Universitat Politècnica de València
Escuela Técnica Superior de Ingeniería de Edificación
Camino de Vera Valencia

**Master of Science in Engineering Technology: Construction**

# Evaluating the comfort of the school building of the ETSIE faculty based on an acoustic and thermal study

An analysis made with the appropriate software ODEON and PHPP

Promotors: Dr. Arch. Jaime Llinares Millán
Dr. Carolina Aparicio Fernández

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Marlies Declerck

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## ABSTRACT

The objective of the thesis is to make an analysis of the comfort of the school building at the ETSIE faculty at UPV. This evaluation of comfort will be based on two separate studies. First of all an acoustic study of the Aula Magna at the faculty building. This is an auditorium used for conferences and lectures but also for small concerts. To goal is to measure the acoustic quality parameters and evaluate these parameters with the help of the software program ODEON. Another important analysis in the process of determining the working and studying comfort in the school is to do a thermal study. With the help of the Passive House Planning Package (PHPP), the cooling and heating demand is calculated and these results can be compared to the recommended values for a passive house.

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# PART 1: ACOUSTIC ANALYSIS

## 1. Objective

In the first part of the thesis, an acoustic analysis of the Aula Magna at the school of building engineering (ETSIE) at UPV will be made. As an introduction, several parameter that determine the acoustic quality of a room are explained. For every parameter there are recommended standard values that lead to a good acoustic quality of the room. To compare the values of the parameters in the Aula Magna with the ones that are recommended, measurements are taken in the hall. Finally a 3D model of the Aula Magna will be made and put into the program ODEON. The model inserted in the program has to be adapted so that it represents the real situation as good as possible. Once the model is properly adapted and can be compared to the real life Aula Magna, changes can be made in the program to meet the proper acoustic requirements.

## 2. Parameters

### 2.1 Background noise

Background noise is the noise that originates from activities taking place in adjoining premises, noise from inside the space itself (like noise from the cooling systems, the lights,… ). Or it can be caused by outside noise from traffic or other nearby facilities. So the background noise can be defined as the noise level at a given location and time, measured in the absence of any alleged noise nuisance or sound sources being studied. It is also being referred to as the Ambient or the Residual Noise.

The presence of ambient noise can cause an inability to hear the necessary sounds of the activity that takes place in the measured space. To estimate the degree of interference with the activity, the spectrum can be compared with reference levels. For any kind of activity there is a different level specified. In this case, the criteria are defined by the NC curves.

The Noise Criterion (NC) was established in the U.S. for rating indoor noise, noise from air-conditioning equipment, etc… Loudness curves based on the sound pressure level measurements are used in buildings as reference for various types of activities. The NC - curves were developed by Beranek in 1957 to establish satisfactory conditions for speech intelligibility and general living environments (Fig. 2.1.1)[1].

[1] Marshall Long (2006).*Architectural Acoustics*. California, US: Elsevier Academic Press.

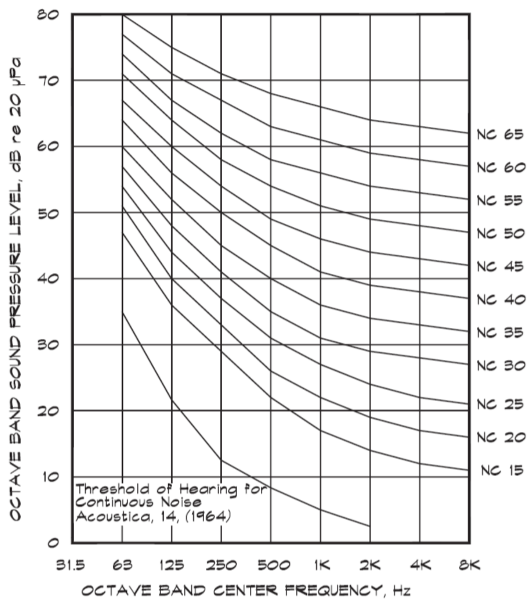



**Fig. 2.1.1**

The recommended NC-values depend on the use of the room. In this case the room can be defined as an auditorium (used for speech and chamber music activities) for which the Noise Criterion level is set at NC-25.

| Noise Criterion | Octave Band Centre Frequency (Hz) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
| | Sound Pressure Levels (dB) | | | | | | | |
| NC-25 | 54 | 44 | 37 | 31 | 27 | 24 | 22 | 21 |

**Table 2.1.1**

On the other hand, there are also the Room Criterion (RC) curves. They have been developed in 1981 by Blazier based a study of heating, ventilating, and air conditioning (HVAC) noise in office environments. They have been developed to replace the NC-curves for rating only air conditioning noise in unoccupied spaces.

In contrary to the NC-curves, the RC curves include the 16Hz and 31,5Hz levels. The interest in these low bands stems from the fact that a level of the order of 70dB or higher may lead to vibrations (induced by the noise) that can be felt by the occupants of a room. Especially when the structure of the room is very light.

The acceptable RC ratings for background noise in rooms as a result of air conditioning are listed in the table below. For this case, that falls under the category schools and lecture rooms, the recommended RC value is 25.

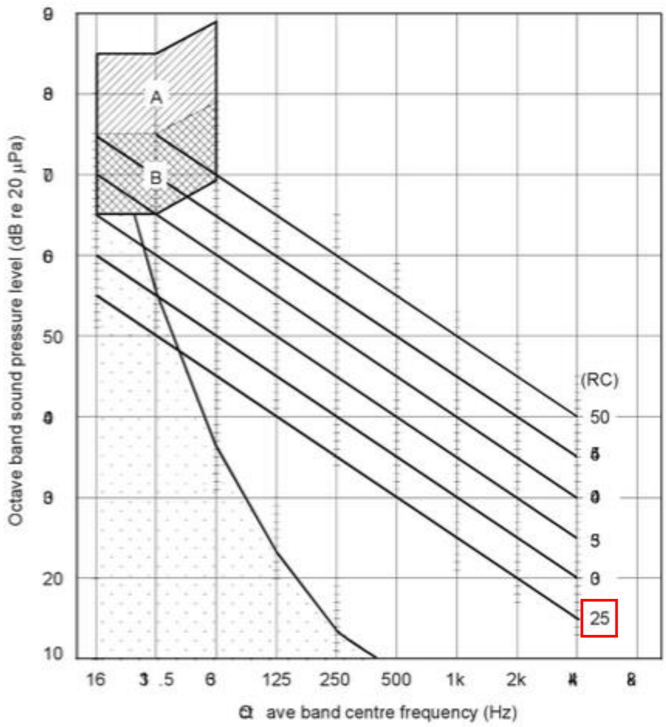



**Fig. 2.1.2**: RC curves; regions A and B – noise induced vibration in the structures.

| Room type | Acceptable RC(N) | Room type | Acceptable RC(N) |
|---|---|---|---|
| Residence | 25-35 | performing arts spaces | 25 |
| Hotel meeting rooms | 25-35 | Music practice rooms | 30-35 |
| Hotel suites | 25-35 | Laboratories | 40-50 |
| Other hotel areas | 35-45 | Churches | 25-35 |
| Offices and conf. rooms | 25-35 | Schools, lecture rooms | 25-30 |
| Building corridors | 40-45 | Libraries | 30-40 |
| Hospitals | | | |
| Private rooms | 25-35 | Indoor stadiums, gyms | 40-50 |
| Wards | 30-40 | Stadium with speech ampl. | 45-55 |
| Operating rooms | 25-35 | Courtrooms (no mics.) | 25-35 |
| Public areas | 30-40 | Courtrooms (speech ampl.) | 30-40 |

**Fig. 2.1.3:** Acceptable RC ratings for varying types of rooms[2]

[2] David A. Bies and Colin H. Hanse (2009). *Engineering Noise Control: Theory and Practice*. New York, US: Taylor & Francis.

## 2.2 Spaces for chamber music

Spaces that are used for playing music can’t be designed without the study of the acoustics. The geometry and dimension, the materials, … are all different properties of a room that have to be taken into account to make the space work as a tool to spread the music.

Therefore the acoustic quality of a space is put in some mathematical formulas: the quality parameters.

### 2.2.1 Intimacy

The sense that one is playing music in a small room is called ‘intimacy’. A room is intimate if there is a sensation that sound is being played in an appropriately sized room, which is mostly characterized in terms of the initial delay gap. The initial delay time, $t_I$ ,is the difference in milliseconds between the arrival time of the strongest reflection, minus the arrival time of the direct sound, at the center of the audience seating area. To create an acoustic intimacy, the interval must be small. The preferred initial delay time has 20 milliseconds as threshold. There should be sound reflections from surfaces that do not have a great path length to the receiver. At the Aula Magna, first reflections are being realised by the installation of a resonator right above the stage where music is played. Still, for a space to be intimate, the direct sound of the performers must have greater presence than reflecting sound.

This parameter is considered to be one of the most important and valued factors in the analysis of musical acoustics.

### 2.2.2 Clarity

The early-to-late-arriving-sound-energy ratio. The clarity factor is the logarithmic ratio of the sound energy arriving before ‘t’, to that arriving after ‘t’. Time ‘t’ can be 50 of 80 ms. It is measured in an unoccupied room.

It is defined as:

$$C_{50} = 10\log\left(\frac{D_{50}}{1-D_{50}}\right)$$

and expressed in dB. The same formula can be used to calculate this parameter over 80 ms.

The values of the C80 can range from small positive numbers, implying a dead room, to small negative values for very reverberant spaces. They fall into a ± 4 dB range. The preferred values of C80 are between 0 and −4 dB.

### 2.2.3 Definition

The D50 parameter (Definition) is the early-to-total-sound-energy ratio. This parameter is defined as the ratio between the energy that reaches the listener during the first 50 ms after the arrival of the direct sound (includes both the direct sound and the first reflection) and the total energy received by the same listener. It indicates the clarity of speech, if the room would have no definition, the sound received would be blurry. The value of this parameter depends on the reflective surfaces inside (first reflection and initial delay gap ) and is that way related to the intimacy of a room.

It is defined as:

$$D_{50} = \frac{\int_0^{0.050s} p^2(t)dt}{\int_0^{\infty} p^2(t)dt}$$

and expressed in percentage. Again, the same can be done for a time of 80ms (D80).

As illustrated by the formula of ‘definition’, the higher the value of D, the better the word intelligibility, the clearer all music/words can be heard by the receiver and the better the loudness.

Receiving a clear sound as listener is more important in spaces that are used primarily for speech. Therefore, this parameter has more significance in these types of rooms. Overall, the value of D50 is recommended to be higher 0,5 for all frequencies[3].

| | |
|---|---|
| **$C_{50}$** | -6,4dB - +1,0dB |
| **$C_{80}$** | -3,2dB - +0,2dB |
| **$D_{50}$** | 0,34 - 0,56 |
| **$t_s$** | > 140ms |

**Table 2.2.1** : Recommended values for C50, C80, D50 and ts defined by J.S. Bradley, L.Cremer and H.A. Müller.[4]

[3] Source: Jaime Llinares, professor UPV – stated by Spanish regulations

### 2.2.4 Reverberation time

Liveliness or reverberation is the most recognizable acoustical parameter associated with halls where music is played. The reverberation time has been a parameter since its discovery by Sabine.

Wallace Clement Sabine was the first one to put the idea, that there is a time for sound to die out in a room, into a formula. This is called the reverberation time which is the time it took for the sound level to drop 60 dB, for varying amounts of absorptive materials.

The empirical formula he discovered, now called the Sabine reverberation time, is:

**Sabine Equation**

$$\boxed{T = K\frac{V}{A}} \; (seconds)$$

$V$ = Room volume in $ft^3$ ($m^3$)

$A$ = "hole" area in $ft^2$ ($m^2$)

$K$ = 0.049 in *secs/ft* (= 0.161 *secs/m*)

$$\text{Reverberation Time, } T = T_{60} = 0.049\left[\frac{V\left(ft^3\right)}{A\left(ft^2\right)}\right] = 0.161\left[\frac{V\left(m^3\right)}{A\left(m^2\right)}\right] \text{ seconds}$$

= time for sound to decay to $10^{-6}$ of its original intensity.

**Fig. 2.2.1:** The Sabine Equation[5]

The value of A is calculated by the next formula:

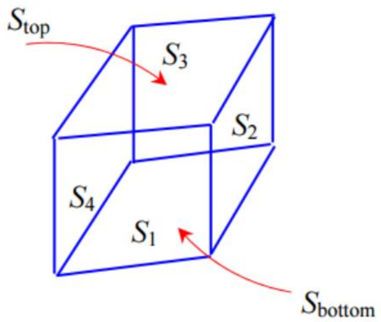
$$A = A_1 + A_2 + A_3 + A_4 + \ldots A_N = \sum_{n=1}^{N} A_n$$

$$= a_1 S_1 + a_2 S_2 + a_3 S_3 + a_4 S_4 + \ldots a_N S_N = \sum_{n=1}^{N} a_n S_n$$

[4] D. Cindrić.(2014) *Acoustics of recording studios and control rooms*. Zagreb. Faculty of electrical engineering and computing.

[5] Professor Steven Errede.( 2002 – 2015). *Acoustical Physics of Music.* Department of Physics, University of Illinois at Urbana-Champaign, Illinois.

- Value of 'S'




Total surface area of room S:

$S = ( S_1 + S_2 + S_3 + S_4 ) + ( S_{top} + S_{bottom} )$

- Value of 'a'

*a* = the absorption coefficient of the material of a specific surface

= $0 \leq a \leq 1$ where: a = 0 if there is no absorption

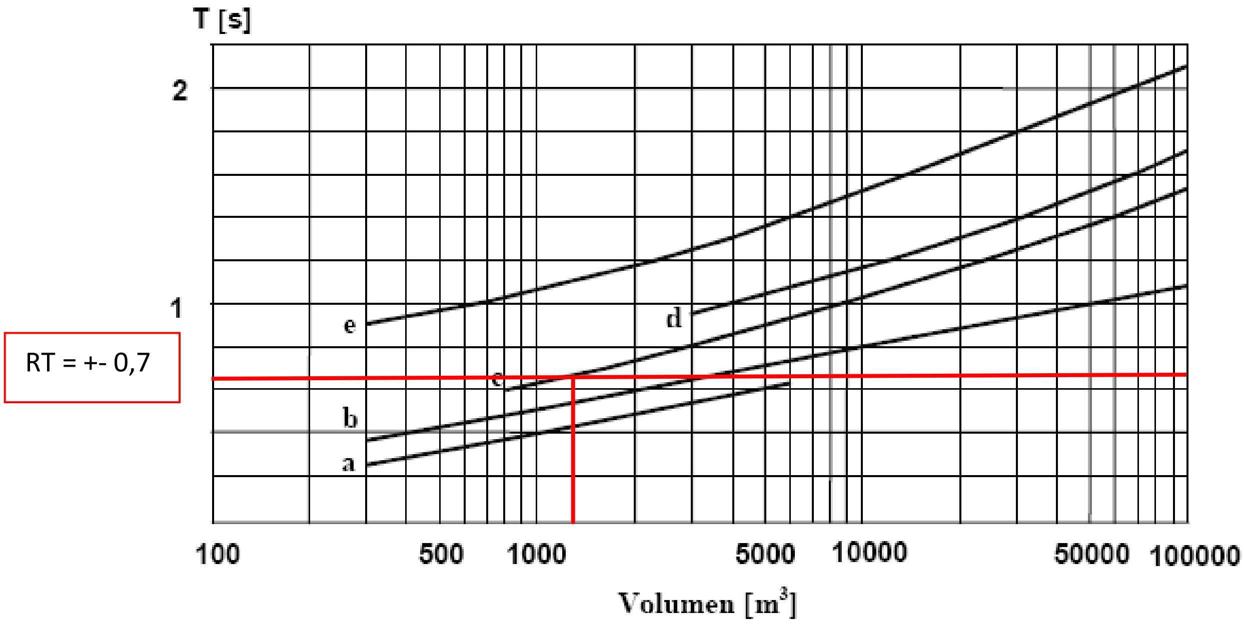
a = 1 if there is total absorption ("hole")

Although it is defined as the time required for the reverberant sound to drop 60 dB after the sound is stopped, it is measured over a range of levels between −5 and −35 dB and then doubled. This TR30 is the reverberation time of the room evaluated over a 30 dB decay range using linear regression techniques. If it were measured over the full 60 dB range, there would be problems with the presence of background noise that is present and the measurements would be corrupt.

The early decay time (EDT) is another measure of liveliness. Formally it is the time taken for the first 10 dB of level reduction multiplied by 6, making it comparable to the reverberation time. This gives a more subjective evaluation of the reverberation time from the initial portion of the room decay curve. Early decay time varies less with occupancy than the reverberation time and is measured without an audience.

*Optimal Reverberation Times*

The optimal reverberation time depends on the size of the room and on the type of performance that is expected to be played.




**The optimal reverberation time in function of the volume of the space (according to L. L. Beranek).**
**(a) Spaces for speech. (b) Conference rooms.**
**(c) Spaces for music. d) Concert halls. (e) Churches.**

**Fig. 2.4.2:** The optimal reverberation time in function of the type of use and the size of the room.

All rooms that are constructed for listening to music, must have a reverberation time suitable to the use and depending on the volume. As in this case study the space is an auditorium used for speech and music, the room falls under both category a and c. The volume of Aula Magna is approximately 1200 m³. According to the graphic above, the reverberation time for this auditorium, for playing music, should more or less be 0,7.

Not only the type of use determines the RT-value, the kind of music played in the enclosed space will also have an influence. Described in the table are the different optimal reverberation depending on the type of music:

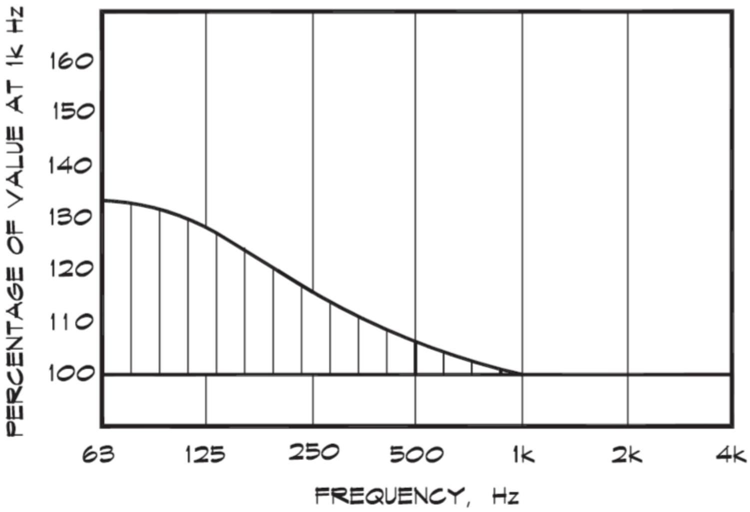
| Type of Music | Reverberation Time (sec) |
|---|---|
| **Organ** | >2.5 |
| **Romantic classical** | 1.8 – 2.2 |
| **Early classical** | 1.6 – 1.8 |
| **Opera** | 1.3 – 1.8 |
| **Chamber** | 1.4 – 1.7 |
| **Drama (spoken word)** | 0.7 – 1.0 |

**Table 2.4.1:** Recommended Occupied Reverberation Times (Barron, 1993)

Note that determining the optimal reverberation time is not an exact science and is subjective. It depends on various factors:

- Time dependent
- Frequency dependent
- Sound level dependent
- Complexity dependent

For a room used to play chamber music, the optimum variations of the reverberation time in function of the frequency is given below.




Recommended variation of $T_{60}$ with frequency for music. At frequencies lower than 1000 Hz the $T_{60}$ should increase according to the values inside the shaded area.

**Fig. 2.4.3:** Variation of RT with frequency

In small auditoria and churches the overall volumes are rarely high enough to raise the bass response to the level shown in this figure. The RT value of common constructions and spaces is quite low for these octave bands at 125Hz and below. For spaces used to play music it is recommended to increase the reverberation time of the low octave bands so it can result in an good bass response and a warm sound. A room having a short reverberation time is usually considered to be 'dry' and acoustically uninteresting.

### 2.2.5 Warmth

Bass reverberation, which is perceived as warmth, is the greater presence of bass sounds than mid frequency sounds. The presence of bass sounds occurs when the low frequencies (below 250 Hz) reverberation time is higher than the one of the mid frequencies (500 or 1000 Hz). If this would not be the case, the sound would be 'fragile' and not perceived as warm and full.

It has been defined by Beranek as the ratio between the average low-frequency reverberation times and those at the mid frequencies. A fraction that is called the bass ratio BR.

$$BR = \frac{T_{60}(125) + T_{60}(250)}{T_{60}(500) + T_{60}(1K)}$$

Beranek cites bass ratios from 1.1 to 1.45 for reverberation times around 1.8 seconds. As previously stated, the preferred reverberation time of the Aula Magna lies between 1.4 and 1.7 for chamber music, so the reference value of BR for a RT of 1.8sec can be used for the auditorium.

### 2.2.6 Lateral Fraction

Harold Marshall identified the importance of reflections that surround the listener with reverberant sound coming from the side. This lateral fraction (LF) is the relationship between the energy that reaches the listener within the first 80 ms laterally since the arrival of the direct sound (the direct sound excluded) and the energy received in all directions in this interval of time.

$$LF = \frac{\int_{.005}^{.08} p^2(t) \cos^2 \theta \, dt}{\int_{0}^{.08} p^2(t) \, dt}$$

The directional integration begins at 5 ms to insure that the direct sound is not included. The sound pressures are taken in the 125–1000 Hz frequency range. The average value of the LF corresponding to this frequency range is called LFE4 and the value recommended is supposed to be greater than 0.15

This definition thus states that the higher the value of the lateral fraction, the more the sound has a spatial effect, which is important in halls where music is played.

Lateral reflections and envelopment come about naturally from rectangular halls having widths on the order of 23 m. Particularly helpful is a shallow slope to the main floor seating area which allows the sound to interact with the walls in a plane above the audience.

For example, deep overhanging balconies produce the opposite effect, cutting the audience off from the reverberant field in the rest of the room since the sound under the overhang only comes from the front.

### 2.2.7 Diffusion, SDI

Diffusion is the spreading of sound in an omnidirectional rather than a specular pattern. It is created by convex or irregular surfaces. Diffusion contributes to envelopment, and the even distribution of reverberant sound. A room will lack the property of broadcasting when there are only smooth walls and ceilings that bring the sound directly to the listener without cross reflections or dispersed sound waves. A numerical value, called the surface diffusivity index (SDI), can be assigned to a surface as follows:

*High Diffusivity (SDI=1)*

Coffered ceiling with deep niches

Random diffusing elements over the whole surface

*Medium Diffusivity (SDI=0.5)*

Broken surfaces with shallow niches

Flat surface behind a semi-transparent hard screen

*Low Diffusivity (SDI=0)*

Smooth flat or curved surfaces

Absorptive surface

Once the SDI has been established for a given surface the ratings for the whole auditorium are calculated based on a weighted average according to area.

## 2.3 Spaces designed for speech

The objective of designing a space for speech is to make sure that the listeners in the room can understand any oral message. The architectural components of these spaces—size, shape, surface, orientation, and materials, as well as the background noise level—all influence intelligibility. The defining of the understanding of the word is more objective than that the perception of music because mainly determined by physical and linguistic factors.

So to specify the quality of a room that will be used for speech, the intelligibility of the word is the most important parameter.  To understand what is being said, the sound has to arrive to the listener with a high enough intensity so it is not disturbed by the presence of background noise. Also the absorption of high frequencies produced by most of the materials and even the air, produces great loss of intelligibility and the distinctive character of different consonants is lost. Whether speech will be intelligible in the presence of noise can be measured by to parameters, 'masking' and the 'speech transmission index (SDI)'.

When people listen to two or more tones simultaneously, if their levels are sufficiently different, it becomes difficult to understand the quieter tone. We say that the quieter sound is masked by the louder. Tones that are close in frequency mask each other more than those that are widely separated. Tones mask upward in frequency rather than downward. The louder the masking tone the wider the range of frequencies it can mask. . In large indoor facilities, such as air terminals or sports arenas, low-frequency reverberant noise can mask the intelligibility of speech.

The speech transmission index (STI) is a measure of speech transmission quality. The degree to which noise inhibits intelligibility is dependent on this parameter, which is simply the signal level minus the noise level in dB. When the noise is higher than the speech level, speech transmission index is negative

Speech intelligibility can be measured by the testing how many words or sentences are being understood by a listener. The most direct method of measuring intelligibility is to use sentences containing individual words or nonsense syllables, which are read to listeners who are asked to identify them. These can be presented at various levels in the presence of background noise or reverberation. Both live and recorded voices are used, however recorded voices are more consistent and controllable. Tests of this type lead to a measure of the fraction, ranging from 0 to 1, of words that are correctly identified.

