AN ARCHITECTURAL LUGGAGE FOR DESIGNING A CONCERT HALL

Graduation thesis where Architecture meets Acoustics.

'People do not care how much you know,
until they know how much you care.'

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'A man who wants to lead an orchestra must turn his back to the audience.'

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ABSTRACT

Evoked by a personal fascination for concert halls, this thesis developed an architectural luggage for architects in designing acoustically well-functioning concert halls. This thesis insistently emphasizes that the luggage should be subordinate to the architect – a toolkit to *serve* the architect, not vice versa. Through the help of literature study in the field of acoustics, seven acoustic attributes are analyzed for generating a set of architectural tools, such as diagrams and numbers for designing concert halls. This so-called toolbox recommends instructions on what to avoid, implement, minimize, maximize, balance and such, varying physical, spatial, structural and geometrical aspects. All this, in the aim to provide feeling and grip to the architect for designing acoustically well-functioning concert halls.

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LIST OF TERMINOLOGY

acoustics, the branch of physics concerned with the properties of sound.

brilliance, an acoustic attribute referring to the bright, crispy ringing harmonic sound of the treble tones (high-frequencies).

clarity, an acoustic attribute referring to the degree which the listener can identify sounds in a musical performance.

envelopment, an acoustic attribute referring to the spatial sensation of being surrounded by sound.

finale, the last movement of a piece that has several movements, such as a sonata, symphony or concerto.

grazing incidence, an incident beam striking in a small angle that is nearly parallel to a surface.

initial-time-delay gap, an acoustic description referring to the difference in time of arrival of the direct sound and first reflected sound.

intimacy, an acoustic attribute referring to the subjective sensation of how closely the music is distanced towards the listener.

overture, a musical composition played by an orchestra as an instrumental introduction for the main piece such as opera or ballet.

passion, a (very) strong feeling or interest for something.

prelude, a musical composition played as a brief introduction or warming-up before a main piece.

reflection, the change of direction of incident sound after reflected from surface.

reverberation, the persistence of sound after the sound is produced, caused by the numerous build up of reflection of sound.

strength, an acoustic attribute referring to the loudness of sound.

transmission, the transportation of sound through and between materials including air.

warmth, an acoustic attribute referring to the fullness of the bass tones (low-frequencies).

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I THE OVERTURE

In this first chapter, you will be introduced to the 'ouverture' of this graduation thesis (literally, French for 'opening'). This chapter serves as an instrumental introduction to the whole piece, analogical to the beginning act of an opera or other symphonic masterpiece.

Origin

In 2008, me and my little brother both have passed the 8th grade exam for piano at the ABRSM (Associate Board of the Royal Schools of Music). I felt very proud and confident in the achievement that we had accomplished, because nevertheless, we did this within a timeframe of three years, starting from zero.

In 2013, after already teaching private piano lessons for several years, things started to change. It all happened after experiencing a masterclass given by Benjamin Zander performed by the Boston youth orchestra. This, in the concert hall amid of the centrum of my hometown; Rotterdam, *De Doelen*. The masterclass was just a few hours short. However, from that day on, I strong-willed decided that no matter what, I will become a conductor to experience *all of this*. In my eyes, it is a life mission worth striving for. A dream that has yet to come true. As a consequence of that determination, branching off my fascination for concert halls in the field of architecture.

Research objective

To my fortunate, the studio 'Explore Lab' offers me the opportunity and freedom to come up with an architectural graduation thesis around my fascination. In this keen of interest it is my aspiration *to design a concert hall*. In a way this objective is also inevitable, since designing itself is also my second passion.

Research question

Given the ambition, it is decisively important that a concert hall functions acoustically. As an architecture student, naturally, I am far from expert in the field of the acoustics. Therefore, in order to reach the goal of designing an acoustic well-functioning concert hall, the following questions are formulated:

i. What acoustic attributes contribute to an acoustic well-functioning concert hall?
ii. What architectural principles are required for designing an acoustic well-functioning concert hall?

Research method

The investigation hunts towards an acoustically well-performing concert hall is mainly based on literature study. Since architects are not acousticians this part of the research is crucially needed. In order to prevent an one-sided view, literature of different experts in that field are studied:

L. Beranek	Music, Acoustics & Architecture (1962)
	Concert and Opera Halls (1996)
	Concert Halls and Opera Houses (2004)
M. Barron	The Acoustics of Performance Halls (2010)
C. Jaffe	Auditorium Acoustics and Architectural Design (2010)

Thesis structure

The thesis is structured into four chapters. Every chapter kicks off with a synopsis telling the reader a general idea in that chapter of what to expect. Chapter two answers the first research question, while chapter three responds to the second question. These two chapters are presented parallel to the reader, in the interest of juxtaposing the findings of the acoustics and architecture. At last, the research thesis resolves with a conclusion and discussion in chapter four, as ‘The Finale’.

II THE ACOUSTICS

Through this second chapter, seven acoustical attributes that improve the acoustic sensations are summed up and tried to explain in concise and comprehensive language. The presented features are mainly selected from the literature of L. Beranek.[1] Please note, that these features do not depict the complete picture, but rather sketch the overall picture which an acoustic well-functioning concert hall should have. Thus, answering the research question: 'what acoustic attributes contribute to an acoustic well-functioning concert hall?'.

[1] Leo Beranek (1914-2016) was an American expert in acoustics. With his revised and extended book *"Concert Halls and Opera Houses"* (Springer, 2004) Beranek travelled 100+ concert halls over 60+ different countries.

The seven acoustic attributes [2]

1. Liveness
2. Intimacy
3. Clarity
4. Strength
5. Warmth
6. Brilliance
7. Envelopment

[2] In *"Concert Halls and Opera Houses"* (Springer, 2004) there are even more acoustical attributes, such as acoustic balance, ensemble and blend. Yet these qualities so to speak are still in their infancy, hence not integrated into the list of the luggage.

III THE ARCHITECTURE

Juxtaposed to the acoustics, this third chapter provides an insight and overview about the principles that architects should know in designing an acoustic well-functioning concert hall. To keep it short and straight to the point, in this chapter the architectural interventions are summed up in bulletpoints. In addition, eight superior and excellent concert halls are selected out of Beranek's "Concert and Opera Halls" (Acoustical Society of America, 1996), p. 58; with the aim to provide the reader the feeling and indication about the standards of top class concert halls. Finally, this chapter answers the second research question: 'what architectural principles are required for designing an acoustic well-functioning concert hall?'.

