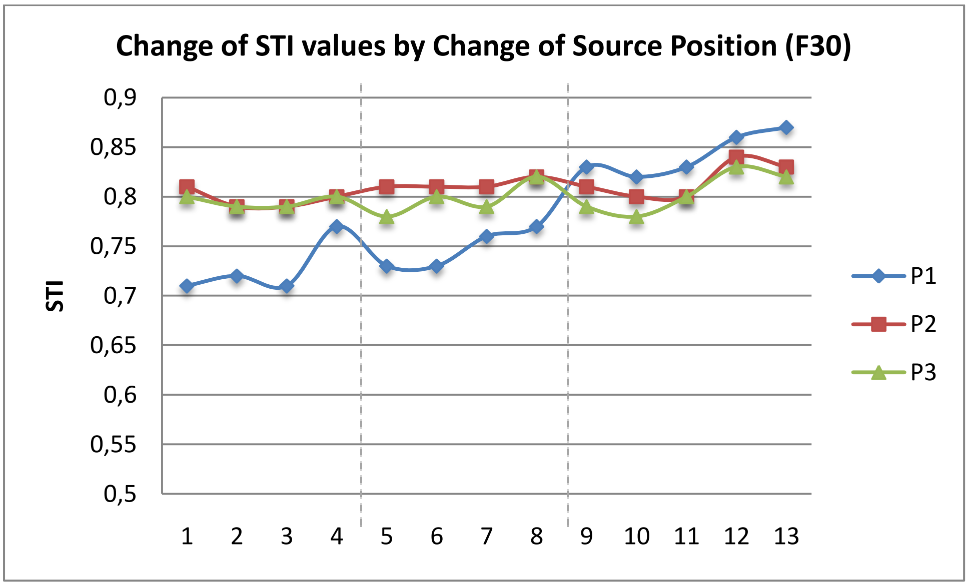


Figure 4.54 D50 values of receiver points in F 30

When the sound source 2 or 3 is activated D50 values of seats are higher than 0,84, and STI scores of the seats are excellent (Figure 4.53 – 4.54). SPL levels of the seats located at the back of the auditorium decrease by the effect of distance. When the sound source 1 is opened, it is seen that STI and D50 values of the first 3 receiver points are relatively low and SPL values of all the receiver points are quite similar (Figure 4.55).

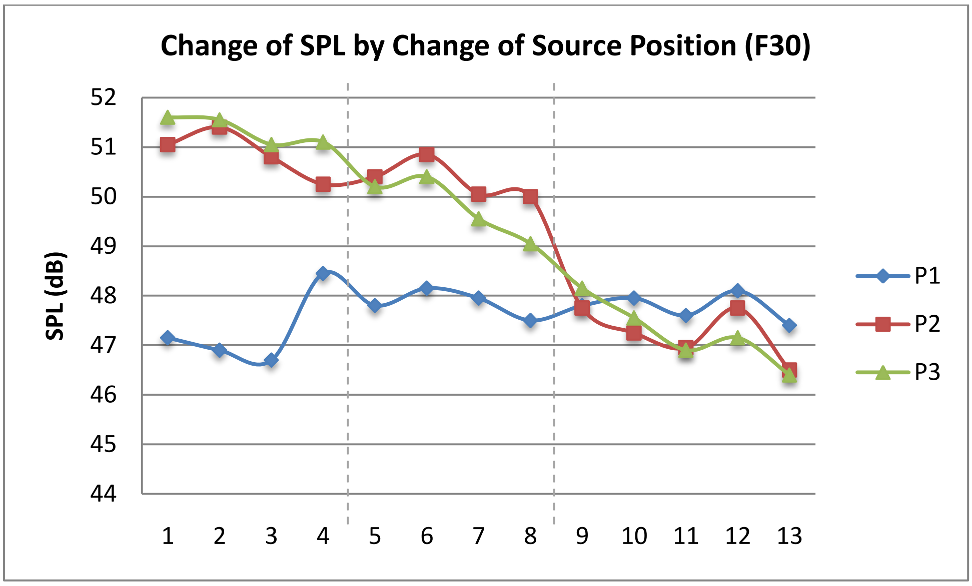


Figure 4.55 SPL values of receiver points in F 30

A summary of the results is shown in table 4.36.

Table 4.36 Descriptive statistics of receiver points in F 30. (Numbers next to the Parameters indicate the source position)

Parameters	**Number of seats**	**Mean Value**	**Standard Deviation**	**Coefficient of Variation**	**Minimum Value**	**Maximum Value**	**Range**
EDT 1	13	0,56	0,32	56,92	0,26	1,22	0,96
T30 1	13	0,84	0,02	2,92	0,79	0,90	0,11
SPL 1	13	47,65	0,51	1,07	46,70	48,45	1,75
D50 1	13	0,81	0,10	11,92	0,64	0,92	0,28
STI 1	13	0,78	0,06	7,43	0,71	0,87	0,16
EDT 2	13	0,37	0,07	19,98	0,30	0,51	0,21
T30 2	13	0,84	0,05	5,75	0,78	0,95	0,17
SPL 2	13	49,31	1,77	3,59	46,50	51,40	4,90
D50 2	13	0,88	0,02	2,33	0,85	0,91	0,06
STI 2	13	0,81	0,01	1,78	0,79	0,84	0,05
EDT 3	13	0,37	0,05	13,10	0,28	0,43	0,15
T30 3	13	0,79	0,05	6,55	0,75	0,94	0,20
SPL 3	13	49,28	1,87	3,80	46,40	51,60	5,20
D50 3	13	0,86	0,02	2,11	0,84	0,89	0,05
STI 3	13	0,80	0,02	1,94	0,78	0,83	0,05

4.2.3.3.6 Fan Shape 30 with Balcony (F 30 B).

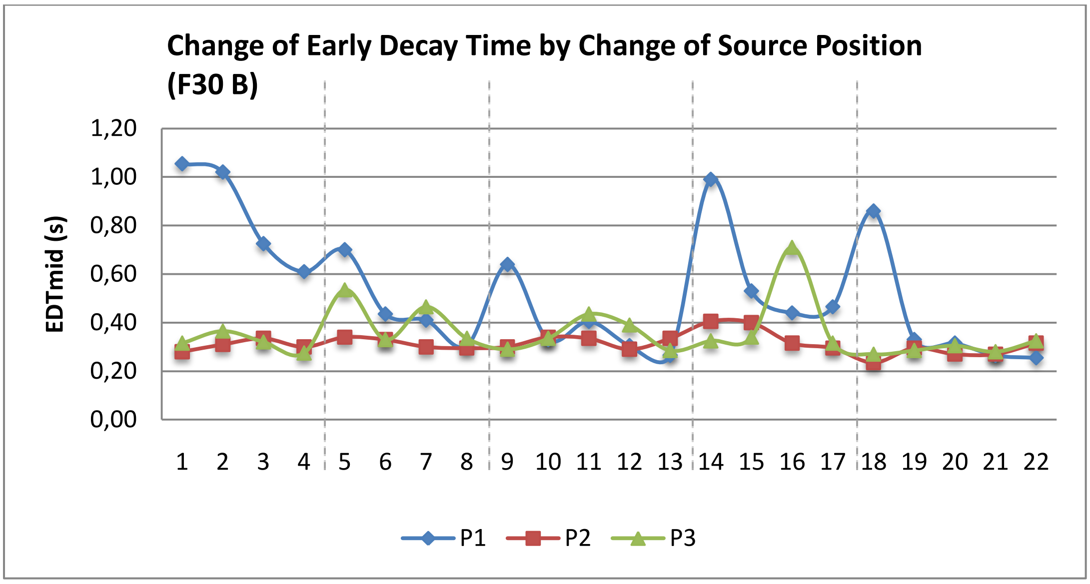


Figure 4.56 EDT values of receiver points in F 30 B

In the room, for 22 defined receiver points, the distribution of T30 values is quite uniform for all source positions, except the peak at 18th receiver point when P3 is activated (Figure 4.57). Except from the peak at 16th receiver point, EDT values are also quite close for P2 and P3. EDT values vary when the source 1 is opened (Figure 4.56).

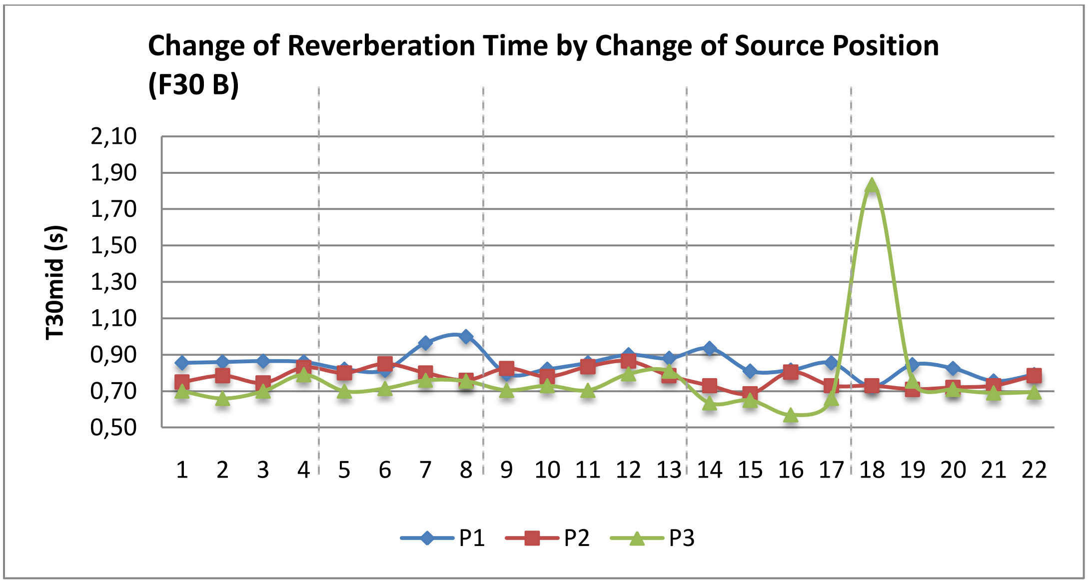


Figure 4.57 T30 values of receiver points in F 30 B

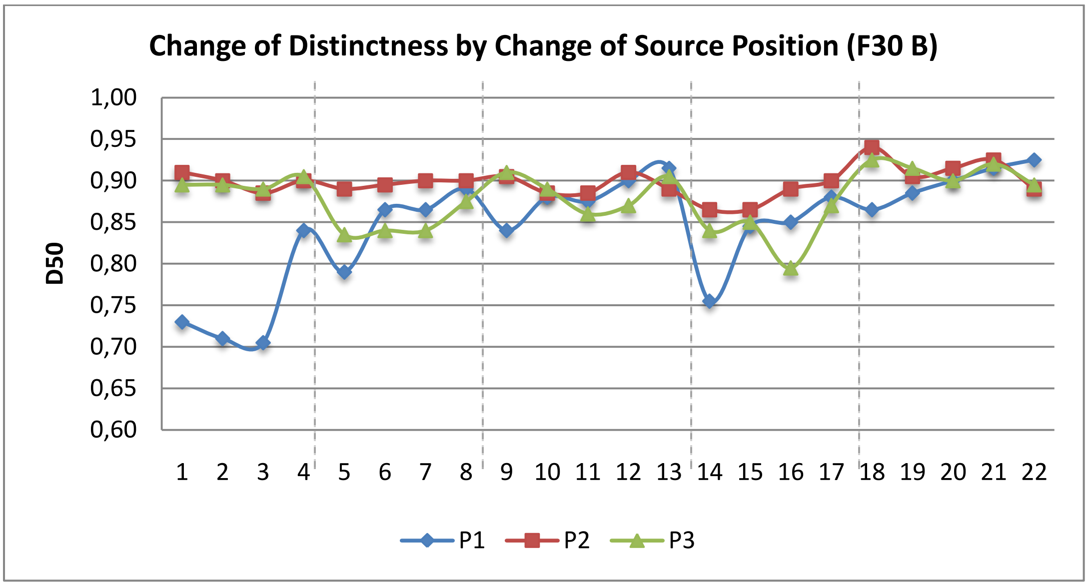


Figure 4.58 D50 values of receiver points in F 30 B

In the graphs, the relation between EDT and D50 values are is quite distinct in this room. D50 values increase by decrease of EDT (Figure 4.58).

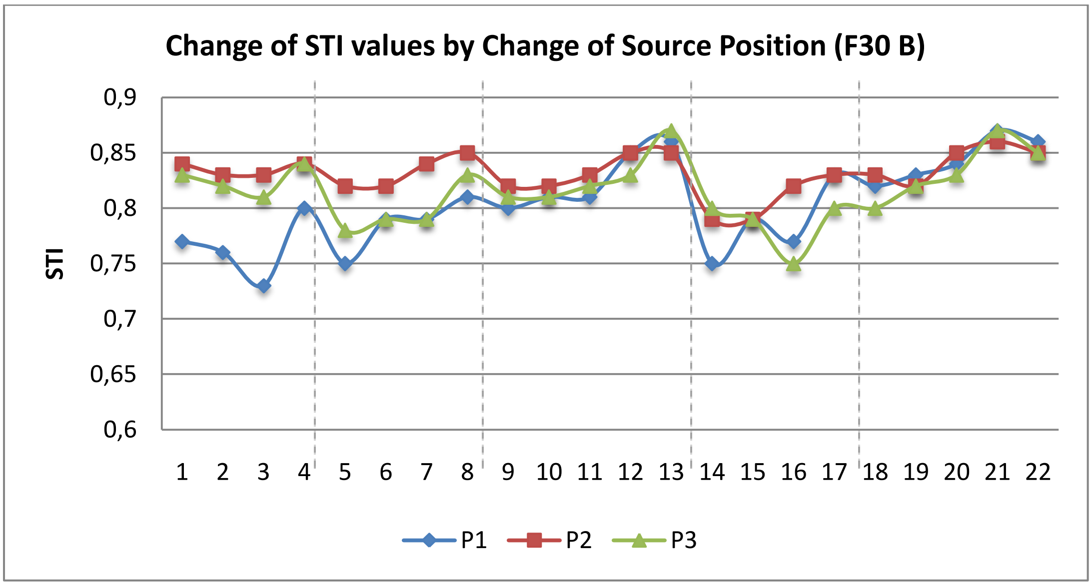


Figure 4.59 STI values of receiver points in F 30 B

In the graph above (Figure 4.59) it is seen that all the receiver points have excellent STI values.

In 5th row SPL values of the seats are around 50 dB while the value decreases about 5 dB in the last row, under balcony (Figure 4.60).

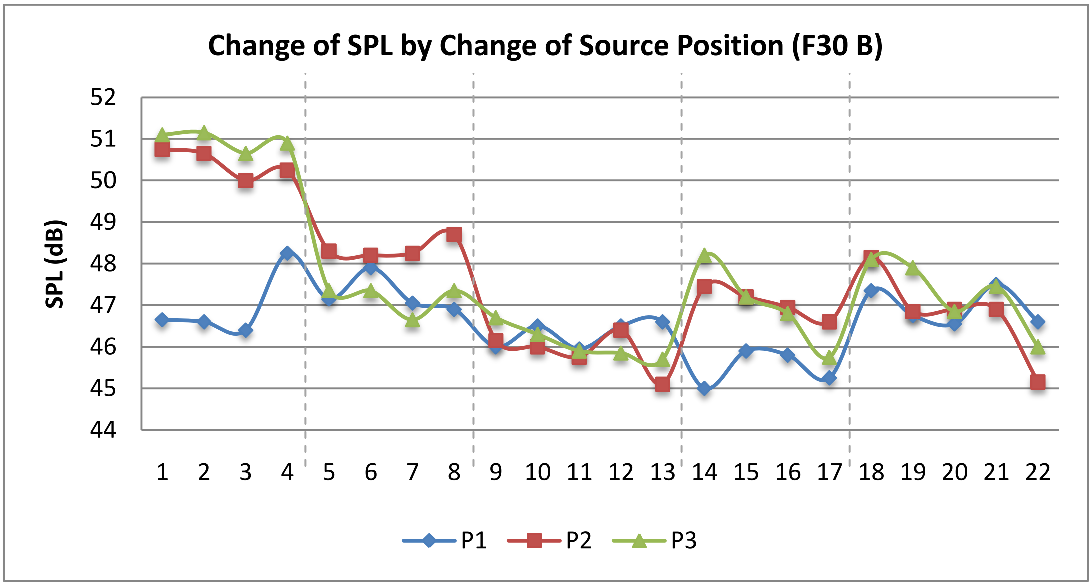


Figure 4.60 SPL values of receiver points in F 30 B

Table 4.37 Descriptive statistics of receiver points in F 30 B. (Numbers next to the Parameters indicate the source position)

Parameters	Number of seats	Mean Value	Standard Deviation	Coefficient of Variation	Minimum Value	Maximum Value	Range
EDT 1	22	0,53	0,26	49,03	0,26	1,06	0,80
T30 1	22	0,85	0,06	7,48	0,73	1,00	0,28
SPL 1	22	46,60	0,78	1,67	45,00	48,25	3,25
D50 1	22	0,85	0,07	7,84	0,71	0,93	0,22
STI 1	22	0,80	0,04	4,85	0,73	0,87	0,14
EDT 2	22	0,31	0,04	12,49	0,24	0,41	0,17
T30 2	22	0,77	0,05	6,33	0,69	0,87	0,18
SPL 2	22	47,58	1,69	3,54	45,10	50,75	5,65
D50 2	22	0,90	0,02	1,90	0,87	0,94	0,08
STI 2	22	0,83	0,02	2,19	0,79	0,86	0,07
EDT 3	22	0,36	0,10	28,88	0,27	0,71	0,44
T30 3	22	0,76	0,25	32,42	0,57	1,84	1,27
SPL 3	22	47,60	1,78	3,73	45,70	51,15	5,45
D50 3	22	0,88	0,03	3,83	0,80	0,93	0,13
STI 3	22	0,82	0,03	3,48	0,75	0,87	0,12

4.2.3.3.7 Rectangular Room (REC).

In the room, for 12 defined receiver points EDT values are quite close when P2 or P3 is activated. But similar to fan shaped rooms, when P1 is opened, EDT values are quite changing at different receiver points (Figure 4.61).

