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Room acoustics and performance practice in two Renaissance theatres in Northern Italy

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Room acoustics and performance practice in two Renaissance theatres in Northern Italy
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Abstract

The Teatro Olimpico in Vicenza and the Teatro all'Antica in Sabbioneta, which were constructed in the late XVI Century in northern Italy, particularly influence the development of scenic theatrical architecture, carrying a new dimension to the theatrical history. Some researches in acoustical view are already investigated, highlighting the deficiency that the room acoustical condition could not correspond to modern standards of speech intelligibility. However, it could be shown that speech intelligibility was sufficient for the time when the theatres were built (Weinzierl et al., 2015).

This thesis aims to prove the possibility that the place of the musicians might have been behind the stage instead of on the stage, in order to balance the effect of music and speech. Room acoustical measurements were implemented at the place according to ISO 3382-1 standard. Computer models of the two theatres with the absorption coefficients closed to the results from the measurement were implied for simulations.

For the simulations based on computer models, loudspeakers were set up behind the stage, comparing to the sound source at the center on the stage. A number of acoustic parameters were calculated for the assessment of the balance of musicians and speakers.

Zusammenfassung

Das Teatro Olimpico in Vicenza und das Teatro all'Antica in Sabbioneta, die im späten 16. Jahrhundert errichtet wurden, hatten einen starken Einfluss auf die weitere Entwicklung der Theaterarchitektur. Sie brachten eine neue Dimension in die Theatergeschichte. Bisherige Studien hinsichtlich der Raumakustik der Theater zeigten, dass die Sprachverständlichkeit zwar nicht dem Standard moderner Theater entspricht, den Anforderungen zur Zeit der Errichtung der Theater aber genügten (Weinzierl et al., 2015).

In der vorliegenden Arbeit wird untersucht ob die Musiker sich bei Aufführungen hinter der Bühne statt auf der Bühne befunden haben könnten um somit das Verhältnis von Sprache und Musik im Zuschauerraum auszugleichen. Raumakustische Messungen wurden vor Ort gemäss ISO 3382-1 Standard durchgeführt. Um anhand von Computermodellen Simulationen durchzuführen wurden vereinfachte Rekonstruktionen der Theater erstellt. wobei eine hinreichende Annäherung an die Messergebnisse angestrebt wurde.

Die Simulationen auf Basis von Computermodellen wurden zunächst mit einer Schallquelle in der Mitte der Bühne und weiteren Schallquellen hinter der Bühne, und anschliessend mit sämtlichen Schallquellen auf der Bühne durchgeführt. Weiterhin wurde eine Reihe akustischer Parameter zur Beurteilung der Balance zwischen Musikern und Sprechern berechnet.

Acknowlegdements

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ACRONYMS

dB decibel

V Volume

T Reverberation time

G Sound strength

C_{80} Clarity

D_{50} Definition

STI Speech transmission index

RASTI Rapid STI

SNR Sound to noise ratio

JND Just noticeable difference

1 Introduction

Room acoustic deals with the sound behavior in an enclosure space. By means of objective acoustic parameters the properties of room acoustic can be assessed and predicted. Computer modelling of room acoustics develops rapid in the recent years. It is more and more applied due to the efficiency and accuracy.

The department of audiocommunication an the Technical University Berlin has been carried out the project 'Die Akustik historischer Aufführungsräume für Musik und Theater' (The acoustics of historical performance spaces for music and theatre), which has been financed by Sonderforschungsbereich 644, Gerda Henkel Stiftung and the Deutsche Forschungsgemeinschaft (DFG) from 2013. The project deals with the acoustics of historical performance spaces for music and theatres in the connection with these performance functions, musical and theatrical performance practices and the instruments of the early days. The research area covers the preserved theatrical and musical performance spaces, whose slope were from new type of performance space emerged in 1550 s, namely monody, early opera, chamber opera, concert, to the performance spaces for public concert life in the 18th and 19th centuries, as well as some other places, which were used for ephemeral performance, such as city room (Piazza).

The theatres in 16th Century has been playing a significant roll in the history of theatrical architecture. One of the most representative masterpieces among them is the Teatro Olimpico in Vicenza designed by Andrea Palladio, which was completed in 1595. After the death of Palladio, the architect Vincenzo Scamozzi took over the project of Teatro Olimpico, who inserted the perspective scenery on the stage. This inspiration continued to influence on the design of the Teatro all'Antica in Sabbioneta, which was commissioned by Duke Vespasiano I Gonzaga.

These heritages as an important legacy of the Renaissance should be preserved and investigated. The measurement in unoccupied condition was conducted by Prodi and Pompoli (Prodi and Pompoli, 2000). Furthermore, occupied and unoccupied conditions were investigated by Weinzierl (Weinzierl et al., 2015). The deficiency of the speech intelligibility was revealed with the reverberation time more than two seconds and definition below 0.5 as well as the speech transmission index below 0.6. Commonly that speech intelligibility and symphonic music can not be satisfactory at the same time due to the reverberation time, namely one second for speech and two second for music (Barron, 2009). One possible alternative will be implemented as follow. Orchestra position would be hypothetically designed behind the stage. The diffraction effect is then considered. Two visions of the theatres, namely with the sound source at the center on the stage and behind the stage, are here compared. The in-situ measurements by the position orchestra on the stage were provided by (Weinzierl et al., 2015) and the reconstructions of the models were obtained from Architect.

The thesis is organized as follows: section 2 describes the two theatres; section 3 presents the procedure of the simulation for the theatres; the room acoustic parameters for both theatres in occupied and unoccupied conditions are compared; last but not least in section 4 conclusion and discussion will be presented.

2 Descriptions of the theatres

Generally, the architectural typology of renaissance theaters are inspired by the Vitruvius's theory, who wrote the most influential masterpiece - the ten books on architecture in 30-20 B.C. *Cavea*, *Orchestra Proscenium* and *Loggia* are the main components.

2.1 Teatro Olimpico in Vicenza

In 1555 the olympic academic was established by a circle of artists and intellectuals aiming at renewing the ancient culture of science, technology, literature, arts and architecture. In order to promote scientific and theatrical activities, the architect Andrea Palladio (1508-1580), as the founding member of the academy, was commissioned to design the Teatro Olimpico in Vicenza.

The theatre is considered as the first freestanding roofed theatrical building. However, there is no significant decoration on the outside of the building, it is overwhelming impressive in the inside. The Palladio's design focused on the integration of the components - cavea, orchestra pit, stage and proscenium as a harmonious whole, organized strictly by scale, inspired by Vitruvius (Beyer and Palladio, 1987). The ground plan was a circle with twelve equal portions. The size of the orchestra pit, the width of proscenium, the main tiers and the stage room were set to four equilateral triangles as lines connecting these twelve checkpoints. He combined not only the concept of Vitruvius, but also humanistic principle and the ancient architectural art. The theatre room were for each single spectator the same. The display wall - *scenae frons* (Figure 1) as the most notable component, which was not included in Vitruvius's theatre, consisted column and decorated with niches and statues.

After the death of Palladio in August 1580, the architect Vincenzo Scamozzi was commission to design the backstage scenery. He inserted the perspective street view of Thebes, the ideal city in ancient Greek. At that time the portal of the display wall was enlarged. The main components were not extremely scaled as Palladio's plan.

In its present form, the volume of the Teatro Olimpico is 9400 m^3 including proscenium area. Weinzierl et al. (2015) presented that the half-oval cavea is 34 m in width and 15 in length (from stage front) with twelve rising tiers, each ca. 0.38 m in height and 0.5 m in depth, yielding a seating rake of 37° closed to the loggia where contains 30 columns. 2.35 m below the audience area is the half-elliptical orchestra pit. The stage is 0.95 m above the orchestra pit with nearly 17.5 m length and 5 m width. The proscenium area is 6.7 m in depth and 25 in width, increasing to 13 m in the central highway. The scenae frons is 23 m wide and 15 m high ranging three storeys. The occupancy condition (Prodi and Pompoli, 2000) at the time, when the theatre was just built, was too crowed with 750 occupancy capacity at the audience area, whereas in present only 450.

Figure 1: The view of perspective scenery in the Teatro Olimpico (Vicenza)

2.2 Teatro all'Antica in Sabbioneta

The architect Vincenzo Scamozzi, who designed the background stage of the Teatro Olimpico in Vicenza, was commissioned by the Duke Vespasiano Gonzaga in 1588 to design Teatro all'Antica in Sabbioneta. As a ruler of the city Sabbioneta, Duke Vespasiano Gonzaga was ambient to build his city orienting to Rome. This theatre was opened in 1590.

According to Scamozzi's design, the audience room was as big as the stagehouse. Compared with the Teatro Olimpico, there was no the symbolic *scenae frons* on the stage. Instead, a central street in the middle and wood buildings with lifelike painting were built on the stage. Spectators could see all the street scenery instead of the part view of the perspective scenery in the Teatro Olimpico in Vicenza. The concept of Scamozzi was to create a natural environment (Confurius, 1991). On the side walls in front of the stage covered with frescoes. The ceiling was painted as sky, so that the spectators could feel like in a real opened circumstance, which imitated the unroofed Roman theatres. Most of structure on the stage was damaged in XVIII century. Which remains today is reconstructed according to the sketch of the architect. The stage, as well as the orchestra pit, were rectangle form and in the same square size, which is 11 m length and 6 m width. The cavea was half circle formed with five tiers in the audience area. There were twelve columns in the loggia above the cavea, decorated with olympic God statues above the columns (Figure 2). Due to the hierarchy, the Duke's seat was designed in the loggia, where could glance the central view of the street scenery and the audience below.

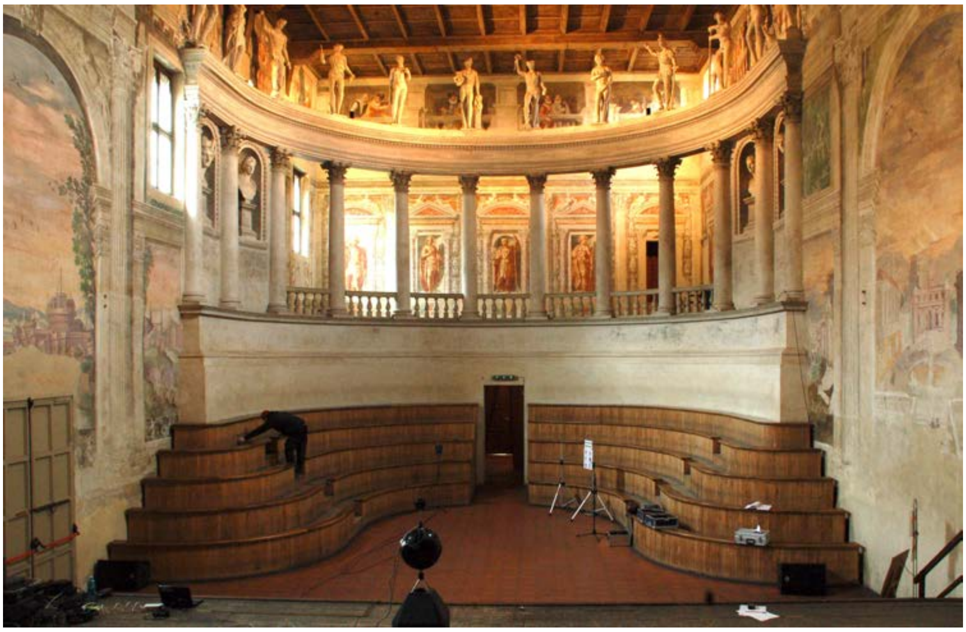

Figure 2: Audience Area for Sabbioneta in current

3 Methodology

The sound waves travel in an enclosed room, consisting direct sound and reflected sound. The direct sound travels directly from the sound source to the receiver, while the reflections are reflected though the floor, walls and ceiling to the receiver. when the receiver place closing to the sound source, the direct sound level is the most part in the total sound level, which is expressed in dB. When the sound source to the receiver distance is twice, the sound level decreases in six dB. At the long distance place from the sound source the reflections dominate. The diffuse field considers that the sound power level at every position are equal. The boundary between the free field and diffuse field are the reverberate radius, where the free field sound power level and the diffuse sound power level are identical. The sound waves travel like light. When the sound waves encounter the finite barriers, the waves with long wavelength can bend around the barriers, which called diffraction. The sound waves at high frequencies with short wavelength travel though the barriers, creating a shadow area. The diffraction is a low frequency phenomenon. Additionally, when the reflected surface is not flat, the sound wave will be scattered, which is like the light scatters by a white paper. The scattering effect is more and more crucial in computer modeling acoustic, but the diffraction is rarely considered. The subjective acoustic parameters can be measured as objective parameters, for instance, loudness can be presented as loudness level. The reverberation time is obviously the most significant parameter. If the reverberation time is long, the early part of sound will be masking by the late part, while if the reverberation time is short, the sound quality will be dry, like in open air. However, the sound quality depends not only on the reverberation time, but also the early fraction proportion in the room impulse response.