The eight superior and excellent concert halls [3]

[3] The listing of the concert halls are in alphabetic order.

i. *Amsterdam,* Concertgebouw (CG)
ii. *Basel,* Stadt-Casino (SC)
iii. *Berlin,* Konzerthaus (KH)
iv. *Boston,* Symphony Hall (SH)
v. *Cardiff,* St. David's Hall (DH)
vi. *New York,* Carnegie Hall (CH)
vii. *Vienna,* Musikvereinssaal (MS)
viii. *Zurich,* Grosser Tonhallesaal (GT)

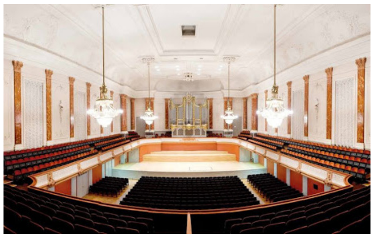
As a general rule of thumb

Although the seven acoustic properties are exemplified in a specific order, yet it is *not* a fixed order for designing concert halls. Alike to Beranek's conclusion[4], it needs to be stressed that there is *no single* acoustic nor architectural attribute which is decisive in distinguishing concert halls being superior or excellent. Neither the liveness, nor the envelopment *solely;* neither the shape, nor the volume. Each acoustic feature has its unique acoustic sensation and value. Not only that, the various features are also severely interrelated with each other, which gives room for endless combinations of different outcomes.

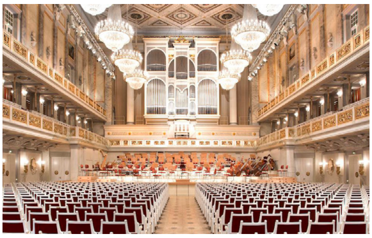
[4] Leo Beranek, *"Concert and Opera Halls"* (Acoustical Society of America, 1996), 539.

Therefore, this luggage should be considered as a toolbox *to play with*, and – I emphasize – *not* to stick with. At most, this luggage gives the architect the feeling, the sense of grip and the direction on how to design an acoustic well-functioning concert hall, coming close to the class of world standards. By now, it should be self-evident that this luggage has the function to *serve* the designer, yet not to be praised.

i. *Amsterdam*, Concertgebouw (CG)

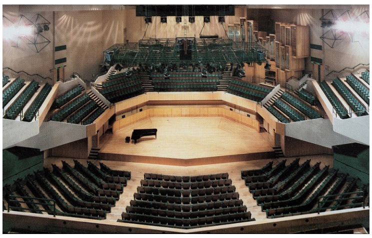


ii. *Basel*, Stadt-Casino (SC)



iii. *Berlin*, Konzerthaus (KH)

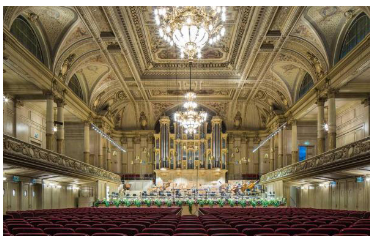
iv. *Boston*, Symphony Hall (SH)



v. *Cardiff*, St. David's Hall (DH)

vi. *New York*, Carnegie Hall (CH)

vii. *Vienna*, Musikvereinssaal (MS)



viii. *Zurich*, Grosser Tonhallesaal (GT)

Figure 1: Reference of eight superior and excellent concert halls in alphabetic order by the findings of Beranek's *"Concert and Opera Halls"* (Acoustical Society of America, 1996) p. 58. Illustrations retrieved from external sources, see 'List of Figures' p. 29.

I. LIVENESS

One of the most significant subjective acoustic qualities in a hall is the sensation of liveness of sound. This phenomenon is strongly related to the reverberation of a room. The more reverberant the hall is, the more lively the hall will sound. Generally this is measured with the law of Sabine, which is mainly composed by the proportion of cubic volume and absorption surfaces.

Primarily, the liveness of a hall is related to the reverberation time at the mid-frequencies (between 350 and 1.400 Hz). With regards to the concert hall, the preferred value for reverberation time of a concert hall for symphonic repertoire lies between the *1,8 to 2,1*.[5]

Although the audience capacity regulate the amount of absorption in a hall, the absorption of audience is *not* simply related to the number of persons comprising it. An audience does not absorb sound in proportion to the number of people in it.[6]

Out of the seven acoustic qualities, liveness is one of the few attributes that is strongly interrelated with the other attributes. Beneath is shown how versatile the attribute of liveness is related among the other acoustic aspects. Hence, liveness is one of the acoustic qualities that is critically allied with the degree of acceptability of a room for music.

i. Reverberant hall increases the fullness of tones;
ii. Rreverberant hall increases the loudness;
iii. Reverberant hall enhances the bass;
iv. Reverberant hall contributes to the blending of instruments;
v. Reverberant hall increases the range of crescendo and decrescendo;
vi. Reverberant hall diffuses the sound throughout the room.

Summary: liveness is an important criterion for the acceptance of music in a room and is mainly determined by the amount of reverberation in a hall

hall	*RT*	*volume*	S_A	*seats*
CG	2,00 sec	18.780 m^3	1.135 m^2	2.037
SC	1,80 sec	10.500 m^3	740 m^2	1.400
KH	2,05 sec	15.000 m^3	740 m^2	1.340
SH	1,85 sec	18.750 m^3	1.370 m^2	2.625
DH	1,95 sec	22.000 m^3	1.235 m^2	1.952
CH	1,80 sec	24.270 m^3	1.600 m^2	2.804
MS	2,00 sec	15.000 m^3	985 m^2	1.680
GT	2,05 sec	11.400 m^3	877 m^2	1.546

Figure 2: Acoustic data of the eight superior/excellent concert halls related to the reverberation time.

[5] Leo Beranek, "*Concert Halls and Opera Houses*" (Springer, 2004), 536.

[6] Leo Beranek, "*Concert Halls and Opera Houses*" (Springer, 2004), 501.

