MASTER

The history of acoustic design before 1900

Postma, B.N.J.

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The history of acoustic design before 1900

Student: Bart Postma

Studentnumber: 0571598

Mentors: Prof. Ir. L.C.J. van Luxemburg
Ir. C.C.J.M. Hak
R.H.C. Wenmaekers Msc

Institution: Technical University Eindhoven

Faculty: Architecture, Building and Planning

Unit: Physics of the Built Environment

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Summary

This report studies why the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw are considered acoustically superior, while these were built before a deep scientific approach was common practice. Therefore, four aspects are studied:

1.) The acoustical knowledge during the 19th century,
2.) The practical applications used in architectural acoustics during the 19th century,
3.) The renovations which were done during the life of the concert halls,
4.) The origin of the reputations of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw.

1. Acoustical Knowledge

For the first aspect, sources about architectural acoustics that were published during the 19th century were studied. The work of Langhans, which was published in 1810, gained influence in this century. His statement that acoustics for music were different from acoustics for speech was important. Furthermore, a "slow fading sound", which he advocated, became accepted in concert hall design during the 19th century, and still is advocated within the acoustic design practice today. Before the 19th century, Vitruvius was the most influential writer about architectural acoustics. Despite the growing importance of Langhans' theories, also the work of Vitruvius was still advocated. His work was most influential on the application of wooden panels, which would resonate with the sound, and were used in most concert halls during the 19th century. Furthermore, his works were the basis of the "horse shoe" hall, which is still used for opera houses.

2. Practical applications

For the second aspect, the design process of six concert halls and opera houses was studied, including the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw. Langhans' and Vitruvius' theories were probably the basis of the design of most concert halls and opera houses, which were built during the second half of the 19th century. Two goals were likely relevant for acoustical design concepts during the second half of the 19th century. The most important goal was the distribution of sound over every position within the concert hall. Therefore, in the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw, two rows of columns were installed and the ceiling was covered with ornaments, which would scatter the sound. In the large concert hall of the Concertgebouw, the corners were rounded at the end where the orchestra played as well, for this purpose. The effect of these applications was studied using the room-acoustical-prediction model Odeon. It was shown that the predicted effect, by 19th century acousticians, was not measured with the currently used acoustic parameters and models. However, it was shown that further investigation is needed to establish the precise effects of these applications. These studies could include the influence of an audience and stage acoustics. The second goal in acoustical design during the 19th century was to achieve a "slow fading sound" within the concert hall. To achieve this, many reflecting surface finishings were used in concert hall design. Furthermore, for this purpose, many wooden panels were installed, because these surfaces would resonate with the music, and therefore enhance the "slow fading sound". Furthermore, in the Grosser Musikvereinssaal, hollow caryatid columns were designed, which would resonate with the music, like the "echea" of Vitruvius. The effect of resonance is questionable. Wooden panels are still used in acoustical design, though they are implemented to absorb sound energy of the lower frequencies. The two main design goals are still used in acoustic design. However, the importance of both goals has shifted and some other goals have been added. The way in which the sound distribution and the "slow fading sound" was attempted to achieve is questionable. At the end of both construction processes, acoustic tests were done. During these tests, the concert halls were judged on the two
main design goals, making the two design goals still the main purpose of concert hall design during the second half of the 19th century.

3. Renovations
For the third aspect, the renovations of both concert halls are studied using the room-acoustical-prediction model Odeon. In the Grosser Musikvereinssaal, the caryatid columns were moved to the side of the concert hall and the stage was widened. It was thought that this renovation of the Grosser Musikvereinssaal might have influenced the acoustic properties. However, it was shown that the renovation of this concert hall has not audibly changed the currently used acoustic parameters in the audience area. Only the apparent source width was probably audibly lower in some positions of the Grosser Musikvereinssaal. In the large concert hall of the Concertgebouw, the slope of the stage was reduced. This renovation was assumed to have heralded the famous acoustic properties. Simulations have shown that in the audience area the ratio between brass and string instruments was not or negatively affected. However, the acoustic circumstances on stage were probably altered. The amount of early reflections was diminished and the subjective level of sound probably became higher between the instruments positioned on the higher and lower parts of the stage. Further investigation is needed to establish the precise effects of these renovations.

4. Origin of the reputations
For the fourth aspect, sources are studied concerning the reputations of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw. The Second World War wrecked much of Europe and its structures. Numerous concert halls had to be rebuilt. The newly constructed concert halls were regarded as acoustically inferior to the music homes constructed before the war. During the 1960's, some studies were undertaken to discover more favorable properties of a concert hall. A byproduct of these studies was the lists of the most-liked concert halls. From these lists, the reputations of the acoustics of the Grosser Musikvereinssaal and Concert hall of the Concertgebouw are originated. Also, from the conclusions of these studies, more acoustical parameters that are used nowadays have evolved. The target values for these newly defined parameters were copied from concert halls that were considered acoustically satisfying, like the Grosser Musikvereinssaal and the last concert hall of the Concertgebouw. During the 1990’s, Haan et al and Beranek again studied the acoustically superior concert halls. Both confirmed the reputations of the Grosser Musikvereinssaal and the last concert hall of the Concertgebouw. There are two facts questioning the results of these last studies. Firstly, the subjects were probably biased because the reputations of both concert halls were very strong. Secondly, the acoustic properties of both concert halls have not fairly been compared with concert halls, which were built after 1962.
Acknowledgements

In front of you lies my thesis. For the result of the final product I am in debt to numerous people.

During my graduation project I have made use of many written sources. For chapter three I have studied the work of various 19th century acousticians like Rhode and Langhans. However, I have also used writings made during the 20th century from Izenour and Ströbel.

In chapter four I have described six different concert halls. For every concert hall I have referenced at least one book that guided me. For the section about the Musikverein, the works of Grasberger et al and Wagner-Rieger have guided me. For the second section, which was about the Palais Garnier, I naturally have made use of the work written by Garnier himself. However, the works of Steinhauser and Kahane et al were very helpful. For the section about the Festspielhaus I particularly have made use of the extensive books of Habel and Schuth. Little was known about the Tracadero Palace. Therefore, I have most prominently used the book of Morel, which is written in 1878. I have found little current information about this concert hall. For the Gewandhaus I have used the extensive studies of Skoda. He has written two books about the three concert halls, which were built in Leipzig and all carried the same name. Finally for the section about the Concertgebouw I have used the extensive works of Lansink who has recovered a wealth of information about the early years of the Concertgebouw.

Beside a literature study I have also visited various locations which helped me during my graduation. I have visited the city archives of Amsterdam and Leipzig. Furthermore, I have visited the archive of the Musikverein. I would like to thank the personnel who have been most helpful. Besides the Amsterdam city archive I have also twice visited the Concertgebouw. I would especially like to thank Alphonse Hutschemaekers for his help during these visits.

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1. General introduction

1.1. Work of Sabine

Wallace Clement Sabine is considered the founder of the scientific approach of acoustics. He was the first acoustic scientist to compose a scientific formula for acoustic design. In 1895, Sabine became involved in attempts to improve the poor acoustics of the lecture hall of the Fogg Art Museum. Sabine had the cushions of the seats of the Sanders Theater in Cambridge, which had good acoustics, transferred to the vestibule of the lecture hall in the Fogg Art Museum. At night, when it was quiet, he brought the pillows one by one inside the conference room. He measured the duration of tone with different configurations of pillows. He produced this tone by blowing on an organ pipe and timed the duration of the tone with a stopwatch. When he was finished with the lecture hall, he focused his attention on 10 other empty spaces, with different volumes and shapes. He selected these spaces for their silence during nighttime and the presence of enough reflective materials. The duration of tone was measured in the same way and the rooms were tested with different configuration of pillows as well. After he was finished, in 1898, he confined himself in his bedroom attempting to find a connection between different variables within the data. After two weeks he concluded, from these numerous measurements, that the sound absorption in a room multiplied by the reverberation time of the room was a constant number. This produced a hyperbola in a graph. Sabine, who lived with his mother at the time of his discovery, stumbled down the stairs and spoke in the kitchen the famous words: "Mother, it is a hyperbola". In 1900, Sabine used his discovery in practice for the first time. He became involved in the architectural process of the Boston Symphony hall, which could contain 2600 listeners. He copied the reverberation time of the Neue Gewandhaus, which was famous for its acoustic properties, and accommodated the amount of the absorbent and reflected material to the volume of the hall. In this way, he accurately created an excellent sounding room with a reverberation time of 1.8 seconds.

1.2. Problem

Before the reverberation formula of Sabine was developed, acoustic measures were based on trial and error or made because they seemed useful at other venues. After Sabine had composed his reverberation formula, concert halls could be tested on a scientific proven formula. Therefore, the design of the Boston Symphony hall can be regarded as the first known scientific approach in acoustics.

However, a remarkable fact occurs when this pivotal point is laid on the design process of the Boston Symphony hall and thus 1900. Nowadays, the Musikverein in Vienna, the Concertgebouw in Amsterdam and the Symphony Hall in Boston are generally regarded as acoustically superior. Both the Musikverein and the Concertgebouw were built and completed before 1900. The Musikverein was opened in 1870 and the first concert in the Concertgebouw took place in 1888. How is it possible that two of the three acoustically superior considered concert halls were built before there was any scientific acoustical approach?

Therefore in this research, the acoustic mores are considered of the period just before the definition of Sabine's formula. What was the state of the theoretical knowledge at the end of the 19th century? Which acoustical measures were undertaken by architects of musical venues in this period and were they effective? And, how did the reputation of the three acoustically superior considered concert halls arise?
1.3. Social interest

Because it is not obvious what the social interest is of a historical study, it is important to cover this subject. The usefulness of history is diffuse and difficult to define. This applies to history in general but for the history of acoustics as well: "Moderne historici geloven al lang niet meer dat er belangrijke lessen uit het verleden kunnen worden geleerd. Daarvoor is het verleden te veel verschillend van het heden. Er kan echter wel worden geconcludeerd dat een mens met compleet geheugenverlies geen mens is. Dit geldt ook voor een samenleving. Een samenleving zonder verleden mist cultuur, kunst en literatuur. Maar ook grotere zaken zoals samenhang en saamhorigheid" [quote 1] [Rossum, 2003].

For these reasons it is important to continue describing history. Although it is complex to specify the exact utility of history, it can still be argued that perhaps the simplest function of history is explaining why some things have been established. This function is pursued in this study. It describes how the acoustic measures during the design of several concert halls built before 1900 have been established. The second social interest of this research is filling the gap in knowledge of the acoustic design prior to the year 1900. During a brief literature review no sources were found that covered the acoustic measures during the design of concert halls built before 1900. Therefore, it is not clear why designers of different venues chose for certain acoustic measures and what the similarities between the various acoustic measures during the design process were.

1.4. Content of the report

In section 1.2 some questions emerged. In this report, attempts are made trying to answer these questions. This section explains in which order these questions are answered. The following chapter considers which changes in acoustical science were caused by the work of Sabine, before the Second World War. After the Second World War, the reputations of the three considered concert halls arose. The origin of these reputations is described in the second part of this chapter. The third chapter covers what theoretical knowledge was available at the end of the 19th century. Here, the opinions about different acoustic subjects of various important and lesser important acousticians of the 19th century are described. The subsequent chapter considers which acoustical knowledge was applied in the concert halls built at the end of the 19th century. Possibly, architects and scientists of that time differed in opinion about the acoustics of concert halls. Naturally, the Musikverein and the Concertgebouw are included. However, the design process of four other important concert halls and opera houses are described as well. The fifth chapter explores the influence of three different applications on the acoustics in the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw. This is done using the room-acoustical-prediction model Odeon. This software is also used for the research of the sixth chapter. This chapter explores whether the renovations of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw could have affected the acoustics. From the renovation in 1899, it is believed that it changed the acoustics of the large concert hall of the Concertgebouw, heralding the famous reputation. Finally, in the seventh and eighth chapter, conclusions are drawn from the information given in the previous chapters and recommendations are made for further research to this topic.

* Most quotes in this report are given in the language they are originally written in. For English translations see appendix 5.
2. Acoustic design in the course of the 20th century

2.1. Introduction

Wallace C. Sabine’s reverberation formula is still the foundation of most current acoustical parameters. Furthermore, for a long period, reverberation time was the only acoustical parameter used by acousticians. The reactions on Sabine’s work are described in the second section of this chapter.

During the Second World War many famous concert halls were destroyed. The newly built concert halls could not equal the acoustical qualities of the old ones. Therefore, studies were undertaken to find more acoustical properties than just the reverberation time. However, as a byproduct of these studies, the lists of acoustically superior concert halls would influence the architectural acoustics as well.

In these studies a number of conductors and music critics were asked to name their favorite music venues. From these questionnaires lists were made for the most liked concert halls. Therefore, these lists are subjective. In the final chapter, some other factors that could have colored the judgements of the interviewed person are mentioned.

2.2. Reactions on Sabine’s work

Sabine published his first findings on reverberation time in The American Architect in 1900. Six years later he followed up his first publication with an article on the absorption coefficients of a number of materials used in auditoria. Another six years later, a publication followed about the correction of acoustical difficulties. In the same year he discussed the acoustics of theaters in a paper. His two latest papers appeared at the start of the First World War. The first was about the sound transmission within buildings and the second considered whispering galleries [Sabine, W.C. 1922]. The First World War ended the endeavors of Sabine.

During the First World War, little progress was made on acoustical architecture. The field of interest changed towards using acoustics in the detection of airplanes and submarines. Furthermore, the localization of guns was required from military interest [Sabine, P.E. 1939]. Just two months after the war had ended Sabine died. Up until 1925, his stopwatch and ear method was the only means available for timing the reverberation. The old organ pipes were used as well. This changed around 1930 when microphones and sound sources, which evolved from the telephone, were invented. With the increasing knowledge of the human ear, the decibel scale was put into practice.
Finally, a number of acoustical societies were started, in various countries [Bruin, 2004]. Along with the improved techniques and grown interest came a remarkable increase in the field of acoustic measurements. The new techniques made it possible to evaluate the gradient of the reverberation curve. Reverberation rooms were built and a number of acoustical engineering companies were established. [Bruin, 2004]

During the thirties, Sabine’s formula became generally accepted. In 1932, a second serious reverberation formula was composed by Eyring. He derived his formula from earlier work of acoustical engineer Norris [Sabine, P.E. 1939]. The study of Beganal and Wood of 1931 is also worth mentioning. This study recommended an optimum line for the ratio between the volume of an auditorium and its reverberation time. This line is still used in acoustical design, today. [Sabine, P.E. 1939]

Between Sabine’s formula and the Second World War, a number of discoveries were made in the acoustical field. However, all of these studies were direct derivatives of Sabine’s work.

### 2.3. The origin of the reputations of the Musikverein, Concertgebouw and Symphony Hall

The Second World War ruined much of Europe and its structures. Among the destroyed buildings were a number of famous Concert halls like the Neue Gewandhaus in Leipzig and the Philharmonic in Berlin. Between 1945 and 1955, large parts of Europe have been rebuilt. Many new concert halls and opera houses were erected. However, the acoustics of these newly built concert houses could not equal the quality of the pre-war built music homes. It was assumed that this was caused by a lack of influence from acoustic consultants within the design team, and the lack of agreement about ideal reverberation time and room shape. Furthermore, the diffusivity of a concert hall and the properties of the decay curve were subject to discussion as well. [Winckel, 1958]

Therefore, studies were conducted to find the best acoustics in concert halls. From these concert halls the properties could be copied and implemented in new music houses. The first known research concerning this matter was published in 1952. Parkin et al studied the reverberation time and acoustical opinions of ten different English music halls. The acoustical opinions were obtained via questionnaires of music critics, professors of music and composers [Parkin et al, 1952]. A year later, a similar study was done by Somerville, who ranked British studios on their acoustic properties. In this study, the ranking was determined by the reputations they enjoyed among the program staffs and artists. [Somerville, 1953]

The first survey which globally ranked the acoustics of concert halls was done by Winckel in 1955. He statistically investigated which concert halls around the world were most liked, concerning their acoustics, among 40 leading conductors. During his research, the conductors were requested to name their six favorite acoustic venues. Winckel concluded that six concert halls were the conductors’ favorites:

- Musikverein, Vienna
- Concertgebouw, Amsterdam
- Symphony Hall, Boston
- Teatro Colon, Buenos Aires
- Konzert Saal, Göteborg
- Teatro San Carlo, Naples

However, Winckel mentioned that a number of great concert halls were not included in the research, because they were relatively new. [Winckel, 1955]

Leo Beranek is another acoustician who globally investigated the acoustical qualities of concert halls. In riding the waves, he described his journeys across the world visiting many concert halls and
conductors. He mentioned a meeting with famous conductor Herbert von Karajan, in Vienna. Von Karajan considered the Musikverein as one of the best concert halls in Europe. However, he preferred the Boston Symphony Hall over the Musikverein. Furthermore, he liked the acoustic properties of the Stadt-Casino of Basel as well [Beranek, 2007]. Beranek also interviewed conductor Leopold Stokowski, in New York. This conductor's favorite concert halls concerning the acoustics were: the Musikverein in Vienna, the academy of music in Philadelphia, and the Philharmonic in Saint Petersburg. According to him the Musikverein outranked both the Symphony Hall and the Concertgebouw. [Beranek, 2008]

During his travels, Beranek interviewed 44 conductors, musicians and music critics. The conclusions of his journey were presented in *Music, Acoustics and Architecture*, of 1962. Beranek classified the concert halls into five categories. When the classification was finished Beranek contacted the interviewed musicians and music critics to check the list. In general, they agreed with the list. However, the list was not published in this book. Instead, comparisons were made between liked halls and less liked halls. From these comparisons, it can be concluded which halls were rated excellent. Of the 47 investigated concert halls, 6 were put into the highest category [Beranek, 1962]:

- Musikverein, Vienna
- Concertgebouw, Amsterdam
- Symphony Hall, Boston
- Teatro Colon, Buenos Aires
- Stadt Casino, Basel
- Tanglewood music shed, Lenox

From these two studies, more acoustical properties and parameters have been derived and the acoustical science would evolve into what it is, today. For example, some important acoustical parameters were defined after the work of Marshall, in 1967 [Marshall, 1967]. From the 15 references used in his study, eight are from the book of Beranek, of 1962. Marshall argued that lateral reflections were important for the appreciation of the acoustics in music homes. This work was the basis for the definition the LF in 1981. [Barron et al, 1981]

However, this is not the field of interest of this study. A byproduct of these studies was a list of the acoustically superior concert halls. These lists were composed in a comparable way. Both studies used interviews with famous conductors. The results were comparable as well. Both Beranek and Winckel recommended for a concert hall the shape of a shoe box, a finish of plaster, and rough surface finishing. Furthermore, both studies enlisted six concert halls in the top category, of which four were equal. Of these four halls one is "horse shoe" shaped and three are shaped like a "shoe box". The hall which was "horse shoe" shaped, namely the Teatro Colon, is mainly used for opera performances. For these two reasons, it could be concluded that the Musikverein, Concertgebouw and Symphony hall were acoustically superior.

Both Beranek and Winckel mentioned these three concert halls in the following years. In 1970, Winckel mentioned them in a book about the Musikverein [Grasberger et al, 1970]. Beranek named these three halls in a paper, in 1975 [Beranek, 1975]. During the 1970's, the number of publications that mentioned these three halls as acoustically superior rapidly increased. During the 1980's the reputations of the three concert hall became established. Therefore, it is no surprise that these three halls were ranked top three in the following studies, which were carried out during the 1990's.

The first scientists with a renewed interest for acoustically superior concert halls were Fricke and Haan. These two scientists sent 110 questionnaires about 74 concert halls to professional musicians who regularly played in many auditoria. Of these questionnaires, 33 were returned. Furthermore, the responses of 40 music critics were obtained. The respondents reacted on 60 of the listed halls; eight were excluded
for various reasons. Of the remaining 52 concert halls, the Grosser Musikvereinssaal, the large concert hall of the Concertgebouw and Symphony Hall were ranked top three in this study [Fricke et al, 1996]. This research was published in the appendix of Concert halls and opera houses: How they sound, written by Beranek. In this book of 1996, Beranek expanded his earlier findings about acoustically superior halls, to take into account newly built concert halls. He again interviewed numerous conductors, musicians, and music critics. The interviewed persons were asked to rank all the halls they knew well. From his findings, Beranek again composed a list of 53 concert halls and opera houses, in which the Grosser Musikvereinssaal, the large hall of the Concertgebouw and the Symphony hall again were ranked top three. [Beranek, 1996]

2.4. Other factors

The outcome of both important studies seems relatively objective, because both studies were done by interviews of conductors and music critics which could judge the acoustics of more concert halls. However, multiple opinions are still subjective. Therefore, in this section a footnote is placed at the judgment of acoustics. There are various factors that could color the judgment of the music critics and conductors.

The most prominent factor is the quality of the orchestra that performs in the concert hall. In the last section, it was mentioned that the first studies of the best concert hall were performed in 1955. However, conductor Wilhelm Furtwangler considered the Wiener Philharmonic, royal Concertgebouw orchestra and the Boston orchestra as the top three orchestras around the world already in 1950. Furtwangler was one of the interviewed conductors in the studies of Winckel and Beranek as well [Royen, 1988]. In 2008, British music magazine Gramaphone declared the royal Concertgebouw orchestra as best of the world. The Wiener Philharmonic ended third and the Boston Symphony was listed 10th in the list which ranked the top 20 of symphonic orchestras.

Besides the quality of the orchestra, there are more factors that influence the acoustic judgement. From the taste of coffee during the brake, to the beauty of the hall and the city it is located in. Therefore, subjective acoustic judgement of a concert hall should be taken with a grain of salt.
3. Theoretical Knowledge

3.1. Introduction

The previous chapter was devoted to the subjective part of acoustics. In the rest of the report, the objective side of acoustics is treated. In the general introduction it was shown that two of the three acoustically superior concert halls were constructed before the first scientific approach was implemented in architectural acoustics. This chapter is devoted to what acoustical knowledge was available at the time of the construction of these two concert halls.

During the 19th century, the emphasis of acoustical science was mainly on musical acoustics. Scientists were interested in how different tones would sound with each other. The application of acoustics into buildings was to be found of a lesser importance. However, some scientists did write about architectural acoustics. The first written source about architectural acoustics is the fifth book of Marcus Vitruvius Polio [Morgan, 1960]. Vitruvius was a Roman architect, who lived one century before Christ. He described in ten books the main mores of contemporary architecture. In his fifth book, some chapters were devoted to acoustics. During the middle ages these writings were lost, not to be found again until 1500. From then, these writings were of considerable influence on the design of buildings with acoustic requirements. Until the early 19th century, his ideas were leading for most acoustic designs.

Due to the book of Carl Ferdinand Langhans (1781-1869), this changed. In 1810, he wrote *Ueber theater, oder, bemerkungen der Kataustik* [Langhans 1810]. In this book he elaborated on the acoustic design mores of the 18th century. Langhans can be regarded as the founder of acoustic design of the 19th century. In 1830, Ernst Florenz Chladni (1756-1827) also commented on architectural acoustics at the end of his book, *Die Akustik* [Chladni, 1830]. Chladni is an example of an acoustical scientist who was more interested in musical acoustics than architectural acoustics. His tests with springing sand have become world famous. Both Langhans and Chladni based their theories about architectural acoustics on *Theorie der Verbreitung des Schalles für Baukünstler*, a book written by Rhode. [Rhode, 1800]

3.1.1. Carl Ferdinand Langhans

3.1.2. Ernst Florenz Chladni

During the 19th century the interest in architectural acoustics grew, which made more acousticians wrote books about this subject. However, these writings have influenced acoustic design to a lesser degree. One of these scientists is Radau, who generally confirmed theories of Langhans in *die Lehre von Schall* [Radau, 1869]. In this book, he gave a complete overview of architectural
acoustics in the seventh decade of the 19th century. The last cited scientist is Lord Rayleigh (1848-1919). In 1896, the second version of *theory of sound* was published [Strutt, 1896]. This book is the foundation of many current theories about sound. However, it did not influence architectural acoustics in a fundamental way.

3.1.3. Lord Rayleigh

In this chapter, the theories of the above mentioned scientists are considered. The theories of other acousticians are included as well. Most of the cited acousticians published their work before 1870. This was the year the Musikverein was opened. The next seven sections will cover the opinions of the cited acousticians about seven different acoustic subjects. In the following section, the emergence of the two most prominent shapes for music halls is described: the "horse shoe" and the "shoe box". Where the "horse shoe" shape was almost universally applied in opera houses during the 19th century, the "shoe box" shape was amongst a number of discussed shapes for concert halls. This discussion is described in the last part of this section. It is a little step from the shape of an auditorium to the dimensions. The main guidelines on dimensions during the 19th century are described in the third section. In the first part the guidelines for length, width and height are covered. In the second part the opinions of the acousticians about volume are treated. The volume of an auditorium was dependent on the distance a voice traveled in the free field, which is described in this section. However, the volume was also determined by the interval between direct sound and first reflection. Acoustic scientists considered the sound arriving within a certain interval to be beneficial for acoustics and sound arriving after this interval harmful for acoustics. The reasons for taking this interval are described in the fourth section. This is the only numerical approach found in the acoustic design of the 19th century.

