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1.0. Introduction

In the last years, the issue of the sustainable building and energy efficiency has been discussed intensely, especially in the field of the construction industry. The reason of this constantly growing interest is the continuous depletion of the raw materials, such as oil and coal, concurrently with the increase in energy demand. The European Union perceived the problem and passed several directives to limit the energy consumption of the building. The directives 2002/91/CE, 2010/31/CE and the 2012/27/UE define target for the energy consumption rate for new structures and for upgraded buildings, excluding nevertheless, some categories. The listed building are not regulated by these directives, due to avoid invasive refurbished works that could damage their historical value. In order to preserve the historical value and at the same time to limit the energy consumption of listed buildings, the EU financed the FP7 project 3Encult. The Weigh-house building of Bolzano (Italy) is one of the eight case studies of the project.

The aim of this thesis is to evaluate the possibility of the cooling load reduction of the Weigh-house through ventilation strategies. The building is a Romanesque edifice (XIII century) that was renovated in the seventeenth and eighteenth centuries and was the seat of a public weighbridge until 1780. The building analysis is conducted on models created with a dynamic simulation software called EnergyPlus. EnergyPlus is a validated software developed from the U.S.A. Energy Department.

Principally the thesis is divided in two part. In the first part a generally overview of the topics treated in the thesis is given. According to the EN 15251, thermal comfort and air quality are taken into consideration. More deeply, it is described how indoor thermal comfort is calculated with the adaptive method and which is the minimum ACH rate for the achievement of acceptable air quality inside the building. After that, the common interventions on a building envelope are taken into consideration, like airtightness and thermal insulation improvement and window replacement with shading system. Stated these interventions are usually considered more appropriate for the energy efficiency improvement in the heating period, is opportune to verify their compatibility in the cooling period. The problem of potential overheating is to avoid. High indoor temperatures influence the potential cooling load reduction through natural ventilation. The theory behind the natural ventilation and their characteristics are discussed. The use of natural ventilation strategies integrated with a mechanical system is also taken into consideration. At last, the use of EnergyPlus software is described in detail and principally the group “AirflowNetwork” is deeply discussed. The AirflowNetwork group is used for the simulation of air flow through leakage component of the building, as example windows, cracks. Furthermore, a software called “Therakles” is introduced and also described. Such a software is developed by the Building and Climatology Institute of TU-Dresden and will be successively used for a “comparative” validation of EnergyPlus Weight-house building model.

In the second part of the thesis, the Weigh-house is treated in detail: the real building and its representative models. First, the climate, in which the building is located is described and then a briefly historical analysis is done. The actual form of the building is the result of several structural interventions occur over the years. Thereafter, with the data materials collected during the various inspections in the
house and through the test carried out on the building elements, the Weigh-house reference model is created. Considering that a model represents in a simplified manner the actual building, the different adopted expedients for its realization are explained. Starting from the model that represents the building in the present state, each improvement on its envelope is analyzed. The effects that airtightness and thermal insulation improvement and window replacement with shading system have on the indoor temperatures in summer period are evaluated. Consequently, ventilation strategies on the improved model are adopted. Several building leakage components, like windows and chimney openings are simultaneously or separately opened in different times for the cooling load reduction. The thermal comfort and the ACH are evaluated. Finally, an alternative method, i.e. a hybrid ventilation system concept is developed, always in order to obtain an indoor temperature decrease. The hybrid ventilation system exploits the “cooling reservoir” of the cellar using an air heat recovery system. The Heat exchange between the cellar and the upper floors is calculated through the heat flux equation. For this simulation, Energy Management System (EMS) application of EnergyPlus was used.
2.0. 3ENCULT Project

The EU has set itself the objective to reduce 20% of Union’s primary energy consumption by 2020 compared to projections in 2007. This will contribute to a reduction of CO₂ emissions and therefore to a decrease of environmental changes. According to the European Directives 2002/91/CE, 2010/31/CE and 2012/27/UE, the energy efficiency is considered as a valuable mean to resolve the problem of the continuous depletion of the raw materials such as petrol and coal concurrently with the increase in energy demand.

Considering that buildings represent 40% of the Union’s final energy consumption (Directive 2012/27/UE), the European policies pay special attention to the requalification of the existing construction. These policies establish the minimum energy performance requirements regarding the renovation of these buildings. However this minimum is not imposed to all categories of edifices. In fact, the EU Directives don’t regulate the requalification of listed buildings. Any decision regarding this field should be agreed with the local governments. The reason is because it is feared, that a building refurbishment can damage the heritage value.

The project 3ENCULT, carried out by the European Community, want to demonstrate, that is possible a reducing of the energy demand respecting the heritage value of listed buildings through the study and development of new renewable energy technologies: "Reducing the energy demand consistently, often by factor 4 and even factor 10, while respecting the heritage value of the building is possible if a multidisciplinary team finds the right solution for the single building" (Troi – Lucchi, 2013). The project includes 10 European countries with a total of 21 partners (Figure 1). These partners come from several technical and commercial areas, so that is possible to face the case studies of the project in the best possible way.

The team of experts is composed (Eurac, 3ENCULT, 2013) by:

- Conservation experts
- Technical experts
- Urban development experts
- Industry partners
- Implementation experts and stakeholder associations

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1 Source: http://www.3encult.eu/
The number of case studies of the project are a total of eight. They were chosen in order to represent:

- different climatic conditions
- different utilizations
- different epochs and degree of conservation restrictions
- different needed/planned interventions
- different time schedule of implementation

The following buildings represent the case studies of the 3Encult project:

1. Public Weigh House, Bozen/Bolzano (Italy)
2. Palazzo d’Accursio, Bologna (Italy)
3. Palazzina della Viola, Bologna (Italy)
4. Fæstningens Materialegård, The Material Court of the Fortress, Copenhagen (Denmark)
5. Monumental School, Innsbruck (Austria)
6. Warehouse City, Potsdam (Germany)
7. Industrial Engineering School, Béjar/Salamanca (Spain)
8. Strickbau, Appenzell (Switzerland)
The Weigh House of Bolzano is the building treated in this thesis. The analysis of the building was also possible through the assistant provided by the local case study team composed by the European Academy of Bolzano/Bozen (EURAC) as focal point for scientific support and integrated design process, the Foundation (STIFTUNG SPARKASSE) as building owner and the local state office for historical monuments (Soprintendenze, ecc….) as conservator.
3.0. Cooling load reduction by focused strategies

3.1. Thermal comfort and air quality

The reduction of the energy consumption and wastefulness of a building should be achieved in compliance with the internal comfort conditions. The EU Standard EN 15251:2008 *Criteria for the Indoor Environment including thermal, indoor air quality, light and noise*, formulated by the CEN (Comité Européen de Normalisation), provides necessary data for the calculation of the building Energy Performance, taking into consideration the already mentioned internal comfort conditions. This standard is valid for non-industrial buildings, i.e. for all the structures where the human presence is more influential than the activities process, for example residential houses, schools, museums, restaurants.

The standard UNI EN ISO 7730 defines thermal comfort as that condition of mind which expresses “satisfaction with the thermal environment”, i.e. the condition when someone is not feeling either too hot or too cold, also called neutral thermal condition.

For temperate seasons, the acceptable comfort temperatures in buildings are calculated through different criteria, depending on the adopted type of air conditioning: passive or active. For active air conditioning the internal reference temperatures are calculated according to the norm UNI EN ISO 7730:2006, while for the adoption of a natural ventilation system, the limit conditions of the internal operative temperatures are calculated with an adaptive method. The adaptive method takes into account dynamic behavioral, physiological and psychological factors, even in relation to the native culture of people (de Santoli - Mariotti, 2011):

- psychological, as previous experiences and expectations change the perception of sensory stimuli and the reaction to them;
- physiological, because in general the body gradually reduces the reaction to the repeated environmental stimuli and prolonged environmental conditions;
- behavioral, because the individual generally acts directly on the heat balance of the human body through the change of clothing or, for example, the posture taken;

Furthermore this method is based on the fact that the neutral thermal conditions change in function of the internal and external environmental temperature. This dynamic approach permits to calculate the neutral operative temperature $T_{o,n}$ in function of the external air temperature $T_e$, averaged on the values of a week:

$$T_{o,n} = 0.33 \times T_e + 18.8 \quad (\text{EN 15251:2008})$$

The standard EN 15251:2008 defines three different “levels of environmental quality” represented by the categories A, B, C. Each of them contains a set of constraints for the psychophysical indices, like thermal comfort, air quality and acoustic comfort. The related permissible deviations $\Delta T_e$ can be defined when the category of the internal environment is chosen:
Caprioli, Tiziano

Simulation models for Cooling load reduction by ventilation strategies

<table>
<thead>
<tr>
<th>Category</th>
<th>$\Delta T_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$\pm 2$</td>
</tr>
<tr>
<td>B</td>
<td>$\pm 3$</td>
</tr>
<tr>
<td>C</td>
<td>$\pm 4$</td>
</tr>
</tbody>
</table>

Figure 2 Permissible deviations for levels of environmental quality (Source: de Santoli – Mariotti, 2011)

In this way the acceptable range of $T_{o,n}$ results:

$$0.33 \times T_{out} + 18.8 - \Delta T_o < T_o < 0.33 \times T_{out} + 18.8 \times \Delta T_o$$

Figure 3 Adaptive Method, Acceptability Intervals (Source: Kees et alii, 2007)

The norm also contains some indications regarding the internal air quality and indicates the minimum air change rate for a determined environmental category with the following formula:

$$q_{tot} = n \times q_p + A \times q_B$$  \hspace{1cm} (EN 15251:2008)

where:
- $q_{tot}$ = total ventilation rate of the room (l/s)
- $n$ = design value for the number of the persons in the room
- $q_p$ = ventilation rate for occupancy per person (l/s/pers)
- $A$ = room floor area (m$^2$)
- $q_B$ = ventilation rate for emissions from building (l/s/m$^2$)
3.2. Building envelope interventions

The decision of intervention types to a building envelope depends principally on the climate conditions of the buildings location. During cold winters, a building requires walls and windows with efficient thermal properties in order to avoid the heat dissipation to the outside and a continuity in the envelope structure, for limiting the presence of thermal bridges and unwanted air infiltrations. These attentions aren’t always compatible for the summer periods: for example an excessive thermal insulation can produce an overheating of the building, and the same can happen with windows that permit the entrance of elevate solar energy. It is also necessary to find a good balance between the winter and summer intervention solutions.

3.2.1. Airtightness

The airtightness of a building envelope influences considerably its internal thermal comfort and air quality. Air infiltration depends basically on the indoor-outdoor pressure difference. This is the sum of the pressure difference due to the wind, pressure difference due to the stack effect, and the pressurization of the ventilation system (Muehleisen - Patrizi, 2012). For the evaluation of the wind pressure difference it is necessary to estimate the $C_p$ value (Wind Pressure Coefficient). There are essentially two methods to estimate the $C_p$ value:

a) Full scale or wind-tunnel test
b) Use of parametric equations

The full scale and the wind-tunnel test are recommended for complex high-rise building due to the larger request of time and experts, which are indispensable because of the difficulty of the tests. For low-rise buildings $C_p$ is normally estimated with the use of parametric equations derived from validated measurement, i.e. where the quality of the results is provided. One of these parametric equations for low-rise building is the Swami and Chandra equation, which is probably the most used (Muehleisen - Patrizi, 2012):

**SWAMI AND CHANDRA EQUATION:**

$$C_p = C_p(0^\circ) \ln \left[1.248 - 0.703 \sin \left(\frac{\Theta}{2}\right) - 1.175 \sin^2 \Theta + 0.131 \sin^3 (2\Theta) + 0.769 \cos \Theta/2 + 0.07G^2 \sin^2 \Theta/2 + 0.171 \cos^2 \Theta/2\right]$$

where:

- $C_p(0^\circ)$ is the normalized pressure coefficient, i.e. is the ratio of the actual average surface $C_p$ to the $C_p$ at zero incidence angle (Swami and Chandra suggested Value for all low-rise building $C_p(0^\circ)= 0.6$)
- $\Theta$ is the incident angle of wind measured from the surface normal
- $G = \ln(S)$ is the natural log of the side ratio $S$ which is the ratio of building length to width

With the introduction of simple correction factors in the Swami and Chandra equation it is possible to take into consideration the effects of shielding by other buildings. The AVIC (Air Infiltration and
Ventilation Centre) developed a database of wind pressure coefficients and produced table for exposed, semi-sheltered (surrounding obstacles with half of the building height) and sheltered buildings (surrounding obstacles with the same height as the building).