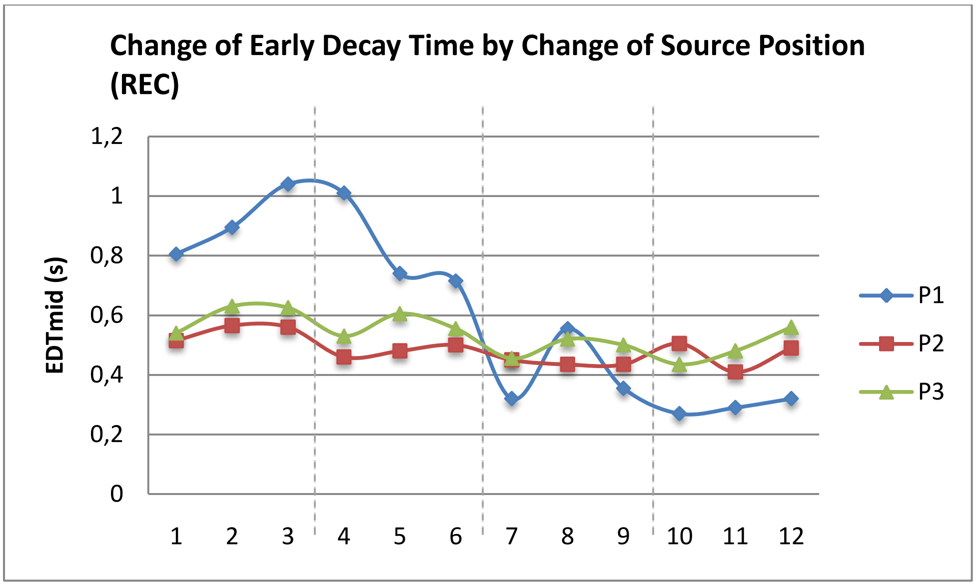


Figure 4.61 EDT values of receiver points in rectangular room

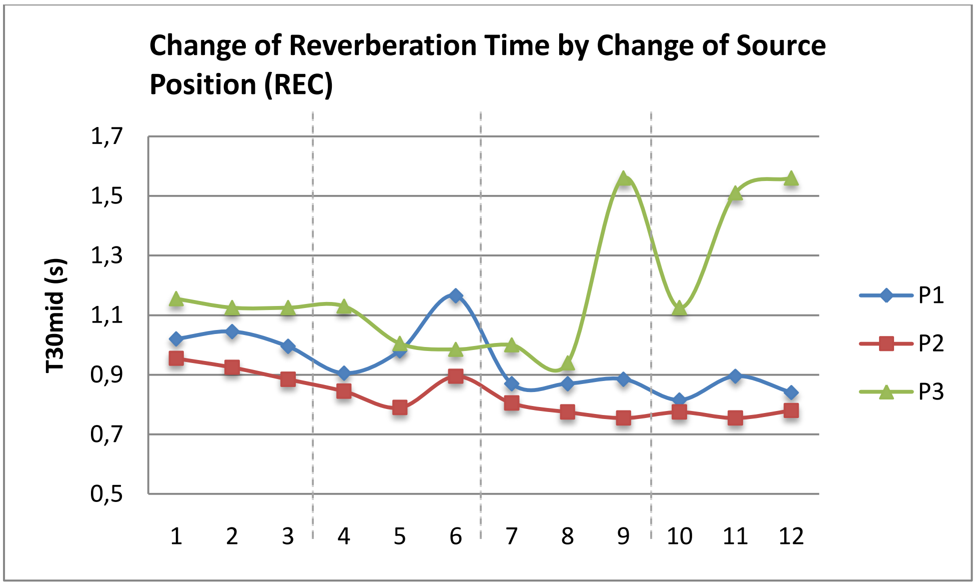


Figure 4.62 T30 values of receiver points in rectangular room

In figure 4.62, T30 results of the rectangular room are quite different from the fan-shaped auditoria. Peaks occur at 9, 11 and 12th receiver points when the sound source 3 is opened. For source position 2, values range between 0,76 – 0,96 seconds.

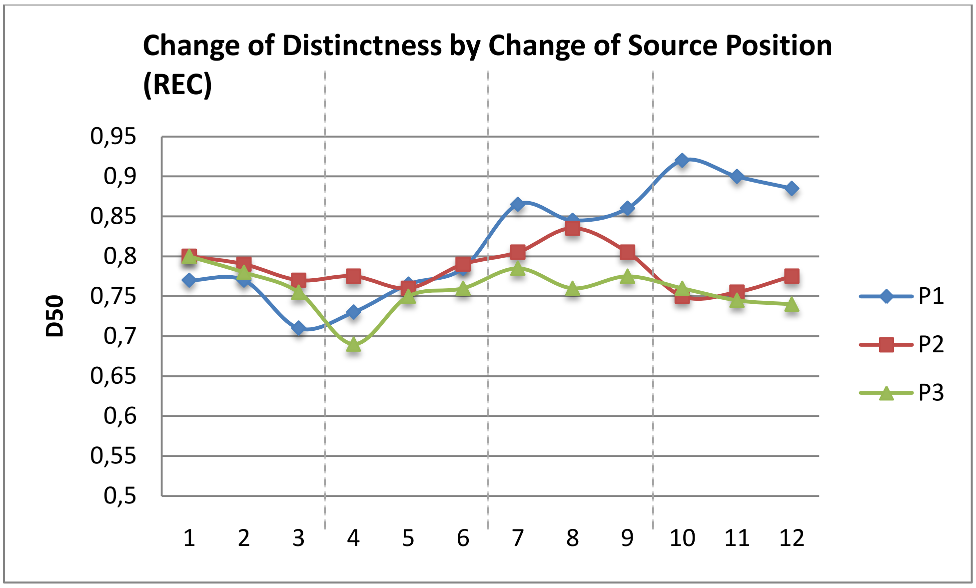


Figure 4.63 D50 values of receiver points in rectangular room

In Figure 4.63 and 4.64, it is seen that D50 and STI values of receiver points are quite good for all source positions.

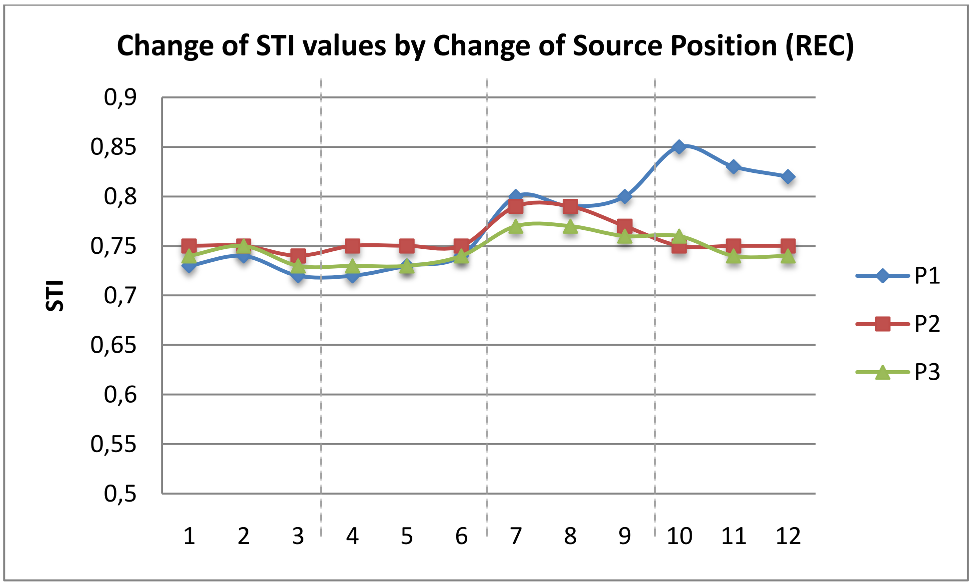


Figure 4.64 STI values of receiver points in rectangular room

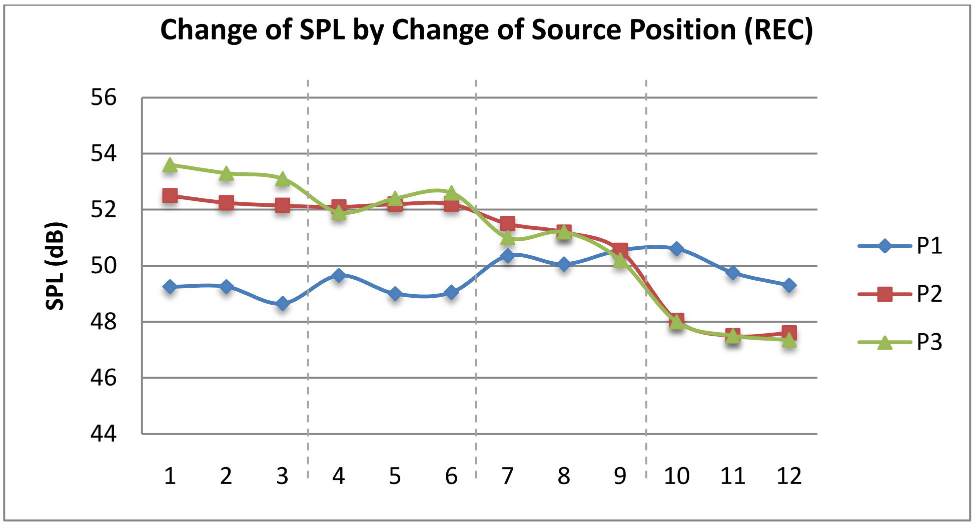


Figure 4.65 SPL values of receiver points in rectangular room

For source positions P2 and P3, SPL levels of the 10th, 11th and 12th receiver points are lower than other seats since they are placed at the back of auditorium (Figure 4.65), although for source position 1, the situation is quite different.

Table 4.38 Descriptive statistics of receiver points in rectangular room. (Numbers next to the Parameters indicate the source position)

Parameters	Number of seats	Mean Value	Standard Deviation	Coefficient of Variation	Minimum Value	Maximum Value	Range
EDT 1	12	0,61	0,29	48,12	0,27	1,04	0,77
T30 1	12	0,94	0,10	10,84	0,82	1,17	0,35
SPL 1	12	49,62	0,65	1,30	48,65	50,60	1,95
D50 1	12	0,82	0,07	8,59	0,71	0,92	0,21
STI 1	12	0,77	0,05	6,12	0,72	0,85	0,13
EDT 2	12	0,48	0,05	10,06	0,41	0,57	0,16
T30 2	12	0,83	0,07	8,47	0,76	0,96	0,20
SPL 2	12	50,82	1,95	3,84	47,50	52,50	5,00
D50 2	12	0,78	0,02	3,16	0,75	0,84	0,09
STI 2	12	0,76	0,02	2,19	0,74	0,79	0,05
EDT 3	12	0,54	0,06	11,79	0,44	0,63	0,20
T30 3	12	1,19	0,23	19,18	0,94	1,56	0,62
SPL 3	12	51,01	2,28	4,46	47,35	53,60	6,25
D50 3	12	0,76	0,03	3,66	0,69	0,80	0,11
STI 3	12	0,75	0,01	2,01	0,73	0,77	0,04

4.2.3.3.8 Rectangular Room with Balcony (REC).

In the room, for 15 defined receiver points EDT values are quite changing by the receiver points. Especially when P1 is activated, differences between values are quite distinct (Figure 4.66).

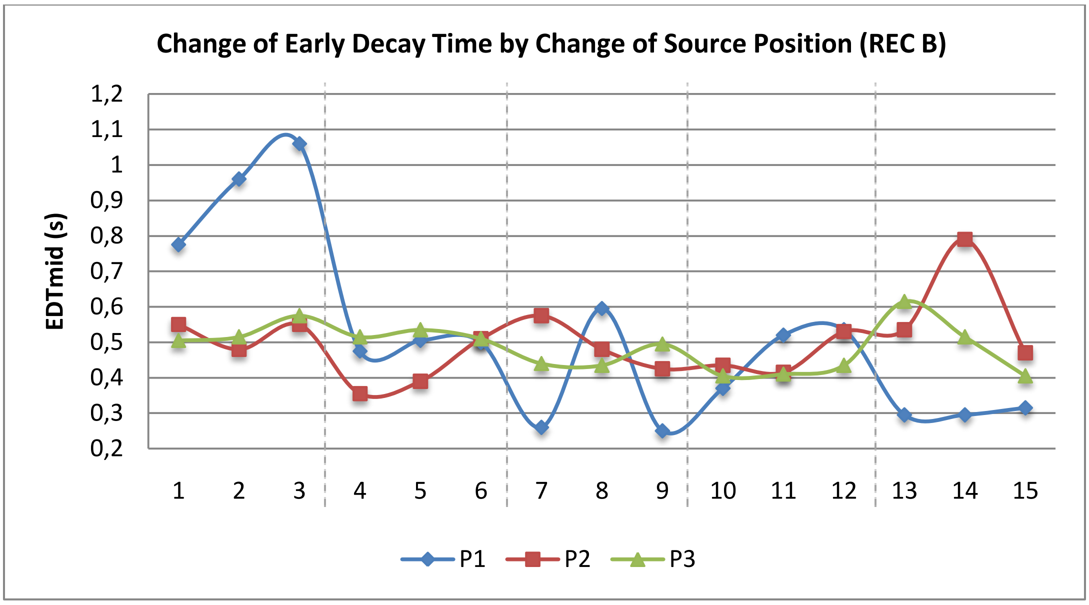


Figure 4.66 EDT values of receiver points in rectangular room with balcony

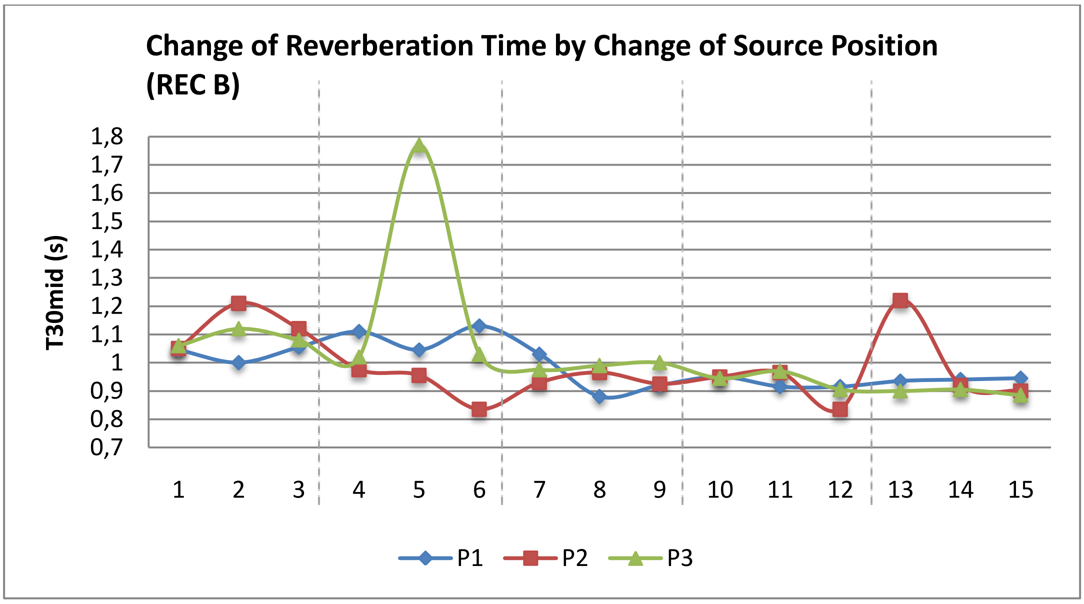


Figure 4.67 T30 values of receiver points in rectangular room with balcony

In the room, there is a peak at the T30 value of 5th receiver when P3 active. For the source position 2, value of the 13th receiver is relatively high but not exceeds the limit (Figure 4.67).

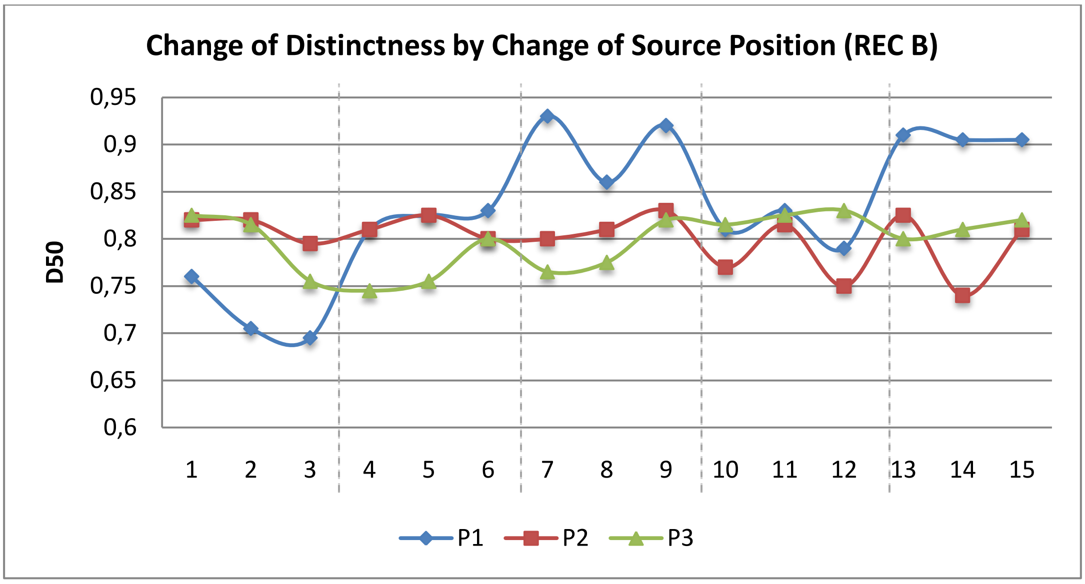


Figure 4.68 D50 values of receiver points in rectangular room with balcony

D50 values of the 7,9, 13,14 and 15th receiver points are maximum (higher than 0,90) while EDT values of them are minimum (about 0,3 s) when source 1 is activated (Figure 4.68). For all source positions, STI values are exceeds 0,7 (Figure 4.69).

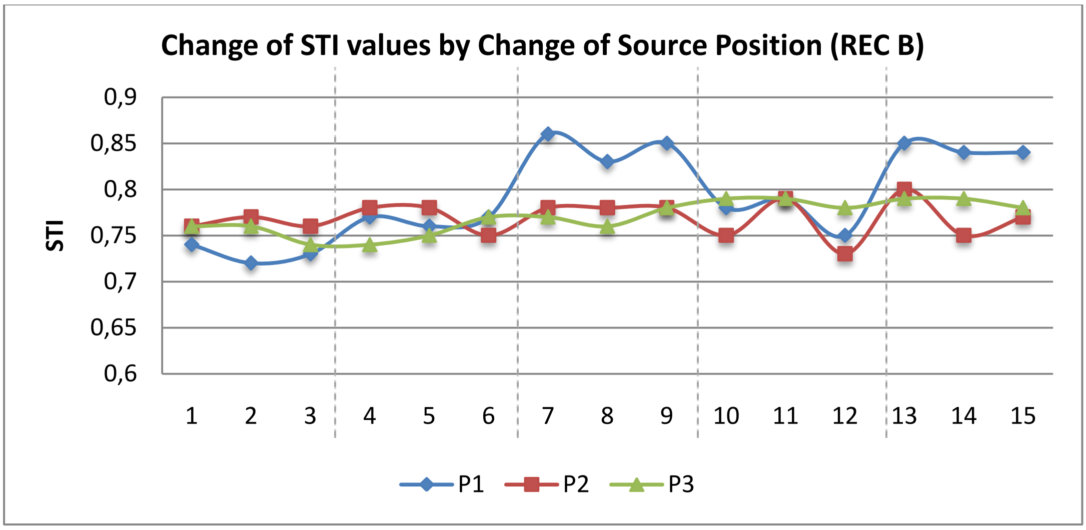


Figure 4.69 STI values of receiver points in rectangular room with balcony

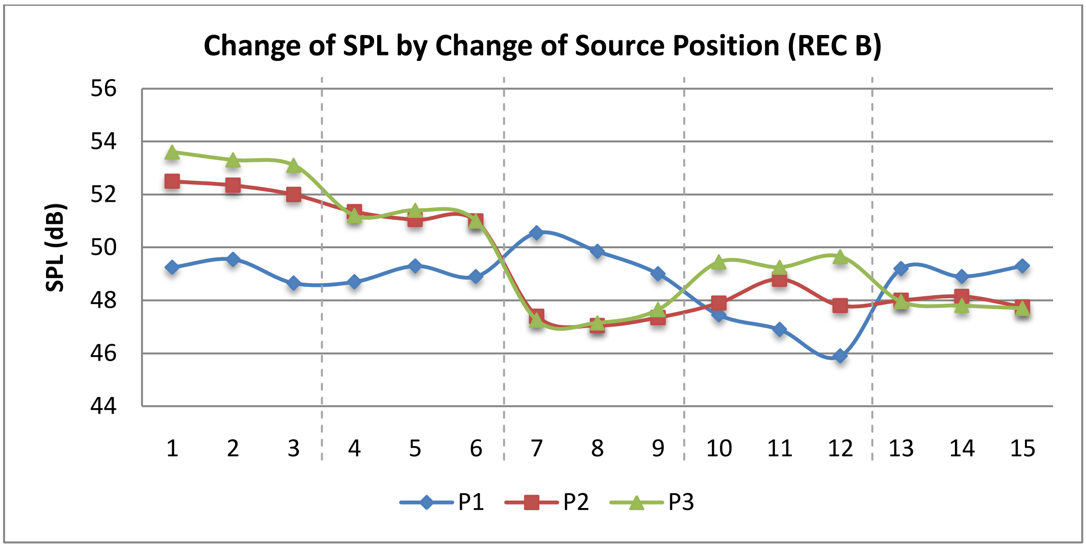


Figure 4.70 SPL values of receiver points in rectangular room with balcony

When the graph above is examined (Figure 4.70) it is seen that SPL values of the receiver points at the back of the auditorium (under balcony) are quite similar with the receivers in the balcony level for source positions P2 and P3.