Because shape and dimensions affect the reverberation time, this subject is covered in the fifth section. During the 19th century, the vocabulary of acoustic scientists was different from the present. Echo and reverberation were sometimes used interchangeably. Sometimes, both referred to the sound arriving after the moment that the human ear could distinguish it from the direct sound. Other times, reverberation was called perceived sound, which was not distinguished from the direct sound. In this report reverberation is regarded as the tempo of the fading of sound. The reverberation time is influenced by the sound absorption of materials. At the start of the 19th century, materials were considered either absorbent or reflective. How this changed into a sound absorption coefficient during the 19th century, is described in the sixth section. Another property of materials is the way in which they scatter the sound. Vitruvius regarded sound scattering as beneficial for acoustics. During the 19th century, most acousticians defended this theory of Vitruvius. However, some rejected his theories. In the seventh section the opinions of different acousticians on this subject are treated. Vitruvius also was opinionated about the resonating wooden surfaces besides sound scattering. He considered these beneficial for acoustics. The ways in which this influenced the acoustic design of many music homes in the 19th century is described in the eighth section. In the last section of the chapter, the theoretical knowledge of the 19th century is compared to the current acoustical knowledge.
3.2. Shape of an acoustic space

As mentioned previously Vitruvius is the first known written source about acoustical architecture. He argued that the ideal shape of a theater is either Greek or Roman. Greek theaters were shaped like semi circles and Roman theaters were shaped like an equilateral triangle. Furthermore, according to Vitruvius the ideal seating arrangements were constantly ascending. This resulted in a democratic placing where each attendant would hear the sound in the same way without echoes. [Morgan, 1960]

Despite these arrangements, the acoustics of these theaters certainly did not satisfy. The performers wore specially designed masks which enhanced their voices. Furthermore, for competitions of poets, singers and orators, odeon’s were built, which were much smaller and located indoors. [Sturmhoefel, 1888]

Around the year 400, Christianity was widely recognized. The existing Roman basilicas were regarded as the most suitable buildings available for public worship of the Christian faith. Before that, a basilica is believed to have served the double purpose of court room and place for the transaction of commercial business [Smith, 1861]. All of the building’s arrangements had reference to the preceding function. For a judicial court some measurements had to be taken concerning the acoustics. For example, a judge must be understood by the attendees. A basilica was always of simple design, oblong and divided by two rows of columns into a nave, with two side aisles. The basilicas were models for the subsequent churches. In the Middle Ages theatrical performances were generally given in these churches. These performances were mostly religious festivities and processions. However, music performances, which were based on stories of the Old and New Testament, were given as well. [Sturmhoefel, 1888]

Throughout the Renaissance and the consequent secularization, performances were given at other venues instead of churches. Classic drama returned during the renaissance period. Because there was little diversity in the Greek and Roman architecture of theatre, and Vitruvius advocated the well known semi-circle shape, the choice of a form was relatively easy. The old shape of theaters was revived. However, these sites were now located indoors. [Langhans, 1810]

At the end of the Renaissance, the general shape of the audience area changed to accommodate a larger public. The ends of the public were extended so that a horseshoe formed with straight ends. [Sturmhoefel, 1888]

3.2.1. The standard shape of a basilica

3.2.2. Palladios Teatro Olympic, Vicenza
3.2.3. Teatro Farnese, Parma

During the 17th and 18th century, the common layout of theaters evolved further. The side walls of the auditorium did not stay parallel, but for practical reasons, were designed to approach each other. The resulting horseshoe shape is still the authoritative basic form of modern opera. [Sturmhoefel, 1888]

3.2.4. Scala, Milan

Though performances were given in churches during the Middle Ages up to the 19th century, little was done for the acoustics purposes. However, much was learned from these buildings in respect to acoustic design of theaters and concert halls. From these venues the "shoe box" shaped concert hall arose. This happened at the start of the 19th century. In 1800, Rhode considered the basilica shape advantageous for acoustics. This was mainly due to the two rows of columns which interrupted sound waves and thus spread the sound. Furthermore, he argued that the laws of the propagation of sound in tubes with parallel walls and in speaking-trumpets had been neglected too much in theater design. Therefore, he regarded side boxes, near the stage, as being very disadvantageous, as they absorbed the sound in excess. He considered straight side walls to be beneficial for the acoustics; they needed to be either parallel or diverging towards the wall opposite to the stage, and without decorations in relief. The ceiling ought not to be too high; it may be parallel to the pit or rising gradually towards the part of the house most remote from the stage. However, when these parallel side walls were applied, the back wall of the acoustic space needed to be absorbent. Therefore, the back wall opposite to the stage might form of a semi circle. An example can be seen in the Teatro Farnese, which is depicted in figure 3.2.3.. [Rhode, 1800]

The distinction between acoustic design for speech and for music was made for the first time at the beginning of the 19th century. In 1810, Langhans, in reaction on Rhode, regarded the rectangular shape as suitable for concert halls [Langhans, 1810]. In this shape, he considered rows of columns, or similar, to be ideal for the shattering of the sound. Therefore, he also defended the original basilica shape. Furthermore, Langhans explained how this form would work in a concert hall. However, he warned that in very large rectangular spaces, sound concentrations can occur at the corners. Therefore, right corners should be avoided. Langhans rejected the idea of an elliptical shape after the failure of the Iffland theater, which was designed by his father. He described that
in circular and elliptical shaped theaters, distracting sound concentration could occur.

3.2.5. Forms according to Langhans Jr.

This signaled the start of the "shoe box" tradition in concert hall design. The shape was adopted by Karl Friedrich Schinkel applying it in the Schauspielhaus in Berlin [Izenour, 1977]. 16 years later, Chladni described the form of a concert hall as well [Chladni, 1826-09-30]. He suggested that the acoustics in an enclosed room were dependent on size and shape. However, he regarded the shape to be more important. For the form of an acoustical space, he advocated shapes mildly equal to a shoe box hall. The basic idea behind these shapes was to make the interval between reflected and direct sound as small as possible. For the shape most comparable to the shoe box, Chladni considered that a parabolic form of the back wall at the end where the orchestra is positioned to be very suitable; the two branches of the parabola were designed to devolve into parallel straight lines. The sound should be produced exactly in the focus of the parabola. Therefore, the reflected sound would reach the attendees in directions parallel to the side walls. Furthermore, he was convinced that an amphitheatrical arrangement of seats was most beneficial for the acoustics.

That the "shoe box" hall was not without discussion is proven by Schilling and Smith. In 1848, Schilling regarded the oval shape ideal for a concert hall [Schilling, 1848]. However, when a rectangular shape was implemented, the corners should be rounded at the end where the orchestra is situated. Smith was not convinced that the "shoe box" hall was ideal for a music venue as well [Smith, 1861]. In 1861, he argued that the rectangular form was most liable to acoustic defect. The obvious method, to avoid these defects was to round the corners, either by a cant or a curve.

Unlike the two above quoted acousticians, the Radau defended the "shoe box" hall. In 1869, he differentiated between music and speech, like Langhans [Radau, 1869]. He argued that the back wall of a lecture hall should be of elliptic shape, as was described by Chladni. The speaker should be positioned in the focus of the arisen parabola so that his speech would be enhanced. For a concert hall, he considered an oblong shape with rounded corners most beneficial for the acoustics. With this form the sound propagation is best divided over the audience. Furthermore, Radau considered a concave rising line for audience arrangement better than a straight line, because in this way the attendees in the rear had a better sound line.

3.2.7. Form according to Radau

Finally, an article of the Centralblatt der Bauverwaltung of 1891 is quoted [Centralblatt der Bauverwaltung, 1891-05-16]. It mentioned a number of measures which were beneficial for acoustics. The round form of the dome of a church is beneficial for the church music, but not recommended for the
spoken word. The placing of the choir was regarded as essential to the acoustic properties of a church with a dome.

### 3.3. Dimensions

In addition to shape, the dimensions of an auditorium are also important. In his book of 1810, Langhans described the stages of a number of theaters [Langhans, 1810]. He showed that the most theaters had a stage width of around 13 meters. Therefore, he concluded that this was the optimal stage width.

In 1848, Schilling discussed the width of the podium as well. He argued that the general guideline for the stage’s width was between 21 and 11 meters. The depth should be only half of the length [Schilling, 1848]. Furthermore, the length, width and height of the audience area should always be in proper proportion, and he was convinced that the orchestra should rise several feet above the audience area and take the entire width of the room, so that all sound waves could only move in one direction.

In 1888, Sturmhoefel argued that to adequately hear the ensemble play of a 100-person orchestra, a distance of at least 18 meters is required. He mentioned that the ensemble play is observed better as the spectator is moved further away from the orchestra. He proved this using the examples of the opera houses in Berlin, Vienna and Paris, as examples, where the ensemble play is best perceived at the outer galleries. [Sturmhoefel, 1888]

It is clear that, wisely, most acousticians of the 19th century did not mention many real dimensions. Beside the dimensions of an acoustic room, the volume of a room with acoustic demands is discussed. In the 20th century, the importance of volume was widely accepted by the discoveries of Sabine. In the 19th century a number of guidelines were used to determine the volume of an auditorium. One is described in the rest of this section. The other is described in the subsequent section.

The first cited acoustician about this guideline is Rhode. In 1880, he described that after careful observations it had been established that the human voice in the free field is understandable up to 28 meters [Rhode, 1880]. These careful observations were made by Saunders. Rhode extensively described this experiment in his book. Saunders drew in a free field a circle with a diameter of 30 meters. On different distances from the center, where a speaking person was positioned, people were placed. The audience could hear the speaker best in front, worse to the left and right and only scarcely behind. Thereafter, Saunders tried multiple positions and concluded that the speaker was best positioned 17 meters behind the center of the circle facing the center. Furthermore, he found that the speaker was audible 28 meters to the front, 22 meters to both sides and 9 meters to the back [Saunders, 1790]. The finding on the distance a human voice travels in the free field of Saunders is quoted on most books from the 19th century on architectural acoustics. Therefore, it is reasonable to assume that his theories were important for acoustical design.

The first example to implement the theories of Saunders into his own works is Chladni. In 1826, he wrote an article about architectural acoustics in the Allgemeine Musikalische Zeitung [Chladni, 1926-09-30]. He stated that the acoustics of an enclosed space were dependent on shape and size. According to him, in a small room the acoustics depended on the natural propagation of sound. Therefore, music homes of humble sizes should be designed like amphitheaters. In larger enclosed spaces more precautions had to be taken regarding the acoustics. In these spaces it was necessary to rely upon

Preferably, the choir should be placed behind the head altar, not under the dome.
"strengthening by refraction of the sound" and "reflection of sound waves". Furthermore, he advised to create an acoustical space that was not larger than required by the destination of the building, because a large air space is harder to put in motion than a smaller one.

Another acoustician who used the work of Saunders, is Smith. In 1861, Smith confirmed that a voice in the open field is audible up to 28 meters. Therefore, he argued that a room with acoustic demand should not exceed 30 meters. However, he advocated that if the limits of direct radiation of sound were exceeded, the sound source should be placed near one extremity of the building, and the arrangement of the room should be made subservient to the aim of first imparting the sound in one initial direction. In essence any very large building, to be acoustically good, ought to have one dimension decidedly predominating over the others, and that dimension was usually its length. [Smith, 1861]

In 1888, Sturmhoefel expanded upon this guideline as well. Using the Royal Albert Hall and the Trocadero Palace as examples, he proved that this guideline was indeed correct. Both these concert halls were of great dimensions and had the acoustics were a failure. [Sturmhoefel, 1888]

Furthermore, some loose remarks of acousticians about volume are discussed. In 1835, Reid argued the need to exclude superfluous space when good acoustics are required, in the British Association Report [Davis et al, 1927]. In 1861, Smith argued that in all cases where distinctness of hearing and ease of speaking are the main essentials, and where musical effect is of secondary importance, it is right to diminish the volume of air contained in the room to smallest amount compatible with good proportion [Smith, 1861]. Furthermore, he explained that acoustic scientist agreed that a large space behind and above the speaker, and a large amount of air above the auditors, was detrimental for the acoustics.

Another aid for determining the volume of a music home was the time difference between direct sound and the first reflection determined.

3.4. Time difference between direct sound and reflections

The time difference between direct sound and the first reflections is the only numerical approach of architectural acoustics in the 19th century. During the 19th century, it was generally accepted that the time difference between direct sound and reflections described whether a sound was reverberant or echoic. When the reflected sound was perceived together with the direct sound it did benefit the acoustics. However, reflection perceived independent from the direct sound were echoic and harmed the acoustics. This theorem was not only the general guide line for the acoustic concepts of architects but also the aid for detection of acoustic errors after the construction of buildings with acoustic demands.

The first acoustic approaches of this theory were of the perceiving part. These scientists would consider the human hearing. In 1793, Gehler explained the difference between reverberation and echo in his physical dictionary [Gehler, 1793]. According to his conclusions, the human ear could only distinguish nine sounds per second. If the difference between direct and reflected sound is shorter than the ninth part of a second, the reflected sound is perceived together with the direct sound. When this interval exceeds 1/9th of a second, the reflected sound is perceived loose from the direct sound.

In 1800, Rhode established by careful observations that an echo was perceived together with the direct sound by the human ear, when the extra distance the echoic sound wave travelled did not exceed 60 feet, or 18 meters. This distance equals a time difference of
1/18th of a second. Rhode considered the reflected sound beneficial when it arrived within the first half of the interval, which was described by Gehler. Therefore, Rhode defended a relatively small acoustic space where every spectator was within 18 meters of the speaker. He believed that in this small room no echo would be present. Furthermore, he believed that the ground form of this theater did not matter. However, when the distance from speaker to audience exceeded 18 meters, the acoustic space is sufficiently large enough to make an echo possible, and that considerations have to be made on the shape of the acoustic room. [Rhode, 1800]

Langhans adopted the theory of Rhode [Langhans, 1810]. He confirmed that echoes occurred when reflected sound arrived 1/9th second later than the direct sound. Langhans considered reflections detrimental for the acoustics when they arrived 1/18th second later than the direct sound as well. Because speed travels at 340 meters per second, the extra path length of the reflected sound should not exceed 18 meters.

In 1848, Schilling described this theory as well [Schilling, 1848]. However, he changed the number of tones that was possible for a person to perceive in a second. He argued that the human ear was able to perceive ten different tones. This equals a time interval of 1/10th of a second. He also did not consider tones arriving within the second half of this time frame detrimental for the acoustics, unlike Rhode and Langhans. Therefore, the difference in traveled distance between direct sound and the first reflection should not exceed 34 meters.

Between 1848 and 1869, approaches of this theory changed from the perceiving part to the radiating part. From then on scientists considered the speaking tempo. In 1869, Radau confirmed that the human ear perceived useful reinforcement of sound within the first one-tenth of a second after the direct sound has arrived [Radau, 1869]. Reflected sound that arrived beyond this one-tenth of a second could be separately received and was thus considered disturbing. However, this was because a rapid speaker could say about ten syllables in one second. Therefore, a reflection which arrived later than one tenth of a second will coincide with the next syllable. Scientist adopted the theory of path length difference. This is shown by the adoption of both Guillemin in 1882 and Sturmhoefel in 1898. [Guillemin, 1882] [Sturmhoefel, 1898]

3.5. Reverberation

Before and during the 19th century, acousticians described reverberation as it is known nowadays: the slow fading of sound. The first cited acoustician and founder of the still-used reverberation theory is Carl Ferdinand Langhans [Langhans, 1810]. In his book, he elaborated on a design of Louis Catel who advocated dampening out all acoustical energy by covering the walls and ceiling of a theater with absorbent hangings. Langhans disagreed with this theorem. He explained this using the example of lighting arrangements within a room. When the surfaces of a room were covered with black materials and a light source was turned on, this room would seem much darker compared to the same room coated with white materials. Furthermore, the latter room would be a finer environment to live in. With the application of sound, he explained this as follows: "Ein nach und nach langsam verlöschen nachhall in kleinen und grossen Gebäuden ist angenehm und nothwendig, um uns den zauber der Musik der Töne geniessen zu lassen" [quote 2]

This theory of Langhans was ahead of his time. This is proven by the fact that scientists did not confirm it until the second half of the 19th century. Furthermore, what Langhans described is basically the first mention of a decay curve. Nowadays, the analysis of this curve is the most prominent occupation in the acoustical science. During the third decade of the 19th century the German architect Schinkel based a
The theories of Langhans were not undisputed during the first half of the 19th century. This is proven by Chladni, in 1826. He clearly distinguishes echo from reverberation. He argued that reverberation was a rapidly repeated echo. Chladni was convinced that the duration of reverberation should not exceed a small part of a second: "Ein nachhall, wenn er nicht zu stark ist, und nur sehr kurz, etwa nur durch einen kleinen Theil einer Secunde, dauert, wird allemal, sowohl bey einem Instrumente, als auch in einem Salle, einer guten Wirkung des Schalles mehr beförderlich, als nachtheilig seyn, weil sonst alles gar zu stumpf klingen würde. Wenn aber ein nachhall lange dauert, so dass man bey jedem Tone oder bey jeder sylbe noch die Wirkung der vorhergehenden forthört, so ist dieses en der Deutlichkeit sehr nachtheiliger Fehler, welcher möglichst vermieden warden muss". [quote 3] He was convinced that a long reverberation was usually caused by defect shapes. This statement is opposite to the works of Langhans. [Chladni, 1826]

However, the reverberation theory was generally put into practice, during the 19th century. This is proven by A rudimentary treatise on the acoustics of public buildings, written by Smith in 1861, and die Lehre von Schall, written by Radau, in 1869 [Smith, 1861] [Radau, 1869]. Smith explained that a degree of resonance is advantageous for music rooms. Radau made a distinction between two acoustic circumstances. He called a space with much resonance sonorous and called a space muffled when no resonance could be heard in any position. He applied this knowledge to existing buildings. In churches and other buildings, which were intended for lectures, long reverberation affected the speech intelligibility. However in concert halls, long reverberation times were pursued, with the sonority of the walls increased by implementing wooden sound panels. Furthermore, in 1872, Orth commented that the theories of Langhans had become the standard on acoustic design in the last 50 years. [Orth, 1872]

The first acoustician that nuanced the reverberation theory of Langhans was Sturmhoefel [Sturmhoefel, 1898]. In 1898, he argued that a space coated only with reflecting surfaces would have a long reverberation and thus become useless. However, a room without any reflections is useless as well. This is because the human voice cannot reach places in certain halls 50 meters or more distant from the source. In these cases reflections are mandatory. He basically argued that reverberation was mandatory however, he discouraged an overlong reverberation.

Furthermore, two examples have been found where the reverberation was measured, probably in the same way as Sabine, during the 19th century. The first found numerical approach of reverberation time dates from 1859. In an article in the Zeitschrift fur Bauwesen, Haege described the design process of an American lecture hall. During this design process, acoustical tests were done in several spaces. In a 17 meters square space an echo of 6 seconds was perceived. Due to the placing of boxes and other obstacles, the echo was diminished to 2 seconds. [Haege, 1859]

Another numerical approach was found in an article in the Centralblatt der Bauverwaltung, of 1891. It covered the acoustic conditions in Roman churches. The length of the echoes was counted. Within some churches it measured 16 seconds [Centralblatt der Bauverwaltung, 1891-05-16]. However, these are the exceptions that prove the rule. No more examples of numerical approaches have been found.
3.6. Sound absorption of materials

Also in the 19th century, it was known that reverberation was dependent on the sound absorption of materials. It was assumed that the laws of the transmission of light and sound were comparable. Because light was supposed to be absorbed or reflected by a surface, this also was assumed for sound.

However, it was unclear which materials were absorbent and which were reflective. There was a general consent that all soft materials absorbed sound. One of many advocates of this assumption was Reid, who mentioned that drapes could reduce reverberation [Davis et al, 1927]. This was confirmed by Smith who perceived a difference in reverberation time between an empty house and a house filled with furniture. [Smith, 1861]

Tyndall was the first to describe the absorbent properties of an audience [Tyndall, 1867]. On May 16, 1865, having to lecture in the Senate House of the University of Cambridge, he first conducted some experiments to measure the loudness of voice necessary to fill the room, and was dismayed to find that a friend placed at a distant part of the hall could not follow him due to echoes. When the room was filled with an audience, the assembled spectators quenched the sonorous waves, so that the echoes were practically absent, and his voice was plainly heard in all parts of the Senate House.

Some scientists considered rough surfaces to be absorbent. In 1835, Reid pointed out that reverberation time could be reduced by increasing the roughness or irregularity [Davis et al, 1927]. In 1861, Smith confirmed this theory; he regarded coffered ceilings as absorbent. [Smith, 1861]

In 1869, Radau summarized the general assumptions on the sound absorption of materials during the first half of the 19th century. "Vorhänge, Teppiche, und im Allgemeinen alle weichen Stoffe bringen diese Wirkung hervor, sie machen einen Sall dumpf, wie buntelfarbigen Stoffe ihn versintern. Deshalb hat auch das beste Piano wenig Ton in einem mit Teppichen und weichgepolsterten Möbeln angefüllten Zimmer" [quote 4] [Radau, 1869]. He also argued that a room filled with an audience is far less reverberant than a room which was empty [Radau, 1869]. Furthermore, he argued that the roughness of surfaces would decrease the reverberation as well.

The first mention of a sound absorption coefficient was done by Gabriel Davioud and Jules Bourdais [Morel, 1878]. In 1876, they designed the Trocadero Palace for the world exhibition in Paris. During the acoustic test in the concert hall, at the end of the construction process, they discovered that the cut between absorption and reflections of materials was not as rigid as thought. Many parts of the walls of the Trocadero Palace were covered with absorbent hangings. Especially during the tests with parts of great fortissimo, the absorption of these hangings was not complete and reflections were observed. Therefore, it was concluded that materials had an absorption coefficient.

This discovery was immediately questioned. In 1888, Sturmhoeefel still believed materials were either absorbent or reflective [Sturmhoeefel, 1888]. He was convinced that the high ceiling above the stage was the reason for late reflections which caused the bad acoustics.

The first known source who treated the absorption of materials mathematically was Lord Rayleigh [Strutt, 1896]. In the second edition of theory of sound, he argued that if the surface was not rigid porous, the material would absorb due to the vibration set up. When it was, sound waves penetrate into the pores of the material, and in this restricted space are dissipated into heat through viscous and allied actions.
In 1898, Sturmhoefel again discussed this subject. However, he was now convinced that materials indeed had an absorption coefficient. He demonstrated this with a simple example: "der merkliche unterschied der Klangstärke, wenn ein redner oder Sänger bei seinem Vortrage eine solche Draperie hinter sich hat und wenn er ganz frei steht" [Sturmhoefel, 1898]. Furthermore, he showed a number of materials with their corresponding absorption coefficients.

### 3.7. Sound scattering

Another property of materials is the way in which they scatter the sound. Sound scattering was a well described subject during the 19th century. In his book of 1810, Langhans advocated a homogenous sound field in a concert hall [Langhans, 1810]. He considered a series of columns, caryatides, console etc. from the front to the back of the music home ideal for this purpose. Furthermore, he argued that flat surfaces would be detrimental for their sound concentrating properties. To prevent this, he described the effects of convex wooden surfaces or stucco ornamentation, which were normally installed for decorative purposes. These would spread the sound and enhance the homogenous sound field. These theories were based on the book of Rhode.

#### 3.7.1 Convex surfaces by Langhans

However, the use of sound scattering was not without discussion. In 1848 Schilling took up position against the statement of Langhans, in his Akustik oder die Lehre von Klangen [Schilling, 1848]. He argued that decorations would lead to echoes. Therefore, he defended smoothened surfaces. However, Schilling is the only found acoustician opposing Vitruvius and Langhans. In the same year, Lachez defended sound scattering. He argued that coffered ceilings, ornamental niches, vaults etc. add to the resonance of concert halls by augmenting the sum of confused noises. These ornaments made little cubes of air vibrate each in their own corresponding vibrations and therefore enhance the reverberation.

These theories were still practiced in the seventh decade of the 19th century. This is proven by Smith and Radau. In 1861, Smith regarded smooth unbroken walls and ceiling liable to foster echoes [Smith, 1861]. Therefore, it was probably always safer to break up these surfaces, according to Smith. This was done by the introduction of columns, roof timbers, and similar features. Smith regarded this of special importance in those parts of the internal surfaces of the building upon which the rays of sound fall at a very flat angle.

In 1869, Radau considered flat surfaces an obstacle for good acoustics as well [Radau, 1869]. He argued that these surfaces increased the risk of echoes. As an example, Radau mentioned catholic churches. The acoustics of catholic churches were good as long as they were decorated. When these churches were striped from decorations echoes occurred. In 1891, the Centralblatt der Bauverwaltung published an article about the acoustic properties within a church [Centralblatt der Bauverwaltung, 1891-05-16]. The author considered a coffered wooden ceiling, which was used in many basilicas, beneficial for the acoustics, for its sound scattering effect.
3.8. Resonating surfaces

The most used material in concert halls in the 19th century was wood. According to the contemporary architects, wooden panels resonate with the music and therefore enhance the acoustics. The assumption of the beneficial effect of wooden resonating surfaces is virtually undisputed during the 19th century. The influence of Vitruvius on concert hall design is most felt on this subject. However, the oldest known example on this subject is not Vitruvius, as many people may think. In the 4th century B.C., Alexander the Great would have ordered a stone stage for a podium of a theater in Pella. However, the architect refused to implement this podium and rather would have constructed it of wood, because: "the voices of the actors would lose their strength" [Sturmhoefel, 1888]. This theorem was defended by Vitruvius [Morgan, 1960]. He concluded that the major difference between Roman and Greek theaters was the construction material. Roman theaters were made of wood where Greek theaters generally were constructed from stony materials. Vitruvius argued that wooden theaters contained a lot of boarding, which was considered resonant and sounded better than theaters constructed with masonry stone or marble, materials which were not resonant. According to Vitruvius, the stage should be constructed of wood as well, for its resonation with sound. However, when the theater was constructed from stony materials, Vitruvius advised echoa to be installed between certain rows of seating. These echoa were inverted vases that reinforced the voices of the actors by the resonance of small bodies of air, which they enclosed in brazen jars. The reinforcing agent was considered not the material of the jar, but the mass of air contained in it.