When designing a lively hall, the following rules need to be considered:

i) In order to achieve a reverberant hall, the cubic volume of the hall is large for the size of the audience. This due to the fact that the audience by nature is a physical absorbent object, which occupies a large portion of absorption ratio in the equation of Sabine.

ii) The more the audience is spread out, the more sound it absorbs in the hall. For a longer and stronger reverberation time it is sensible to keep the audience area compact.

iii) The walls and ceilings should be reflective – except the stage, which is explained in the chapter 'warmth'. However, the walls and ceilings only being reflective is not sufficient. For the hall to sound reverberant, most of the sound energy need to be (temporarily) kept inside, instead of leaking outside. Hence, the transmission of the surfaces need to be minimized by applying heavy and dense materials to maximize the properties of reflection.

iv) Since most of the audience are situated on the main floor, majority of the grazing incidence of sound gets absorbed by the audience which decreases the reverberant quality of the sound. Hence, the concert hall should have a high ceiling in order to let sound reflections persist and reverb (non-absorbently) in the air.

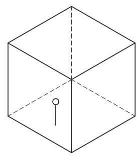


Figure I.i) volume over audience

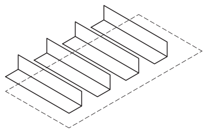


Figure I.ii) compact audience area

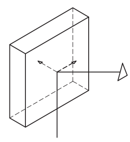


Figure I.iii) maximize reflection

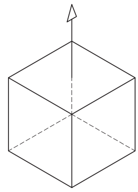


Figure I.iv) high ceiling

II. INTIMACY

In musical terms, 'intimacy' refers to the subjective *sensation* of how closely the music is distanced towards the listener. Whether the listener feels acoustically involved or detached from the music. Therefore, acoustic intimacy is sometimes also referred as 'presence'.

The attribute intimacy is determined by the acoustical technical term: *Initial-Time-Delay Gap*. ITDG is the difference in time of arrival of the direct sound and the first reflected sound from the walls and/or ceilings, see figure 2.

By keeping the ITDG short, the first reflections add strength to the direct sound making the acoustical experience feel intimate. Relating to the law of conservation of energy: the longer the reflection travels, the later it arrives, the less energy it contains. Where the opposite is true also: the shorter the reflection travels, the earlier it arrives, the more energy it contains.

Acoustical measurements suggest that for a good acoustical intimacy the ITDG remains *at or below 25 to 35 milliseconds*.[6] This is measured from the center of the main floor as an ideal reference point.

[6] Leo Beranek, "*Concert Halls and Opera Houses*" (Springer, 2004), 28.

Summary: a narrow hall ensures the sensation of intimacy due to the lateral reflections arrive earlier and stronger to the listener.

hall	*volume*	*length*	*width*	*height*
CG	18.780 m³	26,2 m	27,7 m	17,1 m
SC	10.500 m³	23,5 m	21,0 m	15,2 m
KH	15.000 m³	24,1 m	20,7 m	17,7 m
SH	18.750 m³	39,0 m	22,9 m	18,6 m
DH	22.000 m³	27,4 m	27,4 m	18,0 m
CH	24.270 m³	32,9 m	25,9 m	23,8 m
MS	15.000 m³	35,7 m	19,8 m	17,4 m
GT	11.400 m³	29,6 m	19,5 m	14,0 m

Figure 3: Acoustic data of the eight superior/excellent concert halls related to the acoustic attribute intimacy.

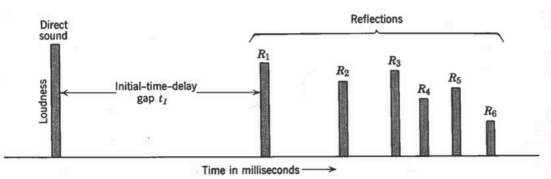


Figure 4: Time diagram showing the arrival of sound and loudness of sound, illustrating the phenomenon of direct sound, initial-time-delay gap (ITDG) and reflections.

For the pursuit of designing an intimate hall, the following rules should be regarded:

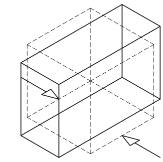


Figure II.i) narrow hall

i) The volume of the hall should be narrow, yet not too high nor too deep in order to constrain the ITDG of the lateral reflections to *25 to 35 milliseconds*, measured from the center of the hall of the main floor.The wider, higher and deeper the hall gets, the greater the distance with the stage, resulting a weaker intimate experience, see figure 3. A too high ceiling often cause that the orchestra players cannot hear themselves nor others playing, resulting a poor ensemble.

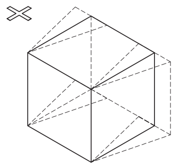


Figure II.ii) avoid fan shapes

ii) The walls of the hall should *not* be sloped like the shape of a fan; neither to the inside, nor to the outside. Because incident sound in a fan shaped hall incline towards the rear corners of the hall, instead of the center of the hall due to the angle of the walls, see figure 4. This has serious problems for the audience located at the middle rear of the hall.

iii) A smaller volume with less seat capacity also adds up to the intimate sensation in a hall. Besides being spatially and visually more intimate with the sound source, acoustically it sounds more near due to the lack of absorption in the hall.

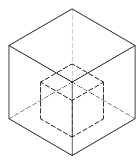


Figure II.iii) smaller volume

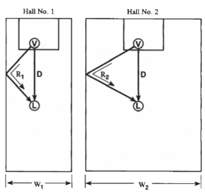


Figure 5: Comparison of reflection patterns between a wide and narrow hall. The reflection pattern of hall no. 1 arrives earlier and stronger than hall no. 2.

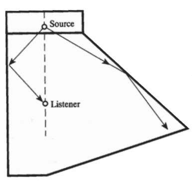


Figure 6: Comparison of reflection patterns between a perpendicular wall and a sloped wall. The reflection pattern of the perpendicular wall reflects towards the center of the hall, while the sloped wall reflects to the rear corner of the hall.

III. CLARITY

The acoustical definition of 'clarity', also named as 'definition', refers to the degree to which the listener can identify sounds in a musical performance. A concert hall that has clarity, individual instruments can be heard from within a large orchestra. As the name already hints, it *defines* how *clear* the individual parts of sound is.

Basically, the clarity of a hall is determined by two factors: i) the reverberation time of the hall and ii) the loudness of the direct sound to that of the reverberant sound (late reflections).

The listener must be able to distinguish the contrast between direct sound and reverberant sound. Physically speaking, all early reflections *within* the 80 milliseconds, will be perceived by the ears as *reinforced sound* that adds up to the direct sound. Whereas sound arriving *after* 80 milliseconds adds to the sense of reverberation.[7]

[7] Leo Beranek, "*Concert and Opera Halls"* (Acoustical Society of America, 1996), 478.