Table 4.39 Descriptive statistics of receiver points in rectangular room with balcony. (Numbers next to the Parameters indicate the source position)

Parameters	Number of seats	Mean Value	Standard Deviation	Coefficient of Variation	Minimum Value	Maximum Value	Range
EDT 1	15	0,51	0,25	48,34	0,25	1,06	0,81
T30 1	15	0,99	0,08	7,81	0,88	1,13	0,25
SPL 1	15	48,76	1,18	2,42	45,90	50,55	4,65
D50 1	15	0,83	0,07	8,95	0,70	0,93	0,24
STI 1	15	0,79	0,05	6,13	0,72	0,86	0,14
EDT 2	15	0,50	0,10	20,65	0,36	0,79	0,44
T30 2	15	0,98	0,12	11,98	0,84	1,22	0,39
SPL 2	15	49,36	2,06	4,17	47,05	52,50	5,45
D50 2	15	0,80	0,03	3,41	0,74	0,83	0,09
STI 2	15	0,77	0,02	2,40	0,73	0,80	0,07
EDT 3	15	0,49	0,06	13,06	0,41	0,62	0,21
T30 3	15	1,04	0,21	20,68	0,89	1,77	0,89
SPL 3	15	49,83	2,30	4,61	47,15	53,60	6,45
D50 3	15	0,80	0,03	3,72	0,75	0,83	0,09
STI 3	15	0,77	0,02	2,30	0,74	0,79	0,05

4.2.3.3.9 Comparison of the Variations of Rooms

After examination of receiver points within each room, calculated coefficient of variation values of the rooms are compared in table 4.40. According to the results in the table, for all the rooms, parameters differ from seat to seat especially when the sound source 1 is active. And most variation is seen among EDT values. When sound source 2 is activated, it is seen that results of the seats within the cases is quite close. Fan shaped auditorium with 15^0 splaying angle and balcony, is the least effected room by the parameter variations for both P1 and P2. When source is located on P2, the maximum variations of EDT, T30 and D50 are observed in F 15.

Table 4.40 Coefficient of variations of parameters depending on receiver points

Parameters	**Room types**							
	F 15	**F 15 B**	**F 22**	**F 22 B**	**F 30**	**F 30 B**	**Rec**	**Rec B**
EDT 1	50,60	43,97	54,97	50,73	56,92	49,03	48,12	48,34
T30 1	6,45	9,58	3,70	4,96	2,92	7,48	10,84	7,81
SPL 1	1,61	9,01	0,81	1,62	1,07	1,67	1,30	2,42
D50 1	13,92	6,11	14,65	9,36	11,92	7,84	8,59	8,95
STI 1	8,99	1,15	7,94	7,02	7,43	4,85	6,12	6,13
EDT 2	27,59	6,39	26,83	16,99	19,98	12,49	10,06	20,65
T30 2	13,53	5,79	11,19	16,98	5,75	6,33	8,47	11,98
SPL 2	2,80	3,82	3,27	3,52	3,59	3,54	3,84	4,17
D50 2	3,82	1,70	2,62	2,61	2,33	1,90	3,16	3,41
STI 2	2,30	1,77	2,51	2,35	1,78	2,19	2,19	2,40
EDT 3	26,03	12,78	18,43	16,39	13,10	28,88	11,79	13,06
T30 3	3,26	6,40	3,82	5,64	6,55	32,42	19,18	20,68
SPL 3	3,45	3,71	3,61	3,43	3,80	3,73	4,46	4,61
D50 3	4,13	3,02	1,72	2,72	2,11	3,83	3,66	3,72
STI 3	2,33	1,78	1,79	2,59	1,94	3,48	2,01	2,30

By considering all the parameters and all the room types, minimum variation is observed when the source 2 is opened. For that reason, for the evaluation process the results obtained for P2 will be used.

4.3 Examination of the Relations between Acoustical and Visual Conditions

4.3.1 Correlations between Mean Scores

Although the use of mean scores of parameters is criticized sometimes, it is a useful way for getting overall information. Results that are obtained from eight different types of designed case are summarized in table 4.41. In the columns of table, calculated mean sightline scores of rooms, mean width and depth of room and mean values of acoustical parameters are listed. By considering the results in the table, it is seen that the rectangular shaped rooms drop behind a little because of the mean sightline scores, in addition to relatively low D50 and STI values.

Table 4.41 Mean scores of rooms

room type	mean score	mean width	depth	$T\ 30_{mid}$	EDT_{mid}	$D50_{mid}$	STI	SPL
f15	80,39	18,4	20,9	0,92	0,43	0,85	0,79	50
f22	83,08	20	19	0,92	0,38	0,88	0,81	49,8
f30	85,02	21,5	18	0,85	0,37	0,88	0,81	49,3
rec	76,75	14,2	22,7	0,83	0,49	0,79	0,76	50,8
f15 b	80,08	17,7	18	0,86	0,31	0,9	0,82	48,7
f22 b	81,51	19,2	17,1	0,87	0,33	0,89	0,82	48,2
f30 b	83,55	20,5	16,2	0,78	0,31	0,9	0,83	47,6
rec b	75,54	14,2	20,8	0,99	0,5	0,8	0,77	49,4

The results obtained before are used to find out if there is a relation between sightline scores and acoustical parameters as well as the geometrical properties of rooms. Mean room width is chosen as a parameter since it depends on the splaying angle of the designed rooms. And depth of the room is related to the distance between source and receiver. Calculated mean sightline scores of rooms are also included in the correlation analysis with the mean values of parameters. In Table 4.42 correlations between parameters by considering all the designed cases are shown. In the table, parameters that show a correlation of above 0.6 of absolute value are deemed as related parameters, since greater value means stronger linear correlation.

In Table 4.42, determined correlations between parameters are examined in three groups. First one is the correlations between sightline scores and geometrical parameters (highlighted with green filling). Second one is correlations between acoustical parameters (highlighted with red filling). And the third one is correlations between acoustical parameters and mean scores and geometrical parameters (highlighted with gray filling).

Table 4.42 Correlations with r value (Pearson's coefficient) between mean values of parameters. (Values higher than 0,6 are highlighted with filling)

	Mean score	**mean width**	**depth**	**T 30 $_{mid}$**	**EDT $_{mid}$**	**D50 ^{mid}**	**STI**
mean width	0,99						
depth	-0,74	-0,78					
T 30 $_{mid}$	-0,49	-0,41	0,45				
EDT $_{mid}$	**-0,74**	**-0,76**	**0,92**	0,57			
D50 $_{mid}$	**0,83**	**0,86**	**-0,91**	-0,41	-0,96		
STI	**0,81**	**0,84**	**-0,96**	-0,46	-0,97	0,99	
SPL	-0,45	-0,50	**0,92**	0,37	0,79	-0,74	-0,82

According to correlation values in Table 4.42, it is not surprising to see negative correlation between mean width and depth of the rooms, since volumes of the rooms are tried to be kept same. But it is obvious that by increase of the room width, the mean sightline score of the room increases too. In other words, for fan shaped rooms, by increase of the splaying angle, sightline scores are increasing.

In the table, it is seen again, the high correlation value between the EDT and D50 as well as the correlation between EDT and STI. Similar negative correlation has been also emphasized at the acoustical evaluation of rooms. In addition, the correlations between D50 and SPL, D50 and STI and SPL and STI are quite high.

According to the correlation result between acoustical parameters and mean scores of rooms, the more the room score, the less the EDT value. But by increase of the mean score of the room, mean EDT and D50 values are increasing. Situation is same for the correlation between room width and acoustical parameters, except T30 and SPL. And it is interesting that by the increase of the depth of the room SPL value increase too.

4.3.2. Evaluation of Rooms

It is mentioned before that the mean scores cannot be reliable enough if the parameters vary greatly in a room. Determining many measures in each hall, at different positions, will guarantee that we will obtain the relevant acoustical information by means of statistical analysis. For that reason, each room is evaluated individually according to sightline scores and acoustic results. Calculated sightline scores and values of acoustical parameters are examined if there is a relation between them. Linear correlations between parameters are calculated. Parameters that show a correlation of above 0.6 are deemed as related parameters.

Correlations between parameters are shown in tables 4.43 – 4.50 for each room. In the columns of tables, distance between source and receiver (distance to P2), orthogonal distance between receiver point and side wall (distance to the side wall), calculated horizontal viewing angle of receiver point to see P2 (angle), and calculated total sightline score of seats are examined with the values of acoustical parameters to see if there are correlations between them. Because of the used calculated method of sightline scores, there are some correlations between parameters related to room geometry (distance to the side wall – horizontal viewing angle, total score – angle, total score – distance), but they are not taken into consideration here. Evaluation of the rooms is made after the tables.

Table 4.43 Overall correlations between acoustical parameters in the F 15 (correlations with r value (Pearson's coefficient) higher in module than 0.6 are expressed with gray filling)

F15									
	distance to P2	*distance to the side wall*	*angle*	*total score*	*EDT mid*	*T30 mid*	*D50 mid*	*STI*	*SPL(A)*
distance to P2	1,00								
Dist. Side wall	0,05	1,00							
angle	-0,25	-0,90	1,00						
total score	-0,53	0,71	-0,63	1,00					
EDT_{mid}	-0,78	-0,16	0,40	0,17	1,00				
$T30_{mid}$	-0,16	-0,33	0,36	-0,25	0,32	1,00			
$D50_{mid}$	0,51	-0,29	0,11	-0,47	-0,57	-0,11	1,00		
STI	0,72	0,01	-0,06	-0,49	-0,71	-0,03	0,77	1,00	
SPL(A)	-0,90	-0,05	0,22	0,47	0,52	0,25	-0,30	-0,49	1,00

Table 4.44 Overall correlations between acoustical parameters in the F 15 B (correlations with r value (Pearson's coefficient) higher in module than 0.6 are expressed with gray filling)

F15 B									
	distance to P2	*distance to the side wall*	*angle*	*total score*	*EDT mid*	*T30 mid*	*D50 mid*	*STI*	*SPL(A)*
distance to P2	1,00								
Dist. side wall	-0,02	1,00							
angle	-0,17	-0,93	1,00						
total score	-0,53	0,77	-0,68	1,00					
EDT mid	-0,32	0,09	-0,01	0,23	1,00				
T30 mid	-0,18	-0,65	0,73	-0,52	0,22	1,00			
D50 mid	0,35	-0,20	0,06	-0,34	-0,60	-0,20	1,00		
STI	-0,04	0,08	0,00	-0,08	-0,44	-0,24	0,73	1,00	
SPL(A)	-0,86	0,05	0,15	0,45	0,33	0,18	-0,25	0,16	1,00

Table 4.45 Overall correlations between acoustical parameters in the F 22 (correlations with r value (Pearson's coefficient) higher in module than 0.6 are expressed with gray filling)

F22									
	distance to P2	*distance to the side wall*	*angle*	*total score*	*EDT mid*	*T30 mid*	*D50 mid*	*STI*	*SPL(A)*
distance to P2	1,00								
Dist. side wall	0,02	1,00							
angle	-0,16	-0,92	1,00						
total score	-0,58	0,70	-0,64	1,00					
EDT mid	-0,76	-0,12	0,34	0,25	1,00				
T30 mid	-0,16	0,62	-0,49	0,42	0,40	1,00			
D50 mid	0,75	0,01	-0,27	-0,35	-0,96	-0,38	1,00		
STI	0,58	-0,38	0,12	-0,53	-0,82	-0,58	0,89	1,00	
SPL(A)	-0,88	-0,02	0,08	0,53	0,40	-0,04	0,40	-0,20	1,00

Table 4.46 Overall correlations between acoustical parameters in the F 22 B (correlations with r value (Pearson's coefficient) higher in module than 0.6 are expressed with gray filling)

F22 B									
	distance to P2	*distance to the side wall*	*angle*	*total score*	*EDT mid*	*T30 mid*	*D50 mid*	*STI*	*SPL(A)*
distance to P2	1,00								
Dist. side wall	-0,10	1,00							
angle	-0,04	-0,95	1,00						
total score	-0,62	0,76	-0,69	1,00					
EDT mid	-0,45	0,08	0,02	0,34	1,00				
T30 mid	-0,26	0,22	-0,20	0,37	0,34	1,00			
D50 mid	0,40	-0,03	-0,03	-0,24	-0,83	-0,23	1,00		
STI	0,26	-0,44	0,37	-0,44	-0,78	-0,09	0,81	1,00	
SPL(A)	-0,87	0,10	0,05	0,52	0,19	0,07	0,07	-0,04	1,00

Table 4.47 Overall correlations between acoustical parameters in the F 30 (correlations with r value (Pearson's coefficient) higher in module than 0.6 are expressed with gray filling)

F30									
	distance to P2	*distance to the side wall*	*angle*	*total score*	*EDT mid*	*T30 mid*	*D50 mid*	*STI*	*SPL(A)*
distance to P2	1,00								
Dist. side wall	0,05	1,00							
angle	-0,17	-0,92	1,00						
total score	-0,59	0,65	-0,59	1,00					
EDT mid	-0,92	0,00	0,06	0,59	1,00				
T30 mid	-0,52	-0,44	0,42	0,16	0,46	1,00			
D50 mid	0,95	-0,06	-0,01	-0,70	-0,96	-0,48	1,00		
STI	0,95	-0,08	-0,03	-0,68	-0,83	-0,42	0,92	1,00	
SPL(A)	0,32	-0,03	0,10	-0,47	-0,43	-0,31	0,53	0,37	1,00

(* In the table, for F 30, there are some correlations between acoustical parameters and total score of seats, they are expressed with red filling)

Table 4.48 Overall correlations between acoustical parameters in the F 30 B (correlations with r value (Pearson's coefficient) higher in module than 0.6 are expressed with gray filling)

F30 B									
	distance to P2	*distance to the side wall*	*angle*	*total score*	*EDT mid*	*T30 mid*	*D50 mid*	*STI*	*SPL(A)*
distance to P2	1,00								
Dist. side wall	-0,06	1,00							
angle	-0,05	-0,95	1,00						
total score	-0,61	0,73	-0,66	1,00					
EDT mid	-0,21	0,11	-0,11	0,23	1,00				
T30 mid	-0,15	-0,13	0,15	0,02	-0,05	1,00			
D50 mid	0,24	0,05	-0,05	-0,13	-0,96	-0,01	1,00		
STI	0,25	-0,60	0,51	-0,50	-0,71	0,22	0,63	1,00	
SPL(A)	-0,88	0,02	0,11	0,47	-0,14	-0,02	0,14	0,00	1,00

Table 4.49 Overall correlations between acoustical parameters in the rectangular room (correlations with r value (Pearson's coefficient) higher in module than 0.6 are expressed with gray filling)

RECTANGLE									
	distance to P2	*distance to the side wall*	*angle*	*total score*	*EDT mid*	*T30 mid*	*D50 mid*	*STI*	*SPL(A)*
distance to P2	1,00								
Dist. side wall	-0,09	1,00							
angle	-0,34	-0,85	1,00						
total score	-0,50	0,83	-0,61	1,00					
EDT mid	-0,66	-0,13	0,51	0,11	1,00				
T30 mid	-0,88	0,09	0,29	0,43	0,74	1,00			
D50 mid	-0,16	-0,04	-0,01	0,11	-0,19	0,14	1,00		
STI	0,32	0,20	-0,36	0,05	-0,57	-0,40	0,76	1,00	
SPL(A)	-0,87	0,10	0,25	0,43	0,38	0,67	0,43	0,07	1,00

Table 4.50 Overall correlations between acoustical parameters in the rectangular room with balcony (correlations with r value (Pearson's coefficient) higher in module than 0.6 are expressed with gray filling)

RECTANGLE	**B**								
	distance to P2	*distance to the side wall*	*angle*	*total score*	*EDT mid*	*T30 mid*	*D50 mid*	*STI*	*SPL(A)*
distance to P2	1,00								
Dist. side wall	-0,09	1,00							
angle	-0,33	-0,86	1,00						
total score	-0,53	0,82	-0,59	1,00					
EDT mid	0,17	-0,02	0,05	-0,17	1,00				
T30 mid	-0,44	0,37	0,00	0,44	0,01	1,00			
D50 mid	-0,28	0,12	-0,06	0,31	-0,61	0,43	1,00		
STI	0,15	0,38	-0,37	0,26	-0,39	0,46	0,77	1,00	
SPL(A)	-0,94	0,05	0,34	0,48	-0,13	0,41	0,28	-0,10	1,00

When the results that are seen in the tables (Table 4.43 – 4.50) are examined, in general, it is difficult to say that there is a distinct correlation between sightline scores of seats and acoustical parameters. For all the rooms, a well known rule is confirmed once more; the decrease of SPL by the distance, except fan shaped room with 30^0 splaying angle. The room is the only one that there is a correlation between sightline score and D50 value of the receiver points. The correlation is negative one, so it means that the seats with the lower sightline scores get the better D50 values within F 30. Similar correlation also exists between total score and STI.

T30 is the only acoustical parameter that is affected by the change of the distance to the side wall for fan shape 15 with balcony and fan shape 22. And there is not such a correlation in other rooms.

For fan shaped rooms without balcony, it is seen that STI value increases by the increase of the distance between source and receiver. For fan shaped rooms 22 and 30, D50 values also increase by the distance. That is probably because of the decrease of EDT values by the distance, since there is a negative correlation between EDT and D50.

When the overall scores of each room are examined, the correlation between EDT and D50, which is also derived from the mean values of rooms, is confirmed. Except the rectangular shaped room, D50 and STI values are increasing while EDT is decreasing in all of the rooms. For rectangular room, there is a positive correlation between T30 and EDT, and this is the only room such a correlation exists. Also, the room differs from the other cases with the correlation between T30 and SPL(A) parameters.

The relations that are described in previous chapters are also shown on the plans of the rooms so that to see the each receiver’s conditions. Each room is evaluated individually. In the plans, score, T30, D50 and STI values of the each receiver point is marked with a coloured point which simulates the relative magnitude of the parameter. To mark the values of parameters at the receiver points, percentile (value that demonstrates a rank based on one hundred percent) of the values are used since by this way, it is possible to evaluate each receiver point relative to others. Red colour simulates the maximum values (> 75%) of a parameter within the room while black simulates the minimum values (< 25%). Gray (> 25%) and light red colours (> 50%) simulate the values between maximum and minimum values (Figure 4.71).