In contrary to a natural ventilation strategy, where the air infiltration through the window openings is intentional, air infiltration through envelope discontinuity should be generally avoided. The critical points of air infiltration are the connection between external wall and window and the connection between the window frame and the sash window. Therefore, window systems with a high airtightness were developed with the aim of an energy consumption reduction. However, an airtight building envelope is linked to a good air ventilation strategy (natural or mechanical), in order to obtain a minimum air change rate inside the structure. If the minimum air change rate is not achieved, the concentration of pollutants in the air can be compromised and can provoke damages to people’s health and also damages to the construction elements, for example the growing of mold and mushrooms on the building surfaces.

3.2.2. Thermal Insulation

The weather conditions influence strongly the choice of a building thermal insulation. When the structure is located in a temperate climate with cold winters and hot summers, the building envelope should be able to reduce the heat dissipation to the outside, exploit the solar gains in winter and protect itself against them in summer. It is also necessary to optimize the winter and the summer performance of the building, i.e. find a general solution which improves the global performance throughout the calendar year.

The thermal insulations can be divided according to their origin, which can be synthetic, mineral, vegetable or animal and according to their structure, which can be fibrous or cellular. More in depth the large quantity and type of thermal insulations present on the market can be divided as following (Fassi – Maina, 2009):

- Totally synthetic materials: they are generally thermoplastic or thermosetting polymers obtained by an oil complex process. Here are some examples: polyester fiber, expanded polystyrene, extruded polystyrene foam, polyurethane foam and polyethylene foam.
- Totally mineral materials: they result from the processing of raw mineral materials such as clay, limestone, volcanic rocks, the quartz sand, recycled glass, without the addition of resins and binders, for example granular materials (pumice) and expanded (clay, perlite, vermiculite and glass granular)
- Totally vegetable materials: the vegetable raw material undergoes a process that does not require the addition of binders and synthetic fibers of support. Some examples: cork, wood fiber, jute

Furthermore, there are insulations realized with the combine of raw materials of different origin:
Mixed mineral-synthetic: a percentage of synthetic resins with a bind functions is added to the raw mineral material. For example: glass wool, rock wool

Mixed plants-synthetic and animal-synthetic: a synthetic fiber, which confers a better stability, is added to the plants or animal raw material.

Mixed plants-mineral: a mineral binder is added to confer a better mechanical resistance to the material. For example: mineralized wood wool.

All the insulation materials undergo more or less complex transformation process, which releases the end product in different texture (panels, mats, flakes, granules), according to the necessity.

In Italy the diffusion and use of the thermal insulation in buildings has been started only after the first oil crisis. Before that, the only utilized insulation materials were makeshifts material, derived from processing of agricultural waste. Nowadays, the ample number of thermal insulation types present on the market allows the choice of the best solution concerning the building insulation. Each material present different thermal, acoustic and fire properties, which characterize the energy efficiency of a structure.

The thermal analysis of the components of a building envelope can be conducted in a steady state or in a dynamic state. In the steady state all the variables are constant in time and the effects related to the thermal storage of the structure are not considered. This type of analysis is mostly indicated for the heat transmission in the winter period or for a building with low thermal inertia. However, the dynamic analysis is more appropriate, when the temperature fluctuation and the solar radiations are significant.

For the steady state analysis the fundamental variable is the thermal transmittance U-value (W/m²K). It is defined as: "the rate at which thermal energy is conducted through unit area, per Kelvin temperature difference between its two sides" (Lübbe, 2007, pp.13). The U-value describes the potential of a wall in relation to the reduction of the incoming or outgoing thermal fluxes, to the control of the internal surface temperatures and to the satisfaction of the thermal comfort requirements. The norm UNI EN ISO 6946 describes a method for the U-value calculation.

\[ U = \frac{1}{R_T} \left[ \frac{W}{m^2K} \right] \]

with

\[ R_T = R_{si} + R_1 + \cdots + R_n + R_{se} \]

Where:

\[ R_{se} = \text{surface heat transfer resistance on outside (convective and radiative)} \left[ \frac{m^2K}{W} \right] \]

\[ R_{si} = \text{surface heat transfer resistance on room side (convective and radiative)} \left[ \frac{m^2K}{W} \right] \]

\[ R_{1,2,n} = \text{total resistance of the building materials in the constructional element} \left[ \frac{m^2K}{W} \right] \]

The thermal resistance R is equal to:

\[ R = \frac{d}{\lambda} \]
where:

d = thickness of the material [m]

\( \lambda \) = conducibility of the layer material [W/mK]

The thermal conducibility is the property of a material’s ability to conduct heat due to a temperature difference. In the steady state the heat passes through the homogeneous material in perpendicular direction to the isothermal lines. Furthermore the conducibility depends on the material temperature, humidity, its ageing and its method of installation and production characteristics.

The thermal analysis in dynamic state is more complex and in the last years several simplified methods have been developed. The norm UNI EN ISO 13786 defines that the dynamic performance of the materials depends on how they are joined together. Especially in the summer period, the most three important properties of the dynamic analysis are the density "\( \rho \)" [Kg/m³], the specific heat "\( c \)" [J/Kg*K] and the thermal conducibility "\( \lambda \)" [W/m*K]. A parameter that joins together these three properties is the thermal diffusivity:

\[
\alpha = \frac{\lambda}{\rho c} \left[ \frac{m^2}{s} \right]
\]

The thermal diffusivity considers also the insulation heat storage properties in a determined material volume. The materials with a high specific heat are more indicated for the summer period.

The position of the thermal insulation in construction element is relevant for the analysis of the condensation phenomena. The construction elements are subjected to the diffusion of water vapor due to the natural migration of the water vapor from the environments with greater vapor pressure to environments with less vapor pressure. In the winter periods and in heated rooms, the generated pressure difference between inside and outside provokes the water vapor diffusivity inside the walls. The contact of the water vapor with materials with temperatures, which can cause the condensation, should be avoided, i.e. for a specific temperature the vapor pressure shouldn’t achieve the saturation value.

3.2.3. Window replacement

The window is considered a critical construction element of the building envelope. It is a weak point in the energy efficiency of the building envelope and in the ability to contribute to the achievement of appropriate thermal comfort conditions inside it.

Besides problems due to bad air tightness (for example between wall and frame or between counterframe and fixed frame) or thermal bridges presence, also problems due to a high transmittance of the window component or the difficulty to block or limit the solar gain in summer are to avoid.

The most common passive solar energy exploiter is the window in which the solar radiation is directly converted to heat in the room. Furthermore, the window allows the natural room illumination.
The heat transfer coefficient for the façade per transmission \( H_{T,\text{façade}} \) is composed by the rate of the wall and the rate of the window (Rainer, 2008).

\[
H_{T,\text{façade}} = U_w \times A_w + U_{\text{win}} \times A_{\text{win}}
\]

where:
- \( H_{T,\text{façade}} \) = façade heat transfer coefficient per transmission
- \( U_w \) = heat transfer coefficient of the wall
- \( U_{\text{win}} \) = heat transfer coefficient of the window
- \( A_w \) = wall area
- \( A_{\text{win}} \) = window area

The thermal performance of windows is principally described by two important variables:

- the heat transfer coefficient, which describes heat flow proportional to window area and temperature difference (W/m²K)
- the total solar energy transmittance, which describes the quantity of total solar energy transmitted by the glazing (g-factor)

These variables allow the calculation of the building usable solar energy flow derived to a simplified heat balance through a room window (Krimmling, 2007):

\[
\dot{Q}_u = \frac{g_w \times G - U_w \times (t_i - t_o)}{A_w} \left[ \frac{W}{m^2} \right]
\]

\[
U_w = \frac{U_g \times A_g + U_f \times A_f}{A_g + A_f} \quad \text{(UNI EN ISO 10077-1)}
\]

where:
- \( \dot{Q}_u \) = usable passive solar heat flow
- \( g_w \) = total solar energy transmittance of the window
- \( G \) = solar radiation [W/m²]
- \( U_w \) = heat transfer coefficient of the window [W/m²K]
- \( U_g \) = heat transfer coefficient of the glazing [W/m²K]
- \( U_f \) = heat transfer coefficient of the frame [W/m²K]
- \( t_i \) = internal temperature
- \( t_o \) = external temperature
- \( A_g \) = glazing area [m²]
- \( A_f \) = frame area [m²]

A low U-value allows the reduction of heat losses through a window and it is achievable through different methods. One of these, is the filling of the gap between two glazing layer with noble gas (for example Argon and Krypton).
A window with an elevated g-factor is convenient to achieve a high solar gain, however it is to consider that a high g-factor value involves an increment risk of high thermal load in the summer season.

![Figure 4 Example of the g-factor effect on the inside thermal condition](source)

A overtaking of 40-60% of window to wall ratio for a south façade is dissuaded in order to avoid the risk of high thermal load inside the rooms (Königstein, 2009). With the overtaking of this percentage is recommended the installation of high performance solar shading.

### 3.2.4. Shading system

The prevention of an excessive solar gains entering the occupied space, in order to obtain acceptable summer conditions, could be done through a good solar control. Besides the size and orientation of the glazed areas, window shading systems are a good and simple solution for the solar control.

From an energetic point of view is the location of the solar shading important. A distinction is made between internal and external shading systems. The external one offers the highest sun protection and don’t obstruct the window opening to the internal side. Some examples of external shading are the shutters and the jalousies.

![Figure 5 External shutter with orientable slats](source)

---


A solar shading can be installed inside the room behind the window. Thereby is the system protect from wind and dirt. However, the absorbed solar radiation by the internal shading system leads to a warming of the room. Furthermore, part of the reflected solar radiation is absorbed by the window glass and again into the room reflected. Some examples of internal shading are the curtains and roller.

![Figure 6 Internal Curtain](image1)

![Figure 7 Internal roller shade](image2)

The total g-factor in the case of a shading system adoption should be multiplied with a reduction factor $f_c$ related to the type of shading. In Germany, the reduction factors are indicated in the norm DIN 4108.

---


3.3. Natural Ventilation

“Natural Ventilation” is claimed to be a good strategy to adopt for the reduction of the energy consumption of a building in the summer period. Development and implementation of specific concepts and related technology systems must consider the local constraints, considering building, architectural, urban and climate contexts. It uses the outside air with the aim to ensure an appropriate air quality (healthy reasons) and indoor thermal comfort, thereby reducing the risk of overheating. Ventilation is not a new method for the building cooling load reduction, since the mechanical ventilation is used for about 150 years (Etheridge, 2012) and passive strategies were developed some centuries ago. Some studies demonstrate the utilization of passive cooling systems in the historic buildings. An example in Italy is Palazzo Pitti in Florence. The rooms of the ground floor of Palazzo Pitti were occupied principally in the summer season. On the floor, in the center of these rooms, were present an iron grill, which allowed the passage of the cold air coming from the undergrounds of the building. (Balocco et alii, 2009).

Figure 8 Palazzo Pitti Firenze

![Figure 8 Palazzo Pitti Firenze](http://www.florenceparking.it/wp-content/uploads/2012/04/Palazzo-Pitti-2.jpg)

Figure 9 Example of air flow in the Building (Source: Balocco et alii, 2009)

With the use of a Natural Ventilation System it is important to guarantee a controllable ventilation rates across a wide ranges, from about 0.5 to 5 ACH or even more (CIBSE, 2005). Furthermore, during unoccupied hours of the building, it should be possible to bring the ventilation rate near zero, especially

---

when the principal source of pollutants is the occupancy. The mechanisms by which the air flow inside a building is generated, are: wind-induced ventilation and the stack effect.

**Wind-induced Ventilation**

The wind-induced ventilation is caused principally by the different building envelope surface pressures. When the wind approaches the façade of the building, the immediate effects are the slowdown of the air and the rise of the pressure over the surface. On the other hand, on the roof and sides of the same building the air accelerates, lowering the pressure of these areas. As a consequence of the separation of the flow from the roofs and sides, a low pressure recirculation zone results at the downstream face.