As we know, that speech contains in any language vowels and consonants. The level of vowels is commonly higher than the consonants due to the different articulations. The vowels create more low frequency sound energy more while the consonants have more high frequency. In spaces with late reflections and long reverberation time the masking effected will be occurred. When the voice level is louder, there is almost no influence at the low frequencies in the decay of sound power level as well as in the sound pressure level. But the decay at high frequencies will be compensated. The human speakers, loudspeaker and other sound sources can be considered omnidirectional at low frequencies, while at high frequencies the directivity is in diversity. The crucial attribute for speech in rooms was the speech intelligibility besides intimacy and reverberation time (Barron, 2009). In an enclosed room the speech intelligibility is influence by the source to receiver distance, the directivity of sound source, the reflections and last but not least the individual speakers. The early energy fraction, namely D_{50} for speech and C_{50} for music, which is a linear measure, is conceptual easy to predict the quality sound production.

3.1 Acoustic Parameters

Subjective acoustic parameters differs from individual judgement, whereas objective acoustic parameters can assess and predict the acoustic properties of performance space. The sound propagation in a room is an invisibly physical process. Since W.C Sabine in 1920s introduced the reverberation time, it was considered for a long time the most significant parameter for room acoustics. However, even two concert halls with the same reverberation time have different acoustic properties. The room acoustic parameters, which are concentrated here, are described in ISO 3382-1, additionally speech transmission index (STI) as complement according to IEC 60268-16:2003. Aiming at improving the speech intelligibility the following acoustic parameters are chosen. According to ISO 3382-1, the parameters, which are dependent on frequency, are presented as mean value ranging from 500-1000 Hz.

3.1.1 Reverberation Time

The reverberation time is a time duration that presents the sound pressure level decreasing by 60 dB after the sound source is turned off. If the decay values of -5 dB to -35 dB below the initial level, it is described as T_{30} and T_{20}, likewise, presents the decay values of -5 dB to -25 dB (ISO3382-1, 2009).

Apart from deriving from the impulse response, the reverberation time can also be predicted by Sabina Equation:

$$Reverberation\ time\ T = 0.163\frac{V}{A} \tag{1}$$

V represents the volume of the enclosed room and A is the total acoustic absorption. According to the Sabina equation (1) the reverberation time (RT) depends on the volume and the absorption surfaces. When the enclosed room is comparably big, the air attenuation should be taken into account, especially at the high frequencies. The Sabina equation can be presented as:

$$RT = \frac{0.16V}{\sum S\alpha + 4mV} \tag{2}$$

Where m is the air absorption coefficient, which depends on the temperature and humidity of the air.

When the room is highly absorbent, the Eyring equation, which is based on the mean free path between reflections, is applied in Eq. 3.

$$RT = \frac{0.16V}{-S \cdot ln(1-\overline{\alpha})} \tag{3}$$

with:

$$\overline{\alpha} = \frac{1}{S}\sum_i S_i \cdot \alpha_i \tag{4}$$

The reverberation time is dependent on the frequency. The decay of the reverberation time for the most rooms is linear. However, the rooms with coupled spaces, for instance the roman theatres with proscenium, are not in that case.

Generally, an enclosed room can not compromise music and speech at the same time due to the reverberation time. It is often quoted, that optimum values of one second for speech and two seconds for music (Barron, 2009). According to the standard DIN 18041(DIN18041, 2004), the normal reverberation time is dependent on the using type and the volume of the space Fig.3.1.1. The normal reverberation time in occupied condition can be obtain from the equation:

- $Music: T = \left(0.45lg\frac{V}{m^3} + 0.07\right)s$
- $Speech: T = \left(0.37lg\frac{V}{m^3} - 0.14\right)s$
- $Lessons: T = \left(0.32lg\frac{V}{m^3} - 0.17\right)s$
- $Sport1: T = \left(1.27lg\frac{V}{m^3} - 2.49\right)s$
- $Sport2: T = \left(0.95lg\frac{V}{m^3} - 1.74\right)s$

Sport 1 represents the sport- and swim halls without audience for single using purpose of one class or one group, while sport 2 represents the sport- and swim halls without audience for multipurpose of more class or more group (DIN18041, 2004).

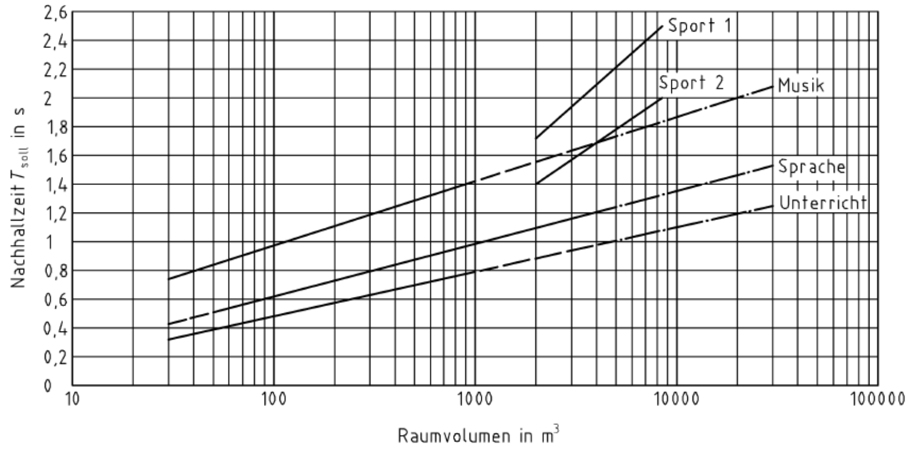

Figure 3: The normal reverberation time depending on the using type and the volume of the space(DIN18041, 2004)

3.1.2 Sound Strength, G

The definition of the sound strength, G, describes a logarithmic ratio of the sound energy of the impulse response measured at the measurement point to that the impulse response measured in a free field at a distance of 10 m sharing the same source (ISO3382-1, 2009).

$$G = \frac{\int_0^\infty p^2(t)dt}{\int_0^\infty p_{10}^2(t)dt} = L_{pE} - L_{pE,10}\ dB \tag{5}$$

where

$p(t)$ is the instantaneous sound pressure of the impulse response measured at the measurement point;

$p_{10}(t)$ is the instantaneous sound pressure of the impulse response measured at a distance of 10 m in a free field;

L_{pE} is the sound pressure exposure level of $p(t)$;

$L_{pE,10}$ is the sound pressure exposure level of $p_{10}(t)$;

When a omnidirectional source is used, the sound strength, G, can be obtained from Equation:

$$G = L_p - L_w + 31\ dB \tag{6}$$

Where L_w is the sound power level of the sound source;

The Eq. 6 means that the sound pressure level is equal to the sound strength, when a omnidirectional source is chosen and overall gain is given by 31 dB.

3.1.3 Clarity

Clarity, C, which represents the quality of symphonic music, is the early to late energy ratio, measured the room impulse response between the source and receiver. The time limit between early to late is set to 0.05 s. The value is as logarithm calculated in Eq. 7 and considered as a linear measure (ISO3382-1, 2009).

$$C_{80} = 10lg\frac{\int_0^{0.08} p^2(t)dt}{\int_{0.08}^{\infty} p^2(t)dt}\ dB \tag{7}$$

3.1.4 Definition

Definition, D, or the early energy fraction represents as well the early to late arriving energy ratio, but for the speech condition. The time limit is to 0.05 s.

$$D_{50} = \frac{\int_0^{0.05} p^2(t)dt}{\int_{0.05}^{\infty} p^2(t)dt} \tag{8}$$

The time limits for clarity and definition was determined by the duration of the speech sounds (Barron, 2009).

3.1.5 Speech Transmission Index, STI

The definition of Speech Transmission Index, STI, in IEC 60268-16 is a metric index ranging between 0 and 1, representing the transmission quality of speech with respect to intelligibility by a speech transmission channel (IEC60268-16, 2003). The room acoustical speech transmission index (RASTI - rapid STI) which is using a condensed version of the STI method, focuses on direct communication between persons without useing an electro-acoustic communication system (IEC60268-16, 2003).

The deterioration of speech signal from sound source such as human speaker or loudspeaker to receiver through a transmission channel can not be avoided due to echoes, noises, reverberation or any other interferences. The STI method calculates modulation transmission indices by means of the modulation transfer function (MTF) of the transmission channel. Sentences, words and phonemes are the fundamental elements of speech. In speech signals, these elements are presented in the temporal fluctuations of the intensity envelope within a certain frequency band. Slow fluctuations correspond with word and sentence boundaries and fast fluctuations correspond with phonemes. The STI test signal is divided into seven octave band ranging from 125-8000 Hz with 14 modulation frequencies at one-third octave intervals ranging from 0.63 Hz to 12.5 Hz.

The modulation transfer function (MTF) is described as

$$m(F) = \frac{1}{\sqrt{1 + \left(2\pi F \frac{T}{13.8}\right)}}^{\frac{1}{1+10^{(-S/N)/10}}} \tag{9}$$

where F is the modulation frequency.

The values of the effective signal-to-noise ratio SNR_{eff} is obtained by

$$SNR_{eff} = 10lg\left(\frac{m(F)}{1 - m(F)}\right) \tag{10}$$

The values of SNR must be limited to the range of -15 dB to +15 dB. The values upper or under the limitations should be replaced by -15 dB or +15 dB.

RASTI is related to SNR:

$$RASTI = (SNR_{eff} + 15)/30 \tag{11}$$

The scale for the evaluation of RASTI or STI is shown in Tab 1.

RASTI value	<0.3	0.3-0.45	0.45-0.60	0.60-0.75	>0.75
Inteligibility	Bad	Poor	Fair	Good	Excellent

Table 1: The scale for the evaluation of RASTI values

3.1.6 Recommended objective acoustic parameters

The recommended objective acoustic parameters can assess and predict the acoustic properties of performance spaces. The objective acoustic parameters can be derived from the impulse response, which is assumed as exponentially delay. The recommended values for objective parameters in unoccupied condition for concert halls are listed in Tab 2 (Gade, 2007) .

Parameters	Symbol	Chamber music	Symphony
Hall size	V/N	2500 m^3 / 300 Seats	25000 m^3 / 2000 seats
Reverberation time	T	1.5 s	2.0-2.4 s
Sound strength	G	10 dB	3 dB
Clarity	C	3 dB	-1 dB

Table 2: The recommended acoustic parameters in unoccupied condition for concert halls

The reverberation time with occupancy should be no more 0.2 s than the recommended reverberation time. For he halls with volume between $2500m^3$ and $25000m^3$ the recommended values can be obtained by interpolation.