Much information about acoustic design was lost during the Middle Ages. There are no documents left describing acoustics of this period. In 1800, Rhode explained the assumed operation of the resonating surfaces: "Der Schall wird durch Schwingungen des Schallenden Körpers hervorgebracht. Diese Schwingungen theilen der Luft eine Erschütterung mit, welche den Schall verbreitet. Treffen diese Erschütterungen auf elastische Körper, welche in Bewegung gesetzt, eben solche Schwingungen hervorbringen, al ser Körper welcher der Luft Erschütterung mit theilte, so gerathen sie bloss durch diese Erschütterung der Luft in Bewegung, und bringen einen ähnlichen, obgleich schwächer Ton hervor, wodurch der erste verstärkt und weiter verbreit wird". [quote 6] [Rhode, 1800]

In 1810, Langhans advocated wooden resonating surfaces as a consequence of his reverberation theory [Langhans, 1810]. He argued that to create reverberation, it is not sufficient to reflect the vibrating air particles, because otherwise any surface of a firm hard body would duplicate the sound. It seems necessary for the reflecting object to have a hollow vaulting which concentrates the diverging beams of sound like a concave mirror to the place where the reverberation can be heard.

This theory was defended by two acousticians in the sixth decade of the 19th century. Firstly, Smith regarded resonating surfaces, especially made of wood, beneficial for the acoustics, 1861 [Smith, 1861]. In his book, he argued that the vibrations of these surfaces were of great value in reinforcing an original sound. Furthermore, this resonation would add character to the sound that it did not naturally possess. He argued that in theory the employment of wooden linings cannot fail to improve acoustics, and in practice will be found to have afforded great advantages. Secondly, Radau considered thin plates of glass, metal and wood in particular, to have a peculiar ability, in 1869 [Radau, 1869]. These materials could resonate with the sound vibrations, which increased the sound under certain conditions significantly. Therefore, Radau argued that the common choice for concert halls was wooden sounds panels in front of a cavity.
Statements from two different acousticians prove that this theory was still adhered at the end of the 19th century. In 1896, Lord Rayleigh stated in his *theory of sound* that it was strongly recommended to construct music homes of wood [Strutt, 1896]. Especially for large spaces this would lead to a desired resonance. However, this resonance would be too strong for little spaces. In 1898, Sturmhoefel regarded resonating surfaces as beneficial for the acoustics as well [Sturmhoefel, 1898]. He compared the resonance box of a violin with a resonating surface. He argued that a violin without a resonance box sounds much worse or not at all. He specially recommended the resonance of a stage.

### 3.9. Comparison between contemporary and current knowledge

In two found cases the reverberation time was counted, just like Sabine did in the lecture hall of the Fogg Art Museum [Haegel, 1859] [Centralblatt der Bauverwaltung, 1891-05-16]. Furthermore, both Sturmhoefel and Rayleigh proposed an approach in which the sound absorption coefficient could be determined numerically, at the end of the 19th century [Strutt, 1896] [Sturmhoefel, 1898]. However, Sabine’s discovery to link volume and reverberation is still admirable, but a logical consequence of the work done at the end of the 19th century [Sabine, 1922]. In the rest of this section the acoustical knowledge of the 19th century is compared with the current knowledge.

The “shoe box” shape, which was used in both the design of the Musikverein and the Concertgebouw, is derived from basilicas. This shape was considered beneficial for the acoustics by both Rhode and Langhans [Rhode, 1800] [Langhans, 1810]. During the 20th century, other shapes for concert halls were designed. These were called the fan and vine yard shape. According to current acousticians these shapes provide more lateral reflections, which make the audience more enveloped by the music [Marshall, 1967] [Morimoto, 1989]. Therefore, these shapes are considered more beneficial for acoustics than the “shoe box” shape. The “horse shoe” shape originated from the theaters of the ancient civilizations [Sturmhoefel, 1888]. This form is still applied in most opera houses and is regarded as acoustically satisfying. [Beranek, 1996]

Few acousticians have described dimensions in the 19th century. According to Langhans and Schilling, the width of the stage should be around 13 meters [Langhans, 1810] [Schilling, 1848]. Furthermore, two aspects were mainly used for determining the volume of an acoustic space. The first one was the distance the human voice traveled in the free field. The experiments about this distance were described by Saunders in a book of 1790, and would influence the acoustic design of the 19th century [Saunders, 1790]. Nowadays, the distance that the human voice travels in the free field, is not used anymore in concert hall design. The other aspect for determining the volume of an acoustic room was the interval between direct and reflected sound. During the 19th century, reflections arriving within the first 1/10th second after the direct sound were considered beneficial for the acoustics, and reflected sound arriving later than 1/10th second was regarded detrimental for acoustics [Radau, 1869]. These findings are not used to determine the volume of an acoustic space anymore, due to the work of Sabine [Sabine, 1922]. However, the time difference is still considered in architectural acoustics. Nowadays, an acoustic parameter is used to describe this property. With the C80, the sound arriving within the first 80 ms is compared with the sound arriving after the first 80 ms. [Reichardt et al, 1975]. When this parameter is relatively high, the audience can understand and locate single instruments relatively easy and these rooms are more suitable for speech.

The description of reverberation by Langhans influenced the acoustical design of many concert halls in the 19th
century. A "slow fading sound" is still advocated by current acousticians for concert halls [Langhans, 1810]. However, too long reverberations are considered detrimental for acoustics, like Sturmhoefel argued, at the end of the 19th century [Sturmhoefel, 1898]. This theory is supported by the current acousticians. However, the ideal reverberation times for concert halls are still subject to discussion. The statement of Langhans about reverberation appears to be opposed to the interval between direct and reflected sound. The reverberation theory of Langhans was intended for music where the interval between direct and reflected sound was intended for speech. However, the interval was used in concert halls as well, which is shown in the subsequent chapter.

Radu illustrated with a clear observation that 19th century acousticians were aware that the absorption of materials influences the reverberation [Radu, 1869]. At the start of the 19th century, materials were acoustically regarded as either absorbent or reflective. Due to the experiments in the Trocadero Palace this changed into the correct assumption that materials possessed a sound absorption coefficient [Morel, 1878]. At the end of the 19th century both Rayleigh and Sturmhoefel proposed an approach to how these sound absorption coefficients could be determined [Strutt, 1896] [Sturmhoefel, 1898]. However, the current measurement of sound absorption coefficients of materials is based on the work of Sabine. [Sabine, 1922]

Sound scattering was generally advocated by acousticians during the 19th century, for its sound dividing effect [Morgan, 1960]. Nowadays, the rough surface finishing is advocated to prevent echoes from occurring. However, the above mentioned localization of instruments, which is easier when the surfaces finishing are smooth, is considered important as well. Therefore, acoustic counselors seek a balance between both applications.

Vitruvius' influence was most felt on the implementation of resonating wooden panels [Morgan, 1960]. The resonation of panels is one of the most strongly discussed acoustical subjects of the 19th century. It was, without exception considered beneficial for the acoustics of a concert hall or opera house. However, wooden panels on cavities are not set in motion by sound produced by an orchestra. Therefore, it can be concluded that the resonation of panels is wrongly implemented during the 19th century. Wooden panels on cavities are still used in the current architectural acoustics. Nowadays, these panels are used to absorb the sound of low frequencies.

Some aspects of current architectural acoustics were unexplored terrain in the 19th century, like lateral reflections. Chladni defended his rectangular shape with the elliptical back wall, with the argument that this wall would reflect the sound in the same direction of the parallel walls, these reflections arrive thus from the front of the listener [Chladni, 1826-09-30]. Currently, it is generally thought that the Musikverein and the Concertgebouw thank their acoustic appreciation due to a great amount of lateral reflection. It is generally assumed that these lateral reflections give a feeling of apparent source width and listener envelopment, which is appreciated. [Marshall, 1967] [Morimoto et al, 1989]

When the theoretical knowledge of the 19th century is considered, some remarkable aspects were already described by this time, like the sound absorbing coefficient of materials and the reverberation, proposed by Langhans [Langhans, 1810]. Some acoustical experiments were undertaken, like Saunders with the human voice in the free field and Sturmhoefel with the sound absorbing coefficient of materials [Saunders, 1790] [Sturmhoefel, 1898]. However, these experiments were not mathematically confirmed. Most knowledge was acquired from empiricism because 19th century acousticians did not have any means to measure the sound energy. Many of these empirical assumptions have been overtaken by
time, like the resonating panels, or have been nuanced, like the sound scattering. The main defect of the acoustic knowledge during the 19th century stemmed from the assumption that materials either absorbed or reflected the sound. Therefore, only the first reflection was taken into account for acoustic design. Nowadays, many more reflections are considered, up to 1000 of orders, for example with ray-trace models.
4. Practical applications of the 19\textsuperscript{th} century

4.1 Introduction

In the previous chapter, it was shown what theoretical assumptions were made about architectural acoustics and which scientist made them. However, some of the considered books were written after the concert halls were built, which are described in this chapter. For example, at the time the Musikverein was constructed, it was generally assumed that materials were either absorbent or reflective. Between the construction of the Musikverein and the Concertgebouw, it was discovered that materials possessed a sound absorption coefficient. In this chapter, it is shown whether and how the knowledge, described in the previous chapter, was put into practice.

Due to a growth in population and wealth, caused by the industrial revolution, the number of concert halls increased during the second half of the 19\textsuperscript{th} century. Also, the seating capacity of these new concert halls increased. The acoustic properties of these concert halls and opera houses became more important. This was due to two reasons. The first reason is that acoustics are more critical in larger halls. Lacking in acoustical knowledge, architects could not predict reverberation times, which in more voluminous spaces led to longer reverberation times. Furthermore, the attitude of the audience during concerts changed. At the start of the 19\textsuperscript{th} century, spectators visited concerts and operas for social purposes. People talked during the music performances, even conversations were held from the parterre to the box seats and galleries. As the 19\textsuperscript{th} century progressed, this changed. People started to pay attention to the performances and were silent during concerts.

The Musikverein in Vienna was the music home that started the concert hall tradition. This concert hall soon became a standard hall, and today it is regarded as an auditorium with perfect acoustical conditions. In continuation of the Musikverein a new concert hall was built in Leipzig, which was another musical center of Europe. Here the Gewandhaus became too small and was replaced by the Neue Gewandhaus. This soon became a concert hall of standard as well. However, it was destroyed during the Second World War. Part of the acoustic concept of the Neue Gewandhaus was copied from the acoustic concept of the Trocadero Palace built in Paris. Though the acoustics of this concert hall failed, it was an important learning moment for acoustical design. Probably, acoustic aspects of the large concert hall of the Concertgebouw in Amsterdam are copied from the Neue Gewandhaus. The acoustics of the large hall of the Concertgebouw became famous after a number of renovations, and the hall is currently considered acoustically superior together with the Musikverein and the Symphony hall.

Furthermore, two famous opera houses were constructed during the second half of the 19\textsuperscript{th} century: the Palais Garnier in Paris and the Festspielhaus in Bayreuth. The contrast between the acoustic concepts of these two is large. Garnier, who was the architect of the Palais Garnier, is believed to have left the acoustics to coincidence. On the other hand, Wagner, who was the creator of the Festspielhaus, is believed to have designed the concert hall’s acoustics to his exact demands. The still-existing four concert halls and opera houses are depicted in figures 4.1.1., 4.1.2., 4.1.3. and 4.1.4..

The construction of the six concert halls are considered in this chapter. This is done using six different sections per hall. In the first section, the reasons for constructing the concert hall are described. The general question of this part is why the concert hall was built and what starting points both client and architects had. In the following section, the career of the architect is considered. Hereby, the general wondering is what experience the architect had with
buildings with acoustical demands. In the third section, the construction process is mentioned. It is described here, which changes are made due to acoustic reasons. The important milestones in the construction process are mentioned as well. In the fourth section, the design of the concert hall is described. This is done to give a general image of the concert hall, when it was opened, and what could be expected from an acoustical standpoint. The most important section is the fifth, wherein the acoustic concept is considered. It will become clear in this part which theoretical knowledge was used in the six considered concert halls. However, acoustic measures are also applied, which were used due to experience or were copied from other concert halls. In the sixth section, the aftercare of the concert halls is mentioned. In this part, the reaction on the acoustics of the concert hall is given. Furthermore, the changes in the design, which could have influenced the acoustics after the opening are mentioned. Finally, the current view on the acoustics of the concert hall is given.

In the final section of this chapter, it is concluded whether the acoustic concept or measures in different concert halls worked. Furthermore, the contemporary knowledge is compared with the current approach of acoustic design.
4.2 The Musikverein in Vienna (1870)

4.2.1 History before the Construction

The Gesellschaft der Musikfreunde increasingly experienced that their music halls no longer met requirements. The old Redoutensaal and the opera house did no longer fulfill the growing demands and the existing conservatory was outdated. Therefore, the Gesellschaft der Musikfreunde had hoped for a costless lot for a new concert hall from 1858 on. Emperor Franz Joseph fulfilled this wish with a lot opposite to the trade academy on February 27, 1863 [Wagner-Rieger, 1980]. This lot was in the area that was vacant after the emperor had decided to demolish the fortification of the city. This area became known as the Ringstrasse, where numerous famous Viennese buildings were constructed. [De opmerker, 1891-02-28]

Two design sketches were made before the plot was promised. Board member Karl Rösner made a sketch, which had a smaller area than the lot given by the emperor. From this plan the financial resources were copied for the construction. Moritz van Lohr proposed another design on October 12, 1859. From this design, the style of the building was copied. [Wagner-Rieger, 1980]

The emperor had a number of demands, when the lot was transferred. The building was required to meet a number of aesthetic demands and the construction should have been performed without any interruption. [Wagner-Rieger, 1980]

Three architects were invited to participate in a competition. The competition asked for a music home with a large and small music hall. The large hall needed to be suitable for symphonic music, and the small hall for chamber music. Both concert halls were also intended for large dances and festivities. Furthermore, good artificial lighting was required. This is because there were no concert halls in Vienna with suitable artificial lighting. Therefore, concerts were usually held during day time. However, sufficient day light was required if artificial lighting was not needing during day time. It was demanded, that this daylight would not enter via the ceiling because this would complicate the construction and harm the acoustics. [Köstlin, 1870]

The two submitted projects were exhibited in the trade academy between April 18 and 25, 1864. The design of Theophil von Hansen was declared the winner early October 1864. However, the judges declared that it was necessary to adjust the design. Hansen changed his design and it was approved in December 1864. [Hansen, 1870]

The emperor, musical nobility and aristocracy were expected to finance a share of the building. Furthermore, it was hoped that fundraisings would provide a significant contribution. Finally, revenues were anticipated from the sale of box seats in the new concert hall. [Wagner-Rieger, 1980]
4.2.2. The architect

Theophil Ritter von Hansen was a Danish architect. He was born in Copenhagen July 13, 1813. He started his studies at the academy of Copenhagen in 1827 with the help of his ten-year-older brother. Like his brother, Von Hansen became an art teacher and in 1831, without any further study, he got the architect title. His career buildup was normal, designing a number of smaller buildings at the start of his career. [Wagner-Rieger, 1980]

Von Hansen decided to leave Copenhagen at the start of 1838. On May 21 of the same year, he departed Copenhagen to live for five weeks in Berlin where especially the buildings of Schinkel inspired him. After much wandering through various European cities, he finally arrived in Athens at October 8, 1838. He worked here for eight years and fell under the influence of the Athenian architecture. [Wagner-Rieger, 1980]

Since 1845, Von Hansen contemplated about a migration to Vienna. He responded to this wish in March 1846. In Vienna, the influence of Athens remained in his work until 1859. In his early Viennese years he collaborated with Christian Ludwig Förster, until 1852. After this partnership ended, Von Hansen designed a number of churches and synagogues in Vienna. [Wagner-Rieger, 1980]

In 1859, a change occurred in the career of Von Hansen. A design competition was held because the emperor had decided to demolish the fortification of Vienna. Therefore, many plots of land became available for new buildings. Von Hansen won this competition and changed his style of designing, after a request of the emperor. Before this competition, he was only asked for military and religious structures. After he won the competition, he was asked for dwellings and utilities as well. [Wagner-Rieger, 1980]

Von Hansen entered the competition for the Musikverein on November 27, 1863. Before this competition he had little experience designing buildings with acoustic requirements. He had designed some churches and synagogues. [Wagner-Rieger, 1980]

The highlight of the career of Von Hansen came with the design of the Austrian building of parliament. He was involved with this building between 1869 and 1883. The period between 1883 and 1891 was characterized by a number of large projects which were not realized and the construction of a large library in Athens. These designs did not equal the qualities of the previous projects. [Wagner-Rieger, 1980]

After a long illness, Von Hansen died on February 17, 1891 at the age of 78 in Vienna. [De opmerker, 1891-02-28]
4.2.3. The construction

After Von Hansen had modified his original design, it received planning permission on April 11, 1866. Exactly three months later, on July 11, 1867, his compensation was agreed upon after he finished the detailed map. The construction of the new music building started on June 17, 1867. [Wagner-Rieger, 1980]

The construction of the foundations was difficult due to the proximity of an underground River. Therefore, additional financial resources were used for the foundations and this caused a deficit for the further construction. For this reason, a crisis arose within the construction committee. The constructions came to a standstill at the end of 1867. Two months later, constructions were resumed on February 24, 1868 [Wagner-Rieger, 1980]. The extra financial resources were made available by influential people.

The First two floors were completed in the October 7, 1868 [Allgemeine Musikalische Zeitung, 1868-10-07]. In the same month, a model of the new music building was exhibited. [Wagner-Rieger, 1980]

The envelop of the Musikverein was completed on December 1868. At the start of the next year, the construction of the decorations was started. In the spring of 1869 Von Hansen became ill, and led the constructions from his sickbed. After May 1, 1869, the cellar and the mezzanine premises were rented. The music academy was opened in the Musikverein on October 4, 1869. At the end of the construction process, the usual acoustic tests were held in the large concert hall. These tests satisfied the highest levels of requirements. [Köstlin, 1870]

The last constructions were speeded to finish the building before the deadline. When a last loan was closed in late autumn 1869, the final stone was placed on December 31, 1869 [Köstlin, 1870]. This was celebrated with a large banquet in honor of the architect and the artists who had decorated the exterior and interior of the Musikverein, on January 5, 1870. [Morgen-Post, 1870-01-06]
4.2.4. The design

When the Musikverein was opened, it accommodated two music halls: one smaller auditorium for chamber music and a large hall for symphonic music. Later, another small concert hall was added, which was also used for chamber music. Furthermore, the Musikverein accommodates numerous musical functions. In this section, the original configuration of the large concert hall or the Grosser Musikvereinssaal is described.

The entrance of the large hall is located on the second floor. The hall is shaped like a “shoe box” with a ratio of height, width and length of 1-1-2. The concert hall is 40.2 meters long, 19.8 meters wide and 17.4 meters high. At the back and side walls boxes were positioned. Above these boxes, galleries were positioned at a height of 3.6 meters. These galleries are supported by caryatid columns. At a height of 7.7 meters an additional gallery is positioned at the back wall.

The illumination during day time comes from large windows which are positioned high in all four walls. The illumination at night is given by eight chandeliers, which are attached to the ceiling. Between the windows and the galleries busts of famous composers are located. The knowledge of which composer is depicted on two of the busts is lost.

Most of the parterre floor is flat. However, towards the back of the hall the floor of the parterre is slightly sloped. The seating facilities are removable, because the large hall was originally intended for balls as well. When removed, the seats are stored in a 2-meter-high space below the floor of the parterre. The stage, which is located one meter higher than the main floor, is flexible in size. With a small stage, the hall can accommodate 1680 persons. With an enlarged stage, the hall can accommodate 1598 listeners.

Specially designed iron trusses were used to span the 19.8 meters between both side walls. On these iron trusses an ornamented ceiling was installed. The ceiling construction is not fixed to the walls. The ceiling is constructed from plaster.

The walls around the stage area are constructed from wood. The fronts of the galleries are made of wood as well, and the rear and side walls are constructed from brick. On all these walls plaster is installed. The floor of the hall is finished with wooden parquet.

The decorations of the hall were constructed from wood. However, they appear as though they were made from stone. The caryatids columns are hollow from the inside.

**Technical properties large hall**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>Width</td>
<td>19,8 m</td>
</tr>
<tr>
<td>Height</td>
<td>17,4 m</td>
</tr>
<tr>
<td>Volume</td>
<td>15000 m³</td>
</tr>
<tr>
<td>Seating capacity</td>
<td>1680</td>
</tr>
<tr>
<td>Floor Finish</td>
<td>Parket</td>
</tr>
<tr>
<td>Wall finish</td>
<td>Plaster</td>
</tr>
<tr>
<td>Ceiling finish</td>
<td>Plaster on wood</td>
</tr>
<tr>
<td>Reverberation time</td>
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</tr>
<tr>
<td>(average 500-1000 Hz)</td>
<td></td>
</tr>
</tbody>
</table>
4.2.5. Acoustics in the design

In this section, the acoustics applications of the Grosser Musikvereinssaal are considered. Because Von Hansen never explained how he approached the issue of acoustics, the design itself should be considered when answering the question of how the issue of acoustics was approached.

Probably the acoustic concept of the Grosser Musikvereinssaal was based on the theories of Langhans. During Von Hansen’s time spent in Berlin, he got inspired by the work of Schinkel, who based his concert halls on the work of Langhans. Langhans described the benefits of a rectangular hall and the music experience by the "slow fading sound". Therefore, Von Hansen copied the dimensions of the redoutensaal, which is a rectangular music hall, and scaled them up 12% [Barron, 1993]. Thereby, he used prominently reflective surface finishing like plaster and wood on an airspace.

Furthermore, caryatid columns were placed along both length sides of the hall, dividing the Musikverein into a nave with two side aisles. Langhans has advocated this measure for its sound scattering effect. This made the Hall comparable to a basilica, a shape which was appreciated for its acoustic properties during the 19th century.

The ceiling was decorated with ornaments. This application is also described by Langhans who considered it advantageous for acoustics because of its ability to scatter sound.

Von Hansen’s travels to Greece were probably of influence on the acoustic concept as well. According to Vitruvius' theories, large surfaces of resonating wooden panels were installed in the hall. For instance, the floor, ceiling and stage were constructed from wood over an airspace. Furthermore, the caryatid statues were constructed from wood and were hollow inside. These are comparable to the echea described in the fifth book of Vitruvius.

The seating arrangement at the gallery at the back wall was based on the fifth book of Vitruvius as well. These seats were positioned in a way where sound and sight would arrive simultaneously.

At the end of the construction process, the concert hall some acoustic tests were done, which satisfied in the highest grade. [Köstlin, 1870]
4.2.6. Aftercare

On January 6, 1870, the concert hall was inaugurated with a festive concert. The reactions on the acoustics of the large hall were, without exception positive. The Wiener Zeitung informed: "Wunderbar erklangen hier Menschenstimmen und Instrumentenmassen, die Akustik ist ein vorzügliche" [quote 7] [Wiener Zeitung, 1870-01-08]. The Neue Freuden-Blatt reported: "Was dem Musikfreunde bei einer Konzertlokalität am meisten am herzen liegt: gunstige Akustik, besitzt der neue Gesellschaftssaal" [quote 8] [Neues Fremden-Blatt, 1870-01-08]. [Morgen Post, 1870-01-06]. The most remarkable and typical for the contemporary acoustical knowledge comment was made by the Neue Freie Presse four days later: "Der Saal gibt den Ton mit Grosser Kraft ohne Echo Zuruck". [quote 9] [Neue Freie Presse, 1870-01-11]

Only 13 days after the opening concert a fire broke out in the concert hall around midnight. The cause was never discovered. The damage was covered by the insurance, and Von Hansen led the renovations which were completed at February 19, 1870.

During the eighth decade of the 19th century, a number of purpose-built concert halls were constructed. The construction of the Musikverein is considered to have put this development in motion. It set new standards for concert halls. [Grasberger et al, 1970]

Since the opening of the Musikverein a number of renovations have been completed. Only the modifications that could have influenced the acoustics are mentioned.

Before 1911, the Musikverein underwent a number of small modifications. However, these modifications were a prelude to the major renovations in 1911. Von Hansen had designed the large music auditorium from an aesthetic starting point, and for small orchestras. However during the end of the 19th century, the musical world had evolved. A larger stage was demanded for compositions and the cloak room was required to be nearby the concert hall. Furthermore, due to a number of buildings with a large audience capacity which were destroyed by fire, safety regulations were tightened. [Grasberger et al, 1970]

Therefore, Ludwig Richter, who was a scholar of Von Hansen, was requested to modify the design to contemporary standards. The galleries were made self supporting and the caryatids columns were relocated to the back against the walls. Furthermore, the stage was broadened to cover the total width of the music hall. This was done at the expense of four boxes. [Grasberger et al, 1970]

The large hall of the Musikverein was reopened on October 17, 1911. The renovations were regarded with suspicion by the Austrian press. Especially, the relocation of the caryatids columns was regarded influential on the acoustics. However after the re-openings concert, the Austrian press was again, without exception, positive about the acoustic properties of the Grosser Musikvereinssaal. [Grasberger et al, 1970]

Nowadays, the large hall of the Musikverein is regarded as one of the three halls acoustically superior concert halls.