As a consequence a pressure difference is generated between the outside and the inside of the building and air flows from the upwind openings to the downwind openings. In this case the pressure difference in correspondence of the opening can be calculated with the following equation (de Santoli – Mariotti, 2011):

\[
\Delta p_v = 0.5 * C_p * \rho * v^2
\]

where:

- \( \Delta p_v \) = pressure difference between inside and outside induced from the wind (Pa)
- \( C_p \) = Pressure Coefficient
- \( \rho \) = air density (kg/m\(^3\))
- \( v \) = wind speed evaluated at the gutter level of the building (m/s)

The pressure distribution depends on:

- wind speed and its direction relative to the building
- shape of the building

A building situated in an open country, is generally subject to higher local wind speed than a house in a city centre. The potential of wind-induced ventilation can be maximized placing attention to the wind direction and the orientation of the building, also considering the topography.
Furthermore the pressure on a building envelope surface increases as the square of wind speed. The surface pressure acting on the building is linked to the wind velocity by the wind pressure coefficient $C_p$, which depends on the type of the façade and it can vary across the façade (CIBSE, 2005).

**Stack Effect**

The "stack" ventilation effect is produced due to the air density difference of cold and warm air. The cold air is heavier than the warm air, so that the cold air tends to flow down and to drive the warm air upwards. According to hydrostatic laws the pressure at a point decreases with the height and the rate this decrease is proportional to the density of the fluid.

With the assumption that the internal air of a building (in this case with the form of a simple box) is warmer than the external air, the following Figure 11 shows that the pressure of the cold air varies with the building height, decreasing more rapidly than the pressure of the warm air, cause its higher density.

![Figure 11 Pressure gradient and NPL (Source: CIBSE, 2005)](image)

The internal and external pressures depend of the height across the separating wall, where the air pressure are calculated as the differences of the two mentioned pressures. This differences determine the volume of air exchange, promoted by holes in the separating wall.

The phenomena can be explained with the adoption of the following three physical relationships (CIBSE, 2005):

- Conservation of mass: the airflow into the building must be balanced by the external flows.

\[ \sum \rho_i q_i = 0 \]

where:

- $\rho_i$ = air density [Kg/m$^3$]
- $q_i$ = flow rate through the opening [m$^3$/s]

- Hydrostatic pressures: the pressure gradient is proportional to the air density. The air is set at a uniform temperature, so the density is constant and the gradient is a straight line.
- Flow equation: flow through cracks and openings depends on the area, the discharge coefficient and the pressure difference.

The neutral pressure level (NPL) indicates where the two pressure are equal. At this level start the inversion of the path flow. Below the NPL air flows from the cold side to the warm and, above the NPL, from the warm to the cold. When the outside temperature exceeds the internal, the flows will reverse.

Nowadays, the decision to adopt a natural ventilation strategy in buildings, like wind-induced ventilation and stack ventilation, strongly depends on the internal gains present in the structure. The internal gains contribute to potential overheating and in some cases the adoption of natural or hybrid ventilation in building could be useless. The three most important internal gains, which are normally considered, are: people, lights and electric equipment.

People dissipate their heat through the human body. The human body is a complex system which through a high number of chemical transformations, transform the food chemical potential energy in other energy forms:

- Electrical energy (in the form of nerve impulses)
- Metabolic energy (also called metabolism)

The unit of measurement of the metabolism “M” is W/m$^2$, but often it is described with the unit “met”:

$$1 \text{ met} = 58.2 \text{ W/m}^2$$

The metabolism M is a function of the degree of activity of the individual. The ISO 8996 contains the related values. The metabolic energy, in turn, produces:

- Thermal energy
- Mechanical energy (utilized for the muscle activities)
- Chemical energy (presents in the reserve substances of the human body)

The electrical energy, the mechanical and the chemical one, after several processes, are also transformed into thermal energy. Lastly, all the produced thermal energy is released in the surroundings in the form of mechanical work and heat dissipation.

In buildings, if the solar loads is about 25 W/m$^2$ and the average coincident internal gains over the day exceed about 15-20 W/m$^2$, then it will be difficult to ensure adequate comfort at all times with the natural ventilation (CIBSE, 2005). For this reason the control of the internal gains rate is relevant for the choice of the ventilation strategy in buildings.
Some strategies of the natural ventilation are the wind-induced ventilation and the stack effect. Their efficiency depends especially and respectively on the wind speed and direction, and on the outdoor air temperature.

### 3.3.1. Wind-induced Ventilation

The cross ventilation differs from single sided ventilation by the location of openings in the zone. By the single sided ventilation the possible more openings are situated only on one side of the room, while in the cross ventilation there are ventilation openings (windows or doors) on both sides of the zone.

![Figure 12 A. Single sided ventilation; B. Cross ventilation (Source: CIBSE, 2005)](image)

The cross ventilation is generally induced by the wind but can also be induced by the stack effect, i.e. by the density differences: an example is the chimney ventilation. The adoption of this type of ventilation strategies requires an in-depth study of the outdoor environment conditions. If the building is situated in an area with a high level of pollutants there is the risk to negatively affect the indoor air quality. Furthermore, extremely high external temperature by a cross ventilation strategy can produce an increment of the internal temperatures and cause a thermal discomfort.

### 3.3.2. Stack Ventilation

The stack ventilation is driven by the air temperature and relative density differences. Under observance of the conservation of the mass, the below picture shows a three storey building, where the cross ventilated spaces relief, due the stack effect, their exhaust air through an opening located in a high and unoccupied zone of the building. To produce this positive flow path, i.e. to avoid that exhaust air reenter in the occupied zones, it is decisive the position of the NPL. A correct position of the NPL is the results of the effective design of the size openings and their location. Modifying the openings size can influence the height of the NPL and could also produce negative effects, when this height is equal to the height of the occupied zones. If it is supposed to give an equal flow rates for each level, it is necessary to realize for each of them different opening size.
The stack ventilation, i.e. the characteristic vertical air flow path, is frequently associated to the chimney ventilation. In principle the chimney ventilation exploits the stack effect for the cooling load reduction in buildings. A method to improve the chimney ventilation is to realize chimney structure with high solar absorptance proprieties.

**THERMAL CHIMNEY EFFECT**

In summer period, when outside air temperature is higher than the internal temperature, it happens a reversion of the stack-induced pressures. As consequence, the ventilation effect changes from cooling to heating. Generally this physic phenomena is unwanted and can be avoid through the creation of warmer unoccupied zones of the building, like solar chimney.

The solar chimney are construction elements very easy to build. They generally consists in zinc conducts, which permit the air flow. The conducts, which form the chimney, are positioned outside the building and orientated on the south direction. In the summer period, the internal temperature inside the chimney can achieve 60° C and so can drive the air flow from the inside to the outside of the building and have in this way a cooling effect.

---

3.4. Hybrid Ventilation concept

The late nineteenth century with the advent of the electricity were developed the first hybrid ventilation systems, which improved the convective air flow rate due the utilization of fans. An example is at the Vienna State Opera, where the underground rooms were designed precisely for the air handling and this type of ventilation. And again in the United States, where on Scientific American journey was proposed a project about the first air cooling system through ice use for a hospital: the room air should be cooled by water, which, passing in a pipe coil, should be in turn cooled by the ice. After that, with the use of fans, the water should be finely spruced from the ceiling into the rooms (Balocco et alii, 2009).

Figure 15 Vienna State Opera – Section (Source: Balocco et alii, 2009)

If the natural ventilation is not enough to guarantee the thermal comfort inside a building, it is necessary to develop an alternative ventilation strategy. Before a complete installation of a mechanical ventilation system and/or air handling unit it is reasonable to try to exploit the potential of the natural ventilation and in the critical periods to assist it with any mechanical devices, like fans.

Different strategies may be applied to different parts of the building or at different times. Some of these are the following (CIBSE, 2005):

- Changeover mixed mode: since the cooling requirements of any space vary from season to season, in extreme weather conditions the mechanical ventilation system replaces the natural ventilation
- Concurrent mixed-mode: the mechanical and natural ventilation systems are adopted simultaneously. The mechanical part is used to guarantee the refresh air in the room, while the natural ventilation, by opening windows, is responsible for the thermal comfort.
4.0. Modelling and simulation tools

4.1. Approach using simulation software

The necessity of the simulation software use depends on the complexity of the model. A model is: "a representation of the construction and working of some system of interest. A model is similar to but simpler than the system of interest" (Anu, 1997, pp 7). If the model is sufficiently simple, it can be described by simple mathematical relations, reaching in this way an exactly solution, called analytic solution. In the case in which the mathematical relations are particularly complex is necessary to work with the simulations, because an analytic solution in not possible.

The term simulation refers to the replication activity through opportune models of an existing or planning reality. For the first case, the aim is the study the effects of possible interventions or predictable events and for the second, to evaluate possible alternative design choices.

The simulation models can be divided into two categories:

- **Static model**: representation of one system in a particular time instant, or representative models of a system, where the time variable won´t be taken into consideration.
- **Dynamic model**: these models represent a system, which develops in time.

In a simulation study, human decisions are almost always indispensable. The only case where human intervention is not required is the running of the simulations through appropriate software. Generally the simulation process includes the following procedures:

1. **Problem analysis**: the most important point of the analysis is to understand the main goals of the study and to identify which components and measurements are essential.
2. **Data collection and elaboration**: this step is closely related to the first point. After the individuation of the goal, it is important to elaborate the collected data in a format adapted to the model. Frequently the data are provided by corporate databases, but in some cases it is necessary to conduct direct field measurements, which can lead to an extension of the execution time.
3. **Model construction and software choice**: the acquired data are required for the model realization. Logically, the model will be constructed with the help of software and tools, which should be chosen in order to satisfy different requirements of the specific study.
4. **Validation of the simulation model**: at this stage it is important to verify, if the realized model gives valid results for the examined system.
5. **Elaboration and presentation of data**: it is necessary to write a report and a presentation, where the complete project is summarized and where the data results are commented.

With considerably improved performance of the calculators the number of energy simulation software is considerably increased. These software employ different approaches to estimate the energy requirements causing difficulties to the quality control, which can’t find easily the gap in the used calculation procedures. One of the first studies regarding the evaluation of the various planning
instruments conducted by the National Renewable Research Laboratory (NREL, earlier called Solar Energy Research Institute) in the first 1980s, showed big differences in the results of these programs, even in the case where the simulations were conducted by experts in the field and the same input data were inserted (Binotto, 2009-2010). According to recent researches having the purpose of the development of tests for the software and of the validation procedures, the causes of the different forecasts regarding the results can be isolated, and that the bug that could produce these anomalies can be individuated and solved with a consequent program improve. The identification of error sources is not an easy process, which constitutes even now a field of interest for many researchers.

VALIDATION METHODOLOGY

**Analytic validation:** the output of a program, of a subroutine or of an algorithm are compared with the analytic solution of ideal test cases, in which the boundary conditions are simplified.

**Empiric validation:** the output of a program, of a subroutine or of an algorithm are compared with the monitored and recorded data of a real building or experiments of laboratory.

**Comparative validation:** a software is compared with himself or with other applications, which can be considered more verified or detailed and presumably more correct.

The execution of the empiric validation is recommended before other types of validation, because it is the only technique, that permits a comparison with the physic real heat transmission processes. Unfortunately it is in an expensive method in terms of human resources and financial aspects, so its use is limited only for determined cases.

The comparative validation instead, involves the execution of some calculation codes, followed by the control and direct comparison between the obtained results. In order to conduct an accurate verification of the software selection, it is preferable to work with programs that already passed validation studies and that use different models for the representation of the reality. The cases, in which the forecasts of the compared applications diverge, indicate the area requiring an additional investigation. The studies of the comparative validation are numerous and the most esteemed available in the literature are the BESTEST procedure.

The BESTEST protocol for evaluation of building energy simulation software was developed by the International Energy Agency in 1995. It permits a comparison between the results of a candidate software with the results of a set of “reference” programs. Reference program results are provided for annual heating and cooling energy, peak heating and cooling demand, total annual incident and transmitted solar radiation, annual maximum and minimum temperatures for free-running buildings, and hourly temperatures and heating and cooling energies for selected days (Delsante, 2004)

If a candidate software shows very different results by comparison with the reference results concerning a particularly variable, probably the candidate software needs a revision. This test is helpful to indicate where it is necessary to operate. A list of reference programs: ESP(UK), BLAST(USA), DOE2(USA), TRNSYS(USA) and SERIRES(Spain).
Summarizing, the simulations are generally an inexact method. They release an empirical result, which is usable only for the particular simulated case. However, the simulations in front of the analytic methods can represent a valuable instrument for the achievement of a “solution”. Like all methods that can be used for research, simulations have advantages and disadvantages (Zoppoli, 2005-06).