The expected sound strength is in accordance with the reverberation time T and the volume V of the performance space, expressed by

$$G_{exp} = 10log_{10}\left(\frac{T}{V}\right) + 45\ dB \tag{12}$$

With the exponential decay, the expected clarity related to reverberation time can be obtain by

$$C_{exp} = 10log_{10}[e^{\frac{1.104}{T}} - 1]dB \tag{13}$$

For the performance spaces with small volume the sound strength is suggested 2 dB less than G_{exp} and clarity 1 dB higher than C_{exp}, while for the large volume halls G should be only 1dB less than or equal to G_{exp} and clarity 2 dB higher than C_{exp}.

3.2 Diffraction Method

Diffraction is an effect created by the presence of one (or more) partial obstacles to wave motion that deform the shape of wave fronts as they pass. Usually plays the diffraction secondary roll in room acoustics due to the lower sound energy comparing to reflections. However, when the source is invisible to receiver, the diffraction should take into account. Pierce deduced the diffraction theory by the means of auxiliary Fresnel functions (Pierce, 1974). The concept of diffraction is clear. The proportion of diffraction energy will be presented below.

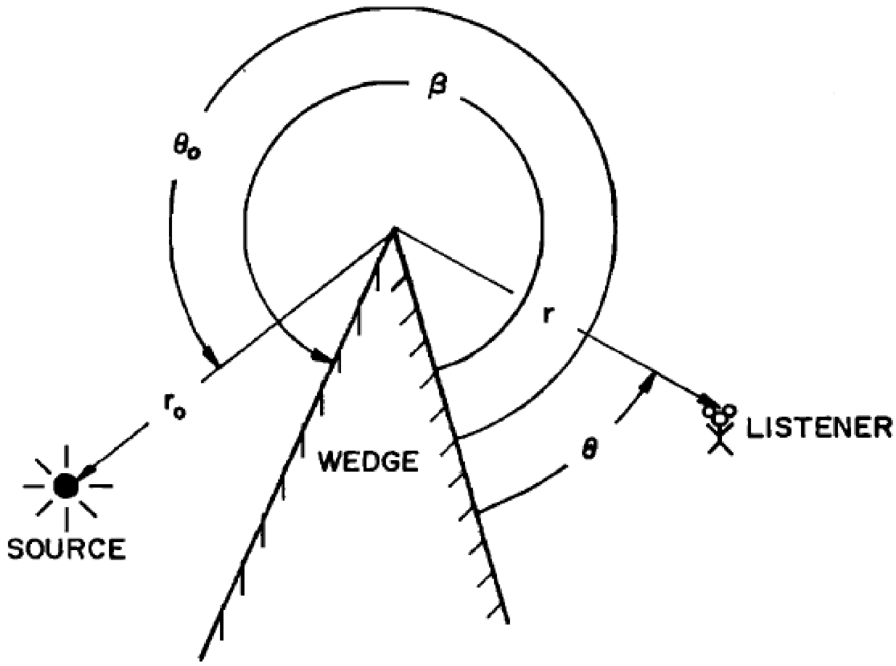

Figure 4: Definition of symbols used in the discussion of sound diffraction by a rigid wedge of exterior angle β (Pierce, 1974)

In the single-edge diffraction situation (Fig. 4) the diffraction sound pressure can be obtained from the Equation

$$\left|\frac{p_{Diffr}}{p_{at\ L}}\right|^2 = \frac{1}{2}\{[f(X_+) + f(X_-)]^2 + [g(X_+) + g(X_-)]^2\} \tag{14}$$

where

L the equivalent distance from source to receiver

f and g auxiliary Fresenel functions

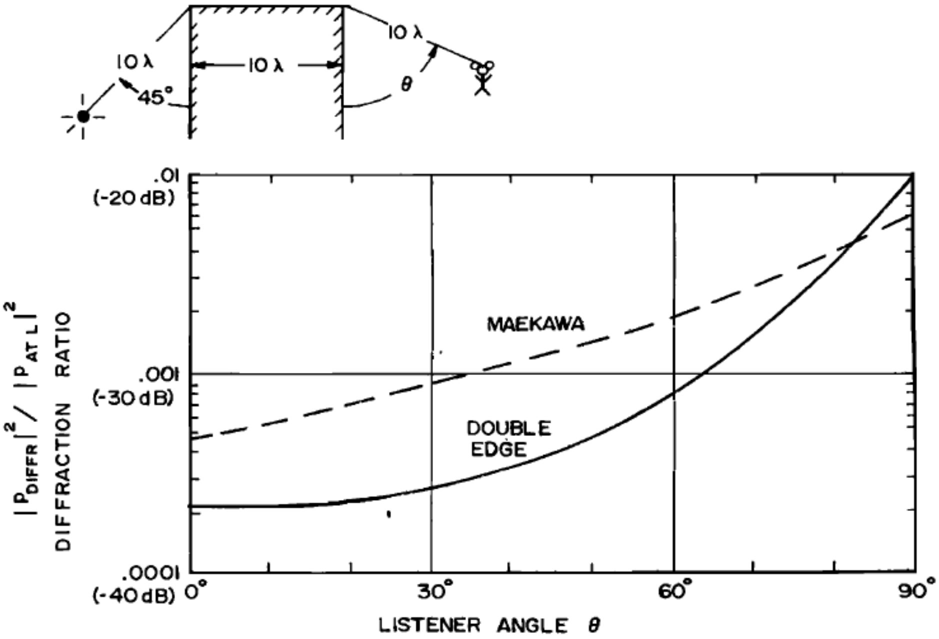

Figure 5: Plot of the ratio of square of diffracted sound pressure amplitude p_{DIFFR} to the square of the amplitued $p_{AT\ L}$ expected at an equivalent distance L from the source in the absence of the barrier. Source and listener locations are as indicated in the sketch with $z_s = z_L$ on the opposite sides of a rectangular three-sided barrier. Computations based on the Maekawa approximation and on the double-edge diffraction theory of the present paper are presented for listener angle θ between $0°$ and $90°$. L represents a distance of $30°$ wavelengths $(10\lambda + 10\lambda + 10\lambda)$ (Pierce, 1974)

In the case of double-edge (Fig. 5) diffraction the corresponding Equation

$$\left|\frac{p_{Diffr}}{p_{at\ L}}\right|^2 = [f^2(Y_>) + g^2(Y_>)][f^2(BY_<) + g^2(BY_<)] \tag{15}$$

where

B characterizing the barrier width

3.3 Basic algorithms of room acoustics computer simulations

Room acoustics computer simulations are based on geometrical acoustics. There are mainly three methods, namely ray tracing, image sources model and hybird method. Ray tracing counts every particle either direct or reflected, which is propagated from source to receivers and contains the information of time and amplitude, while image source method is based on the image source principle, which is assumed that, the sound paths can be backtraced from the receiver to the source by means of image source (Vorländer, 2007). Hybird method combines ray tracing and image source model.

3.3.1 Ray tracing

The ray tracing method counts the rays, which are radiates from sound source at the same initial time. Every ray contains a certain energy. When the rays hit the walls and reflect, due to the absorption the energy of rays will be reduced. In the same case the energy is as well absorbed by air. Air attenuation depends on the flight distances and the attenuation coefficient. There is a detector, which can count the rays within truncation criterion. The attributes of rays, the energy, arrival time, the direction of incidence, will be stored in a histogram of an impulse response with a certain temporal interval at each detection.

There are two ray tracing method. One method calculates the energy by means of multiplying the factor $(1-\alpha)$. The maximum time duration t_{max} and the minimum energy e_{min} should be defined. The detector keeps counting until each of the criterion is reached, the procedure of tracing should stop. The other method is the stochastic annihilation. Apart from t_{max} and e_{min}, a random number $z \in (0,1)$ is chosen to compare the absorption coefficient α. If $z < \alpha$, the rays are vanish and next rays are traced. Generally, the first method is more accurate and the latter one is more fast for computation. Which method should be chosen depends on the purpose of simulation. In the case of auralization, the stochastic annihilation can predict the acoustic parameters of a room quickly. Because a real time capability is provided, even for a large room. Then the stochastic annihilation is recommended.

3.3.2 Image sources model

The image-source model (ISM) are widely used in the fields of acoustic and engineering in the past few decades due to conceptual simplicity. This ISM approach describes the reflections from a source to a receiver, which are reflected at a plane, as radiated from an image source.

An image source is created by mirroring from the original sources and each image source continually mirrored to create higher order image sources until a certain maximum order of image sources is reached (Allen and Berkley, 1979). The energy decay can be predicted by means of simulating the impulse response in enclosures (Lehmann and Johansson, 2008).The reflections are dependent on the distance from the source to receiver, the energy of source and the property of the surfaces. A Cartesian coordinate system with coordinates (x,y,z) is used.

$$p_s = [x_s, y_s, z_s]^T$$

$$p_r = [x_r, y_r, z_r]^T$$

$$r = [L_x, L_y, L_z]^T$$

where

p_s the position vectors of a source

p_r the position vectors of a receiver

r the vector of room dimensions with length L_x, width L_y and height L_z

$[\cdot]^T$ the matrix transpose operator

The property of the surfaces corresponds with a sound reflection coefficient β, which is related to the absorption coefficient α:

$$\alpha = 1 - \beta^2 \tag{16}$$

$$\beta = \begin{bmatrix} \beta_{x,1} & \beta_{x,2} \\ \beta_{y,1} & \beta_{y,2} \\ \beta_{z,1} & \beta_{z,2} \end{bmatrix} \tag{17}$$

where It is assumed that the reflection coefficients β are angle independent but frequency dependent. The subindex 1 refers to the wall closest to the origin.

The room impulse response (RIR) can be obtained:

$$h(t) = \sum_{u=0}^{1} \sum_{l=-\infty}^{\infty} A(\boldsymbol{u}, \boldsymbol{l}) \cdot \delta[t - \tau(\boldsymbol{u}, \boldsymbol{l})] \tag{18}$$

where

t time,

$\delta(\cdot)$ the Dirac impulse function,

$\boldsymbol{u} = (u, v, w)$, $\boldsymbol{l} = (l, m, n)$ parameters controlling the indexing of the image sources in all dimensions.

The attenuation factor $A(\cdot)$ and time delay $\tau(\cdot)$ are defined:

$$A(u,l) = \frac{\beta_{x,1}^{|l-u|}\beta_{x,2}^{|l|}\beta_{y,1}^{|m-v|}\beta_{y,2}^{|m|}\beta_{z,1}^{|n-w|}\beta_{z,2}^{|n|}}{4\pi \cdot d(u,l)} \tag{19}$$

$$\tau(\boldsymbol{u},\boldsymbol{l}) = d(\boldsymbol{u},\boldsymbol{l})/c \tag{20}$$

where

c the sound propagation velocity.

$d(\cdot)$ the distance from the image source to the receiver.

$$\mathbf{d}(\boldsymbol{u},\boldsymbol{l}) = \left\| \begin{matrix} (2u-1)x_s + x_r - 2lL_x \\ (2v-1)y_s + y_r - 2mL_y \\ (2w-1)z_s + x_r - 2nL_z \end{matrix} \right\| \tag{21}$$

where

$||\cdot||$ the Euclidean norm

The number of image sources in the Eq. 18 is increased exponentially according to:

$$2^3(2N+1)^3$$

Where N is the considered order of reflections.