4.2.11. An impression of the current configuration of the Grosser Musikvereinssaal
4.3 The opera Garnier in Paris (1875)

4.3.1. History before the construction

The history of the Palais Garnier already started at the end of the 18th century. The old opera house of Paris was destroyed by a fire on June 8, 1781 [Steinhauser, 1969]. For the next 100 years, the opera was accommodated at different venues. [Allgemeine Musikalische Zeitung, 1873-09-03]

A site for a new opera house became available on September 29, 1860 [Leniaud, 2003]. Three months later Comte de Walewski, who was state minister of the regime of Napoleon III, announced a competition for a new opera house. [Steinhauser, 1969]

The very short program of requirement of this opera house was published on December 30, 1860. The jury, which was led by the state minister, consisted of 13 persons. The head was assisted by eight delegates of the section d'Architecture de l'Academie des Beaux arts and four representatives of the Conseil des Batiments Civils. [Steinhauser, 1969]

The competition was closely followed by press and public, because the opera house would become a national monument. Many articles were devoted to the competition and the submitted designs. [Steinhauser, 1969]

171 architects participated in the competition. The architects of the best five designs were invited to submit improved versions of their designs at the beginning of May 1861. Unlike the first competition round, the program of requirements for the second competition round was an extensive and complete text. [Steinhauser, 1969]

One aspect, stated in the program of requirements, was that the opera house would need to accommodate 2000 listeners. A depth of 30 meters was demanded for the stage. Furthermore, the position of box seats was determined. However, no demands were made concerning the acoustics. [Steinhauser, 1969]

To the surprise of the followers, Garnier, who finished fifth in the first competition round, was declared winner of the second competition round in May 1861. Garnier was officially appointed architect of the new opera house by the state minister on June 6, 1861. A theater in Bordeaux, which was built in 1780, and designed by Victor Louis, served as model for the design of Garnier. [Steinhauser, 1969]
4.3.2. The architect

Charles Garnier was born in Paris on November 6, 1825. His parents were of humble origin. Garnier became an apprentice of architect Leveil in 1840. Thereafter, he followed a study at the Ecole des beaux arts between 1842 and 1848 [Architectura, 1898-08-27]. At the end of his study he journeyed to Italy and Greece.

5 years later he returned to Paris, which had changed dramatically. The regime of France had changed from a republic into an empire. The new regime provided opportunities for architects, because it was interested in redesigning the city of Paris. However, Garnier suffered from a depression caused by the large transition from the splendor of the Mediterranean to the gloomy climate in Paris. He would stay in the scope of this disease his entire life. [Leniaud, 2003]

Between 1853 and 1860 Garnier did some small jobs for civilian buildings because it was unusual to have a young architect in Paris. Thus, the competition offered a great opportunity for Garnier. At the time he won the competition he was 35 years old and relatively inexperienced. He had no experience designing buildings with acoustic demands. [Leniaud, 2003]

During and after the construction of the Opera, Garnier designed numerous buildings. However, he considered the opera his most important achievement. Charles Garnier died on the August 3, 1898. [De opmerker, 1898-08-13]

4.3.3. The construction

The construction started at the end of 1861. During the excavations, an underground river was discovered, which formed an extra obstacle for the further construction. The land was drained on March 1862 [Kahane et al, 1987]. The First Stone was laid on July 21, 1862. In 1863 the project suffered from financial deficits, because the regime of Napoleon III spent its money (from a propagandistic position) on a luxurious hotel. [Kahane et al, 1987]

The constructions were resumed and the façade of the building was revealed for the world exhibition in Paris in 1867 [Steinhauser, 1969]. Shortly after the opening of the façade, constructions again came to a standstill. The work was resumed two years later [Allgemeine Musikalische Zeitung, 1869-05-25]. The envelop was completed in 1870. The war between Prussia and France and the subsequent civil war in France again interrupted constructions. Both wars ended the regime of Napoleon III. The regime of France was resumed by the third republic, which did not support the project. Therefore the project again suffered from financial problems and constructions were paused for the third time. [Kahane et al, 1987]

The opera house on the Rue le Peletier, which was used for operas since the appointment of the new regime, was destroyed by a fire during the night of October 27, 1873 [Allgemeine Musikalische Zeitung, 1873-11-12]. Lack of an opera house forced the regime to act quickly. It was decided to resume the construction of Garnier's opera house. [Allgemeine Musikalische Zeitung, 1873-11-19]

At the end of the constructions, acoustic tests were done. Because the orchestra sounded "hollow" and the two tested overtures "dull", it was decided to raise the stage. However, during these tests it was also noticed that the voices sounded well and attendees could hear all nuances [Allgemeine Musikalische Zeitung, 1874-04-23]. The opera was ready for its opening in January 1875.
4.3.4. The design

The large auditorium of the Opera is divided into two sections: a stage area and an audience area. The stage area is rectangular shaped with an area of 244 square meters. Its surface level is 0.66 meters higher than the floor level of the first row seats.

An orchestra pit is located between the stage and the front rows of the audience area. The area of the orchestra pit is 78 square meters. The audience area is "horse shoe" shaped. Its maximum length is 27.7 meters and maximum width is 18.9 meters. The auditorium, which has a height of 20.7 meters, is relatively high.

Four stories of box seats and galleries are positioned around the walls of the "horse shoe". The highest story is a gallery and the lowest three are box seats. In the mean seating area 19 rows of seats are installed. The level of the front 12 rows slightly increases. Behind the 12th row a difference in height was created. The last seven rows are therefore augmented and increase in height to the back as well.

A dome was placed in the ceiling above the audience area. At the center of the dome hangs a large chandelier, which can light the opera hall.

The stage floor is covered with wood over an airspace. The walls at this section are made of wood coated with plaster. The floor of the orchestra pit is made of wood over an airspace. The walls of this section are made of solid wood.

The floor of the main seating area and the box seats are covered by carpet. All visible walls are made of wood which is covered with plaster and the back walls of the box seats are made of curtains, which separate them from the cloak rooms. The ceiling of the main seating area is made of plaster and the ceiling of the boxes is made of plaster on which damask is installed.

Technical data Palais Garnier

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4.3.5. Map of the Palais Garnier

4.3.6. Section of the Palais Garnier
4.3.5. Acoustics in the design

Even before the constructions were finished, Garnier wrote about the acoustics of his opera. In 1871, he wrote: "Il faut bien que j’explique que je n’ai eu aucun guide, que je n’ai adopté aucun principe, qu je ne me suis base sur aucune théoried que c’est du hazard seul que j’attends ou l’insucces ou la réussite". [quote 10] He ends his comments about acoustics with: "Cela montre, je crois, que jadis comme aujourd’hui la science de l’acoustique appliqué aux theatres, etait une science puérile et que c’est le hasard seul qui dans ce cas special a de tous temps été le "Deux ex machine". [quote 11] [Orth, 1872] This means that he has adopted no acoustic principle and that he left the success of his acoustics to change.

In this book Garnier comments that he has read all sources about architectural acoustics. However, this text proves that Garnier has no knowledge about the writings of Langhans, whose theories were commonly used in the 19th century for buildings with acoustic demands. [Orth, 1872]

After the constructions were finished, Garnier wrote another two books about his opera. In both books he has devoted a chapter to acoustics. In the first book he also wrote chapters about the shape of the room and the decoration of the room. In both chapters he realized that they influenced the acoustics. However, he did not know in which way.

In the chapter about acoustics he almost apologizes for the fact that he did not know why the opera house, which he constructed, had good acoustics. He complained about the absence of an acoustic formula. He had looked in books about acoustics in which he could only find opposing statements. Even the buried vases of Vitruvius and the springing sand of Chladni are shortly mentioned. However he did not know how to implement these in an acoustic design. From this he concluded that the only thing left to do was to travel through Europe for answers. However, during his journeys he again only came across opposing statements. Therefore he concluded that: "après toutes ces études, a découvrir ceci: c’est qu’une salle, pour être sonore et avoir un timbre agreeable, devait etre longue ou large, etre haute ou basse etre en bois ou en pierre, ronde ou carrée etc.". [quote 12] [Garnier, 1878]

In this chapter he also mentioned the Festspielhaus in Bayreuth. He admired Wagner for his firm vision on acoustics. [Garnier, 1878]

This is in the contrary of what Garnier makes his readers believe. He in fact made some very clear observations about the propagation of sound, so that most contemporaries did not believe that the acoustics of the Palais Garnier were just dependent on coincidence. [Berlage, 1895]

Although Garnier was convinced that acoustics were accidental, he still made some changes to the design for acoustic reasons. For instance, he responded on the augmentation of the stage floor, which was previously mentioned. The stage’s height was decreased. Also because it was requested by the ministers and directors, he lowered the floor of the orchestra. Not the requested 0.8 meters, but 0.17 meters. This was because the requested reduction was too extreme. [Garnier, 1878]

When the design itself is considered, Garnier implemented a few properties which were generally considered beneficial for acoustics. He used a "horse shoe" shape which was used in many contemporary opera houses. Furthermore, he designed a stage and back wall made of wood on a cavity. The floor of the orchestra pit was constructed of wood as well. Ever since Vitruvius, this was considered advantages for acoustics. Finally, Garnier made sure that there were enough absorbent materials present in the opera house, so that the reverberation became not too long.
4.3.6. Aftercare

The completed opera house was opened with a performance on January 5, 1875 [Allgemeine Musikalische Zeitung, 01-13]. The opening was attended by Macmahon who was president of the third republic of France. Furthermore, the opening was visited by more dignitaries from around Europe; amongst them were the king of Spain and the mayor of Amsterdam. [Algemeen Handelsblad, 1875-01-08]

The press judged the opera in different ways: extremely positive, pensive and even negative. These critiques mainly addressed the architectonic properties of the building. [Kahane, 1987]

The opinions about the acoustics were divided as well. The music editor of the Allgemeine Musikalische Zeitung argued that the voices of the singers could be heard clearly. On the other hand, the symphonic performance was less audible. The music editor also complained about the lack of respect from the audience, which largely did not listen to the music. [Allgemeine Musikalische Zeitung, 1875-05-12]

After some years the opinions about the acoustics were more moderate. In his second book Garnier reacted on these doubts. Although he himself did not know what the qualities of the acoustics were, he suggested some improvements for the acoustics of the opera house. The general complaints were that the singers and violins could not be heard clearly [Garnier, 1881]

He suggested a roadmap of six steps to improve the acoustics. The First step was to do nothing. The second step was the installation of a little platform, on which the violinists were seated. Third step was to increase the number of violinists. The fourth step followed from both the second and third step. When the number of violinists grew the (in the second step), the platform should increase as well. The fifth step was to relocate the front row of the audience area to make place for a bigger stage. The final step was to bring the proscenium 0.6 meters forward. The book did not mention whether these changes had been made. [Garnier, 1881]

Sturmhoefel reacted on the statements which Garnier made in his two books. He was convinced that the acoustics of the opera were too good to depend on chance. Furthermore, he believed that the roadmap offered in the second book gave instructive remarks. [Sturmhoefel, 1888]
4.4 The Festspielhaus in Bayreuth

4.4.1. History before the construction

For many years, Richard Wagner contemplated about an opera house specially constructed for his work. He wrote about this auditorium in a letter about the Ring des Nibelungen as early as November 20, 1851. This idea became stronger, because Wagner considered a number of opening concerts a failure. Therefore, Wagner wanted to control everything, including the acoustics of a concert hall. [Habel, 1985]

Initially, Wagner considered Munich as the ideal location for this concert hall. Wagner and architect Gottfried Semper had made advanced plans for this Festspielhaus. However, Wagner was forced to leave Munich in 1865, which postponed the plans for a Festspielhaus. [Habel, 1985]

Wagner continued to pursue his dream of a Festspielhaus in 1870. The choice of location was coincidental. The old court theater of Bayreuth, which was completed in 1748, had the largest stage in Germany. Wagner and his wife visited this theater because the large dimensions seemed ideal for his new production. [Skelton, 1976]

At a glance it became clear that this hall did not meet Wagner’s requirements. The stage was large, but the hall could only accommodate 100 listeners. Although, the hall did not measure up to Wagner’s expectations, Bayreuth itself was suitable. Soon, Wagner got acquainted with influential people who were interested in the idea of a purpose-built Festspielhaus for Wagners work. [Skelton, 1976]

The Bayreuth city council decided to support Wagner’s plan on November 7, 1871 [Schuth, 2007]. The choice for the location within Bayreuth for the Festspielhaus was coincidental as well.

Previous locations were rejected because the soil of the first could not support a large structure and on the second location the building would block the water supply for a factory, which could not miss the water. In December 1871, the city council declared that the chosen location was provided with roads and other facilities. [Habel, 1985]

Wagner received a large donation from his patron, Ludwig II, after the location was decided. These funds could not prevent financial problems during the construction of the Festspielhaus. [Skelton, 1976]

Wagner tried to collect the residual necessary funding by performing concerts and by establishing a patron’s society [Schuth, 2007]. Wagner himself laid the first stone of the foundation on his 59th birthday, on the May 22, 1872 without awaiting the results of the fund raisers. [Skelton, 1976]
4.4.2. The architect

Originally, Alfred Neuman was the architect of the Festspielhaus [Schuth, 2007]. He was replaced only one month before the first stone of the foundation was laid. By telegram, Richard Wagner requested Paul Otto Brückwald to replace Neuman. However, Brückwald can hardly be considered architect. The design was strongly based on the design of the Festspielhaus in Munich, which was designed by Gottfried Semper. Furthermore, the opinions of Brückwald were overshadowed by Richard Wagner’s dominant views [Habel, 1985]. Because of these reasons, Brückwald’s role resembles that of a superintendent and it is more logical to describe Semper’s career.

Gottfried Semper was born in 1803. He studied in Paris and Munich. Semper travelled to Greece and Italy to complete his studies. He started his career with a job at the Academy of visual arts in 1834. The first two buildings he designed were a synagogue and a theater building in Koningsberg. Thereafter, he designed the Theater in Dresden, which was built from 1838 to 1841. The design of this building was strongly based on a Roman theater. It was destroyed by a fire in 1869. [Berlage, 1884-05-25]

Semper took part in a revolt in Dresden in 1849, which stopped his career in Germany for six years. After this pause, he became professor of Architecture on the Polytechnicum. His first architectural work after his break was the design of the Polytechnicum itself. He designed this building in cooperation with architect Wolff between 1861 and 1863. [Berlage, 1884-05-25]

Semper and Wagner began designing the Festspielhaus in 1863. Semper had some experience designing buildings with acoustic requirements. However, he had never constructed a concert hall or opera house before designing the Festspielhaus. Because of the forced departure of Wagner, this Festspielhaus was never constructed. [Berlage, 1884-05-25]

Semper was asked to replace the Theater in Dresden which had been destroyed by fire, in 1870. His oldest son was superintendent of the construction. The building, which would have Semper’s name, was completed in 1878. During the construction, Semper was asked to design two museums in Vienna. Therefore, he went to the Austrian Capital where he designed the two museums based on the Foro Romanun. [Berlage, 1884-05-25]

Semper died in Rome on May 15, 1879 where he sought cure for his illness. He was buried beside the pyramid of Cestius. [Berlage, 1884-05-25]
4.4.3. The Construction

The excavations for the foundations of the Festspielhaus started on the morning of April 29th, 1872. The first meeting between Wagner, Brückwald and Wagner’s advisor Brandt was two days later, on May 1. [Habel, 1985]

When Wagner, between many trips, during which he gave concerts to raise money, visited the site around Christmas 1872, he was very pleased with the progress. A few days later when he took a look at the building with a friend, he even compared the substructure with an Egyptian temple. [Habel, 1985]

The city council approved the maps and sections of the Festspielhaus on April 4, 1873. The project continued having financial difficulties during the Construction. Wagner repeatedly tried to convince Ludwig II that he should fund the project. At the end of 1873, the financial distress escalated [Allgemeine Musikalische Zeitung, 1873-09-24]. The envelop of the building was completed; however the interior still had to be installed. A lack of financial resources had arisen. Therefore, the project was near cancelation. However, an interest-free loan from Ludwig II prevented the impending bankruptcy of Wagner. [Skelton, 1976]

The Festspielhaus was completed in the summer of 1875, with the exception of the interior decorations. Therefore, Wagner could inform Ludwig II that the envelop and interior were completed and could show his gratitude for his financial support. [Habel, 1985]

The rehearsals within the Festspielhaus started in July 1875. Immediately on the first test, Wagner was satisfied with the acoustics. Later on, the hall, which was not fully decorated yet, was tested by a complete women’s choir, which sang a piece of Rheingold. Both Wagner and the choir were satisfied with the acoustic properties of the auditorium. Rehearsals with a full orchestra took place between 1st and 12th of August. The sunken orchestra pit was used for the first time during these rehearsals. Wagner appeared very satisfied about the acoustics with the sunken orchestra pit. He called it a divine sound effect, which made the wind instruments seem less raw. [Habel, 1985]

The time between the first auditions and the opening of the Festspielhaus was also characterized by financial difficulties. The material of the ceiling still had to be chosen. It was decided that it would be covered with canvas in March 1876. A third and last series of rehearsals was held at the beginning of August 1876. [Habel, 1985]

During a banquet, which took place to celebrate the opening on August 1, 1876, Wagner thanked his employees, and especially his advisor Brandt, for their cooperation. [Habel, 1985]
THE HISTORY OF ACOUSTIC DESIGN BEFORE 1900

June 24, 2011

4.4.4. The design

Contrary to what many people think, the design of the Festspielhaus was not driven by acoustic reasons. The concept was focusing the attention of the audience on stage [Schuth, 2007]. Besides an impression of the hall, a number of applications that enhance this concept are described in this section.

The opera hall of the Festspielhaus is divided into two: a section for the stage and a section for the audience. The stage area is 27.7 meters wide and 35.6 meters long. The height between the stage floor and the machinery is 29.2 meters.

A large, dark space was created between the stage and the audience area. At the bottom of this space, the orchestra pit was positioned. The orchestra pit is not visible for the audience because the movement of the musicians would distract the audience from the proceedings on stage. Furthermore, with this large dark space it was attempted to create an illusion in which the audience imagined itself in the center of the performance. [Habel, 1985]

The six pairs of niches which are located at the front of the audience area are the most remarkable feature of the design. On the walls, which enclose these niches, columns are positioned supporting the ceiling. The aim of these niches was also to focus the attention of the audience on the stage. [Schuth, 2007]

The audience section is 32.3 meters long and 33.2 meters wide. Because the audience area is ascending towards the back of the hall, the height of the audience area is varying. The height decreases from 18 meters to 12.8 meters. The audience section is shaped like a classic amphitheater; a semi-circle without galleries or box seats.

Galleries and box seats are missing because Wagner despised audiences that attended the opera for social purposes. This way, it was prevented that people in the box seats and galleries could socialize with people in the regular audience [Amerongen, 1983]. However, in the back wall box seats are positioned.

The floor is finished with wooden slats [Schuth, 2007]. The rear and side walls too are finished with slats, on which plaster is installed. The walls are intentionally made with few ornaments to prevent the audience from getting distracted. The ceiling is made from wooden slats on which painted canvas is installed. [Brückwald, 1875]

Gas lights lit the opera house, which was unique for that time. Also, this lighting was used to draw the attention to the stage by turning the lights off during performances. [Brückwald, 1875]

Technical data Festspielhaus

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4.4.5 Acoustics in the design

Wagner tried to achieve the architectural concept with the support of acoustics. Therefore, it was important to strengthen the sound of the singers and reduce the sound of the instruments.

The first purpose of the orchestra pit was to prevent the distraction of the audience by the movement of musicians. However, it was also designed for an acoustic reason. The string instruments were placed under a ceiling which was used as a resonance screen, the wooden wind instruments were positioned in a ceiling-less part of the orchestra pit, and the brass wind instruments were positioned under a ceiling that was covered with fabric. This was done to enhance the tones of the string instruments and reduce the tones of the brass wind instruments. With the sunken orchestra pit, Wagner envisioned that singers would not be overruled by the instruments. [Habel, 1985]

On the stage, some measures were taken to enhance the acoustic concept of the orchestra pit. A special wall reflected the sound of the singers and orchestra into the audience area. [Schuth, 2007]

Furthermore, the amphitheatric seating arrangement was partly chosen to enhance the acoustical concept. This would shorten the sound line and thus enhance the sound expansion. Elements were placed to scatter the sound waves. The niches were partly designed to scatter of sound waves. [Habel, 1985]

Besides the strengthening of the architectural concept, Wagner also used a material that was mainly presumed to have a positive effect on the acoustics. Like many contemporary music auditoria, the opera hall of the Festspielhaus was made of wood. The main reason to construct music halls in wood was that the space would work in the same way as the resonance box of a violin. [Habel, 1985]

Finally, Wagner was aware that there was no scientific method to measure the acoustics. Therefore, tests were done at the end of the construction process to discover whether the acoustics met Wagner's demands. Experiments were conducted with decorations. However, little of the interior was changed. [Habel, 1985]

After the completion of the construction, Wagner was convinced that in addition to the original view on the stage and the entrances, which are located between the niches, the acoustics would also give the Festspielhaus its timeless meaning. [Habel, 1985]
4.4.6 Aftercare

The Festspielhaus was officially opened with a performance of the Ring des Nibelungen on 13 August 1876 [Eisendoom, 1983]. This performance was also carried out according to the exact vision of Wagner, who travelled around Germany to select the singers [Algemeen Handelsblad, 1875-03-16]. The opening of the Festspielhaus was attended by many dignitaries, including Kaiser Wilhelm I and philosopher Friedrich Nietzsche, who was a close friend of Wagner. The second and third performances were attended by Ludwig II. [Habel, 1985]

According to Wagner, the opening of the Festspielhaus should be considered as the most important event in human history. The reactions from press and the audience were more reserved [Amerongen, 1983]. Paul Lindau, who was a music editor of the Schlesische Presse, argued that the sound of a visible orchestra is different from the sound of an invisible orchestra. According to him the sound became one mass, because of the even damping of the sound of the instruments. For instance, the trumpet lost its cheerful sound because it is overruled by other instruments [Lindau, 187-10-11]. The music editor of the Neue freie presse was not positive either. He missed large parts of Rheingold because according to him the orchestra pit was sunken too deep. Furthermore, the singing was overruled by the instruments and the loud sounding instruments sounded muted [Neue Freie Presse, 1876-08-17].

After the opening, a number of renovations were made. Only the changes which could have influenced the acoustics are mentioned.

Because the sound of the string instruments was too weak, according to Wagner, an additional sound board was installed at the front of the stage during the second Bayreuthter festspielen in 1882. [Schuth, 2007]

On July 17, 1889, it became clear that the wooden construction and the lower parts of the stage were affected by soil moisture. These needed to be renovated. In this rebuilding, the lower parts were replaced by stone, which supported insulation plates. [Habel, 1985]

A series of renovations were completed between 1958 and 1973. During these renovations the north, east walls and the seating was replaced and the audience area was renovated [Habel, 1985]. The wooden construction of the orchestra pit was replaced by an iron construction covered with wood. In this renovation, the volume of the orchestra pit was also enlarged by the debasement of its floor. Whether these changes have influenced the acoustics is unknown.

A series of new renovations was done during the Mid-1990s. The interior was refurbished and the balustrades of the box seats at the rear were made slightly curvy, instead of straight, for acoustic reasons. [Schuth, 2007]
4.5. The Trocadero palace in Paris (1878)

4.5.1. History before the construction

The Trocadero Palace owes its existence to the idea to let music be heard at the world exhibition of 1878. Mr. Alphand, who was the director of buildings in Paris and creator of the world exhibitions of 1867 and 1878, got impressed by the Royal Albert Hall when visiting London, and wanted to create a Parisian counterpart [The Graphic, 1876-07-01]. A lot between the Ecole Militaire and Les Invalides was selected as location. This land was named after a battle of 1823 between the French and Spanish armies, in which the French army occupied the Andalusian fortress Trocadero. [Gournay, 1985]

On April 20, 1878 a competition was issued for a concert hall at the Trocadero Hill between architects and engineers of all countries. In the program of this "popular opera", a combination was made between a concert hall that could seat 10000 listeners, and exhibition rooms. On May 15, which was only 25 days after the opening of the competition, 94 projects were returned and architect Gabriel Davioud and engineer Jules Bourdais were awarded with the First price. In the final draft, however, there was room for only 6000 listeners. [Gournay, 1985]

Before Davioud and Bourdais participated in the competition they had once been involved in a debate about large concert halls. Alphonse Sax, who invented the saxophone, argued that a large opera hall for 9000 to 10000 listeners could ask low entrance prices. Davioud, from an optical point of view and Bourdais, from an acoustical point of view, defended this idea of a large popular opera hall. [The Graphic-1875-11-20]

In 1875 Gounod firmly repudiated this idea. According to him, a large concert hall would mean the death of the musical art because a large space between performers and listeners would create a vacuum, in which the musicians cannot be heard anymore. [The Graphic-1875-11-20]

A sub-committee further developed the final design of Davioud and Bourdais. Hereby several components of other designs of the competition were incorporated. On June 15, 1876, the final design of the sub-committee was submitted to the jury, which approved it. On August 25, the city council approved the definitive plan as well. [Morel, 1878]
4.5.2. The architect

Davioud and Bourdais were men of science. Davioud was interested in the optical area. Bourdais was interested in the acoustical area. In this cooperation Davioud was architect and Bourdais was engineer.

