ACOUSTIC DESIGN OF THEATRES FOR NATURAL SPEECH AND/OR VARIABLE ACOUSTICS

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1 INTRODUCTION

Basically there are two types of acoustics: the acoustics of the open air and the acoustics of closed spaces. The first type has minimal reflections, the sound that travels in a straight line between the speaker and the listener (direct sound) is dominant over the sound reflected by nearby objects. This type of acoustics is specifically suitable for transferring information, like speech, and to determine the direction of a sound source. It is the acoustics for the consonants. It has high definition.
In the second type the direct sound is of little significance. Almost all energy reaches the listener in an indirect manner, by many reflections originating from the boundaries of the closed space. This type of acoustics is generally felt to be most suitable for musical sounds and vowels. It has low definition.
The open-air and the speech-theatre are characterised by short and/or very weak reverberation and the concert hall by long and/or strong reverberation; this makes a variation in acoustic properties necessary when a hall is used for both types of performances. One of the challenges designing halls with variable acoustics is not to compromise the strength of sound in the theatre mode. Specific acoustic requirements, as well as experiences and developments over the last 30 – 40 years with the design of theatres with natural variable acoustic will be illustrated, ending with an almost uncompromised theatre with variable acoustics in Zwolle (NL).

2 ACOUSTIC FACTORS

2.1 Reverberation

Generally speaking, reverberation is considered to be an important parameter for describing room acoustics. The reverberation time (RT60) is the time needed for the sound pressure level to decrease by 60 dB after the sound has stopped.
In concert halls reverberation is an important parameter, although it is understood nowadays that there are many other aspects involved regarding concert halls[3]. In the concert hall for classical symphonic music, a reverberation time of approximately 2 seconds is ideal for this type of music. This follows from the way this music was composed and orchestrated, but also from the way our hearing mechanism integrates sounds. In addition, the way the 19th and 20th century musical compositions and orchestra sizes have developed to the taste of the audiences, must have played a role in reaching consensus regarding the 'ideal' reverberation time all over the world.
The larger the hall, the longer the 'optimal' reverberation time will be. A reverberation time of 2 s would sound too dry in a very large hall such as the Royal Albert Hall (V= 80.000 m^3), but too reverberant in a small recital hall such as the glass Amvest Hall (V=2000 m^3).
In addition, the 'optimal' reverberation time also depends on the type of music. More reverberation will give a 'fuller' sound, whereas less reverberation enables us to hear the details in the music, especially important for chamber music or modern classic music. For example, the *Muziekgebouw aan 't IJ* in Amsterdam (opened in 2005) has variable acoustics to adjust the reverberation time and the acoustic volume. The concept of 'reverberation chamber' or reverberation gallery is present in the Royal Albert Hall and is successfully applied in *De Spiegel* in Zwolle, in this case enabling variation of reverberation time. This variability introduces new challenges for the user of the facility: what mode to use in what situation? Who decides and based on what? This is especially true given that there is no such thing as 'ideal acoustics': tastes differ.

Too much reverberation in principle has a degrading effect on the intelligibility of speech. In theatres for natural speech, the reverberation time therefore needs to be sufficiently short. Nevertheless a certain level of reverberant sound is necessary to gain sufficient loudness above the background noise level, because of the limitations in the sound power of the human voice. This is important for the intelligibility of speech, especially for those seated at large distances from the actors. This combination of demands requires a sufficiently small room volume for the theatre. When a hall has to be used for both kinds of performance, symphonic music as well as spoken word (theatre), a variation in acoustic properties such as reverberation time will be necessary.

2.2 Definition and intelligibility

Definition or clarity is the counterpart of reverberation. It concerns the distinction between single notes or words. Chamber music with fast melodies and quickly changing harmonies will sound blurred in a large concert hall with long reverberation. But even with the same reverberation time there can be differences in definition between halls. Definition can be improved by adding early reflections or by reducing reverberation. Definition is better at positions closer to the stage. For concert halls, the clarity required is specified using the parameter value C80 (ratio between early energy (0-80 ms) and late energy (80-800 ms), that should be < 0 dB).
Where for concert halls a form of sound blending is needed, in theatres this would negatively effect the main acoustical requirement, namely transferring speech. Here we need high definition and clarity. Usually values for C80 above +4 dB are required. This can be achieved by a proper design giving many beneficial early reflections and a low reverberation.

A true measure for the speech intelligibility is the parameter AL_{cons} (Articulation Loss of Consonants). This is really the percentage of wrongly understood consonants which means that test persons have to be used since they are the ones that understand. Not only the transmission channel determines the speech intelligibility, but also speaker-listener effects (proficiency of speaker, complexity of message, familiarity with content etc.). The speech intelligibility can be judged as good if the AL_{cons} value is below 10%, reasonable if between 10 and 15% and bad above 15%. Peutz defined a way to predict the AL_{cons} of the transmission channel based on distance, source directivity, room volume, reverberation time and the noise[5]. Another method is to calculate the AL_{cons} based on the direct/reverberant ratio, reverberation time and the signal/noise ratio[6]. There are also other prediction algorithms for AL_{cons} that distinguish between early and late sound, and are based on information indices[4,7]. These can be used when measuring impulse-responses, from which often also the parameter STI (Speech Transmission Index[8]) is deduced as a prediction for speech intelligibility. Peutz stated that without direct sound AL_{cons} will be limited to 9 * RT60 [%], for situations without noise. Based on statistical relations in the reverberation field without direct sound, it was shown that a good intelligibility can be realized with RT60 values of 0,8 to 0,9 s. In that case at least 55-60% of the sound energy will arrive at the listener within 50 ms[11]. This part belongs to the early sound. It means that provided sufficient sound energy is supplied by early reflections, there is no need for a direct sound to get a good intelligibility[11].