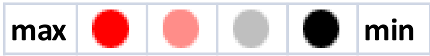


Figure 4.71 Used marks and colours for evaluation of receiver points

As mentioned above, there are four parameters compared for each seat to see the change of the acoustical and visual conditions from seat to seat. In the following figures, the receiver points are evaluated with the method that is described above on the plan of each case. First point in the box simulates total score of the seat (SC). Second one simulates the value of T30. Third point simulates D50 value of the seat and the last one simulates STI value (Figure 4.72). D50 and STI values are chosen to make comparison between sightline score and speech intelligibility. And T30 value is included to see where the reverberation time decrease or increase. For STI, D50 and SC the higher values mean better conditions for seats. Most of the time this situation is true also for T30 since almost all receiver points in the rooms have appropriate values of T30. Also, it may be useful to mention again that in all rooms, all of the receiver points have acceptable values of STI and D50. For that reason, comparison of receiver points on the plans shows relative relations between receiver points, more than defining if they are appropriate or not from the acoustical point of view. From the point of view sightline scores, it can be said that receiver points that are remarked with black colour indicates that they have the values below 55, in other words, at that point a spectator can see less than 50 percent of the stage area without head movement.

Figure 4.72 An example of used parameters and marks for evaluation

In the Figures 4.73-4.80 plans of the cases are shown.

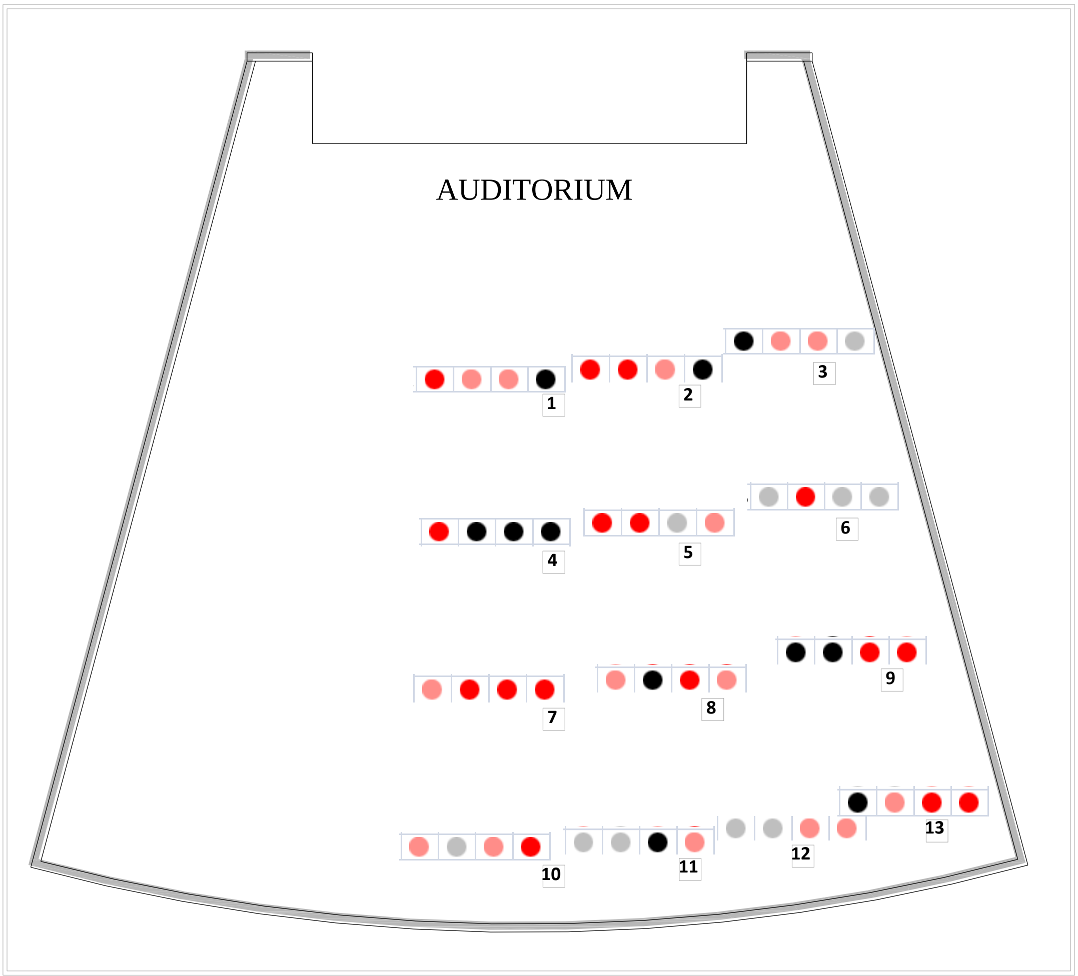


Figure 4.73 Evaluation of receiver points in F 15

By considering the Figure 4.73, it is possible to say that best seat in the F15 is number 7. Although sightline score is not at maximum at that point, acoustical parameters have the maximum values•.

Just opposite to the situation in F15, seat one has high STI value and can be evaluated as one of the best seats in the floor level. In the balcony level, it is seen that seats in the back row have better values (Figure 4.74).

• The calculated values of the parameters in each room is given in previous parts of the study, to avoid repetition they are not shown here.

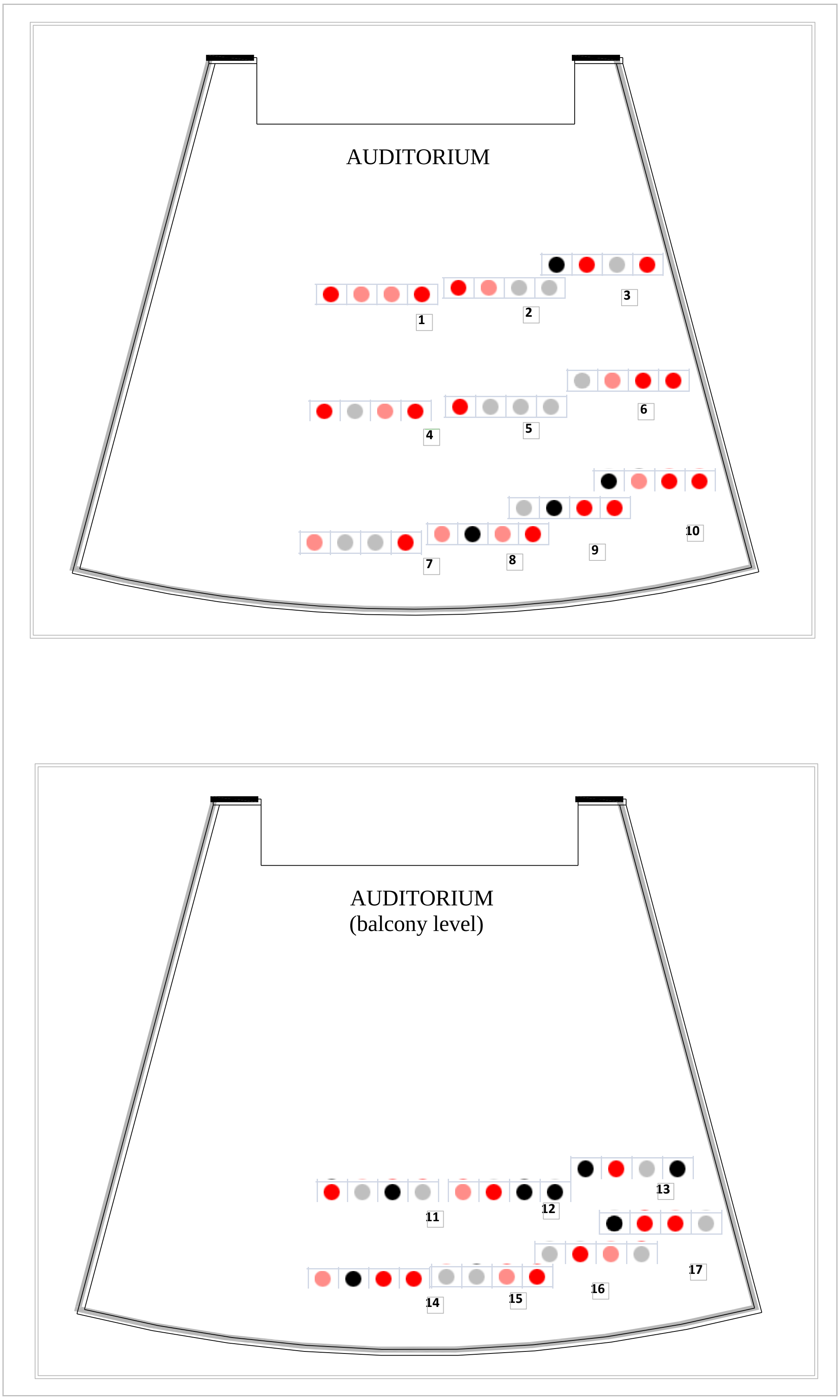


Figure 4.74 Evaluation of receiver points in F 15 B

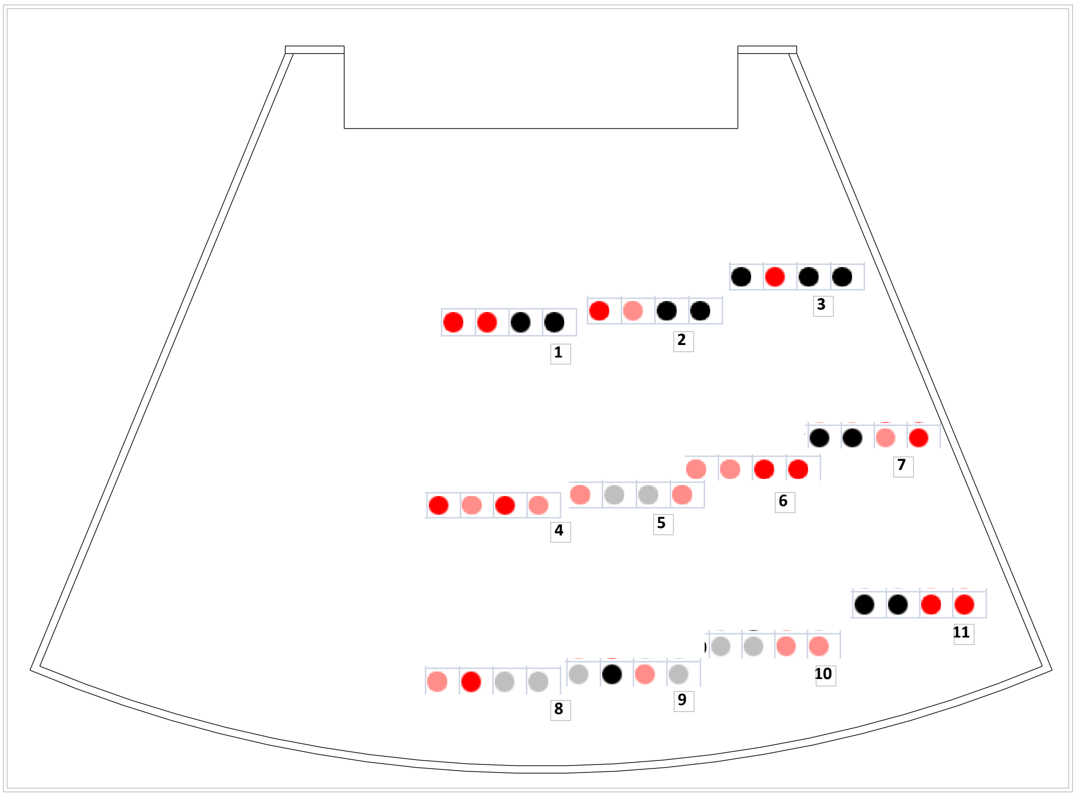
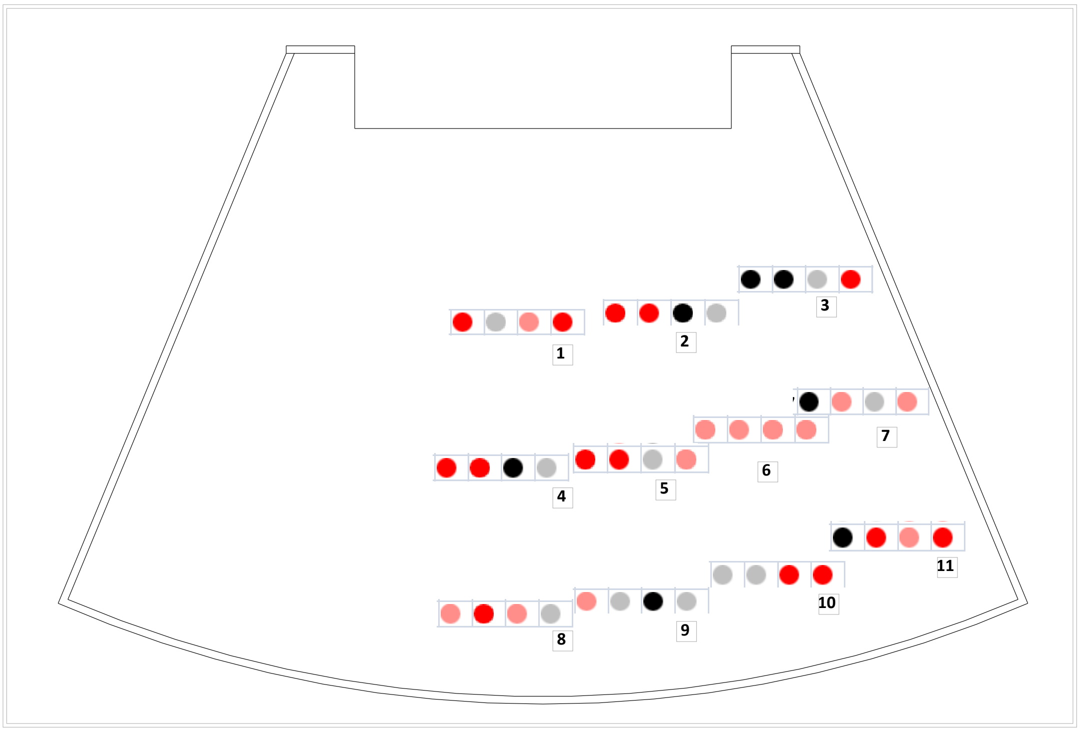


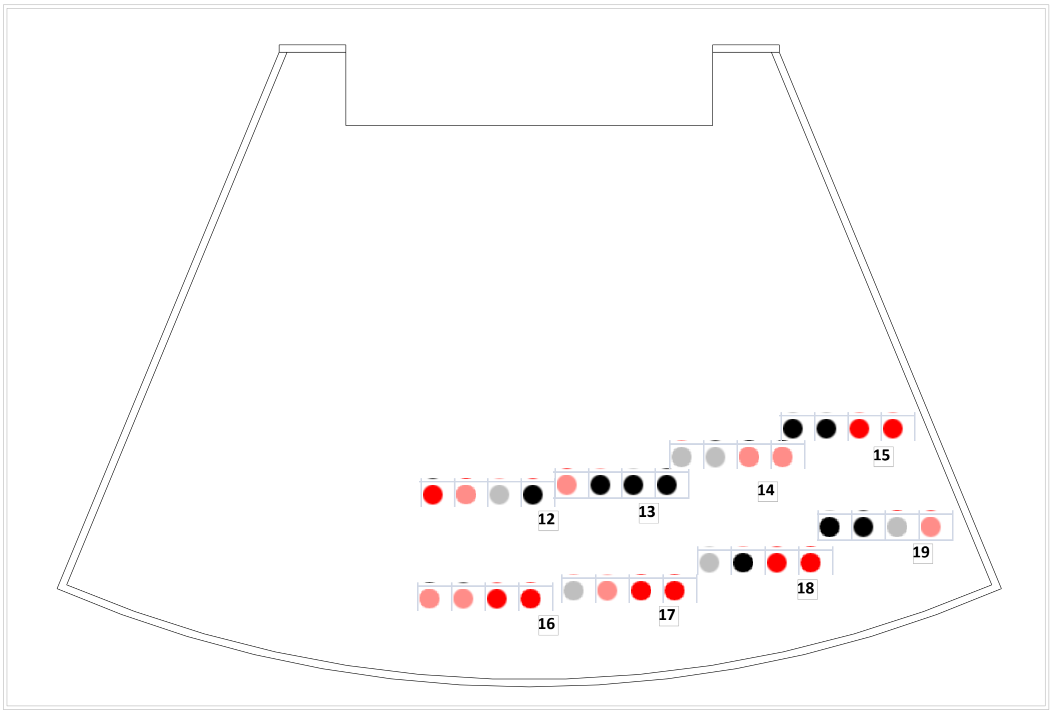
Figure 4.75 Evaluation of receiver points in F 22

In F22, receivers four and six have better values, relative to the other points (Figure 4.75).

In F22 B, receiver six is such a “medium” seat since all the values at that point are close to the average. Similar to the F15 B, seats in the back row of the balcony have better values (Figure 4.76).