Gabriel Davioud was born in Paris in 1824 [Krümpelmans, 1981]. He studied at the Ecole des beaux-arts. He won the second Grand Prix in 1849. However, as most contemporary young French architects, he encountered difficulties finding work because French construction tradition dictated that a building was to be designed by an old architect.

In 1855, Davioud designed his first building with acoustic requirements. He was architect of the Theater de rond-Point. In 1857 Davioud became chief architect of service walks and plantations [Leniaud, 2003].

Between 1860 and 1876 Davioud designed two theaters: the first in 1860 and the second in 1862. Both were located at the Place du Chatelet. Therefore, Davioud had some experience designing buildings with acoustic requirements before he was the architect of the Trocadero Palace. However, he had never designed an opera house or a concert hall.

Davioud died in 1881, three years after the Trocadero Palace was completed. [Krümpelmans, 1981]

4.5.3. The construction

The excavations of the foundation started on October 25, 1876. In June of the following year, the envelop of the building was completed. The next phase was to apply the decorations on the walls and the manufacture of the columns which supported the galleries. [The Graphic, 1877-06-23]

At the end of October 1877 both wings of the building were completed, except for the glazing, which still had to be placed [The penny illustrated paper and illustrated times, 1877-10-20]. Marshall MacMahon, who was president of the third French republic, visited the building site of the Trocadero Palace on December 29, 1877. After closely inspecting the building, the Marshall expressed some doubt as to whether the building would be finished on the opening day of the world exhibition. However, Krantz, who was supervisor, reassured the Marshall that all work would be finished at the opening of the world exhibition. [The Graphic, 1877-12-15]

The organ, which would be placed in the concert hall of the Trocadero Palace, was completed on April 1878. However, it would not be placed for the next two months [The Graphic, 1878-04-27]. A mere 18 months after the start, on June 5, 1878, the construction process of the Trocadero Palace was completed [Morel, 1878]. This was a month after the world exhibition was opened at May 1, 1878.

4.5.3. A section of the Salle des Fetes

4.5.4. An impression of the Salle des fetes
### 4.5.4. The design

Two music rooms could be found in the Trocadero Palace: A small room which was intended for chamber music and a large concert hall. The main focus of this chapter is this large concert hall which was called the Salle des fetes or ferry hall. This concert hall was intended for music festivals. However, it could also be used for solo performances and small theater performances.

The Salle des fetes was shaped like a large horse shoe. The maximum width of the horse-shoe was 50 meters. When the dimensions of the box seats were added this width increased to 62 meters. The maximum length of the horse shoe was 62 meters. Furthermore, the maximum height of the concert hall was 55 meters. The ceiling was shaped like an arch. [Berlage, 1895-01-19]

The construction of the ceiling was made with six even arches which all went through the centre point off the ceiling. These arches divided the walls of the concert hall into 12 even compartments. A niche, which was intended for the musicians and choir, broke the perfect shape of the horse-shoe and the construction. This niche contained a podium, which could accommodate 350 musicians, and an organ [De tijd, 1878-05-02]. The length of the niche was 30 meters and the total area of the niche was 275 square meters. The height of the niche was 23.5 meters [Sturmhoevel, 1898]. The back wall was arc shaped. This shape was determined by the requirements of the acoustics.

Except for the niche and its near surroundings, the concert hall was covered with fabric. This fabric was made of silk, which was chosen for both its sound absorbing properties and its ability to paint on. The niche and its near surrounding were built in brick covered with smoothed plaster. [Morel, 1878]

Nine large windows were placed high in the walls. These windows were evenly divided over the 12 compartments. Only the forward three compartments lack windows, because the podium occupies their space. [Morel, 1878]

The main floor had room for an audience of 5000 people. Galleries were positioned over the whole length of the walls [De tijd, 1878-05-02]. In these galleries there was room for an audience of 1000 men. [Morel, 1878]

The reverberation time of the Salle des fetes was more than 6 seconds [Rotterdamsche courant, 1927-10-27]. It is unknown which octave bands are concerned and whether this concerned an occupied or unoccupied concert hall.

#### Technical data Salle des fetes

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</tr>
<tr>
<td>Reverberation time</td>
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</tr>
</tbody>
</table>
4.5.5. Acoustics in the design

Probably due to Bourdais' interest in the acoustic science, Davioud and Bourdais constructed the Salle de fetes according to the contemporary acoustical knowledge. They have extensively described their acoustical concept in a paper. The concept was based on two aspect described in sections 3.4. and 3.6.. In short, the concept was based on the rigid distinction between absorbent and reflective materials and the time difference of 1/10th of a second between direct sound and reflections.

Because sound travels with 340 meters per second, it was concluded that sound reflected from surfaces further than 17 meters from the orchestra were perceived as harmful for the acoustics. Therefore, all surfaces located less than 17 meters from the orchestra were constructed from reflective materials. These surfaces were made of masonry which was covered with plaster. The surfaces more than 17 meters from the orchestra were made absorbent. This was done with silk on which paintings were made.

However, Davioud and Bourdais realized that this measure alone was not enough. Therefore, the back wall of the stage was divided into hundred separate zones. Each of these zones was focused on a different one hundredth of the room.

Because of disagreement between both architects about this acoustic measure, it was decided to test this theory. This was done with a small model. For it was assumed that the laws of transmission of light and sound were comparable, the sound source was modeled with a light bulb. The absorbing surfaces were modeled with embossed copper and the reflective areas with polished silver. The light bulb was placed at the centre of the stage, and it was tested, how the light divided over the model. The results showed that the strengthening of the sound was equal over every position in the hall. [Morel, 1878]

This did not meet the desires of the architects, because the positions near the orchestra did not need these reflections. Therefore, a new configuration of the back wall was tried, which significantly increased the importance of the reflective parts for the rear parts of the hall. Both architects were satisfied with the results.

When the hall was taken into use, the envelop at the back of the orchestra performed as intended in the acoustical concept. However, the fabric did not. Especially, with parts of great fortissimo, absorption was not complete and reflections were observed. After more experiments it was concluded that materials possessed an absorption coefficient. [Morel, 1878]
4.5.6. Aftercare

The World exhibition opened on May 1, 1878. Architects Davioud and Bourdais were both appointed officers of the Legion of Honor at the opening ceremony [De tijd, 1878-05-07]. The Salle des fetes was first used at the fifth of June 1878 for a French national concert. [The Graphic, 1878-06-15]

The acoustics of the Salle des fetes were very poor. In many places it was even difficult to hear the music of the orchestra [Sturmhoefel, 1898]. Or, as the Rotterdamsche courant would declare: "De akoestiek was er jammerlijk. Op bepaalde plaatsen hoorde men er geen sikkepeit, op andere dubbel" [quote 13] [Rotterdamsche courant, 1922-10-11]. The acoustical concept of Davioud and Bourdais only worked at the higher galleries on the rear wall [Het vaderland, 1937-06-14]. When the World exhibition ended, the ownership of the Trocadero Palace was transferred to the French government. [Gournay, 1985]

In 1888, Sturmhoefel devoted an article in Zeitung der Bauwesen to podiums of several concert halls. He attempted to explain the bad acoustics of the Salle des fetes. It was generally believed that the fabrics did not absorb sound completely. However, Sturmhoefel argued that the acoustics of this concert hall strongly varied within the room. Therefore, he concluded that the difference between the arrival of direct and reflected sound was too grave. This phenomenon occurred, according to the author, because of the excessive height of the niche in which the orchestra played. The ceiling of this niche, which was made of smoothened plaster, was located more than 17 meters above the ground floor and thus radiated disturbing reflections. [Sturmhoefel, 1888]

The surrounding area of the Trocadero Palace altered in 1889. In this year the world expedition again took place at the Trocadero area. Because the Eiffel tower was built in the near surroundings of the Trocadero Palace the scale of the once overwhelming building seemed less impressive. Furthermore, its appearance became outdated with the construction of the Eiffel tower. The Salle des fetes was used again for concerts during this World exhibition. [Gournay, 1985]

An attempt was made to improve the acoustics of the Salle des fetes in 1909. This was led by Gustave Lyon. Firstly, all positions that radiated disturbing reflections were mathematically determined. Then these places were confirmed with a specially built measure device, which consisted of a soundproof box and two horn-like tubes. Thereafter, a method was developed wherein these disturbing echoes were absorbed. This was tried with a concave mirror and panels of different types of fabric. However, all these attempts failed. Later, it was discovered that when these panels were placed, with a certain distance in front of the mirror, they suppressed the echo. These special constructions were placed beneath the ceiling of the niche. [Popular mechanics, 1909-08] Furthermore, Gustave Lyon replaced the silk fabric by molton, which should have diminished the reverberation time. [Rotterdamsche Courant, 1928-11-16]

The world exhibition of 1937 again took place on the Trocadero area. In 1932 a competition was issued for the modernization of the Trocadero area. The design of the winning project, which won over 76 other projects, did not accommodate the Trocadero Palace. Therefore, the Trocadero Palace, which existed from 1878 to 1937, was demolished [Gournay, 1985]. Many acoustic lessons were learned from the failure of the acoustics of the Salle des fetes. The acoustical concept was partially adopted for the Neue Gewandhaus. Gustave Lyon became acoustic counselor of the 'Salle Pleyel' in Paris. With his experiences in the 'Salle des fetes', Lyon designed an acoustically satisfying concert hall. He changed the interval for the edge of reinforcing and disturbing sound from 1/10 into 1/15 of a second [Rotterdamsche courant, 1928-11-16]. Consequently the 'ideal dimension' of 22 meters for the width of a concert hall arose.
4.6 The Neue Gewandhaus in Leipzig (1884)

4.6.1 History before the construction

Leipzig had become the musical centre of Germany in the middle of the 19th century. Besides its conservatory and composers, especially the Gewandhaus orchestra and its concert hall had contributed to this. [Centralblatt der Bauverwaltung, 1883-11-24]

This concert hall was opened in 1781 and was named after the original function of the building. This hall was placed in a building, in which wool and textiles were processed. This was called a cloth hall or in German a gewandhaus [Centralblatt der Bauverwaltung, 1883-11-24]. During the 18th century, the form of a concert hall and acoustic measures were based on experiences of other projects. Therefore, architect Johann Friedrich Carl Dauthe chose for a hall with rounded corners, resulting in an oval-shaped hall. Furthermore, experiences showed that a flat ceiling and columns within the lines of sight would harm the acoustics. For this reason, these properties were avoided in the design. At the same time, Dauthe designed box seats at both sides of the hall, which were considered to aid the acoustics. Finally, the hall was surrounded by corridors and the walls were covered with wood, which would make the concert hall work like the resonance box of a violin. [Centralblatt der Bauverwaltung, 1895-01-19]

This concert hall, in time, built up an excellent reputation. When Mendelssohn Bartholdy was concert director, between 1835 and 1847, he started, what is now known as, the "Leipzig concert hall tradition" [Deutsche Bauzeitung, 1884-12-24]. This reputation and the increasing interest in music during the twenties of the 19th century caused a shortage in seats. However, a large scale renovation was postponed, because it could harm the excellent acoustics. Finally, it was decided to increase the capacity from 500 to 1000 persons in 1842. Because no differences in acoustics were perceived, the renovations were considered successful. [Skoda, 1985]

Due to the continuous growing interest in music, a deficit of seating became more common, despite the renovation [Bagge, 1863]. It was attempted to solve this problem by placing additional seats. Because this influenced the quality of concerts and therefore, the reputation of the hall, concerns rose within the city council and the board of the Gewandhaus [Skoda, 1985]. Thus the First plans for a new concert hall arose. However, two aspects made it difficult to implement these intentions. Firstly, there was a lack of financial resources, which resulted in quarrels between the city council and the direction of the Gewandhaus. Secondly, the new concert hall, having the same acoustic qualities as the existing concert hall, could not be guaranteed. [Skoda, 1985]

A successful initiative to construct a new concert hall was undertaken in 1877. The direction of the Gewandhaus decided to participate in the construction of a new concert hall in Leipzig. Thereby, it was agreed that the existing hall, due to its excellent acoustics, was not demolished [Skoda, 1985]. After various discussions about the location of the new concert hall and the financial aspects of the construction, a competition was launched on March 20, 1880. To safeguard the acoustic qualities, it was recommended in the program of requirements to use the same form and materials as the old music hall. [Deutsche Baunzeitung, 1880-06-21]

The due-date was originally set for May 31. However, this period was prolonged with fifteen days. 75 Austrian and German architects participated in the competition. The final designs were exhibited at the University of Leipzig. Martin Gropius and Heino Schmieden were proclaimed winners on June 27, 1880. The winners had studied various concert halls and also sought acoustic counseling with Joseph Joachim, who was an important violinist from Berlin. [Skoda, 2001]
4.6.2. The architects

Martin Gropius was born in Berlin on August 11, 1824. After graduating at the trade institute of Berlin, his drawing skills were enhanced under the supervision of A. von Kloeber. He visited the construction academy and was employed under Heinrich Starck as well. He passed the test for architecture in 1855. Hereafter, he mostly designed mansions between 1855 and 1866. [Skoda, 1985]

Heino Schmieden was born in Soldin on May 15, 1835. He completed his studies at the construction academy in Berlin in 1866. In the same year, Gropius and Schmieden established their architect firm in Berlin. Soon, this company grew into a leading architect cooperation of the German Capital. [Klinkott, 1971]

The cooperation designed a number of homes, as well as a hospital and a pavilion during the first years. They built a few buildings with acoustical demands; a college building in Kiel and chapel in Bovenburg [Skoda, 1985]. However, the acoustical demands of these buildings are different from a concert hall.

Giesenberg, who was assisted by Speer, was added to the design team of the Neue Gewandhaus. Only six months after the competition, Gropius died [Deutsche Bauzeitung, 1880-12-18]. After his death Von Weltzien completed the design team. [Centralblatt der bauverwaltung, 1883-12-08]

4.6.3. The construction

The Leipzig city council probably decided to postpone the construction of the Neue Gewandhaus because they did not feel consulted during the competition. Constructions of the Neue Gewandhaus finally started at the end of May 1882. [Schmieden, 1886]

Very little of the plan of the building was adjusted during the construction. Some changes were made at the back of the building due to the extension of the program of requirements, which suddenly asked for an extra concert hall intended for chamber music. [Schmieden, 1886]

The construction progressed well and the envelop was completed at the end of 1883 [Centralblatt der bauverwaltung, 1883-11-24]. At the final stage of the construction process, the usual acoustic tests were held. These were very satisfying.

The building was ready for its inauguration at December 1884. The total construction lasted for 31 months.
4.6.4. The design

Two music rooms were located within the Neue Gewandhaus: a smaller hall, which is a copy of the original Gewandhaus, and a larger hall for symphonic music. Gropius and Schmieden had most artistic freedom for the larger auditorium. However, it was recommended by the board to construct the hall from the same materials as the original Gewandhaus, and to use the same form [Schmieden, 1886]. This hall is the main focus of this section.

The entrances of the large auditorium were located on the second floor. The hall was 38 meters long and 19 meters wide. The height of the hall was 14.6 meters. The main audience area was flat. [Schmieden, 1886]

Box seats were positioned around the walls. The entrances of these box seats were located on the third floor. The breastwork of the box seats was decorated with paintings. Above these box seats, large windows were situated. [Schmieden, 1886]

The area of the stage was variable. This was a direct consequence of the program of requirements. 80 square meters was added to the stage for performances with a choir. This reduced the seating capacity by 80 seats. [Schmieden, 1886]

The stage was staircase-shaped. The back of the podium was 2.52 meters higher than the bottom of the hall. The height of the front of the stage was dependent on the type of stage. With the enlarged stage the difference in height was 0.85 meter. With the smaller stage the difference in height was 1.1 meters.

Despite the requested 1700 listeners in the program of requirements, the hall could accommodate 1533 or 1453 persons, depending on the performance. By installing smaller seats, the number of listeners could be increased to 1700 or 1620. [Schmieden, 1886]

The lower part of the hall was painted in a brown-red color and the upper parts and ceiling were painted in a light shade of green.

The span of the hall was realized by metal trusses, on which an ornamented ceiling was installed. All walls, except those located at the box seats, were covered with wood over an airspace. Curtains were hung in front of the back walls of the box seats. [Schmieden, 1886]

The reverberation time of the Neue Gewandhaus is unclear. Most current sources assume that the large hall had a reverberation of 1.5 s. However, contemporary sources assumed that it had a reverberation time of 2.0 s.

**Technical data large hall**

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</tr>
<tr>
<td>Reverberation time</td>
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</tr>
</tbody>
</table>

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4.6.3. Map of the second floor

4.6.4. Map of the third floor

4.6.5. Section of the Neue Gewandhaus
4.6.5. Acoustics in the design

Fortunately, the design team made a document about the design in 1886. This document contains information about the acoustic measures taken in the large auditorium of the Gewandhaus. This document gives a remarkable view into the acoustic knowledge of that time.

This document proves that the acoustic design of the Neue Gewandhaus was based on two other concert halls: the original Gewandhaus and the Trocadero Palace in Paris.

The first acoustic measure the document described is the resonance box. Like the original Gewandhaus, the new hall is surrounded by corridors and constructed of wood. In the document the design team compared this to the resonance box of a violin. However, it was uncertain whether this would work with a larger hall than the original Gewandhaus. It was assumed that by the lasting effect, the sound of the wood would improve just like the sound of a violin. [Schmieden, 1886]

Another aspect, which was copied from the original Gewandhaus, was the rounded corners. The architects assumed that sound could get stuck in 90° corners.

Finally, the coffered ceiling was copied from the original Gewandhaus for its acoustic properties. Its acoustic purpose was to scatter the sound.

From the acoustic concept of the Trocadero Palace, it was concluded that echoes should be avoided. In this case, standing waves were meant, because the need to avoid sound transmission back and forth between parallel surfaces is mentioned. The main concerns on this matter were the opposing parallel sidewalls of the concert hall. These walls were only interrupted by columns. After a few experiments, the architects decided to install tapestry-like paintings on these walls. [Schmieden, 1886]

The second part, which was copied from the acoustic concept of the Trocadero Palace, was the interval between direct sound and reflections. The document of the Neue Gewandhaus mentioned an interval of 1/12th second. However, it can be assumed that this was a slip of the pen, because it also mentioned a distance of 17 meters. Therefore, the interval of 1/10th of a second was actually used. Just as the Salle des fetes, surfaces more than 17 meters away from the centre of the stage were made absorbing and surfaces less than 17 meters away were made reflecting [Schmieden, 1886]. Also for this reason, the back wall of the concert hall was covered with an application that had proved useful in a concert hall in Hessen. In front of the back wall, drapes of fabric were hung. [Polytechnische weekblad, 1922-10-06]

Finally, the architects of the Gewandhaus assumed chandeliers had a positive effect on the acoustics due to their scattering of the sound. [Schmieden, 1886]

4.6.6. An impression of the large concert hall of the Neue Gewandhaus

4.6.7. An impression of the large concert hall of the Neue Gewandhaus
4.6.6. Aftercare

The Neue Gewandhaus was opened on December 11, 1884. This was graced by three days of festivities with the presence of the King and Queen of Saxony. [Schmieden, 1886]

The press was, without exception, positive about the acoustic properties of the Neue Gewandhaus. The Leipziger nachrichten: "the acoustics of the new music home exceeds even the wildest expectations" [Bogel, 1884-12-13]. The musical editor of the Leipziger Tageblatt und Anzeiger had attended the acoustic tests, which were undertaken just a few days before the Concert hall opened its doors. During these tests he concluded that: "even at the position below the gallery at the extreme corner of the hall, the music is totally intact" [Leipziger Tageblatt und Anzeiger, 1884-12-13].

The acoustics of the Neue Gewandhaus were famous. It quickly became a concert hall standard. It is certain that the Boston Symphony hall is based on its design. It is probable that some aspects have been copied for the Concertgebouw in Amsterdam.

With the exception of the usual repairs and maintenance, little was changed during the 60 years that the Neue Gewandhaus existed. This was due to the large financial resources which were spent during the construction. The only changes made in the design were ordered by the building inspection due to fire safety.

The Neue Gewandhaus suffered a tragic end. Leipzig suffered from an English bombardment during the night of February 20, 1944. The Neue Gewandhaus was hit by three heavy bombs. The woodwork in the building caught fire and the Neue Gewandhaus could not be saved from its destruction. The final demolition and clearance of the building took place in 1968. A converted congress hall was used by the Gewandhaus orchestra between 1946 and 1981. A new concert hall, in what was once the musical centre of Germany, was not built until 1981. This hall was again called the Neue Gewandhaus. [Skoda, 1985]
4.7. The Concertgebouw in Amsterdam (1888)

4.7.1. History before the construction

"De Parkzaal zal worden gesloopt, en daardoor zal Amsterdam zijn eenige concertzaal verliezen ..." [quote 14] according to Hayward, who responded on the proposed demolition of the Parkzaal, in 1881 [Hayward, 1881-06-26]. The Parkzaal was replaced by a city theater. The Parkzaal was loved for its acoustic properties. However, the plan was impractical and there was little room on stage. [De opmerker, 1883-01-20]

Beside the Parkzaal, Amsterdam possessed the Felix Meritus, the Odeon and the Paleis voor volksvlijt, for music performances. The oval concert hall of the Felix Meritus was renowned for its acoustic qualities. However, this concert hall could not accommodate a large audience. The Odeon could not accommodate a symphonic orchestra. The Paleis voor Volksvlijt did have a large auditorium. However, this hall was not purpose constructed for the purpose of musical performances. Therefore, the acoustics of this hall were poor. Or in the words of the Opmerker: "Het Paleis voor Volksvlijt resonneert op een zinstorende wijze". [quote 15] [De opmerker, 1883-01-20]

In 1875, it was attempted to place an organ in the large hall of the Paleis voor Volksvlijt. Therefore, it was attempted to improve the acoustics with the stretching of cotton wires, which was a common acoustic measure during the 19th century [Algemeen Handelsblad, 1875-02-09]. Although the immediate reactions were positive, three years later another attempt was undertaken to improve the acoustics with the help of the architect of the Tonhalle in Dusseldorf [De tijd, 1878-12-11]. This was attempted with the hanging of cardboard and linen. All these measures did not fundamentally improve the acoustics. [De opmerker, 1883-01-20]

The initiative for the construction of a new concert hall needed to come from the bourgeoisie because the city council was liberal [Royen, 1988]. In the previously mentioned article, Hayward pleaded for a new concert hall. He stated that a new concert hall did not had to be expensive and still could make a "solemn impression". [Hayward, 1881-06-26]

Following this article, six music enthusiasts, who formed a board, took an initiative for the construction of a concert hall. P.J.H. Cuypers, who was architect of the Rijksmuseum, became their advisor. A lot in the polder between Amsterdam and Nieuwer-Amstel was chosen for the location of the concert hall [De opmerker, 1883-01-20]. The Hayward’s recommendation of using the Tonhalle in Dusseldorf as a starting point was followed. This is proven by a report of a board meeting and a folder to attract shareholders. [Algemeen Handelsblad, 1882-03-07] [Amsterdam City Archive, Arch 1089]

A reaction was written, on the intention to base the new concert hall on the design of the Tonhalle by W.F. Thoof who studied in Rotterdam and Leipzig. This article offers a remarkable view into the contemporary acoustic knowledge. Thoof recognized that acoustics was an uncertain science. However, he suggested that a number of measures, which were easy to apply, would have a good effect on acoustics. Thoof considered a square form, which was also used in the Tonhalle in Dusseldorf, to be harmful for the acoustics of a concert hall meant for an audience over 2000 listeners. The tones would be weakened by the extensive sound line. The seating that would be lost by the above mentioned measure could be replaced by seats located on galleries.

4.7.1. An impression of the Parkzaal
However, in galleries opposite to the stage, which arise with a square form, sound could "get stuck". Therefore, every form that has angles should be avoided when designing a concert hall. The sound line is shortened and the application of galleries is less dangerous when using a round shape. Furthermore, Thooft stated that a concert hall possessing no walls directly bordering the outside would be acoustically superior. He considered the Felix Meritus and the Gewandhaus as examples [Thooft, 1882]. Thooft probably referred to the old Gewandhaus that was constructed in 1781, because the acoustics of the Neue Gewandhaus were unknown at this time.