2.3 Loudness and noise

In concert halls generally the walls and ceiling are made of reflecting materials. The public and the chairs on which they sit constitute the sound absorbing dimension. The loudness is directly dependent on the number of seats. This loudness is usually indicated by the factor G[(3)], which is defined as the sound level difference at positions in the hall beyond 10 m from an omni-directional source on stage, and the sound level at 10m distance of the same source in a free field. Assuming a diffuse sound field in a single room volume an estimate for G can be deduced, based on

$G[dB]=31-10\log(S\alpha_r/4)-10\log(1-\alpha_s)$, with S total surface, α_r the average absorption coefficient of the room (determining RT60), and α_s the average absorption coefficient as "seen" by the source. Note that α_r and α_s may be different, except for an omni-directional source. Additionally a decrease of the reverberant field with distance should also be implemented[10].

In the concert hall for classical music loudness should have a defined value, determined by the size of a symphonic orchestra and the number of seats. Values to achieve in symphonic concert halls for G are 2 to 5 dB, and for chamber music 6 to 9 dB[3]. Too large concert halls generally have a too low loudness level. For that reason it is important to limit the size of concert halls, but the effectivity of the absorption can also influence the loudness of a hall. Rigid criteria for the dimensions of concert halls are hard to give. For symphonic music goals are a depth of 40-45 m, a width beneath 25 m and a maximum height of 15 to 20 m. In figure 1 and 2 an example of a 1000 seat-concert hall (*Muziekcentrum Enschede* (NL) is schematically drawn, together with a small theatre.

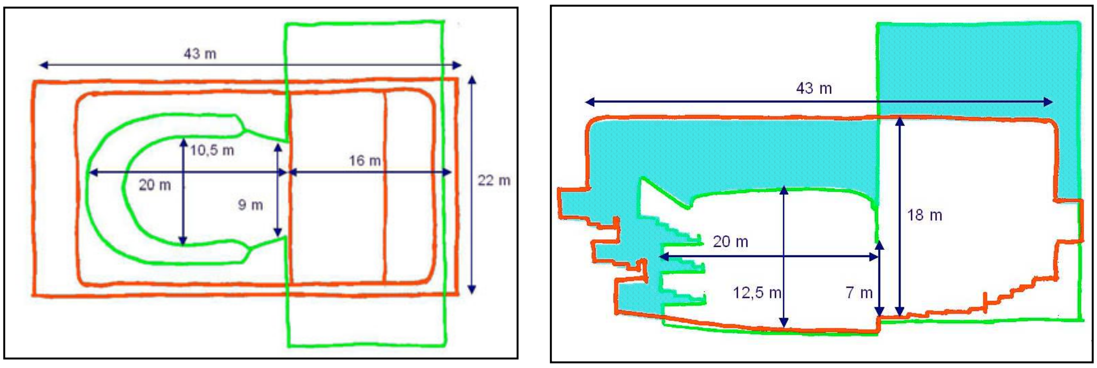

Figure 1, 2. Schematic plan (1) and cross section (2) of a typical intimate small theatre for natural speech (*Stadsschouwburg The Hague*, V=2800 m^3), and a regular shoebox concert hall (*Muziekcentrum Enschede* (V=16.000 m^3).

For theatres in which the spoken word is natural, an acoustic must be created that is as loud as possible, because of the limitations in the sound power of the human voice. But the acoustic should also have as much as possible direct (and early) sound and minimal (late) reverberation, because sound which is too reverberant may degrade speech intelligibility. The reverberation time should generally be limited to less than 1 second. In that case, provided there is sufficient loudness of the hall, the intelligibility of the reverberant (speech) sound will still be good, even at the furthest distances where direct sound is not relevant. According to the basis statistical laws of room acoustics the best space for speech therefore is as small as possible, with reflective walls and ceiling, the only sound absorbing area being the audience. Additional absorption should be limited as much as possible, to maintain loudness and strength of early reflections. RT values above 1.0 s. are undesirable because then AL_{cons} increase above 9-10% at the furthest distances. Although rigid criteria are hard to give, because a certain adaptation of the voice is well possible, the best theatres for classical plays are all smaller than 4,000- 5,000 m^3, with a reverberation time of 1 second or less. Related demands for their dimensions are a depth of the hall below 23 m, a width beneath 20 m, a height beneath 13m, a width of stage opening below 14 m and a maximum room volume of 5 m^3 per person. Amongst these theatres, those with RT60 values of 0,8 á 0,9 s. have a noticeably better intelligibility (AL_{cons} < 7%), as is illustrated in the example of the Stadsschouwburg in The Hague (see chapter 3). In this theatre AL_{cons} values between 3-5 % are measured due to added early reflections. The dimensions of this intimate theatre are schematically drawn in figure 1 and 2 (green lines), together with those of a concert hall (red lines). The comparison between the two halls in these figures illustrates the contradictory requirements and the challenge when these two different uses have to be combined in one multi-purpose hall.

Besides reverberation, the strength of sound (loudness) is another determining factor. Since our ears need a certain sound level to hear properly and there is always a certain amount of background noise, the acoustic signal has to be loud enough. Degrading of speech intelligibility by background noise in a theatre may be significant. Usually ventilation noise (air conditioning) should be below 25 dB(A), as should be the case for fan noise of lamps etc. as well. However, lowest background noise levels due to audience of at least 30-35 dB(A) may occur in the audience area during theatre performances. However, in very quiet concert halls, with ventilation noise below 15 dB(A), it appears that the audience adapts to this silence during performances and can be very silent too, which is favourable for the dynamics of the music and to hear the softest pianissimo's of the orchestra and/or of soloist instruments. For hearing the most of the natural dynamics of speech by actors this would be favourable too in theatres. More detailed research in that matter will be performed in future.