3.3.3 Hybird method

Both ray tracing method and image source method have own advantages and disadvantages.The hybird method combines the ray tracing method and the image source method. One hybird method concept is an audibility test of image sources in the forward detection (Vorländer, 2007). In other words, every image source can be counted only once due to the energetic overlap between rays. The hybird method, which is applied in ODEON (Christensen and Koutsouris, 2013), separates the order of reflections using ray tracing method and image model method. Firstly, a transition order (TO) is selected. The early reflections below the selected TO are calculated by combination of image source method and early scattering rays. Other reflections are calculated according to the ray tracing method along with scattering. From monaural information to binaural representation of the reflection applies by Head Related Transfer Function (HRTF), each reflection is represented by left and right canal elements, convolving with FIR filters in range from 63 Hz to 16 kHz octave bands. So that we can obtain binaural room impulse responses.

3.4 Computer modelling of room acoustics

The benefits of computer modelling of room acoustics are obviously. Compared to room acoustic scale model computer modelling is more user-friendly, more accurate and, last but not least, cheaper (Vorländer, 2007). The problem by computer modelling is that which kinds of model should be chosen to apply. The model with high geometrical fidelity does not support the high frequency methods, while the simplified model might not practice good acoustical behaviour. Shinokawa and Rindel (Rindel et al., 1999) proved that in the case of concert hall the simplified model, that simplifies the platform of computer simulation model with high geometrical fidelity, whether including the audience area or not, is mostly suitable for acoustical simulation. The basic principal to simply a model is that the reflecting surfaces in model should large enough compared to the wavelengths (Vorländer, 2007).

4 Simulation

For the simulation of the occupied case and the unoccupied case are calculated in computer models. The original models are constructed by Architect. The models of the architectural aspects are in details, including every interior construction, even the decoration, as well as exterior facades. However, from room acoustical aspect, using this kind of model takes excessive time for calculating. The first step of simulation is to simplify the models. The complexity of the models should be low. Furniture and decoration must be abandoned. Curved surfaces are replaced simply by flat surfaces. All the simplifications were complemented by CAD software SketchUp. Layers were defined according to the types of absorption were. A SketchUp plugin - $CleanUp$[3] is here recommended. Redundancy geometry can be partly automatically reduced. The attempts decrease the surfaces of model for Teatro Olimpico in Vicenza (Vicenza) from 1,984,980 to 678, for Teatro All'Antica in Sabbioneta (Sabbioneta) from 63,713 to 645 (Tab.3). Therefore, the calculations in acoustic software could be made faster.

	Surfaces		Edges	
	Before	After	Before	After
Sabbioneta	63,713	645	205,280	1635
Vicenza	1,984,980	678	3,269,875	2,617

Table 3: Simplification for the Models of the two theatros

The measurement for Vizenca and Sabbioneta were already conducted by Weinzierl and Büttner (Weinzierl et al., 2015). Here the measured reverberation time as reference was used for the adjustment of absorption coefficient of residual surfaces. To determine the sound absorption coefficients for the residual surfaces in both theatres, in initial calculation the residual surfaces would roughly set up and subsequently adjusted until the average reverberation time T_{30} at all the receiver positions were almost equal to the measured value. The scattering coefficients were not considered.

The simplified model for Vicenza contains simplified platform and audience area (Fig. 6), while only the platform was simplified for Sabbioneta (Fig. 7).

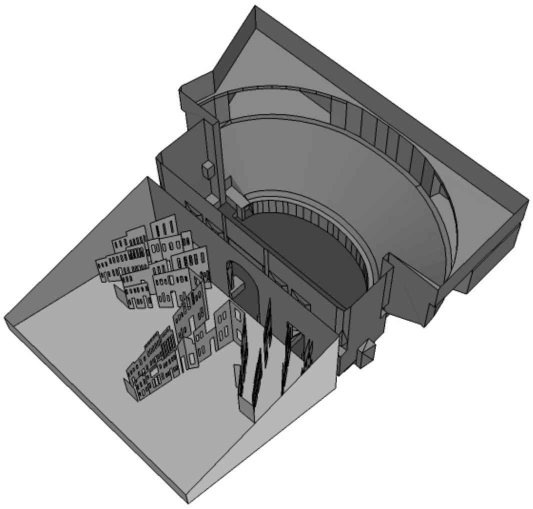

Figure 6: 3-D view of the room acoustical model for Teatro Olimpico in Vicenza

Material	125	250	500	1000	2000	4000
Stein Glatt Mod Fit FIES	0,300	0,160	0,105	0,095	0,093	0,090
Holzboden	0,150	0,110	0,100	0,070	0,060	0,070
Publikum Holz Fasold	0,190	0,140	0,090	0,060	0,060	0,050
Adjusted Absorption Coefficient	0,06	0,1	0,1	0,18	0,12	0,1
Audience on wooden chairs 1. per. sq. m	0.16	0.24	0.56	0.69	0.81	0.78

Table 4: Absorption coefficients for Vicenza

The inner space volume of Vicenza is 9400 m^3. The Model for Vicenza were divided into two parts. The whole proscenium area including walls, floor and ceiling around were initially set to 10 precent absorption coefficient, meanwhile the surfaces of audience area were set to *Publikum Holz Fasold*, floor was set to *Holzboden* and the other surfaces were set to *Stein Glatt Mod Fit FIES* (Tab.4). The absorption coefficient for the proscenium area kept changing until the reverberation time was equal to the measured reverberation time. The tolerance limit was 10 percent of JND.

The total volume of reconstructive model for Teatro all'Antica, Sabbioneta is approximately 3400 m^3. The surfaces were divided into two mainly group according to the type of absorption factor, which are shown in Tab 4. The absorption coefficient of the surfaces at audience area and stage were set to *wood, 25 mm with airspace* in unoccupied situation. The others

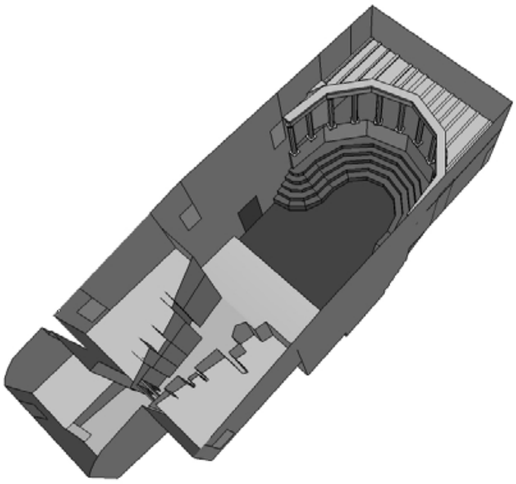

Figure 7: 3-D view of the room acoustical model for Teatro all'Antica Sabbioneta

Material	125	250	500	1000	2000	4000
Wood, 25mm with airspace	0.19	0.14	0.09	0.06	0.06	0.05
Residual Absorption, Type 4	0.16	0.13	0.1	0.09	0.08	0.07
Adjusted residual absorption coefficient	0.125	0.115	0.11	0.115	0.112	0.11

Table 5: Absorption coefficients for Sabbioneta

were initially chosen by *Residual Absorption, Type 4*, which means at least 25 of the side wall surfaces are 0.5 in. gypsum board; floor of stage of wood; floors parquet; some sound absorbing materials used of control echoes; ceiling 0.75 in. (1.8cm) plaster (Beranek, 1995). As same as the procedure for Vicenza residual absorption coefficient was adjusted.

Fig. 8 and Fig. 9 show the sources and receivers positions in the two models in acoustical software ODEON. Only on one-half of the hall were positioned the receivers due to the symmetry of the hall. The number of the receiver positions is depending on the size of the hall.

For the simulations with occupancy of the both theatres, the absorption coefficient of the cavea was assigned by *Audience on wooden chairs 1. per. sq. m.*

There were nine receivers in Vicenza and six receivers in Sabbioneta at 1.2 m above the seating area facing the sound source. The sound sources were at 1.5 m height above the floor. In Vicenza one source was in the centre of the stage and the other one was behind the stage, deviating left. In Sabbioneta there was a source in the centre of the stage and the other

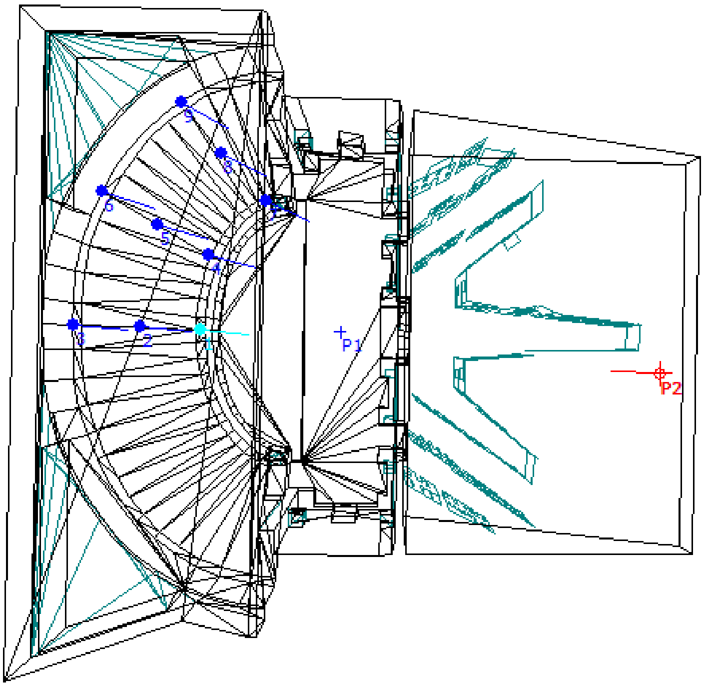

Figure 8: Sources and Receivers positions of ODEON for Vicenza

source was located behind the stage in the middle of the hypothetical orchestra pit (Fig.9). Eight simulations were complemented with each sound sources in occupied or unoccupied conditions.

Tab.6 shows the distance between the sources and receivers positions. For the front three position, R1, R4, R7, the source to receivers distances are nearly three times, while for the behind three receivers, R3, R6, R9, the distances are more than twice. Tab. 7 shows the distances between sources and receivers in model Sabbioneta. The distance to source is more than twice for each receiver, besides receiver 6.

The first several simulation for Sabbioneta were unsatisfactory, because the diffraction portion was not included (Fig. 10). The acoustic simulation software ODOEN provides single-edge diffraction and double-edge diffraction methods. In the case of Teatro All'Antica in Sabbioneta between the behind source to the receivers there were above two edges. The developed model is shown in Fig. 11.