Advantages:

1. The simulations permits to test system with complex internal connection, for example as a company, public building or economic system
2. Through the simulation it is possible to study the effect on the behavior of system by changing its structure and its features.
3. A detailed observation of the simulated system permits a better comprehension of the system, and consequently its improvement.
4. The simulation of complex systems helps to individuate the most important variables and their interaction.
5. The simulations permit to test new unknown cases providing an important information regarding the possible results.
6. The simulations are very useful in order to divide a complex system into more simple subsystems that can be analyzed singularly.
7. The simulations permit to study dynamic systems in terms of time, i.e. it is possible to observe the behavior of the system in the past, present and future.

---

Figure 16 Example BESTEST Comparison Procedure

---

8. Thanks to the simulation, it is possible to identify eventual problems that could emerge in the system due to the introduction of new elements. The most significant characteristic of simulation, which makes it particularly advantageous in comparison with another experimental methods, is the reproducibility. The simulations are flexible and allows more degrees of freedom in the real system in exam.

Disadvantages:

1. The simulation is a slow and expensive method for the analysis of a better system
2. The simulations give numerical and no theoretical solutions. The latter are valid in general every time the hypotheses are respected, whereas the numerical solutions are related to the particular simulated case.

4.1.1. EnergyPlus

EnergyPlus is a free and stand-alone dynamic simulation software and derive from the BLAST (Building Loads Analysis Thermodynamics) and the DOE-2 programs. Both programs were developed and released between 70s and 80s years and were used to size an appropriate HVAC equipment, develop retrofit studies for life cycling cost analysis, optimize energy performance (EnergyPlus, Get.Start, 2013).

With EnergyPlus is possible to conduct an accurate simulation which is composed of different details. For example it can be calculated the heating and cooling loads necessary to maintain thermal control setpoints, conditions throughout an secondary HVAC system and coil loads, and the energy consumption of primary plant equipment. The extended quantity of simulation details is useful to compare the results of the simulation to the actual performance of the building. This software has not a user-friendly interface, i.e. the input and output commands are normal ASCII text that frequently were replaced with a GUI (graphical user interface), like Sketch-Up or DesignBuilder, for ease of use. It is worth noting that EnergyPlus does not replace the architect or the design engineers, because it does not evaluate the acceptability of the simulation’s results.

Energy Plus can calculate the heat conduction through the building envelope using different algorithms. As default algorithm the program uses the “Conduction Transfer Function Algorithm”. The heat fluxes and temperatures of the wall surfaces are calculated by a weighted sum of the past wall surface temperatures and heat fluxes. The weights are the CTF coefficients and represent the response of the wall to a fixed temperature pulse. The CTF coefficients depend on the wall composition and on the time step, but not on environmental conditions. Thus, the temperatures and heat fluxes within the wall are unknown.

The other numerical method available in EnergyPlus is the Finite Difference (FD) method which approximates the derivatives in the heat conduction equation by differences and computes the temperatures and heat fluxes at a number of nodes within the wall.
WEATHER FILE

The analysis of model simulations which use passive ventilation system for the cooling load reduction requires at least hourly data of the meteorological variables corresponding to geographic site under exam. These meteorological variables are the solar radiation (direct and diffuse on the horizontal plane), the temperature, the air relative humidity and the air speed. For a reliable simulation analysis the hourly distributions of the meteorological variables should represent the most probable temporary sequences. taking this into account weather files should be obtained by statistical series of climate data during possibly twenty years.

For the Weigh-house model was used the weather file of Bolzano available on the page site of EnergyPlus. EnergyPlus weather file derives from the “Italian Climatic data Collection Gianni De Giorgio” (IGDG) based on a 1951-1970 period of record⁹.

BUILDING ELEMENT PART CONSTRUCTION

The Objects “Zone” and “BuildingSurface” describe the thermal zone and their surfaces characteristics, like x,y,z surface vertices coordinates, sun and wind exposure and surface type ( wall, ceiling). In the object “FenestrationSurface:Detailed” all the window and door size with their x,y,z coordinates are included. The object “Construction” lists every building element part. In each element part the related materials and their position in the structure is described. The thermal properties of the materials are set in the object “Material” (Figure 17).

<table>
<thead>
<tr>
<th>Field</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td></td>
</tr>
<tr>
<td>Roughness</td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>m</td>
</tr>
<tr>
<td>Conductivity</td>
<td>W/mK</td>
</tr>
<tr>
<td>Density</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>J/kg.K</td>
</tr>
<tr>
<td>Thermal Absorptance</td>
<td></td>
</tr>
<tr>
<td>Solar Absorptance</td>
<td></td>
</tr>
<tr>
<td>Visible Absorptance</td>
<td></td>
</tr>
</tbody>
</table>

Figure 17 Material object (Source: EnergyPlus software)

AIRFLOW NETWORK

The Airflow Network model provides the ability to simulate multizone airflows driven by wind, thermal effect or by a forced air distribution system. Network models represent the building as one or more well-mixed zones, assumed to have a uniform temperature and a pressure varying hydrostatically, connected by one or more airflow paths. each building zone represents a node of the network which is linked to the other zones and to the exterior environment through openings (windows, doors, vents, cracks, etc.). Environmental conditions are represented by external nodes. All the pressure losses are considered concentrated on the openings, on which is associated a mass flux described by orifice

⁹ Source: http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_sources.cfm#IGDG (Day Accessed 13 03 2014)
equations. The AirflowNetwork is solved through an iterative method and its outcomes are associated to each node/zone. The environmental conditions are determined by the weather data, while internal temperature conditions are calculated by the tool.

Each node is associated to temperature, pressure and relative humidity values and with the leakages are connected by airflow paths. Energy and mass are conserved along each closed airflow path.

Each opening has an inlet and an outlet node, linked by a relationship between mass flow and pressure difference (Eq. 1). The mass airflow in the AirflowNetwork is calculated integrating airflow velocity function (Eq. 2) in the relative gaps of airflow way. In turn, the airflow velocity depends on the pressure difference (Eq. 3), determined assuming Bernoulli hypothesis and that air density and pressure difference are linear functions of the height. Pressure difference calculation takes also into account the turbulence effect.

\[
\dot{m} = C_d \cdot \Theta \cdot \int \rho \cdot v(z) \cdot W \cdot dz \quad \text{(Eq. 1)}
\]

\[
v(z) = \sqrt{\frac{2 \cdot (P_1(z) - P_2(z))}{\rho}} \quad \text{(Eq. 2)}
\]

\[
P_1(z) - P_2(z) = (P_{01} - P_{02}) - g \left[ \left( \rho_{01} \cdot z + \frac{b_1 \cdot z^2}{2} \right) - \left( \rho_{02} \cdot z + \frac{b_2 \cdot z^2}{2} \right) \right] + (P_{t0} + b_t \cdot z) \quad \text{(Eq. 3)}
\]

where:

- \( C_d \) = discharge coefficient [-]
- \( \Theta \) = area reduction factor [-]
- \( W \) = Opening width [m]
- \( b_1 \) and \( b_t \) = turbulence effect
- \( V(z) \) = velocity of air flow at any \( z \) levels

---

10 Source: EnergyPlus Software
P₁(z) – P₂(z) = pressure difference at any z level

The discharge coefficient depends on the geometry of the opening, the Reynolds number of the flow, and includes the influence of contraction and friction. For sharp-edge orifice flow the discharge coefficient is almost independent of the Reynolds number. Typical discharge coefficients given in textbooks vary between 0.6 and 0.65 (ASHRAE Fundamentals, 2001) for small square edged (Karava et alii, 2004).

In AirflowNetwork, airflows through the building are calculated considering different factors as wind speed and direction, size and position of the openings, outdoor and indoor air temperature. Some of these factors were defined in the AirflowNetwork input object, while part of them, like geometrical informations are extracted from building model. Input object for AirflowNetwork are described in the following paragraph.

**AirflowNetwork::SimulationControl**: defines basic run parameters for the air flow calculations.

<table>
<thead>
<tr>
<th>Field</th>
<th>Units</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td></td>
<td></td>
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<tr>
<td>AirflowNetwork: Control</td>
<td>MultizoneWithoutDistribution</td>
<td></td>
</tr>
<tr>
<td>Wind Pressure Coefficient Type</td>
<td>Input</td>
<td></td>
</tr>
<tr>
<td>AirflowNetwork: Wind Pressure Coefficient Area Name</td>
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<td></td>
</tr>
<tr>
<td>Height Selection for Local Wind Pressure Calculation</td>
<td>ExternalNode</td>
<td></td>
</tr>
<tr>
<td>Building Type</td>
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<td></td>
</tr>
<tr>
<td>Maximum Number of Iterations</td>
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<td>500</td>
</tr>
<tr>
<td>Initialization Type</td>
<td>ZeroNodePresh</td>
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</tr>
<tr>
<td>Relative Airflow Convergence Tolerance</td>
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</tr>
<tr>
<td>Absolute Airflow Convergence Tolerance</td>
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<td>0.000002</td>
</tr>
<tr>
<td>Convergence Acceleration Limit</td>
<td>dimensionless</td>
<td>0.05</td>
</tr>
<tr>
<td>Azimuth Angle of Long Axis of Building</td>
<td>deg</td>
<td></td>
</tr>
<tr>
<td>Ratio of Building Width Along Short Axis to Width Along</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Figure 19 AirflowNetwork::SimulationControl object (Source: EnergyPlus software)

In absence of a distribution system the option “MultizoneWithoutDistribution” is to be selected at the field AirflowNetwork Control. The wind pressure coefficients can be input by the user or, for rectangular building, by the program. If the pressure coefficients are insert by the user (AirflowNetwork: Multizone: WindPressureCoefficient Values), it is necessary to create an array with the wind directions corresponding to the wind pressure coefficient (AirflowNetwork: Multizone: Wind Pressure Coefficient Array). Wind pressure coefficient related to each wind direction are attributed to each external node (AirflowNetwork: Multizone: ExternalNode), which are associated to each external opening. The other voices listed in the object refer to initialization method and convergence tolerances necessary for the airflow calculation through iterative method.

**AirflowNetwork::Multizone:Zone**: the object specifies the ventilation control mode at zone level. Through the selection of the following Ventilation Control Mode it is defined if natural ventilation is allowed.

- No Vent (never active)
- Constant (always active)
- Temperature (active if T_{zone} > T_{out} and T_{zone} > T_{set})
- Entalphy (active if H_{zone} > H_{out} and H_{zone} > H_{set})
- ASHRAEE 55 Adaptive Comfort/CEN15251 Adaptive Comfort (active if T_{operative} > T_{comfort})
All these control types are considered only if the “On” option is selected in the Venting Available Schedule.
Surface-level ventilation control can be used to override the zone-level ventilation control if required.

**AirflowNetwork:MultiZone:Surface**: the object indicates whether a heat transfer surface has a crack or opening, described in the AirflowNetwork:MultiZone:Surface/Component. The opening or crack connected two internal nodes or internal node with external one. Through a dimensionless factor is indicated if the opening or crack are open or close. A factor = 0 means close, while a factor = 1 means total open. The values between 0 and 1 determined in which proportion the opening is open related to its area.

- AirflowNetwork:MultiZone:Surface:Crack
- AirflowNetwork:MultiZone:Surface:EffectiveLeakageArea
- AirflowNetwork:MultiZone:Component:SimpleOpening
- AirflowNetwork:MultiZone:Component:DetailedOpening

4.1.2. Therakles

Therakles is a thermal single zone simulation software developed in year 2009 by the Institute for Building Climatology for the research project of federal ministry of economy and Technology “EnOB:MONITOR (Begleitforschung Energieoptimierte Gebäude)“.

The tool is a validated software according to EN 13792 and it is a very intuitive and it is easy to use. The graphic interface is simple and the simulation time is short. It can be used as reference tool.