As an example for the influence of noise let us suppose a theatre of 5000 m^3 and an RT60 of 1 second, with an average absorption factor (α_r and α_s) of 25%. The strength or gain for an omnidirectional source in the middle of the stage opening is then G=+2 dB. Suppose an actor is talking (Q=2) with a sound power of L_w=70 dB (1-2 kHz) from stage. Using algorithms for the decrease of sound level with distance[1], the calculated speech levels at 15 m distance are about 45 dB (direct sound 38 dB, reverberant sound 44 dB). With noise levels below 20 dB, the signal-noise ratio (S/N) will be at least 25 dB, and a value for AL_{cons} of 6% is predicted, which would be a good speech intelligibility. When higher noise levels of for instance 25, 30 or 35 dB due to the audience are to be expected, the S/N-ratio reduces from 20 to 15 down to 10 dB, and subsequently higher AL_{cons} values are predicted from 7%, 8% up to 10%. At further distances of 20 m these values would be 8%, 9% and 12%, and speech intelligibility becomes fair. If the actor was to turn away from the audience and talk to the side, the direct as well as the reverberant sound reduces and the S/N-ratio's becomes smaller with values of S/N=16; 11 and 5 dB. Related AL_{cons} values raise to 9%, 11% up to 15 %, and speech intelligibility becomes worse.

These examples indicate that if there is noise it will have a significant influence on speech intelligibility, and that every dB increase of strength that can be achieved is worthwhile. Compared to the criteria of 4,000-5,000 m^3 and 1 second reverberation as mentioned before, this can only be achieved with even smaller volumes down to 3,000 m^3.

2.4 Energy loss and parameter Q_{room}

Contrary to concert halls, churches or other rooms with single volumes, in a theatre a certain part of the (direct) sound energy of a sound source on stage is lost into the stage environment (stage tower or alike), being (mostly) absorbed by curtains and alike. This part of the source energy does therefore not contribute (or not fully) to the reverberant sound level in the audience. This can be accounted for in the calculations of reverberation level and loudness (G) introducing a factor which we propose to call Q_{room}. This is the inverse of that part of the source energy being projected into the hall. For instance, a Q_{room}=5 means that 1/5 th of the source's energy is projected into the hall.
The factor Q_{room} depends of several parameters:

- the source position relative to the stage opening (see figure 7,8);
- the size of the stage opening;
- the directivity factor and directivity pattern of the source (omnidirectional for G factor[3]);
- the orientation of the source (if not omnidirectional). In practise actors voices may have an other directivity factor depending on the direction of their mouth (Q=2-2.5 if talking to the audience, Q=1 if talking sideways, Q=0.3 if talking with their back to the audience). Q=1 can be considered as a reasonable value to maintain for a worst case situation with natural speech on stage.
- the average absorption coefficient of the stage environment (side walls, backwall, ceiling) stage curtains, and stage scenery (reflective/absorptive elements). For reasons of simplicity it may be assumed that all the sound projected directly from the source into the stage area will be fully absorbed on its first reflection (100% absorption). In reality there will be also intermediate situations, for instance with a reflective backwall or with reflective parts of the stage scenery.

The factor Q_{room} can then be calculated from: Q_{room} = (180/(vertical opening angle towards the hall)) x (360/(horizontal opening angle towards the hall)). In figure 3 and 4 a plan and a cross section of a

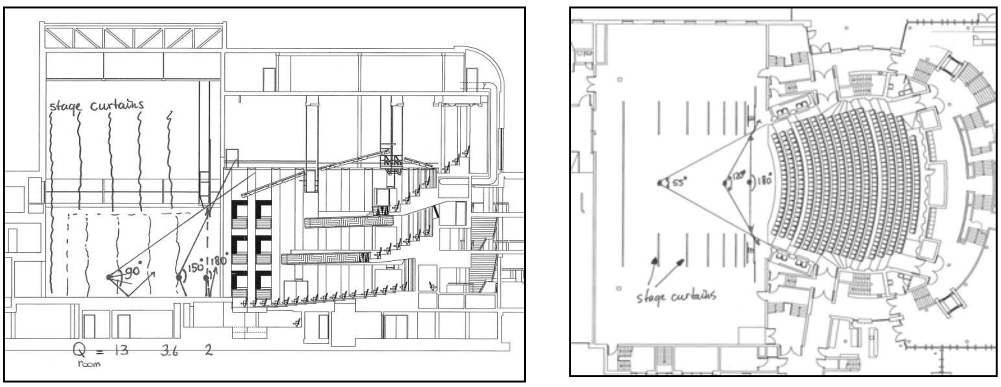

Figure 3 and 4. Plan and cross section of a theatre with variable acoustics in Zwolle (NL). Source angles determining factor Q(room) for different source positions are indicated.

theatre are presented, in which the relevant angles towards the room are indicated for three different source positions on stage, and related values for Q_{room} are given. For an omnidirectional source in the middle of the stage opening, 2 m backwards and 10 m backwards the corresponding values for Q_{room} are respectively 2, 3.6 and 13. Related loss of reverberant source energy into the stage tower corresponds to 10 log Q_{room}, which give values of 3, 5.5 and 11 dB.

Because the factor Q_{room} is highly depending on the source position, this is also the case for the value of G in a theatre. G values measured in theatres should therefore always mention the source position used, to avoid misunderstandings.

With more directional sources as the human voice of actors speaking towards the audience, these reductions will be less in practice. For instance for a actor in the middle of the stage opening (Q= 2.5), Q_{room} will be about 1.1 - 1.2, because just a small energy part (say 20%) is being radiated backwards from the speaker into the stage tower. When speaking to the side (angle 90º with room axis) Q_{room} will be 2, because 50% of the source energy is directed into the stage area. In fact, with a non-omnidirectional source Q_{room} has to be determined by integrating the directivity pattern of the source over a solid 3-D angle into the hall, with its boundaries at the sides of the stage opening in the horizontal and vertical plane. Part of the direct sound radiated to the stage floor can be accounted for to reflect directly into the hall, for instance through a first floor reflection, so than this part of the solid 3-d angle should be implemented in determining Q_{room}.