Floor level



Balcony level

Figure 4.76 Evaluation of receiver points in F 22 B

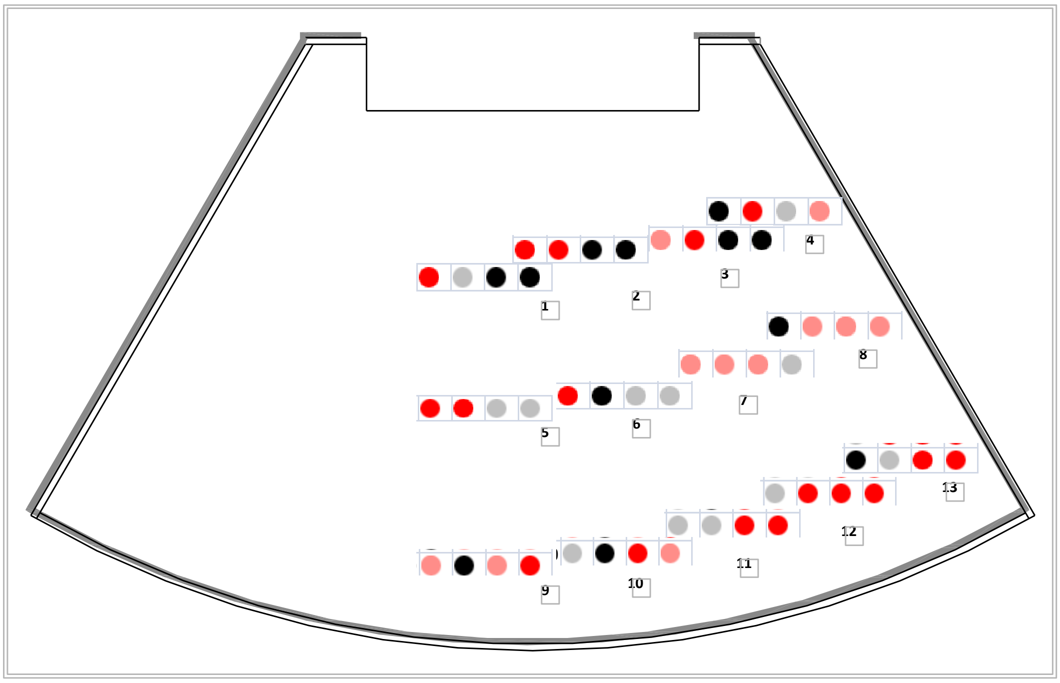
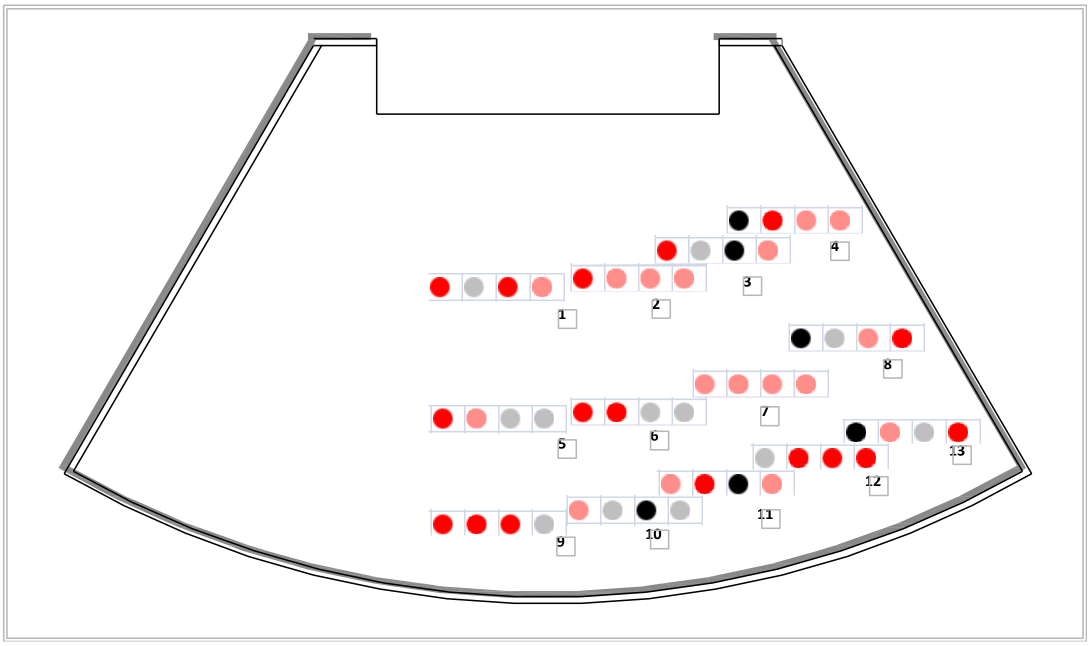


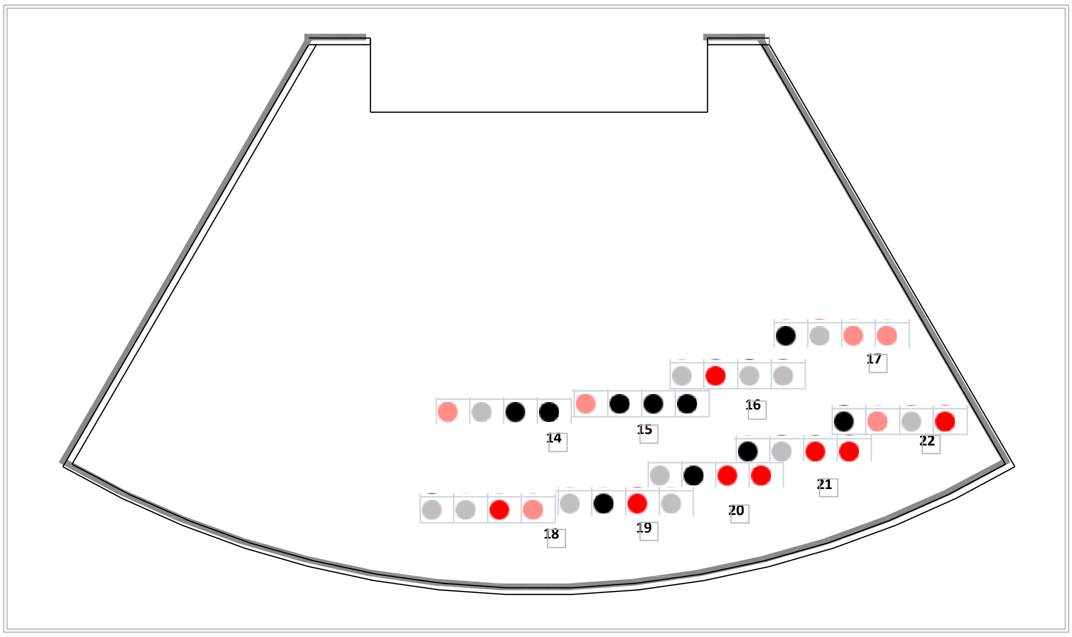
Figure 4.77 Evaluation of receiver points in F 30

12th receiver point has the maximum values of acoustical parameters in F30. Also 11th and 13th receiver points have maximum STI and D50 values. Seats in the front row have quite bad conditions relative to back rows (Figure 4.77).

Seats in the first row in the floor level of F30 B, have better values than seats in the back row. This situation is just opposite of the F 30. In the balcony level, seats at the back row have better values of acoustical parameters (Figure 4.78).



Floor level



Balcony level

Figure 4.78 Evaluation of receiver points in F 30 B

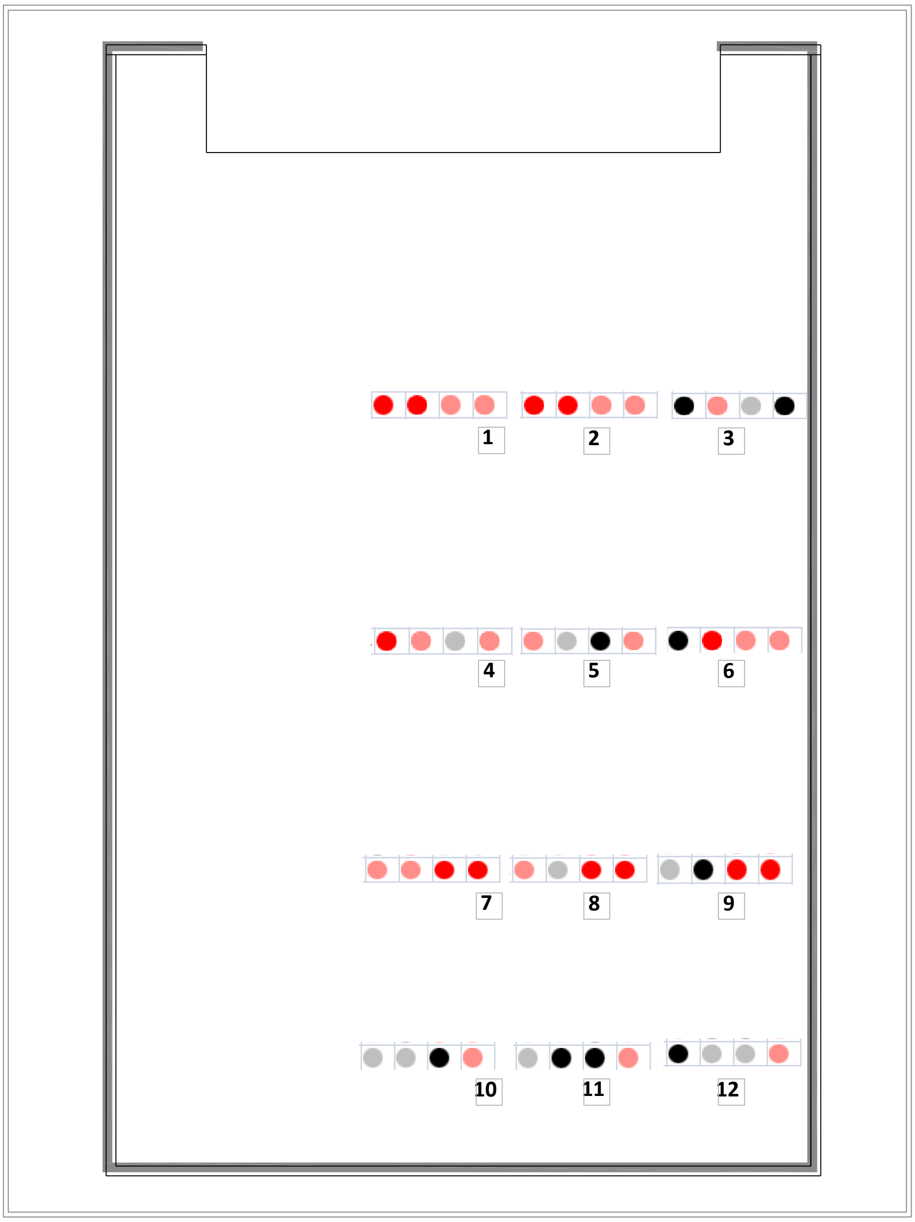


Figure 4.79 Evaluation of receiver points in rectangular room

In general, it can be said that seats located in the middle of the auditorium have better values in rectangular room. Especially at 7th, 8th and 9th receiver points STI and D50 values have high values (Figure 4.79).

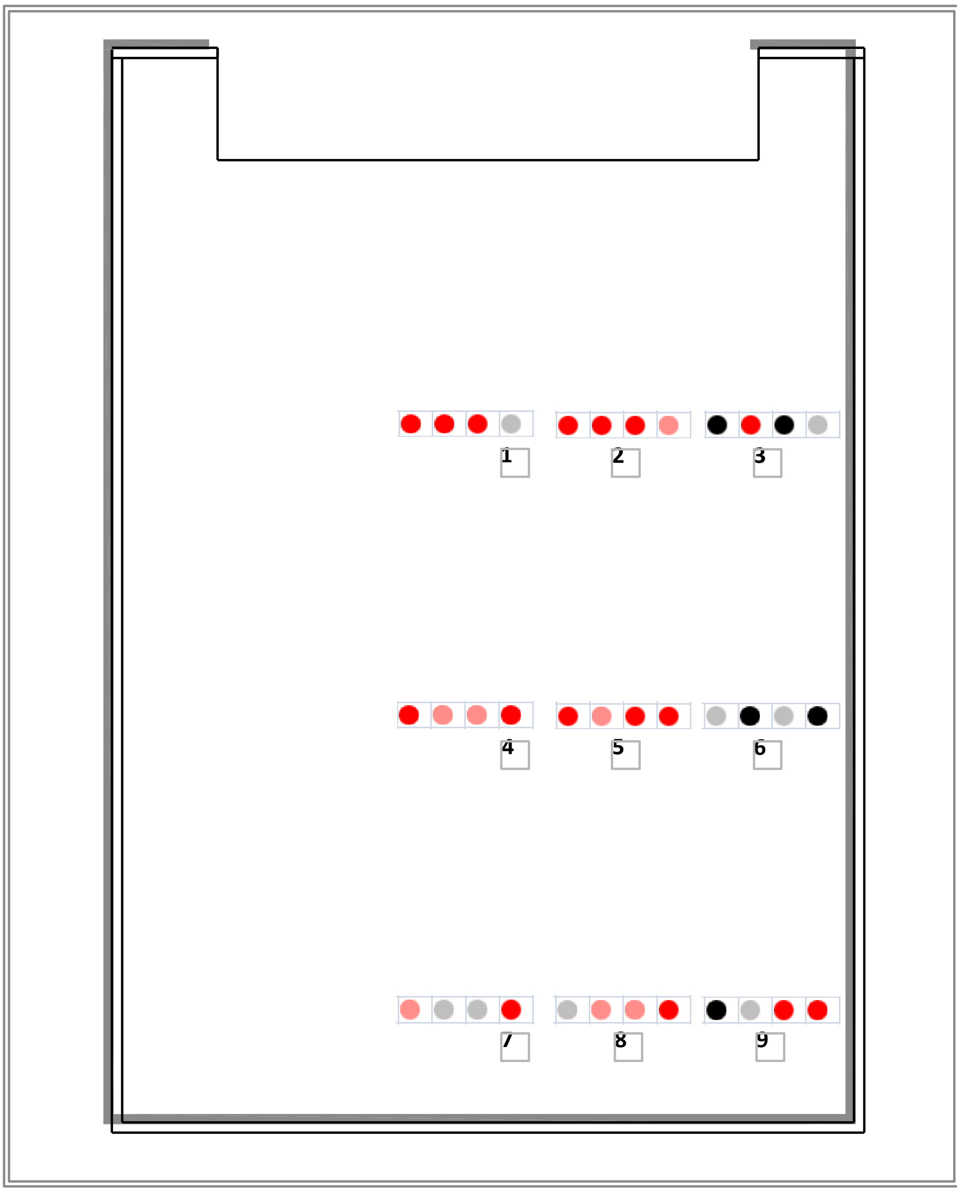


Figure 4.80 Evaluation of receiver points in Rec B (floor level)

In the floor level of Rec B, 4th and 5th receiver points have high values of D50 and STI as well as sightline score (Figure 4.80).

In the balcony level of the room 12th and 14th receiver points get the worst scores while the 13th seat has the best condition.

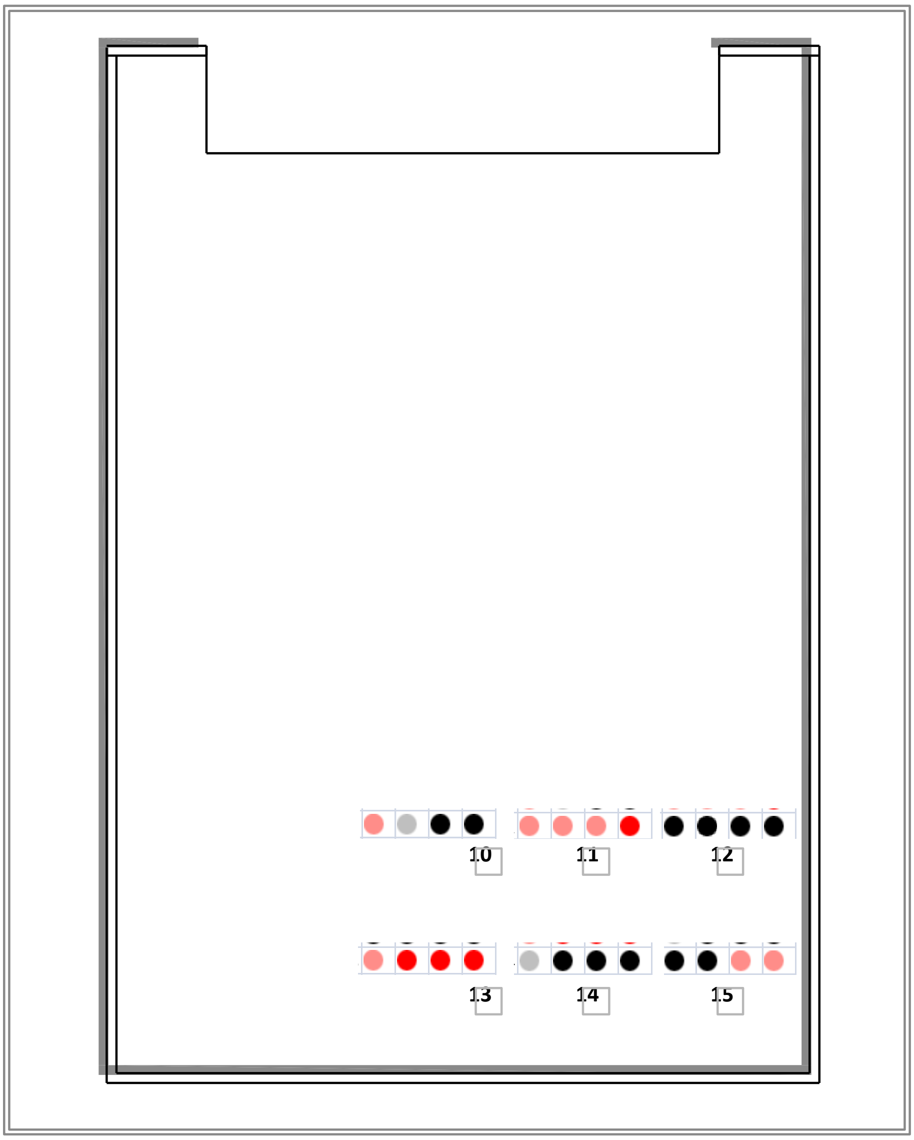


Figure 4.81 Evaluation of receiver points in Rec B (balcony level)

CHAPTER FIVE
CONCLUSIONS

Drama theatres are one of the most important listening environments and it is aimed to examine them in detail in this study. There are two important requirements for a drama theatre from the point of spectators; hearing and seeing what is on the stage. For that reason, design criteria that are important for both acoustical and visual comfort conditions are considered. Eight different types of theatres are designed, as cases, to make comparisons between them. It is thought that this kind of evaluation methodology makes possible to obtain correlations between parameters. Evaluation process includes two main parts. First one is evaluation of mean values of rooms, in other words comparison of designed cases. Second part is evaluation of the distribution of the parameters within each room.

Before the evaluation of the designed cases, in chapters one and two some definitions are made to understand the properties and necessities of the theatres. In chapter one, history of theatre architecture is briefly described. In the following chapter (chapter two), important design criteria are described. In addition, present examples of theatre architecture are examined in the same chapter. Examples of drama theatres are used to get some additional information about theatre design. The geometrical properties of these examples are compared with the designed cases at the end of chapter three.

It is thought that, defining the designed cases in a separate chapter will be easier, and less complicated, so acceptances and design considerations related to designed room are described in chapter three. Three fan-shaped, and a rectangular shaped rooms and balcony added versions of them are designed and stage design is kept same for all the rooms. The fly-tower on the stage is not separated or evaluated as a different space, to obtain the similar environment with theatre examples that are examined.

Chapter four is the most important and original part of the study, since the evaluation of the cases is made in this chapter. During the evaluation process, first, cases are examined from the point of visual and acoustical conditions separately. Acoustical and visual evaluations are based on the simulated results of the rooms. Mean scores are used to compare room types. On the other hand, each room is evaluated according to results obtained by receiver points. As a final step, correlations between the acoustical parameters and geometrical properties of rooms are examined.

In this chapter, results are explained briefly;

By considering the sightline design,

- Fan shaped auditoria have better scores than rectangular examples and mean room score is increasing by the increase of the splaying angle.
- For the rooms with balcony, with the effect of increase of distance, sightline scores of the seats in the balcony decrease. And this decrease affects the mean room score.

From the point of acoustical conditions,

- By considering the mean values of the parameters, it is possible to say that all the rooms meet the requirements of acoustical quality of drama theatres.
- Again, considering the mean values, it is observed that fan-shaped auditoria have better results.
- Addition of balcony does not cause distinctive problems or negative effect on the designed cases.
- Most distinctive variation of the room parameters are seen by the change of source position. The reason of this variation is mostly the big volume of the fly tower.

By considering the relation between parameters, results can be summarized as follows:

- From the acoustical point of view; most distinctive correlation is seen between the EDT and D50 values of the receiver points for all the rooms except rectangle room. It is observed that the value of the D50 parameter increases while EDT value is decreasing. The observation is obtained from both mean values of the rooms and room results.
- In most of the rooms, also it is seen that when the EDT value decrease, STI value increase, like D50 parameter. This also means that there is a positive correlation between D50 and STI.
- When the results are examined, it cannot be found clear linear correlations between sightline scores of seats and any of the acoustical parameters, for all room types except fan-shaped auditorium with 30^0 splaying angle. In this room, there is a negative correlation between total sightline score of the seats and D50 or STI parameters. In other words, if a seat has a high sightline score, its acoustic quality is decreasing relatively. Since the front rows of the room and the seats near the middle axis have better sightline scores, it can be said that values of the acoustical parameters increase near the side walls, in the F 30.
- There is not a distinctive correlation between the acoustical parameters and the distances of receiver points to the side wall, except from F15 with balcony and F 22. In these rooms, correlation between the distance to side wall and reverberation value is found. But in F15 there is a negative correlation, while in F 22 it is a positive one.
- Study also confirms the decrease of the SPL by distance, except F 30.

Finally, it is found that the effect of fly tower is more distinctive than change of splaying angle or balcony effect, by considering the variation of acoustical parameters.

And study confirms that fan-shaped auditoria provide better environment for speech than rectangular rooms. Increase of splaying angle also makes both acoustical and visual conditions better.