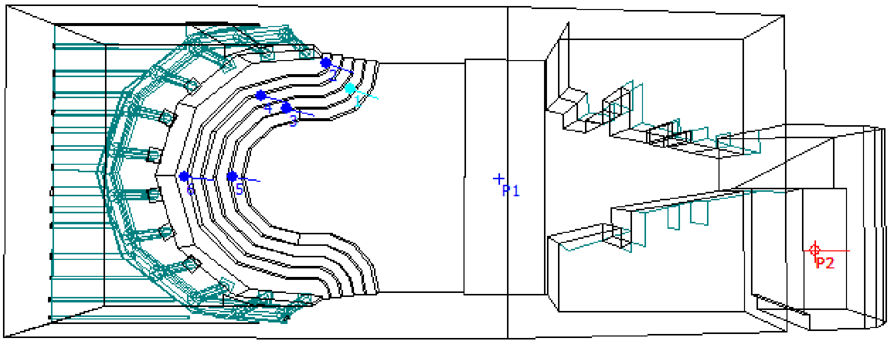

Figure 9: Sources and Receivers positions of ODEON for Sabbioneta

Rn	Distance	
	Center	Behind
R1	8.86	28.85
R2	12.39	31.96
R3	16.14	35.27
R4	9.68	29.21
R5	13.04	32.06
R6	16.59	35.09
R7	9.51	26.90
R8	13.28	30.09
R9	16.86	33.00

Table 6: Distance between sources to receivers in Vicenza

Rn	Distance	
	Center	Behind
R1	8.18	21.92
R2	9.60	23.07
R3	10.55	24.37
R4	11.64	25.30
R5	12.52	26.03
R6	14.50	27.83

Table 7: Distance between sources to receivers in Sabbioneta

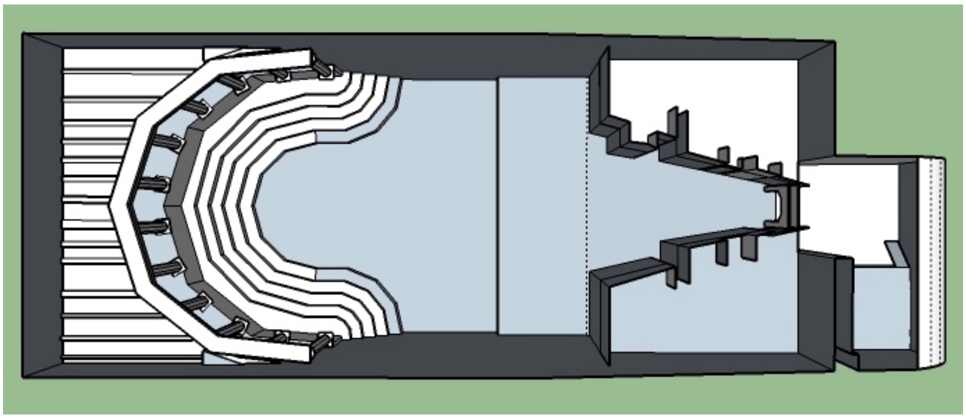

Figure 10: Model for SA without diffraction

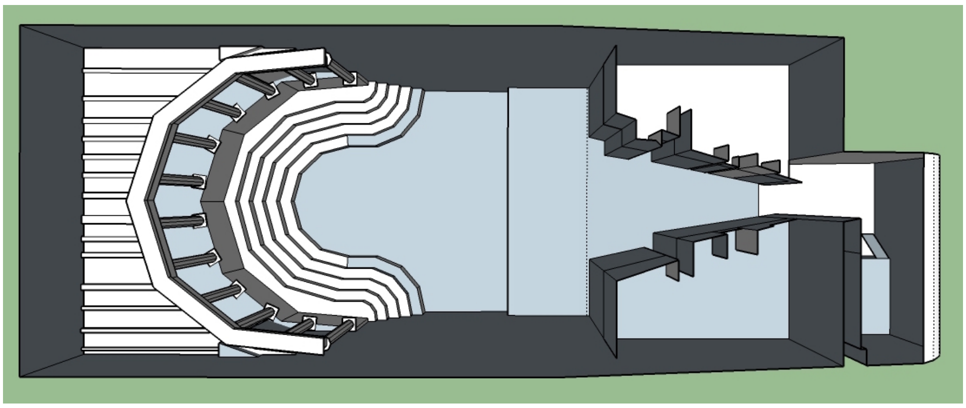

Figure 11: Model for SA with diffraction

Four types of diffraction paths in ODEON (Christensen and Koutsouris, 2013) (Fig. 12).

- a) Odeon detects a 1 point diffraction path over a thin screen.
- b) Odeon detects a 2 point diffraction path over a wide barrier.
- c) Odeon fails to detect a diffraction path because the path from A_n-B_m is obscured by a third surface. In fact it is not a 3 point diffraction path.
- d) Odeon detects a diffraction path over two thin barriers.

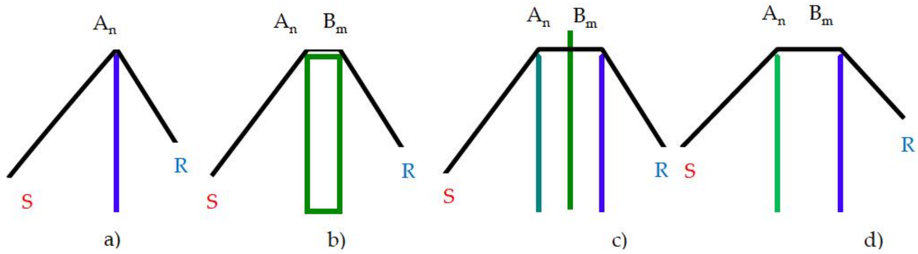

Figure 12: The diffraction paths in ODEON

An additional simulation was investigated to reveal the acoustical effects at the 'Duke's Seat'. Two visions are compared. The source position behind the stage is not considered. With and without the wood ceiling conditions were taken into account. The wood ceiling are not existed in current. Fig.13 and Fig. 14 show the comparison of the different structure of the simulations for the Duke's seat.

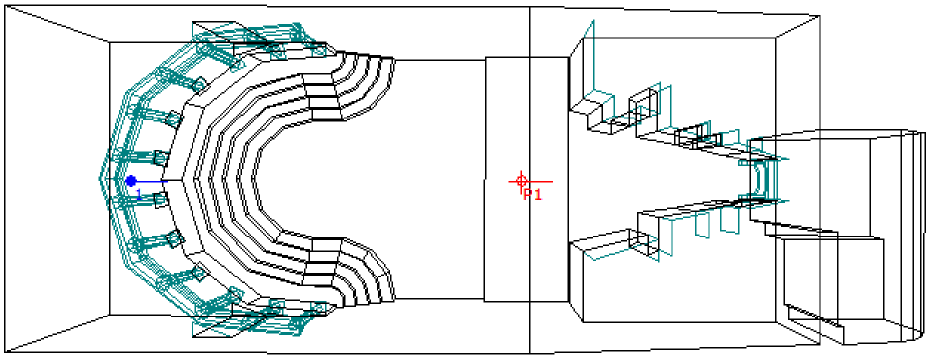

Figure 13: Source and Receiver position for prince seat simulation without second ceiling

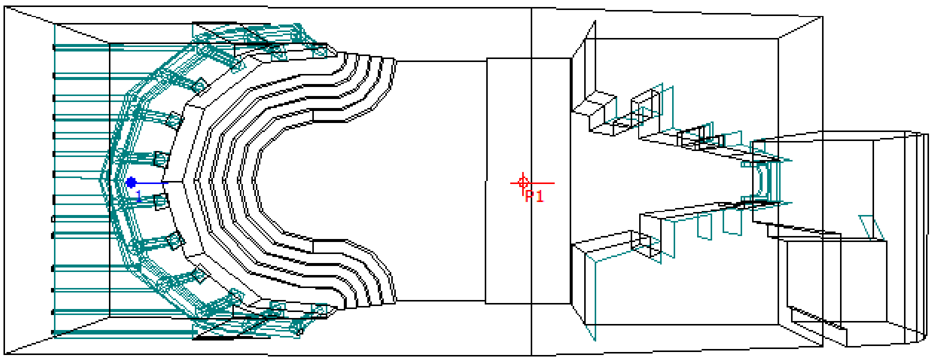

Figure 14: Source and Receiver position for prince seat simulation with second ceiling

For each simulation the following parameters were calculated at the frequency range 125-4000 Hz. Except the simulation for STI, the omnidirectional sources were implied, which were combined overage gain 31 dB. To calculated STI the source with natural effect and background noise was used.

- T_{30} the reverberation time
- D_{50} the Definition index
- C_{80} the Clarity index
- G_{10} the sound strength factor
- STI the speech transmission index

T_{30m},D_{50m},C_{80m},G_{10m} were calculated as the arithmetic average value of the 500-1000 Hz. STI was calculated with background noise at the level 35 dB according to IEC 60268-16:2011.

The STI simulations were implemented according to the application note (Rindel, 2014), which is provided by ODEON. Although the original STI method is based on the modulated speech signal and the modulation transfer function in seven octave bands with 14 modulation frequencies, the procedure of STI in Odeon utilizes indirect method by Schroeder (Schroeder, 1981). The indirect method defines a complex modulation transfer function (CMTF), which is the Fourier Transform of the squared impulse response of a linear passive system. The speech transmission function is calculated by means of the measurement of the CMTF simultaneously at different frequencies.

To simulate the STI values, the source was set to *BB93_RAISED_NATURAL.S08*, which was defined in the calculation guidance to the British Building Bulletin 93 in the situation that teacher to student communication (Rindela et al., 2012). The background noise was set as in Tab. 8, assuming a low frequency noise spectrum with 35 dB.

frequency, Hz	63	125	250	500	1000	2000	4000	8000
Noise, dB	50	39	32	25	20	17	15	14

Table 8: Background noise curve in octave bands for STI simulation

5 Results

The results present the acoustic parameters in octave frequency intervals for the Teatro Olimpico in Vicenza (Vicenza) and the Teatro all'Antica in Sabbioneta (Sabbioneta). The higher frequency revolution will occur fluctuations. The definition of the parameters in details is described in Section 3.

5.1 Vicenza

A comparison of the sources positioning at the center on the stage and behind the stage is presented.

5.1.1 Reverberation Time

The Table 9 shows the simulated reverberation time T_{30} for Vicenza in unoccupied and occupied condition with the sound sources positioning at the center on the stage and behind the stage, and the measurement reverberation time (Weinzierl et al., 2015) as well in the case of the sound source on the stage in unoccupied and occupied condition. It becomes evidence that the reverberation time in simulation and measurement with the sound source on the stage are in agreement. According to DIN 18041 the normal reverberation time for Vicenza with volume 9400 m^3 in occupied condition should be 2.49 s. The simulated reverberation time T_{30} for the source centre the stage or behind the stage are 0.3 s below the normal reverberation time. However, the normal reverberation time for the purpose of speech venues with this volume should be 1.33 s, which is far from the simulated T_{30} values.

5.1.2 Room acoustic parameters

Figure 15 shows the average G over the nine receiver positions ranging from 125-4000 Hz octave intervals for Vicenza with two source positions in unoccupied and occupied conditions. When the source position behind the stage for the unoccupied and occupied case at frequency 1000 Hz the sound strength decrease dramatically and at 2000 Hz increase. The values with the source on the stage is much higher than the values with the source behind the stage, because the

Rn	$T_{30\ unoccupied}$		$T_{30\ occupied}$	
	Centre	Behind	Centre	Behind
R1	3.34	3.38	2.15	2.17
R2	3.33	3.32	2.10	2.18
R3	3.31	3.35	2.06	2.11
R4	3.37	3.33	2.10	2.20
R5	3.35	3.37	2.11	2.17
R6	3.34	3.36	2.10	2.19
R7	3.34	3.34	2.10	2.21
R8	3.35	3.32	2.11	2.19
R9	3.34	3.37	2.11	2.22
Average	3.34	3.35	2.10	2.18
Measured	3.29	2.25	2.28	

Table 9: Reverberation Time T_{30m} for Vicenza in unoccupied and occupied condition with the sound sources positioning at the center on the stage and behind the stage. u-unoccupied, o-occupied, c-the sound source in the centre on the stage, b-the sound source backstage. The measured values are early decay time (EDT_m) (Weinzierl et al., 2015)

sound pressure level decreases 6 dB when the distance between source and receiver is double. With the volume $9400\ m^3$ the expected sound strength value without occupancy should be 10.519 dB as average. The value in unoccupied condition with the sound source on the stage is 10.90 dB, while the value with backstage sound source is 1.90 dB, which is not satisfactory. The sound source backstage could not provide good hearing experience on the audience area.

The differences of values between the sources front and behind become more with higher frequencies. For the simulations of the nine receiver positions four among them, R1, R6, R7, R8, have the diffraction effects and the other five, R2, R3, R4, R5, R9 are not including diffraction. The simulated results of G as average for two groups, which are with diffraction group and without diffraction group, are shown in Tab. 10.