For omni-directional sources, often used in room-acoustic measurements, the expected value of Q_{room} can be deduced using room acoustical computer models, or using this factor as a curve-fitting parameter to fit the measured decay with distance to the theoretical decay. Another method to determine Q_{room} in theatres with variable acoustics, is to compare the measured sound levels in the reverberant field for situations with and without an orchestra shell.

With a maximum room volume of 5000 m^3 and a reverberation time of preferably 0.8 – 0.9 s. (with a average absorption α_r and α_s <20%) it can be calculated that the average G-value is 4 to 5 dB if the source would be in the middle of the room. However, due to energy loss of the source into the stage tower, in most theatres in practice smaller G-values will result, as discussed above. For a omni-directional source position in the middle of the stage opening (usually indicated in the Peutz measurement layout as position 4) corresponding G-values in the audience area with the above room characteristics are about 2 to 3 dB lower. This means that in case of using a theatre volume of 4,000-5,000 m^3, a G-factor of at least 2 to 3 dB should be attainable (source in middle of the stage opening). If higher G-values are reached an even more efficient room design is realised, which is beneficial for the strength and intelligibility of natural speech.

However, there also seems to be a tendency to make theatre hall volumes larger, partly due to theatre technical demands, such as lighting bridges all over the audience. With room volumes up to 7,000-8,000 m^3, corresponding absorption values α_r and α_s values will be higher (up to 60-70%), to keep the reverberation time sufficiently low. Subsequently low G-values down to 0 dB or lower are to be expected in many of such flat rectangular floor theatres, which compromises the strength for speech.

2.5 Effectivity of absorption

For the audience in concert halls, it is obviously nice to have a good view of the performers, but not absolutely necessary to enjoy the music. But giving everyone a good view means steep floor levels. From his perspective the performer will see a lot of the audience, which in turn means a lot of absorption. An important part of his or her music will be absorbed directly by the public and not contribute to the reverberant sound field. In general, good concert halls, with examples in NL like the *Concertgebouw Amsterdam*, *Dr Anton Philipszaal* (The Hague), *Muziekcentrum Enschede* and *Concert Hall Tilburg* have marginal lines of sight.

Other considerations have to be made for theatres. In a theatre good sightlines are a prerequisite to see the entire stage floor and scenery, and distances should preferably be within 25 m distance to see sufficient facial expression of the actors. Too steep floor levels should however be prevented (using also alternating rows), because this reduces the strength of the reverberant speech, caused by increased effectivity of the audience absorption which increases the average absorption α_s (as seen by the source) within the room. To maintain high G values the α_r absorption α_r and α_s should exceed 20-30% in theatres, which can be achieved keeping walls and ceilings reflective.

3 COMPACT THEATRE DESIGN

To fulfill the demands as mentioned before on loudness, reverberation and sightlines, a compact theatre design is necessary for good acoustics for natural speech. The theatre in The Hague is a good example of such a small, intimate theatre. It has a very efficient theatre design (V=2800 m^3; 675 seats, 3 balconies) with dimensions of 20x10.5-14x13 m (dxwxh) and a stage opening of 9x7 m (wxh). Some of its characteristics are illustrated in figures 5 - 8, based on measurements.

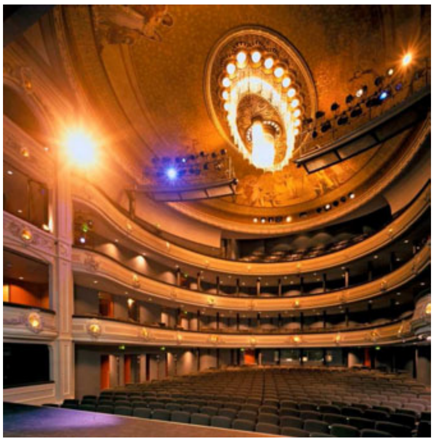

Figure 5. Interior photo of the intimate theatre *Stadsschouwburg The Hague*

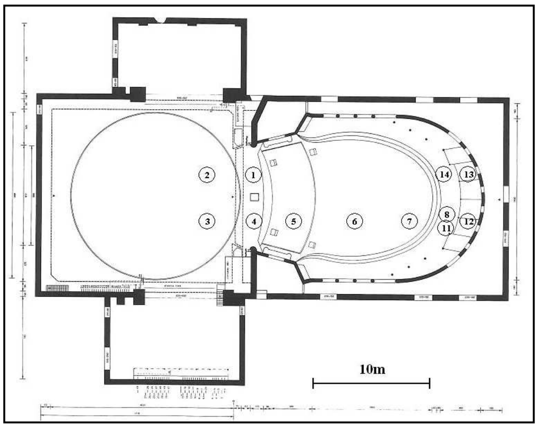

Figure 6. Plan of theatre *the Stadsschouwburg in The Hague* (NL), with indication of standard (Peutz) measuring positions for impulse responses.

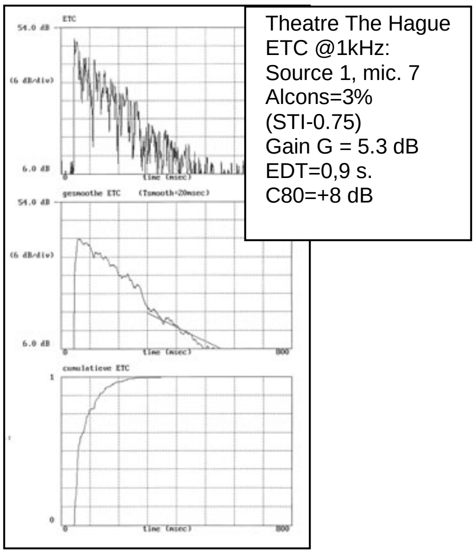

Fig 7. Energy Time Curve (ETC) of Impulse response in theatre The Hague.