The more speech content there is to the sound, the lower the ideal reverberation time. The hearing of the word requires greater clarity than that for music. This can be achieved by direct sound, immediately followed by some strong reflections so a little of energy is left for the process of reverb. For classrooms and small lecture halls reverberation times below one second are preferred (longer reverberation times are desirable for music). For speech the reverberation time behaviour with varying frequency is preferably flat.

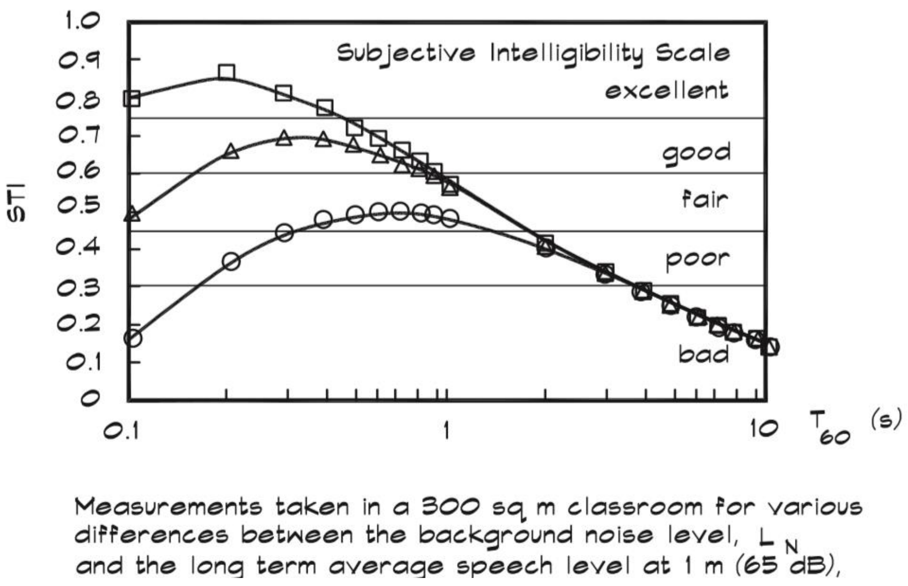



**Fig. 2.3.1:** Speech transmission index vs. Reverberation time (Bistafa and Bradley, 2000)

| | |
|---|---|
| Bad | STI ≤ 0.3 |
| Poor | 0.3 ≤ STI ≤ 0.45 |
| Weak | 0.45 ≤ STI ≤ 0.60 |
| Good | 0.60 ≤ STI ≤ 0.75 |
| Excellent | 0.75 ≤ STI ≤ 0.90 |

Table 2.3.1 : Quality of the speech intelligibility measured by parameter STI

In a verbal hearing room the recommended value of STI should be at least 0.45. This represents a 70% comprehension of words and an 98% of phrases.

So finally in the process of designing a room for speech, several fundamental requirements should be accounted for:

1. There must be adequate loudness
2. The sound level must be relatively uniform
3. The reverberation characteristics of the room must be appropriate (0.7 ≤ RT ≤ 1.2)
4. There must be a high signal-to-noise ratio (STI ≥ 0.45)
5. Background noise levels must be low enough to not interfere with the listening environment (NC-25)
6. The room must be free from acoustical defects such as long delayed reflections, flutter echoes, focusing, and resonance.

## 2.4 Summary of recommended values for the different parameters

Summary of the recommended values of all parameters for Aula Magna at ETSIE-UPV, a multipurpose auditorium.

| **Parameters** | **Multipurpose auditorium** | |
|---|---|---|
| | Lecture auditorium, speech | Chamber music |
| **Volume [m³]** | 1200 | 1200 |
| **Level of ambient noise** | NC-25, RC-25 | NC-25, RC-25 |
| **Intimacy [s]** | ≤35ms | ≤20ms |
| **Reverberation time RT [s]** | 0,7 – 1,2 | 1,4 – 1,7 |
| **Warmth** | 1,1 – 1,45 | 1,1 – 1,45 |
| **Speech intelligibility, STI** | >0,45 | |
| **Clarity, Definition** | D50>0,5% | D50>0,5% |

## 2.5 Echo, focus and resonance

In any kind of room (whether it is for speech or music) acoustic problems such as echo, resonance and focus should be avoided.

Echo is a first-order problem that can occur when there is a delay between the direct sound and the first reflection or between two following reflections of more than 50ms.

Surfaces in the room that give reflections to any part of the room with a big delay have to be treated with an absorbent material. That way the problem of echo can be eliminated.

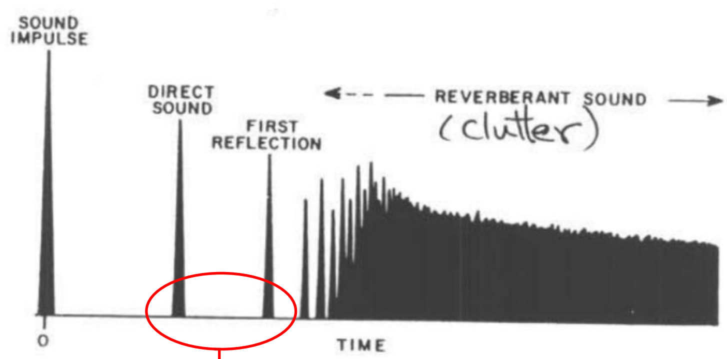



FIG. 2. Multiple reflections of a sound impulse as heard by a listener.

If the time gap would be bigger than 50ms: echo-effect

If all sound waves would arrive in one point, there would be a focus or concentration of the acoustic energy. This phenomenon can be caused by reflections on concave surfaces, so that the use of it loses all its advantages.

An isolated natural or resonant frequency could also lead to acoustic problems in room. So to keep a uniformity within the conservation of frequencies, multiple modes of resonance have to emerge in the space. A solution is to avoid parallel surfaces, especially in the area that is close to the source of the sound.

# 3 Properties of the hall

## 3.1 About Aula Magna

This acoustic study takes place at the Aula Magna in the faculty building of ETSIE (Escuela Técnica Superior de Ingeniería de Edificación) at the Universitat Politècnica de València. To get a good idea of the space where the study was held, the main properties of the auditorium are discussed in this section.

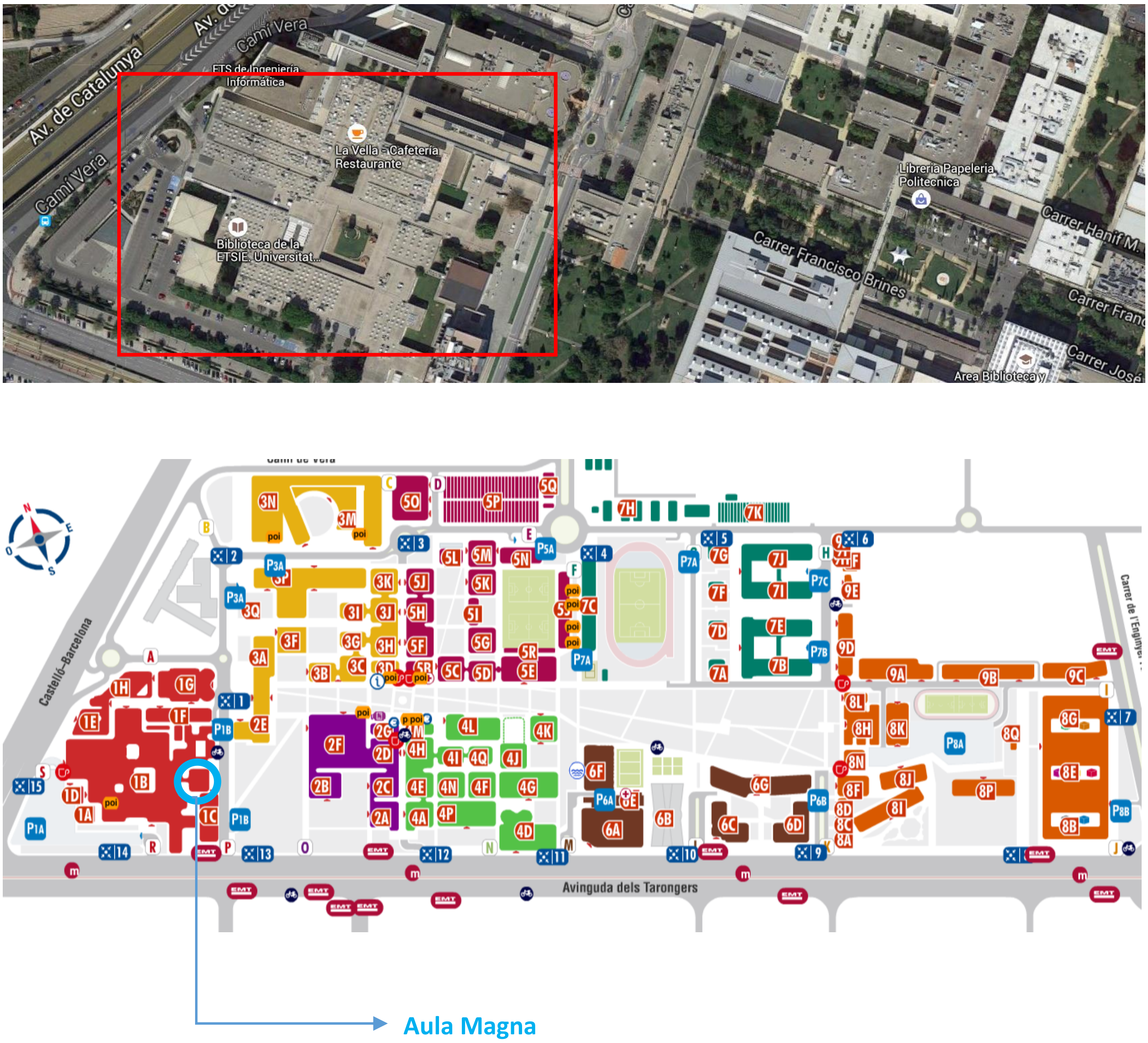



**Fig. 3.1.1:** UPV – Faculty of Building Engineering (ETSIE) – Valencia (Spain)

The Aula Magna is part of the ETSIE building that was built around 40 years back. For several years it was used as a regular classroom and it wasn't until later that the room was transferred to an auditorium.

The transformation consisted of putting a stage, constructing a slope with appropriate seating, installing a media room in the back,… The auditorium also needed the right acoustic installations. This concerned a resonator above the stage, curtains at the front and back wall and putting wooden, reflective panels against the lateral walls. Also a false ceiling with the right acoustic properties was added to the auditorium.

Still, after making all these changes, the Aula Magna does not meet all acoustic quality requirements. The reason for that is mainly because the original construction was not carried out well. One example of this is that in the lateral walls, the use of insulation is not consistent. In some parts, insulation was used and in other parts not.

But not only the original construction had problems, the way the new materials were installed are also a reason the quality of the room is not good. The reflective wooden panels are attached to the wall of the original structure. The manner in which they were attached differs from panel to panel. One time, the panels are manually placed with nails, other times with a nail gun… making that the strength with which they are attached against the wall differs as well.

This whole process of construction and all the problems that come with it have to be taken into account in the next sections of the acoustic study because they will have a big influence on the results.

**Fig. 3.1.2:** Aula Magna (seating area and the back wall of the auditorium)

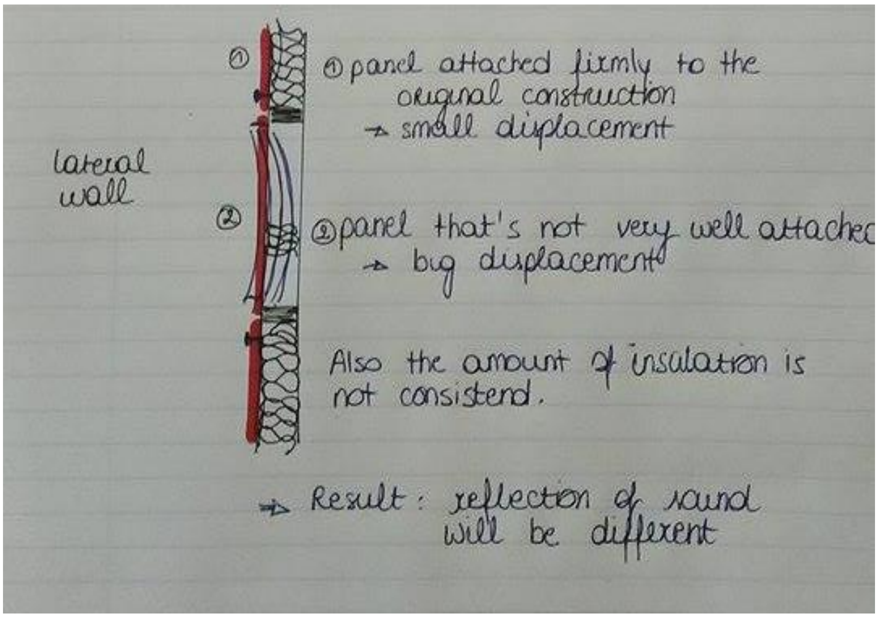



**Fig. 3.1.3:** Sketch of the lateral wall construction and possible problems

## 3.2 Plans of the aula

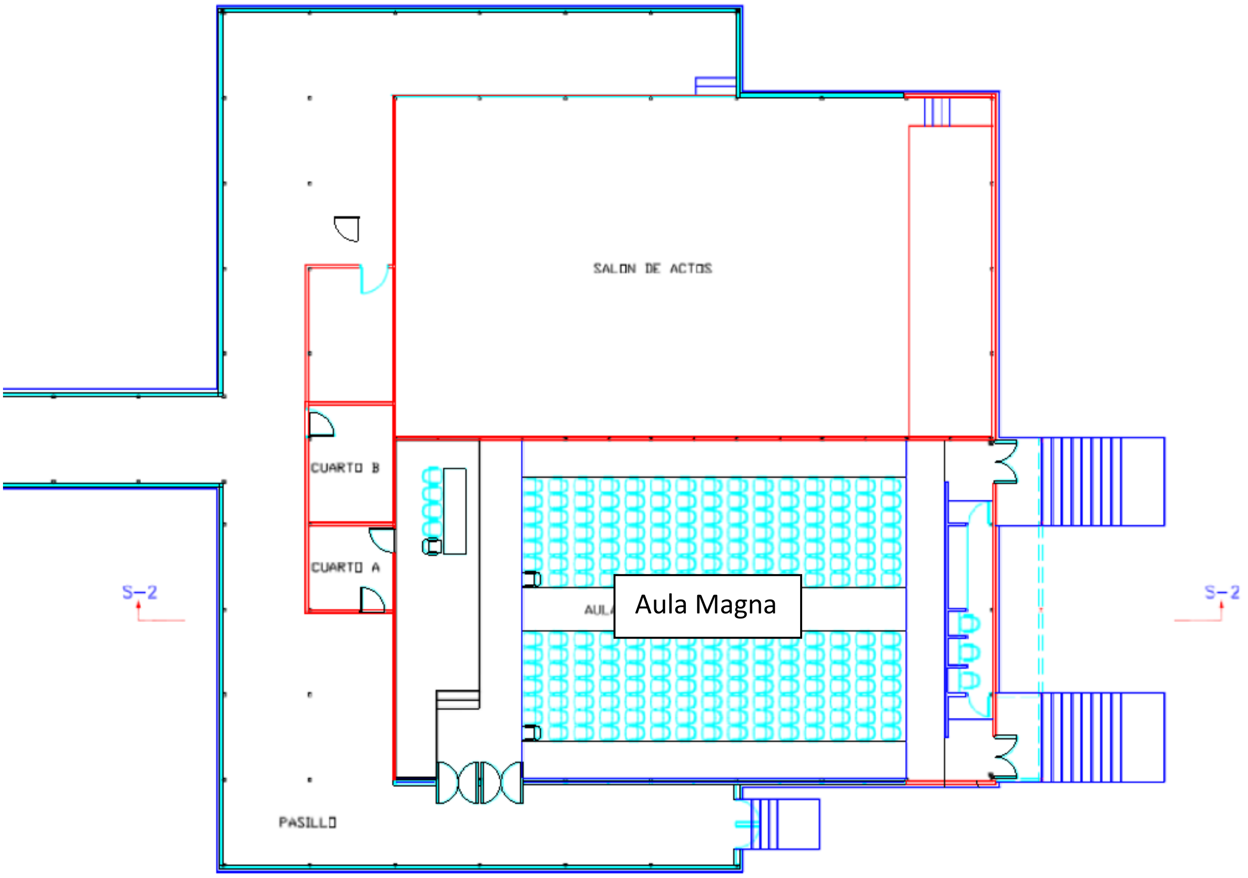



**Fig. 3.2.1:** Floor plan of Aula Magna

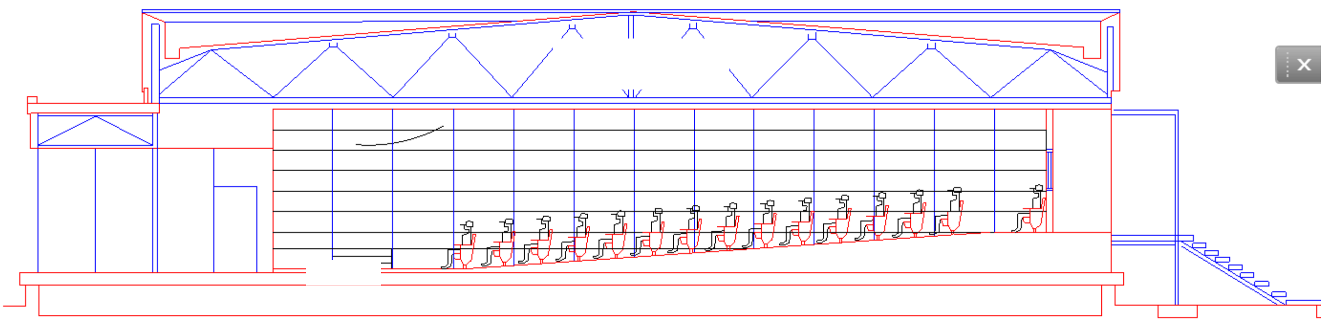
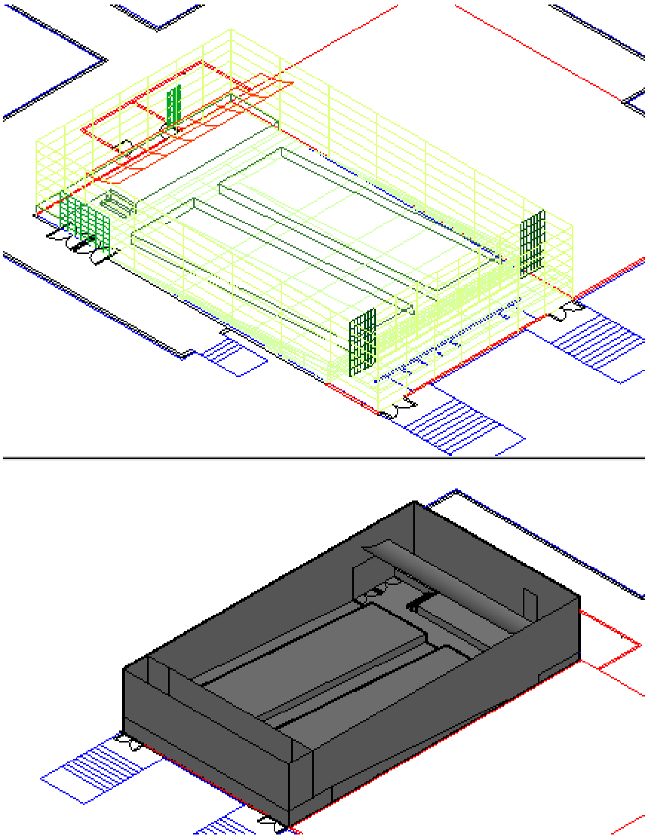


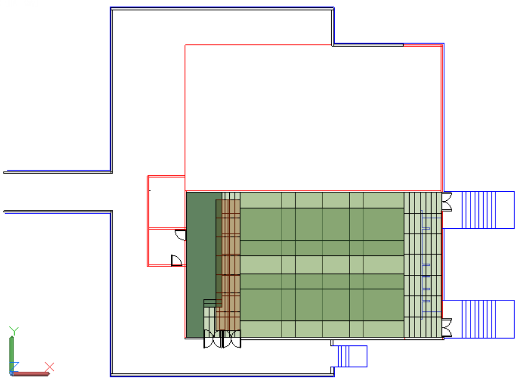
**Fig. 3.2.1:** Section S-2 of Aula Magna

| Dimensions of the Aula Magna | |
|---|---|
| **Volume** | 1152 $m^3$ |
| **Height** | 4 m |
| **Width** | 12 m |
| **Length** | 24 m |
| **Amount of seats** | 14 x 7 x 2 = 196 seats |

## 3.3 3D model



A 3D model of the room has to be made into AutoCAD because later on, the AutoCAD-file needs to be imported in the software that will evaluate the acoustic parameters of the auditorium.



## 3.4 Geometry of the Aula Magna

When designing a space for speech and music, two very important properties can't be overlooked. These are the visibility in a space and direct sound and first reflection of sound.

### 3.4.1 Visibility

The floor of an auditorium should be sloped to provide adequate sight lines. Good sight lines result in good listening conditions and lead to good direct sound. These sight lines can be obtained by raising the talker on a platform or by raising the angle of the slope of the seating area. Sight lines are set so that the audience can see the point of interest on stage, called the arrival point of sight (APS), over the head of the person sitting in front of them.

In lecture halls, where sight lines are set at or above the waist of the lecturer the lowest point of interest on stage, the slope can be modest. In this case, the slope is 3°.