By evaluating the drama theatres and including fly tower and balconies in the cases, it is possible to say that the study reached quite considerable results. On the other hand, study can be broadened with the application of different room finishes, different stage types or/and dimensions, as well as the increase of room shapes in the future studies. Also, it is possible to make comparisons with the rooms having different volumes. Examination of the effect of lateral movement of source position can be considered in the future studies, too. And finally obtained simulation results can be checked with an existing drama theatre(s) to have more definite results.

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APPENDIX A

CALCULATED SIGHTLINE SCORES OF THE SEATS ACCORDING TO DEFINED STAGE POINTS

Fan Shape 15

Table A.1 Seat scores of F15 for three stage points

row number	seat number	stage point	distance	angle	score
5	1	P1	1143	1,81	0,49
5	1	P2	836	2,82	0,65
5	1	P3	733	3,35	0,73
5	2	P1	1183	12,45	0,30
5	2	P2	898	18,83	0,25
5	2	P3	807	21,94	0,20
5	3	P1	1279	21,45	0,13
5	3	P2	1037	30,91	0,00
5	3	P3	965	35,07	0,00
9	4	P1	1522	1,21	0,38
9	4	P2	1215	1,74	0,47
9	4	P3	1113	1,98	0,50
9	5	P1	1550	8,53	0,28
9	5	P2	1254	12,02	0,29
9	5	P3	1157	13,57	0,28
9	6	P1	1631	16,11	0,17
9	6	P2	1367	22,16	0,11
9	6	P3	1284	24,72	0,08
13	7	P1	1902	0,88	0,31
13	7	P2	1595	1,20	0,36
13	7	P3	1492	1,34	0,38
13	8	P1	1928	6,94	0,24
13	8	P2	1631	9,40	0,25
13	8	P3	1532	10,43	0,26
13	9	P1	2006	13,34	0,17
13	9	P2	1735	17,77	0,14
13	9	P3	1647	19,56	0,13
17	10	P1	2282	0,67	0,26
17	10	P2	1975	0,89	0,29
17	10	P3	1872	0,97	0,31
17	11	P1	2297	4,68	0,22
17	11	P2	1995	6,16	0,24
17	11	P3	1894	6,75	0,25
17	12	P1	2328	7,90	0,19
17	12	P2	2034	10,35	0,19
17	12	P3	1938	11,33	0,19

17	13	P1	2383	11,56	0,15
17	13	P2	2107	15,00	0,14
17	13	P3	2017	16,36	0,14

Fan Shape 15 with Balcony

Table A.2 Seat scores of F 15 with balcony for three stage points

row number	seat number	stage point	distance	angle	score
5	1	P1	1143	1,81	0,49
5	1	P2	836	2,82	0,65
5	1	P3	733	3,35	0,73
5	2	P1	1183	12,45	0,30
5	2	P2	898	18,83	0,25
5	2	P3	807	21,94	0,20
5	3	P1	1279	21,45	0,13
5	3	P2	1037	30,91	0,00
5	3	P3	965	35,07	0,00
9	4	P1	1522	1,21	0,38
9	4	P2	1215	1,74	0,47
9	4	P3	1113	1,98	0,50
9	5	P1	1550	8,54	0,28
9	5	P2	1254	12,02	0,29
9	5	P3	1157	13,57	0,28
9	6	P1	1631	16,11	0,17
9	6	P2	1367	22,16	0,11
9	6	P3	1284	24,72	0,08
14	7	P1	1997	0,81	0,29
14	7	P2	1690	1,10	0,34
14	7	P3	1587	1,22	0,36
14	8	P1	2011	4,87	0,25
14	8	P2	1708	6,56	0,27
14	8	P3	1608	7,27	0,28
14	9	P1	2044	8,80	0,21
14	9	P2	1752	11,77	0,21
14	9	P3	1656	12,99	0,21
14	10	P1	2107	13,19	0,16
14	10	P2	1836	17,41	0,14
14	10	P3	1748	19,11	0,12
B1	11	P1	1830	1,02	0,32
B1	11	P2	1546	1,42	0,37
B1	11	P3	1453	1,60	0,39
B1	12	P1	1858	8,24	0,23
B1	12	P2	1585	11,30	0,24
B1	12	P3	1496	12,62	0,23
B1	13	P1	1930	14,68	0,16

B1	13	P2	1679	19,81	0,12
B1	13	P3	1600	21,93	0,10
B4	14	P1	2154	0,81	0,27
B4	14	P2	1873	1,10	0,31
B4	14	P3	1781	1,22	0,32
B4	15	P1	2167	4,87	0,23
B4	15	P2	1889	6,56	0,25
B4	15	P3	1799	7,27	0,25
B4	16	P1	2197	8,80	0,19
B4	16	P2	1929	11,77	0,19
B4	16	P3	1842	12,99	0,18
B4	17	P1	2256	13,19	0,15
B4	17	P2	2005	17,41	0,13
B4	17	P3	1925	19,11	0,11

Fan Shape 22,5

Table A.3 Seat scores of F 22,5 for three stage points

row number	seat number	stage point	distance	angle	score
5	1	P1	1143	1,45	0,50
5	1	P2	836	2,47	0,66
5	1	P3	734	2,99	0,74
5	2	P1	1176	9,92	0,34
5	2	P2	891	16,38	0,31
5	2	P3	800	19,54	0,26
5	3	P1	1271	18,36	0,18
5	3	P2	1040	28,50	0,03
5	3	P3	973	32,90	0,00
10	4	P1	1618	0,87	0,36
10	4	P2	1311	1,32	0,44
10	4	P3	1208	1,53	0,47
10	5	P1	1632	5,12	0,30
10	5	P2	1332	7,79	0,33
10	5	P3	1233	8,97	0,34
10	6	P1	1676	9,95	0,24
10	6	P2	1398	14,87	0,22
10	6	P3	1308	16,98	0,20
10	7	P1	1745	14,23	0,18
10	7	P2	1499	20,79	0,12
10	7	P3	1423	23,46	0,09
15	8	P1	2093	0,57	0,28
15	8	P2	1785	0,83	0,33

15	8	P3	1683	0,94	0,35
15	9	P1	2106	3,98	0,25
15	9	P2	1804	5,76	0,27
15	9	P3	1704	6,49	0,28
15	10	P1	2145	7,77	0,21
15	10	P2	1861	11,14	0,20
15	10	P3	1768	12,50	0,20
15	11	P1	2209	11,23	0,17
15	11	P2	1951	15,87	0,14
15	11	P3	1869	17,69	0,13

Fan Shape 22,5 with Balcony

Table A.4 Seat scores of F 22,5 with balcony for three stage points

row number	seat number	stage point	distance	angle	score
5	1	P1	1143	1,45	0,50
5	1	P2	836	2,47	0,66
5	1	P3	734	2,99	0,74
5	2	P1	1176	9,92	0,34
5	2	P2	891	16,38	0,31
5	2	P3	800	19,54	0,26
5	3	P1	1271	18,36	0,18
5	3	P2	1040	28,50	0,03
5	3	P3	973	32,90	0,00
9	4	P1	1523	0,94	0,38
9	4	P2	1216	1,46	0,47
9	4	P3	1113	1,70	0,51
9	5	P1	1539	5,61	0,32
9	5	P2	1240	8,65	0,34
9	5	P3	1142	10,01	0,35
9	6	P1	1576	10,03	0,25
9	6	P2	1297	15,21	0,23
9	6	P3	1207	17,46	0,21
9	7	P1	1647	14,76	0,19
9	7	P2	1402	21,78	0,12
9	7	P3	1327	24,68	0,08
13	8	P1	1903	0,67	0,31
13	8	P2	1595	0,99	0,36
13	8	P3	1493	1,12	0,39
13	9	P1	1918	4,63	0,26
13	9	P2	1618	6,81	0,29
13	9	P3	1519	7,73	0,29

13	10	P1	1964	8,99	0,21
13	10	P2	1685	13,06	0,20
13	10	P3	1594	14,73	0,19
13	11	P1	2025	12,38	0,17
13	11	P2	1772	17,68	0,14
13	11	P3	1692	19,79	0,12
B1	12	P1	1740	0,87	0,33
B1	12	P2	1458	1,32	0,39
B1	12	P3	1367	1,53	0,42
B1	13	P1	1753	5,13	0,28
B1	13	P2	1478	7,79	0,30
B1	13	P3	1390	8,97	0,30
B1	14	P1	1794	9,95	0,22
B1	14	P2	1537	14,87	0,20
B1	14	P3	1456	16,98	0,18
B1	15	P1	1859	14,23	0,17
B1	15	P2	1630	20,79	0,11
B1	15	P3	1560	23,46	0,08
B4	16	P1	2068	0,67	0,28
B4	16	P2	1789	0,99	0,32
B4	16	P3	1699	1,12	0,34
B4	17	P1	2082	4,63	0,24
B4	17	P2	1809	6,81	0,26
B4	17	P3	1721	7,73	0,26
B4	18	P1	2124	8,99	0,20
B4	18	P2	1869	13,06	0,18
B4	18	P3	1788	14,73	0,17
B4	19	P1	2181	12,38	0,16
B4	19	P2	1949	17,68	0,13
B4	19	P3	1876	19,79	0,11

Fan Shape 30

Table A.5 Seat scores of F 30 for three stage points

row number	seat number	stage point	distance	angle	score
5	1	P1	1142	1,19	0,50
5	1	P2	835	2,21	0,67
5	1	P3	733	2,74	0,74
5	2	P1	1162	6,99	0,40
5	2	P2	871	12,72	0,40
5	2	P3	777	15,57	0,37
5	3	P1	1208	12,25	0,29
5	3	P2	953	21,41	0,18

5	3	P3	875	25,62	0,10
5	4	P1	1277	16,69	0,21
5	4	P2	1068	27,76	0,04
5	4	P3	1009	32,41	0,00
9	5	P1	1522	0,75	0,38
9	5	P2	1215	1,27	0,47
9	5	P3	1112	1,51	0,51
9	6	P1	1534	4,45	0,33
9	6	P2	1236	7,50	0,36
9	6	P3	1137	8,88	0,37
9	7	P1	1572	8,63	0,27
9	7	P2	1299	14,26	0,24
9	7	P3	1211	16,69	0,22
9	8	P1	1644	12,86	0,21
9	8	P2	1415	20,55	0,13
9	8	P3	1345	23,67	0,09
14	9	P1	1997	0,48	0,30
14	9	P2	1689	0,76	0,35
14	9	P3	1587	0,89	0,37
14	10	P1	2005	2,85	0,27
14	10	P2	1702	4,55	0,30
14	10	P3	1602	5,25	0,31
14	11	P1	2029	5,58	0,24
14	11	P2	1741	8,84	0,24
14	11	P3	1646	10,18	0,24
14	12	P1	2069	8,14	0,21
14	12	P2	1803	12,73	0,19
14	12	P3	1717	14,57	0,18
14	13	P1	2122	10,43	0,18
14	13	P2	1885	16,05	0,15
14	13	P3	1811	18,24	0,13

Fan Shape 30 with Balcony

Table A.6 Seat scores of F 30 with balcony for three stage points

row number	seat number	stage point	distance	angle	score
5	1	P1	1142	1,19	0,50
5	1	P2	835	2,21	0,67
5	1	P3	733	2,74	0,74

5	2	P1	1162	6,99	0,40
5	2	P2	871	12,72	0,40
5	2	P3	777	15,57	0,37
5	3	P1	1208	12,25	0,29
5	3	P2	953	21,41	0,18
5	3	P3	875	25,62	0,10
5	4	P1	1277	16,69	0,21
5	4	P2	1068	27,76	0,04
5	4	P3	1009	32,41	0,00
9	5	P1	1522	0,75	0,38
9	5	P2	1215	1,27	0,47
9	5	P3	1112	1,51	0,51
9	6	P1	1534	4,45	0,33
9	6	P2	1236	7,50	0,36
9	6	P3	1137	8,88	0,37
9	7	P1	1572	8,63	0,27
9	7	P2	1299	14,26	0,24
9	7	P3	1211	16,69	0,22
9	8	P1	1644	12,86	0,21
9	8	P2	1415	20,55	0,13
9	8	P3	1345	23,67	0,09
12	9	P1	1807	0,56	0,33
12	9	P2	1499	0,92	0,39
12	9	P3	1397	1,07	0,41
12	10	P1	1816	3,35	0,29
12	10	P2	1515	5,46	0,32
12	10	P3	1415	6,36	0,33
12	11	P1	1839	6,05	0,26
12	11	P2	1551	9,76	0,26
12	11	P3	1457	11,31	0,26
12	12	P1	1874	8,57	0,23
12	12	P2	1607	13,63	0,20
12	12	P3	1522	15,71	0,19
12	13	P1	1931	11,28	0,19
12	13	P2	1696	17,58	0,15
12	13	P3	1624	20,07	0,12
B1	14	P1	1643	0,75	0,36
B1	14	P2	1363	1,27	0,42
B1	14	P3	1272	1,51	0,45
B1	15	P1	1654	4,45	0,31
B1	15	P2	1382	7,50	0,33
B1	15	P3	1294	8,88	0,33
B1	16	P1	1689	8,63	0,25

B1	16	P2	1438	14,26	0,22
B1	16	P3	1360	16,69	0,20
B1	17	P1	1757	12,86	0,20
B1	17	P2	1544	20,55	0,12
B1	17	P3	1480	23,67	0,09
B4	18	P1	1974	0,56	0,30
B4	18	P2	1697	0,92	0,34
B4	18	P3	1607	1,07	0,36
B4	19	P1	1983	3,35	0,27
B4	19	P2	1711	5,46	0,29
B4	19	P3	1623	6,36	0,29
B4	20	P1	2003	6,05	0,24
B4	20	P2	1743	9,76	0,23
B4	20	P3	1660	11,31	0,23
B4	21	P1	2036	8,57	0,21
B4	21	P2	1793	13,63	0,18
B4	21	P3	1717	15,71	0,17
B4	22	P1	2088	11,28	0,18
B4	22	P2	1873	17,58	0,13
B4	22	P3	1808	20,07	0,11

Rectangular Room

Table A.7 Seat scores of rectangular room for three stage points

row number	seat number	stage point	distance	angle	score
5	1	P1	1130	2,79	0,48
5	1	P2	823	3,83	0,64
5	1	P3	721	4,38	0,71
5	2	P1	1162	13,70	0,28
5	2	P2	866	18,52	0,27
5	2	P3	769	20,94	0,24
5	3	P1	1255	25,98	0,06
5	3	P2	988	33,82	0,00
5	3	P3	905	37,43	0,00
10	4	P1	1604	1,96	0,35
10	4	P2	1297	2,43	0,43
10	4	P3	1195	2,64	0,46
10	5	P1	1627	9,73	0,25
10	5	P2	1325	11,98	0,27
10	5	P3	1225	12,98	0,28

10	6	P1	1695	18,93	0,13
10	6	P2	1408	23,00	0,10
10	6	P3	1314	24,74	0,08
15	7	P1	2079	1,52	0,27
15	7	P2	1772	1,78	0,32
15	7	P3	1669	1,89	0,34
15	8	P1	2097	7,54	0,21
15	8	P2	1792	8,83	0,24
15	8	P3	1691	9,36	0,24
15	9	P1	2150	14,82	0,14
15	9	P2	1854	17,25	0,14
15	9	P3	1757	18,24	0,13
19	10	P1	2459	1,28	0,23
19	10	P2	2152	1,46	0,27
19	10	P3	2049	1,54	0,28
19	11	P1	2474	6,38	0,19
19	11	P2	2169	7,29	0,21
19	11	P3	2067	7,65	0,22
19	12	P1	2519	12,61	0,14
19	12	P2	2220	14,34	0,14
19	12	P3	2121	15,03	0,14

Rectangular Room with Balcony

Table A.8 Seat scores of rectangular room with balcony for three stage points

row number	**seat number**	**stage point**	**distance**	**angle**	**score**
5	1	P1	1129,84	2,79	0,48
5	1	P2	822,84	3,83	0,64
5	1	P3	720,60	4,38	0,71
5	2	P1	1161,52	13,70	0,28
5	2	P2	865,83	18,52	0,27
5	2	P3	769,33	20,94	0,24
5	3	P1	1255,39	25,98	0,06
5	3	P2	988,20	33,82	0,00
5	3	P3	904,84	37,43	0,00
11	4	P1	1699,39	1,85	0,33
11	4	P2	1392,09	2,26	0,40
11	4	P3	1289,67	2,44	0,43
11	5	P1	1720,62	9,20	0,24
11	5	P2	1417,92	11,18	0,27
11	5	P3	1317,52	12,05	0,27

11	6	P1	1785,33	17,94	0,14
11	6	P2	1495,79	21,57	0,11
11	6	P3	1400,98	23,12	0,10
17	7	P1	2269,17	1,39	0,25
17	7	P2	1961,77	1,61	0,29
17	7	P3	1859,31	1,70	0,30
17	8	P1	2285,11	6,91	0,20
17	8	P2	1980,19	7,98	0,22
17	8	P3	1878,74	8,42	0,23
17	9	P1	2334,22	13,63	0,14
17	9	P2	2036,67	15,67	0,14
17	9	P3	1938,18	16,49	0,14
B1	10	P1	2111,19	1,59	0,27
B1	10	P2	1825,33	1,88	0,31
B1	10	P3	1731,70	2,00	0,32
B1	11	P1	2128,32	7,89	0,21
B1	11	P2	1845,11	9,32	0,22
B1	11	P3	1752,53	9,91	0,23
B1	12	P1	2180,97	15,50	0,13
B1	12	P2	1905,60	18,17	0,12
B1	12	P3	1816,11	19,27	0,12
B4	13	P1	2432,02	1,39	0,24
B4	13	P2	2148,06	1,61	0,26
B4	13	P3	2054,91	1,70	0,28
B4	14	P1	2446,91	6,91	0,19
B4	14	P2	2164,90	7,98	0,20
B4	14	P3	2072,50	8,42	0,21
B4	15	P1	2492,83	13,63	0,13
B4	15	P2	2216,68	15,67	0,13
B4	15	P3	2126,53	16,49	0,13

APPENDIX B

RESULTS OF ACOUSTICAL SIMULATION OF THE DESIGNED CASES

F15 – SOURCE 2

EDT(s) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,84	1,1	0,91	0,67	0,47	0,28	0,22	0,15
2	0,81	0,97	0,83	0,7	0,42	0,28	0,23	0,16
3	0,79	1,18	0,88	0,69	0,58	0,31	0,2	0,13
4	0,56	0,68	0,71	0,49	0,53	0,44	0,34	0,23
5	0,44	0,6	0,45	0,37	0,28	0,31	0,31	0,21
6	0,68	0,69	0,64	0,63	0,48	0,32	0,34	0,23
7	0,42	0,4	0,5	0,35	0,32	0,26	0,25	0,21
8	0,47	0,6	0,42	0,34	0,34	0,28	0,27	0,24
9	0,54	0,6	0,31	0,35	0,3	0,27	0,28	0,25
10	0,51	0,37	0,34	0,31	0,48	0,28	0,26	0,22
11	0,5	0,36	0,39	0,46	0,23	0,3	0,29	0,22
12	0,42	0,44	0,39	0,38	0,34	0,3	0,28	0,24
13	0,26	0,35	0,49	0,33	0,29	0,25	0,25	0,22