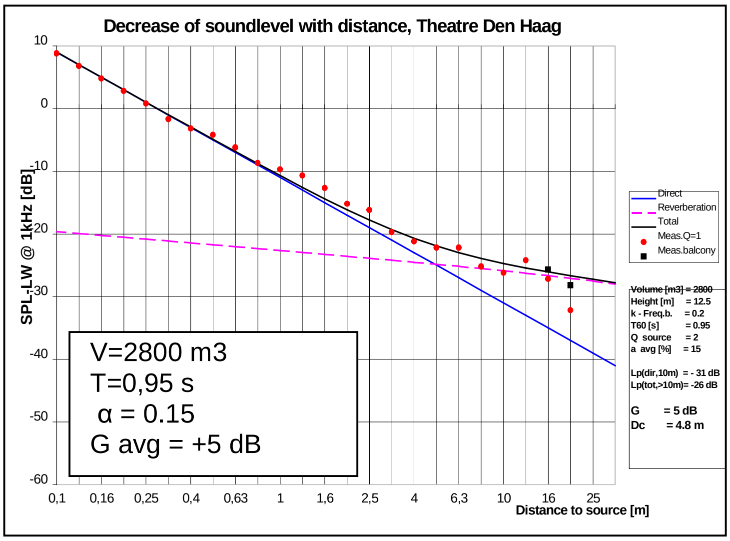

Figure 8. Decrease with distance curve (@1kHz) in theatre The Hague, along a straight line from source position 4 into the hall. Average value for G = 6 dB.

Figure 5 gives an impression of the interior of this theatre, and figure 6 gives a plan of this theatre, in which the measuring positions according a standardized scheme, used for impulse response measurements by Peutz, are indicated.

In figure 7 an example of such a measurement in this theatre is shown between source position 1 and microphone at position 7 at 16 m distance in the stalls. The graph of the arrival of the cumulative energy (at the bottom in figure 7) shows that within 50 ms after the direct sound already 80% of the energy has arrived, which is due to many early reflections. This determines the very good intelligibility (AL_{cons}=3%). Therefore also the clarity value C80 is high (+8 dB). Compared to the larger theatres of 4,000-5,000 m^3 its strength is higher, with a value of G=+5 dB (source at position 4). The decrease with distance measured in this theatre at 1 kHz octave is presented in figure 8, together with the theoretical lines that were used to fit the acoustical room parameters. This results in an acoustic volume of 2,800 m^3, a reverberation time of RT60=0.95 and an average value for absorption coefficients (α_r and α_s) of 15%. The latter is partly due to the efficient audience arrangement and efficient sight lines, with rather flat floors and balconies that are not too steep.

The following recommendations can be given for designing theatres for natural speech:

- Keep the effective acoustical room volume below 4,000-,5000 m^3;
- Keep the number of seats below 850-900. Use regular seat width (53-55 cm), and as narrow row distance as possible (90-95 cm), to keep the amount of audience absorption limited.
- Keep background noise levels due to ventilation systems etc. below 25 dB(A) for theatre-use and preferably 15-20 dB(A) if used as concer thall as well. Strict demands for sound levels caused by theatre lighting and cooling fans of computers and power equipment should also be set.
- Keep the walls and ceilings inside the hall as much as possible sound reflective. This is necessary to get sufficient early sound energy at the audience, not only if the actor faces the audience, but also in situations when an actor, who's voice has a certain directivity, turns sideways away from the audience. Possible negative focussing effects of curved (rear) walls have to be accounted for. When using balconies, back walls will often be (mostly) shielded acoustically by audience.
- Make the sides of the stage opening as reflective as possible, for instance by using diffusive side-boxes with seats, and by making the underside of the first stage-bridge reflective. Such reflective elements around the stage opening are also beneficial to give support to an opera orchestra if playing in the orchestra-pit. They also supply usefull early reflections to obtain a higher clarity (C80) value which is usefull for speech intelligibility.
- Apply a well designed first sound reflector in the front part of the hall, that smoothens the acoustic transition between the limited height of the stage opening and the height of the hall. Such a sound reflector will enhance the directivity and actual sound level of an actor and will be beneficial for the rearest rows on the balconies. This reflector should be movable if the hall has variable acoustics or is also being used for opera (orchestra-pit).
- To make or keep certain parts of the stage reflective, especially in smaller stage environments this might be beneficial for the sound level of the actor in the hall, and can be done without introducing too much risk on echo effects. However, the reverberation time of the stage environment/house may not influence the reverberation time of the hall, so generally it should be preferably lower, although this might be difficult for the low frequencies in case of a very large stage house. In theatre *De Spiegel in Zwolle* (see chapter 4) the reverberation time of the stage tower is lower than the reverberation of the hall. In order to achieve this, more than 80% of the walls inside the stage house have been cladded with 80 mm thick sound absorption.
- Apply preferably two or three balconies to keep the furthest distance to the stage limited in order to keep good natural view of the facial impression of the actors;
- Keep the furthest rows within 25 meter of the stage opening for the same reason;
- Make a forestage allowing actors or comedians to approach the audience and to allow them acoustically to project their voices directly in the hall's volume without loosing too much vocal energy into the stage house.
- Aim for a reverberation time of maximum 1.0 s., but preferably 0.8 to 0.9 seconds. Without having to add absorption (this would result in lower sound levels) this can only be done by making the room volume even smaller than 5,000 m^3, which will make a very room-efficient design necessary. In theatre De Spiegel in Zwolle (see chapter 4) the room volume for speech is about 3,800 m^3. In case of theatres with variable acoustic that have also to be suitable for symphonic music, there will be a delicate balance necessary. The reverberation needs to be long for symphonic music (1.9 to 2.0 seconds), requiring a large volume, and sufficiently short for drama/theatre (<0.9-1.0 s). Developments in that field are discussed in chapter 4.