The architect was selected by a competition in July 1882. Five contenders were invited to participate in this competition. They were judged by a jury of three architects, which was presided by P.J.H. Cuypers. [De opmerker, 1883-01-20]

The program of requirements demanded two concert halls: a small hall for chamber music and a large auditorium that could accommodate 2000 listeners, for symphonic music. It was also demanded that the small hall was a copy of the Felix Meritus. There were no requirements regarding the acoustics. [Amsterdam City Archive, Arch 1089]

During the time the architects had to finish their designs, the plan of the Tonhalle was at their disposal [Amsterdam City Archive]. The preliminary designs had to be returned to the jury on October 1, 1882. This is the only section of the Amsterdam city archive where the word acoustics is used concerning the Concertgebouw. Also, it is remarkable that these preliminary designs were returned without the specification of materials. [Amsterdam City Archive]

The verdict of the jury was announced in January 1883. Two participants were requested to return an improved version of their preliminary designs [De opmerker, 1883-01-20]. The five preliminary designs were exhibited in the building of Arti en Amicitiat [Het nieuws van den dag, 1883-01-17]. Both the assessment of the jury and two articles from weekly magazines have been used to give a look into the contemporary acoustic knowledge. Both magazines assume that the architects have used the design of the Neue Gewandhaus as a basis. Furthermore, the Opmerker stated that the smooth ceiling of the design of Van Gendt would have a bad influence on the acoustics. [Bouwkundig Weekblad, 1883-01-18] [De opmerker, 1883-01-20]

The jury agreed with the remarks about the ceiling and considered the smooth ceiling as an acoustic flaw. Furthermore, a glazed ceiling, which was placed in two designs, was regarded undesirable. The jury was, like Thooft, convinced that a square form, which was used in various designs, would have a bad influence on the acoustics. Finally, the jury considered three hall designs too wide relative to their length. [Amsterdam City Archive, Arch 1089]

The two remaining architects returned their improved designs in March 1883. The design of Adolf van Gendt was declared winner. [Royen, 1988]
4.7.2. The architect

Van Gendt became the architect of the Concertgebouw. He was born in Alkmaar in 1835 and studied at the Royal academy of visual arts in Amsterdam. His style of designing can best be typed as that of a salesman. He manufactured what his clients wished for. Weisman, who was his best known student, wrote the following words with his passing:

“De jongeren van die dagen hebben deze liberaliteit niet op haar juiste waarde geschat. Zij zagen er een gemis aan zelfstandigheid in, maar zij beoordeelden Van Gendt verkeerd. Niet welken stijl een gebouw vertoont, doch of het doeltreffend is ingericht bepaalt zijn innerlijke waarde. Het publiek zag dit zeer goed in; het geheim van het groote succes, dat aan Van Gendt te beurt is gevallen ligt daarin, dat men zeker was, als men hem een opdracht gaf, iets werkelijks bruikbaars te zullen verkrijgen. Zijn eigen ik hield Van Gendt op de achtergrond; zijn enig streven was, om aan de wensen zijner bestellers te voldoen. Kunstbroeders zijn hem daarover soms hard gevallen, hebben hem gebrek aan karakter verweten. Maar zij vergaten, dat een bouwwerk niet ten behoeve van dan architect, doch ten gerieve van den patroon wordt ondernomen. Voor Van Gendt moest de bouwmeester in de eerste plaats een man van zaken zijn. ... Hij heeft er nooit een geheim van gemaakt, dat er een koopmansgeest in hem school; hij was daar fier op, en wilde nimmer als kunstenaar poseren.” [quote 16] [Weisman, 1901-05-04]

Generally, the designs of Van Gendt were well judged despite the criticism. Especially, the technical skills of Van Gendt were praised. He called himself a “technical architect”. This technical approach is proved by his publications which were always technical and never about architectural aspects of a building. [Keuning et al, 1999]

Van Gendt had little experience with halls meant for music when he entered the competition for the design of the Concertgebouw. He had won a prize for the design of a never-constructed transportable building that would have been used for music festivals. Furthermore, Van Gendt designed the summer theater Frascati in 1879. However, these buildings have less acoustical demands. [Lansink et al, 1978]

It can be assumed that Van Gendt did not fancy music. His son Dolf jr. once said: “het is voor de nazaten altijd een raadsel geweest hoe een Van Gendt, ‘excusez-zo muzikaal als een koe’, een van de beste concertzalen ter wereld heeft kunnen ontwerpen” [quote 17] [Keuning et al, 1999]. Adolf van Gendt died in 1901, just after the passing of his wife. [Weisman, 1901-05-04]
4.7.3. The construction

The design by Van Gendt for the second round of the competition was not totally satisfactory to the board. Some adjustments still had to be made [Lansink et al, 1978]. The contract for the construction of the foundation was put out on June 16, 1883. These were completed by May 15, 1884 [Het nieuws van den dag, 1884-05-15]. The final design of the Concertgebouw was approved by the mayor and city council in November 1883. However, the start of the construction had to be postponed due to money problems [Lansink et al, 1978]

Meanwhile, many efforts to raise money were made by the board members. Furthermore, board member Cnoop Koopmans travelled to Leipzig at the end of 1883. Colleague board member Van Ogtrop asked him whether he could pay attention to what seating was installed and the size and costs of the organ in the Neue Gewandhaus [Amsterdam City Archive, Arch. 1089].

20 days later, the price list from a producer of organs was discussed in a board meeting. Malcher organ manufactures, that also built the organ in the Neue Gewandhaus, composed this price list [Amsterdam City Archive, Arch. 1089].

The envelop of the Concertgebouw was completed at the end of 1886. Immediately, the lack of financial resources showed again. Funds were needed for the building cost, the interior, the layout of the garden and the purchase of the organ. Slowly, the required financial resources were collected so that the last phases of the construction could be completed. The opening concert was announced on March 16, 1888 [Royen, 1988]. It is remarkable that in the proceedings of the board meetings between 1882 and 1888 the word acoustics was mentioned not even once.

No direct correlation has been found, however, Van Gendt inquired in a letter about drawings of the heating and ventilation of the Neue Gewandhaus on 5 January 1884. With these drawings, Van Gendt could compose the conditions for the producers of the heating and ventilation [Amsterdam City Archive, Arch. 1089]. Probably, Cnoop Koopmans took these drawings with him from his journey to Leipzig.

Finally, the contract of the Construction was put out on 19 February 1885 [Het nieuws van den dag, 1885-02-21]. The Board members again referred to the Neue Gewandhaus during the construction. It was decided that the stage initially was too small and that Van Gendt had to rebuild it using the new stage in the Neue Gewandhaus as a basis [Amsterdam City Archive, Arch. 1089].

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4.7.4. The design

Two Music halls are located within the Concertgebouw. A small concert hall, which was intended for chamber music, was built almost as a copy of the Felix Meritus. Van Gendt had most artistic freedom for the large concert hall, which was intended for symphonic music [Gendt, 1888-01-07]. The main focus of this section is the large concert hall.

The entrances to this concert hall are located on the first floor. This hall is shaped like a "shoe box" with a ratio between height, width and length of 2.3-5. The length of this "shoe box" is 44 meters. The width of the concert hall is 27.8 meters. The height of the music room is 17.5 meters. Galleries are positioned on the back and side walls. [Gendt, 1888-01-07]

The ceiling's construction consists of specially designed trusses on which a coffered ceiling was constructed. The walls are covered with plaster. The plaster is installed on brick beneath the galleries and on reed above the galleries. The floor was made of hard wooden plates. Large windows were placed high in the side walls [Beranek, 1996]. The stage could accommodate 180 musicians and 500 singers. At the time of the opening, the reverberation time of the large concert hall of the Concertgebouw was 2.0 s when filled and 2.8 s when empty.

It is unclear whether the large concert hall of the Concertgebouw is a copy of the large concert hall of the Neue Gewandhaus. There are many analogies between both concert halls. Firstly, both halls are completely surrounded by corridors and shaped like a "shoe box", in which right angles are avoided. Furthermore, the interiors of both halls are comparable. In these halls, the ceiling is ornamented probably to scatter sound. Daylight entered both halls via windows, which are situated high in the side walls.

It is certain that a number of components were studied in Leipzig. The stage of the large concert hall of the Concertgebouw was built after the stage of the large concert hall of the Neue Gewandhaus. The seating, the organ and the ventilation system were studied in Leipzig. The organ was made by the same manufacturer. [Amsterdam City Archive, Arch 1089]

However, there are some differences as well. The main difference is that the large concert hall of the Concertgebouw is wider than the large concert hall of the Neue Gewandhaus.

It is uncertain whether the large concert hall of the Concertgebouw is copied. Another remarkable fact is that Van Gendt owned a picture of the Neue Gewandhaus, which was published in 1886, and that he declared in a speech that the Concertgebouw had become for Amsterdam what the Neue Gewandhaus was for Leipzig. [Lansink et al, 1978]

**Technical data large hall**
- **Length**: 44.0 m
- **Width**: 27.8 m
- **Height**: 17.5 m
- **Volume**: 18780 m³
- **Seating capacity**: 2037
- **Floor finish**: Hard wooden plates
- **Wall finish**: Plaster on brick
- **Ceiling finish**: Coffered
- **Average reverberation time (500-1000 Hz)**: 2.0 sec

4.7.7. An impression of the large concert hall of the Concertgebouw after the renovation of 1899
4.7.5. Acoustics in the design

In this section, only the acoustics measures of the large hall of the Concertgebouw are considered. Van Gendt has never explained his acoustic concept. Therefore, three aspects are considered which give information about the acoustic design. Firstly, the comments of the board and jury members about acoustics are described. Secondly the design itself is analyzed according to the acoustical knowledge of the 19th century, which was described in the previous chapter. Finally, the design is compared with the Neue Gewandhaus in Leipzig. The acoustic applications of this concert hall were described in the previous section.

The comments of board and jury members during the competition have certainly influenced the acoustic concept. They made sure that the concert hall was not too high. With this, they prevented the sound from “losing itself in the space”. Furthermore, they ensured that the ceiling was coffered to scatter the sound. The sound scattering function was also implemented on the walls. These were finished with stucco surfaces. Finally, the advisors prevented the hall from getting too wide.

Subsequently, the design itself is analyzed with the acoustical knowledge of the 19th century. When the design is considered, it is clear that the large auditorium resembles a basilica, just like the Musikverein. Therefore, it is reasonable to assume that the design of the large music room is based on the theories of Langhans. The basilica shape was especially appreciated for its two rows of columns, which would scatter the sound.

Furthermore, the rounded corners at the front wall make an ellipse appear. The orchestra is placed in the focus of this ellipse, which was recommended by Chladni and others. The distance between the rounded wall and the focus is exactly 17 meters. Therefore, it can be assumed that the back wall was used for the same reason as in the Trocadero palace and the Neue Gewandhaus. It divided the first reflection over the concert hall. To enhance this function, the back wall was covered with absorbing materials. This consisted of various drapes. These would prevent reflections to arrive 1/10th of a second later than the direct sound. Beside the dividing aspect of the front wall, the rounded corners also prevented the sound to get stuck into a corner.

The 19th century acousticians recommended large amounts of resonating wooden panels. These were implemented in the floor, front wall and ceiling. However, the resonance box of a violin, which was described by the architects of the Neue Gewandhaus, was not totally implemented. It can be assumed that these materializations were used for acoustic reasons.

In the Neue Gewandhaus attempts were made to prevent standing waves from occurring. No evidence is found that this also was attempted in the large concert hall of the Concertgebouw. Both side walls are coated with plaster.
### 4.7.6. Aftercare

The large concert hall of the Concertgebouw was festively opened with a concert on April 11, 1888 [Het nieuws van den dag, 1888-04-11]. The opinions about the acoustics were divided: "Door personen die op onderscheidende punten der zaal gezeten hoorden we de akoestiek roemen". [quote 18] But also: "zonder dat echter ergens het resoneeren geheel gemist werd". [quote 19] The most constructive criticism was: "dat de strijkers werden overstemd door de koperen blaasinstrumenten" [quote 20] [Royen, 1989]. The position of the organ, which was not installed, was covered with a draping during the first concert. The desired organ was not installed until 1891 due to money problems. [De opmerker, 1893-05-06]

The problem of the not-entirely-satisfying acoustics existed between 1888 and 1899. The problem of the acoustics was most denounced by the director of the openings concert, Henri Viotta. Mostly palliatives were used trying to solve this problem. The most remarkable ‘solution’ was the positioning of plants, which would “sip up” the sound of the brass instruments. [Royen, 1988] The final contribution to the Concertgebouw of Van Gendt was the correction of the not-entirely-successful acoustics. Under his supervision the podium was lowered and the slope was diminished in September 1899. This rebuilding was done according to the advice of secretary Stumpff and orchestra director Mengelberg [Royen, 1988]. The change immediately provoked enthusiastic reactions regarding the acoustics. [Het nieuws van den dag, 1899-09-12]

The reputation of the acoustics of the large concert hall significantly improved due to this rebuilding. More renovations were done after the opening of the Concertgebouw. It was realized that these interventions could influence the acoustics. [Lansink et al, 1978]

Thus, subsequent renovations were limited. The floor of the large auditorium was affected by dry rot in 1951. Therefore, concrete was applied underneath the floor. The ceiling was renovated in 1962. During this renovation, the profile of the ceiling was diminished. In 1970, money was raised to refurbish the large concert hall, which existed for 100 years [Lansink et al, 1978]. The ceiling was brought back to its original proportions in 1997. During this renovation the interior was again refreshed.

According to the contemporary vision, it was the renovation of the stage that led to the excellent acoustic reputation of the large concert hall of the Concertgebouw [Lansink et al, 1978]. The other minor renovations have not harmed the acoustics. Nowadays, the Concertgebouw is regarded as one of the three acoustically superior concert halls.
4.8 Comparison between contemporary and current knowledge

4.8.1. Comparison per concert hall

*Musikverein*
Because Von Hansen never explained his approach regarding the acoustics, it is uncertain which acoustic design applications were used in the Grosser Musikvereinssaal. It is reasonable to assume that Von Hansen based the acoustic design on the theories of Langhans. Firstly, he copied the shape and columns of the large concert hall from a basilica. The effect of the columns on the acoustics is studied in the next chapter. Furthermore, Von Hansen copied the acoustic aspects he considered beneficial from three concert halls designed by Friedrich Schinkel, which were based on the reverberation theory of Langhans [Gaubman, 1998]. During the existence of the Musikverein a number of aspects of the design were changed. In 1911, the Grosser Musikvereinssaal underwent a large renovation caused by the growing orchestra and shifted goal of presence during concerts [Grasberger, 1970]. In the sixth chapter it is investigated whether this renovation influenced the acoustics of this concert hall.

*Palais Garnier*
The Palais Garnier is a special case. Though Garnier thoroughly studied architectural acoustics, according to him, he could not find a positive rule to guide him [Garnier, 1878]. Maybe this statement needs to be nuanced. The form of the opera house was copied from another opera house and was used in most contemporary opera houses [Steinhauser, 1969]. The stage was constructed from wood on a cavity, which was assumed to be beneficial for acoustics during the 19th century [Morgan, 1960]. Furthermore, in his second book he made a number of constructive remarks about improving the acoustics of the Palais Garnier [Garnier, 1881]. Finally, the 19th century, acousticians did not believe that the acoustics of the Palais Garnier were based on coincidence. [Sturmhoefel, 1888] [Berlage, 1895]

*Festspielhaus*
It is safe to conclude that Wagner and Semper had an acoustic concept regarding the Festspielhaus. This concept was supposed to second the optical concept. Wagner tried to influence the ratio of sound from singers and various groups of instruments. Therefore, he attempted to increase the sound of the singers and to dampen the sound of the brass wind instruments. That this acoustic concept worked, is shown in figure 4.8.1. [Schuth, 2007]. The singers are perceived stronger than the string instruments, which are perceived stronger than the copper wind instruments. The most important aspect of the Festspielhaus was the turning down of the lights during the performances. This caused a revolution in the concert and opera experience which enabled the audience to concentrate on the performance and hear the acoustics better.

4.8.1. G measured on one position due to four different source position in the Festspielhaus

*Trocadero Palace*
Though the Trocadero palace was built according to the laws of the contemporary acoustic science, [Morel, 1878] the acoustics were a complete failure [Rotterdamsche courant, 1922-10-11]. Due to a very large space and a wrong use of materials, a very long reverberation time arose. Furthermore, due to the wrongly applied back wall, in
some places the sound was too loud and in other places the sound was barely audible. However, the Trocadero Palace should be considered important in the evolution of acoustic designing. Both the prevention of standing waves and an interval between sound and reflected sound, which were implemented in this concert hall, are still used in acoustic design [Schmieden, 1886]. Furthermore, the existence of an absorption coefficient instead of a rigid distinction between absorbent and non-absorbent materials was discovered. [Morel, 1878]

**Neue Gewandhaus**

It is not possible to conclude there was an overarching acoustical concept on the design of the Neue Gewandhaus. The architects used a number of acoustical applications, which were assumed preferable for the acoustics [Schmieden, 1886]. A number of them were copied from the Trocadero Palace and most of them are considered beneficial for the acoustics, nowadays. However, the time interval between direct and reflected sound, which was implemented in this concert hall, was defined for speech. Nowadays, this aspect is used in the acoustic parameter c80, which is defined for music. Therefore, this application was wrongly implemented. Furthermore, the scattering of the sound by the chandelier was considered beneficial for the acoustics. Current acousticians are cautious with the implementation of chandeliers because they can resonate with the sound and the sound scattering effect is limited to the higher frequencies of sound.

**Concertgebouw**

Because Van Gendt never explained his acoustical design approach, it is uncertain whether the Concertgebouw was designed according to an acoustical concept. Probably, a number of acoustical applications that were thought to be beneficial for the acoustics were applied, like the columns and the rounded corners at the end where the orchestra plays [Lansink et al, 1978]. The effect of a number of these applications on the acoustics is studied in the next chapter. The opinions about the acoustics were divided at the opening. It is generally thought that the renovation of 1899 would have given the Concertgebouw its famous acoustics [Royen, 1988]. The sixth chapter studies how this renovation has influenced the acoustics.

### 4.8.2. General comparison

All architects were aware that acoustics as a science was in its infancy. There were not many guidelines, which is made clear by the example of Garnier. However in most cases, acoustic applications were used that are still put into practice today. In all cases the architect did not have any experience with the construction of other concert halls. However, most architects had some experience with the design of buildings with acoustic demands, like theaters and churches. However, during the 19th century, acousticians were aware that these acoustic demands differed from a concert hall.

Five of the six considered concert halls had a familiar shape of audience area: three concert halls were shaped like a “shoe box” and two opera houses had the form of a “horse shoe”. The stranger in their midst is the Festspielhaus, which is square shaped and used specially for Wagner’s music. The familiar shapes were copied from other concert halls.

Furthermore, in all of the concert halls wood was used to finish of various surfaces. In all cases, the stage was constructed out of wood. It was done, because it was assumed to increase the volume of the music. In some cases, where many surfaces of the hall were coated with wooden panels, this was assumed to operate like the resonance box of a violin. It is uncertain what the exact acoustic effect of this application is. In the previous chapter it was shown that these wooden panels are used for other reasons within the architectural acoustics nowadays. Furthermore, some current concert halls are made of concrete and have satisfying acoustics. In a number of the considered music homes, the concert hall is not adjacent to the outer wall. This was done to enhance the working of the assumed
resonance box. The loose wall would resonate with the sound. It is unlikely that this influences the acoustic properties of a concert hall. At the end of every construction process, all the halls underwent acoustic tests. After these tests, little was changed.

The largest difference between the contemporary acoustic design and the acoustic design during the second half of the 19th century is that current acoustic concepts are depending on the reverberation and the shape of the decay curve. This was just a minor goal for concert hall design during the 19th century. The main goal of the acoustic concepts was to distribute the sound over every position as loud as possible.

In appendix 6 a canon, which is a list of works that are thought valuable for a specific field of interest, appears about important architectural acoustical events in respect to the considered concert halls.
5. The influence of the applications on acoustics

5.1 Introduction

In the two previous chapters, it was shown that a number of applications were chosen in the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw for their acoustic properties. In this chapter, the influence on the acoustics of three of these applications is studied. This is done with the room-acoustical-prediction model Odeon, using models of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw found on the website of Odeon. In the subsequent section it is explained in which way the results of this room-acoustical-prediction model are generated and analyzed.

Thereafter, the applications are described and the results of the simulations are analyzed. The first investigated application is the columns used in both concert halls. Already in 1800, Rhode advocated the basilica shape [Rhode, 1800]. He especially recommended two rows of columns, which would divide the sound over the room. The influence of this measure on the acoustics of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw is studied in the third section.

In section 4.7., it was shown that the jury of the design competition for the large concert hall of the Concertgebouw considered a flat ceiling detrimental to the acoustics [Amsterdam City Archive, Arch 1089]. Therefore, a coffered ceiling was installed in the large concert hall of the Concertgebouw. Like the columns, the assumed effect on the acoustics of this measure was to distribute the sound over the concert hall. In the Grosser Musikvereinssaal an ornamented ceiling was used. In the fourth section the effect of the coffered and ornamented ceiling is studied.

In the works of Chladni some room shapes were proposed which were assumed to be beneficial for the acoustics [Chladni, 1826-09-30]. The most prominent being the rectangular shape with an elliptical back wall, at the end where the orchestra played. This application was more or less implemented in the design of the large concert hall of the Concertgebouw. This application was probably copied from the Neue Gewandhaus. The architects of the Neue Gewandhaus, at their turn, copied the rounded corners from the Trocadero palace. However, the influence of this application on the acoustics is questionable and this measure is rarely applied in current concert hall design. Therefore, the effect of this application is studied in the last section.

5.1.1. Model of the Grosser Musikvereinssaal found on the website of the room-acoustical-prediction model Odeon

5.1.2. Model of the large concert hall of the Concertgebouw found on the website of the room-acoustical-prediction model Odeon
5.2. Method

The results are generated with the room-acoustical-prediction model Odeon. On the website of this software, models were found of both the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw. These models were adjusted to the configurations of the original designs of both concert halls.

The simulations were done according the measurement description in the ISO 3382 standard. This standard discusses the measurements of room acoustic parameters. It states that a point source is placed on two different positions on stage and an impulse response is measured at a minimum of ten different positions in the audience area. Therefore, in the adjusted models, two point sources were placed at different placed on stage. A grid simulation, with a grid width of 1.5 meters, was done over the first floor on all seating areas. The result of both point sources was averaged for the measurement positions.

Thereafter, the studied acoustical application was removed from the models of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw. The simulation, with the same source positions and grids, was performed again. The results of both point sources were averaged as well. The simulation setup is depicted in figures 5.2.1., 5.2.2., 5.2.3., and 5.2.4..

This is a schematic approach of reality. In reality, acoustics are judged with a complete symphonic orchestra. In these cases, only two point sources are installed, which simulate a complete symphonic orchestra. Furthermore, the parameters are measured only in the audience area. Similarly, the acoustics on stage are important as well. When the acoustical properties on stage enable single musicians of an orchestra to hear other instruments separately, the ensemble play will be better. This improves the sound produced by the orchestra, and consequently, the performance.

Furthermore, the simulations were done while the concert halls were unoccupied because the models were calibrated with values of an empty Grosser Musikvereinssaal and Concert hall of the Concertgebouw. In reality, the acoustics are experienced while these concert halls are filled with an audience. The sound absorbing properties of chairs differ from the sound absorbing properties of people. For these three reasons, the acoustic properties of the simulated models might differ from reality. Some other considerations, regarding the difference between the acoustical applications in reality and the acoustical applications in the models, are made in the following three sections about the implementation of the columns, ornamented ceiling and rounded corners.
The results are analyzed using the ISO 3382 standard as well. Within this norm, a number of parameters are mentioned. For this study, five of these parameters are used: C80, EDT, G, LF, and T30.

The C80 is defined as $10 \times \log$ of the sound energy arriving within the first 80 ms after the direct sound divided by the sound energy arriving later than the first 80 ms after the direct sound. This is depicted in figure 5.2.5. This parameter is used to define the degree of localization and intelligibility of instruments. Therefore, the C80 is usually named the clarity. While the C80 was defined in 1975, it was shown in section 3.4. that this parameter has a history which reaches back into the 18th century. [Reichhard et al, 1975]

As shown in chapter 1., Sabine defined reverberation time around the year 1900. The reverberation time is the period in seconds that would be required for the sound pressure level to decrease by 60 dB. Two parameters are used to which describe this aspect. The EDT is the period in seconds for the initial 10 dB
of the decay multiplied by six. The T30 is the period in seconds between the decay of 5 and 35 dB multiplied by two. These parameters are depicted in figure 5.2.6. EDT is subjectively more important and related to perceived reverberance, while the T30 is related to the physical properties of the auditorium.

As shown in section 4.8., the main goal of the acoustic design during the 19th century was to distribute the sound over all the positions in the hall. The G is a parameter that is used to measure the distribution of sound over an auditorium today. This parameter describes the subjective level of sound and is defined as the sound level of a sound source measured in a position, minus the sound level of the same source measured 10 meters in the free field. Due to this subtraction, the value of this parameter is independent from the power of the used sound source.

For the last studied parameter, no relations before 1900 have been found. The LF is defined as the fraction of energy from lateral directions compared with the energy from all directions, both arriving within the first 80 ms. This is depicted in figure 5.2.7. This parameter was defined in 1981 [Barron et al., 1981]. The energy from all positions is measured with an omnidirectional microphone and the energy from lateral directions is measured with a figure-of-eight microphone. This parameter is supposed to describe the subjective listener aspect Apparent Source Width.