Summary: the contrast between the direct sound and reverberant sound determine the clarity of the sound.

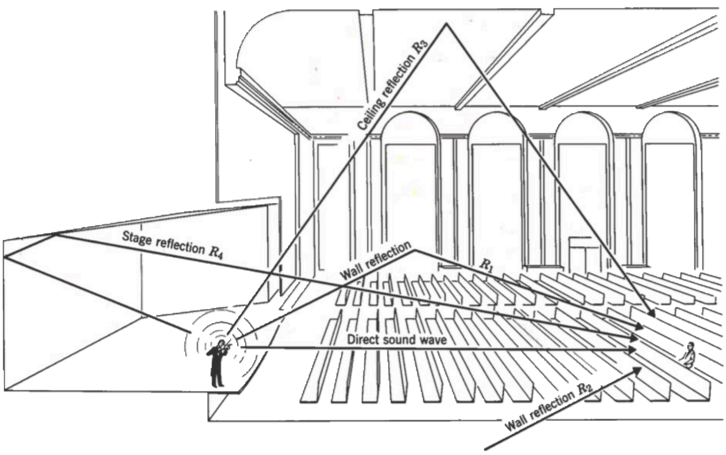


Figure 7: Illustration showing the path of direct sound and different types of reflected sound waves in a concert halls.

In order to stimulate clarity in a concert hall, the following rules need to be considered:

i) The surfaces must be in the right margin of distance and angled in the proper orientation to constrain the early reflections within the 80 milliseconds.

ii) It is important that the reverberant sound does not mask out the direct sound, see figure 8, especially at the rear of the hall where the direct sound has already been weakened. To compensate this, extra attention should be given to the reflection patterns to the rear of a hall. For instance, thinking of suspended angled ceiling reflectors for shortening the reflection patterns within the 80 milliseconds.

iii) Surfaces with an irregular geometry helps scattering brittle and harsh sound, as a result smoothing the overwhelming spikes in the music. This has to do with the fact that not all instruments have the same sound power, some instrument overemphasize over the other. Especially the percussions and brass section in the orchestra.

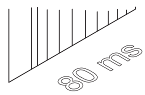


Figure III.i) early reflection within 80 ms

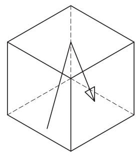


Figure III.ii) attention for rear reflection

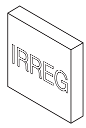


Figure III.iii) irregular geometric surface

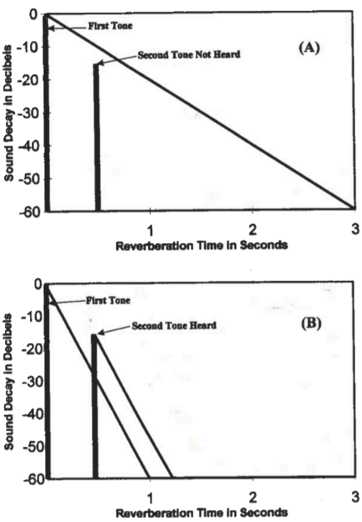


Figure 8: Diagrams demonstrating how a long reverberation time masks (hides or drowns out) a musical note.

IV. STRENGTH

The musical feature 'strength' indicates the loudness of sound. Roughly speaking, the phenomenon of loudness in a hall is mainly constituted of i) the loudness of the direct sound and early sound; and ii) the reverberant sound.

It is obvious that the loudness of sound is dependent on the loudness of *direct* sound. The closer the source, the louder it gets; the further the source, the quieter it gets. As sound travels, the intensity of sound decreases along its way because of its spherical spreading, see figure 9.

Essentially, to hear sound, the reflection patterns of sound has to *travel to* and *arrive at* the listener's ears. Since sound cannot bend, naturally, obstacles need to be prevented and/or minimized in order to attain high value of loudness of sound.

As mentioned in prior chapters, the property of reverberation also contributes to the quality of loudness of sound. Reviewing figure 10, (sound) energy is lost when the surfaces are absorbent. This is particularly true to the high frequency register.

Although, important to say, it is the total audience area that is significant for the reduction of loudness of sound, and not the numbers of seats in a hall. In other words, the more spread spaced seatings, the more decrease will occur in the loudness of sound (see chapter liveness, page 7).

Summary: a small hall with low seats capacity and less absorption sounds louder than a hall with all the opposite.

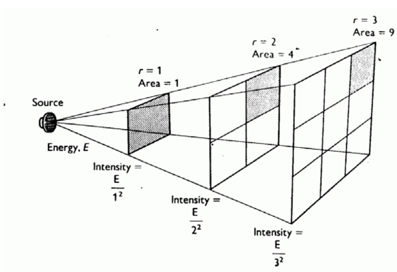


Figure 9: Illustration of how sound energy emenates and reduces as distance increases.

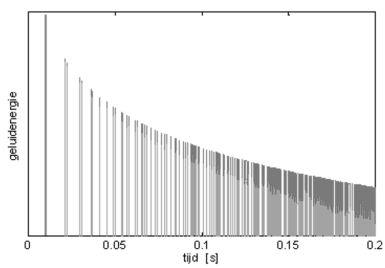


Figure 10: Graph showing the reduction of sound energy due to absorption. The dark-colored lines represent the amount of reduction due to absorption.

In the interest of creating a loud hall, there are several principals that have to be considered:

i) Probably the most important factor is to not overextend the distance away from the sound source in order to secure the strength of sound; as the greater the distance, the greater the decrease – especially for the direct sound. By making the room smaller and narrow, sound reflections travel much shorter, quicker and stronger to the listener.

ii) Because of rule number i), the seating capacity of a hall should also be limited. The more seat numbers in a hall, the more space is needed, resulting an increase of distance away from the sound source. Moreover, audience area absorbs a huge part of the loudness. Therefore, the hall with less seats will sound louder.

iii) Even though the seating capacity should be limited, the audience area should also not be divided in too many seating blocks, for the reason that the 'sides' of the blocks absorb sound as well.

iv) The row-to-row spacing of the seats should be designed dense and compact in order to limit the audience area. As already discussed in chapter 'liveness', it is the audience area that determines the amount of absorption, not the audience capacity.

v) It is also important to have a reverberant hall, allowing the countless reflections resonate through the hall. Which means that in order to obtain a high reverberation time, the cubic volume is mostly lengthened in the height because of the constraint of rule number i).

vi) The surfaces of the hall need to be enclosed, reflective and mostly made of heavy and dense material, so that the produced sound energy level does not leak and reduce extensively by transmission nor absorption.

vii) Seats should be thin in upholstery and raked for the purpose of avoiding obstacles in front of the listener, such as heads and seats. Because of the raked floor, the direct sound will not strike in a grazing angle where a large part of the sound will be absorbed by the seats and audience. This especially benefits the rear seats of the hall.