4 DEVELOPMENTS IN VARIABLE ACOUSTICS

Because of the different acoustic requirements for symphonic music and theatre use, as discussed before, a significant variation in acoustic properties will be necessary when a hall has to be used for both kinds of performance. This involves mainly reverberation time and volume (sizes), as can be seen in figures 1 and 2 of chapter 2, as well as related factors as definition and clarity.

In many places theatre buildings have to be built that have to accommodate a wide variety of performances. If for reasons of building budget or running costs only one main hall can be built, it is of course possible to create a compromise in its acoustics that will work more or less for all performances. Halls that are designed this way usually have a bad reputation regarding the acoustics (multi purpose is no purpose), when they have a size of more than 500 - 600 seats. For halls of smaller size the compromise is well possible, if properly designed.

In the 1970's variable acoustics started to be applied in this typical 'receiving' type of city theatre. With the acoustic requirements as mentioned above in mind, Peutz' acoustic design philosophy started from the hall size necessary for symphonic music. This was initially implemented in the *Stadsschouwburg Heerlen* (1962, V=4.200-5,000 m^3), but more clearly in *the Theater aan de Parade* (1976, V=4,500-5,000 m^3). A schematic plan and cross-section of this theatre is given in figures 9 and 10 (black lines), together with the previous example of an intimate theatre (in The Hague) and concert hall. This theatre was designed with a relatively large volume and stage

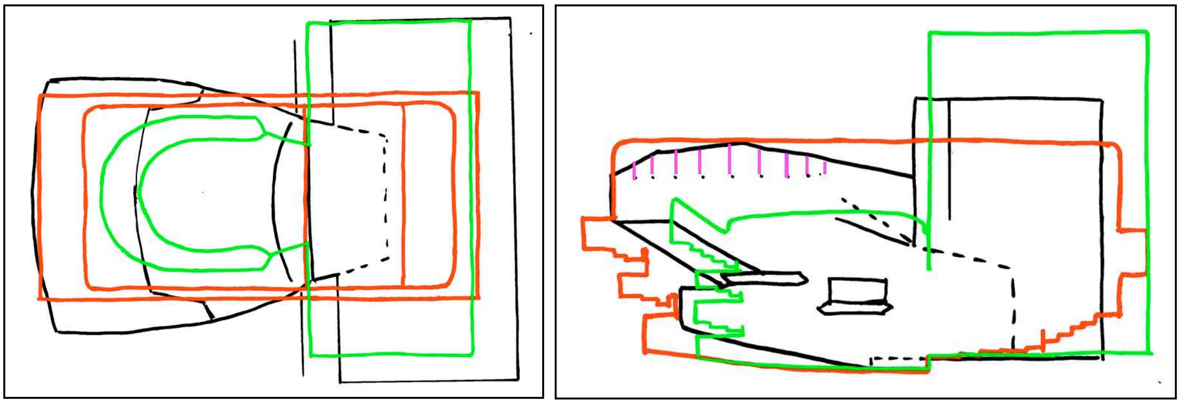

Figure 9 10. Schematic plan (9) and cross section (10) of *Theater aan de Parade* (1976, V=4,500-5,000 m^3) (black lines), together with the previous example of an intimate theatre (in The Hague) and concert hall.

opening. The stage was equipped with a movable orchestra shell. This basis would give a moderately long reverberation time of 1.5 - 1.7 s. To adapt the hall for classical plays the stage opening can be reduced by movable manteaux. A large amount of vertical curtains can be unrolled from the ceiling to add absorption, in order to shorten the reverberation time. The effective acoustic volume is reduced at the same time. On the other hand a hall is created with a strongly sound absorbing ceiling; this is a clear concession to optimal conditions for natural speech.

This concept of hall with variable acoustics was further developed in *De Lawei* in Drachten (1988), and the *Theater aan het Vrijthof* in Maastricht (1991), the *Stadstheater Zoetermeer* (1992) and in the *Zaantheater* (1998). A schematic plan and cross-section of this theatre *De Lawei* in Drachten are presented in figures 11 and 12 (black lines), together with the previous example of an intimate theatre (in The Hague) and concerthall. The basic shape of these halls is a rectangular box with sufficient volume for symphonic use. They have a stage opening of approximately 20 meters wide and 11-13 m high, a single main balcony and a gross height of 16-18 metres (to be reduced by vertical curtains to 12-13 metres, total area of curtains 1,000 m^2 or more). The size of the orchestra shell is usually 20x14x12 m (dxwxh). The total room volume of these halls including orchestra shell is 9,000 - 11,000 m^3. The (effective) volume in the theatre mode is approximately 5,000 – 6,000 m^3. The reverberation time ranges usually from 0.9 – 1.1 seconds in theatre mode to 1.6 - 2.0 seconds in concert mode. This concept for variable acoustics works technically quite well. The only drawbacks are the extra sound absorption in the theatre mode, where strength of sound is lost and a slightly less full, reverberant sound, due to the absorption of the chairs resulting from the good sight lines. Another disadvantage may be a certain loss in architectural freedom for the hall design, and that these halls are not really intimate.