Table 5.2.1. Acoustic quantities grouped according to listener aspect [ISO, 2 1997]

<table>
<thead>
<tr>
<th>Subjective listener aspect</th>
<th>Acoustic parameter</th>
<th>Single number frequency averaging (Hz)</th>
<th>Just noticeable difference (JND)</th>
<th>Typical Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perceived clarity of sound</td>
<td>Clarity, C80 in dB</td>
<td>500 to 1000</td>
<td>1 dB</td>
<td>-5 dB; 5 dB</td>
</tr>
<tr>
<td>Perceived reverberance</td>
<td>Early Decay Time, EDT in s</td>
<td>500 to 100</td>
<td>Rel. 5%</td>
<td>1,0 s; 3,0 s</td>
</tr>
<tr>
<td></td>
<td>Reverberation time, T30 in s</td>
<td>500 to 1000</td>
<td>Rel. 5%</td>
<td>1,0 s; 3,0 s</td>
</tr>
<tr>
<td>Subjective level of sound</td>
<td>Sound Strength, G, in DB</td>
<td>500 to 1000</td>
<td>1 dB</td>
<td>-2 dB; 10 dB</td>
</tr>
<tr>
<td>Apparent Source Width</td>
<td>Early Lateral Energy Fraction, LF</td>
<td>125 to 1000</td>
<td>0,05</td>
<td>0,05;0,35</td>
</tr>
</tbody>
</table>

5.3 Columns

5.3.1. Problem

In section 3.2., it was shown that the fundamentals of the “shoe box” shaped hall lay in the form of the basilica. Within the basilica the most prominent feature is the two rows of columns from the front to the back of the hall, which divided the space into a nave and two side aisles. Furthermore, in section 3.7., it was shown that during the 19th century, sound distribution was considered to be beneficial for the acoustics. For this reason columns were
thought to be beneficial for the acoustic properties. The architects of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw probably implemented these columns for the previously mentioned reasons.

Nowadays, the sound scattering effect of columns is still advocated. In 1997, Fricke and Haan argued that: "Many of the finest concert halls were built in the 19th century, have coffered ceilings, and columns, niches or statues on the side walls, all of which are thought to help with sound diffusion" [Haan et al, 1997]. This section studies whether the columns scattered the sound as they were intended to, and which other effects resulted from this application.

Some considerations are made regarding the implementation of the columns in the simulation models. The caryatid columns in the Grosser Musikvereinssaal possess a high degree of scattering. This is due to their surface, which is highly ornamented. In the model, these are simulated as square columns with a length and width of 0.5 meters and a scatterings coefficient of 0.05. In the large concert hall of the Concertgebouw, the columns are round. In the model, these are simulated as square columns with a length and width of 0.2 meters and a scatterings coefficient of 0.05. To verify whether the models gave results that could be compared, the Tsab is determined. The results are shown in tables 5.3.1. and 5.3.2. From these results it can be concluded that both models can be used.

<table>
<thead>
<tr>
<th>Table 5.3.1. Tsab in both models of the Grosser Musikvereinssaal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Model with columns</td>
</tr>
<tr>
<td>Model without columns</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5.3.2. Tsab in both models of the large concert hall of the Concertgebouw</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Model with columns</td>
</tr>
<tr>
<td>Model without columns</td>
</tr>
</tbody>
</table>

5.3.1. Grosser Musikvereinssaal without columns

5.3.2. Large concert hall of the Concertgebouw without columns

5.3.2. Results

The depicted results in this section are shown in tables with three columns. In the left column, the values of the depicted parameter are shown within the original configuration of the concert hall. In the middle column, the values of the depicted parameter are shown within the configuration of the concert hall without the studied acoustic application. In the right column, the results of the subtraction of the latter from the former are shown. The parameters are shown as a single number frequency average and they are shown in a surface plot. The JND is used as the graph scale. When there is no audible difference between the former and the latter, the parameter in the surface plot of the right column is depicted with a white color. The results which are not shown in this chapter appear in appendix 3.

Because the columns are reflective, the total acoustical energy did not change by removing the columns. Therefore, no audible differences occurred in C80, EDT
and T30. It is more remarkable that the G showed no audible difference in both concert halls, because the columns were intended to influence the distribution of the sound energy.

The LF showed some audible differences, especially within the Grosser Musikvereinssaal. This is probably due to the independence of the LF from the decay curve slope. The results of the single number frequency average of the LF are shown in tables 5.3.3. and 5.3.4.. The LF generated different results. In the Grosser Musikvereinssaal, the LF was audibly higher in the side aisles within the configuration with columns. An explanation for these results can be given with the assumption that the LF is lower when the room is wider [Barron, 2000]. Because the columns within the Grosser Musikvereinssaal are relatively large, the two rows can be regarded as fictitious wall. When this is done, the side aisles of the Grosser Musikvereinssaal were much wider when the columns were removed.

Table 5.3.3. The LF within the Grosser Musikvereinssaal

<table>
<thead>
<tr>
<th>LF within the configuration at the opening</th>
<th>LF within the configuration at the opening without columns</th>
<th>The latter minus the former</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20-0.25</td>
<td>0.25-0.30</td>
<td>-0.20--0.15</td>
</tr>
<tr>
<td>0.30-0.35</td>
<td>0.35-0.40</td>
<td>-0.10--0.05</td>
</tr>
<tr>
<td>0.40-0.45</td>
<td>0.45-0.50</td>
<td>0.00-0.05</td>
</tr>
<tr>
<td>0.50-0.55</td>
<td></td>
<td>0.10-0.15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Average</th>
<th>0.24</th>
<th>Average</th>
<th>0.24</th>
<th>Average</th>
<th>0.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0.15</td>
<td>Minimum</td>
<td>0.17</td>
<td>Minimum</td>
<td>-0.07</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.52</td>
<td>Maximum</td>
<td>0.37</td>
<td>Maximum</td>
<td>0.16</td>
</tr>
<tr>
<td>St. dev.</td>
<td>0.07</td>
<td>St. dev.</td>
<td>0.05</td>
<td>St. dev.</td>
<td>0.04</td>
</tr>
</tbody>
</table>
In the large concert hall of the Concertgebouw, no receiver positions were placed in the side aisles. The results of the nave are not comparable. In the large concert hall of the Concertgebouw, the LF is not changed by the removal of the columns. In the Grosser Musikvereinssaal, the LF is lower (though not audibly) in the configuration with columns. This difference between the concert halls is caused by the different size of the columns. In the Grosser Musikvereinssaal probably, a substantial part of the early lateral reflections is prevented by the columns from getting to the receiver positions in the nave, within the given time interval of 80ms. In the large concert hall of the Concertgebouw, the columns are smaller and block less lateral reflections.

Some considerations are made regarding the implementation of columns in simulation models. The columns in both simulations are a schematic approach of reality. The sound might pass a column in reality, especially the lower frequencies, due to diffraction where this is blocked in the model, which will influence the LF. Therefore, the results were studied per frequency band. In the models of both the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw, no significant difference was found between various frequency bands.

Table 5.3.4. The LF within the large concert hall of the Concertgebouw

<table>
<thead>
<tr>
<th>LF within the configuration at the opening</th>
<th>LF within the configuration at the opening without columns</th>
<th>The latter minus the former</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>0.00-0.05</th>
<th>0.05-0.10</th>
<th></th>
<th>0.00-0.05</th>
<th>0.05-0.10</th>
<th></th>
<th></th>
<th>-0.20-0.15</th>
<th>-0.15-0.10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.10-0.15</td>
<td>0.15-0.20</td>
<td></td>
<td>0.10-0.15</td>
<td>0.15-0.20</td>
<td></td>
<td></td>
<td>-0.19-0.06</td>
<td>-0.05-0.00</td>
</tr>
<tr>
<td></td>
<td>0.20-0.25</td>
<td>0.25-0.30</td>
<td></td>
<td>0.20-0.25</td>
<td>0.25-0.30</td>
<td></td>
<td></td>
<td>0.00-0.05</td>
<td>0.05-0.10</td>
</tr>
<tr>
<td></td>
<td>0.30-0.35</td>
<td>0.35-0.40</td>
<td></td>
<td>0.30-0.35</td>
<td>0.35-0.40</td>
<td></td>
<td></td>
<td>0.10-0.15</td>
<td>0.15-0.20</td>
</tr>
<tr>
<td></td>
<td>0.40-0.45</td>
<td>0.45-0.50</td>
<td></td>
<td>0.40-0.45</td>
<td>0.45-0.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.50-0.55</td>
<td></td>
<td></td>
<td>0.50-0.55</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Average</th>
<th>0.21</th>
<th>Average</th>
<th>0.21</th>
<th>Average</th>
<th>-0.01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0.35</td>
<td>Minimum</td>
<td>0.36</td>
<td>Minimum</td>
<td>0.10</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.04</td>
<td>Maximum</td>
<td>0.04</td>
<td>Maximum</td>
<td>-0.10</td>
</tr>
<tr>
<td>St. dev.</td>
<td>0.06</td>
<td>St. dev.</td>
<td>0.06</td>
<td>St. dev.</td>
<td>0.03</td>
</tr>
</tbody>
</table>
5.4 Ornamented ceiling

5.4.1. Problem

In section 3.5., it was shown that during the 19th century sound scattering was considered to be beneficial for the acoustics. A number of applications were thought to have this property. One of these applications is the coffered ceiling, which was possibly adopted from basilicas and implemented in the large concert hall of the Concertgebouw. The ceiling of the Grosser Musikvereinssaal was not flat either. It was covered with various ornaments. In this section, the influence of both ceilings on the acoustics is studied.

Nowadays, the effect of the ornamented ceilings is still regarded as being beneficial for the acoustic properties of a concert hall. In 1996, Beranek commented about the fine ornamentation used in concert halls built during the last decades of the 19th century [Beranek, 1996]. He regarded the effect of the ornaments as being positive for two reasons: the diffusion of the early sound and the diffusion of the reverberant sound. The first one is liked because the reflections of smooth surfaces are perceived as harsh, where the reflections of ornamented surfaces are perceived as pleasant. The second one appears to be more dependent from arrival directions of the reverberant sound. However, both of these senses cannot be tested with the currently used acoustic parameters.

Also Fricke and Haan investigated the diffusity of halls in their study of 1997 [Fricke and Haan, 1997]. In this study, which was mentioned in chapter two, they confirmed the reputation of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw. From their findings they concluded that: "Surface diffusity appears to be largely responsible for the difference between halls which are rated excellent as opposed to those rated as good or mediocre".

Therefore, a simulation is done with two models. First, a simulation is done with the configuration of the original configuration. In the original model of the Grosser Musikvereinssaal, the ornamented ceiling is modeled with an almost flat ceiling, except for the positions of the construction. The diffusion coefficient of the horizontal ceiling and the surfaces modeling the construction of the ceiling is 0.05. In the original model of the large concert hall of the Concertgebouw, the coffered ceiling is modeled by various vertical surfaces which divide the ceiling into 40 squares and possess a diffusity coefficient of 0.05. The diffusity coefficient of the horizontal surface is 0.02. After this simulation, the ornamented ceiling is replaced by a flat ceiling, and a new simulation is performed. In the Grosser Musikvereinssaal, the surfaces modeling the constructions of the Grosser Musikvereinssaal are removed and the ceiling is replaced by one flat surface, which possesses the same sound absorption coefficient and a diffusity coefficient of 0.0. In the large concert hall of the Concertgebouw, the vertical surfaces are removed and the horizontal surfaces are replaced by one surface with the same sound absorption coefficient and a diffusity coefficient of 0.0. To verify whether these models gave results which could be compared, the Tsab is determined. The results are shown in tables 5.4.1. and 5.4.2. The results do not audibly differ in both the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw.

| Table 5.4.1. Tsab in both models of the Grosser Musikvereinssaal |
|-----------------|----------|----------|
|                  | 500      | 1000     |
| Model with ornamented ceiling | 3.30     | 3.03     |
| Model without ornamented ceiling | 3.24    | 2.98     |

| Table 5.4.2. Tsab in both models of the large concert hall of the Concertgebouw |
|-----------------|----------|----------|
|                  | 500      | 1000     |
| Model with coffered ceiling | 2.62     | 2.67     |
| Model without coffered ceiling | 2.65    | 2.70     |
There was no difference between the single number frequency average of the LF between both configurations of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw. This also applies for the separate frequency bands from 63 Hz to 8000 Hz. Possibly, a shift in arrival directions was present. However, this possible change was too small to observe with the LF. Furthermore, in both concert halls, the ratio between early arriving and late arriving sound did not audibly change by the removal of the ornamented ceilings, considering the similarity between the results of the C80. This was also verified for separate frequency bands ranging from 63 Hz to 8000 Hz. Finally, the results of the G showed no audible differences in the frequency bands ranging from 63 Hz to 8000 Hz, which can be explained by the fact that the ornamented ceilings did not largely influence the distribution of the sound energy over the halls.

Though the C80 did not audibly change, due to the removal of the ornamented ceilings, the two parameters describing reverberation times have changed in both concert halls. The T30 and the EDT are audibly longer in the configuration with the flat ceiling in both concert halls. This effect was stronger in the lower and middle frequency bands than the higher frequency bands. The T30 and EDT being higher, in the configuration with the flat ceiling, is in contradiction with tables 5.4.1. and 5.4.2.. These tables suggest that the reverberation times are stable, while the ceiling is changed. This difference might be caused by the difference of diffusion in the sound fields. In the approach with the T sab, which is used in tables 5.4.1. and 5.4.2., the reverberation is always determined with the principle of a totally diffuse sound field. In the simulations, the sound fields differ in diffusion between both tested configurations. This might indicate that the difference in diffusion of the sound field influences the sound absorbing properties. This effect was also presumed by Nishihara, in 2001: "It was surmised that the difference between audience absorption coefficients at low frequencies in reverberation chambers and those measured in halls for music was caused by the differences in the diffusion of their respective sound fields" [Nishihara, 2001]. The results of the T30 are shown in tables 5.4.3. and 5.4.4..
Table 5.4.3. The T30 within the Grosser Musikvereinssaal

<table>
<thead>
<tr>
<th>Frequency</th>
<th>63</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>8000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average original layout</td>
<td>2.70</td>
<td>2.81</td>
<td>3.26</td>
<td>3.34</td>
<td>3.12</td>
<td>2.79</td>
<td>2.05</td>
<td>1.05</td>
</tr>
<tr>
<td>Minimum original layout</td>
<td>2.65</td>
<td>2.76</td>
<td>3.21</td>
<td>3.28</td>
<td>3.04</td>
<td>2.72</td>
<td>1.99</td>
<td>1.01</td>
</tr>
<tr>
<td>Maximum original layout</td>
<td>2.77</td>
<td>2.88</td>
<td>3.34</td>
<td>3.43</td>
<td>3.19</td>
<td>2.84</td>
<td>2.08</td>
<td>1.09</td>
</tr>
<tr>
<td>Average without ornamented ceiling</td>
<td>2.78</td>
<td>2.92</td>
<td>3.41</td>
<td>3.55</td>
<td>3.35</td>
<td>2.98</td>
<td>2.14</td>
<td>1.06</td>
</tr>
<tr>
<td>Minimum without ornamented ceiling</td>
<td>2.71</td>
<td>2.85</td>
<td>3.37</td>
<td>3.47</td>
<td>3.28</td>
<td>2.92</td>
<td>2.11</td>
<td>1.01</td>
</tr>
<tr>
<td>Maximum without ornamented ceiling</td>
<td>2.94</td>
<td>3.04</td>
<td>3.52</td>
<td>3.73</td>
<td>3.49</td>
<td>3.08</td>
<td>2.20</td>
<td>1.11</td>
</tr>
</tbody>
</table>

Table 5.4.4. The T30 within the large concert hall of the Concertgebouw

<table>
<thead>
<tr>
<th>Frequency</th>
<th>63</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>8000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average original layout</td>
<td>2.14</td>
<td>2.42</td>
<td>2.44</td>
<td>2.52</td>
<td>2.56</td>
<td>2.50</td>
<td>2.03</td>
<td>1.06</td>
</tr>
<tr>
<td>Minimum original layout</td>
<td>2.04</td>
<td>2.34</td>
<td>2.34</td>
<td>2.43</td>
<td>2.38</td>
<td>2.39</td>
<td>1.94</td>
<td>0.98</td>
</tr>
<tr>
<td>Maximum original layout</td>
<td>2.23</td>
<td>2.50</td>
<td>2.53</td>
<td>2.64</td>
<td>2.72</td>
<td>2.60</td>
<td>2.12</td>
<td>1.20</td>
</tr>
<tr>
<td>Average without ornamented ceiling</td>
<td>2.31</td>
<td>2.62</td>
<td>2.61</td>
<td>2.70</td>
<td>2.72</td>
<td>2.61</td>
<td>2.10</td>
<td>1.07</td>
</tr>
<tr>
<td>Minimum without ornamented ceiling</td>
<td>2.19</td>
<td>2.51</td>
<td>2.52</td>
<td>2.59</td>
<td>2.58</td>
<td>2.51</td>
<td>2.02</td>
<td>0.98</td>
</tr>
<tr>
<td>Maximum without ornamented ceiling</td>
<td>2.40</td>
<td>2.70</td>
<td>2.71</td>
<td>2.79</td>
<td>2.85</td>
<td>2.74</td>
<td>2.21</td>
<td>1.18</td>
</tr>
</tbody>
</table>
5.5 Rounded corners

5.5.1. Problem

In section 3.2., it was shown that after his famous citations about the springing sand, Chladni discussed some shapes of an acoustic room [Chladni, 1826-09-30]. One of the described shapes was rectangular with an elliptical wall at the end where the orchestra played. When the orchestra was positioned in the focus point of the ellipse, the back wall would divide the sound evenly over the auditorium. This acoustic application was more or less used in many concert halls constructed during the 19th century, including the Salle de fetes located in the Tracadero palace, the large concert hall in the Neue Gewandhaus, and the large concert hall of the Concertgebouw.

5.5.1. large concert hall of the Concertgebouw without rounded corners

In the design of the large concert hall of the Concertgebouw, the back wall was not elliptically shaped. However, the corners at the end where the orchestra played were rounded. The wall with the rounded corners was positioned 17 meters from the center of the stage. According to contemporary acoustic science, direct sound would be enhanced by reflections arriving within 1/10th of a second or reflections, which travelled an extra path length that did not exceed 34 meters were considered useful reinforcement [Radau, 1869]. Therefore, it can be assumed that this wall was used to enhance the direct sound by the first reflection.

The rounded corners are one of the outstanding features in the design of the large concert hall of the Concertgebouw. Its assumed role in the large concert hall of the Concertgebouw was not limited to its sound dividing purpose. In the article of Thooft, he argued that sound could "get stuck" in 90° corners [Thooft, 1881]. Also, in 1861, Smith regarded the rounded corners as remedy against acoustic defects, which, according to him, were a more prominent danger in rectangular shaped halls [Smith, 1861]. This section studies whether these rounded corners divided the sound and if sound "got stuck" in the 90° corners.

In current concert hall design, rounded corners are not implemented anymore. Furthermore, no current studies have been found that covered the influence of this application on the acoustics.

Some considerations are made regarding the implementation of the rounded corners in the large concert hall of the Concertgebouw. In reality, this is a smooth surface that is covered with plaster. Because the room-acoustical-prediction model Odeon is not able to simulate rounded surfaces, in the model, the rounded corners are simulated with six rectangular surfaces that possess a sound scattering coefficient of 0.05. In the model with the square corners, the same material is used. Furthermore, the volume is larger in the configuration without the rounded corners. This explains the higher $T_s$. This is depicted in Table 5.5.1.

<table>
<thead>
<tr>
<th>Model</th>
<th>500</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model with rounded corners</td>
<td>2.62</td>
<td>2.67</td>
</tr>
<tr>
<td>Model without rounded corners</td>
<td>2.69</td>
<td>2.75</td>
</tr>
</tbody>
</table>

5.5.2 Results

The results showed no audible difference in C80, G and LF between the tested configurations. This applied for the frequency bands ranging from 63 to 8000 Hz. The similarity between the LF over all frequency bands is remarkable because Chladni assumed that this back
wall would influence the reflections. This difference between the model and the assumed effect is possibly due to the scattering properties of materials. Chladni assumed with his theories that the angle of incidence equaled the angle of reflections [Chladni, 1826-09-30]. However, hardly any material exactly reflects a sound in the angle it coincides. Therefore, it can be concluded that the rounded angles do not affect the distribution of sound. Furthermore, the fact that the G is not affected proves that the sound did not "get stuck" in the corners.

Both the T30 and the EDT were slightly longer in the configuration without the rounded corners. This corresponds with the Tsab. It is safe to assume that this is due to the increased volume of the auditorium. As established by Sabine, the reverberation of a space increases when the volume is enlarged [Sabine, 1922].
6. Changes in the design of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw after the hall was opened

6.1 Introduction

In sections 4.2. and 4.7., it was shown that the configurations of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw have changed during their existence. In 1999, Clements wrote about these renovations: "It is not widely known that Europe’s two leading concert halls were renovated in the past, renovation that perhaps significantly affected the acoustical quality of the spaces" [Clements, 1999]. This chapter studies how these alterations have influenced the acoustics of both symphony halls.

This is done using the room-acoustical-prediction model Odeon, which was also used in the previous chapter. The models found on the website of this software are used to simulate the configuration after the renovation of both concert halls. Thereafter, the models are adjusted to the configurations before the renovation and simulations are done in the adapted models.

Firstly, the renovations of the Grosser Musikvereinssaal are covered. This is done in the subsequent section in which the first part is devoted to the renovation and the second part to the changes in acoustics caused by the renovation. Subsequently, the change in design of the large concert hall of the Concertgebouw is discussed. In the first section, it is shown what changes are made in the design. In the second section the acoustical consequences are discussed. For this section, some follow-up simulations are done because the observations of the press did not equal the results of the first simulation.

6.2 Renovation of the Grosser Musikvereinssaal

6.2.1. Problem

During the last decades of the 19th century, symphony orchestras grew significantly due to an increasing interest in classical music. Therefore, the stage of the Grosser Musikvereinssaal became too small. Furthermore, the reason for classical music visits shifted. Where, during the first decades of the 19th century, the audience visited classical music performances for social reasons, in the later decades of the 19th century, audiences started to visit performances for more musical purposes. Therefore, the visibility of the orchestra became more important. These were the two major reasons for a renovation of the Grosser Musikvereinssaal in 1911. However, a renovation was risky because at that point little acoustical knowledge was available. In 1870 after the opening concert, the press was very positive about the acoustics properties of the Grosser Musikvereinssaal. Therefore, this renovation was assumed to be hazardous for the favorable acoustics of the Grosser Musikvereinssaal, and was minutely followed by the Austrian press. [Grasberger et al, 1970]
During the renovation, the caryatid columns, which supported the galleries, were moved towards the side walls, creating extra visibility for the audience. The galleries were made to be self-supporting. Furthermore, the stage was broadened to cover the total width of the concert hall making it accessible for a larger orchestra. [Grasberger et al, 1970]

During the first concert after the renovation, the Austrian Press judged that the Grosser Musikvereinssaal had kept its favorable acoustic properties [Grasberger et al, 1970]. However, it is still possible that this renovation had an effect on the acoustics. The influence of this renovation is studied in this section.

The properties of the simulation models are comparable to the models used in the previous chapter. The sources and receivers were placed at the same position. The columns were relocated to the side against the wall, and they possess the same acoustical properties as in the previous chapter. The stage is widened, covering the full width of the Grosser Musikvereinssaal. Therefore, some audience positions were lost. Finally, the simulations were done in both an empty and a filled Grosser Musikvereinssaal. The sound absorbing properties of the seating, with and without spectators, were copied from appendix five of the book: *How they sound concert halls and opera houses.* [Beranek, 2006]

6.2.3. Simulation setup in the Grosser Musikvereinssaal

6.2.4. Grosser Musikvereinssaal before the renovation

6.2.5. Grosser Musikvereinssaal after the renovation

6.2.2. Results

The results of this section are analyzed and depicted in the way they were presented in section 5.3.. They are shown in a table with three columns. In the left column the results of the configuration before the renovation are shown. In the middle column, the results of the configuration after the renovation
are presented. In the right, the latter is subtracted from the former. The parameters are shown as a single number frequency average and they are shown in a surface plot. The JND is used as the graph scale. When there is no audible difference between both configurations, the parameter in the right column is depicted with a white color in the surface plot. The results, which are not shown in this chapter, appear in appendix 4.

Table 6.2.1. The LF before and after the renovation in the Grosser Musikvereinsaal

<table>
<thead>
<tr>
<th>LF within the configuration before the renovation</th>
<th>LF within the configuration after the renovation</th>
<th>The latter minus the former</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10-0.15</td>
<td>0.15-0.20</td>
<td>0.10-0.15</td>
</tr>
<tr>
<td>0.20-0.25</td>
<td>0.25-0.30</td>
<td>0.20-0.25</td>
</tr>
<tr>
<td>0.30-0.35</td>
<td>0.35-0.40</td>
<td>0.30-0.35</td>
</tr>
<tr>
<td>0.40-0.45</td>
<td>0.45-0.50</td>
<td>0.40-0.45</td>
</tr>
<tr>
<td>0.50-0.55</td>
<td></td>
<td>0.50-0.55</td>
</tr>
</tbody>
</table>

The effect of the renovation was comparable for an empty and a filled Grosser Musikvereinsaal. In this section, the results of the simulation without an audience are discussed. The C80, EDT, G, and T30 showed no audible differences between the configurations before and after the renovation. This applied for both the single number frequency average and for every separate frequency band ranging from 63 to 8000 Hz. It is probable that there are no audible differences in reverberation because during the renovation the volume and the total sound absorption of the Grosser Musikvereinsaal were not significantly changed. Therefore, the EDT and the...
T30 showed no audible differences. Beside the reverberation time not being affected, the ratio between early arriving reflections and late arriving sound is not altered as well. Therefore, the C80 shows no audible differences either. Finally, the G did not show any audible differences. Therefore it is safe to conclude that the distribution of sound energy did not change due to the renovation.