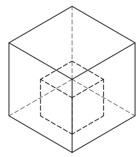


Figure IV.i) smaller volume

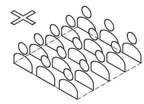


Figure IV.ii) limited seat capacity

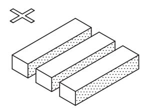


Figure IV.iii) limited audience blocks

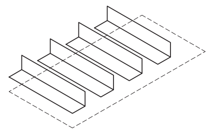


Figure IV.iv) compact audience area

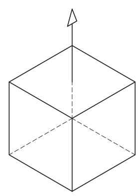


Figure IV.v) long reverberation time

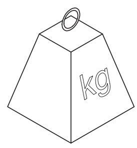


Figure IV.vi) heavy and dense material

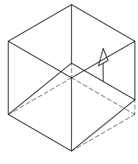


Figure IV.vii) raked floor

V. WARMTH

In music, the acoustical attribute 'warmth' is defined as the liveness of the bass; or the fullness of the bass tones. The liveness of the bass correlates to the reverberation time of the low-frequencies (75 to 350 Hz). The warmth of a music is controlled by the persistence of sound at low-frequencies.

For a hall to have warmer tones, the low-frequency (75 to 350 Hz) reverberation time is somewhat longer than the reverberation time of the middle-frequency (350 to 1.400 Hz). The warm sound in a hall is measured by the ratio of the low-frequency and middle. It is called the bass ratio (BR), see figure 11.[9]

According to Leopold Stokowski, one of the top leading conductors of the early and mid-20th century, strongly believed that the most serious acoustical problem in modern concert halls was the lack of bass. He corroborated that especially the basses of the string instruments were suffering and lacking in producing warm harmonic acoustics in the most modern concert halls.[10]

Summary: the persistance of sound at low-frequencies determine the warmth in a hall.

[9] Leo Beranek, "*Concert and Opera Halls*" (Acoustical Society of America, 1996), 432.

[10] Leo Beranek, "*Music, Acoustics & Architecture*" (John Wiley & Sons, 1962), 433.

$$BR = \frac{RT_{125} + RT_{250}}{RT_{500} + RT_{1000}}$$

Figure 11: Equation for the bass ratio (low/mid-frequency).

hall	*BR*	*construction*
CG	1,08	plaster
SC	1,17	plaster with small amount wood
KH	1,23	plaster or thick plasterboard
SH	1,03	plaster, except stage enclosure (wood >19 mm)
DH	0,96	heavy surfaces except surfaces around stage (plywood)
CH	1,14	plaster
MS	1,11	plaster, except stage (wood of medium thickness)
GT	1,23	plaster, except walls beneath balcony (plywood)

Figure 12: Acoustic data of the eight superior/excellent concert halls related to the acoustic attribute warmth.

For the pursuit of warm sound in a hall, all the causes of loss of bass should be avoided:

i) Avoid thin wood paneling. Particularly lightweight panel constructions absorb the low-frequency sound waves, so these constructions must be avoided. On the other hand, thick wood, wood of any thickness that is securely cemented to thick smooth plaster, plaster or concrete, is acoustically satisfactory.

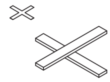


Figure V.i) avoid thin wood paneling

ii) All surfaces of the hall should be made of heavy and dense material, except the stage. Preferably, the stage need to be constructed out of lightweight, flexible wood in order to allow the vibrations of the cello's and double-basses transfer the low-frequency sound waves through the whole stage. This stimulates the sensation of a warm sound.

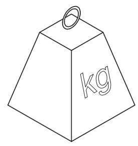


Figure V.ii) heavy and dense material

iii) Avoid overly aborbent seats. The backs and underseat surfaces should be of dense material, for example molded plywood ca. 12,5 mm. Whereas the upholstering on the top of the seat bottom should be only as thick as necessary for reasonable comfort, if possible no thicker than 75 mm.

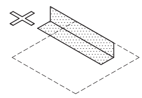


Figure V.iii) avoid overly absorbent seats

iv) Avoid all openings such as seams and cracks of doors, windows and ventilation grilles. Moreover, the transmission of sound should be minimized and preserved inside as much as possible. Not only to minimize the produced noise to the outside, but also to secure the reflection ratio inside the hall of high value.

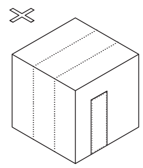


Figure V.iv) avoid openings

VI. BRILLIANCE

'Brilliance' describes the persistence of sound at *high-frequencies*. It refers to the bright ringing harmonic sound and relates to the treble frequencies (> 2.000 Hz) that decays slowly.

Brilliance is mainly measured through the 'treble ratio'. Where in the previous chapter the bass ratio measures the reverberation times of the low-frequencies with the middle-frequencies, the treble ratio measures the reverberation times of the high-frequencies with the middle-frequencies, see figure 13.[11]

[11] Leo Beranek, "*Concert and Opera Halls*" (Acoustical Society of America, 1996), 427.

Besides that the hall needs a longer persistence of sound at high-frequencies in comparison with the middle-frequencies, brilliance also possess the characteristic of a clear crispy quality, where every note is articulated defined and intelligible. This relates back to the prior mentioned acoustical features: *clarity* and *intimacy*.

Summary: a hall that has liveness at the high-frequencies, acoustical clarity and intimacy, has the trait of brilliance.

$$TR = \frac{RT_{2000} + RT_{4000}}{RT_{500} + RT_{1000}}$$

Figure 13: Equation for the treble ratio (high/mid-frequency).

hall	*500 Hz*	*1.000 Hz*	*2.000 Hz*	*4.000 Hz*	*TR*
CG	2,05	1,95	1,80	1,55	0,84
SC	1,80	1,75	1,60	1,50	0,87
KH	2,34	2,05	1,74	1,59	0,76
SH	1,90	1,95	1,59	1,43	0,78
DH	1,96	1,96	1,80	1,56	0,86
CH	1,83	1,75	1,57	1,28	0,80
MS	2,01	1,94	1,71	1,55	0,83
GT	2,15	1,95	1,75	1,62	0,82

Figure 14: Acoustical data of eight superior/excellent concert halls related to the acoustic attribute of brilliance. The treble ratio of the different bandwidth are self calculated with the treble ratio equation, through the source of Leo Beranek, *"Concert Halls and Opera Houses"* (Springer, 2004), 585.