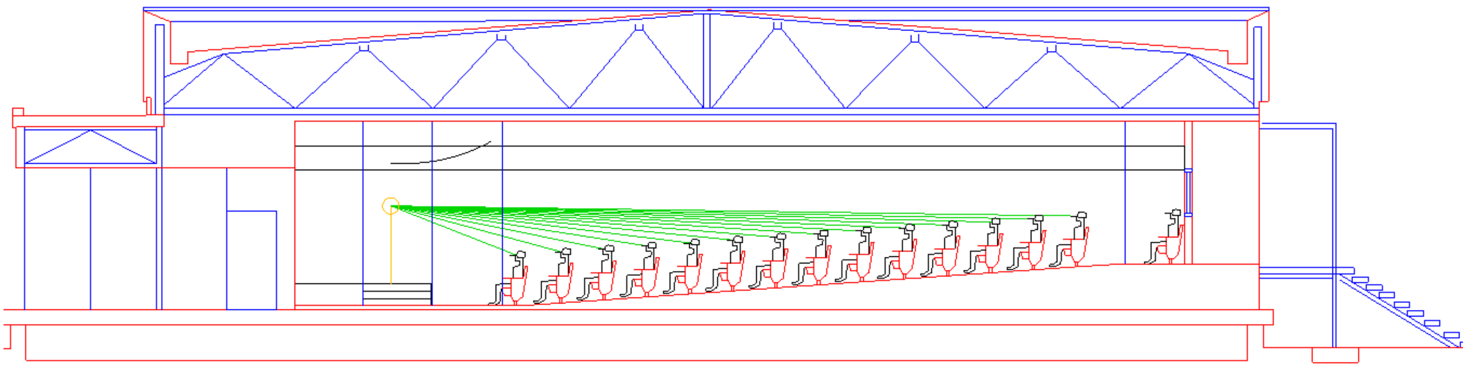


**Fig. 3.4.1:** Visibility

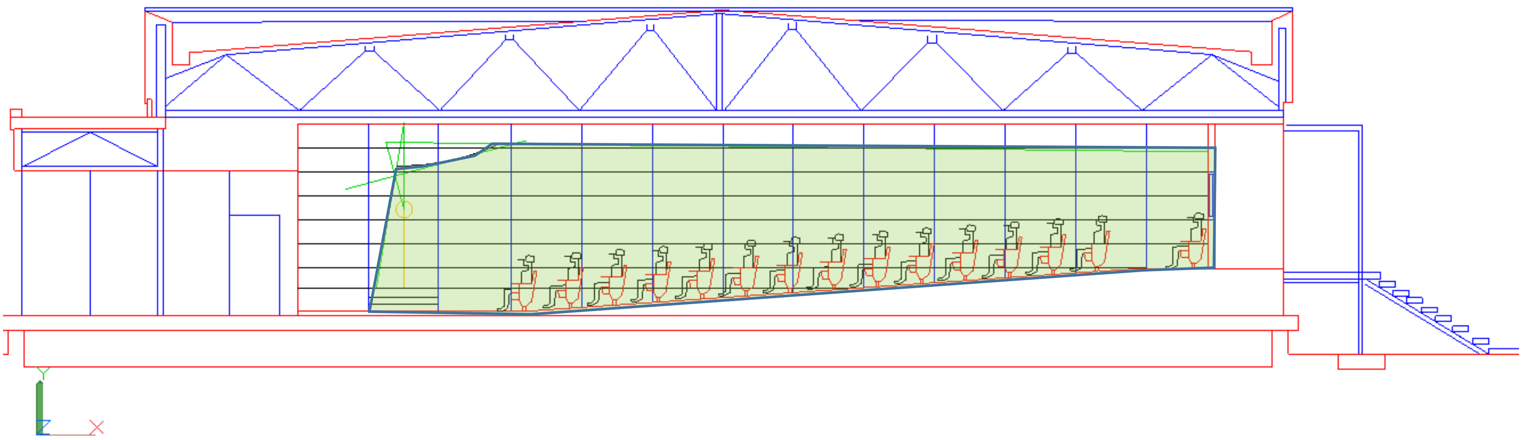
### 3.4.2 First Reflection

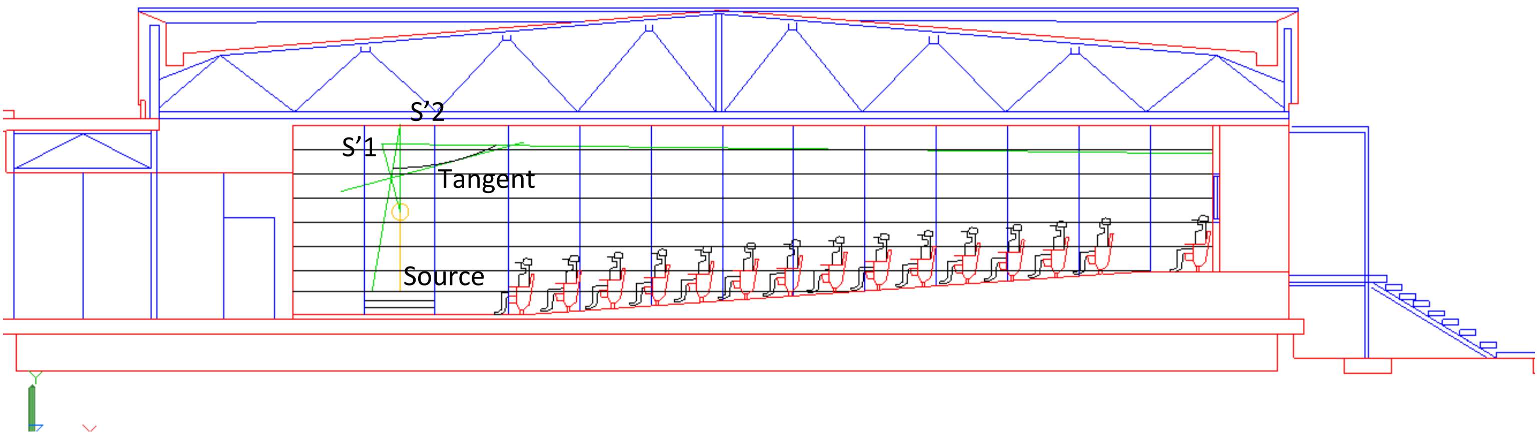
In the Aula Magna are various reflective surfaces installed that will provide the possibility of first reflections. The materials that have this reflective property are the wooden panels hanging on the lateral walls and the resonator above the stage, also made of the same reflective wood.

Because of the convex shape of the resonator the first reflection of the sound, originated at the source located on the stage, covers the entire seating area of the receivers. This is the study of the first reflection in section.

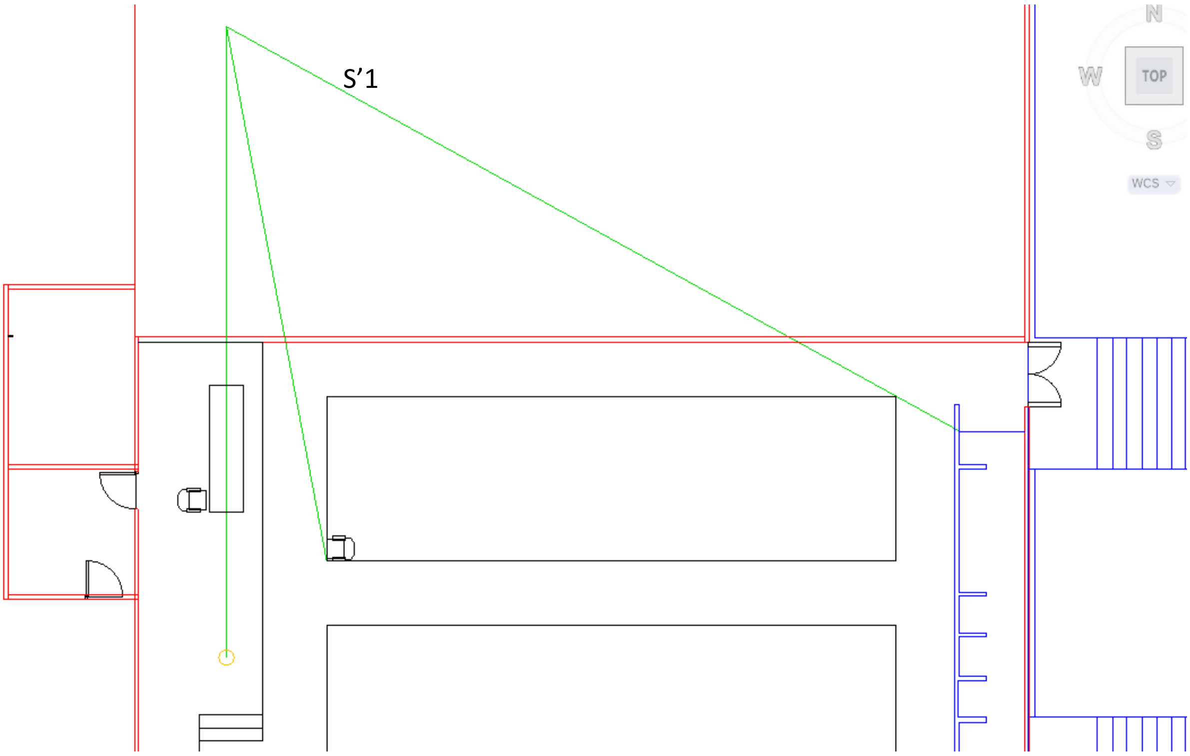
To define the position of the fictional source for a convex surface, the tangent of the curve of the surface defines the reflective surface. It is not the tangent at both ends of the convex surface that has to be taken into account, but the last tangent where the reflective surface works for the entire hall.

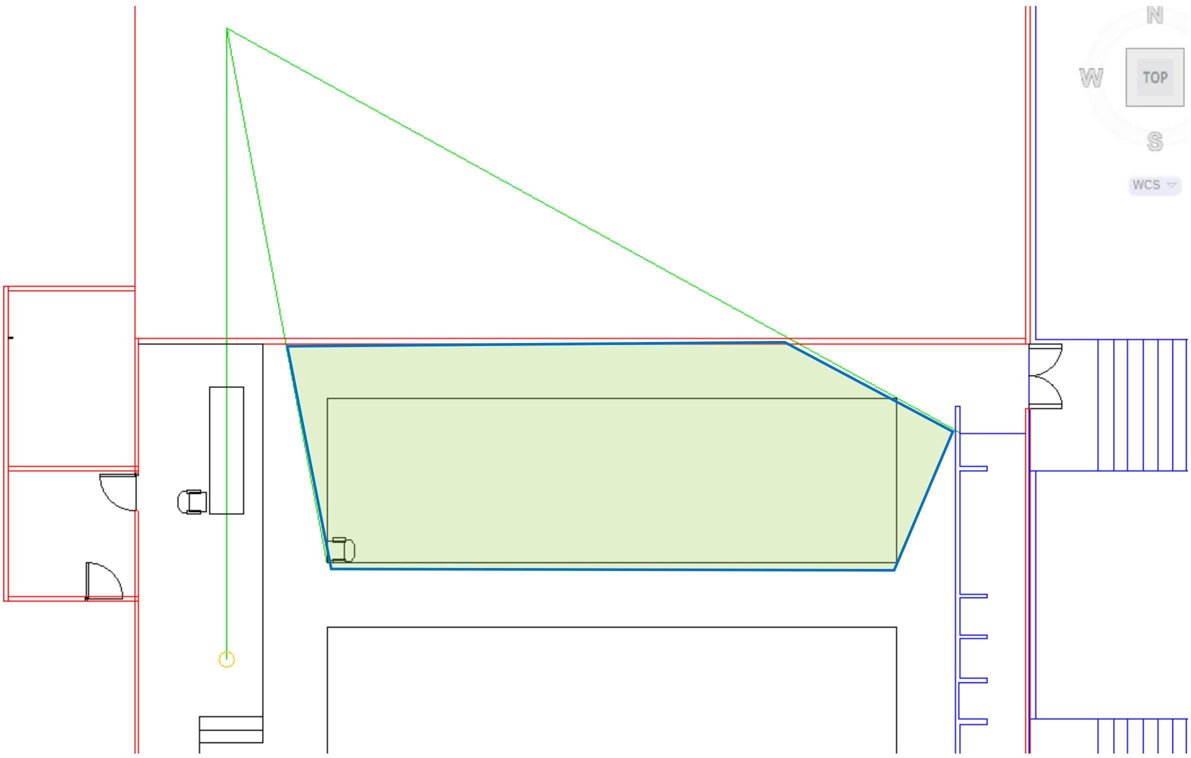
For the Aula Magna, this is the tangent where the perpendicular intersection point between the source and the tangent, lies above the source.





The same study has to be done in plan, so the first reflection covers not only all the seating rows but also all the columns. This first reflection will be realised by the lateral walls. Which are made up by wooden panels that are fixed between metallic battens and are totally reflective. The reflections cover again the complete area of listeners and form a uniform, horizontal platform.



# 4 Measurements and Analysis

## 4.1 Objective

The objective is now to evaluate the acoustic quality of the Aula Magna. The parameters that will be studied, will determine if the quality of sound for the listeners sitting in the chairs is good. Therefore these parameters will first be measured with the appropriate equipment in the unoccupied Aula Magna. After, the results of the real acoustic situation are compared to the recommended values of the parameters (previously discussed in paragraph 2). This way, the quality of the room can be evaluated.

If there are results that don’t meet the required values, the hall should be adapted so the quality will improve. To know what properties, materials, …. of the Aula Magna need to be changed, the parameters can also be calculated by the software ‘ODEON’. This program can determine all parameter values virtually so the same results occur. After, the materials that are used for the auditorium can be changed in the program so the perfect results are created. The help of this program makes it easy to make ‘virtual’ changes in the hall, create a good acoustic quality and make later the virtual changes in real life.

## 4.2 Measurements

### 4.2.1 Method

The first step in the process is to measure the real acoustic quality of the hall. This is done by using a sound source and a sonometer that works as the receiver of the sound (thus the listeners in the hall).

The source is placed on the stage, but be careful not to put it in the middle so the symmetry in the room can’t do its work. As source, an omnipower sound source makes sure the sound gets send out in all directions of the hall.

The sonometer, that plays the role of the receiver, is composed of a microphone and a computer so the results of the measurements can be send to the computer that shows all values on screen. This way it is easy to copy the results in an excel file and make graphics. Again, the microphone records sound in all directions.

To get a good idea of the acoustic quality, the emitted sound (that reaches a frequency up to 20K Hz) is measured in different positions in the hall. In total, 15 receiver points are divided over the whole sitting area of the hall. The microphone is always placed at a point where there is a seating place for a listener, and it is held at the same height of the heads of the listeners. All different positions of the microphones are illustrated in the next figure. The exact coordinates are inserted as an attachment in *Annex 1.*

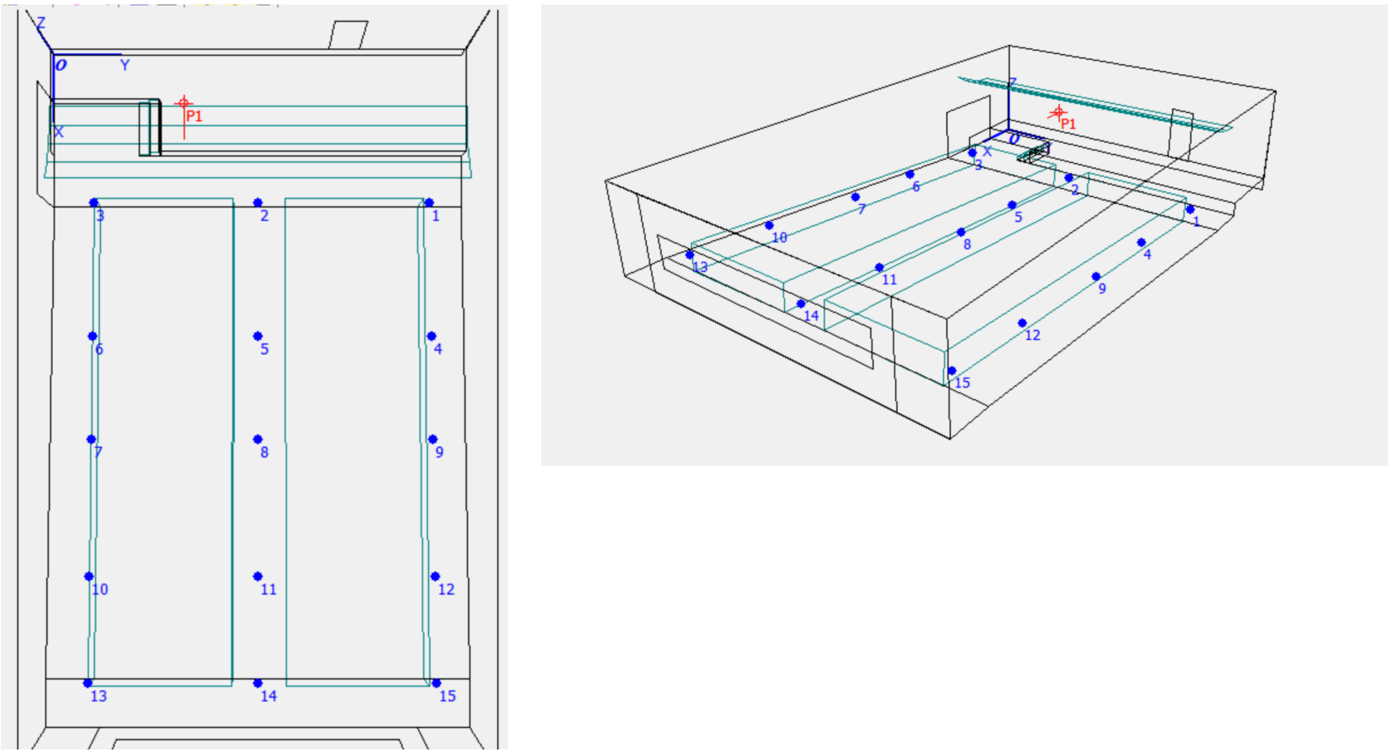



**Fig. 4.2.1:** Position of the receiver points and the source

### 4.2.2 Materials used for the measurements

Technical overview of measuring process:

| | |
|---|---|
| Location | Aula Magna - ETSIE |
| Date and time | 27/04/2015 – 10h |
| Engineers | Mr Jaime Llinares – Phebe van de Heyning, Lissa Coignau and Marlies Declerck |
| Source | OmniPower Sound Source - Type 4292-L (Brüel&Kjaer) |
| Receiver | Sound Level Meter - Type 2250 (Brüel&Kjaer) |
| Software | Room acoustics measurements - DIRAC - Type 7841 |

*Source - OmniPower Sound Source*

For most building acoustics measurements, the sound source must record sound evenly in all directions to give reliable results. The relevant acoustics measurements standards (ISO 140 and ISO3382) require therefore the use of an omnidirectional sound source.

The omnidirectional source uses 12 loudspeakers in a round configuration that distribute the sound evenly.

Important to note is the presence of background noise. This is most of the time the enemy of a good building acoustic measurement session. Especially at low frequencies where the traffic noise and the noise of the cooling system are one of the main disturbers. To overcome this, the sound source is made that way that it delivers its peak performance in the range of 100Hz and 200Hz, where the maximum power is needed most.

### 4.2.3 Results of the measurements

After performing the measurements for all points of receivers, the obtained data has to be processed. The parameters that were measured are: the early decay time (EDT), reverberation time for different drops (T10, T15, T20, T30 and RT), clarity (C20, C50 and C80), definition (D50 and D80) and the intelligibility (STI male and female). The results of all data can be found in the file *'Main Hall – Measurements'* under the tab *'Data'.*

Only the relevant data will be processed. This is the temporary parameter T30, the energy parameters C50, C80, D50 and D80 and finally the intelligibility parameter STI.

*Temporary Parameter T30*

The parameter T30 is the parameter that gives us the reverberation time measured over a drop of 30dB and multiplied by 2. The graphic below illustrates the variation of the reverberation time over the range of frequencies from 63Hz to 8000Hz. This variation is an average for all the 15 receiver points that were measured.

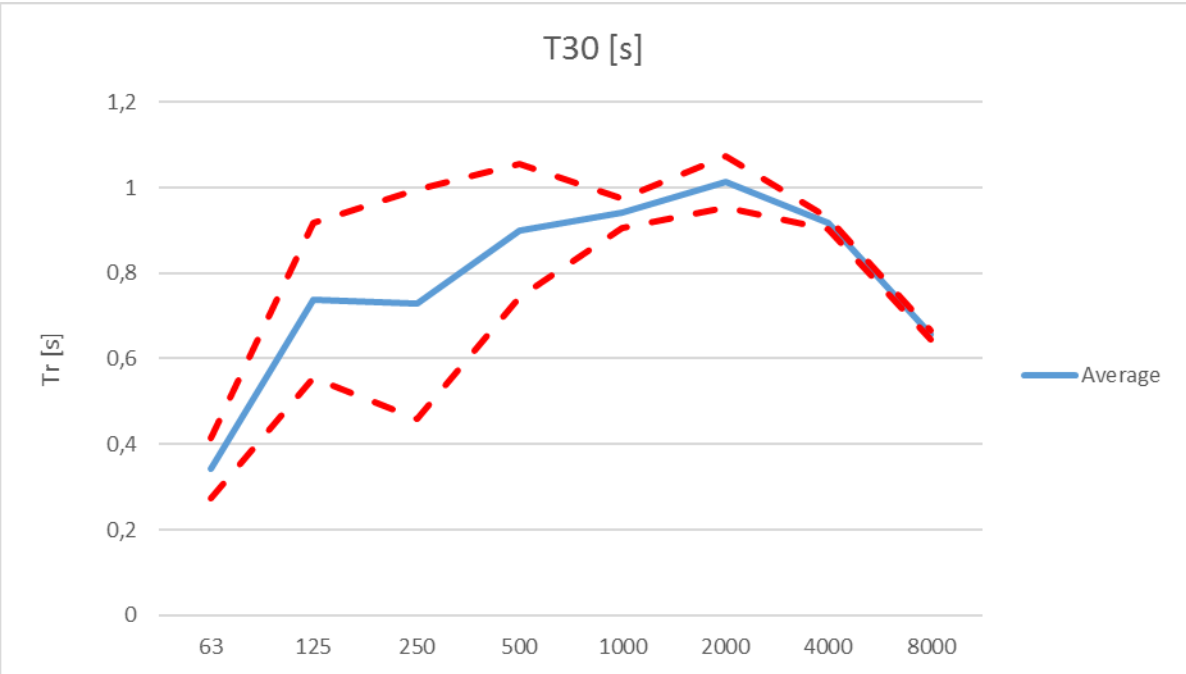



**Fig. 4.2.3.1:** Average reverberation time measured in the Aula Magna.[6]

In this case, only the average value of the reverberation time is considered to compare it to the recommended values. This is because the construction of the Aula Magna was carried out very badly and the result of the reverberation time differs a lot from point to point.

Comparing these results to the recommended value of reverberation time in a room for speech (which lies between 0,7 – 1,2) it can be stated that the values for the lower frequencies (63 to 250Hz) and the high frequency of 8000 Hz don't fall in this interval.

[6] The graphic of the reverberation time for all the receiver points separately can be found in the excel file 'Main Hall – Measurements' under the tab 'T30'.

A second problem is the variation of the reverberation time over the different frequencies. In a room for speech, the graphic should have a gradient as presented in the figure below:

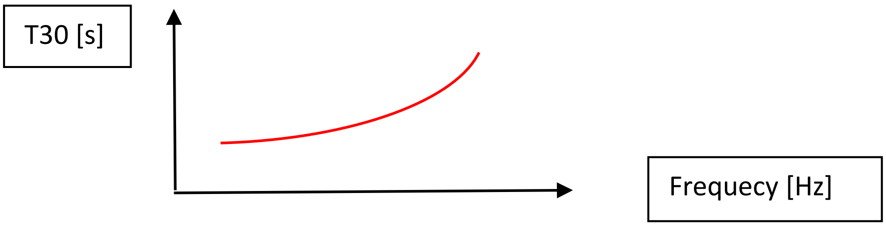



**Fig. 4.2.3.2:** Sketch of the optimum variation of the reverberation time for different frequencies in a room designed for speech.

In an optimal situation, the reverberation time has to increase for higher frequencies. This is because the sound waves of high frequencies should be able to reach the end of the room. If the reverberation time is too low for these frequencies, this is a problem and the receivers at the end of the hall won't be able to catch sound of these frequencies.

The opposite goes for room where music is played. There the reverberation time for the bass frequencies has to be higher and decrease for higher frequencies. A graphic of this process was previously added in chapter 2 'parameters'.

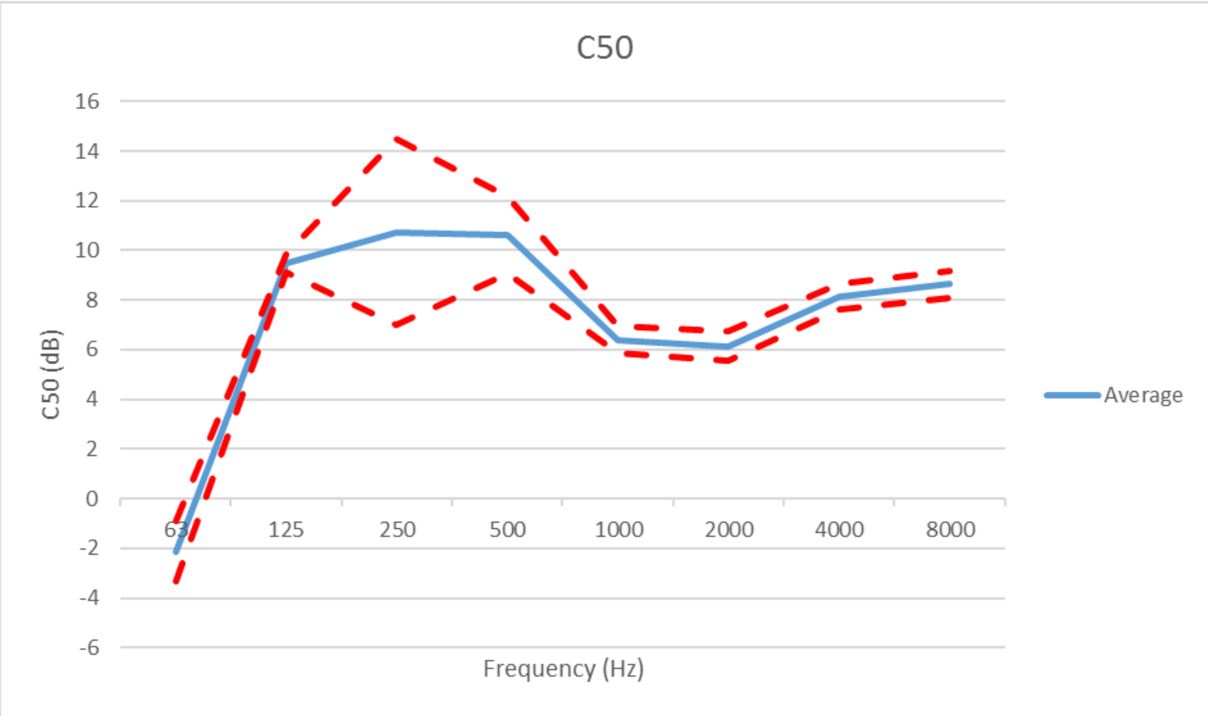
The Aula Magna at the ETSIE building is used for both speech and chamber music, but the curve of the reverberation time doesn't meet either of the requirements.

*Energy parameters – Clarity and Definition*

The second set of parameters that were measured in the hall are the energy parameters. First of all there is the clarity parameters C50 and C80.