The thermal room model Therakles calculates the dynamic behaviour of a room and its construction parts in function of a real climatic boundary conditions and equipment and occupants/users behaviours. Most of the principal basis heat transport mechanisms are identical to the Therakles CLIMT Model. In some point there are considerable differences (Nicolai, 2013):

- The limiting constructions of the room are multilayer, one-dimensional constructions. So their effective present heat storage capacity can be describe without any correction factor.
- For each construction it was calculated the independent temperature and the respective different surface temperature. In this way it is possible to achieve a better appraisal of the radiation temperature and in consequence of the operative temperature.
- The calculation procedure is numeric and can good describe by time control algorithms the heating and cooling system function.
- For the calculation of the sun path is used an alternative equation for the Azimuth angle. In this way it is possible to use the model for all kind of latitudinal lines.

The program solves the Transfer heat conduction of a wall by a finite volume discretization method. The finite volume method (FVM) is a discretization technique for partial differential equations, for example equations that derived of conservation laws. FVM uses a volume integral formulation of the problem with a finite partitioning set of volumes to discretize the equations: the equations should be
integrated in a volume, on whose volume boundaries are imposed the boundary conditions. The internal
of this domain is divided in several elementary volumes, so that, the relations between the various
neighboring volumes are defined through the equation integral form related to the considered problem.
In this manner the relation could be solved with an analytic method or through the calculator use. The
size of the small volumes (finite dimensions and not infinitesimal) defined the approximation of the
method. As for the FD method of Energy Plus, the FVM provides the temperatures and heat fluxes at
the nodes within the wall.

The program needs for the simulation the geographical coordinate (latitude, longitude, m above sea
level) of the room and the climatic boundary conditions, and more precisely the solar radiation (direct
and diffuse solar radiation) and the ambient temperature of the air.

After that it is important to give the dimension of the room as net area and height and to set up the type
of the element construction. In the program is possible to choose three types of element construction:

- Outside Construction
- Inside Construction
- Construction to fixed-temperature zone

Outside construction: the surface of the room confines with the external air and is exposed to the
solar radiation. For this construction it is to define the Area (m²), Orientation, Inclination, possibly
window construction and respective shadowing elements, absorption factor and two-sided thermal
transmittance.

Inside construction: these surfaces confine with zone with similar temperate rooms. Through these
elements flows no heat input or losses in the thermal zone. They only act on their storage capacity. For
this type of construction it is to define the Area, and internal thermal transmittance.

Construction to fixed-temperature: these surfaces confine with different temperate rooms. The heat
flows through the entire wall and the adjacent zone maintain a set up constant temperature. For this
type of construction it is to define the Area, the two-sided thermal transmittance and the temperature of
the adjacent zones.

Therakles permits to set up Heating, Cooling in a constant mode or with a daily cycle or also by an
annual hourly schedule. The same can be done with the parameters Mechanical Ventilation, Infiltration
and for the internal thermal loads, and Shading Control. In Shading Control it is possible to regulate
when the shading element has to be fully close by the set up radiation intensity on the window.

As output the program drop out the room air and operative temperature, the thermal comfort according
to EN15251, the radiation loads and the thermal loads. The simulation results are in text form or they
are showed in a history chart.
5.0. The Weigh House

5.1. Climate analysis

The study of the climate and of climate changes is important to analyze their effects on the buildings. The climate of a particular territory strongly influences the internal environmental condition of a structure, especially when the building is not provided with improved construction elements, for example adequate thermal insulation, new windows,… For this reason, the understanding of the climate change causes and the envisagement of new scenarios for the future climate is useful to develop instruments for building conservation and prevention.

EURAC Researchers estimated that the yearly average temperature in Alto Adige will see a rise of 1.2-2.7 °C by 2050. This can be seen as a direct consequence of global warming, along with scarceness of water resources and extreme phenomena like intense rainfall, storm and heat waves; the main cause of global warming appears to be the greenhouse effect, produced by greenhouse gases like water vapor, carbon dioxide (CO$_2$), methane (CH$_4$) and the nitrogen oxide (N$_2$O). In the last 30 years an increase of about 70% in greenhouse gases emission (due to anthropogenic activities) was registered (Zebisch, 2011).

The average temperature in Bolzano has risen of about 1.5 degrees Celsius over the last thirty years. The highest temperature was observed in June 2010: 3°-5°C above the average of the month. Furthermore, over the last 20 years the number of tropical nights has considerably increased. Before 1995 it was five per year, while in 2010 it reached the number of 20 (Zebisch, 2011).

Climate in Alto Adige is strongly influenced by the mountainous morphology of the territory. The altitude of the province of Bolzano varies from 200 m above sea level in the Bassa Atesina to 400 m in the Ortles. The higher altitudes involve an increment of rainfalls and a decrease of the temperature. The mountain ranges surrounding the region protect Alto Adige from humid currents and make the region dry, in comparison with the other alpine areas. Due to the high mountains, the Province of Bolzano is furthermore characterized by two particular effects: the “föho” and the “stau”. The first brings dry air and the second, with low pressure on the Gulf of Genoa and on Adriatic, causes significant rainfalls.

The city of Bolzano is situated in a deep valley where the climate is temperate and warm, with average temperatures over 20°C in summer and with a mild winter. Moreover, a fluctuation of 12°C in the daily temperature can be appreciated in the summer months, while in winter it does not go beyond 8°C. Bolzano stands out significantly also from the Italy wide temperature statistics: in the summer the state capital is often the hottest city in the entire national territory, in winter it is often the coldest provincial capital of Italy\textsuperscript{11}. The average daily maximum temperature in summer is 27-29°C, the average overnight lowest values in winter month are -1 to 5° C (Eurac, 3ENCULT, 2013)

\textsuperscript{11} Source: http://wetter.bz.it/klima_suedtirol.html (Day Accessed: 26.02.2014)
<table>
<thead>
<tr>
<th></th>
<th>Temperature °C</th>
<th>Monthly average Temperature °C (year 1921 – 2012)</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Max. average</td>
<td>Min. average</td>
</tr>
<tr>
<td>Jan</td>
<td>5,9</td>
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</tr>
<tr>
<td>Feb</td>
<td>9,3</td>
<td>-2,4</td>
</tr>
<tr>
<td>Mar</td>
<td>14,6</td>
<td>1,5</td>
</tr>
<tr>
<td>Apr</td>
<td>18,8</td>
<td>5,3</td>
</tr>
<tr>
<td>May</td>
<td>23,2</td>
<td>9,2</td>
</tr>
<tr>
<td>Jun</td>
<td>26,8</td>
<td>12,7</td>
</tr>
<tr>
<td>Jul</td>
<td>29,2</td>
<td>14,8</td>
</tr>
<tr>
<td>Aug</td>
<td>28,3</td>
<td>14,5</td>
</tr>
<tr>
<td>Sept</td>
<td>24,8</td>
<td>11,2</td>
</tr>
<tr>
<td>Oct</td>
<td>18,7</td>
<td>5,5</td>
</tr>
<tr>
<td>Nov</td>
<td>11</td>
<td>-3</td>
</tr>
<tr>
<td>Dec</td>
<td>6,5</td>
<td>-4,4</td>
</tr>
<tr>
<td>Year</td>
<td></td>
<td>12,3</td>
</tr>
</tbody>
</table>

Table 1: Average minimum and maximum temperatures over the year and monthly average temperature (from 1921 -2012) (Source: Eurac, 3ENCULT, 2013)

In the Bolzano area outweigh the west and southwest winds in spring, summer and autumn. In winter there is often no wind or wind from north and northeast. Northwest and west winds generally are less frequently. The wind has an average speed of 1.6 - 3.3 m/s (Eurac, 3ENCULT, 2013).

Figure 20: Prevailing wind direction (Source: Eurac, 3ENCULT, 2013)
5.2. Historic analysis

The Weigh-house is a Romanesque edifice of the XIII century and it is situated in the historic centre of Bolzano (Italy) in “Piazza del Grano”. The building is part of one of the biggest (300 m from east to west) and historic commercial street of the city, also called “via dei Portici”. The origin of the “Portici” or “Arbors” precedes the Renaissance period, in which it was extremely popular architectonically. The “Arbors” are the successor of the Roman architecture elements “Arcades”. Since the Renaissance, the arbor type construction could be found in castles, town halls and also in arcade houses, due to the increasing importance of the middle class and bourgeoisie. The arcade-house model spread through Tyrol over southeastern Bavaria, then to Bohemia, Silesia and finally to Prussia. Their “western path” went instead from the South of France and eastern Switzerland to Westphalia.

The distinctive structure of the Portici of Bolzano is the continuous arcades along the aligned houses, and it comes from southern Germany and Tyrol, where it was originally developed to cover the road. Today, it can also be observed around the marketplaces.

Till 1780 the Weigh-house was the location of a public weighbridge. Since the 90s the structure, except the ground floor with its shops, has been neglected. The local authorities in cooperation with the building owner (the Foundation “Stiftung Südtiroler Sparkasse”, since 2009) plan to transform it into a photographic museum called “La Casa della Fotografia”, which will host galleries and labs.

The building presents all the typical characteristics of a building of “Via dei Portici”, such as shops, dwellings and warehouse. The Weigh-house is composed by two basement floors and four floors above the ground level. Generally the basement floor was used for the storage and conservation of wares, which were exposed and sold in the ground floor shop. The first and upper floors all contained apartments, except the top floor, which was not originally inhabited.

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Source: [http://u01151612502.user.hosting-agency.de/malexwiki/index.php/Laubenh%C3%A4user](http://u01151612502.user.hosting-agency.de/malexwiki/index.php/Laubenh%C3%A4user) (Day Accessed: 25.02.2014)
In the course of its history the building underwent several structural changes. Since the XIII century, numerous extension works were performed and some building units have been added to the original edifice; the floors of the entire complex have been aligned only in a second time (Eurac, 3ENCULT, 2013). Figure 24 shows the evolution of the building for each floor during the centuries:

Figure 24: WP6 Diachronic Analysis (Source: Eurac, 3ENCULT, 2013)
Towards the end of this Century, a major intervention was made. This included the unification of window openings, the extension on the east and west side and the subdivision of the second floor with interior walls. Finally, during the last Century several inside partition walls were added. The original window is mainly a wooden box-type window from the late baroque era but it has been replaced in many cases by a coupled window. For shading and darkening a wooden window shutter is used. The building has not heated (Eurac, 3ENCULT, 2013).

The historical importance of the building has been explored together with a close analysis of the construction phases and elements (walls, roof, ceilings, chimneys etc.). A further inspection and a parallel analysis of other buildings with similar features were useful to determine the dating and the constructive typology of the edifice’s different parts. In particular, it is to underlines the support that the historical plans and report by Arch. Adriano Salvoni in concomitance with photos and building surveys, were helpful for the determination of the chimneys number and their location.

5.3. Structure and masonry

The Weigh House is part of the “Portici Street”, but it is separated by arcade houses on both long sides through a narrow alley. Through these alleys “Piazza del Grano” can be reached.

![Weigh-house location](Modified from Eurac, 3ENCULT, 2013)

The listed building consists of 3 full stories, a top floor and two basement floors. According to the historical analysis and the inspected building rooms, it was counted the presence of eight chimneys in the building. Most of the chimneys are located on the second floor and only a few of them are present on the first floor. On the ground floor, in the inspected rooms no chimneys were found. This stresses the fact that the ground floor was used as a shop, while the upper floors as apartments.
All full storeys and the cellar are built in masonry of natural stones and lime mortar. The exterior walls have a thickness of about 60-80 cm. All walls (except on basement level) are plastered with lime plaster. The construction of the saddle roof is made of timber rafters with wooden casing and roof tiles. The ceilings of the upper floors are built in wooden beams with wooden casing and filling material in between. The underside of the ceiling is plastered with lime plaster. Especially on the ground floor and the basement, the ceilings are vaulted.

Several samples of material has been taken with a core drill hole from walls, wooden beams, filling of the ceilings and plaster samples. This permitted to analyze the materials characteristics related to water absorption, porosity, density, thermal conductivity and capacity. (Eurac, 3ENCULT, 2013).