It is obviously that values of G for simulations with diffraction effects is higher than without diffraction effects, especially at low frequencies. Fig 16 shows the average acoustic parameter G for Vicenza in unoccupied condition with the source position behind the stage. It becomes evidence that the differences between the with diffraction and without diffraction are

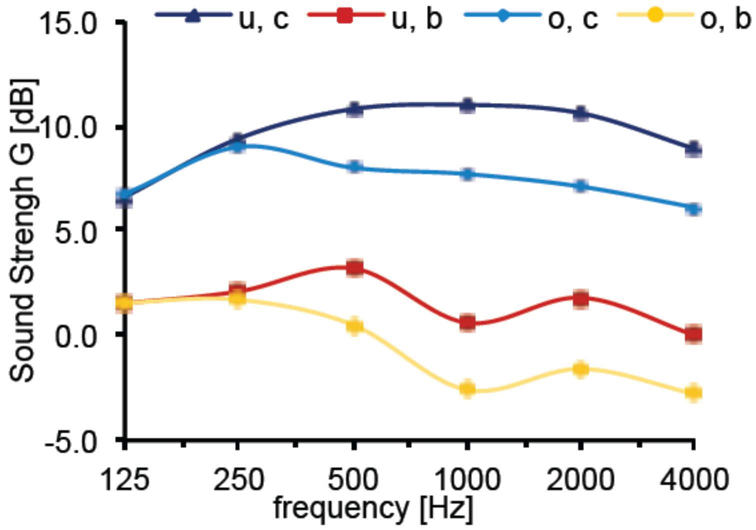

Figure 15: The average acoustic parameter G for Vicenza in unoccupied and occupied condition with the sound source positioning at the center on the stage and behind the stage. u-unoccupied, o-occupied, c-the sound source in the centre on the stage, b-the sound source backstage

in agreement with low frequency phenomenon. Sound waves at low frequency along with lang wavelength should more easily travel across barriers.

The early to late fraction ratio C_{80} and D_{50} are shown in Fig.17 and Fig.18. When the early reflections are not more than 50-80 s, the degree of the direct sound will be influenced by noise or reverberance. The speech loss intelligibility because the low level of consonants are masked by the vowels with high level.

The clarity values decrease from 125-250 Hz in occupied condition and from 125-500 Hz in unoccupied condition, then increase. The clarity with the source on the stage is 2.45 dB more than with the source behind the stage in unoccupied condition and 2.05 dB more in occupied condition (Tab.14 and Tab.15 in Appendix). It means that the source on the stage is heard more clearly than the source behind the stage for symphonic music. The average value with the source behind the stage in unoccupied condition is -4.4 dB, which is not satisfactory comparing to the modern standard.

Fig. 18 shows the Definition, D_{50m} for Vicenza in unoccupied and occupied condition for the source positions in the centre on the stage and behind the stage. To achieve the good speech intelligibility the degree of the definition should above 0.5. Thus, the results of the sound source positioning back the stage are not satisfactory. The patterns of definition are

With diffraction	125	250	500	1000	2000	4000
u, c	6.62	9.40	10.79	10.94	10.54	8.79
u, b	6.70	8.97	8.01	7.68	7.13	6.11
o, c	1.86	2.37	3.47	0.91	2.00	0.22
o, b	1.96	2.01	0.93	-2.07	-1.12	-2.23
Without diffraction						
u, c	6.52	9.33	10.72	10.90	10.52	8.78
u, b	6.60	8.87	7.82	7.49	6.86	5.88
o, c	1.92	2.42	3.50	0.94	2.04	0.26
o, b	1.99	2.01	0.89	-2.13	-1.29	-2.37

Table 10: The average Sound Strength, G, for Vicenza in unoccupied and occupied condition with the sound sources positioning at the center on the stage and behind the stage. R1, R6, R7, R8 are in with diffraction group and R2, R3, R4, R5, R6 are in without diffraction group. u-unoccupied, o-occupied, c-the sound source in the centre on the stage, b-the sound source backstage

similar compared with clarity.

The Tab. 11 is the results of the STI simulation. According to Tab. 1, the STI values in the occupancy condition with the source on the stage at all the receiver positions are fair and in unoccupied condition at five receiver positions are fair and the others are satisfactory. The results are not in the agreement with (Weinzierl et al., 2015) due to the different SIT simulation procedure. However, with the sound source backstage the STI is poor nether in the unoccupied condition or the occupied condition at almost each position. The values with the backstage source at the receiver position R1, R2, R3, which are positioned in the middle of the Cavea, is much more higher than the others. It becomes evidence that STI for the sound source behind stage are not improved but decreased instead.

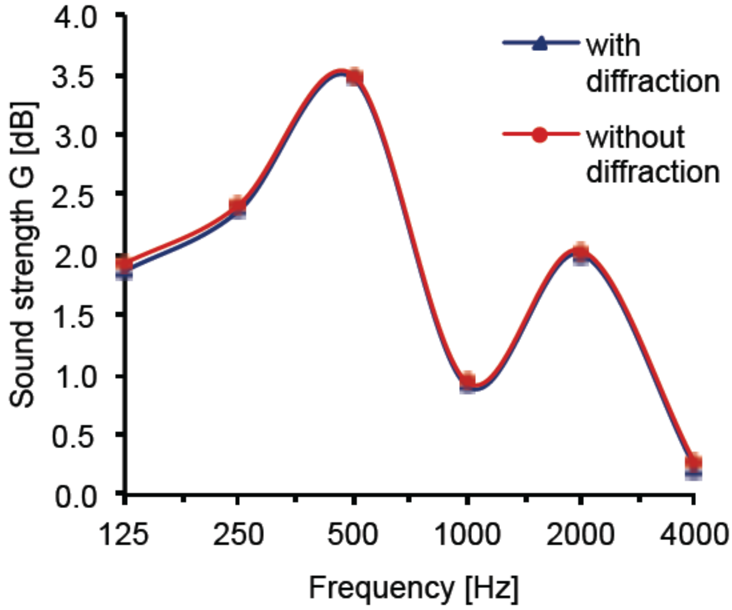

Figure 16: The average acoustic parameter G for Vicenza in unoccupied condition for the source position behind the stage

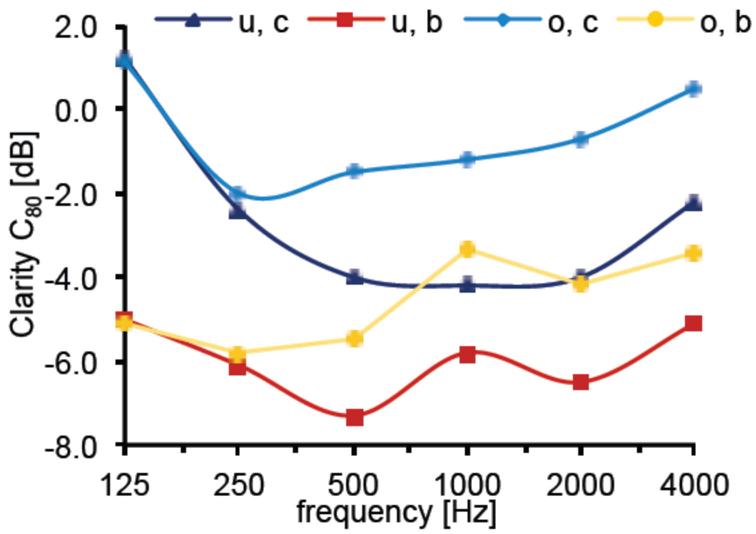

Figure 17: The average acoustic parameter Clarity, C_{80m} for Vicenza in unoccupied and occupied condition for the source positions in the centre on the stage and behind the stage. u-unoccupied, c-centre on the stage, o-occupied, b-behind the stage.

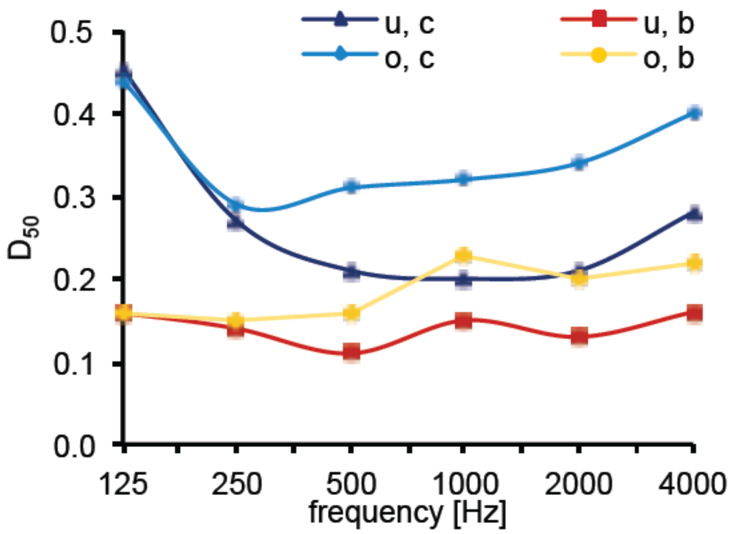

Figure 18: The average acoustic parameter Definition, D_{50m} for Vicenza in unoccupied and occupied condition for the source positions in the centre on the stage and behind the stage. u-unoccupied, c-centre on the stage, o-occupied, b-behind the stage.

Rn	*Centre*		*Behind*	
	Unoccupied	Occupied	Unoccupied	Occupied
R1	0.42	0.51	0.37	0.42
R2	0.46	0.52	0.40	0.46
R3	0.48	0.54	0.35	0.38
R4	0.40	0.50	0.26	0.30
R5	0.41	0.49	0.26	0.29
R6	0.43	0.50	0.24	0.27
R7	0.45	0.54	0.24	0.29
R8	0.46	0.54	0.25	0.27
R9	0.46	0.51	0.23	0.25
Average	0.44	0.52	0.29	0.33

Table 11: STI for Vicenza in each unoccupied and occupied condition

5.2 Sabbioneta

Two versions of the models for Sabbioneta are conducted. One including the diffraction effect is presented and the other take no diffraction effect into account, shown in Appendix A.

5.2.1 Reverberation Time

The Tab.12 shows the reverberation time for Teatro all'Antica in Sabbioneta abbreviated to 'Sabbioneta' in unoccupied and occupied condition.

Rn	$T_{30\ unoccupied}$		$T_{30\ occupied}$	
	Center	Behind	Center	Behind
R1	2.59	2.57	2.10	1.99
R2	2.61	2.58	2.07	2.16
R3	2.56	2.54	2.07	1.99
R4	2.59	2.55	2.06	1.93
R5	2.60	2.52	2.06	1.80
R6	2.55	2.53	2.03	1.52
Average	2.58	2.55	2.06	1.90
Measured	2.4		1.7	

Table 12: Reverberation Time T_{30} for Sabbioneta in each unoccupied and occupied condition including diffraction. u-unoccupied, c-center on the stage, o-occupied, b-behind the stage.

According to the standard DIN 18041 the normal reverberation time for Sabbioneta with volume 3400 m^3 should be 2.28 s. Both unoccupied and occupied condition with the source position center on the stage have nearly 0.3 s more than the normal reverberation, while the other value for the source position behind the stage are almost 0.2 s less than the normal reverberation.