It is known that the recommended values of the clarity parameter have to fall into a a ± 4 dB range. With preferred values between 0 and −4 dB. If the results of the average clarity parameters are evaluated it can be stated that all the values fall in a range of ± 4 dB but all values are quite high and positive. This implies a high energy drop between the first sound received by the listener and the energy that is left after 50/80 ms.

| Clarity (average) | 63 Hz | 125 Hz | 250 Hz | 500 Hz | 1000 Hz | 2000 Hz | 4000 Hz | 8000 Hz |
|---|---|---|---|---|---|---|---|---|
| C50 | -2,128 | 9,466111 | 10,74256 | 10,60356 | 6,4 | 6,145333 | 8,153333 | 8,645333 |
| C80 | 6,816333 | 13,468 | 10,43869 | 13,59244 | 8,507111 | 9,081556 | 11,282 | 12,506 |



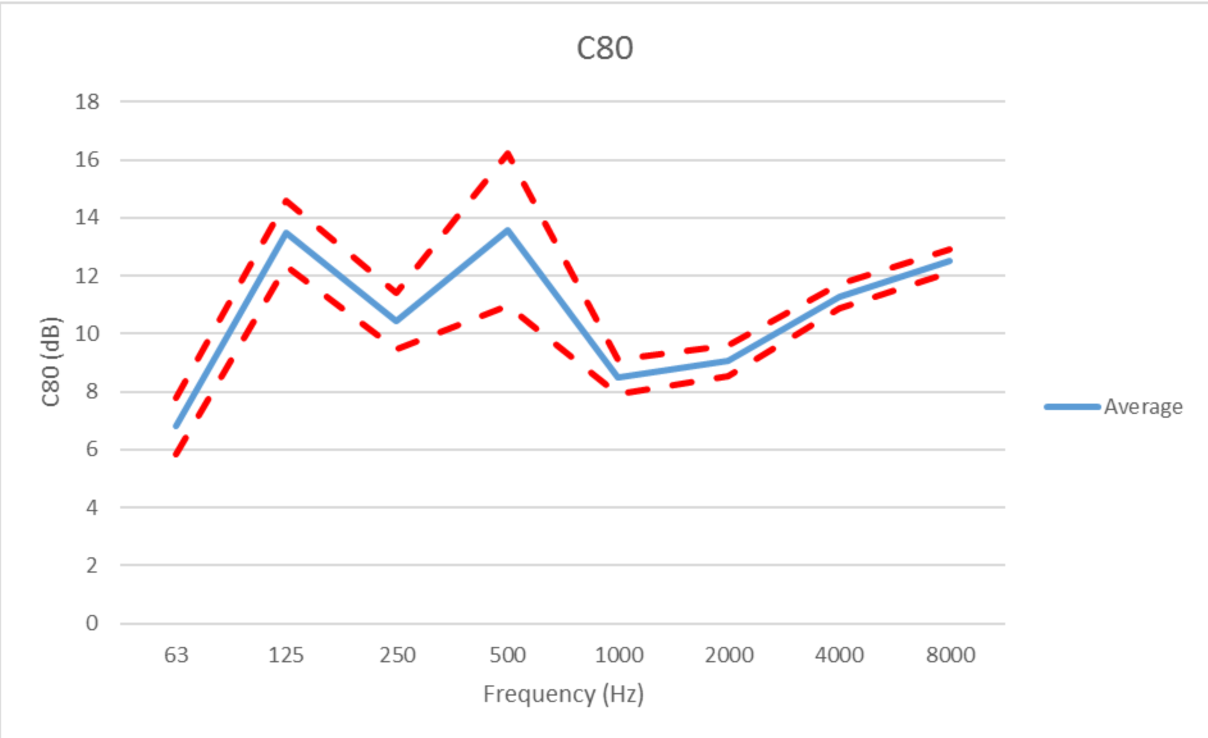
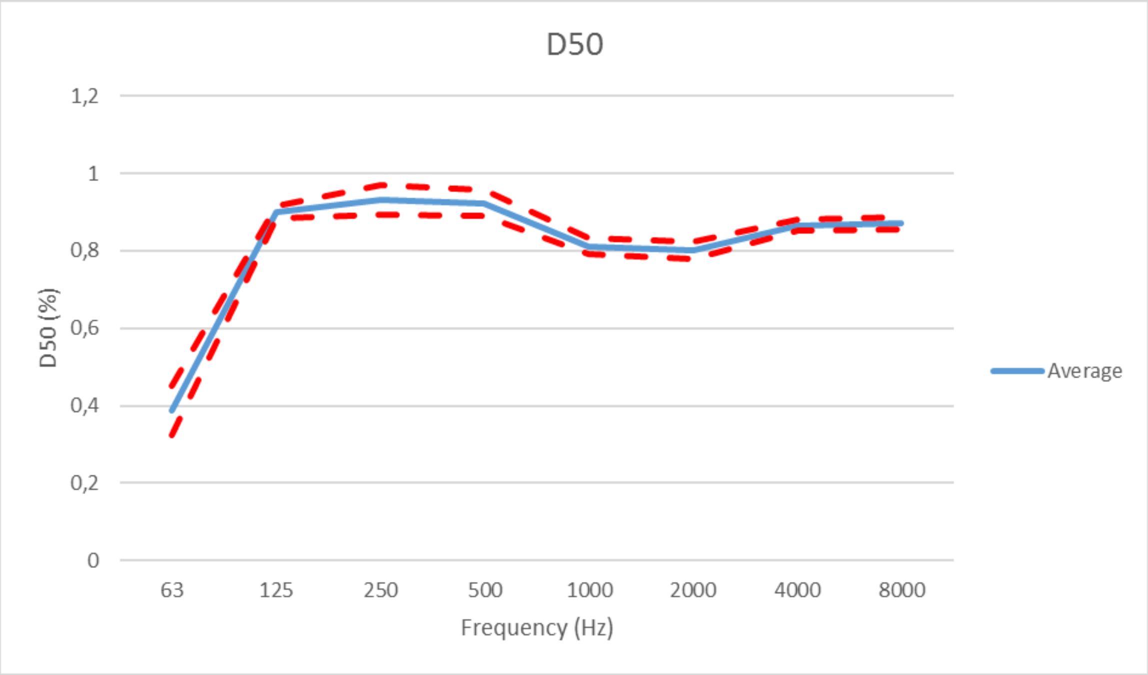



**Fig. 4.2.3.3:** Graphics of the average values for C50 and C80

The definition is also an indicator of the energy of sound. Both D50 and D80 parameters were measured in the Aula Magna. The recommended value of D50 is higher or at least 0,5% for a room for music as well as for speech. Illustrated by the graphics beneath, the required values are met in the Aula Magna. This means that the listener will receive a clear sound and this is primarily important in rooms for speech.



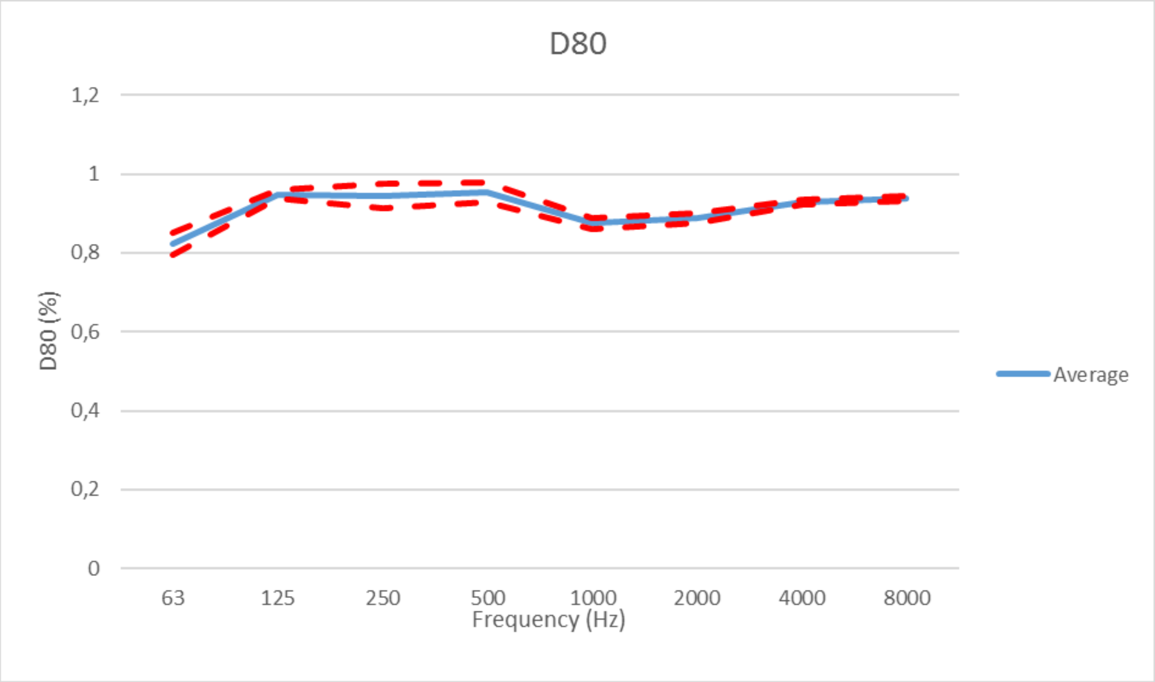




**Fig. 4.2.3.3:** Graphics of the average values for D50 and D80.

## 4.3 Software – ODEON

The measurements are done and the results of the parameters for the real situation are known. Now it is possible to make a model in the software program 'ODEON' and simulate the same results as in real life. If the model is adapted that way that it is a good representation of the real situation, materials and other properties can be adapted to make improvements to the hall.

### 4.3.1 Method

To make the software work, a three dimensional model has to be drawn in AutoCAD. It is important that the whole 3D model is composed of planar surfaces and that there are no volumes used. This is because any volumes won't be recognized by the program ODEON. Only the room in which the sound is emitted has to be drawn and imported in the software. Nearby rooms and spaces don't have to be introduced in the program.

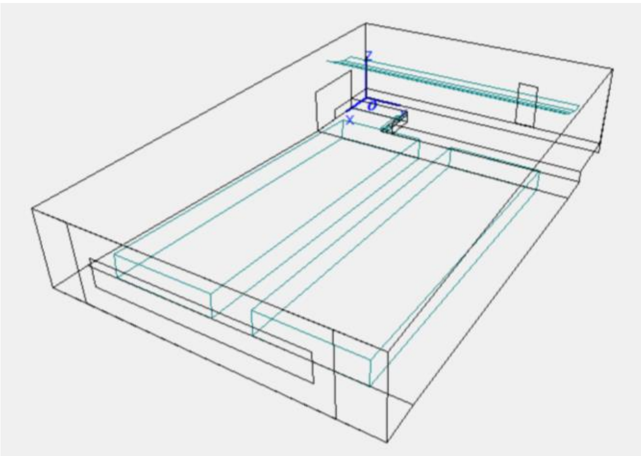


**Fig. 4.3.1.1:** First step of the acoustic analysis with help of the software: import the 3D-model from autoCAD to ODEON

The next step is to define the location of the source when the measurements were taken. Also the coordinates of all the receivers have to be put into the software. This can be done under the tab 'source receiver list' in the ODEON software. The exact coordinates of the source and the 15 receiver points can be found in 'Annex 1'

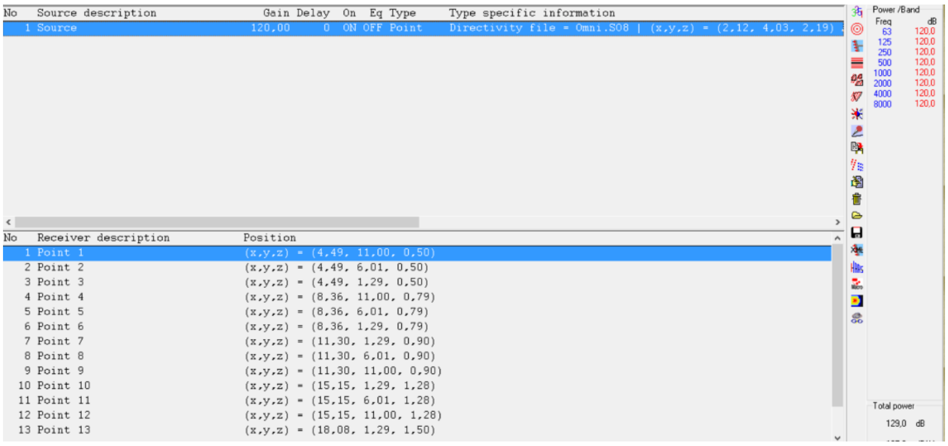



**Fig. 4.3.1.2:** Step 2: coordinates of the source and the receiver are introduced in the program.

The next important step in the process of using the software is to define the materials that were used in the Aula Magna. In the program there is a library available with a list of different kind of materials and their specific properties, thus their absorption coefficient of the materials. This list can be used but it is also possible to create a material of your own and specify the absorption coefficients for all frequencies of the material. It is possible that the kind of material you want to use is in the library but the absorption coefficients are different than the values you want to put in for your material. This is because of the way the absorption coefficients for materials in the program are determined.

*The absorption coefficient of the materials*

Acoustic absorption refers to the process by which a material, structure, or object takes in sound energy when sound waves are encountered, as opposed to reflecting the energy. Part of the absorbed energy is transformed into heat and part is transmitted through the absorbing body.

To measure the absorption of an architectural material the experiment is done in a reverberant test chamber using the reverberation time method. A reverberation chamber is a hard room with concrete surfaces and a long reverberation time, with sufficient volume to have an adequate density of modes at the frequency of interest. Since the average absorption coefficient in the room is quite small under these conditions, the Sabine equation can be used. The reverberation time of the empty chamber is defined by the Sabine equation. After determining the reverberation time of the empty chamber (RT). The material that needs to be tested is put into the room. Than the reverberation time is measured again and the result is RT*. Now the amount of absorption of the specific material is the difference between RT and RT*. In these tests there is some dependence on the position of the sample in the room. Materials placed in the centre of a surface are more effective absorbers, and make higher absorption coefficients, than materials located in the corners.

The materials used in the Aula Magna at the ETSIE building are presented in the next table along with their absorption coefficients.

| **SURFACE** | **MATERIALS** | **ABSORPTION COEFFICIENT** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **63** | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
| **CHAIRS** | Completely in fabric | 0,49 | 0,49 | 0,66 | 0,8 | 0,88 | 0,82 | 0,7 | 0,7 |
| **CEILING** | Perforated metalic panels | 0,3 | 0,3 | 0,25 | 0,2 | 0,17 | 0,15 | 0,1 | 0,1 |
| **RESONATOR** | Wood | 0,3 | 0,3 | 0,65 | 0,84 | 0,8 | 0,58 | 0,37 | 0,37 |
| **FLOOR** | Linolium | 0,02 | 0,02 | 0,03 | 0,03 | 0,04 | 0,04 | 0,04 | 0,04 |
| **FRONT WALL** | Smooth painted concrete | 0,01 | 0,01 | 0,01 | 0,01 | 0,02 | 0,02 | 0,02 | 0,02 |
| **BACK WALL** | Windows | 0,08 | 0,08 | 0,04 | 0,03 | 0,03 | 0,02 | 0,02 | 0,02 |
| | Curtains | 0,03 | 0,03 | 0,45 | 0,65 | 0,56 | 0,59 | 0,71 | 0,71 |
| | Wooden panels | 0,04 | 0,04 | 0,04 | 0,03 | 0,03 | 0,03 | 0,02 | 0,02 |
| **LATERAL WALLS** | Wooden panels attached to wall | 0,04 | 0,04 | 0,04 | 0,03 | 0,03 | 0,03 | 0,02 | 0,02 |
| **STAGE** | Wooden parquet | 0,09 | 0,09 | 0,09 | 0,08 | 0,09 | 0,1 | 0,07 | 0,07 |

**Table 4.3.1.1:** Used materials in the Aula Magna and their absorption coefficients [7]

All these materials are created in the ODEON program and then paired with the right surface in the room. It is very important that every surface is defined by the right material. This because every material has a specific array of absorption coefficients and these coefficients have an influence on the reverberation time of the hall.

[7] Values of the absorption coefficients of the materials were given by Dr. J.Llinares

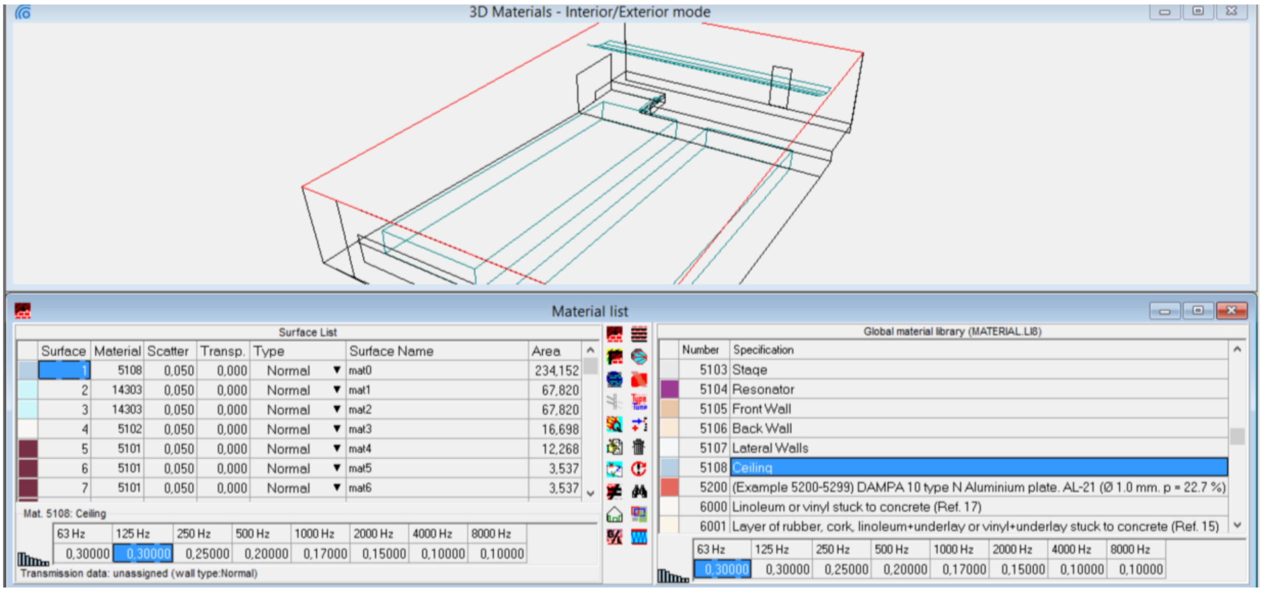



**Fig. 4.3.1.3:** Step 3 – define for every surface of the Aula Magna the right kind of material and thus the right absorption coefficients.

The next step is to check if there are no abnormalities and holes in the drawn 3D model that will lead to a leakage of sound. If all the trace rays of the sound stay inside the model and all locations in the room get hit equally by the rays, the model has no abnormalities and the process can be continued.

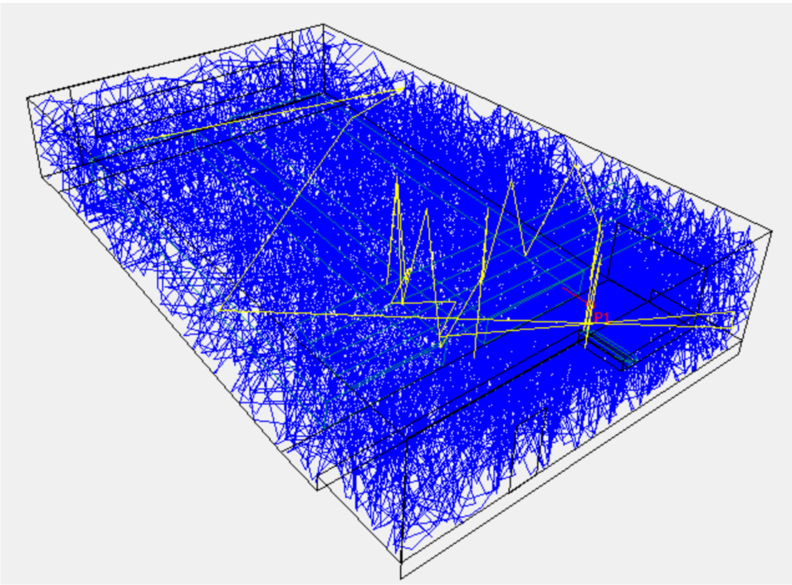


**Fig. 4.3.1.3:** Step 4 – checking for any abnormalities or holes in the 3D model

The last thing to do before calculations can be made is defining the room setup settings. In this part of the program it is possible to choose if you want a quick survey of the calculations of the parameters for the multiple receivers or precise calculation. The difference is in the number of rays. For a survey the number of rays is 500 for every receiver and in the precision job the number is 5000.

What is important to adapt is the impulse response rate. This depends on the maximum reverberation time in the Aula Magna. The highest value found is 1,73 seconds or 1730 ms at receiver point 5. That is why the impulse response rate will be set at 2000ms.

Now all the steps are done, the final thing to do is to let the program run all calculations. Select therefore the 'job list', give a good job description, select the source and run a 'single job'. Afterwards the results are given in a text file. First run a survey calculation to check if there are any problems or abnormalities in the results. If everything is okay, run a precision job.

### 4.3.2 Results of the virtual model

The calculations are made and the results are presented by the program. The first calculations have been made for the Aula Magna, defined by the original materials and their absorption coefficients. These results have to be compared with the ones obtained with the measurements. The parameter that will be discussed in this chapter is the reverberation time. This is the most important parameter in determining the acoustic quality of a hall. Once the results of this parameter are accepted, the virtual model will represent the real situation. If the results fall within an interval of ±10% of the original results for the reverberation time, the values can be considered as true. When that is not the case, the materials and their absorption coefficient have to adapted so in the end, the virtual and the real results align.

| | **63** | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| Std Dev.- | 0,271839 | 0,556171 | 0,460559 | 0,742998 | 0,906147 | 0,953096 | 0,902288 | 0,645659 |
| **Average** | 0,3423 | 0,7372 | 0,728444 | 0,899867 | 0,940222 | 1,013489 | 0,916578 | 0,6563 |
| Std Dev.+ | 0,412761 | 0,918229 | 0,99633 | 1,056735 | 0,974297 | 1,073882 | 0,930868 | 0,666941 |

**Table 4.3.2.1:** The results for the reverberation time of the real situation

Virtual results of the calculated reverberation time after a precision calculation with the original materials and absorption coefficients:

| | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | |
| Average | 0,939333333 | 1,0866667 | 0,948667 | 0,917333 | 0,989333 | 1,075333 | 0,910667 | 0,588 |
| Std Dev. | ONWAAR | ONWAAR | WAAR | WAAR | ONWAAR | ONWAAR | WAAR | ONWAAR |
| Within the 10% | ONWAAR | ONWAAR | ONWAAR | WAAR | WAAR | WAAR | WAAR | ONWAAR |

**Table 4.3.2.2:** The virtual results of the average reverberation time of the Aula Magna after a precision calculation[8]

Legend of the table above:

**Average** = average values of the reverberation time calculated by the software for the different frequencies

**Std Dev**. = lies the virtual result within the standard deviation of the average values of the real reverberation time or not?

**Within the 10%** = lies the virtual result for the reverberation time within the interval of 10% of the values of the real reverberation time or not?

ONWAAR = NOT TRUE = the value doesn't answer to the conditioning = the result of the reverberation time is too different of the result in the real situation

WAAR = TRUE = the value does answer to the conditioning = the results is a good presentation of the real situation

So as illustrated in the table above it is obvious that, when using the original materials and their absorption coefficients, there are some results for the reverberation time with a result that is too different from the real situation.

Important to note is that the results of the reverberation times for the frequencies 63Hz and 8000Hz. The fluctuations in the measured results for RT for these frequencies are very high and almost impossible to simulate with the ODEON. As these are frequencies that fall out of the range of the frequencies of the human voice and the frequencies of music in general (only and the lowest pedal

[8] The results for all parameters of the first calculations with the software ODEON can be found under 'Annex Annex 3 – *Results of the calculation in the software ODEON using the original materials and their specific absorption coefficients – minimum, maximum and average values for the different parameters'*.

notes of a pipe organ reach values lower than 63), the values belonging to these frequencies can be neglected.

To change the virtual obtained values of the average reverberation time, the absorption coefficients of the materials have to be adapted. As previously discussed there were a lot of shortcomings in the original construction of the Aula Magna, especially in the lateral walls (non-continuous amounts of insulations, different ways of attaching the wooden panels,…). That is way the absorption coefficients of the lateral walls will be changed first.