T30(s) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,84	0,96	0,93	0,89	0,88	0,94	0,88	0,51
2	0,96	1,11	1,01	0,91	0,91	1,02	1	0,49
3	0,86	0,97	0,9	0,87	0,91	1	0,98	0,6
4	0,79	0,94	0,88	0,82	0,85	0,91	0,87	0,5
5	0,85	0,96	0,89	0,91	0,92	0,91	0,93	0,53
6	0,88	1,04	1,21	1,31	1,32	1,18	1,07	0,46
7	0,8	0,89	0,87	0,9	0,96	0,96	0,93	0,47
8	0,74	0,87	0,88	0,82	0,89	0,88	0,81	0,48
9	0,74	0,86	0,79	0,83	0,87	0,92	1,03	0,54
10	0,73	0,84	0,8	0,86	0,9	0,93	0,95	0,48
11	0,75	0,85	0,77	0,86	0,87	0,92	0,95	0,53
12	0,73	0,87	0,82	0,86	0,86	0,89	0,94	0,61
13	0,74	0,87	0,85	0,85	0,93	0,96	0,94	0,54

SPL(dB) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	42,8	43,6	48,1	52,7	49,6	42,3	36,3	26,6
2	42,8	43,6	48,2	53	49,6	42,4	36	25,7
3	42,5	43,3	47,9	52,7	49	41,6	35	24,2
4	42,6	43,4	47,6	52,4	49,1	41,5	35,1	25,4
5	43,3	44,1	48,3	53,1	49,6	42,2	35,7	25,5
6	42,4	43,1	47,7	52,6	49,1	41,6	35	24,4
7	42,1	43,2	47,6	52,8	49	41,4	34,8	24,8
8	41,9	42,9	47,3	52,2	48,6	41	34,5	24,3
9	41,1	42,1	46,7	51,8	48,2	40,8	34	23,5
10	40,1	41,4	45,6	50,2	46,2	38,5	32,1	20,8
11	39,8	41	45,3	49,8	46,1	38,3	31,9	20,8
12	40	41	45,4	50	46,1	38,2	31,6	20,2
13	39,7	40,9	45,3	49,8	46	38,5	31,8	20,6

D50 simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,74	0,63	0,74	0,81	0,86	0,9	0,92	0,96
2	0,74	0,65	0,74	0,81	0,86	0,91	0,92	0,95
3	0,76	0,66	0,75	0,82	0,85	0,9	0,91	0,95
4	0,65	0,58	0,66	0,75	0,81	0,87	0,89	0,94
5	0,75	0,69	0,75	0,81	0,85	0,89	0,9	0,94
6	0,72	0,65	0,73	0,8	0,86	0,89	0,88	0,93
7	0,78	0,74	0,81	0,87	0,89	0,92	0,93	0,97
8	0,79	0,74	0,8	0,85	0,89	0,92	0,93	0,96
9	0,8	0,75	0,82	0,88	0,91	0,94	0,94	0,97
10	0,78	0,73	0,8	0,84	0,87	0,91	0,92	0,96
11	0,76	0,7	0,76	0,8	0,84	0,9	0,91	0,96
12	0,8	0,76	0,81	0,84	0,87	0,92	0,93	0,96
13	0,84	0,81	0,85	0,88	0,91	0,94	0,95	0,97

F15 B – SOURCE 2

EDT(s) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,35	0,63	0,47	0,36	0,26	0,19	0,16	0,15
2	0,38	0,61	0,5	0,35	0,29	0,21	0,21	0,16
3	0,36	0,54	0,52	0,36	0,28	0,18	0,16	0,14
4	0,33	0,5	0,38	0,41	0,26	0,22	0,21	0,15
5	0,49	0,58	0,52	0,33	0,28	0,22	0,22	0,16
6	0,34	0,51	0,32	0,32	0,26	0,2	0,2	0,14
7	0,33	0,44	0,46	0,32	0,3	0,23	0,2	0,16
8	0,33	0,32	0,35	0,33	0,29	0,23	0,2	0,18
9	0,29	0,33	0,3	0,29	0,28	0,23	0,22	0,19
10	0,3	0,32	0,3	0,3	0,29	0,25	0,24	0,2
11	0,36	0,32	0,41	0,33	0,32	0,27	0,26	0,2
12	0,3	0,36	0,53	0,26	0,36	0,3	0,29	0,23
13	0,3	0,58	0,44	0,37	0,3	0,24	0,24	0,2
14	0,28	0,31	0,3	0,28	0,25	0,21	0,2	0,18
15	0,29	0,33	0,31	0,32	0,35	0,25	0,22	0,18
16	0,31	0,34	0,33	0,32	0,31	0,27	0,25	0,19
17	0,28	0,3	0,3	0,29	0,28	0,25	0,25	0,21

T30(s) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000

1	0,95	1,02	0,88	0,84	0,87	0,99	1,06	0,47
2	0,79	0,93	0,86	0,87	0,86	0,94	0,97	0,49
3	0,75	0,9	0,84	1	0,98	0,97	0,96	0,5
4	0,81	0,92	0,9	0,82	0,84	0,94	0,97	0,48
5	0,76	0,92	0,83	0,85	0,82	0,93	0,91	0,49
6	0,75	0,89	0,84	0,83	0,87	0,93	0,94	0,54
7	0,7	0,82	0,8	0,81	0,84	0,89	0,9	0,57
8	0,73	0,8	0,79	0,78	0,79	0,95	0,91	0,51
9	0,72	0,75	0,75	0,81	0,83	0,85	0,84	0,51
10	0,72	0,77	0,8	0,81	0,92	0,92	0,91	0,54
11	0,7	0,85	0,78	0,81	0,84	0,88	0,89	0,52
12	0,69	0,8	0,77	0,86	0,92	0,91	0,87	0,54
13	0,69	0,8	0,81	0,92	0,91	0,88	0,92	0,51
14	0,68	0,77	0,77	0,84	0,8	0,87	0,88	0,5
15	0,7	0,82	0,8	0,84	0,81	0,83	0,86	0,49
16	0,73	0,77	0,82	0,9	0,95	0,93	0,94	0,57
17	0,89	0,89	0,86	0,89	0,87	0,89	0,92	0,57

SPL(dB) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	42,8	43,3	48,1	53	50,2	42,8	36,7	27,1
2	42,6	43,1	47,9	52,8	49,8	42,7	36,2	26,1
3	41,9	42,3	47,3	52,5	49,2	41,8	35,2	24,6
4	41,3	42	46,6	51,5	49	41,6	35,1	25,4
5	41,4	42,2	46,8	51,7	48,9	41,6	34,9	24,9
6	41,2	41,9	46,7	51,8	48,9	41,7	35	24,4
7	38,7	39,9	44,1	48,2	44,3	37,2	31,5	21
8	38,8	40	44,4	48,7	44,9	37,6	31,6	20,9
9	39,1	40,4	44,6	48,8	44,9	37,7	31,5	20,4
10	38,4	39,7	43,9	48	43,8	36,7	30,4	19,6
11	40,1	41,3	45,6	51,1	46,7	38,6	32,3	22,8
12	39,5	40,5	44,6	49,9	45,6	37,7	31,2	21,2
13	38,8	39,9	44,5	49,9	46,2	38,6	31,6	21,2
14	40	41,1	45,3	50,1	46,7	38,8	32,1	21,5
15	40	41,3	46	50,8	47,7	39,7	33	21,9
16	39,6	40,7	45	49,5	45,8	38	31,5	20,8
17	39	40,2	44,3	48,8	44,5	36,5	29,8	18,9

D50 simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,88	0,82	0,86	0,88	0,91	0,94	0,95	0,97
2	0,87	0,8	0,85	0,87	0,9	0,94	0,94	0,97
3	0,87	0,81	0,85	0,88	0,9	0,93	0,94	0,96
4	0,86	0,8	0,85	0,88	0,92	0,95	0,95	0,98
5	0,83	0,75	0,82	0,86	0,91	0,94	0,94	0,97
6	0,88	0,82	0,87	0,89	0,93	0,95	0,95	0,98
7	0,88	0,85	0,87	0,88	0,9	0,94	0,95	0,98
8	0,89	0,85	0,88	0,89	0,91	0,94	0,96	0,98
9	0,9	0,87	0,9	0,9	0,92	0,94	0,96	0,98
10	0,91	0,88	0,9	0,91	0,92	0,95	0,96	0,98
11	0,84	0,78	0,81	0,87	0,88	0,92	0,93	0,97
12	0,83	0,77	0,8	0,85	0,87	0,9	0,91	0,96
13	0,83	0,75	0,81	0,87	0,9	0,94	0,94	0,97
14	0,92	0,89	0,9	0,91	0,92	0,95	0,95	0,98
15	0,91	0,88	0,9	0,9	0,89	0,91	0,93	0,98
16	0,91	0,87	0,88	0,89	0,91	0,94	0,94	0,98
17	0,93	0,9	0,91	0,91	0,92	0,94	0,94	0,98

FAN 22 – SOURCE 2

EDT(s) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,62	0,95	0,87	0,61	0,4	0,24	0,19	0,15
2	0,77	1,11	0,94	0,57	0,43	0,23	0,19	0,15
3	0,68	0,87	0,8	0,68	0,5	0,28	0,2	0,15
4	0,46	0,44	0,48	0,35	0,28	0,25	0,24	0,22
5	0,5	0,47	0,43	0,38	0,31	0,27	0,26	0,22
6	0,39	0,52	0,5	0,34	0,29	0,24	0,23	0,18
7	0,32	0,46	0,41	0,32	0,3	0,23	0,21	0,16
8	0,32	0,4	0,45	0,46	0,31	0,26	0,24	0,21
9	0,42	0,46	0,37	0,29	0,3	0,26	0,24	0,22
10	0,3	0,31	0,37	0,35	0,29	0,24	0,23	0,21
11	0,29	0,44	0,56	0,33	0,29	0,22	0,21	0,19

T30(s) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,79	1,01	0,89	0,99	1,08	1,23	1,16	0,51

2	1,02	1,06	1,02	0,92	0,91	0,98	0,94	0,53
3	0,81	0,95	0,88	0,89	0,95	1,02	1,03	0,52
4	0,74	0,94	0,89	0,87	0,93	0,98	0,98	0,45
5	0,73	0,91	0,84	0,85	0,89	0,92	0,96	0,45
6	0,75	0,87	0,81	0,87	0,93	0,96	0,92	0,46
7	0,75	0,87	0,86	0,83	0,78	0,87	0,86	0,48
8	0,72	0,92	0,9	1,41	0,93	0,92	0,95	0,76
9	0,71	0,87	0,78	0,82	0,88	0,91	0,99	0,61
10	0,78	0,89	0,85	0,87	0,87	0,87	0,94	0,49
11	0,69	0,89	0,81	0,82	0,87	0,87	0,86	0,5

SPL(dB) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	43,5	44,2	48,7	53,2	50,3	42,9	36,8	27,3
2	42,6	43,5	47,9	52,5	49,3	42,5	35,9	26
3	41,7	42,6	47,2	52	48,4	41	34,5	23,4
4	42,7	43,5	47,7	52,7	49,4	41,7	35,2	26
5	42,3	43,3	47,5	52,6	49,2	41,5	35	25,5
6	42,3	43,1	47,4	52,6	49	41,5	35	25,1
7	42	42,8	47,3	52,5	48,9	41,4	34,8	24,1
8	39,8	40,8	45	49,6	46,1	38,1	31,7	20,8
9	40	41,1	45,3	49,9	46,3	38,2	31,8	20,7
10	39,9	40,9	45,1	49,8	46	38,5	31,8	20,9
11	39,2	40,5	44,7	49,2	45,3	38,6	31,8	20,9

D50 simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,78	0,68	0,76	0,82	0,88	0,92	0,93	0,97
2	0,75	0,65	0,75	0,82	0,87	0,92	0,93	0,96
3	0,72	0,63	0,74	0,81	0,86	0,9	0,91	0,94
4	0,82	0,77	0,82	0,88	0,91	0,94	0,94	0,97
5	0,78	0,73	0,79	0,86	0,9	0,93	0,94	0,97
6	0,82	0,76	0,82	0,88	0,91	0,94	0,94	0,97
7	0,82	0,78	0,84	0,88	0,9	0,94	0,95	0,97
8	0,79	0,75	0,8	0,85	0,9	0,92	0,94	0,97
9	0,78	0,75	0,81	0,86	0,91	0,93	0,94	0,97
10	0,81	0,77	0,82	0,87	0,9	0,93	0,94	0,97
11	0,84	0,82	0,86	0,89	0,92	0,95	0,96	0,98

FAN 22 B – SOURCE 2

EDT(s) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,26	0,47	0,35	0,33	0,24	0,18	0,17	0,15
2	0,28	0,63	0,52	0,48	0,36	0,18	0,16	0,14
3	0,27	0,49	0,35	0,35	0,31	0,21	0,19	0,15
4	0,36	0,58	0,45	0,37	0,33	0,22	0,2	0,16
5	0,34	0,63	0,48	0,48	0,3	0,2	0,19	0,14
6	0,45	0,45	0,46	0,41	0,29	0,19	0,18	0,14
7	0,32	0,59	0,56	0,4	0,32	0,21	0,19	0,15
8	0,25	0,36	0,34	0,44	0,3	0,24	0,21	0,16
9	0,27	0,37	0,42	0,3	0,29	0,26	0,22	0,17
10	0,23	0,29	0,28	0,25	0,24	0,2	0,19	0,13
11	0,26	0,35	0,34	0,33	0,31	0,2	0,17	0,13
12	0,31	0,44	0,53	0,35	0,33	0,3	0,28	0,19
13	0,31	0,52	0,53	0,43	0,46	0,32	0,3	0,2
14	0,29	0,5	0,36	0,32	0,3	0,25	0,25	0,18
15	0,28	0,33	0,31	0,27	0,26	0,19	0,17	0,1
16	0,24	0,28	0,28	0,27	0,25	0,22	0,21	0,17
17	0,25	0,3	0,3	0,29	0,26	0,23	0,22	0,17
18	0,25	0,29	0,29	0,28	0,25	0,21	0,2	0,14
19	0,24	0,34	0,35	0,34	0,33	0,2	0,16	0,15

T30(s) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,67	0,8	0,76	0,8	0,85	0,85	0,85	0,5
2	0,63	0,75	0,68	0,84	1	1,01	1,07	0,48
3	0,57	0,73	0,68	0,74	0,82	0,92	0,99	0,5
4	0,6	0,86	0,76	0,89	0,96	1,07	1,1	0,53
5	0,65	0,82	1,08	1,48	1,4	1,14	0,95	0,52
6	0,63	0,71	0,76	0,81	0,88	0,96	0,97	0,49
7	0,51	0,65	0,72	0,84	0,91	1	1,11	0,5
8	0,6	0,72	0,74	0,89	1	1,02	1,05	0,49
9	0,58	0,73	0,68	0,81	0,85	0,89	0,95	0,6
10	0,52	0,69	0,66	0,8	0,87	0,92	0,9	0,55
11	0,54	0,65	0,63	0,87	0,94	0,93	0,95	0,46
12	0,57	0,76	0,67	0,79	0,9	1,01	0,95	0,49
13	0,55	0,71	0,69	0,71	0,82	0,93	1	0,47
14	0,54	0,78	0,73	0,77	0,88	0,94	0,9	0,49
15	0,57	0,69	0,67	0,79	0,81	0,92	0,91	0,47
16	0,48	0,68	0,69	0,8	0,89	1,05	1,04	0,48
17	0,58	0,69	0,71	0,76	0,96	1,03	1,03	0,5
18	0,57	0,64	0,65	0,73	0,79	0,87	0,89	0,5
19	0,55	0,59	0,62	0,72	0,79	0,85	0,83	0,49

SPL(dB) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	43,2	43,7	48,5	53,1	50,6	43,3	37	27,5
2	41,5	42,2	47,1	52	48,5	41,9	35,5	25,5
3	42,1	42,8	47,7	52,8	49,5	41,8	35,2	24,3
4	40,3	41,2	45,8	50,3	47,9	40,7	34,3	24,5
5	39,5	40,4	45,2	49,9	47,5	40,6	34	24
6	39,5	40,6	45,3	50,1	47,1	40,4	33,8	23,5
7	39	40	44,8	49,8	46,4	39,7	33,1	22,3
8	37,1	39,1	43,6	48,1	44,6	37,2	31,5	21,2

9	37,2	39	43,4	48	44,3	37,2	31,3	20,8
10	38,1	40,2	44,5	49,6	45,3	37,8	31,9	21,4
11	37	39	43,3	47,6	43,2	36,5	30,2	19,3
12	38,2	39,9	44,3	50,1	46,1	37,8	31,4	22,3
13	39,1	40,5	44,8	50,5	47	38,9	32	22,5
14	38,4	39,6	44,1	49,8	45,8	38,2	31,3	21,5
15	38,2	39,3	44	50	45,8	38,1	31,6	21,2
16	38,4	40,2	44,5	49,6	46,3	37,9	31,2	21,3
17	38,3	39,9	44,3	49,6	46,2	38,2	31,6	21,3
18	38,2	39,7	44,4	49,7	45,9	38,5	31,8	21,1
19	36,5	38,4	42,8	47,7	43,3	36,5	30	19,2

D50 simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,93	0,85	0,88	0,89	0,93	0,95	0,95	0,98
2	0,91	0,81	0,84	0,85	0,89	0,93	0,94	0,97
3	0,92	0,83	0,85	0,86	0,9	0,92	0,93	0,95
4	0,8	0,71	0,78	0,82	0,9	0,94	0,95	0,98
5	0,87	0,77	0,83	0,85	0,9	0,94	0,95	0,98
6	0,86	0,76	0,83	0,87	0,91	0,95	0,95	0,98
7	0,89	0,79	0,83	0,86	0,89	0,93	0,95	0,97
8	0,93	0,87	0,89	0,88	0,9	0,93	0,95	0,98
9	0,93	0,86	0,87	0,86	0,88	0,92	0,94	0,98
10	0,94	0,91	0,91	0,93	0,93	0,95	0,97	0,99
11	0,93	0,87	0,88	0,88	0,89	0,94	0,95	0,98
12	0,89	0,8	0,82	0,87	0,88	0,9	0,92	0,97
13	0,9	0,77	0,83	0,85	0,87	0,89	0,9	0,96
14	0,9	0,83	0,85	0,88	0,9	0,93	0,94	0,97
15	0,92	0,87	0,89	0,92	0,92	0,95	0,96	0,98
16	0,95	0,92	0,92	0,92	0,93	0,94	0,95	0,98
17	0,95	0,9	0,9	0,91	0,93	0,94	0,95	0,98
18	0,95	0,91	0,91	0,92	0,93	0,95	0,96	0,98
19	0,94	0,87	0,87	0,88	0,88	0,94	0,95	0,98

FAN 30 – SOURCE 2

EDT(s) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,61	0,94	0,81	0,5	0,31	0,18	0,15	0,15
2	0,65	0,89	0,74	0,64	0,29	0,22	0,21	0,16
3	0,71	0,9	0,8	0,57	0,44	0,24	0,21	0,15
4	0,59	0,7	0,76	0,55	0,43	0,28	0,19	0,15
5	0,5	0,61	0,41	0,36	0,29	0,25	0,25	0,22
6	0,43	0,5	0,45	0,35	0,29	0,25	0,25	0,2
7	0,42	0,54	0,44	0,44	0,29	0,23	0,24	0,18
8	0,44	0,57	0,39	0,35	0,3	0,26	0,23	0,17
9	0,44	0,33	0,29	0,34	0,26	0,24	0,23	0,2
10	0,37	0,52	0,46	0,37	0,28	0,25	0,24	0,21
11	0,45	0,49	0,31	0,51	0,31	0,25	0,23	0,21
12	0,36	0,53	0,35	0,32	0,27	0,2	0,19	0,17
13	0,33	0,54	0,31	0,34	0,29	0,21	0,19	0,17