To preserve acoustical brilliance in a hall, the following rules need to be considered:

i) The surfaces of the hall need to be reflective, which also means that the surfaces are made of heavy and dense material to minimize the transmission portion of the incident sound.

ii) The ratio between the reverberation time at the high-frequencies with the middle-frequencies are maintained around the given reference ratios (0,76 to 0,86). To secure this, highly absorbent material such as carpets and draperies should be strictly avoided or applied in limited areas in order to avoid the loss of brilliance.

iii) If absorbing materials are unavoidable, like carpets, a) it should only be used in aisles as thin as possible, cemented directly to a solid backing; b) or only used when necessary to eliminate echoes or acoustical glare, then again, as little as possible.

iv) Avoid overly aborbent seats. As discussed in the previous chapter, the upholstering on the top of the seat bottom should be only as thick as necessary for reasonable comfort, if possible no thicker than 75 mm.

v) The rules of the chapters *clarity* and *intimacy* (see page) also apply for this feature.

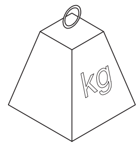


Figure VI.i) heavy and dense material

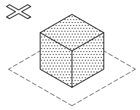


Figure VI.ii) avoid highly absorbent materials

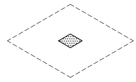


Figure VI.iii) minimize the use of carpets

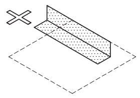


Figure VI.iv) avoid overly absorbent seats

VII. ENVELOPMENT

As the terminology already suggests, 'envelopment' refers to the degree to which the *reverberant sound* seems to surround the listener, also known as 'listener envelopment' an acoustic spatial sensation, see figure 15. It is a phenomenon where as if sound comes from all directions – frontal, lateral, overhead, back – rather than from limited directions.

In 2008, Wukada and Furuya investigated the direction and the total amount of late sound energy on LEV, through listening tests. The research concluded that the LEV increased as the relative sound levels of each directional late energy (after 80 milliseconds) increased. That is to say, that the experience of LEV depends on the late arrival sound reflections and the sound level of the source (loudness).

Primarily, the lateral angle had the most influence on the LEV. Sound coming from this angle create a strong perception of envelopment. Adjoining to that, the late arriving reflections from the *back* and *overhead* also create the sense of envelopment. In comparison to the lateral angle, the back influenced approximately 50 to 60% of the total sound energy whereas the overhead approximately 30 to 50%. Lastly, the angle of the front was found to be influencing the least on LEV.[12]

[12] Dan Nyberg, *"Listener Envelopment"* (Luleå University of Technology, 2008), 15.

Summary: (lateral) late arriving reflections determine the acoustic spatial sensation of envelopment.

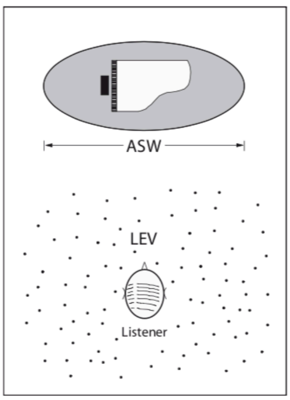


Figure 15: Diagram illustrating the spatial effect of listener envelopment (LEV).

For the spatial sensation of envelopment, the following rules need to be considered:

i) The surfaces of the hall need to be reflective, which also means that the surfaces are made of heavy and dense material to minimize the transmission portion of the incident sound. Especially the lateral surfaces need to be more reflective.

ii) Besides (especially) the side walls, make sure that also the rear walls have enough surface to reflect back to the listener. For this reason a strongly raked floors, or a too large, dence balcony in a hall have *weaker* envelopment, due to the lack of rear wall reflections. Even worse is, if the rear wall also has too much absorbent.

iii) If absorbing materials are unavoidable, like carpets, a) then it should only be used in aisles as thin as possible, cemented directly to a solid backing; or b) only used when necessary to eliminate echoes or acoustical glare, then again, as little as possible.

iv) Avoid overly absorbent seats. The backs and underseat surfaces should be of dense material, for example molded plywood ca. 12,5 mm. Whereas the upholstering on the top of the seat bottom should be only as thick as necessary for reasonable comfort, if possible no thicker than 75 mm.

v) By designing a narrow hall the lateral reflections travel less far, arrive more faster and stronger, creating a stronger sense of envelopment.

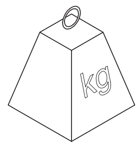


Figure VII.i) heavy and dense material

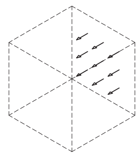


Figure VII.ii) rear surface reflection

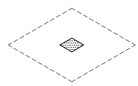


Figure VII.iii) minimize the use of carpets

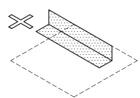


Figure VII.iv) avoid overly absorbent seats

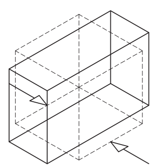


Figure VII.v) narrow hall

RESULTS

On the next page, an overview of all the prior analyzed architectural principles and references about the acoustics of concert halls are presented in front of you: an architectural luggage. An outline of architectural data, involving physical, spatial, structural, geometrical and architectural references concerning the best performing concert halls before the 20th century, conform L. Beranek's research.