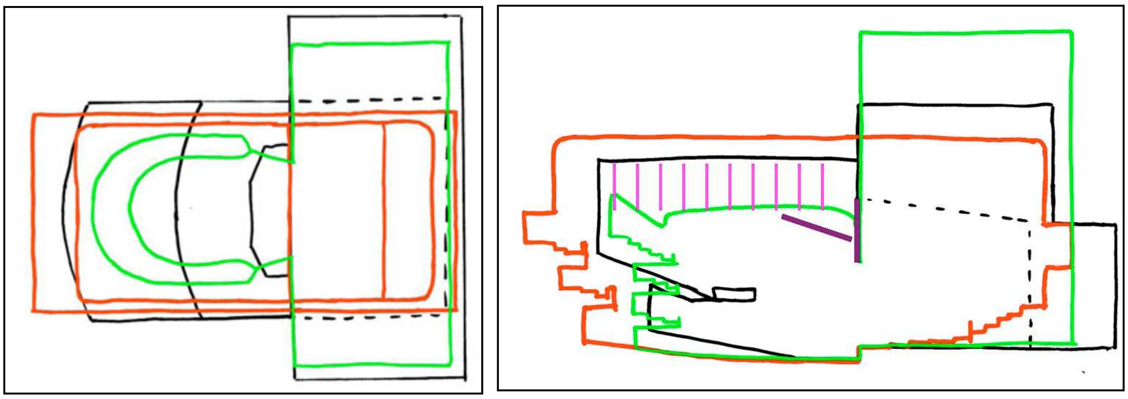

Figure 11,12. Schematic plan (11) and cross section (12) *of Theater de* Lawei in Drachten (1976, V=4,800-11,000 m^3) (black lines), together with schematic lines of the previous example of an intimate theatre (in The Hague) and of a concert hall.

A next step in the development should therefore be to create a more effective volume variation, so that in the theatre mode less or no increase in total sound absorption would be necessary. A step in this direction was made in the main hall of *De Harmonie* in Leeuwarden (1994) where approximately 60 % of the ceiling consists of large panels that can be lowered to vary the hall's height. On top of these elements and exactly in the same position under the roof of the hall, strongly absorbing material is applied, to make the space above the lowered ceiling as 'dead' as possible, so the 40 % area between the ceiling panels acts almost as 100 % absorptive area. In the concert mode, with the ceiling in its highest position, all this absorption is disconnected from the hall by closing it off. The advantage of this solution is that less energy is lost in the theatre mode, but the range in reverberation time is somewhat reduced.

The final step in development was made in theatre *De Spiegel* in Zwolle (NL, 2006). Based on the experience with good and intimate theatres for natural speech like in The Hague (as described in chapter 2 and 3), this hall was designed as compact as possible. Contrary to the previous halls, in this case the start of the design was not the concert hall, but a small theatre with 850 seats of approximately 3,500 m3. It has 2 horseshoe shaped balconies, and an average room depth of 18m and a maximum room width of 20 m. Although the amount of seats (850) is higher than in the example of the theatre in The Hague (675), theatre *De Spiegel* can still be considered an intimate theatre, as is illustrated in figure 13 and 14.

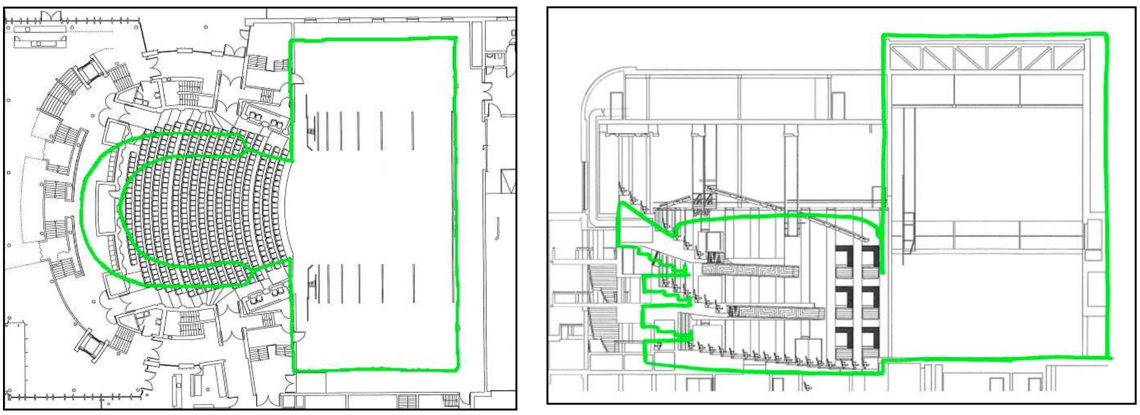

Figure 13, 14. Plan (ground floor) and cross section of theatre *De Spiegel in Zwolle* in theatre mode, with schematic lines (green) of plan and cross-section of the theatre in The Hague.

In these figures the plan and cross-section of *De Spiegel* are drawn, together with the schematic plan and cross-section of the theatre in The Hague. The ceiling in theatre mode is as low as possible: approximately 12 metres, mainly determined by the position of the light bridges. The width of the stage opening can be adapted from 18 to 14m width using turnable side-boxes, that also adapt the width of the hall to a smaller stage opening. In figure 15 and 16 the effective acoustical volume of the theatre in the theatre mode is illustrated (red area).

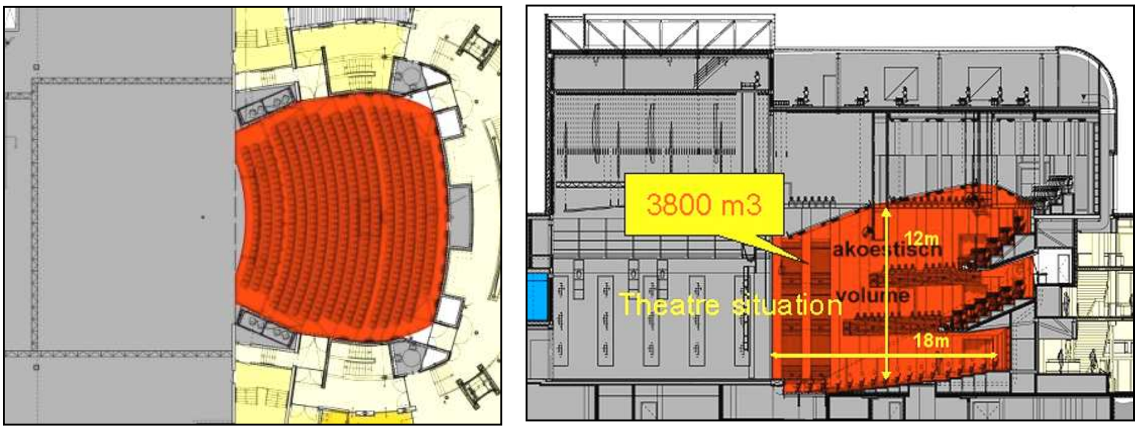

Figure 15, 16. Plan and cross section intimate theatre for natural speech *De Spiegel in Zwolle* (V=3,800 – 10,800 m^3), in theatre mode.