The average reverberation time for the frequencies 125Hz, 250Hz, 1000Hz and 2000Hz deviates too much from the measured average so the absorption coefficients of the lateral walls for these frequencies have to be changed first. The values of the reverberation time are too high and has to be lower so this means that the value of the absorption coefficient will have to increase (the reverberation time is inversely proportional to the absorption coefficient of a material – Sabine equation).

**ORIGINAL ABSORPTION COEFFICIENTS OF THE LATERAL WALLS**

| **FREQUENCY** | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|
| **ABSORPTION COEFFCIENT** | 0,04 | 0,04 | 0,04 | 0,03 | 0,03 | 0,03 | 0,02 | 0,02 |

**Table 4.3.2.3:** New absorption coefficients of the lateral walls

**FIRST ADJUSTMENT OF THE ABSORPTION COEFFICIENTS OF THE LATERAL WALLS**

| **FREQUENCY** | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|
| **ABSORPTION COEFFCIENT** | 0,08 | 0,06 | 0,04 | 0,03 | 0,04 | 0,04 | 0,02 | 0,02 |

**Table 4.3.2.4:** New absorption coefficients of the lateral walls

After doing the first adjusment to the absorption coefficient, the value of the reverberation times still couldn't be accepted. This is illustrated in the next table.

| | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|
| 2 | | | | | | | | |
| Average | 0,88 | 1,02 | 0,95 | 0,92 | 0,96 | 1,03 | 0,91 | 0,59 |
| Voorwaarde is stddev | ONWAAR | ONWAAR | WAAR | WAAR | WAAR | WAAR | WAAR | ONWAAR |
| Voorwaarde is 10% | ONWAAR | ONWAAR | ONWAAR | WAAR | WAAR | WAAR | WAAR | ONWAAR |

**Table 4.3.2.5:** Results for the average reverberation time after the first adjustments of the absorption coefficients of the lateral walls

After making a range of small adjustments and comparing the results for the reverberation time with the measured results, the final adjustment is in the next table. The absorption coefficients of the lateral walls are adapted in such a way that the values for the reverberation time can be accepted. Now the model can be seen as a good representation of the real situation.

**FINAL ADJUSTMENT OF THE ABSORPTION COEFFICIENTS OF THE LATERAL WALLS**

| **FREQUENCY** | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|
| **ABSORPTION COEFFCIENT** | 0,4 | 0,2 | 0,16 | 0,03 | 0,04 | 0,04 | 0,02 | 0,02 |

**Table 4.3.2.6:** Final adjustment of the absorption coefficients of the lateral walls

| | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|
| 5 | | | | | | | | |
| Average | 0,69 | 0,79 | 0,77 | 0,92 | 0,96 | 1,03 | 0,91 | 0,59 |
| Voorwaarde is stddev | ONWAAR | WAAR | WAAR | WAAR | WAAR | WAAR | WAAR | ONWAAR |
| Voorwaarde is 10% | ONWAAR | WAAR | WAAR | WAAR | WAAR | WAAR | WAAR | ONWAAR |

**Table 4.3.2.7:** Results for the values of the reverberation time after the final adjustment of the lateral wall. All values are considered to be 'TRUE' and a good representation of the real measured reverberation time.

Now the virtual model is adapted to the real situation, final calculations can be done by the software. This is called a 'grid calculation'. Until now, the results of the parameters where based on the results obtained by only 15 receiver points in the Aula Magna. These 15 points were equally divided over the seating area in the hall to obtain a complete result that can represent the whole seating area.

But in this software it is possible to define a grid measurement so the program calculates the different parameters for as many receiver points as possible for the whole seating area. In this case, a grid size of 0,20m was chosen. This means a distance of 0,2m between every virtual receiver. These calculations take a long time of course, because instead of 15 receiver points, there are now more than 2000 receiver points.

After doing this calculations a final and precise result for the reverberation time is obtained:

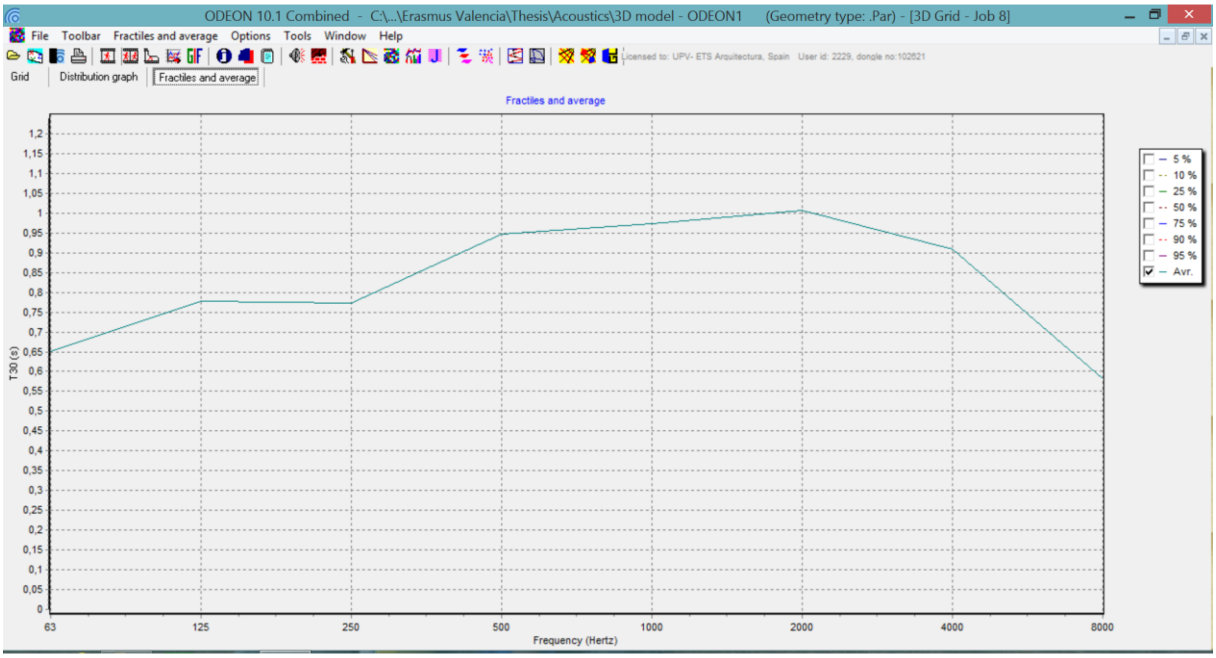
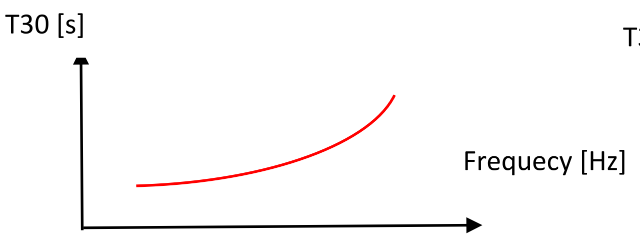


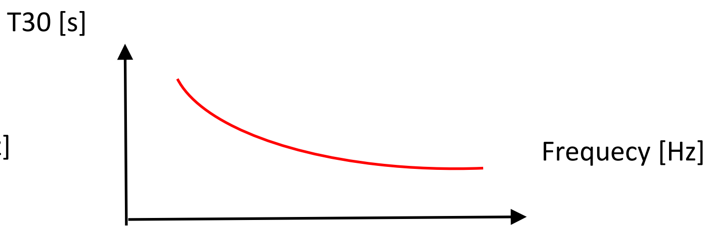

**Fig. 4.3.2.1:** Final average value of the reverberation time of the Aula Magna at ETSIE building for a varying frequency.

This leads to the final part of the acoustic analysis of the Aula Magna, improvement of the acoustic quality of the Aula Magna, so the curve of the average reverberation time follows the optimum variation of the reverberation time for speech and music.

Optimal for speech




Optimal for music



# 5 Suggestions for improvements and conclusion

After analysing the Aula Magna at the ETSIE faculty with the help of real measurements and simulations in ODEON, some conclusions can be made.

It can be said that the curve of the reverberation time of the hall doesn't follow either of the optimum curves recommended for speech or music. A solution could be to change some of the materials. By changing materials, the absorption coefficients are changed and so does the reverberation time. This hall has to be able to adapt to two kind of activities (music and speech) which lead to two different kind of variations of the reverberation time. To solve this problem, panels with two different sides, a reflective surface and an absorption surface, can be installed in the auditorium. That way a room can either serve as music hall or a lecture room.

In this case though, the problem lies more in the way that everything was constructed than in the quality of the materials that were used. It starts already with the construction of the original building of the classroom before it was even changed to the Aula Magna. For example the inconsistent way that insulation was placed has a big effect on the results of the reverberation time. Also when changing the classroom to an auditorium, the changes were not done in a proper way. If any improvements should occur in real life, they would have to start with solving these problems for the lateral walls.

The conclusion can be made that the acoustic comfort for speech and music in the Aula Magna is not ideal and changes need to be made so the Aula Magna can adapt in a proper way to either musical performances or lectures given in the auditorium.

PART 2: THERMAL ANALYSIS

## 1. Objective

The objective of the thermal analysis is to evaluate the thermal conditions of the ETSIE building at UPV. This is done with the help of the passive house program PHPP (Passive House Planning Package). The building is a university building. This means that this is a non-residential building. The following criteria have to be obtained to receive a passive house certificate:

- Specific space heating demand: ≤ 15 kWh/(m²a)
- Specific useful cooling demand: ≤ 15 kWh/(m²a)
- Total specific primary energy demand: ≤ 120 kWh/(m²a)
- Airtightness: ≤ 0.6/h

All these parameters are calculated by the program. Once the results are obtained for a specific area of the ETSIE building, they can be compared to the required standard for passive houses. Improvements such as insulation, renewable energy, better equipment for cooling/heating, ventilation etc. are all important factors to achieve this quality design. A passive house is the example of such a design, it's a building with comfortable indoor conditions throughout the year, achieved with minimum energy input. The design and construction are very important in this matter.

The studied area is housed at the Universitat Politecnica de Valencia, Campus de Vera. It is located in building 1B: ETS d'Enginyeria d'Edificacion. A picture of the location and a floor plan of the studied 'Area 4' can be found below.


**Fig. 1.1:** Location of building 1B at the Vera Campus of Universitat Politecnica de Valencia

**Fig. 1.2:** Picture of the location of ‘area 4’ at ETSIE Building

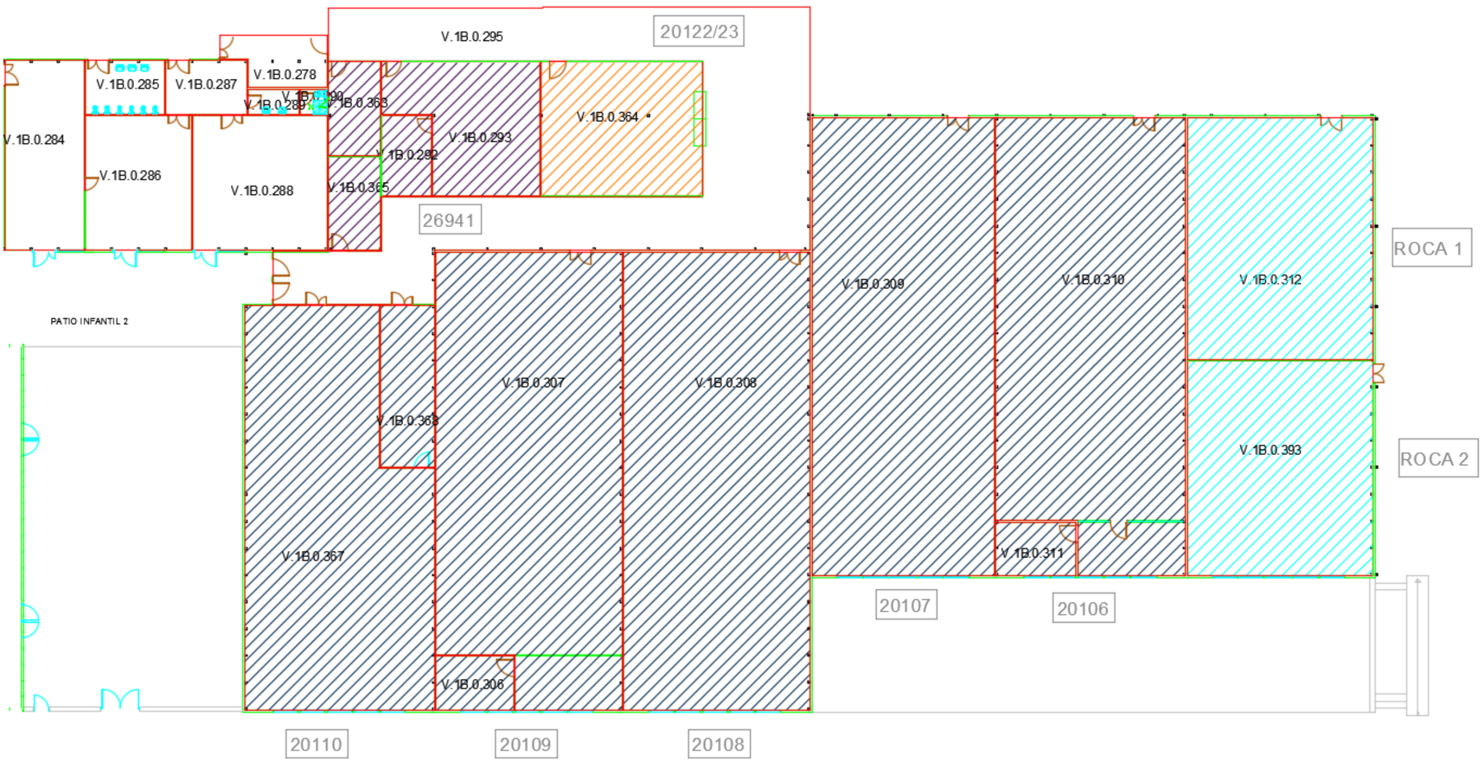



Fig. 1.3: Floor plan of ‘Area 4’ – the hatched area is the working area of 1740 m²

As previously stated, the thermal analysis consists of an evaluation of the heating and cooling criteria and the primary energy demand. This with the help of the excel file 'Thermal Study' that is included on the CD. To determine this parameters, the different steps, that have been laid down by the program PHPP, need to be followed.

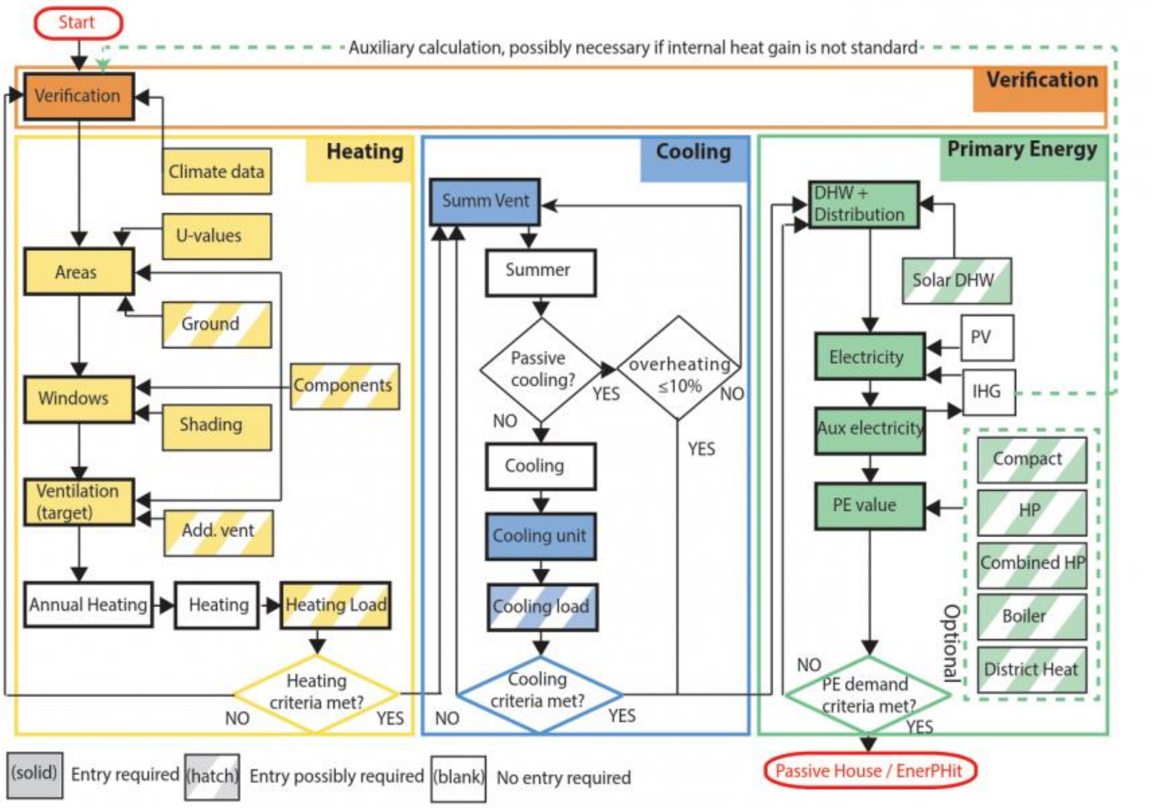



**Fig. 1.4:** Overview of the working of the program PHPP[9]

## 2. The heating demand

### 2.1 Climate

The climate is the first parameter that has to be taken into account when determining the heating demand. Because the seasons and the heat outside have a big influence. In a warm climate like the one in Valencia, it's primarily important to focus on the cooling demand and less on the heating demand. Specific data concerning the climate is motivated under the tab 'Clima'. In this case the city is not Valencia but Barcelona. This is because the data for Valencia was available to choose in the excel file, so Barcelona was chosen as the next best option. This has an effect on the outside temperature and the solar radiation, as illustrated in the next graphic.

[9] The Passive House Resource - http://www.passipedia.org/

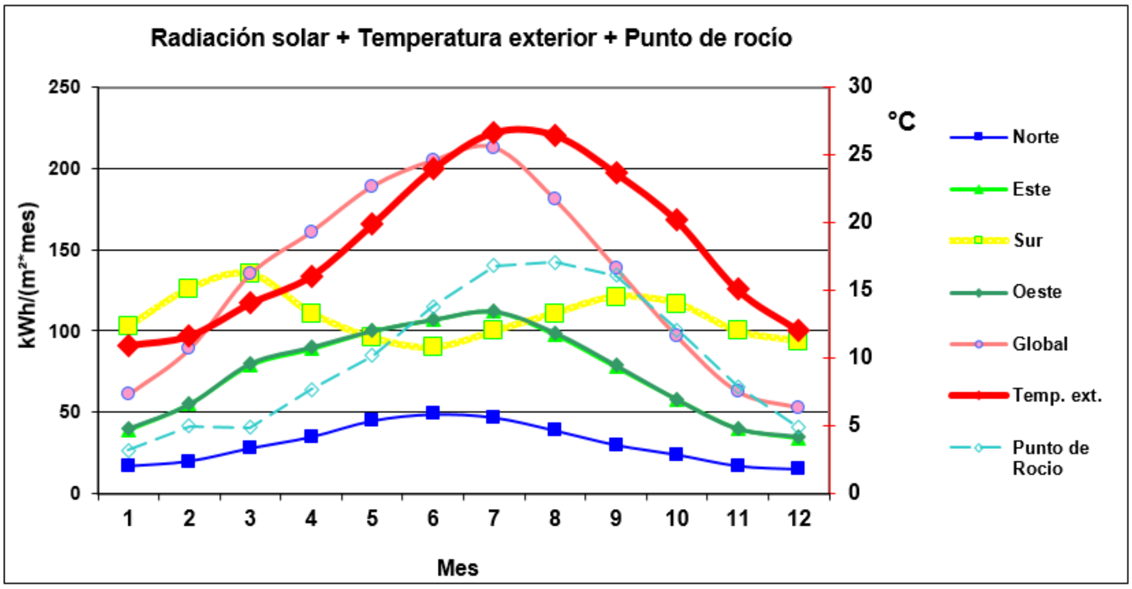



**Fig. 2.1.1:** Graphic of the solar radiation and the exterior temperature, determined by the location of the building

## 2.2 Calculation of heat losses by transmission

To know the heat losses caused by transmission, the thermal conductivity of all elements needs to be calculated. The overall heat transfer coefficient (U-value) describes how well a building element conducts heat (in watts) through one square metre of a structure, divided by the difference in temperature across the structure. The higher the U-value, the more heat gets lost by transmission. All calculations of U-values can be found under the tab 'Valores-U' in the excel file.

The building has been constructed in a single storey and the floor has an elevation of about 0,50m compared to the ground level. Underneath the floor there is also a low ventilated basement with an average height of 0,80m. Between the roof and the working area, there is also a false ceiling with a height of 1m. The total height of the building is 4,5m and the height of the working area is 3,5m. The building is more than 40 years old and a lot of simple prefabricated construction materials were used for the floor, the roof and the walls.

### 2.2.1 U-values

**WALL**

The walls are made out of prefabricated panels. The dimensions of the panels are 1,50m length by 0,50m height. The prefabricated panels on the inside walls have a thickness of 7cm and those for the exterior walls are 10cm thick. They are made out of a main layer of wood fibre between 2 layers of cement mortar. There is no structural function to the panels, this is completed by the steel frame where they are attached to. This frame of U-profiles makes sure there is a structural balance. All the U-profiles have the same section and only differ in length. The steel profiles are welded together per two so they get a rectangular shape and are hollow inside. The composition of the walls and the calculation of the heat transfer coefficient for the interior and the exterior wall is presented below.

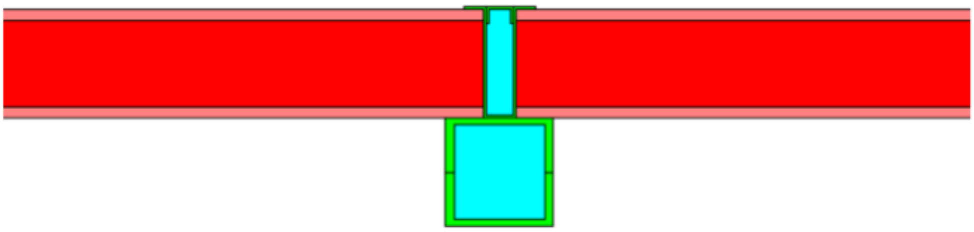


**Fig. 2.2.1:** Section of the exterior wall

| Nr. elem. cons. | Denominación de elemento constructivo | ¿Aislamiento interior? |
|---|---|---|
| 1 | Exterior Wall | |

Resistencia térmica superficial [m²K/W] interior $R_{si}$: 0,13 exterior $R_{se}$: 0,04

| | Superficie parcial 1 | λ [W/(mK)] | Superficie parcial 2 (opcional) | λ [W/(mK)] | Superficie parcial 3 (opcional) | λ [W/(mK)] | Espesor [mm] |
|---|---|---|---|---|---|---|---|
| 1. | Cement Mortar | 1,300 | | | | | 10 |
| 2. | Wood Fibre | 0,160 | | | | | 80 |
| 3. | Cement Mortar | 1,300 | | | | | 10 |
| 4. | | | | | | | |
| 5. | | | | | | | |
| 6. | | | | | | | |
| 7. | | | | | | | |
| 8. | | | | | | | |
| | Porcentaje superficie parcial 1 | 100% | Porcentaje superficie parcial 2 | | Porcentaje superficie parcial 3 | | Total 10,0 cm |

Suplemento al valor-U W/(m²K) **Valor-U: 1,459** W/(m²K)

**Table 2.2.1:** Calculation U-value of the exterior wall

| 2 | Interior Wall |
|---|---|

Resistencia térmica superficial [m²K/W] interior $R_{si}$: 0,13
exterior $R_{se}$: 0,13

| | Superficie parcial 1 | λ [W/(mK)] | Superficie parcial 2 (opcional) | λ [W/(mK)] | Superficie parcial 3 (opcional) | λ [W/(mK)] | Espesor [mm] |
|---|---|---|---|---|---|---|---|
| 1. | Cement Mortar | 1,300 | | | | | 10 |
| 2. | Wood Fibre | 0,160 | | | | | 50 |
| 3. | Cement Mortar | 1,300 | | | | | 10 |
| 4. | | | | | | | |
| 5. | | | | | | | |
| 6. | | | | | | | |
| 7. | | | | | | | |
| 8. | | | | | | | |
| | Porcentaje superficie parcial 1 | 100% | Porcentaje superficie parcial 2 | | Porcentaje superficie parcial 3 | | Total 7,0 cm |

Suplemento al valor-U W/(m²K) **Valor-U:** 1,701 W/(m²K)

**Table 2.2.2:** Calculation U-value of the exterior wall

**FLOOR**

The ground floor is the floor between the basement and the working area. It has an elevation of approximately 0.50m compared to the ground level. Underneath the floor slab there is a ventilated low basement of 0.80m high. The basement beneath the floor is ventilated so the same temperature as outside is supposed.