Non-Destructive Testing (NDT) has played an important role in obtaining precious information about conservation aspects and energy performance (IR-thermography, heat flow-meter measurement, Blower Door Test, Gas Tracers test and so on). The IR-thermography revealed the most important energy anomalies related to thermal bridges, structure of the construction, material used, low performances of envelope, air leakages, decay and cracking of plaster, moisture, water percolation and changes that have arisen in the course of its history, such as closing of windows or openings. The thermal transmission properties of building envelope has been measured using the heat flow-meter measurement (HFM) applied directly in situ. The appropriate location has been investigated by IR-thermography, in accordance to the internationals standard (ISO 9869, 1994) to avoid the influence of direct solar radiation, rain, snow, thermal bridges and influences of windows, natural and artificial ventilation. The monitoring period was of 120-144 h related to the thickness of constructive detail (instead of 72 h foresee in the standard). It has been chosen to provide a stable average of the U-value (Baker, 2008 and 2011) which takes into account the thermal inertia of the walls.
<table>
<thead>
<tr>
<th>Component</th>
<th>Materials</th>
<th>Thickness</th>
<th>Conductance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior wall</td>
<td>Stone, mortar</td>
<td>62 cm</td>
<td>1,355 W/m²K</td>
</tr>
<tr>
<td>Parapet under window</td>
<td>Stone, mortar</td>
<td>20 cm</td>
<td>2,86 W/m²K</td>
</tr>
<tr>
<td>Ceiling over porticos</td>
<td>Wooden beam, earth, sand</td>
<td>40 cm</td>
<td>0,48 W/m²K</td>
</tr>
</tbody>
</table>

*Table 2 Building element parts – Thermal properties (Source: Eurac, 3ENCULT, 2013)*

The attic is internal insulated with 8 cm of rock wool, which is supported from plasterboard. The total transmittance $U$ is equal to 1,38 W/m² (measured in site). However, the thermal insulation presents discontinuity along several points of the attic (the $U$-value achieved a value of about 2,61 W/m²) (Eurac, 3ENCULT, 2013) and it is not coupled with any air tightness system.

The most parts of the original windows were replaced in the ’50/’60 years with a box-type window system, not considered valuable by the conservation experts. The existing windows have glass system thermal transmittance $U_g$ of about 2,7 W/m²K, while the thermal transmittance of the frame $U_f$ is equal to 2,5 W/m²K. (Eurac, 3ENCULT, 2013).
6.0. Model description and simulation results

For the impact evaluation of the energy retrofit solutions a model of the entire building was realized with EnergyPlus. The model realization required the collection of specific data that resulted from several site inspections, tests (like the blower door test), historical analysis and study of scientific researches. According to the Italian law 9/1/91 and subsequent amendments, which establish the ignition and times of use of heating for the province of Bolzano, a cooling simulation period from 16th April till 14th October is considered.

6.1. State of the art

In the program Energy Plus, the “As is State” model should represent the Weigh-house in its actual conditions, as are described in part in the previous chapter. Walls, windows and all the construction elements of the building were created with the use of the data collected during the 3ENCULT project. Mainly, the “As is State” model is the reference model, the starting point of all the following assumptions about the building cooling load reduction.

Figure 27 A. and B.: 3D Model in EnergyPlus: South-West and South-East View

Figure 28 A. and B.: 3D Model in EnergyPlus: North-East and North-West View
THERMAL ZONES

In the Energy Plus model, the entire building is divided into several Thermal Zones. Without thermal zones and surfaces, the building can not be simulated. In total the model contains 39 thermal zones distributed in the building floors as follows:

<table>
<thead>
<tr>
<th>Basement</th>
<th>Ground floor</th>
<th>First floor</th>
<th>Second floor</th>
<th>Top floor</th>
<th>Chimney</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basement -1</td>
<td>GF_1</td>
<td>F1_1</td>
<td>F2_1</td>
<td>TF_1</td>
<td>Chimney 1</td>
</tr>
<tr>
<td>GF_2</td>
<td>F1_2</td>
<td>F2_2</td>
<td>TF_2</td>
<td>Chimney 2</td>
<td></td>
</tr>
<tr>
<td>GF_3</td>
<td>F1_3</td>
<td>F2_3</td>
<td>TF_3</td>
<td>Chimney 3</td>
<td></td>
</tr>
<tr>
<td>GF_4</td>
<td>F1_4</td>
<td>F2_4</td>
<td>TF_8</td>
<td>Chimney 4</td>
<td></td>
</tr>
<tr>
<td>GF_5</td>
<td>F1_5</td>
<td>F2_5</td>
<td>Chimney 5</td>
<td>Chimney 5</td>
<td></td>
</tr>
<tr>
<td>room 30</td>
<td>GF_2</td>
<td>F1_6</td>
<td>F2_6</td>
<td>room 45</td>
<td>Chimney 6</td>
</tr>
<tr>
<td>room 32</td>
<td>F1_7</td>
<td>F2_7</td>
<td>room 46</td>
<td>Chimney 7</td>
<td></td>
</tr>
<tr>
<td>room 33</td>
<td>room 34</td>
<td>F2_11</td>
<td>room 50</td>
<td>Chimney 8</td>
<td></td>
</tr>
<tr>
<td>room 45</td>
<td>room 51</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3 Thermal zones nomenclature

In order to identify the part of the building, which has been treated, the following drawings have been adopted. The building plan is useful to understand the orientation of the rooms in the building.

The basement of the Weigh-house consists of two undergrounds floors. The passage to the basement is allowed through a door, placed in the room called GF_4 of the ground floor. In the model the two underground floors are considered as a unique volume.

<table>
<thead>
<tr>
<th>UNDERGROUND FLOOR</th>
<th>Area [m²]</th>
<th>Volume [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basement_1</td>
<td>105.54</td>
<td>667.08</td>
</tr>
</tbody>
</table>

Table 4 Underground floor dimension
The entry of the Weigh-house museum is located in the GF_4 room. It is also possible to go up to the upper floors through this room. The rest of the rooms is used as shops or warehouses at the moment and they are not part of the future museum.

![Figure 30 Ground floor plan](image)

<table>
<thead>
<tr>
<th>GROUND FLOOR</th>
<th>Area [m²]</th>
<th>Volume [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF_1</td>
<td>18.12</td>
<td>69.04</td>
</tr>
<tr>
<td>GF_2</td>
<td>72.35</td>
<td>275.65</td>
</tr>
<tr>
<td>GF_3</td>
<td>41.56</td>
<td>158.34</td>
</tr>
<tr>
<td>GF_4</td>
<td>19.52</td>
<td>74.37</td>
</tr>
<tr>
<td>GF_5</td>
<td>97.69</td>
<td>372.20</td>
</tr>
</tbody>
</table>

*Table 5 Ground floor dimensions*

The first floor should contain the exhibition area of the museum. The room called F1_5 is the big atrium of the building, which is positioned at the stairwell. The plan shows the chimney position.

![Figure 31 First floor](image)
The second floor should also contain the exhibition area of the museum. The room called F2_5 is a big atrium, which is positioned near the stairwell to reach the top floor. The plan shows where the chimneys are situated.
The top floor is taken into consideration for the analysis of thermal comfort. The zone is thought as depot place and not as exhibition area.

![Figure 33 Top floor view](image)

<table>
<thead>
<tr>
<th>TOP FLOOR</th>
<th>Area [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Area</td>
<td>331.8</td>
</tr>
</tbody>
</table>

Table 8 Top floor dimensions

INTERNAL GAINS

The main internal gains, namely People, Lights and Electric Equipment, were introduced for the simulation analysis starting from the “As is State” model. At the moment the real building is unsupplied of them, however, in order to impose to the model the same boundary conditions and to proceed with the planned elaborations, the mentioned internal gains have been taken into consideration.

The values of internal gains were calculated according to the norm UNI/TS 11300-1:2008 “Determinazione del fabbisogno di energia termica dell'edificio per la climatizzazione estiva ed invernale”. In the norm, the types of internal load and their values are given depending on the intended use of the building. An average value of about 8 W/m² for a museum is suggested. This value is not imposed, that is why it can be changed according to the designer choice. An average value of maximum 15 W/m² was set for the Weigh-house.

- People: 5 W/m² (class of "Occupant Density": III)
- Lights: 7.5 W/m²
- Electric Equipment: 2.5 W/m²

In order to regulate the amount of W/m² during the day, schedules in EnergyPlus were created for the mentioned internal gains.
AIRFLOWNETWORK

The type of openings is defined after the input of wind pressure coefficients related to each wind direction and to each external nodes:

- **AirflowNetwork:MultiZone:Surface:Crack**: to the crack was associated the openings which represented the stairwell opening.
- **AirflowNetwork:MultiZone:Component:SimpleOpening**: to the SimpleOpening was associated all the interior and exterior doors of the building. The chimneys openings are considered like small doors.
- **AirflowNetwork:MultiZone:Component:DetailedOpening**: to the DetailedOpening was associated the external window of the house.
- **AirflowNetwork:MultiZone:Surface:EffectiveLeakageArea**: the Effective Leakage Area (ELA) values were used only for the “As is State” model. In the following paragraph it is explained how the ELA values were obtained. The rest of the models considers the walls of the building airtight and the air infiltration occurs through the CLOSED windows.

The Effective Leakage Area (ELA) values were obtained through the “Blower Door Test”. It consists on a fan positioned either on the outside door of the building or on the door of the rooms. Before proceeding with the measurements the tight which would normally be locked should be closed so that the thermal assessment of the building would have no distortion. The airtightness factor permits to determine the air infiltration and air leakage into the building thanks to the creation, by means of the fan, of a pressure difference between the interior and the exterior. The legislation UNI EN 13829 and the ASTM E779-10 and ASM 1827 describes the procedure to calculate the infiltration rate $n_{50}$ with the unit [1/h] at a testing pressure difference of 50 Pa.

$$n_{50} = \frac{V_{50}}{V} \left[ \frac{1}{h} \right]$$

$V_{50}$ : volumetric flow of the leakage [m$^3$/h]
$V$ : building air volume [m$^3$]

The $n_{50}$ factor does not depend on the size of the building. From this factor it is possible to determine the Effective Leakage Area from each rooms of the building. High ELA values are justified by the presence of interruptions in the airtight envelope of the Weigh-house.

For the Weigh-house case the “Blower Door Test” was conducted in two rooms, assumed as “reference rooms”. Afterward, the ELA was calculated at a pressure difference of 4 Pa and in function of the number of windows present in the rooms, it was attributed to each window the equivalent ELA.
The following values are calculated on the assumptions that:

- major responsible of air infiltration into the building are the windows: this assumption was confirmed using gas tracing instrument
- the windows type is the same for all rooms

ELA, Cracks, Windows and Doors are controlled by specific Schedules. The Schedules establish when the opening should be opened or closed during the hours of the day. Chapter “Ventilation strategies” will explain the settings of these schedules indispensable for the AirflowNetwork creation.

*Figure 35 AirflowNetwork Scheme: First Floor*
The doors D5 and D11 have deliberately not been considered in the AirflowNetwork: for the Weigh-house museum an ideal path of the future visitors has been recreated. The D5 and D11 doors can be considered closed. The Ground floor, except the “room GF_4” and the Top floor are not included in the complete analysis, because they will not be used as museum, i.e. as exhibition area. In the AirflowNetwork configuration, all external windows and external doors for the Ground floor are assumed to be closed, while the external windows of the Top floor are assumed to be opened.
6.2. Comparison between EnergyPlus\Therakles for one modeled single room

As already mentioned Energy Plus and Therakles are two validated simulation software. Whereas Therakles is more indicated for simple thermodynamic system, Energy Plus cover more complex fields, so that a vast number of variables have to be considered. The different in complexity of the two software clearly appear if we consider that Energy Plus can take into consideration an entire building and its HVAC, while Therakles, according to its intuitive use, was develop for the thermodynamic study of single rooms. Therakles is indicated as reference program.

The two programs are developed by two different companies with their own interface tool. Even the modality of the data input is different: Therakles often needs average parametric values for the simulation running, while EnergyPlus often requires the value of singular factor or variable in time function. This different input data modality can cause difficulties to define the same boundary conditions for the two models. In several case, in order to obtain acceptable results for the comparison, some simplifications to the model were necessary. To decrease the uncertainty of results, the same values or values that differ little between them should be inserted.