LF did show audible differences, on various positions within the Grosser Musikvereinssaal. These differences were only present in the low and middle frequency bands. These frequency bands are considered to be most important for the experience of Apparent Source Width [Barron et al, 1981]. The results of the single number frequency average are depicted in table 6.2.1. The averaged LF is lower after the renovation, especially between the columns and the side wall. An explanation for these results can be given with the assumption that the LF is lower when the room is wider [Barron, 2000]. When the columns are regarded as a fictitious wall, the side aisles of the Grosser Musikvereinssaal are much wider when the columns are removed. This explanation equals the one given in section 5.3.. The difference at the center-front of the audience area is audible as well. The LF is considered to describe the subjective parameter apparent source width; however, the stage was widened during the renovation.

6.3 Renovation of the large concert hall of the Concertgebouw

6.3.1 Problem

After the opening concert, the press was divided about the acoustic qualities of the large concert hall of the Concertgebouw. According to the most constructive criticism, the brass instruments overpowered the string instruments. During the first years of its existence, attempts were made trying to solve this problem with palliatives. However, these applications did not influence the acoustics in a beneficial way. Therefore, a large renovation of the stage was undertaken in 1899. The stage height was lowered by 0.2 meters and the slope was reduced. The back of the stage was lowered by 2.3 meters and the stage near the side walls was lowered by 1.2 meters. The judgments about the acoustics after this renovation were positive. According to the Dutch press, the brass instruments did not overpower the string instruments anymore. Nowadays, it is assumed that this renovation has caused the current acoustical properties that are world famous.

This renovation mended a clear complaint regarding sound levels of various instruments. To investigate sound levels, the parameter G, which describes the subjective level of sound, is considered. However, the renovation could also have influenced the reverberation time.
Therefore, the T30 is also considered in this section. The G is used to test whether the renovation of the stage has affected the ratio between brass and string instruments. On stage, in the large concert hall of the Concertgebouw, the string instruments are usually positioned at the center of the front of the stage. The brass instruments are positioned at the center of the back of the stage. Therefore, the source positions are changed in comparison to the previous chapter. The new source positions are depicted in figure 6.3.1.

The configuration during after and before the renovation are depicted in figures 6.3.2., 6.3.3., 6.3.4., and 6.3.5..

Some considerations are made regarding the model before the renovation. Because no plan was available of the original stage, the stage is modeled according to the section depicted in figure 6.3.2. and the changing heights, which were given previously. Therefore, the configuration before the renovation might not correspond completely with reality.

The results of the G are presented in table 6.3.1.. In this table, the values of the G are depicted as a single number frequency average. In the left column, the level difference is shown subtracting the G caused by source 1, which is positioned at the back of the stage, from the G caused by source 2, which is positioned at the front of the stage, from the configuration before the renovation. In the middle column this subtraction is done for the configuration after the renovation. In the right column, the latter is subtracted from the former. Consequently, when this last subtraction results in a positive number, the string
instruments are easier heard in the configuration after the renovation. Almost no audible differences are present between both configurations.

The T30 showed no audible differences as well. This is in contrast with the general complaint about the acoustics during the first eleven years of the large concert hall of the Concertgebouw.

Table 6.3.1. The G difference in the configuration before and after the renovation of the large concert hall of the Concertgebouw

<table>
<thead>
<tr>
<th>Difference in G in the configuration before the renovation</th>
<th>Difference in G in the configuration after the renovation</th>
<th>The latter minus the former</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ -7.00--6.00 □ -6.00--5.00</td>
<td>□ -7.00--6.00 □ -6.00--5.00</td>
<td>□ -3.00--2.00 □ -2.00--1.00</td>
</tr>
<tr>
<td>□ -5.00--4.00 □ -4.00--3.00</td>
<td>□ -5.00--4.00 □ -4.00--3.00</td>
<td>□ -1.00--0.00 □ 0.00--1.00</td>
</tr>
<tr>
<td>□ -3.00--2.00 □ -2.00--1.00</td>
<td>□ -3.00--2.00 □ -2.00--1.00</td>
<td>□ 1.00--2.00 □ 2.00--3.00</td>
</tr>
<tr>
<td>□ -1.00--0.00 □ 0.00--1.00</td>
<td>□ -1.00--0.00 □ 0.00--1.00</td>
<td>□                  □</td>
</tr>
</tbody>
</table>

There are various reasons that can explain the disagreement between the simulation and the observation. Four reasons are studied within this report. Firstly, the directivity of the sources might influence the results. In the described simulation, both sources were modeled with an omnidirectional source. However, in reality, both sources have different directivity. Therefore, a simulation is done with sound sources that take into account the directivity properties of a trumpet and violin.

Secondly, the simulations were done in an empty concert hall. However, during performances, an audience is present. The presence of an audience will influence the acoustic properties of a concert hall, because the sound absorbing properties of people are different than empty chairs. Therefore, simulations are done that take this aspect into account. The sound absorbing properties of the seating, with and without spectators, were copied from appendix five of the book: *How they sound concert halls and opera houses.* [Beranek, 2006]

Thirdly, the disagreement between the simulation and the observation might also be caused by the lacking of an orchestra in the simulation models. The musicians, their instruments and the seating, might block a part of the sound.
that is produced by the brass instruments. With a steeper stage, sound might pass other musicians and their instruments, where it is blocked with a less steep stage. Therefore, a simulation is performed in which an orchestra is taken into account. This is done according to the PhD. research of Dammerud [Dammerud, 2009]. He defined two musicians as a bench with a length of 0.75 meter, a width of 1.5 meter and a height of 0.5 meter. This bench is located 0.5 meter above the floor. This is shown in figure 6.3.5. The absorption, scattering and transparency factors were copied from this report as well. These values are shown in table 6.3.2. Because only one value can be inserted for scattering and transparency in Odeon, and the factors were given for limited frequency bands, these values were averaged. These values were used in the models for all frequency bands.

6.3.5. Orchestra on stage in the large concert hall of the Concertgebouw

Table 6.3.2. Coefficients according to Dammerud [Dammerud, 2009]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption</td>
<td>0.40</td>
<td>0.65</td>
<td>0.75</td>
</tr>
<tr>
<td>Scattering</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Transparency</td>
<td>0.70</td>
<td>0.60</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Table 6.3.2. The subtraction of the G difference in the large concert hall of the Concertgebouw with various additions

<table>
<thead>
<tr>
<th>With directivity of a trumpet and a violin</th>
<th>With audience</th>
<th>With orchestra</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3.00--2.00</td>
<td>-3.00--2.00</td>
<td>-3.00--2.00</td>
</tr>
<tr>
<td>-1.00-0.00</td>
<td>-1.00-0.00</td>
<td>-1.00-0.00</td>
</tr>
<tr>
<td>1.00-2.00</td>
<td>1.00-2.00</td>
<td>1.00-2.00</td>
</tr>
<tr>
<td>-2.00--1.00</td>
<td>-2.00--1.00</td>
<td>-2.00--1.00</td>
</tr>
<tr>
<td>0.00-1.00</td>
<td>0.00-1.00</td>
<td>0.00-1.00</td>
</tr>
<tr>
<td>2.00-3.00</td>
<td>2.00-3.00</td>
<td>2.00-3.00</td>
</tr>
</tbody>
</table>

The results of the three simulations are shown in table 6.3.2. The simulation with an audience presence generated an audible difference over various positions in the large concert hall of the Concertgebouw. However, the audible differences are all negative, suggesting that the brass instruments are relatively
louder in comparison with the string instruments. This is in contrast to the observation of the press. In both other configurations, there are not many audible differences over the surface between the two configurations in the three studied situations. The T30 did not change as well in these three simulations. Therefore, it can be concluded that this renovation has not positively affected the ratio of sound level between string and brass instruments within the large concert hall of the Concertgebouw.

However, the renovation might have influenced the acoustic properties on stage. When the acoustical properties on stage are improved, it is beneficial for the ensemble playing which improves the quality of the performance. This was also known during the 19th century. This is shown by a quote of Chladni: "Der raum, welchen ein orchester einnimmt, darf auch nicht grosser seyn, als nöthig ist, weil sonst der Schall nicht schnell genug von einem ende des Orchester zum anderen gelangen, und jeder mitspieler die entferntern zu spät hören würde, so dass also kein genaues Uebereintreffen im Takte Statt finden könnte, ..." [quote 21] [Chladni, 1826-09-30]

Therefore, two more simulations were done. Due to a limited time frame these simulation were only done in the configuration without an orchestra and an audience. Furthermore, the used sources were omnidirectional, thus the directivity of the sources is not taken into account either. In the first simulation three point sources were positioned on the higher part of the stage. A grid, with a distance between the receivers of 1 meter resulting in 50 receivers, was positioned at the lower part of the stage. This was done in both configurations. In the second simulation the three sources were positioned at the lower part of the stage, and the receiver grid was positioned at the higher part of the stage, which possessed 35 receiver positions. Therefore, the transmission between the higher and the lower parts is simulated. Both simulation setups are depicted in figures 6.3.6. and 6.3.7.:

The results of the first simulation setup are given in table 6.3.3., 6.3.4. and 6.3.5. In table 6.3.3. the average EDT of all the receivers in the configuration after the renovation is subtracted from the average of all receivers in the configuration before the renovation. This is separately done for the three sources. In table 6.3.4. this is done for the T30 and in table 6.3.5. for the G. The T30 is virtually not changed while the EDT shows several differences. This suggests that due to the renovation, the amount of early reflections on the lower part of the stage, which are coming from instruments positioned on the higher part, have been diminished by the renovation. Furthermore, the EDT audibly differed per source position. While the results of source 3 show no audible differences between both configurations while source 1 is audibly lower in the configuration after the renovation, especially in the lower frequencies. The G has changed audibly as well, due to the renovation. The G has
changed as well due to the renovation. For source 1 and 2, the G is audibly higher in the configuration after the renovation. For source 3, the G is lower, though not audibly. Because the brass instruments are usually positioned at the center back of the stage, this suggests that the brass instruments are heard louder on the lower parts of the stage.

Table 6.3.3. Transmission from the higher to the lower parts: difference in EDT

<table>
<thead>
<tr>
<th>Frequency</th>
<th>63</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>8000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source 1</td>
<td>0.31</td>
<td>0.22</td>
<td>0.12</td>
<td>0.07</td>
<td>0.05</td>
<td>0.04</td>
<td>0.10</td>
<td>0.13</td>
</tr>
<tr>
<td>Source 2</td>
<td>0.23</td>
<td>0.19</td>
<td>0.11</td>
<td>0.04</td>
<td>0.02</td>
<td>0.01</td>
<td>0.06</td>
<td>0.15</td>
</tr>
<tr>
<td>Source 3</td>
<td>0.03</td>
<td>-0.09</td>
<td>-0.08</td>
<td>0.02</td>
<td>-0.05</td>
<td>-0.01</td>
<td>-0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 6.3.4. Transmission from the higher to the lower parts: difference in T30

<table>
<thead>
<tr>
<th>Frequency</th>
<th>63</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>8000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source 1</td>
<td>0.08</td>
<td>0.05</td>
<td>0.05</td>
<td>0.04</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Source 2</td>
<td>0.03</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td>0.00</td>
<td>-0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Source 3</td>
<td>0.03</td>
<td>-0.00</td>
<td>-0.02</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.00</td>
<td>0.02</td>
</tr>
</tbody>
</table>
The results of the second simulation are depicted in table 6.3.6., 6.3.7. and 6.3.8.. The results of the second simulation are comparable with the first simulation. The EDT was audibly lower in the configuration after the renovation, especially in the lower frequencies, while the T30 showed no audible differences. This suggests that due to the renovation, the amount of early reflections on the higher part of the stage, which are coming from instruments positioned on the lower part of the stage, are diminished by the renovation. The G was audibly higher in the configuration after the renovation, suggesting that the string instruments were more audible on the higher parts of the stage.
The diminishing of the early reflections might be caused by the steeper slope of the audience behind the stage. This audience area might absorb a part of the early sound, where in the configuration before the renovation, this early sound was reflected by the rounded back wall. The higher $G$ between the higher and lower parts of the stage might be caused by the reduction in traveled path. Because the height of the higher part was diminished, the distance between the higher and lower part became less. These two aspects might positively influence the ensemble playing in the large concert hall of the Concertgebouw.
7. Conclusion

In this chapter, an attempt is made to explain why the Grosser Musikvereinssaal and large concert hall of the Concertgebouw are considered acoustically superior, while these were constructed before a deep scientific approach was common practice in architectural acoustics. The information given in this report is summarized chronologically. At the end, some considerations are made regarding the reputations of the acoustics of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw.

During the 19th century, Langhans’ work on acoustics gained influence. His statement that acoustics for music were very different from acoustics for speech was important. He advocated the basilica shape which resulted in the “shoe box” shape for concert hall design. Furthermore, a “slow fading sound”, which he advocated, became accepted in concert hall design during the second half of the 19th century, and still is advocated within the acoustic design practices of today.

Before the 19th century, the most influential acoustician was Vitruvius. Despite the growing importance of Langhans’ theories during the 19th century, the work of Vitruvius was still advocated by many acousticians. Vitruvius’ work was most influential on the application of wooden panels, which would resonate with the sound and were used in most concert halls during the 19th century. Furthermore, his works were the basis of the “horse shoe” hall, which is still considered a good shape for an opera house.

However, the architectural acoustic science was still in its infancy during the 19th century. This is shown by the example of the Palais Garnier. Its designer, Charles Garnier, missed an acoustic formula on which he could base the acoustical concept of his design. He stated that he based the acoustics of his opera on coincidence. Furthermore, some persistent wrong assumptions were present in architectural acoustics during the 19th century. The most prominent being the sound absorption of materials. Due to the assumption that materials are either absorbent or reflective, 19th century acousticians generally considered only the first-order reflection of sound in an acoustic design. In that context, shape and volume were regarded as very important in concert hall design. Consequently, the guideline, which was derived from the interval between direct and reflected sound, gained influence. This application was defined for the use of venues, which had acoustical demands regarding speech. However, this application was also used in concert halls. Due to this guideline, and the assumption that materials were either absorbent or reflective, the acoustics of the Salle des fetes located in the Trocadero palace failed. Due to this failure, it was discovered that materials possessed a sound absorption coefficient. Furthermore, the maximum interval between direct and reflected sound evolved into the guideline that concert halls should not have a width exceeding 22 meters.

Concert hall design was partially based on copying. The dimensions of the Grosser Musikvereinssaal were copied from the Redoutensaal, and applications of the large concert hall of the Concertgebouw were possibly copied from the Neue Gewandhaus. Besides copying from other concert halls, the theories of famous acousticians were the basis of concert hall design. Langhans’ and Vitruvius’ theories were probably the basis of the design of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw. Probably, two goals were relevant for acoustical design concepts. The most important goal was the distribution of sound over every position within the concert hall. Therefore, in both concert halls, two rows of columns were installed, and the ceiling was covered with ornaments that would scatter the sound. In the large concert hall of the Concertgebouw, the corners were rounded at the end where the orchestra played as well, for this...
purpose. In chapter 5 it was shown that the predicted effect, by 19th century acousticians, was not measured with the currently used acoustic parameters. However, the scattering of the coffered ceiling and the columns are still advocated within architectural acoustics. The second goal in acoustical design during the 19th century was to achieve a “slow fading sound” within the concert hall. To achieve this, many reflecting surface finishings were used, like plaster in the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw. Furthermore, for this purpose, many wooden panels were installed because these surfaces would resonate with the music, and, therefore, enhance the “slow fading sound”. Likewise, Von Hansen possibly designed hollow caryatid columns, which would resonate with the music like the echo of Vitruvius. In section 3.9., it was shown that the effect of resonation is questionable. Wooden resonating panels are still used in acoustical design, though they are implemented to absorb sound energy of the lower frequencies. For the above mentioned reasons, it can be concluded that the acoustic properties of the Grosser Musikvereinssaal and large concert hall of the Concertgebouw were not coincidental or dependent on wrongly based design goals. However, the way in which these two goals were pursued is questionable and probably not based on correct assumptions. Therefore, the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw were still completed with distribution of sound as loud as possible over every position and a “slow fading sound”, as the basis of the acoustic concept. The two pursued goals are still used today, though the importance of the second goal has become more prominent and other design purposes have been added, like lateral reflections.

Besides the starting points of the acoustic concepts during the 19th century, renovations performed in the 20th century could also have positively influenced the acoustical quality of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw. It was thought that the renovation of the Grosser Musikvereinssaal might have influenced the acoustic properties. However, it was shown that the renovation of this concert hall has not influenced the currently used acoustic parameters in a significant way. Probably, the apparent source width became audibly lower in some positions of the Grosser Musikvereinssaal. The renovation of the large concert hall of the Concertgebouw is assumed to have heralded the famous acoustic properties of the large concert hall of the Concertgebouw. This renovation was carried out after complaints about the brass instruments overpowering the string instruments. It was shown that the renovation has either negatively affected the ratio between the string and brass instruments in the audience area, or has not affected it at all. However, due to the renovation, the acoustics on stage were audibly different. The brass instruments were better heard by the string instruments, and vice versa. This might cause a better communication between the instruments, affecting the ratio between the discussed instruments. Furthermore, the amount of early reflection was possibly diminished on stage. These two aspects could have improved the ensemble playing of the orchestra in the large concert hall of the Concertgebouw, and consequently have affected the ratio between brass instruments and string instruments.

Towards the end of the 19th century, materials were not considered to be either absorbent or reflective anymore. During the construction process of the Trocadero Palace (1876-1878), it was found that materials possessed a sound absorption coefficient. Both Rayleigh and Sturmhoefel proposed an approach for how to determine a sound absorption coefficient numerically. Furthermore, two examples were found in which the echo was counted and thus considered the reverberation time numerically. Therefore, the reverberation formula of Sabine was a natural extension of the acoustical work done during the 19th century. It possibly changed the emphasis of architectural acoustics from the distribution of sound to the reverberation. This is likely because from
Meanwhile, the reputations of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw, regarding the acoustics, became 1970's and 1980's. During the 1990's two more studies were completed confirming the reputations of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw.

There are two facts questioning the results of these last studies, and consequently, the reputations of the acoustical properties of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw. Most importantly, the reputations were established while the acoustical science was evolving. The reverberation time was the only established acoustical parameter when the first studies to acoustically superior concert halls around the world were carried out. When other parameters were defined the target values were copied from these concert halls, confirming the reputations. For these two reasons, the reputation of the Grosser Musikvereinssaal and large concert hall of the Concertgebouw grew, probably to the extent that the subjects of the second round of studies on the acoustically superior concert halls may have been biased.

Secondly, no studies after 1996 have been found regarding the acoustically superior concert halls. It takes time before the reputation of the acoustics of a concert hall is established, as was shown in section 2.3..

For these two reasons, it can be concluded that the Grosser Musikvereinssaal the large concert hall of the Concertgebouw and the concert hall of Symphony hall are constructed on reasonable starting points and are possibly acoustically superior over other remaining concert halls built before 1962. However, the acoustics of these three concert halls have never been fairly compared with concert halls built after 1962.
8. Recommendations

In this chapter, recommendations are made for further studies regarding the history of acoustics. For every chapter, a number of recommendations are made.

The second chapter showed how the reputation of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw arose. The recommendations about this chapter are twofold. Firstly, it is recommended to study the origin of these reputations more thoroughly. Due to a limited time frame, only a few examples have been found that mention the reputations of the Grosser Musikvereinssaal, large concert hall of the Concertgebouw and Symphony Hall. It has been found when and where the first mentioning of these reputations, has been made, however, how these reputations have been exactly established was not found. For example, when the staff of the Grosser Musikvereinssaal and large concert hall of the Concertgebouw extensively promoted these reputations, it is less credible than when these reputations are confirmed by scientific research. Secondly, it is recommended to study the history of architectural acoustics during the second half of the 20th century. When these two aspects have been studied, the timelines of the reputations can be compared with the evolution of the scientific architectural acoustics. The state of architectural acoustics determines the value of these reputations. For example, when these reputations were established while architectural acoustics only possessed one scientific formula, the acoustics of the Grosser Musikvereinssaal, large concert hall of the Concertgebouw and Symphony Hall were only compared with concert halls that were acoustically designed not fundamentally different than these.

In the third chapter, it was shown which theoretical knowledge was possessed by the 19th century acousticians. Due to limited time frame not all written sources about architectural acoustical during the 19th century, have been covered. Therefore, some books need to be studied more thoroughly. A number of these books are:
- Patte (1782) Essais sur l'architecture theatrale
- Saunders (1790) Treatise on theaters
- K.G. Langhans (1800) Vergleichung des neuen Schauspielhauses zu Berlin mit verschieden ältere und neue Schauspielhäusern in Rücksicht auf Akustik und optik Grundsätze
- Catel (1802) Vorschlage zur verbesserung der Schauspielhauser
- Lachez (1879) acoustique et optique des salles des reunion

Furthermore, architectural and musical magazines which were published during the 19th century can be studied, the most prominent being the Allgemeine Musikalische Zeitung, which appeared from 1798 to 1882. During this study, it became established that most writings about architectural acoustics during the 19th century originate from Germany, especially the region of Leipzig. Therefore, it is recommended for subsequent research to study German literature of this period.

In the fourth chapter, the construction process and the acoustic approach of six concert halls was described. The purpose of this chapter was to describe the concert hall design mores at the end of the 19th century. Therefore, six concert halls were chosen, which were built during the seventh, eight and ninth decade of the 19th century. However, there are more famous concert halls constructed during this period, the most prominent example being the Royal Albert Hall, which was completed in 1871. This and other concert halls can be studied to give a more complete view of the acoustic design approach during the end of the 19th century. Furthermore, because the six studied concert halls were constructed within a relatively short period of time, no conclusions can be drawn regarding the process of acoustical design during the 19th century. Therefore, it is recommended to study the design processes of concert halls constructed in various periods, the most prominent being the Konzerthaus...
in Berlin, which was the first concert hall built according the theories of Langhans.

In the fifth chapter, the influence of three design applications on the acoustics of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw were studied. The goal of this chapter was to study whether the implemented acoustic applications did what they were intended to do. This was studied with a simulation model in the room-acoustical-prediction model Odeon. Some cautious conclusions were drawn. However, it was shown that further investigation is needed to establish the precise effects of these applications. These studies could include the influence of the audience. The simulations were only done in an empty concert hall. The influence of audience is established. The sound absorption coefficients of the seating in both halls are significantly lower than that of an audience. Another aspect which can be studied is the influence of the applications on the stage acoustics. When the acoustical properties on stage are good, it will improve the ensemble playing, which is beneficial for the quality of the performance.

In the sixth chapter, the influence of the renovations on the acoustics of the Grosser Musikvereinssaal and the large concert hall of the Concertgebouw was studied. In the large concert hall of the Concertgebouw, the renovation caused a change in stage acoustics. However, due to a limited time frame, this effect was only researched for an empty concert hall. Therefore, the effect of an orchestra, an audience and the directivity of the sources was not taken into account. It is recommended to study the affect on the stage acoustics of these aspects. Furthermore, there are specially defined parameters for stage acoustics. These can be taken into account with, additional study. In the Grosser Musikvereinssaal, the renovation did not change the acoustics of the audience area. The acoustics on stage were not studied. A subsequent study might investigate the influence of the renovation on the stage acoustics in the Grosser Musikvereinssaal.
9. Literature

9.1 Chronological literature

9.1.1. Chapter 1.


9.1.2. Chapter 2.


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9.1.3. Chapter 3.


Gehler, J.S.T. (1793) Physikalisches
Wörterbuch, im schwickereschen Verlage, Leipzig.


Tyndall, J. (1867) Sound; A course of eight lectures, Longmans, Green, and Co., London.


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Sturmhoefel, A. (1898) Akustik des Baumeisters, Gerhard Kühtmann, Dresden


9.1.4. Chapter 4.

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(1867-06-04) *Theaters on the place the chatelet*, Penny illustrated.


(1869-03-17) *Berichte, Nachrichten und bemerkungen*, Allgemeine musikalische Zeitung, Leipzig, p. 86


(1870-01-06) *Die schlusssteinlegung im Hause der Musikfreunde*, Morgen-Post, p. 1

(1870-01-08) *Kleine Chronik*, Wiener Zeitung, p 68

(1870-01-08) *Das Eröffnungskonzert im neuen Hause der Gesellschaft der Musikfreunde*, Neues Fremden-Blatt, p. 5

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(1870-01-20) *Der brand im neuen Musikvereinsgebade*, Neue Freie Presse, p. 18

(1870-01-21) *Kleine Chronik Wiener Zeitung*, p. 15

(1870-02-03) Das gebaude des musikvereines in Wien, Deutsche Bauzeitung, p.40

(1870-03-16) Berichte, Nachrichten und bemerkungen, Allgemeine musikalische Zeitung, Leipzig, p. 86


Köstlin (1870) Das musikvereinsgebäude in Wien, Allgemeine Bauzeitung p 41-43.


(1871-08-09) Uber Pariser music- und theaterzustande, Allgemeine musikalische Zeitung, Leipzig, p. 506-508

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