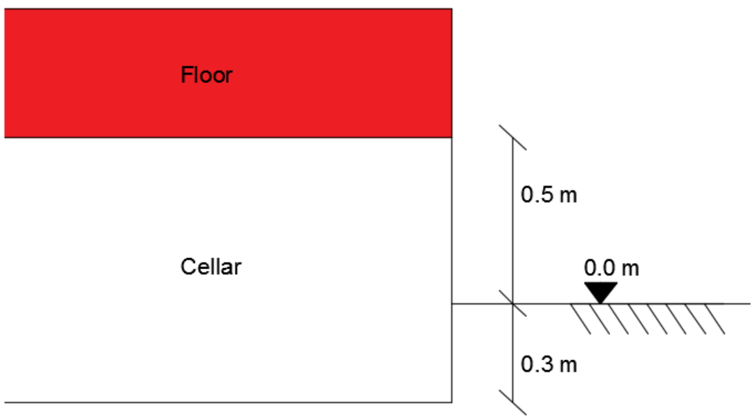



**Fig. 2.2.2:** Sketch of the location of the floor and cellar compared to the ground level

| 3 | Floor |
|---|---|

Resistencia térmica superficial [m²K/W] interior $R_{si}$: 0,17 exterior $R_{se}$: 0,04

| | Superficie parcial 1 | λ [W/(mK)] | Superficie parcial 2 (opcional) | λ [W/(mK)] | Superficie parcial 3 (opcional) | λ [W/(mK)] | Espesor [mm] |
|---|---|---|---|---|---|---|---|
| 1. | Tiles | 1,300 | | | | | 30 |
| 2. | Mortar | 0,800 | | | | | 30 |
| 3. | Sand | 2,000 | | | | | 30 |
| 4. | Reinforced Concrete (de | 1,430 | | | | | 300 |
| 5. | | | | | | | |
| 6. | | | | | | | |
| 7. | | | | | | | |
| 8. | | | | | | | |
| | Porcentaje superficie parcial 1 | 100% | Porcentaje superficie parcial 2 | | Porcentaje superficie parcial 2 | | Total 39,0 cm |

Suplemento al valor-U W/(m²K) **Valor-U:** **2,019** W/(m²K)

**Table 2.2.3:** Calculation U-value of the floor

## ROOF

The roof is made out of a concrete slab that takes care of the stiffness. This concrete layer has a thickness of 0,30m, which is very thick for a roof that has to be supported by a steel frame. The packed sand ensures the slope of 3cm/m to drain the roof. To calculate the packed sand as a layer with a constant thickness, the intermediate value of the thickness of the slope is used. The stones on top of the impermeable layer have multiple purposes, as there are the protection of the underlying layers against the influences of the wind and the sun.

| 4 | Roof |
|---|---|

Resistencia térmica superficial [m²K/W] interior $R_{si}$: 0,10 exterior $R_{se}$: 0,04

| | Superficie parcial 1 | λ [W/(mK)] | Superficie parcial 2 (opcional) | λ [W/(mK)] | Superficie parcial 3 (opcional) | λ [W/(mK)] | Espesor [mm] |
|---|---|---|---|---|---|---|---|
| 1. | Gravel | 2,000 | | | | | 50 |
| 2. | Bitumen | 0,170 | | | | | 10 |
| 3. | Packed Sand | 2,000 | | | | | 150 |
| 4. | Reinforced Concrete (me | 0,550 | | | | | 150 |
| 5. | Prefabricated Concrete ( | 1,150 | | | | | 150 |
| 6. | | | | | | | |
| 7. | | | | | | | |
| 8. | | | | | | | |
| | Porcentaje superficie parcial 1 | 100% | Porcentaje superficie parcial 2 | | Porcentaje superficie parcial 3 | | Total 51,0 cm |

Suplemento al valor-U W/(m²K) **Valor-U:** **1,425** W/(m²K)

**Table 2.2.4:** Calculation of the U-value of the roof

## FALSE CEILING

The false ceiling is composed out of tiles of synthetic fibre with the dimensions of 150x50x3 cm. The layout of the false ceiling is a web of U-profiles every one and a half metre with in-between the synthetic tiles. The installation of a false ceiling makes a space where pipes can run through without people seeing them. It's a barrier between this zone and the working area. It is only the working area that needs to have a comfortable temperature so the lower the U-value of the false ceiling, the better. That way heat doesn't escape to the 'pipe-zone' where it is not needed.  If not, the zone that has to be heated up becomes much bigger.

| 5 | False Ceiling |
|---|---|

| Resistencia térmica superficial [m²K/W] | | |
|---|---|---|
| | interior $R_{si}$: | 0,10 |
| | exterior $R_{se}$: | 0,10 |

| | Superficie parcial 1 | λ [W/(mK)] | Superficie parcial 2 (opcional) | λ [W/(mK)] | Superficie parcial 3 (opcional) | λ [W/(mK)] | Espesor [mm] |
|---|---|---|---|---|---|---|---|
| 1. | Synthetic Fibre | 0,030 | | | | | 30 |
| 2. | | | | | | | |
| 3. | | | | | | | |
| 4. | | | | | | | |
| 5. | | | | | | | |
| 6. | | | | | | | |
| 7. | | | | | | | |
| 8. | | | | | | | |
| | Porcentaje superficie parcial 1 | | Porcentaje superficie parcial 2 | | Porcentaje superficie parcial 3 | | Total |
| | | 100% | | | | | 3,0 cm |

| Suplemento al valor-U | | W/(m²K) | Valor-U: | 0,833 | W/(m²K) |
|---|---|---|---|---|---|

**Table 2.2.5:** Calculation U-value of the false ceiling

## WINDOWS

The last elements that are part of the thermal envelope are the windows. All the windows in 'Area 4' have the same dimensions, with a height of 1,5m and a width of 1,41m. The frame is made out of stainless steel and the glass that is used is a single glass of 6mm thick. The heat transfer coefficient (U-value) of the glass is 5.68 W/m²K and the window solar factor (g-value) is 0.91.

Overview of the properties of the glass:

- g-value (Solar factor ): 0.91 %/100
- U-value (Thermal Transmittance): 5.68 W / m²K
- Single glass (6 mm)

Overview of the properties of the framework:

Framework: U-value = 4,50 W/m²K

Ψ(spacer) = 0,03

Ψ(installation) = 0,04

As the exact values of the parameters are not known in this case. So the values that are used here are based on a framework defined as ‘Metal framework without thermal break’ found in the library of the PHPP program. The U-value is the same for all sides of the frame.

### 2.2.2 Shadows

The effect of shadow can’t be forgotten in the calculation of heat gains/losses through windows. The blinds in front of every window play in important part in this. Every window, disregarding the orientation, is equipped with permanent adjustable outdoor blinds. The type of shading is Venetian blinds. They allow controlling the light flow that enters the secretariat, protect the windows from external influences and prevent heating of the glass. The blades are made out of PVC and the dimension of each blade is 70x15x1.5 cm. The distance between the blades is 15 cm so there are 10 blades for each window. The inclination of each column of blades can be manually adjusted on the outside. The blinds already are very old, a lot of them can’t be adjusted anymore because they are rusted.

The formula to calculate the amount of shadow created by different factors is (with 100% = no shadow ; 0% = all shadow):

$$r_S = r_{Hori} * r_{Tel} * r_{Vol} * r_{otro}$$

As stated by the formula, the amount of shadow created is not only due to the blinds. There are for different factors that all togheter determine the total shadow percentage.

- r(hori) = the shadow due to buildings nearby the building. Here there are no buildings nearby the windows that can cause shadow so the value for r(hori) = 100%
- r(tel) = shadow caused by the fact that the window is built in in the exterior wall. As the thickness of the window is less than that of the exterior wall, a part of the side corner of the wall can cause a shadow.

d(tel) = 0,14m

o(tel) = 0,05m

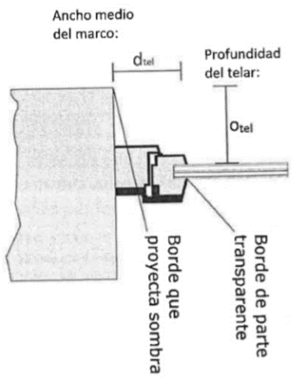



**Fig. 2.2.3:** Dimensions of d(tel) and o(tel)

- r(vol) = due to balconies or other projecting elements : not present here
- r(otro) = extra shadow factors for winter and summer, for example for shadows that are caused by trees. Trees are present here.
    - Winter: r(otro) = 50%
    - Summer r(otro) = 20%

As the exact values are not known for the type of trees in front of the window, the average values are supposed.

The last reduction factor is one that states if there is solar protection are not. Here you can count in the effect of the blinds in front of every window as the reduction factor 'z'. In the manual of the PHPP program there are different standard values for 'z', dependent on the kind of blinds.

según [DIN V 18599-2].

| | Acristalamiento aislado triple | | Acristalamiento aislado doble | |
|---|---|---|---|---|
| Tipo de protección solar | Posición exterior | Posición interior | Posición exterior | Posición interior |
| Persiana con láminas verticales: | 0.06 | 0.7 | 0.07 | 0.6 |

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| | | | | |
|---|---|---|---|---|
| Persianas con láminas a 45°: | 0.1 | 0.75 | 0.12 | 0.65 |
| Persiana enrollable / toldo blanco | 0.24 | 0.6 | 0.25 | 0.5 |
| Persiana enrollable / toldo gris | 0.12 | 0.8 | 0.14 | 0.75 |
| Lámina de plástico | - | 0.6 | - | 0.5 |

**Fig. 2.2.4:** Values for reduction factor 'z' ; shadow caused by blinds in front of the windows

For this building the type of blinds are of the category 'Persianas con láminas a 45°'. Be careful with the value for z because it is for double glass. If a simple calculation (without taking the thickness of the glass into consideration) is made to determine the percentage of shadow caused by the blinds, this value can be compared to the one in the tables of the manual of PHPP. If the values don't differ too much, the value in the table of the PHPP manual can be used, even though it is for double glass.

blinds = 10*0.15*sin(45°) =1,06

⇨ 1,06m of 1,5m is shaded, so this makes 70,67%.

This value is very similar to the one given in the table so we will suppose the one given in the table, thus 65%.

### 2.2.3 Surfaces

In the table beneath are all the elements of the thermal envelope where heat transmission can occur. Also the temperature zone of which they belong needs to be defined. There are two main categories:

- Temperature zone A: element in contact with the exterior air
- Temperature zone B: element in contact with the soil

Groups for specific types of areas are already defined in the program PHPP. In this building, the exterior walls, the windows and the roof all belong temperature zone A. For the floor there is also a pre-defined group, number '11'. But this group can't be used in this case as the floor of the building has a ventilated basement beneath it with outside conditions. So a new group has to be created for the floor where the temperature zone is A. This will have an influence on the calculation of the heat losses by transmission.

| Nr. de grupos | Grupo de superficies | Zona de temperatura |
|---|---|---|
| 1 | SRE (sup. de referencia energética) | |
| 2 | Ventanas al norte | A |
| 3 | Ventanas al este | A |
| 4 | Ventanas al sur | A |
| 5 | Ventanas al oeste | A |
| 6 | Ventanas horizontales | A |
| 7 | Puerta exterior | A |
| 8 | Muro ext. - aire ext. | A |
| 9 | Muro ext. - terreno | B |
| 10 | Techo / cubierta - Aire ext. | A |
| 11 | Solera / losa piso / forjado sanitario | B |
| 12 | Floor with ventilated basement ben | A |

**Fig. 2.2.5:** The different types of surfaces in the building and the temperature zone they belong to.

| NAME | DIMENSIONS | AREA [M²] |
|---|---|---|
| **SRE** | | 1733,1938 |
| **WINDOWS** | 6 x (1,5*5*1,41) | 63,45 |
| **FLOOR** | | 1770,31 |
| **EXTERIOR WALLS (CONTACT WITH AIR)** | | |
| **SOUTH-WEST** | (4,5*70,81) | 318,645 |
| **NORTH-WEST** | (4,5*24,4) | 109,8 |
| **ROOF (CONTACT AIR)** | | 1770,31 |

**Table 2.2.6:** Values of the different types of surfaces

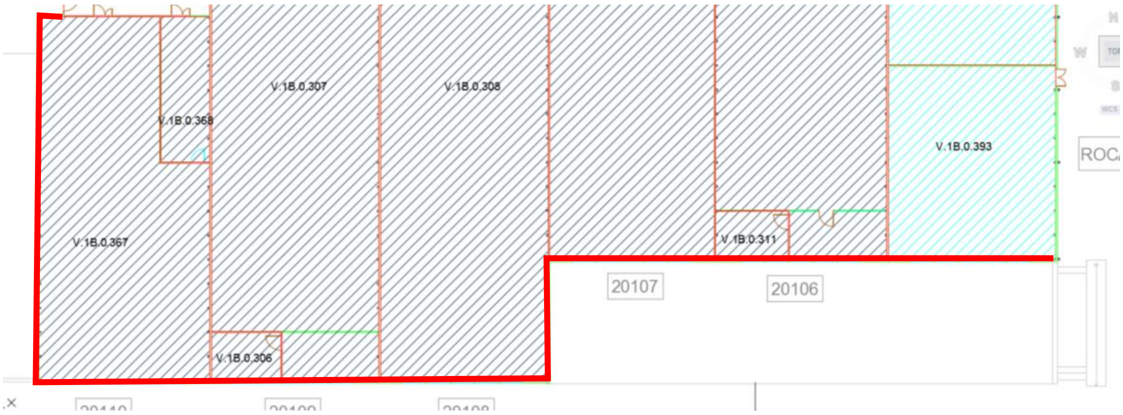
### 2.2.4 Thermal Bridges

The last phenomenon that has to be taken into account while calculating the heat losses by transmission is the fact that heat can also escape where there are thermal bridges. A thermal bridge is when a connection between two separate elements of the thermal envelope is not totally air tight. The two most thermal bridges for 'Area 4' are the connection between the exterior wall and the roof and the connection between the exterior wall and the floor. If the value of the linear thermal transmittance values Ψ is lower than 0,01 W/mK, the construction of the thermal bridge can be considered good and it doesn't have to be put into the program. The values of the two thermal bridges and the length over which these thermal bridges run in 'Area 4' are given below.

| Thermal Bridge | Linear transmittance Ψ [W/mK] |
|---|---|
| Exterior Wall – Roof | 0,106 |
| Exterior Wall – Floor | 0,438 |

**Table 2.2.7:** Linear transmittance values[10]

[10] Values of the linear transmittance – Thesis. *Passive house standard in a warm climate. Analysis of closures with tests in a university building. Passive house modelling with advanced computer tools.*
4




### 2.2.5 Result – heat loss by transmission

| Elemento constructivo | Zona de temperatura | Superficie m² | | Valor-U W/(m²K) | | Fact. red. mensual | | $G_t$ kKh/a | | kWh/a | Por m² de superficie de referencia energética |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Muro ext. - aire ext. | A | 365,0 | * | 1,459 | * | 1,00 | * | 34 | = | 17989 | 10,38 |
| Muro ext. - terreno | B | | * | | * | 1,00 | * | | = | | |
| Techo / cubierta - Aire ext. | A | 1733,2 | * | 1,425 | * | 1,00 | * | 34 | = | 83403 | 48,12 |
| Solera / losa piso / forjado sai | B | | * | | * | 1,00 | * | | = | | |
| Floor with ventilated basement l | A | 1733,2 | * | 2,019 | * | 1,00 | * | 34 | = | 118190 | 68,19 |
| | A | | * | | * | 1,00 | * | | = | | |
| | X | | * | | * | 0,75 | * | | = | | |
| Ventanas | A | 63,5 | * | 2,114 | * | 1,00 | * | 34 | = | 4531 | 2,61 |
| Puerta exterior | A | | * | | * | 1,00 | * | | = | | |
| Puentes térmicos exteriores(lon | A | 182,7 | * | 0,272 | * | 1,00 | * | 34 | = | 1679 | 0,97 |
| Puentes térmicos perímetro (lon | P | | * | | * | 1,00 | * | | = | | 0,00 |
| Puentes térmicos piso (longitud | B | | * | | * | 1,00 | * | | = | | 0,00 |
| | | | | | | | | | | ----------- | kWh/(m²a) |
| **Pérdidas de calor por transmisión QT** | | | | | | | | | Total | 225792 | 130,3 |

The final results for heat losses by transmission can be found under the tab 'Calefacción' where the calculation are made based on the monthly method. As seen in the table above, the value of this kind of heat losses is very high. This is mostly due to the fact that the heat transfer coefficients for all the elements are way too high. A solution can be to add insulation for the roof, walls and the floor. The effect of this type of solution will be tested and the results can be found in chapter 5 'Improvements'.

## 2.3 Calculation Heat losses by ventilation

The second factor that can lead to heat losses in the school building is the effect of ventilation. The school of building engineering is heated, cooled and ventilated with the same installations (placed on the roof) and the same pipe networks. . Fresh air is conditioned and then blown into the different spaces. The set points for the heating and cooling installation are 20°C and 25°C respectively. These temperatures should ensure comfortable working conditions during working hours. The school hours are set from 8 a.m. to 8 p.m. from Monday until Friday for the whole building. This schedule is considered the same for all active conditioning devices that are used in the building. By night all the devices are switched off.

There is no information available about the present installations so the results of the calculations won't reflect the current situation precisely. So to classify the result as good or bad is really hard because there had to be made a lot of assumptions that could cause a big difference in the results obtained by the program and the real situation.

Formula to calculate the heat losses due to ventilation:

$$Q_V = n_V \cdot V_V \cdot c \cdot G_t$$

$n_V$ = energy efficient air exchange rate

$V_V$ = effective air volume (SRE x free height); in this case $V_V$ = 1733 x 3,5 = 6066m³

c = specific air warmth = 0,33 Wh/m³K

$G_t$ = depends on the period of heating and the climate = 34 kKh/a

The value for $n_V$ is dependent on the air exchange rate caused by the installed ventilation system and the air exchange rate due to the airtightness of the thermal envelope. So it can be pointed out the that heat losses by ventilation depend on the quality of the ventilation system and the quality of the construction of the building. The better these qualities, the lower the value of the energy efficient air exchange rate and the lower the heat losses are.

The airtightness of the thermal envelope can be measured by doing a BlowerDoor test in one of the classes. The BlowerDoor test is a way to examine uncontrolled air exchange, locate leakages in the thermal envelope and determine the rate of air exchange. By measuring the differential pressure the airtightness of a building is determined. Both under and overpressure of 50 Pa are used. Performing this test, many disadvantages can be eliminated or prevented. The value of the airtightness of the thermal envelope of 'Area 4' hasn't been measured so standard will be used to calculate the air exchange rate caused by infiltration. For a passive house the air change rate is maximum 0.6 times the volume per hour. In older buildings with single glass windows, this value is located somewhere between 8 and 10 volumes per hour.

**Tasa de renovación de aire por infiltración**

| Coeficientes de protección al viento e y f | | |
|---|---|---|
| Coeficiente e de clase de protección de viento | Varios lados expuestos al viento | Sólo un lado expuesto al viento |
| Sin protección del viento | 0,10 | 0,03 |
| Protección del viento moderada | 0,07 | 0,02 |
| Protección del viento alta | 0,04 | 0,01 |
| Coeficiente f | 15 | 20 |

| | | | P/ demanda anual | P/ periodo calefacción: | | |
|---|---|---|---|---|---|---|
| Coeficiente de protección al viento e | | | 0,02 | 0,05 | | |
| Coeficiente del protección al viento f | | | 20 | 20 | Volumen de aire neto para el ensayo de presión | $V_{n50}$ |
| Tasa renovación aire ensayo presión | $n_{50}$ | 1/h | 10,00 | 10,00 | 6066 | m³ |
| | | | P/ demanda anual | P/ periodo calefacción: | | |
| Exceso de aire de extracción | | 1/h | 0,00 | 0,00 | | |
| Tasa renovación aire por infiltración | $n_{V,Infiltración}$ | 1/h | 0,200 | 0,500 | | |

**Fig. 2.3.1:** Calculation of the air exchange rate due to infiltration

The second factor, the air exchange rate caused by the ventilation system, depends on the efficiency of the system. The exact installed ventilation system is not known for this building, so the standard value of an efficiency of 75% will be taken into account. This efficiency is probably higher than the one actually installed because the system is quite old so this has to be taken into account when evaluating the final results. Also important to know is that in two classrooms of the building (classroom V.1B.0.312 and V.1B.0.393)[11] a new ventilation/heating/cooling system has been installed. So there the efficiency will be higher. This isn't put into account when analysing the thermal quality because the results for the classrooms with the oldest systems (worst case scenarios) are important to make suggestions for improvement.

The choice of a ventilation system with a standard efficiency of 75% leads to a standard average air exchange of 0,425 1/h.

[11] The location of these two classrooms can be seen on the floor plan of 'Area 4' in chapter 1. The classrooms with the blue hatches are the ones with a new installed system.

Results for the heat losses due to ventilation:

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Caudal de aire efectivo $V_v$ | | $A_{SRE}$ m² | | Altura libre habitación m | | m³ | |
| | | | | | 1733 | * | 3,50 | = | 6066 | |
| | $n_{V,sist}$ 1/h | | $\eta^*_{ITA}$ | | $\eta_{HR}$ | | $n_{V,Res}$ 1/h | | $n_{V,equi,fracción}$ 1/h | |
| Renovación de aire efectiva exterior $n_{ventilación,efectiva}$ | 0,425 | *(1- | 0% | )*(1- | 0,75 | )+ | 0,200 | = | 0,306 | |
| Renovación de aire efectiva terreno $n_{ventilación,terreno}$ | 0,425 | * | 0% | *(1- | 0,75 | ) | | = | 0,000 | |
| | $V_V$ m³ | | $n_{V,equi,frac}$ 1/h | | $c_{aire}$ Wh/(m³K) | | $G_t$ kKh/a | | kWh/a | kWh/(m²a) |
| **Pérdidas de ventilación, exterior $Q_{Vent,e}$** | 6066 | * | 0,306 | * | 0,33 | * | 34 | = | 20750 | 12,0 |
| **Pérdidas de ventilación, terreno $Q_{Vent,ter}$** | 6066 | * | 0,000 | * | 0,33 | * | 4 | = | 0 | 0,0 |
| **Pérdidas de calor ventilación $Q_{Vent}$** | | | | | | | | Total | 20750 | 12,0 |

**Fig. 2.3.2:** Heat losses due to ventilation

## 2.4 Calculation Heat Gains: Internal and solar radiation

### 2.4.1 Internal Heat Gains

The internal heat gains are composed out of the different loads, these are the internal gains caused by the number of people occupying the classrooms. Second of all the heat gains caused by the illumination of the classrooms and third of the caused by other electrical devices that are present in 'Area 4'. To calculate the total internal heat gains with the help of the PHPP program for a non-residential building, several steps have to be followed.

First of all, the use of the classrooms by professors and students has to be defined with help of the tab 'Uso-NR' in the excel file. This makes it possible to create different types of rooms with each a typical user profile. This profiles consist of parameters to declare the hours the rooms are used, the number of days in a year they are use, the intensity of light that has to be present in the rooms and the percentage of usage of the lights.

| | Perfil de uso | Periodo de uso y operación | Hora de comienzo de uso [h] | Hora de fin de uso [h] | Número horas de uso por día (horas/día) | Número días de uso por año (d/a) | Horas de uso por año (h/a) | Horas de uso diurno por año (h/a) | Horas de uso nocturno por año (h/a) | Horas de operación diarias calefacción | Horas de operación diarias ventilación | Iluminación | Intensidad de iluminación (lux) | Altura del nivel de utilización (0.8 ó 0.0m) | Altura del nivel de utilización (0.8 ó 0.0m) | Ausencia relativa | Factor de uso parcial periodo tiempo de funcionamiento iluminación | Promedio de la ocupación (m²/persona) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Aula de clases | | 8 | 20 | 12 | 220 | 2640 | 2205 | 435 | 14 | 14 | | 300 | 0,8 | 0,8 | 0,25 | 0,8 | 2,0 |
| 2 | Library | | 8 | 20 | 12 | 220 | 2640 | 2205 | 435 | 14 | 14 | | 200 | 0,8 | 0,8 | 0,90 | 0,8 | |
| 3 | Small Classes | | 8 | 20 | 12 | 220 | 2640 | 2205 | 435 | 14 | 14 | | 100 | 0,8 | 0,8 | 0,90 | 0,5 | |
| 4 | | | | | 0 | | 0 | 0 | 0 | 2 | 2 | | | | 0,8 | | | |

For ‘Area 4’ there are three main types of rooms. The normal classroom, the library and the small classes. The small classes are all the rooms in ‘Area 4’ with an area of less than 30m².