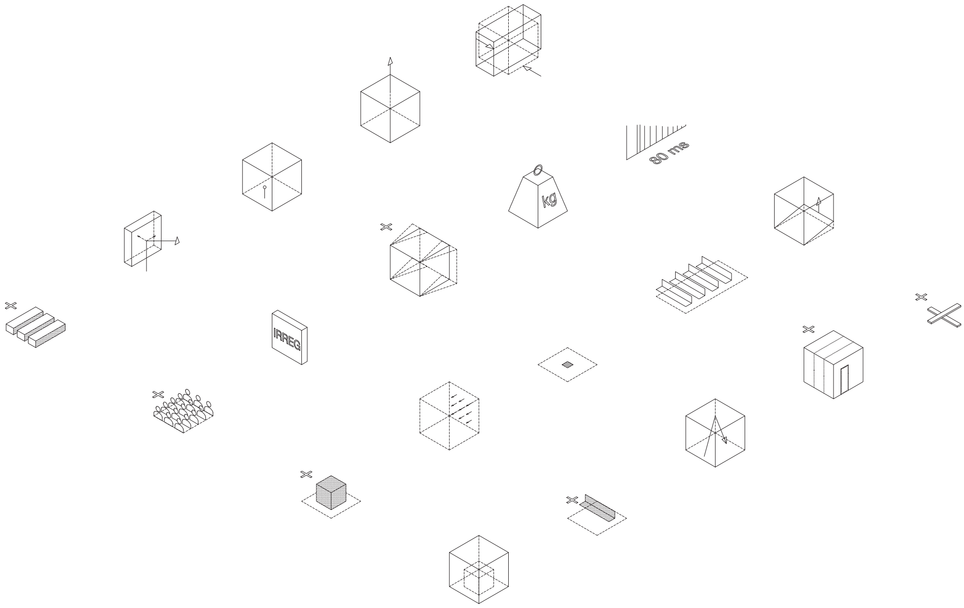
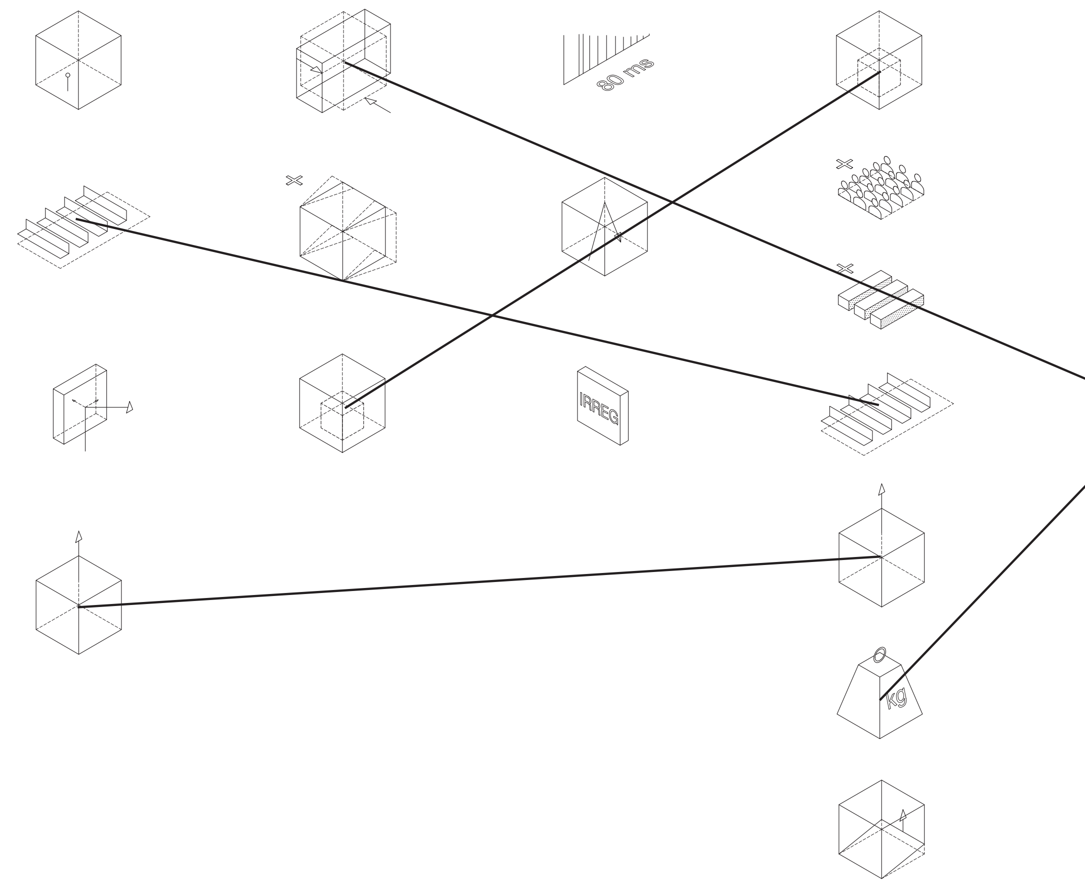


Figure 16: Isometric overview of all the prior found architectural principles for designing an acoustic well-functioning concert hall (own illustration).