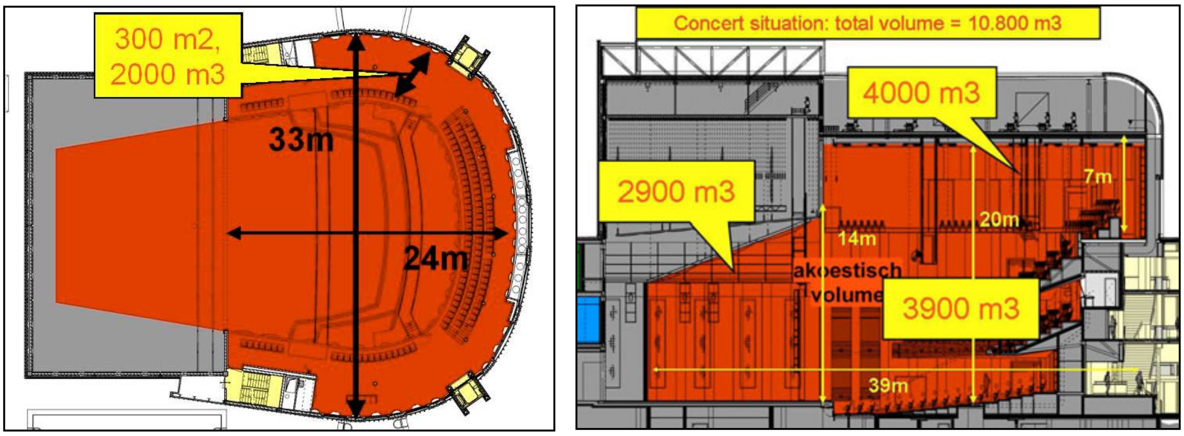

Figure 17, 18. Plan (gallery-level) and cross section of theatre *De Spiegel in Zwolle* in concert mode (V=10,800 m^3).

To create the hall for symphonic music, this ceiling can be set at 20 metres height and in this situation an extra volume of over 4,000 m^3 is added to the hall as a kind of gallery with an additional 150 seats. This added volume using a gallery was based on experiences from the Royal Albert Hall project as consulted by Peutz. In figure 17 and 18 a plan of the gallery level and a cross-section of the hall in the concert mode are presented, together with several dimensions and acoustic volume (red area).
Including the installation of an orchestra shell a total volume of 11,000 m^3 is created in this theatre in Zwolle, a factor three over the theatre mode. This concept was extensively tested in the design phase using scale model research[1]. Measurement results reveal its interesting properties, that fulfill the goals set: The range in reverberation time is from just under 1 second to 2 seconds without compromise to the strength of the sound in the theatre mode. G-values are +6 dB in concert mode, and +3 to +4 dB in theater mode (with omni-directional source in the middle of the stage opening). Average clarity $C_{80}(3)$ values range from 0 dB for concert use to +7 dB for theatre.

The design process and conception of this new theatre in Zwolle are described in English in the book "*De Spiegel: Theatre architecture as a mirror of experience*"[9]. The acoustics realized in this theatre are described in several previous papers[1,2]. Since its opening this new concept for variable acoustics has inspired others for similar projects abroad.

We feel that the development towards the creation of multi purpose theatres with acceptable acoustics for a wide range of performances, which began some 30 years ago, has reached a (temporary) final point in Zwolle. These days, virtually no concessions are made to acoustic quality for natural speech and quality for symphonic music. In the past it was often said that a multi purpose theatre was a no purpose theatre. But with sound variable acoustics it has proven to be possible to create multi purpose theatres, without compromises.

5 REFERENCES

1. M. Luykx, R. Metkemeijer, The new theatre in Zwolle (NL): Acoustical design and scale model study. Proceedings of the Institute of Acoustics **28**. Pt.2 (2006).
2. M. Luykx, R. Metkemeijer, M. Vercammen. Variable acoustics of theatre De Spiegel in Zwolle (NL): Proceedings of the I.S.R.A, Sevilla, 2007;
3. L. Beranek, Concert Halls and opera houses, Music, Acoustics and Architecture. 2nd Edition, 2004, Springer-Verlag New York Inc.
4. Speech information and speech intelligibility, V.M.A. Peutz, AES Convention 1988.
5. Designing sound systems for speech intelligibility, V.M.A. Peutz, AES Convention 1974.
6. What you specify is what you get (part 1), J.v.d.Werff e.a, 114th AES convention 2003.
7. What you specify is what you get (part 2), J.v.d.Werff e.a, 114th AES convention 2003.
8. Houtgast T, Steeneken HJM, Plomp R. Predicting Speech Intelligibility in Rooms from the Modulation Transfer Function. I. General Room Acoustics. Acustica 1980;46:60- 72.
9. Hilde de Haan, De Spiegel, theatre architecture as a mirror of experience. ", Architectura & natura Press, Amsterdam 2007, ISBN 978 90 7686 353 5.
10. Behaviour of loudspeaker sound in autotunnels. J.v.d. Werf, 90th AES convention 1991.
11. Speech-intelligibility and room-size. R.A. Metkemeijer, journal of the NAG 81 (1986).