The model room that has been analyzed for a comparative “validation” between the software Energy Plus and Therakles, is the room called “Room 34” in EnergyPlus. The room is situated on the first floor of the Weigh-house and is composed of two external surfaces, oriented respectively to South and to West. The room has two windows located respectively on the Western and Southern façade.

The model in EnergyPlus was already created. The most difficult work was its adaptation to the Therakles software. The comparison procedure requires that each component of the program must be studied, and afterward put in relation with the EnergyPlus components.

WEATEHR FILE

The charge into the software of the weather data file, corresponding to the location of the building, is very important. Depending on the weather file, the model responds in different way. For Therakles the values of the direct and diffuse solar radiation and the ambient temperature are necessary. Instead in
EnergyPlus the weather file contains more parameters and factors used to solve the various functions that the designer intends to simulate: an example is the wind, which is set equal to zero.

In EnergyPlus temperature values of the Weather file refer to the measured values at the local meteorological station. The program needs these values to calculate the external temperature at a high level (EnergyPlus vol. Eng. Ref., 2013). In this case the external temperatures of the Room 34 zone are taken into consideration and utilized also for Therakles Weather file.

\[ T_z = T_b + L \cdot (H_z - H_b) \]

- \( T_z \) = outdoor air temperature at altitude \( z \) (the altitude \( z \) refers to the height above ground level)
- \( T_b \) = air temperature at the base of the layer, i.e. ground level for the troposphere
- \( L \) = air temperature gradient, equal to -0.0065 K/s in the troposphere
- \( H_b \) = offset equal to zero for the troposphere
- \( H_z \) = geopotential altitude

**THERAKLES ROOM MODEL CONSTRUCTION**

The area and the height of the room 34 inserted in EnergyPlus are also imported in Therakles. After giving the area and the height of the room the surfaces that delimited the room and their orientation respect to the geographic north were setup:

- 4 external surfaces: 2 external walls and 2 external windows
- 4 internal surfaces: 2 internal walls, 1 internal basement and 1 internal ceiling

Figure 39 Geometry and Climate Page of Therakles

To guarantee the same boundary conditions, the adjacent rooms of Room 34 are set up with a constant temperature of 20°C. In EnergyPlus the objects HVAC Template: Zone: IdealLoadsAirSystem and HVAC Template: Thermostat are used and a constant Heating/Cooling Setpoint of 20°C was added. While in Therakles, in the page "Geometry and Climate", the voice "Construction to fixed-temperature zone" was selected and the voice "Opposite room temperature" was filled with the desired temperature value.
HEATING AND COOLING

In reality, no conditional air system exists in the Weigh house at the state of the art. Considering this, and having focused the comparison only on the cooling period, the introduction of an ideal Heating System has no relevant influence on the summer period analysis. For this reason, the Heating control was set up in both programs only for training purpose: a constant temperature of 20°C during the time between 6:00 and 23:00 o'clock for the period from 15 October to 15 April was selected. For the examined period, namely from 16th April to 14th October, no cooling system has been supposed.

VENTILATION AND INFILTRATION

For natural ventilation, the ventilation rates in a non-domestic building should be across a wide range, from about 0.5 to 5 ACH or even more (CIBSE, 2005). For both models a constant infiltration rate of 1.67 [1/h] was set. In Energy Plus the Simulation Parameter: “ZoneInfiltration:DesignFlow Rate was used to set a constant air change air, No Mechanical ventilation is taken into consideration for the simulation.

INTERNAL THERMAL LOADS

No electric equipment is in operation at the state of the art of the building and the entire structure is uninhabited. As a consequence the internal thermal loads were not considered for the simulation and set equal to zero.
SHADOWING AND SHADING ELEMENTS

In Energy Plus it is necessary to specify the Solar Distribution, i.e. how EnergyPlus treats beam solar radiation and reflectances from exterior surfaces that strike the building and, ultimately, enter the zone.\(^\text{13}\) In EnergyPlus the function MinimalShadowing was selected, while in Therakles there is no option to specify Solar Distribution. Minimal Shadowing means that: "there is no exterior shadowing except from window and door reveals. All beam solar radiation entering the zone is assumed to fall on the floor, where it is absorbed according to the floor’s solar absorptance. Any reflected by the floor is added to the transmitted diffuse radiation, which is assumed to be uniformly distributed on all interior surfaces."\(^\text{14}\)

Therakles software do not consider the shadow effects due to the presence of adjacent buildings. For this reason in Energy Plus these effects were not considered. The windows of the building do not have shading elements at their state of the art, so in the program they are not added.

PHYSIC MATERIAL/CONSTRUCTION PARAMETERS

For each material of the element construction the respective physic parameter value is provided:

- Density [kg/m\(^3\)]
- Heat Capacity [J/KgK]
- Thermal Conductivity [W/mK]
- Solar absorption on outside surfaces [0….1]
- Thermal and Solar Absorbtance [0….1]

For the windows:

- Window U-Factor [W/m2K]
- Solar Heat Gain Coefficient (glass only)
- Glass fraction [dimensionless]

By both programs the windows were considered without frame. This choice was taken for simplify the input data operation, i.e. for avoid diverged entry values on the setting page of the softwares.

Therakles considers an average U-factor value between glazing and frame (window U-factor). With EnergyPlus it is possible to consider glazing and frame U-factor separately. After these considerations, in Therakles on the voice “Glass fraction” was imposed the value 1, which means no frame. In EnergyPlus the same values were inserted using the object “WindowMaterial:SimpleGlazingSystem”

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\(^{13}\) Source: InputOutputReference.pdf (version 8.0 EnergyPlus, pag 16)
\(^{14}\) Source: InputOutputReference.pdf (version 8.0 EnergyPlus, pag 16)
The general formula to calculate the U-Factor for a wall is:

\[
U = \frac{1}{R_e + R_{\text{at}} + R_i} \left[ \frac{W}{m^2K} \right]
\]

Where:

\(R_e\) = surface heat transfer resistance on outside (convective and radiative) \(\left[ \frac{m^2K}{W} \right]\)

\(R_i\) = surface heat transfer resistance on room side (convective and radiative) \(\left[ \frac{m^2K}{W} \right]\)

\(R_{\text{at}}\) = total resistance of the building materials in the constructional element \(\left[ \frac{m^2K}{W} \right]\)

Both programs require convective coefficient values. These have to be associated with the related surface. Therakles requires average fixed values of \(R_e\) and \(R_i\), while in EnergyPlus it is possible to use fixed values or several algorithms that calculate the outside and inside convective coefficients. Fixed convective coefficients in EnergyPlus are inserted filling the object “SurfaceProperty:ConvectionCoefficients:MultipleSurface.”
The analysis of the results was made on steps. Firstly, the internal air temperatures of the room were analyzed without considering the glass surfaces; then, these values were compared to the results of the same analysis keeping the glass surfaces into consideration. The procedure was useful to check possible errors in the input data or in the worst case software bugs.

**ROOM WITHOUT WINDOWS**

![Room 34 - Mean Air Temperature Comparison - EnergyPlus / Therakles [C] - July](image1)

*Figure 44 Air Temperature Comparison - EnergyPlus / Therakles – Model without windows*

Figure 44 shows the trend of the Mean Air Temperature of the Room 34 calculated with the two different software. For the analyzed period no considerable temperature divergences are calculated. A maximum air temperature of about 23.4 °C was calculated for EnergyPlus, while a maximum air temperature equal to 23.7 °C was calculated in Therakles. Figure 45 shows in which percentage the temperature divergence is contained in fixed range.

![Room 34 - Temperature divergence ΔT [C] - Energy Plus / Therakles](image2)

*Figure 45 Temperature divergence – EnergyPlus / Therakles – Model without windows*
Through the interpretation of the results, it is possible to assert that the heat transmission through the walls guarantees an equivalent room thermal condition for both models. More of the 70% is less than the 0.1°C of temperature divergence, while the rest do not overtake the 0.4°C. These minimal deviations could depend principally on the approximation, in term of decimal places, of the values inserted in the input data phase and on the software tolerance.

ROOM WITH WINDOWS

Successively the windows belong to the room 34 are inserted in both models. Also in this case was compared the simulation results of the two software.

Figure 46 shows an increase of room air temperature divergence between the results. The major divergence occurs during the hottest months. As consequence of the windows addition to the room, the internal air temperatures are higher than the in the case without windows. A maximum air temperature of about 23.9°C was calculated for EnergyPlus, while a maximum air temperature equal to 25.3°C was calculated in Therakles. In the following table the temperature divergences are showed in more detail.
According to Figure 47, the major temperature difference lies in the range of 0.5-0.8 °C with a percentage of about 40%. A small 7% is included in the range of 1.0-1.5 °C. Major temperature divergences are mainly registered in July and August, when the solar radiation rate, which meets the transparent surfaces, is higher. Possible causes of the little temperature divergence can be:

- Different method for the solar gains calculation on the transparent surfaces
- Different method for calculation of the sun path. In Therakles an alternative equation for the Azimuth angle is used, like before mentioned.
- Approximations errors

6.3. Energy efficiency improvements on the building envelope

The energy efficiency of a building is achievable through different methods. The interventions adopted into the model are the reduction of air infiltration of the building envelope, the application of a thermal insulation to some structural elements and the replacement of old windows with new ones. The applied set of interventions is discussed with a team of Eurac and independent conservation experts, in order to achieve acceptable heating load reduction for the Weigh-house. The analysis simulation in Energy Plus for the heating load reduction reveals that the proposed refurbishment works lead to a heating demand of about 89 kWh/m²a (Eurac, 3ENCULT, 2013) compared to the 545 kWh/m²a (Eurac, 3ENCULT, 2013) of the “WG As is State” model. In the following chapter it will be verified if this set of interventions, concerning the building envelope, is compatible also for the summer period, i.e. for cooling load reduction analysis.

For the part of the energy efficiency improvement it is supposed that all the windows and the chimney openings remain closed during the all simulations. In this way is possible to compare the trend of the internal air temperature after each refurbishment intervention and to verify if the proposed works are applicable for the summer period with extreme external high temperature. If the internal temperatures
achieve an acceptable increment, the probability to guarantee a thermal comfort through a natural ventilation strategy is more elevated.

Starting from the “As is State” model, each building improvement is analyzed. For the “thermal insulation improvement” models, a simple analysis of material insulation in term of thermal benefits-costs health was done, in order to choose the most adequate material for the related building element part. Also for “Window Replacement” and for “Shading System on Window” models, the selection of the best solution was done.

1. As is State Model
2. Airtightness Improvement
3. Thermal Insulation Improvement
4. Window Replacement
5. Shading System on Window

Material type:
- Wood Fiber
- EPS
- Perlite
- Rock Wool
- Cellulose

Building Element Part:
- Roof
- Ground-/Basement Floor
- Portici Floor
- Coupled Single Glazing + Air
- Double Glazing + Argon
- Triple Glazing + Krypton
- External Blind
- Internal Blind

Figure 48 Energy Efficiency analysis procedure

AIRTIGHTNESS IMPROVEMENT

The first “intervention” to the “WG As is State” model is the improvement of the airtightness building envelope. Considering that the most air infiltration, measured with the gas tracer, occurs along the window frames (Eurac, 3ENCULT, 2013), a reduction of the ELA-value related to the window airtightness was considered. The ELA-value of a tight window is considered and successively, through the following Formulas, transformed into the Air Flow Mass Coefficient for a closed window.

\[
c = \frac{C_d A_L}{10000} \times \frac{2}{\sqrt{p}} \times \Delta p^{0.5-n} \quad \text{(ASHRAE Handbook [2.8])}
\]

\[
Q = c_T \times c \times \Delta p^n \quad \text{(EnergyPlus, I/O Ref., 2013)}
\]

where:

\( C_d = \) discharge coefficient [-]

\( A_L = \) equivalent or effective air leakage area [cm²]
\( \rho \) = air density [kg/m\(^3\)]
\( \Delta p \) = pressure difference across crack [Pa]
\( n \) = air flow exponent
\( c_T \) = reference condition temperature correction factor [-]
\( Q \) = air mass flow [Kg/s]
\( C \) = air mass flow coefficient [kg/s @ 1Pa]

**Figure 49** room 51 - Airtightness Improvement – Mean Air temperature [C] - April and Mai

Figure 49 shows the internal air temperature trend between the two models. The internal air temperature of the analyzed room varies in relation to the discontinuity of the building envelope. Through the graphic it is possible to observe the increment of the internal temperature with the average increment of the external temperatures. Furthermore, there is a difference of temperature between the two simulated models, due to a more airtight building envelope.
In July, the “room 51” in the “WG As is State” model reached an internal temperature of about 32.3 °C, while for the “Airtightness Improvement” model, the highest temperature achieved a value of 32.8 °C. For both models the highest temperature value was calculated on 12th July at 15:00 o'clock. The maximal temperature divergence achieves 1.7 °C in the month of July (Figure 50).