The number of days that the rooms are used in a year are an estimation and are calculated the following way:

52 weeks x 5 days/week = 260 days

- 2 times a holiday of 14 days, so 10 days less
- 1 time a long holiday of 2 months, so 2x4x5 = 60 days

= 220 days

Second of all the internal heat gains due to electrical applications, the lights and other electrical devices, has to be calculated. This with the help of the tab ‘Electricidad-NR’ in the excel file.

The internal heat gains by illumination are based on the amount of energy needed to illuminate all rooms properly. To calculate the illumination demand for all rooms in ‘Area 4’ the next parameters have to be taken into account:

- The surface of the room
- The type of room (predefined in the tab ‘Uso-NR’)
- Are there windows present?
- Dimensions
    - Depth and width of the room
    - Height and width of the windows
- How is the lighting controlled?

| Iluminación /edificio no residencial | Proporción de SRE | Categoría de habitación | Categoría de habitación | Intensidad de iluminación nominal | Fachada con ventanas: Desviación con respecto al norte | Fachada con ventanas: Orientación | Fachada con ventanas: Transmisión de luz por el vidrio | Ventana existente (1/0) |
|---|---|---|---|---|---|---|---|---|
| Habitación / zona | | | | Lux | grados | | - | |
| ¡El total de las superficies supera el 100%! | | | 2 | 15 | | | | |
| Classroom V.1B.0.368 | 2% | 1 | Aula de clases | 300 | 135 | Este | 90% | 0 |
| Library | 14% | 2 | Library | 200 | 135 | Este | 90% | 1 |
| Classroom V.1B.0.307 | 15% | 1 | Aula de clases | 300 | 135 | Este | 90% | 1 |
| Classroom V.1B.0.308 | 15% | 1 | Aula de clases | 300 | 135 | Este | 90% | 1 |
| Classroom V.1B.0.309 | 15% | 1 | Aula de clases | 300 | 135 | Este | 90% | 1 |
| Classroom V.1B.0.310 | 15% | 1 | Aula de clases | 300 | 135 | Este | 90% | 0 |
| Classroom V.1B.0.311 | 1% | 3 | Small Classes | 100 | 135 | Este | 90% | 1 |

| Iluminación /edificio no residencial | Geometría de la habitación: Introducción de una habitación tipo: Profundidad de la habitación | Anchura de la habitación | Altura de la habitación | Altura del dintel | Anchura de la ventana | Advertencia de introducción de datos | Aprovechamiento iluminación natural | Valores propios: potencia instalada de iluminación. | Potencia instalada de la iluminación (estándar) | Control de iluminación |
|---|---|---|---|---|---|---|---|---|---|---|
| Habitación / zona | m | m | m | m | m | | | W/m² | W/m² | |
| Classroom V.1B.0.368 | 9,0 | 3,0 | 3,5 | | | ¡Contradicción: Comprobar datos de anchura y altura! | ninguna | | 9,8 | 1 |
| Library | 22,5 | 10,0 | 3,5 | 3,0 | 7,0 | | ninguna | | 7,2 | 1 |
| Classroom V.1B.0.307 | 22,5 | 10,0 | 3,5 | 3,0 | 7,0 | | ninguna | | 9,8 | 1 |
| Classroom V.1B.0.308 | 22,5 | 10,0 | 3,5 | 3,0 | 7,0 | | ninguna | | 9,8 | 1 |
| Classroom V.1B.0.309 | 22,5 | 10,0 | 3,5 | 3,0 | 7,0 | | ninguna | | 9,8 | 1 |
| Classroom V.1B.0.310 | 22,5 | 10,0 | 3,5 | | | ¡Contradicción: Comprobar datos de anchura y altura! | ninguna | | 9,8 | 1 |
| Classroom V.1B.0.311 | 3,0 | 4,0 | 3,5 | 3,0 | 3,0 | | ninguna | | 4,6 | 1 |

All these parameters are calculated for every separate room in ‘Area 4’ and can be found under tab ‘Electricidad-NR’. Finally, the illumination demand is 30 568 kWh/a and based on this value the internal heat gain will be calculated.

There are also some electrical devices present in 'Area 4' that creat an internal heat as well. Because the amount of all devices is not exactly known for all classes, only the devices permenantly present in the library are taken into account. These are two computers and one copy machine.

Finally, all this data is used to calculate the final heat gain and these calculations can be found under the tab 'GIC-NR' in the excel file.

### 2.4.2 Solar Radiation

Not only the internal working of a building but also the presence of the sun and the fact that there are windows in the building that capture this sunlight lead to heat gains. The more windows there are in the building, the more sunlight can be brought into the classrooms. But there are some factors that lead to a reduction of the warmth caused by sunlight falling into a room. It's not possible to just multiply the area of windows by the global radiation because the presence of shadows, the solar energy transmittance of glass (g-value), … are all factors that lead to a decrease of the heat gains by solar radiation. Here the reduction factor is 0,26 and that is mainly caused by the effect of the shadow because of the blinds in front of the window and the trees nearby the building. The calculation of the effect of shadow was previously discussed in chapter 2.2.2.

*Global Radiation*

The solar radiation energy during a given time is a parameter to define the solar irradiance. The solar irradiance is a measure of the irradiance (power per unit area on the earth's surface) produced by the sun in the form of electromagnetic radiation, which is perceived by people as sunlight. The outside temperatures as well as the surface temperatures are highly influenced by the solar irradiance. Therefore it has a big influence on the heating and cooling demand. When there is a lot of solar irradiation reaching the earth's surface we can determine higher temperatures and vice versa. So when there is sun, it's warm. When there are a lot of clouds, and thereby little solar irradiance the outside temperatures are lower. Here the specific values of the solar radiation are set when choosing a specific climate.

| Orientación de la superficie | Factor de reducción Compare c/ hoja 'Ventanas' | | Valor g (Radiación perpendicular) | | Superficie m² | | Radiación global kWh/(m²a) | | kWh/a | kWh/(m²a) |
|---|---|---|---|---|---|---|---|---|---|---|
| Norte | 0,00 | * | 0,00 | * | 0,0 | * | 201 | = | 0 | |
| Este | 0,00 | * | 0,00 | * | 0,0 | * | 494 | = | 0 | |
| Sur | 0,26 | * | 0,91 | * | 63,5 | * | 761 | = | 11295 | |
| Oeste | 0,00 | * | 0,00 | * | 0,0 | * | 498 | = | 0 | |
| Horizontal | 0,00 | * | 0,00 | * | 0,0 | * | 848 | = | 0 | |
| Total superficies opacas | | | | | | | | | 71208 | |
| **Ganancias de calor por radiación solar $Q_S$** | | | | | | | | Total | 82503 | 47,6 |

## 2.5 Result: total heating demand

After bringing all the previous parameters and calculations into consideration, the final heating demand for ‘Area 4’ at the building 1B of the faculty ETSIE is 93kWh/m²year. From which can be concluded that the building doesn’t meet the requirement for heating of the passive house standards. This is no surprise because the building is 40years old and back than there were no considerations made for constructing a low energy building.

In the graphic beneath (and also in the excel-fil under the tab ‘Calefacción’ the red bar illustrates the amount of heating demanded to have a balance between heat losses and gains.

For the bar that represents the gains, it can be stated that most of the gains come from solar heat gains. This is due to the fact that the windows have a high value for the the solar energy transmittance and also to the influence of the climate the building is situated. The windows don’t only have a high solar energy transmittance value but are also made of single glass of 6mm thick which lead to a heat loss.

The heat losses are mostly caused by heat transmission through the roof and the floor. The ventilation is another important factor in the calculation of the heating demand. As the type of ventilation system is not known and the efficiency of the system is set on a standard value this result can’t be supposed as true. Because a lot of assumptions had to be made it’s important to be carefull with drawing conclusions out of these results. One thing is for sure, the building doesn’t meet the necessary requirements for passive houses so changes have to made.

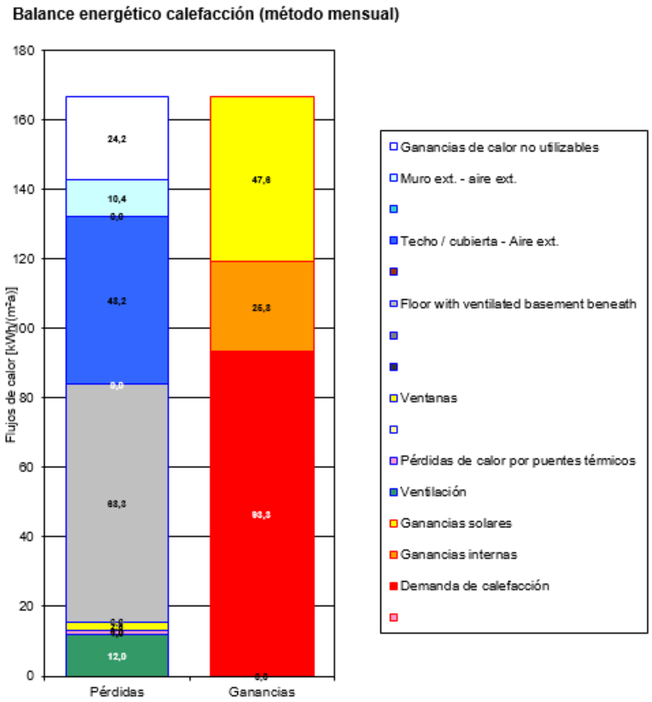
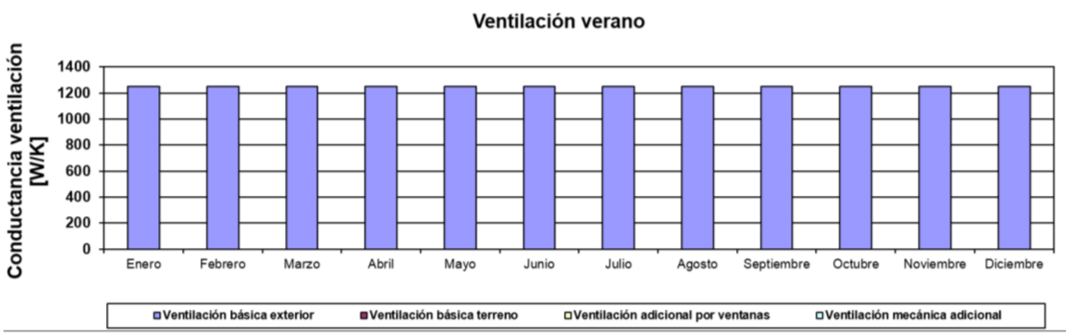



**Fig. 2.5.1:** Graphic illustration of the results for the heating demands in 'Area 4'

## 3. The cooling demand

Not only is there a specific heating demand but also a cooling demand. Especially for a Mediterranean climate like the one in Valencia with mild winters and hot summers. To make out the necessary cooling in building 'Area 4' an extra parameter has to be taken into account, that is the ventilation in summer. The data for these calculations need be filled in under the tab 'Ventilacíon – V'. Because the school of building engineering is heated, cooled and ventilated with the same installations (placed on the roof) and there is no information on the installations, the same ventilation conditions are used for winter and summer. So in the graphic of the overview of the ventilation systems for the summer, there is only one system working and it has the same performances for the entire year.



So heat losses caused by ventilation will only be due to the same standard ventilation because there are no extra measurements supposed.

The other heat losses will be caused by transmission. In case of cooling it is thus a good thing that the floor is above a ventilated basement. This is a passive way of cooling. Again there are transmission losses through the other elements of the thermal envelope as well. As there are no extra considerations need to be made for the calculation of the cooling demand, the result can be obtained in the tab 'Refrigeración' in the excel-file.

The final cooling demand would be 50 kWh/m². But there is a warning given by the program. Due to high fluctuations in the daily inside temperature, the result is not reliable. This means that there is not enough solar protection and chances of overheating (overheating: when the inside temperature will be higher than the maximum temperature of 25°C) are great.

Frecuencia de sobrecalentamiento $h_{\vartheta \geq \vartheta máx}$ **30,0%** **en base al límite establecido $\vartheta_{máx}$ = 25 °C**

Cuando la "frecuencia sobre 25°C" rebasa el 10%, son necesarias otras medidas de protección contra calor en el verano.

**Fig. 3.1:** Frequency of overheating in building 'Area 4'

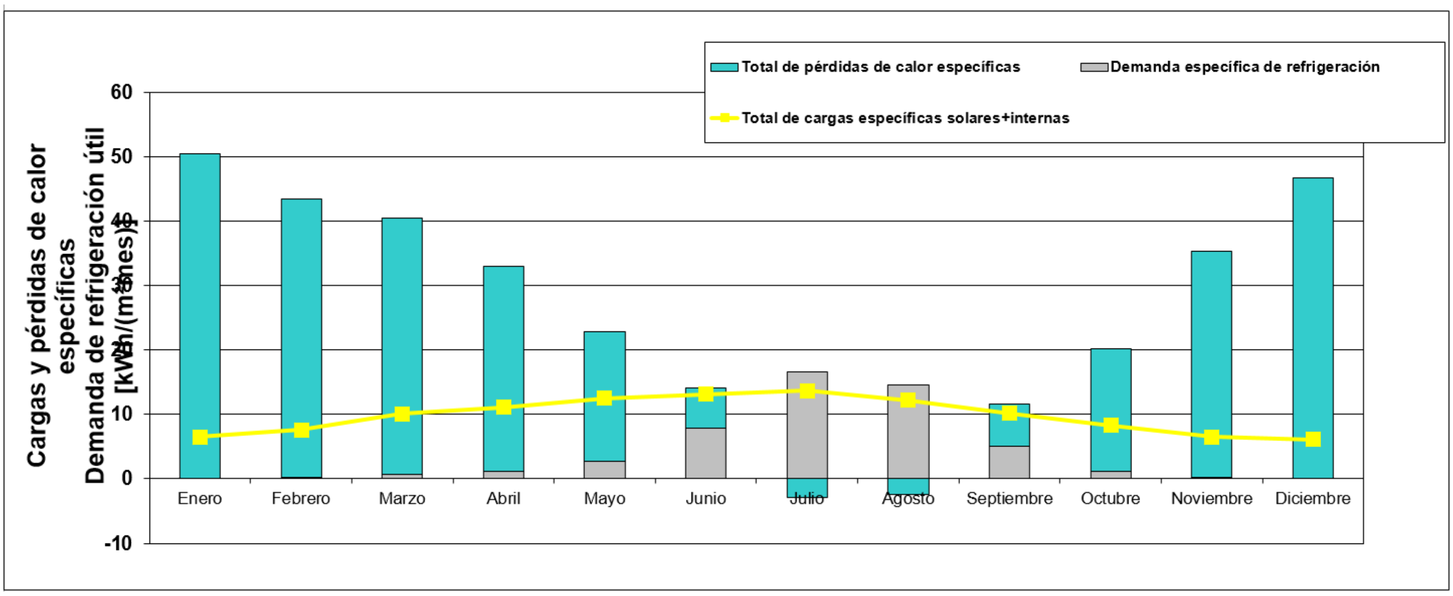



**Fig. 3.2:** Cooling demand (grey bars) in the building 'area 4' during the year

Without going into detail, because assumptions of the ventilation/heating system had to made, there can be two main conclusions drawn out of these results. First of all, the chances that overheating occurs are too high so extra solar protection has to be installed (changing the windows, insulation,..) and second of all the cooling demand is too high. It exceeds the required value of 15 kWh/m$^2$year for passive houses.

## 4. Primary energy demand

The only parameter left to determine is the primary energy demand. This is been calculated in chapter 2 because the internal heat gains caused by illumination and other electronic devices needed to be known for the heating demand.

Except for the lights and the electronic devices, the energy to make the installations work also needs to be taken into consideration. But because there is not enough information about the machines used in this zone it is impossible to calculate this value. There is no hot water in the building and there is no specific data about the heating, cooling and extra electrical devices. So without knowing the energy needed to obtain the 15 kWh/(m$^2$a) for cooling and heating, it is very hard to get a value for the auxiliary energy.

The primary energy demand for only the devices and the lights in the building is given below and can also be found under the tab 'Electricidad-NR' in the excel file.

| Demanda de electricidad (kWh/a) | | Demanda de energía primaria (kWh/a) | |
|---|---|---|---|
| 40948 | kWh/a | 106465 | kWh/a |
| 24 | kWh/(m$^2$a) | 61 | kWh/(m$^2$a) |

**Fig. 4.1:** Electricity and primary energy demand due to the lights and electrical devices in building 'Area 4'

There is a difference in the electricity needed to make the lights and the electrical devices work and the final energy demand. The primary energy is defined as the energy needed at the source to cover the final end use of energy. The conversion factor to know how much energy is needed at the source is 2,6 kWh/kWh. This means that for the use of 1kWh electricity, there is 2,6 kWh energy needed at the source.

The value of 61 kWh/m²a can't be compared to the maximum primary energy use of 120 kWh/m²a in passive houses because the energy needed to make the installations in the building work is not calculated in this result.

# 5. Suggestions for improvements

It can be concluded from the previous results that a lot of improvements have to made before this building will meet all the requirements of a passive building. In this last chapter of the thermal analysis of building 'Area 4' some suggestions for improvements will be made. By inserting these changes in the PHPP program, the effect on the heat, cooling and primary energy demand will be evaluated. One thing to take in consideration though is that these changes are all theoretical propositions. If the improvements would be installed in real life, an important factor should be taken in consideration and that is the financial one.

List of the improvements that will be evaluated:

- Insulation in the walls, the roof and the floor
- Different types of windows and framework
- Infiltration
- Ventilation

## 5.1 Insulation in the walls, floor and the roof

Based on the results of the initial model, some changes are made to the compositions of the walls, roof and floor. The insulation is added to the structure for two different thicknesses: 3cm and 6cm. Afterwards conclusions are drawn which improvements are the best to accomplish the conditions for a passive house. The type of insulation that will be used is PUR insulation with a λ-value of 0,023 W/mK.

The position of the insulation for the roof is between the stones and the bitumen. The position of the insulation in the floor is between the sand and the reinforced concrete.

| THICKNESS OF THE INSULATION | U-VALUE EXTERIOR WALL [W/M²K] | U-VALUE FLOOR [W/M²K] | U-VALUE ROOF [W/M²K] | HEAT DEMAND [KWH/M²A] | COOLING DEMAND [KWH/M²A] |
|---|---|---|---|---|---|
| **3 CM** | 0,503 | 0,556 | 0,498 | 23 | 27 |
| **6 CM** | 0,304 | 0,322 | 0,302 | 12 | 22 |

**Table 5.1.1:** Changes after adding 3 of 6cm PUR insulation in the exterior wall, the roof and the floor

Adding thermal insulation to the outer wall has a positive influence on the heating demand and on the cooling demand. The thermal insulation decreases the heat transfer trough the wall. So conditions inside are less influenced by the outside weather conditions in winter and summer. To that extent there is a decrease of both heating and cooling demand It is to be noted that the difference in cooling and heating demand for 3 or 6cm is not that big of a difference.

| THICKNESS OF THE INSULATION | HEAT DEMAND [KWH/M²A] | COOLING DEMAND [KWH/M²A] |
|---|---|---|
| **3 CM** | 88 | 86 |
| **6 CM** | 49 | 49 |

**Table 5.1.1:** Changes after adding 3 of 6cm PUR insulation in the exterior wall.

Adding thermal insulation to the roof slab has a positive influence on both the heating and cooling demand. The thermal insulation decreases the heat transfer through the roof slab. This positive effect on the heating demand is the same as for the wall insulation. Less heat is lost in winter. The positive effect on the cooling demand has two opposite effects. The building can't lose the heat that easy but on the other hand it's also more difficult for the heat to enter the building when the sun is shining on the roof and the surface temperature becomes really high.

| THICKNESS OF THE INSULATION | HEAT DEMAND [KWH/M²A] | COOLING DEMAND [KWH/M²A] |
|---|---|---|
| **3 CM** | 70 | 65 |
| **6 CM** | 29 | 25 |

**Table 5.1.3:** Changes after adding 3 of 6cm PUR insulation to the roof

Finally when adding insulation to the floor, two very opposite results are obtained. First of all it has the best influence on the heating demand. During winter the colder soil temperature will cool down the air in the basement. This will affect the temperature in the room due to the heat stream from the rooms to the basement. This means that the heating has to do an effort to keep the temperature on level. When we insert insulation, this will be reduced. But by installing insulation in the floor, the natural cooling effect of the ventilated basement will disappear. So installing floor insulation has no effect on cooling. And because the building is situated in a warm climate where cooling is important, the installing of floor insulation is not considered to be an improvement.

| THICKNESS OF THE INSULATION | HEAT DEMAND [KWH/M²A] | COOLING DEMAND [KWH/M²A] |
|---|---|---|
| **3 CM** | 52 | 46 |
| **6 CM** | 49 | 49 |

**Table 5.1.3:** Changes after adding 3 of 6cm PUR insulation to the floor

## 5.2 Changing the type of windows and framework

When changing the type of the window and the framework, two influences should be taken into consideration. First of all there is  the improvement of the insulating capacity of the windows caused by the air (or sometimes gas) between the two glass plates and by the bigger thermal resistance of the framework. Also the airtightness of the windows is improved. Secondly the solar energy transmittance (g-factor) of the glass is decreased.

In building 'Area 4' single glass is installed and this makes that the heat flows very easily to the colder volume. The heating demand decreases when the single glass is changed by double glass. The better the insulating part the more the heat transfer is decreased. This has positive effect on the heating demand and a negative effect on the cooling demand. The magnitude of the effect depends on the quantity of the two previous explained values.

These are the changes that are suspected to occur when the improvements are made. In this case though, the amount of windows, compared to the total area that is studied, is very low. As the results of the original heat losses and gains caused by the presence of the windows are evaluated, it is clear that they don't have a big influence on the final heating and cooling demand. But by installing new windows, the airtightness will improve and the aire exchange rate value n(50) will be lower. In the original calculations, the value of n(50) has been defined as a standard value for old building, this is 10 1/h. This value will lower with the installation of other windows and a framework with a better thermal resistance, but the influence can't be calculated with the program.

## 5.3 Natural ventilation

To meet the requirements for a passive house, it is important that there is as much passive cooling as possible present in a building that is situated in a warm climate. A way for passive cooling is by natural ventilation. This way the building will be cooled  down the building during the night. This can be done when the ventilation is activated when certain conditions are obtained. When the ventilation is working, the cooling is inactive.

First of all, the system has be by working only when cooling is needed and it can be active on every moment of the day. Second of the is that the temperature outside has to be lower than the one inside. Otherwise the ventilation doesn't contribute to cooling down the building. As the maximum temperature inside is set at 25 degrees (if more, the cooling system is activated), the outside temperature can't be more than 25 degrees when the ventilation is working. This means that the building will mostly be cooled down during the night.

Other passive cooling techniques are: high thermal mass, high thermal mass with night ventilation and evaporative cooling.

High thermal mass depends on the ability of materials in the building to absorb heat during the day. Each night the mass releases heat, making it ready to absorb heat again the next day. To be effective, thermal mass must be exposed to the living spaces.

High thermal mass with night ventilation relies on the daily heat storage of thermal mass combined with night ventilation that cools the mass. The building must be closed during the day and opened at night to flush the heat away.

Evaporative cooling lowers the indoor air temperature by evaporating water. In dry climates, this is commonly done directly in the space.

All these ways are not very effective for this kind of building and climate so the natural ventilation is the best way to go

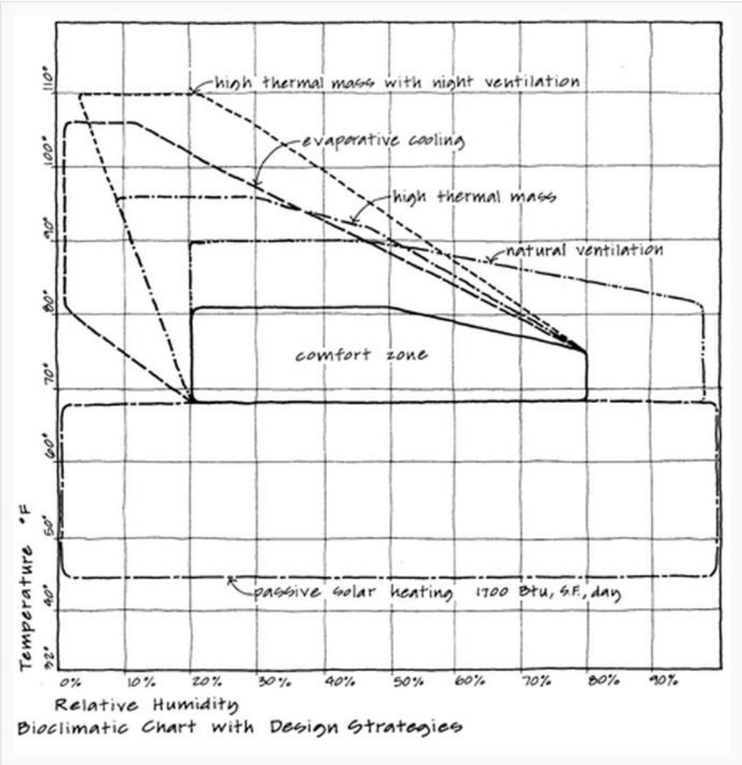



**Fig. 5.3.1:** method of passive cooling in function of the relative humidity and temperature

# CONCLUSION

First of all there is the Aula Magna, a classroom that got renovated to an auditorium, located at the school building of the ETSIE faculty. The different parameters that determine the acoustic quality of the room don’t meet the required values and this due to poor construction. The room is used for lectures and small concerts, but is not properly adapted to either of these activities. This conclusion was made after determining the reverberation time for the auditorium. The values of the reverberation time are low for the low frequencies, increase with the increasing frequencies but then decreases again when the frequency reaches values of 4000Hz and more.