T30(s) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,86	0,98	0,92	0,84	0,83	0,91	0,96	0,48
2	0,82	0,91	0,87	0,84	0,87	0,97	0,96	0,54
3	0,8	0,95	0,88	0,86	0,91	0,97	0,95	0,53
4	0,76	0,92	0,87	0,88	0,94	1,1	1,13	0,53

5	0,72	0,88	0,8	0,86	0,88	0,9	0,89	0,43
6	0,72	0,85	0,79	0,83	0,79	0,86	0,93	0,47
7	0,68	0,86	0,78	0,82	0,77	0,88	0,88	0,43
8	0,75	0,88	0,8	0,83	0,85	0,98	0,99	0,49
9	0,73	0,86	0,77	0,8	0,81	0,99	1	0,48
10	0,72	0,85	0,82	0,97	0,92	0,97	1,03	0,51
11	0,72	0,86	0,82	0,8	0,81	0,92	0,97	0,46
12	0,72	0,81	0,77	0,76	0,8	0,85	0,84	0,44
13	0,68	0,81	0,82	0,81	0,84	0,84	0,84	0,47

SPL(dB) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	43	43,8	48,1	52,5	49,6	42,6	36,4	27,2
2	43,1	44,1	48,5	53	49,8	42,7	36,2	26,4
3	42,5	43,4	47,8	52,5	49,1	41,9	35,4	25
4	41,3	42,2	46,9	51,9	48,6	40,8	34,5	23,2
5	42,1	43	47,2	51,8	49	41,5	34,9	25,7
6	42,3	43,2	47,4	52,5	49,2	41,5	35,2	25,7
7	41,6	42,3	46,7	51,7	48,4	41,1	34,4	24,5
8	40,8	41,8	46,5	51,6	48,4	40,6	34	23,1
9	39,8	40,7	44,8	49,2	46,3	37,8	31,4	20,8
10	39,3	40,4	44,6	49	45,5	37,4	31	20,3
11	39	40,2	44,4	48,9	45	37,5	31	20,2
12	39,7	40,9	45,3	49,9	45,6	38,6	32,1	21
13	38,2	39,6	43,9	48,5	44,5	37,7	31,1	20

D50 simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,8	0,7	0,78	0,84	0,9	0,94	0,95	0,97
2	0,76	0,67	0,75	0,81	0,88	0,93	0,93	0,96
3	0,74	0,64	0,73	0,82	0,87	0,91	0,92	0,95
4	0,77	0,69	0,77	0,83	0,87	0,91	0,92	0,94
5	0,81	0,75	0,8	0,86	0,92	0,94	0,94	0,97
6	0,8	0,74	0,8	0,87	0,91	0,94	0,94	0,97
7	0,79	0,72	0,79	0,86	0,91	0,93	0,93	0,96
8	0,81	0,75	0,81	0,87	0,91	0,93	0,94	0,96
9	0,83	0,78	0,84	0,88	0,93	0,94	0,95	0,98
10	0,81	0,76	0,82	0,86	0,91	0,93	0,94	0,97
11	0,81	0,77	0,82	0,86	0,9	0,93	0,95	0,97
12	0,84	0,82	0,86	0,89	0,92	0,95	0,96	0,98
13	0,81	0,8	0,83	0,86	0,9	0,94	0,95	0,97

FAN 30 B – SOURCE 2

EDT(s) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,23	0,47	0,41	0,33	0,23	0,15	0,14	0,13
2	0,23	0,54	0,4	0,36	0,26	0,16	0,15	0,14
3	0,27	0,65	0,44	0,39	0,28	0,2	0,18	0,13
4	0,24	0,48	0,44	0,33	0,27	0,17	0,16	0,14
5	0,33	0,61	0,55	0,41	0,27	0,19	0,18	0,14
6	0,28	0,43	0,45	0,39	0,27	0,18	0,18	0,15
7	0,26	0,42	0,25	0,35	0,25	0,18	0,17	0,15
8	0,29	0,44	0,35	0,34	0,25	0,17	0,15	0,13
9	0,24	0,32	0,31	0,33	0,27	0,22	0,2	0,16

10	0,28	0,36	0,34	0,35	0,33	0,25	0,2	0,14
11	0,27	0,35	0,32	0,34	0,33	0,22	0,17	0,13
12	0,25	0,31	0,3	0,29	0,29	0,2	0,15	0,13
13	0,22	0,3	0,29	0,34	0,33	0,16	0,13	0,12
14	0,3	0,38	0,49	0,48	0,33	0,34	0,34	0,22
15	0,31	0,42	0,43	0,45	0,35	0,33	0,31	0,22
16	0,29	0,43	0,28	0,33	0,3	0,27	0,26	0,21
17	0,28	0,27	0,28	0,3	0,29	0,26	0,22	0,17
18	0,22	0,29	0,27	0,25	0,22	0,21	0,21	0,17
19	0,24	0,32	0,34	0,32	0,27	0,23	0,22	0,14
20	0,22	0,29	0,29	0,28	0,26	0,21	0,17	0,13
21	0,22	0,29	0,29	0,28	0,26	0,18	0,14	0,12
22	0,24	0,32	0,32	0,32	0,31	0,2	0,14	0,11

T30(s) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,61	0,81	0,76	0,73	0,77	0,84	0,87	0,48
2	0,6	0,8	0,75	0,78	0,79	0,88	0,86	0,46
3	0,55	0,76	0,72	0,71	0,78	0,83	0,87	0,47
4	0,52	0,71	0,72	0,78	0,88	0,93	0,97	0,49
5	0,66	0,72	0,68	0,79	0,81	0,99	1,02	0,54
6	0,62	0,74	0,71	0,85	0,85	0,89	0,92	0,54
7	0,61	0,76	0,68	0,79	0,81	0,94	0,87	0,46
8	0,53	0,74	0,7	0,73	0,79	0,81	0,83	0,46
9	0,58	0,74	0,69	0,8	0,85	0,9	0,92	0,5
10	0,59	0,69	0,68	0,73	0,83	0,94	1,01	0,48
11	0,53	0,71	0,67	0,8	0,87	0,94	0,91	0,52
12	0,52	0,68	0,72	0,85	0,88	0,89	0,97	0,54
13	0,52	0,69	0,68	0,76	0,81	0,89	1,01	0,56
14	0,57	0,74	0,67	0,71	0,75	0,86	0,85	0,44
15	0,59	0,72	0,69	0,67	0,7	0,78	0,82	0,48
16	0,55	0,76	0,76	0,79	0,82	0,89	0,9	0,5
17	0,56	0,74	0,66	0,69	0,77	0,84	0,87	0,44
18	0,53	0,65	0,68	0,71	0,75	0,8	0,78	0,45
19	0,55	0,7	0,64	0,68	0,74	0,78	0,79	0,59
20	0,55	0,69	0,62	0,7	0,74	0,76	0,8	0,51
21	0,48	0,65	0,62	0,7	0,76	0,8	0,81	0,54
22	0,46	0,65	0,66	0,76	0,81	0,86	0,86	0,51

SPL(dB) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	42,2	42,8	47,6	52,2	49,3	42,4	36,2	27
2	41,8	42,5	47,3	52,1	49,2	42,4	36	26,1
3	40,8	41,6	46,5	51,6	48,4	41,3	35	24,7

4	40,9	41,6	46,5	51,8	48,7	40,8	34,5	23,2
5	39,3	40,3	44,9	49,4	47,2	40,2	33,7	24,2
6	39	40	44,8	49,4	47	40,1	33,5	23,9
7	39	40,1	44,8	49,6	46,9	40,1	33,5	23,3
8	39,1	40,3	45,2	50,2	47,2	40	33,6	22,3
9	37,3	39,1	43,5	47,8	44,5	37	31,3	21,3
10	36,7	38,6	43,3	47,9	44,1	36,8	31	20,9
11	36,6	38,5	43,3	47,8	43,7	37	31	20,6
12	37	39,1	43,7	48,6	44,2	37,5	31,5	20,8
13	36,7	38,5	42,9	47,3	42,9	36,1	30,1	18,8
14	38	39,6	43,7	49,3	45,6	36,8	29,9	20,7
15	37,4	39	43,4	49,1	45,3	36,6	29,6	20,2
16	37,4	38,7	43,1	48,9	45	36,5	29,7	19,6
17	37,1	38,5	42,8	48,6	44,6	36,3	29,9	19
18	38,5	40	44,4	49,5	46,8	38	31,2	21,4
19	37,2	38,9	43,4	48,5	45,2	37,1	30,6	21,1
20	37,4	38,9	43,6	48,8	45	37,1	30,4	20,4
21	37,4	39	43,6	48,9	44,9	37,8	31,1	20,4
22	36	37,7	42,2	47,4	42,9	35,3	28,7	17,5

D50 simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,93	0,85	0,89	0,89	0,93	0,95	0,96	0,98
2	0,93	0,85	0,88	0,88	0,92	0,95	0,95	0,97
3	0,91	0,8	0,85	0,87	0,9	0,94	0,94	0,97
4	0,93	0,86	0,88	0,89	0,91	0,93	0,94	0,96
5	0,89	0,78	0,84	0,86	0,92	0,95	0,95	0,98
6	0,92	0,82	0,86	0,87	0,92	0,95	0,96	0,98
7	0,92	0,84	0,87	0,88	0,92	0,95	0,96	0,98
8	0,91	0,84	0,87	0,88	0,92	0,94	0,96	0,98
9	0,94	0,89	0,9	0,89	0,92	0,94	0,96	0,98
10	0,93	0,88	0,89	0,88	0,89	0,93	0,95	0,98
11	0,93	0,87	0,88	0,88	0,89	0,93	0,95	0,98
12	0,94	0,9	0,9	0,91	0,91	0,94	0,96	0,98
13	0,94	0,9	0,9	0,89	0,89	0,94	0,96	0,98
14	0,9	0,79	0,79	0,85	0,88	0,89	0,88	0,95
15	0,89	0,79	0,81	0,85	0,88	0,89	0,9	0,96
16	0,9	0,83	0,84	0,88	0,9	0,92	0,93	0,97
17	0,92	0,86	0,86	0,89	0,91	0,92	0,94	0,97
18	0,96	0,91	0,92	0,93	0,95	0,95	0,96	0,98
19	0,95	0,89	0,89	0,89	0,92	0,94	0,94	0,98
20	0,95	0,9	0,91	0,91	0,92	0,94	0,95	0,98
21	0,96	0,91	0,91	0,92	0,93	0,95	0,96	0,98
22	0,94	0,89	0,89	0,89	0,89	0,93	0,94	0,97

RECTANGLE – SOURCE 2

EDT(s) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,84	0,99	0,73	0,57	0,46	0,46	0,44	0,21
2	0,92	0,95	0,73	0,57	0,56	0,5	0,34	0,2
3	0,89	0,95	0,73	0,57	0,55	0,52	0,56	0,26
4	0,72	0,85	0,58	0,52	0,4	0,41	0,42	0,25
5	0,61	0,73	0,64	0,44	0,52	0,37	0,42	0,29
6	0,63	0,81	0,69	0,45	0,55	0,41	0,4	0,25
7	0,5	0,61	0,46	0,39	0,51	0,32	0,33	0,24
8	0,52	0,7	0,56	0,52	0,35	0,31	0,31	0,2
9	0,59	0,69	0,57	0,53	0,34	0,34	0,34	0,23
10	0,6	0,61	0,44	0,67	0,34	0,34	0,33	0,26
11	0,51	0,64	0,49	0,36	0,46	0,35	0,34	0,26
12	0,64	0,59	0,39	0,64	0,34	0,35	0,35	0,27

T30(s) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	1,05	1,12	0,99	0,96	0,95	1,02	0,98	0,5
2	1,01	1,07	0,96	0,9	0,95	0,99	0,94	0,57
3	0,97	1,02	0,93	0,9	0,87	0,93	0,89	0,56
4	0,91	0,95	0,85	0,83	0,86	0,88	0,88	0,49
5	0,85	0,93	0,88	0,8	0,78	0,9	0,9	0,52
6	0,89	0,96	0,87	0,84	0,95	1,19	1,15	0,5
7	0,82	0,89	0,81	0,79	0,82	0,86	0,82	0,42
8	0,8	0,86	0,78	0,75	0,8	0,82	0,76	0,46
9	0,79	0,84	0,77	0,76	0,75	0,81	0,79	0,44
10	0,78	0,85	0,82	0,77	0,78	0,78	0,8	0,54
11	0,85	0,9	0,84	0,75	0,76	0,81	0,81	0,54
12	0,83	0,88	0,78	0,79	0,77	0,85	0,83	0,53

SPL(dB) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	44,2	44,5	49,4	54,2	50,8	43,4	37,2	27,1
2	43,9	44,2	49,2	54	50,5	43,2	36,8	26,4
3	43,9	44,2	49,1	54	50,3	42,9	36,2	25,5
4	43,8	44,3	48,9	53,7	50,5	42,9	36,2	25,8
5	44,1	44,6	49,1	53,9	50,5	42,9	36,2	25,7
6	44,1	44,6	49	54,1	50,3	42,7	36	25,7
7	43,9	44,4	48,9	53,4	49,6	42,4	35,6	25,1
8	43,3	43,8	48,3	53,1	49,3	42,1	35,2	25
9	42,4	43,2	47,7	52,5	48,6	41,2	34,2	23,8
10	41,3	42	46	50,2	45,9	38,6	31,9	20,7
11	40,9	41,7	45,6	49,7	45,3	37,8	31,1	20
12	41,1	41,9	45,8	49,9	45,3	37,9	31,2	19,9

D50 simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,76	0,74	0,79	0,8	0,8	0,86	0,88	0,95
2	0,74	0,73	0,78	0,79	0,79	0,86	0,88	0,94
3	0,71	0,69	0,75	0,77	0,77	0,85	0,86	0,93
4	0,67	0,65	0,72	0,75	0,8	0,85	0,85	0,92
5	0,62	0,61	0,69	0,74	0,78	0,84	0,84	0,91
6	0,66	0,64	0,71	0,78	0,8	0,86	0,86	0,93

7	0,72	0,7	0,76	0,79	0,82	0,88	0,88	0,94
8	0,7	0,67	0,76	0,82	0,85	0,9	0,9	0,95
9	0,65	0,63	0,72	0,78	0,83	0,88	0,87	0,94
10	0,64	0,61	0,68	0,73	0,77	0,86	0,87	0,94
11	0,65	0,62	0,69	0,73	0,78	0,86	0,86	0,93
12	0,65	0,61	0,69	0,75	0,8	0,87	0,87	0,93

RECTANGLE B – SOURCE 2

EDT(s) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,67	0,77	0,67	0,55	0,55	0,39	0,36	0,21
2	0,7	0,94	0,66	0,49	0,47	0,35	0,33	0,19
3	0,83	0,96	0,74	0,56	0,54	0,55	0,41	0,21
4	0,56	0,68	0,59	0,38	0,33	0,34	0,34	0,2
5	0,61	0,66	0,54	0,41	0,37	0,34	0,34	0,22
6	0,71	0,85	0,77	0,49	0,53	0,45	0,46	0,22
7	0,4	0,49	0,67	0,56	0,59	0,31	0,3	0,2
8	0,5	0,46	0,57	0,5	0,46	0,32	0,3	0,19
9	0,57	0,38	0,52	0,31	0,54	0,32	0,3	0,21
10	0,47	0,59	0,52	0,35	0,52	0,28	0,28	0,26
11	0,37	0,43	0,54	0,47	0,36	0,32	0,32	0,21
12	0,74	0,8	0,65	0,6	0,46	0,55	0,33	0,27
13	0,41	0,34	0,54	0,53	0,54	0,3	0,29	0,17
14	0,52	0,43	0,59	0,87	0,71	0,54	0,44	0,25
15	0,45	0,61	0,58	0,35	0,59	0,34	0,34	0,22

T30(s) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,93	0,98	0,94	1,03	1,07	1,05	0,99	0,55
2	0,96	1,03	0,97	1,19	1,23	1,15	1,03	0,52
3	0,97	0,97	0,97	1,11	1,13	1,07	1,03	0,55
4	0,88	0,93	0,89	0,96	0,99	0,95	0,89	0,55
5	0,9	0,92	0,87	0,94	0,97	0,93	0,92	0,52
6	0,81	0,82	0,8	0,82	0,85	0,84	0,82	0,52
7	0,75	0,83	0,78	0,89	0,97	0,98	0,94	0,56
8	0,83	0,91	0,81	0,92	1,01	0,91	0,91	0,49
9	0,82	0,83	0,79	0,93	0,92	0,95	0,85	0,52
10	0,84	0,87	0,88	0,96	0,94	0,97	0,91	0,52
11	0,85	0,86	0,85	0,93	1	0,94	0,92	0,47
12	0,78	0,78	0,73	0,81	0,86	0,9	0,81	0,47
13	1,06	1,09	1,22	1,27	1,17	1,05	0,99	0,61

14	0,84	0,91	0,93	0,91	0,93	0,94	0,9	0,5
15	0,79	0,85	0,85	0,89	0,91	0,89	0,84	0,55

SPL(dB) simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	44,3	44,6	49,5	54,2	50,8	43,4	37,2	27,1
2	44,1	44,4	49,3	54	50,7	43,3	36,9	26,5
3	43,6	44	48,9	53,7	50,3	42,9	36,2	25,5
4	42,9	43,5	48,1	52,9	49,8	42,3	35,5	25,1
5	42,5	43,2	47,8	52,7	49,4	42,1	35,3	24,9
6	42,5	43,1	47,6	52,7	49,3	41,9	35	24,4
7	40,1	41,2	45,4	49,5	45,3	38,3	31,7	20,6
8	40	41,1	45,3	49,2	44,9	37,6	31,1	20
9	40,2	41,3	45,5	49,6	45,1	37,7	31,1	20
10	41,2	41,9	45,5	50,3	45,5	37,6	31,1	21,1
11	41,9	42,5	46,3	51,1	46,5	38,7	32,2	22,1
12	41,4	42,3	45,8	50,3	45,3	37,3	30,8	20,4
13	41,7	42,5	46,1	50,2	45,8	38,3	31,4	20,9
14	41,9	42,9	46,6	50,5	45,8	37,9	31,1	20,4
15	41,5	42,4	46,2	50,1	45,4	37,6	30,7	19,9

D50 simulated

Rec. no.	63	125	250	500	1000	2000	4000	8000
1	0,8	0,78	0,82	0,82	0,82	0,87	0,89	0,95
2	0,79	0,77	0,82	0,82	0,82	0,88	0,89	0,95
3	0,76	0,73	0,79	0,8	0,79	0,87	0,87	0,94
4	0,73	0,7	0,76	0,79	0,83	0,88	0,88	0,94
5	0,71	0,69	0,77	0,81	0,84	0,89	0,89	0,95
6	0,65	0,62	0,72	0,78	0,82	0,88	0,88	0,94
7	0,73	0,69	0,75	0,78	0,82	0,89	0,9	0,95
8	0,76	0,73	0,78	0,8	0,82	0,89	0,9	0,96
9	0,79	0,76	0,8	0,82	0,84	0,9	0,9	0,96
10	0,68	0,63	0,68	0,77	0,77	0,84	0,86	0,94
11	0,76	0,73	0,76	0,81	0,82	0,88	0,88	0,95
12	0,64	0,6	0,65	0,75	0,75	0,82	0,83	0,93
13	0,8	0,77	0,79	0,81	0,84	0,9	0,9	0,96
14	0,78	0,73	0,74	0,71	0,77	0,85	0,85	0,92
15	0,78	0,75	0,78	0,79	0,83	0,89	0,88	0,95