5.2.2 Room acoustic parameters

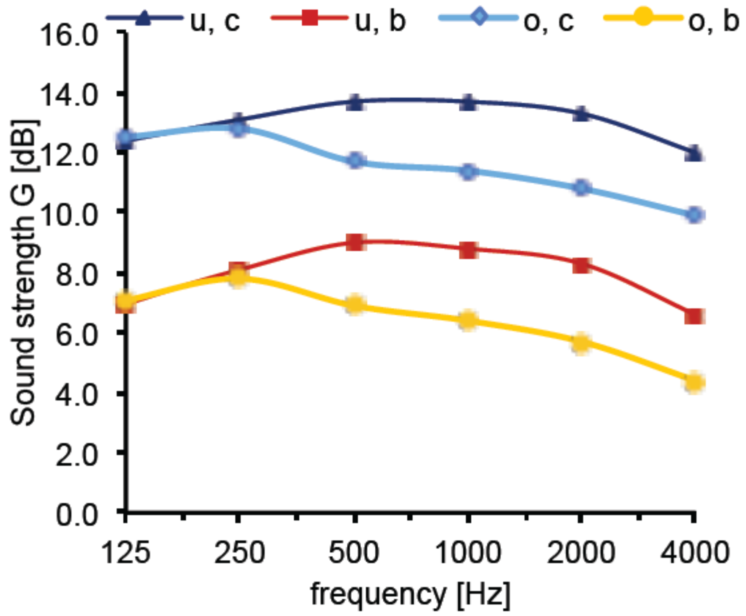

Figure 19: Simulated acoustic parameter G_m for Sabbioneta in each unoccupied and occupied condition. u-unoccupied, c-center on the stage, o-occupied, b-behind the stage.

The Fig. 21 shows the sound strength, G, for Sabbioneta in the both unoccupied and occupied condition with two source position, center on the stage and behind the stage. As we can observe, the trends of patterns between the unoccupied and occupied condition at the frequency ranging 500-4000 Hz are almost the same. Therefore, only unoccupied condition will be considered below. The discrepancy may arise from the absorption coefficient, which is chosen for audience area in occupancy.

The values either for clarity or definition with the source behind the stage are much less than with the source on the stage. The speech intelligibility is not improved when the source is behind the stage.

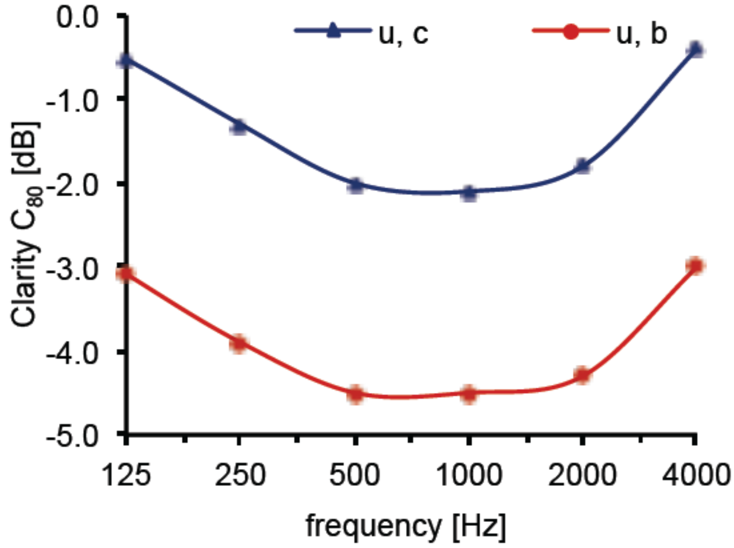

Figure 20: Simulated acoustic parameter C_{80m} for Sabbioneta in unoccupied condition. u-unoccupied, c-center on the stage, b-behind the stage.

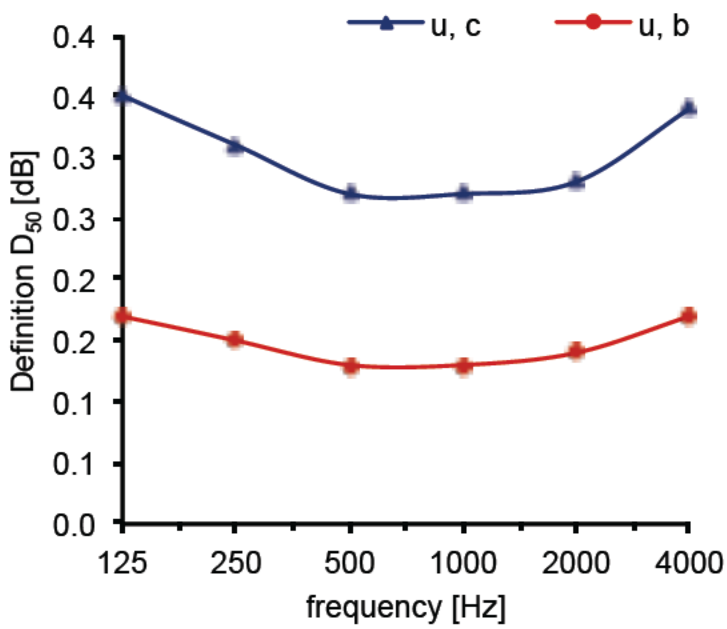

Figure 21: Simulated acoustic parameter D_{50m} for Sabbioneta in each unoccupied and occupied condition. u-unoccupied, c-center on the stage, o-occupied, b-behind the stage.

5.2.3 Duke's seat in Sabbioneta

The loudspeaker at duke's seat are deduced as well in the condition with- and without the second ceiling. The results are presented as grid graphics in below. Although this kind of seat is now not existed.

	T_{30m}	G_m	D_{50m}	C_{80m}	STI
with ceiling	2.53	12.05	0.22	-2.95	0.38
without ceiling	2.68	12.35	0.22	-2.95	0.37

Table 13: Room acoustic parameters of the Teatro all'Antica in Sabbioneta with the sound source on the stage in the unoccupied condition, as derived from simulations with and without ceiling above the duke's seat.

The Tab. 13 presents the room acoustic parameters with the sound source on the stage and receiver position at the duke's seat, as derived from the simulations with and without ceiling above the loggia. The values in the case with and without ceiling are not very different.

In addition, the simulations with grid response, which contained the sound source at the duke's seat, were conducted. The grid responses as result are presented in Appendix B. Due to the hierarchy of the time, when the theatre were constructed, the acoustic effects should be considered relating to the duke's seat.

6 Conclusion and discussion

In order to balance the speech and symphonic music in the two Renaissance theatres in northern Italy, the simulations with the sound sources positioning on the stage and backstage were conducted. In the meanwhile, due to the backstage sound source position the diffraction effect was taken into account. Even though the energy of diffraction is small comparing to the whole sound energy. The extra simulations for Duke's seat were as well investigated.

The good speech intelligibility according to the contemporary standard indicates that the room acoustic parameter definition reaching 0.5 and the speech transmission index above 0.6. Unfortunately the results of the simulations mentioned above could not reach the modern standard. Moreover, the modern recommended reverberation time for speech is 1.0 s or less. The reverberation time T_{30m} for Teatro Olimpico in Vicenza without occupancy and sound source backstage is 3.34 s, which is far from the recommended value. The speech intelligibility was not improved in the simulations for the two theatres. Additionally, with the clarity value lower -5 dB the backstage source is judged that the appropriated hearing experience could be not provided, especially for Teatro Olimpico in Vicenza. In a whole, the speech intelligibility for both theatres is poor to fair and even worse with the backstage source.

However, Weinzierl and Büttner (Weinzierl et al., 2015) pointed out that the acoustic condition was satisfactory at the time when these theatres were built. When considering the cultural context and the performance in the Renaissance period, the two theatres were regarded as appropriate performance spaces.

It is difficult to guaranty the speech intelligibility and symphonic music at the same time due to the different recommended reverberation time for speech and music. Nevertheless the attempt to balance speech and music is meaningful.

The may reason of the unsatisfactory simulated values could be the long distance between the receiver and source, when the source was positioned backstage. For further investigation, the proper position should be identified for orchestra.

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A Acoustical Parameters

R_n	T_{30}		STI		D_{50}		C_{80}		G_{10}	
	U	O	U	O	U	O	U	O	U	O
R1	3.38	2.17	0.37	0.42	0.26	0.37	-3.65	-1.15	3.10	0.70
R2	3.32	2.18	0.40	0.46	0.30	0.44	-2.80	-0.10	3.35	0.70
R3	3.35	2.11	0.35	0.38	0.23	0.29	-4.35	-2.85	3.05	0.60
R4	3.33	2.20	0.26	0.30	0.12	0.18	-6.70	-4.35	2.05	-1.00
R5	3.37	2.17	0.26	0.29	0.11	0.18	-6.80	-4.50	1.55	-1.85
R6	3.36	2.19	0.24	0.27	0.09	0.11	-8.00	-6.45	1.15	-1.85
R7	3.34	2.21	0.24	0.29	0.05	0.10	-8.55	-5.90	1.50	-1.35
R8	3.32	2.19	0.25	0.27	0.04	0.07	-8.55	-6.75	1.00	-2.75
R9	3.37	2.22	0.23	0.25	0.03	0.04	-9.45	-7.80	0.50	-2.50
Average	3.35	2.18	0.29	0.33	0.13	0.20	-6.55	-4.40	1.90	-1.05

Table 14: Room acoustical parameters (average values ranging 500-1000 Hz) in Vicenza for the occupied (O) and unoccupied (U) conditions and the source position behind the stage

R_n	T_{30}		STI		D_{50}		C_{80}		G_{10}	
	U	O	U	O	U	O	U	O	U	O
R1	3.34	2.15	0.42	0.51	0.13	0.25	-5.65	-2.10	11.05	8.05
R2	3.33	2.10	0.46	0.52	0.22	0.31	-4.30	-1.95	10.90	7.40
R3	3.31	2.06	0.48	0.54	0.23	0.33	-4.30	-2.05	10.95	8.15
R4	3.37	2.10	0.40	0.50	0.12	0.25	-5.80	-2.10	10.90	7.70
R5	3.35	2.11	0.41	0.49	0.16	0.27	-5.30	-2.35	10.50	6.85
R6	3.34	2.10	0.43	0.50	0.19	0.29	-4.30	-1.75	10.30	7.45
R7	3.34	2.10	0.45	0.54	0.24	0.39	-3.00	0.25	11.50	9.25
R8	3.35	2.11	0.46	0.54	0.28	0.39	-2.55	0.15	11.10	7.70
R9	3.34	2.11	0.46	0.51	0.28	0.36	-2.00	0.05	10.80	8.05
Average	3.34	2.10	0.44	0.52	0.21	0.32	-4.10	-1.35	10.90	7.85

Table 15: Room acoustical parameters (average values ranging 500-1000 Hz) in Vicenza for the occupied (O) and unoccupied (U) conditions and the source position on the center of the stage

R_n	T_{30}		STI		D_{50}		C_{80}		G_{10}	
	U	O	U	O	U	O	U	O	U	O
R1	2.57	1.56	0.36	0.39	0.12	0.15	-5.15	-4.1	9.00	6.6
R2	2.58	1.52	0.36	0.39	0.13	0.18	-5.20	-3.5	8.70	7.0
R3	2.54	1.52	0.37	0.40	0.10	0.13	-5.65	-4.0	8.75	6.0
R4	2.55	1.51	0.39	0.42	0.11	0.14	-4.80	-3.6	8.75	6.5
R5	2.52	1.51	0.38	0.40	0.14	0.17	-3.95	-3.0	8.90	6.3
R6	2.53	1.49	0.42	0.45	0.20	0.25	-2.40	-1.3	9.25	7.5
Average	2.55	1.52	0.38	0.41	0.13	0.17	-4.50	-3.3	8.90	6.7

Table 16: Room acoustical parameters (average values ranging 500-1000 Hz) in Sabbioneta for the occupied (O) and unoccupied (U) conditions and the source position behind the stage with diffraction effect

R_n	T_{30}		STI		D_{50}		C_{80}		G_{10}	
	U	O	U	O	U	O	U	O	U	O
R1	2.59	2.10	0.37	0.40	0.27	0.34	-2.1	-0.75	14.45	12.55
R2	2.61	2.07	0.38	0.40	0.23	0.30	-2.6	-0.95	14.15	12.60
R3	2.56	2.07	0.37	0.40	0.22	0.26	-2.9	-1.60	13.60	10.90
R4	2.59	2.06	0.37	0.40	0.25	0.33	-2.4	-0.70	13.55	11.35
R5	2.60	2.06	0.38	0.41	0.31	0.34	-1.3	-0.35	13.40	10.70
R6	2.55	2.03	0.42	0.45	0.36	0.46	-0.95	1.00	13.15	11.25
Average	2.58	2.06	0.38	0.41	0.27	0.335	-2.05	-0.55	13.70	11.55

Table 17: Room acoustical parameters (average values ranging 500-1000 Hz) in Sabbioneta for the occupied (O) and unoccupied (U) conditions and the source position on the center of the stage with diffraction effect

Rn	T	STI	D	C	G
R1	2.56	0.40	0.13	-5.00	8.90
R2	2.56	0.39	0.14	-5.15	9.15
R3	2.51	0.36	0.10	-6.10	8.80
R4	2.51	0.38	0.11	-5.10	8.80
R5	2.52	0.36	0.11	-5.10	8.70
R6	2.53	0.38	0.14	-4.10	9.00
Average	2.53	0.38	0.12	-5.1	8.90

Table 18: Room acoustical parameters (average values ranging 500-1000 Hz) in Sabbioneta in the unoccupied (U) conditions and the source position behind the stage without diffraction effect

B Grid response

The grid response for the acoustic parameters, G, D_{50}, C_{80} at 1000 Hz frequency are shown in the following.