Then there is the thermal study. The importance of a passive house is reaching a high level of comfort inside together with very low energy consumption. Active cooling and heating should be low and passive heating and cooling techniques should be used as much as possible. The calculated values for the heating demand and cooling demand are compared to the ones required by the passive house standard, considering this the optimal and comfortable situation.

The values of the heating and cooling demand were much higher than the maximum of the passive house standard. This is caused by some main factors. First of all there is no insulation, making the heat losses due through transmission very high and in days of warm weather, warmth enters the building easily. The windows are from single glass, changing them to double glass would decrease the heating demand. The adaptable shadings have a big influence on the cooling demand. With an adaptable angle natural heat can be obtained in summer and avoided during the summer. Finally the influence of the cooling/heating/ventilation system is hard to evaluate because there is no specific information about the current system. What is known is that there is only one system with a low efficiency and not adapted to winter/summer. Using natural ventilation would be a good improvement.

The evaluated ETSIE building at UPV is one of the first schools at UPV to be built some 40 years ago and that gets noticed in the evaluation of the comfort. Both the results of the acoustic and thermal analysis are in the end seen as very poor. Some necessary changes need to made in order to create a pleasant and comfortable work and study environment. In the end, some suggestions for improvement are made for the acoustic and thermal conditions. The next step in the process would be to make concrete plans and decision preferably while working together with a somebody with a management background as nowadays it is not only about good technique but about money as well.

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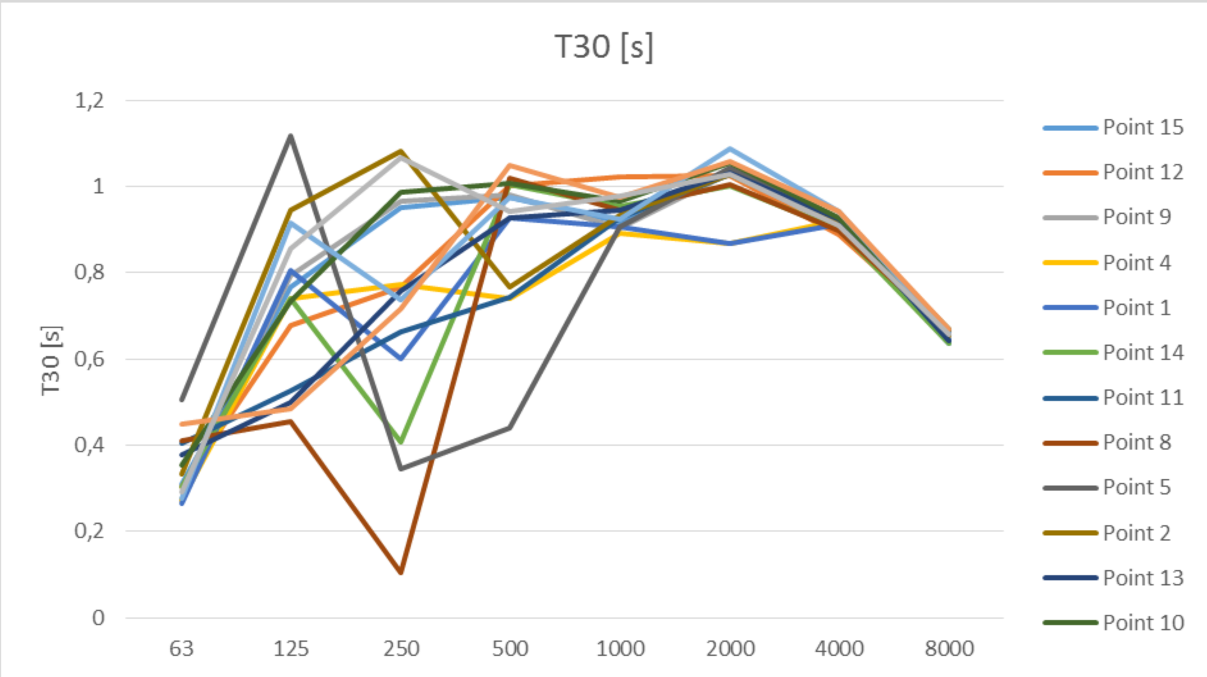
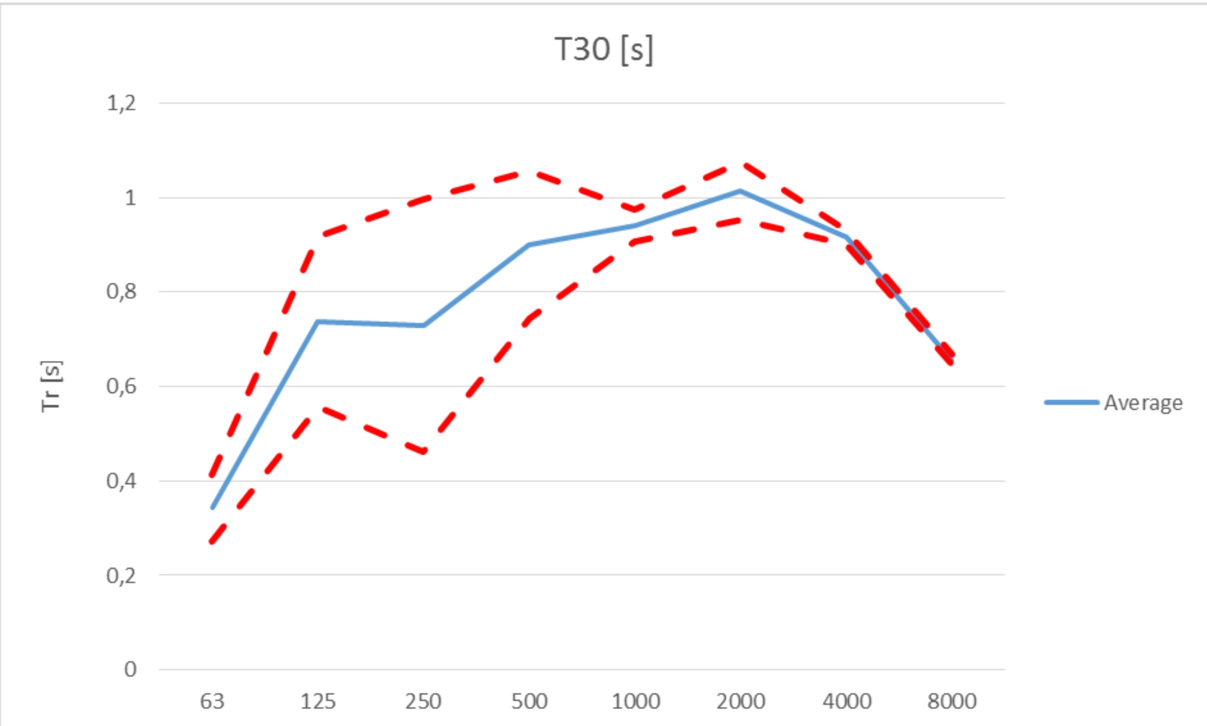
## ANNEXES

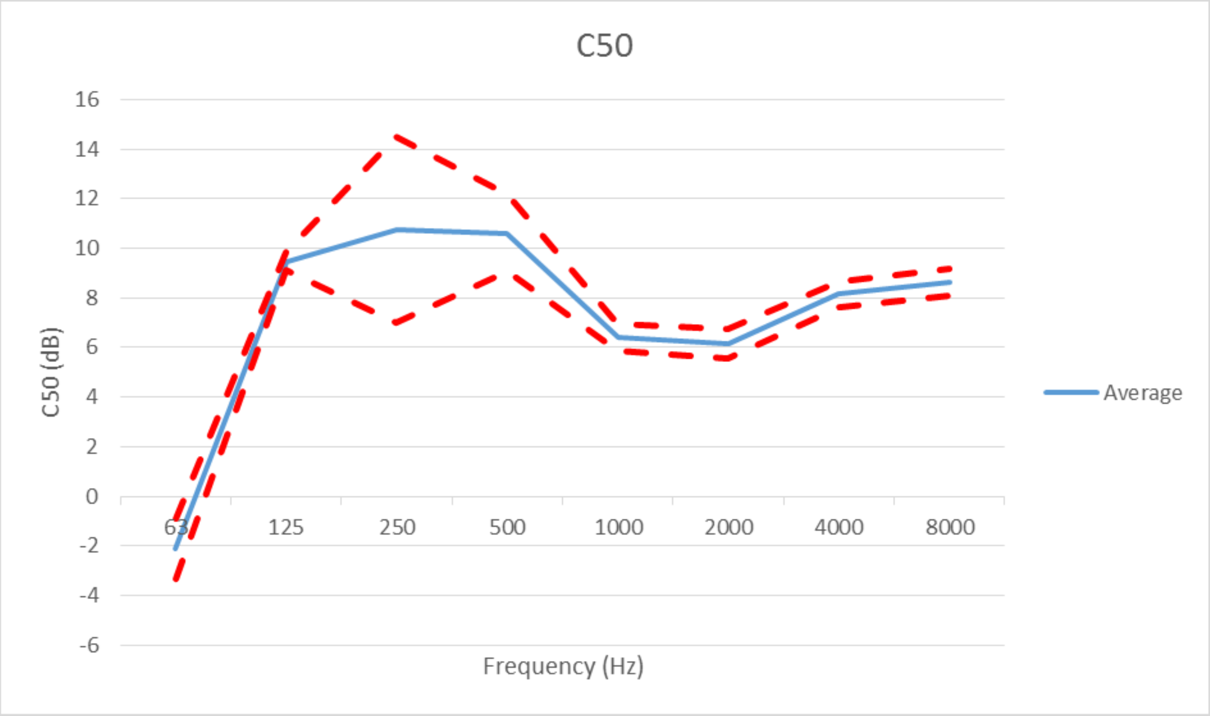
### *Annex 1 – Exact coordinates of source and receivers*

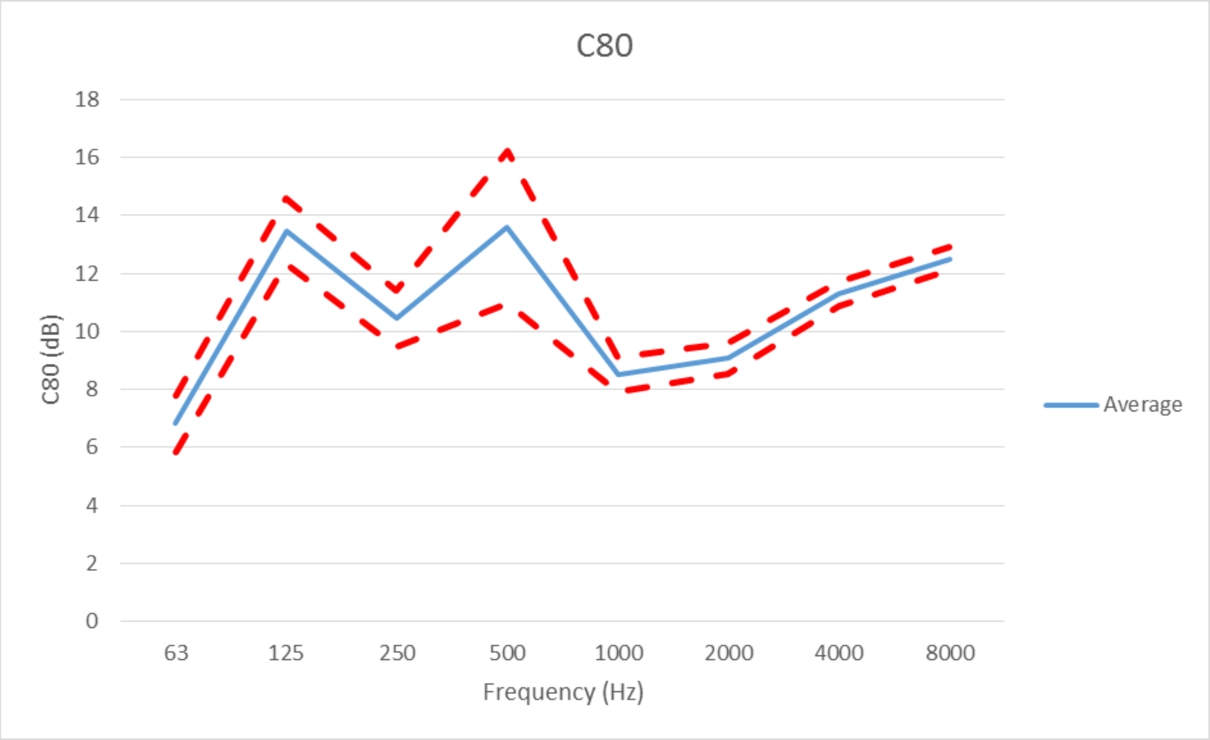
| | x | y | z |
|---|---|---|---|
| **Source** | 2,1236 | 4,0343 | 2,1926 |
| **Receivers** | | | |
| Point 1 | 4,488 | 10,6611 | 0 |
| Point 2 | 4,488 | 6,0149 | 0 |
| Point 3 | 4,488 | 1,295 | 0 |
| Point 4 | 8,363 | 10,6611 | 0,2846 |
| Point 5 | 8,363 | 6,0149 | 0,2846 |
| Point 6 | 8,363 | 1,295 | 0,2846 |
| Point 7 | 11,3041 | 1,295 | 0,5006 |
| Point 8 | 11,3041 | 6,0149 | 0,5006 |
| Point 9 | 11,3041 | 10,6611 | 0,5006 |
| Point 10 | 15,1468 | 1,295 | 0,7829 |
| Point 11 | 15,1468 | 6,0149 | 0,7829 |
| Point 12 | 15,1468 | 10,6611 | 0,7829 |
| Point 13 | 18,0756 | 1,295 | 0,9979 |
| Point 14 | 18,0756 | 6,0149 | 0,9979 |
| Point 15 | 18,0756 | 10,6611 | 0,9979 |

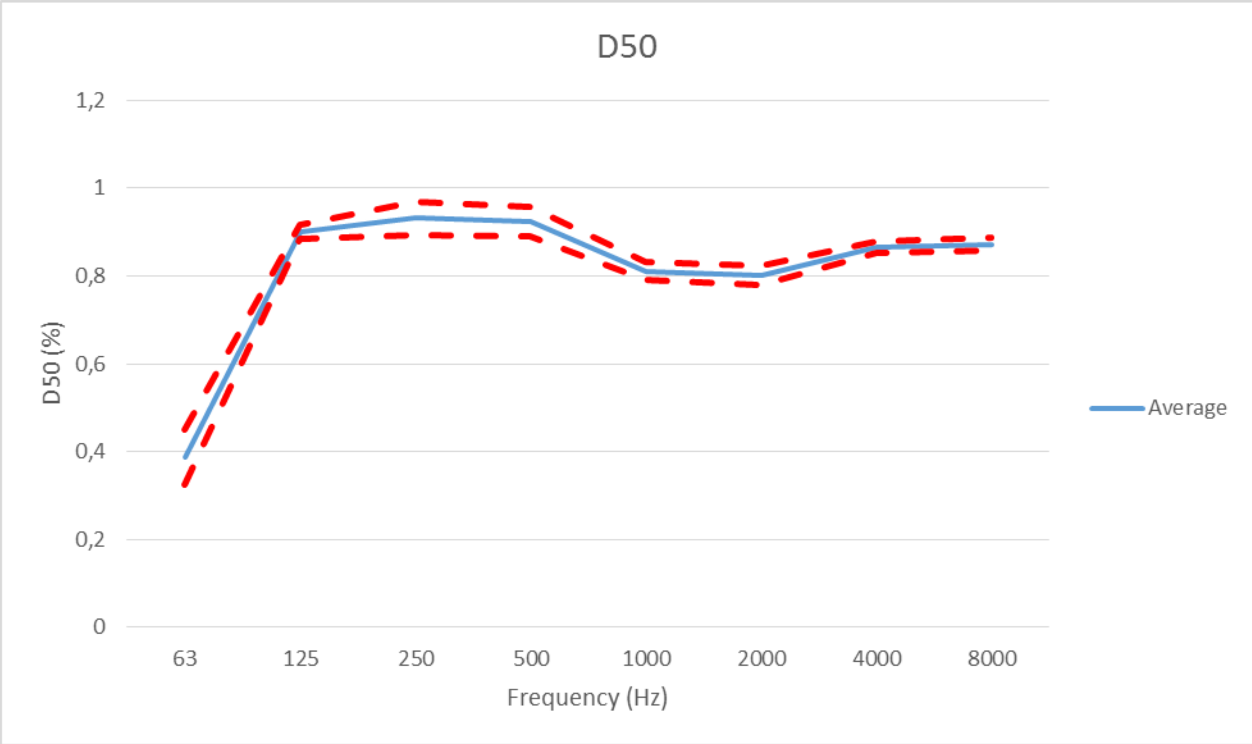
## *Annex 2 – Graphics of the measured parameters*

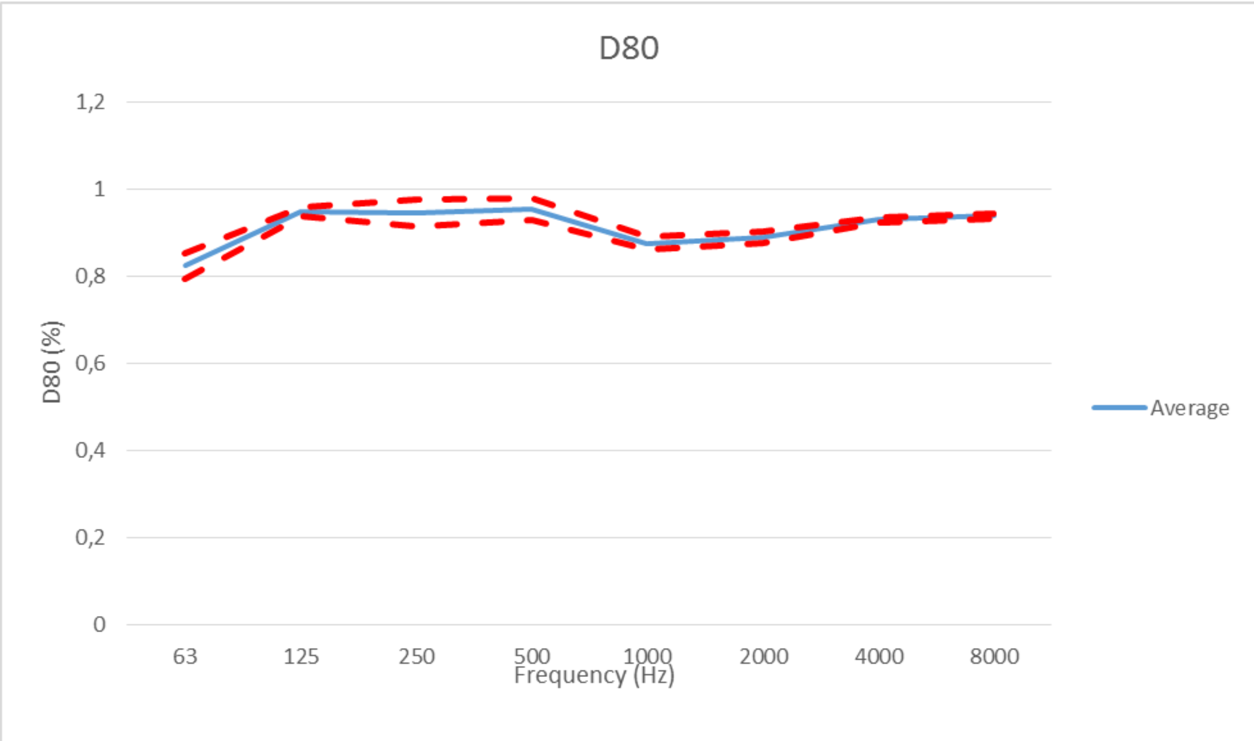



C50
C50 (dB)
16
14
12
10
8
6
4
2
0
-2
-4
-6
63
125
250
500
1000
2000
4000
8000
Frequency (Hz)
Average


C80
C80 (dB)
18
16
14
12
10
8
6
4
2
0
63
125
250
500
1000
2000
4000
8000
Frequency (Hz)
Average


D50
1,2
1
0,8
0,6
0,4
0,2
0
D50 (%)
63
125
250
500
1000
2000
4000
8000
Frequency (Hz)
Average


D80
1,2
1
0,8
0,6
0,4
0,2
0
D80 (%)
63
125
250
500
1000
2000
4000
8000
Frequency (Hz)
Average

## ***Annex 3 – Results of the calculation in the software ODEON using the original materials and their specific absorption coefficients –*** *minimum, maximum and average values for the different parameters*

**DT(s)**

| Frequency | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|
| Mimimum | 0,41 | 0,62 | 0,44 | 0,33 | 0,33 | 0,40 | 0,51 | 0,33 |
| Average | 0,68 | 0,79 | 0,68 | 0,61 | 0,56 | 0,60 | 0,64 | 0,44 |
| Maximum | 0,88 | 0,95 | 0,87 | 0,81 | 0,75 | 0,75 | 0,79 | 0,60 |

**T30(s)**

| Frequency | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|
| Mimimum | 0,79 | 0,87 | 0,82 | 0,72 | 0,71 | 0,68 | 0,68 | 0,47 |
| Average | 0,96 | 1,11 | 0,97 | 0,90 | 0,92 | 1,00 | 0,86 | 0,56 |
| Maximum | 1,16 | 1,39 | 1,18 | 1,05 | 1,30 | 1,51 | 1,33 | 0,63 |

**SPL(dB)**

| Frequency | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|
| Mimimum | 96,9 | 99,3 | 96,8 | 95,5 | 94,6 | 95,2 | 95,9 | 93,2 |
| Average | 99,2 | 101,0 | 99,1 | 98,2 | 97,6 | 98,2 | 98,7 | 96,7 |
| Maximum | 104,5 | 105,5 | 104,5 | 104,0 | 103,8 | 104,1 | 104,4 | 103,3 |

**C80(dB)**

| Frequency | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|
| Mimimum | 5,5 | 3,7 | 5,7 | 6,0 | 6,0 | 5,7 | 5,5 | 7,9 |
| Average | 7,1 | 5,8 | 7,4 | 8,2 | 8,5 | 8,1 | 7,6 | 10,3 |
| Maximum | 10,7 | 8,9 | 11,1 | 12,0 | 12,0 | 11,0 | 9,8 | 12,8 |

**D50**

| Frequency | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Mimimum | 0,62 | 0,54 | 0,64 | 0,67 | 0,68 | 0,65 | 0,62 | 0,72 |
| Average | 0,71 | 0,65 | 0,73 | 0,76 | 0,77 | 0,75 | 0,72 | 0,81 |
| Maximum | 0,87 | 0,82 | 0,87 | 0,89 | 0,89 | 0,87 | 0,83 | 0,90 |

**Ts(ms)**

| Frequency | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|
| Mimimum | 23 | 29 | 22 | 20 | 20 | 22 | 25 | 17 |
| Average | 44 | 51 | 42 | 37 | 36 | 38 | 40 | 29 |
| Maximum | 54 | 60 | 51 | 48 | 47 | 50 | 51 | 39 |

**LF80**

| Frequency | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|
| Mimimum | 0,110 | 0,144 | 0,111 | 0,096 | 0,091 | 0,105 | 0,125 | 0,111 |
| Average | 0,235 | 0,254 | 0,233 | 0,227 | 0,228 | 0,235 | 0,240 | 0,231 |
| Maximum | 0,379 | 0,390 | 0,384 | 0,402 | 0,416 | 0,404 | 0,382 | 0,380 |

**STI**

STI,min 0,68

STI,avr 0,71

STI,max0,79