RESULTS

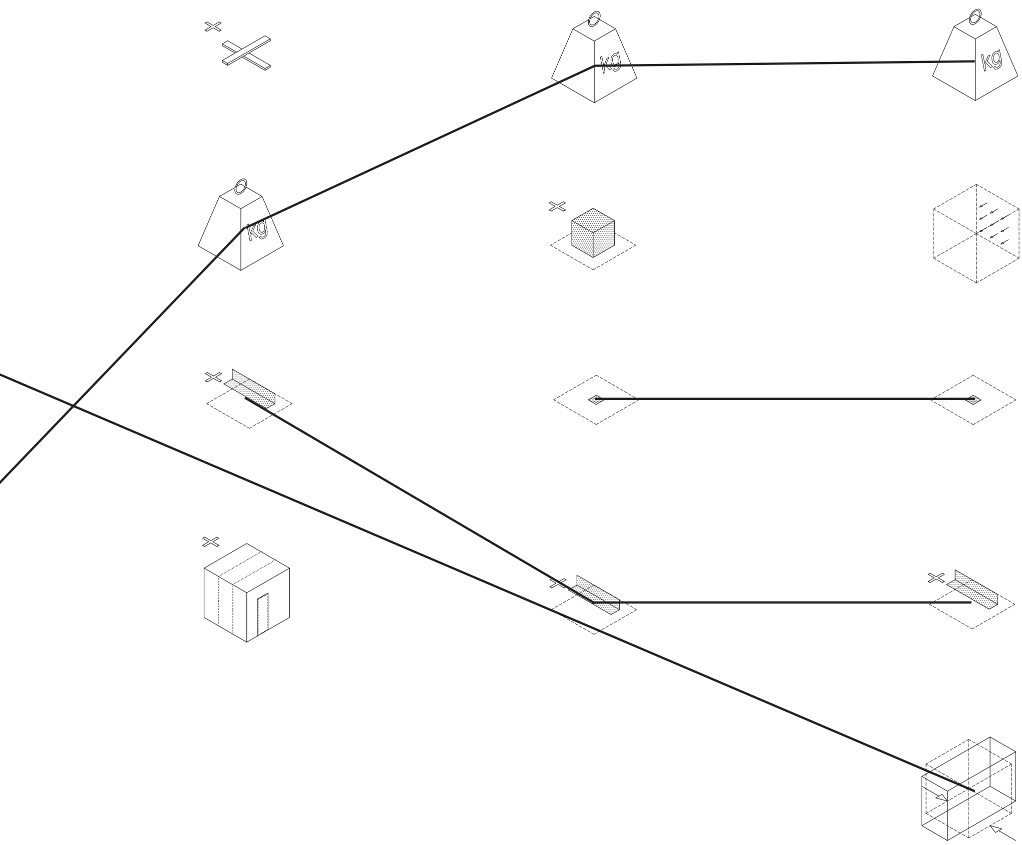
I. LIVENESS II. INTIMACY III. CLARITY IV. STRENGTH



city / hall	volume	length	width	height	seats	S_A	RT
Amsterdam, Concertgebouw (CG)	18.780 m³	26,2 m	27,7 m	17,1 m	2.037	1.135 m²	2,00 sec
Basel, Stadt-Casino (SC)	10.500 m³	23,5 m	21,0 m	15,2 m	1.400	740 m²	1,80 sec
Berlin, Konzerthaus (KH)	15.000 m³	24,1 m	20,7 m	17,7 m	1.340	740 m²	2,05 sec
Boston, Symphony Hall (SH)	18.750 m³	39,0 m	22,9 m	18,6 m	2.625	1.370 m²	1,85 sec
Cardiff, St. David's Hall (DH)	22.000 m³	27,4 m	27,4 m	18,0 m	1.952	1.235 m²	1,95 sec
New York, Carnege Hall (CH)	24.270 m³	32,9 m	25,9 m	23,8 m	2.804	1.600 m²	1,80 sec
Vienna, Musikvereinssaal (MS)	15.000 m³	35,7 m	19,8 m	17,4 m	1.680	985 m²	2,00 sec
Zurich, Grosser Tonhallesaal (GT)	11.400 m³	29,6 m	19,5 m	14,0 m	1.546	877 m²	2,05 sec

Figure 17: Overview of all the prior found architectural principles and acoustic data of superior/excellent concert halls for designing an acoustic well-functioning concert hall; the black lines indicate the relationships between the different attributes (own illustration).

V. WARMTH VI. BRILLIANCE VII. ENVELOPMENT



BRˣ	*TRˣ*	*construction*
1,08	0,84	plaster
1,17	0,87	plaster with small amount wood
1,23	0,76	plaster or thick plasterboard
1,03	0,78	plaster, except stage enclosure (wood >19 mm)
0,96	0,86	heavy surfaces except surfaces around stage (plywood)
1,14	0,80	plaster
1,11	0,83	plaster, except stage (wood of medium thickness)
1,23	0,82	plaster, except walls beneath balcony (plywood)

IV THE FINALE

Unlike 'the finale' of a symphonic piece – one which closes with a big gesture – this chapter concludes (and discusses) relatively concisely about the prior findings, and recapitulates back to the original essence: an architectural luggage for designing a concert hall.

Conclusion

With the declared fascination and ambition in designing concert halls, this thesis attempts to develop an architectural toolbox for architects in designing concert halls. Mainly, through the literature study of Beranek's list of acoustic attributes, seven acoustic sensations are filtered out for this research thesis: liveness, intimacy, clarity, strength, warmth, brilliance and envelopment. Important to note, there is no hierarchical order for designing a concert hall. With this said, each attribute has its own acoustic sensation and value which makes them indispensable. With the aid of other authors and experts on acoustics such as Barron and Jaffe the literature got enlarged.

By analyzing each acoustic attribute and juxtaposing it to the field of architecture, a set of of architectural diagrams, schemes, formulas, rules and numbers has been developed as an instrument in designing a concert hall. This luggage advises guidelines for the architect on what to avoid, implement, minimize, maximize, balance and such, varying physical, spatial, structural and geometrical aspects.

Last but not least, crucially to know, this luggage is deliberately developed to *serve* the architect for designing specifically. The user of this luggage should be aware to play *with* the toolkit, yet be careful not to be played *by* the toolkit. Perhaps, master the rules; unlearn the rules; ultimately, break the rules.

Discussion

Besides my personal fascination and interest in developing this toolbox, it came to me as a shock that many concert halls constructed before 20th century did not score well.[13] Imagine conservatorium students and (professional) musicians who have practiced hours and hours, day in day out, perservered for many many years, ending up on a stage where the acoustics are out of standards. The consolation part of this fact is that we now can learn from the bad examples, enhance the good ones and secure the better ones.

[13] Leo Beranek, "*Concert Halls and Opera Houses*" (Acoustical Society of America, 1996), 58.

In Beranek's study of concert halls constructed before 20th century, it appears self-evidently that the shoebox typology conquers as the overall winner in the ranking of acoustically well-performing concert halls. Despite this fact, architects seem to prefer the contemporary ideals and values of the vineyard typology, for example the rise of Philharmonie de Paris (2015), Elbphilharmonie (2017) and many others. In essence, the vineyard configuration attempts to offer a more closer, intimate, theatrical (visual) experience, trying to compromise the far positioned deficient seats as in comparison with the shoebox typology. However, it needs to be stressed that Beranek included many vineyard halls in his study (16 out of the 100), where surprisingly only one of them (St. David's Hall) succeeded to reach into the superior/excellent category. Understandably, the experience of a performance in a concert hall is *not only* about the acoustics but also about the spatial and visual senses. In the end it is the art of weighing the pros and cons of the different typology, directed to the objective.

Essentially, the significance of this thesis lies probably in the fact of giving architects effective insights about the field of acoustics. Being equipped with this knowledge this at least reduces the risk of designing rooms with bad acoustical qualities. Since concert halls are by nature considerably colossal already, the necessity to prevent and minimize costs and losses lies even higher. It would be trivial, if all the collective effort were based on constructing an unfunctional concert hall, ignorantly.

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Figure 16, Isometric overview of all the prior found architectural principles for designing an acoustic well-functioning concert hall (own illustration).

Figure 17, Overview of all the prior found architectural principles and acoustic data of superior/excellent concert halls for designing an acoustic well-functioning concert hall; the black lines indicate the relationships between the different attributes (own illustration).

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