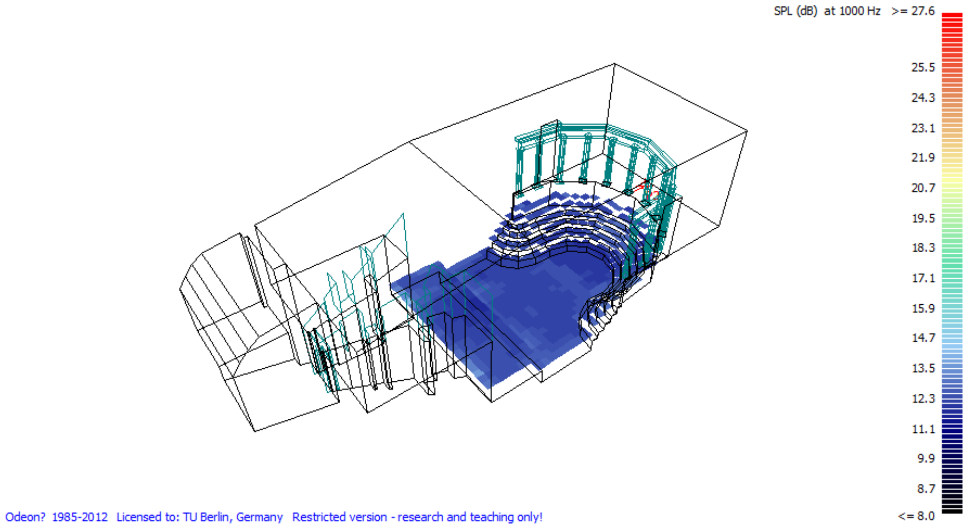

Figure 22: The grid response showing the sound strength (G) at 1000 Hz, source at the duke's seat, 3D model without wood ceiling

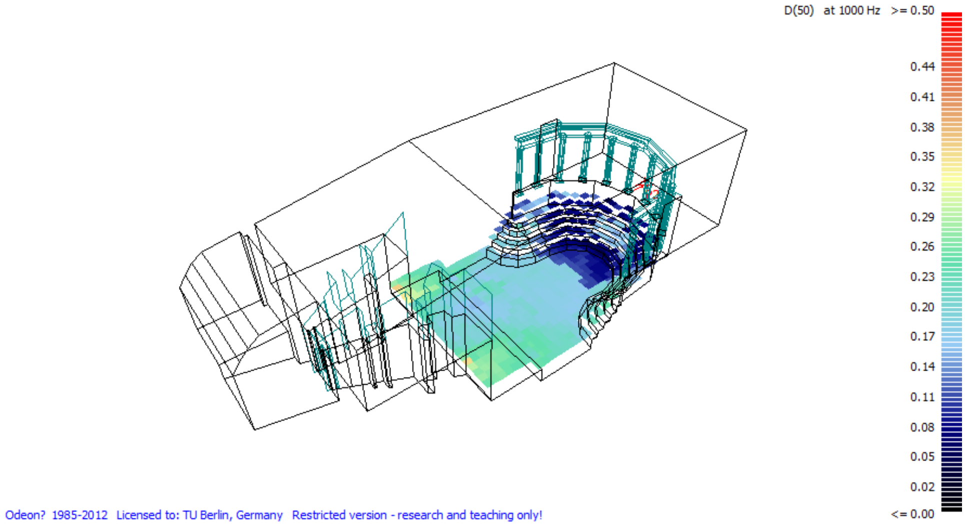

Figure 23: The grid response showing the definition (D_{50}) at 1000 Hz, source at the duke's seat, 3D model without wood ceiling

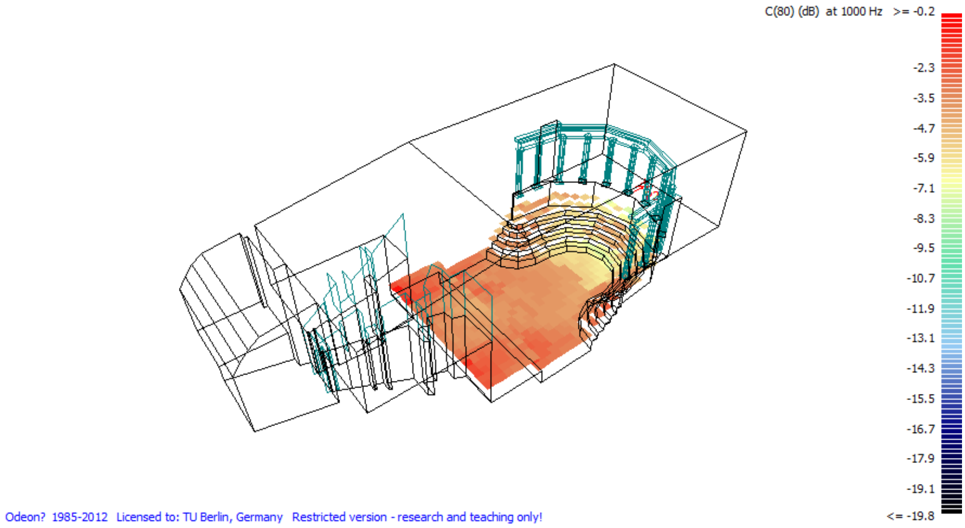

Figure 24: The grid response showing the clarity (C_{80}) at 1000 Hz, source at the duke's seat, 3D model without wood ceiling

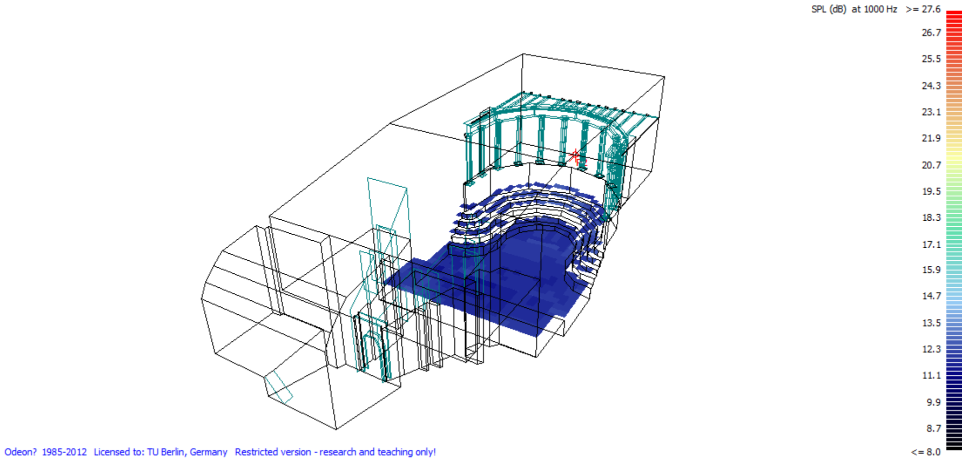

Figure 25: The grid response showing the sound strength (G) at 1000 Hz, source at the duke's seat, 3D model with wood ceiling

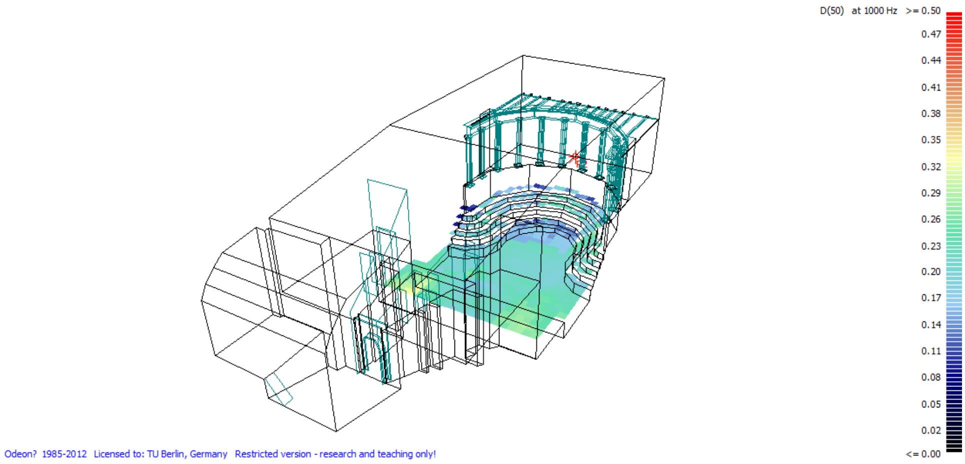

Figure 26: The grid response showing the definition (D_{50}) at 1000 Hz, source at the duke's seat, 3D model with wood ceiling

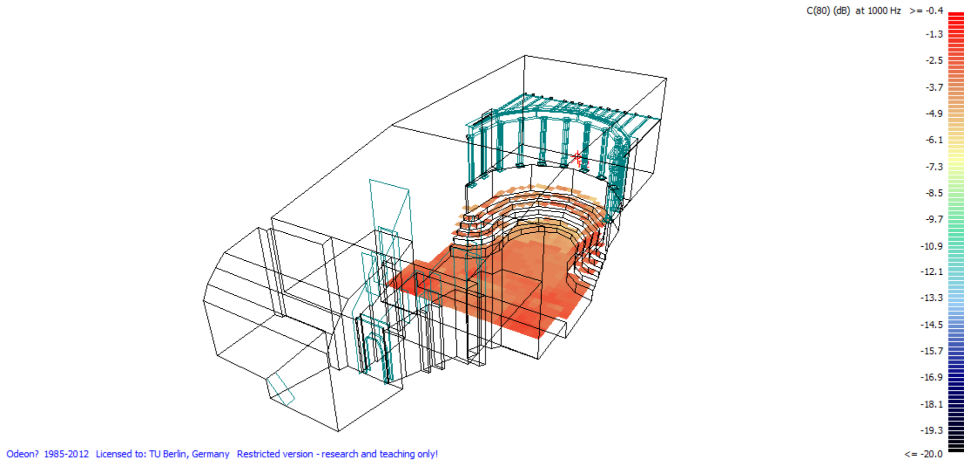

Figure 27: The grid response showing the definition (C_{80}) at 1000 Hz, source at the duke's seat, 3D model with wood ceiling