According to the imposed control settings, the results demonstrate how a minimum of air infiltration inside a room is not a disadvantage in term of temperature in the cooling period. In the “WG As is State” model the air infiltration is uncontrolled and occurs through cracks. Ventilation strategies, explained in the next chapter, aim to demonstrate how controlled ventilation can reduce the cooling load of the Weigh-house.

THERMAL INSULATION

The second step regards the improvement of the model with the application of thermal insulation for specific parts of the building. The set of interventions, according to the conservation experts, regards the roof, the cellar ceiling, the floor slab of the ground floor and the “Portici” floor overlooking the external passage. For each of these element part, the appropriate thermal insulations between some types of materials with different origin was taken into consideration: two of mineral origin, one fossil and two of vegetable, where one of which is recycled and the other of local production. The choice of the analyzed materials was done after a target selection, due to the elevated number of insulation types on the market and was influenced by the related physical properties of the insulation and their applicability in the contest. The choice fell in total on five types of materials and they are the wood fiber, EPS, Expanded Perlite, Rock Wool and the Cellulose Fiber.
- Wood Fiber

**Material origin:** Vegetable

![Figure 51 Wood Fiber Material](image)

**Properties:** the wood fiber panels have good thermal and acoustic properties. Through their high specific heat, the panels possess a greater capacity for heat storage, in relation with the other materials. That means that in the summer period the board is able to shift the phase of heat passage inside the structure and as consequence to implement the protection against the summer heat. The open pore structure permits an excellent breathability. Furthermore, it is a hygroscopic material: the absorbed humidity penetrates into the fiber and the space between the fibers, which is responsible of its porosity, remains full of air. As consequence the panel don’t reduce its power insulation. In contrary to the wood fiber, the fibers of materials of mineral origin are not able to absorb the humidity inside them and so the water remains between the fibers and takes the air place. This mechanism reduces considerably the power insulation.

**Manufacturing:** the panels of wood fiber are produced through the processing of waste wood from sawmills, sustainable forestry and clean up the woods. Waterproof panels usually contain 10% of a waterproofing substance: bitumen, wax and natural resins. Panels with high thickness are realized gluing the single layers with a non-toxic glue, generally polyvinyl acetate based.

**Use:** the panels are utilized for the thermal and acoustic insulation in cavities in wood or masonry structures, outer coats ventilated or not, interior trim with any type of finish, flat and pitched roofs with structure of any kind, floors and dry or wet underfloors. The panels should be cut with a sharp knife or circular saw. They should be stored in a dry place and horizontally placed.

**Health risk:** in case of fire don’t released toxic gases but the normal combustion gas. Furthermore, the panels generally don’t contain substances hazardous to health.

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\[ Table \text{ 9 Wood Fiber Properties (Source: Benedetti et alii, 2010)} \]

<table>
<thead>
<tr>
<th>Thermal Insulation Type</th>
<th>Wood Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conducivity [W/m K]</td>
<td>0.038-0.080</td>
</tr>
<tr>
<td>Density [kg/m$^3$]</td>
<td>30-300</td>
</tr>
<tr>
<td>Specific Heat [J/Kg K]</td>
<td>1600-2100</td>
</tr>
</tbody>
</table>

Environmental impact: the raw material is regenerable and practically available in unlimited quantity. The panel production produce a moderately low energy consumption. The panels produced with synthetic binder are not recyclable and they should be burned or brought to the landfill.

EU Fire Classification: Class E (EN 13501-1)

Average unit price: 150-300 (€/m³) (Benedetti et alii, 2010) + local pricelist of Bolzano

- EPS (Expanded Polystyrene)

Material origin: Fossil

![EPS Material](http://www.tekneco.it/prodotto/lastra-eps-100/)

**Table 10 EPS Properties** (Source: Benedetti et alii, 2010)

<table>
<thead>
<tr>
<th>Thermal Insulation Type</th>
<th>EPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conducivity [W/m K]</td>
<td>0.032-0.056</td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td>10-50</td>
</tr>
<tr>
<td>Specific Heat [J/Kg K]</td>
<td>1200-1500</td>
</tr>
</tbody>
</table>

Properties: EPS can achieve very good thermal insulation properties, however the material doesn’t offer a good resistance to compressive stresses. EPS isn’t a hygroscopic material and doesn’t permit vapour exchange with the external environmental. It is completely waterproof. It is a polymeric product, rigid, with a reduced weight, formed of carbon, hydrogen and 96-99% of air trapped in cells, which dimension impede convective heat exchange. The material is made with styrene: monomer derived from petroleum, foaming agent, flame retardant HBDC and stabilizers.

Manufacturing: through a polymerization process, the addiction of a foaming agent to the styrene comports the formation of the polystyrene grains. In a second phase, the grains with a diameter up to 3 mm were expanded with a pentane gas, which induces a volume increase of about 20-50 times the original volume. In this process (water vapour treatment at 90° C), the foaming agent evaporates and as consequences it is obtained a structure with closed cells, which trapped the air. In the cooling phase, the plastic grains are subjected to another treatment with water vapour at a temperature of 110-120° C, called sintering. The process forms a material with a homogeneous compactness. After a drying phase the blocks with a big size are cut in plate and outlined. The performance of the product depends on the density and on the grain compactness in the plates.

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Use: EPS is used for the insulation of interfloors or non-practicable floors, roofs and foundation rafts.

Health risk: The products generally don’t reveal negative effects to the human health. It is to pay attention to the dust released during the manufacturing process, which can cause irritations to the first respiratory tracts. The styrene is in Group 3 in the CMR list. The CMR Coordination Group focuses on substances that are carcinogenic, mutagenic or toxic to reproduction (CMR).

Environmental impact: the thermal processes for the petroleum transformation into the different hydrocarbons release high quantity of sulphur dioxide and nitrogen compounds. The mixture of pentane released into the environmental are extremely toxic for the aquatic organisms. The energy consumption related to the productive process is elevated. The environmental impact related to the transport may be relevant if the distance to cover between petroleum extraction place and the place of production is elevated.

EU Fire Classification: Class E (EN 13501-1)

Average unit price: 50-250 (€/m³) (Benedetti et alii, 2010) + local pricelist of Bolzano

- Expanded Perlite

Material origin: Mineral

![Figure 53 Expanded Perlite Material](source)

<table>
<thead>
<tr>
<th>Thermal Insulation Type</th>
<th>Expanded Perlite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity [W/m K]</td>
<td>0.045-0.070</td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td>30-490</td>
</tr>
<tr>
<td>Specific Heat [J/Kg K]</td>
<td>840-1200</td>
</tr>
</tbody>
</table>

Table 11 Exp. Perlite Properties (Source: Benedetti et alii, 2010)

Properties: the expanded perlite has discrete thermal insulation and sound absorption properties. It is a breathable material able to regulate the passage of steam. Its behavior related to the humidity depends on the waterproofing: the non-waterproofed grains are moisture sensitive and need to be protected with wickers and cloths. The rocks is very resistant to the high temperature and as plate

---

shape can be used for application that require high compressive stresses. The non-treated expanded perlite is not combustible.

**Manufacturing:** the perlite grains have a white colour and there are obtained by the expansion of a vitreous rock, derived principally from submarine volcanos. The perlite grains were finely grinded and successively undergone to thermal treatment in oven for the expansion at a temperature around 850 - 1000° C. The perlite is subjected to a volume increasing of about 15-20 times its original volume. As consequences the grain became a cellular structure with closed micro-cavities, which don’t communicate each other and with the external, so that the thermal properties and the water resistance are improved. To improve the water-repellent characteristic and the moisture sensitivity of the material, the expanded perlite can be treated with silicone or potassium silicate. Furthermore the perlite panels are produced by the mixing of: water-resistance expanded perlite (45-60%), glass fibers (10-20%), cellulosic fibers (20-35%), bitumen (3-6%) and starch (2-5%). All the mixture was dried and successively cut in the required sizes.

**Use:** the expanded perlite is used in bulk for the filling of cavities of perimeter walls, roofs and uninhabited underroofs. The material mixed with water and hydraulic lime is used for the realization of undercoats and screeds for interfloors and floors on the ground, inhabited underroofs and roofs.

**Health risk:** the products could contain a light natural radioactivity and only a possible treatment with bitumen can release toxic substances. During the production could rise up fine dust, which can provoke respiratory disease. In the United States were conducted many test for the evaluating of the expanded perlite toxicity with negative response.

**Environmental impact:** The natural resource consumption is not so relevant, due to the elevated availability of the raw material in nature. The uncontrolled extraction of the raw material should be attended in order to avoid a landscape damage. The energy consumption is rather elevated, due to the expansion process with high temperature. The environmental impact related to the transport can be significant and depend on the distance between the place of collection and the place of the production of the products. The processes at a high temperature produce a not negligible CO$_2$ emissions.

**EU Fire Classification:** Class from A1, d0 to D-s1, d0 (EN 13501-1)

**Average unit price:** 100-250 (€/m$^3$) (Benedetti et alii, 2010) + local pricelist of Bolzano
• Rock Wool

**Material origin:** Mineral

![Rock Wool Material](image)

**Properties:** The rock wool is a good thermal insulation material with moderate soundproof properties. It is a breathable material and has a very good fire resistance with a temperature fusion above the 1000°C. The rock wool is an inorganic material formed of fibers with a grey-green color. The fibers are waterproof and don't absorb the water. The raw materials are different types of rocks like dolostone, limestone, and diabase.

**Manufacturing:** The raw materials were liquefied in tanks at 1400-1500°C and then conducted to a beater, which operates differently depending on the manufacturer.

**Use:** Rock wool is generally used for the insulation of roofs, external walls, and interfloors.

**Health risk:** According to the European norms TRGS (“Technical Rules for Hazardous Substances”) the rock wool can be used in the building construction only after specific tests related to the carcinogenicity of the product. In Germany the rock wool has to be accompanied by a quality mark RAL 338 “Products based on mineral wools”. The index of carcinogenicity (IC) doesn't exceed 40 points. The IARC (International Agency for Research on Cancer) has classified the Rock Wool in the Group 3 in the CMR list (some typology of product can contain formaldehyde and other harmful agents). Before 1996 the products are all carcinogenic. In addition to problems related to cancer the rock wool can provoke respiratory problems.

**Environmental impact:** Thanks to the great abundance of the raw materials the consumption of natural source is reduced. While, the energy consumption is quite elevated, due to the fusion process with high temperature. The fusion process with high temperature and the bitumen treatment contribute to a CO₂

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19 Source: [http://www.rockwool.it/perch%C3%A9+rockwool/rockwool+4in1](http://www.rockwool.it/perch%C3%A9+rockwool/rockwool+4in1) (Day Accessed: 10.04.2014)
emission increase. The environmental impact related to the transport is reduced due to the easy availability and transportability of the product.

**EU Fire Classification:** Class A1 (EN 13501-1)

**Average unit price:** 85-250 (€/m³) (Benedetti et alii, 2010) + local pricelist of Bolzano

- Cellulose Fiber

**Material origin:** Vegetable

![Cellulose Material](http://www.nesocell.com/cms/en.html)

**Properties:** the cellulose is an ecological material having recycled newspaper as raw material. The cellulose fiber is breathable and hygroscopic and is able to absorb humidity from the environmental and to release it in a second moment. Furthermore, the cellulose fiber doesn’t contain toxic substances and doesn’t provoke reactions in contact with skins. The original parallel structure of the wood was changed during the transformation process and the fibres are oriented in all directions, so that the porosity is greater. The porosity is responsible for the thermal performance of a material.

**Manufacturing:** the recycled newsprint is furnished by industry that works in the recycling and recovery filed. The newsprint is well-broken and dry mixed with 15% of boron salts (pesticide and treatment and fireproofing). After the mixing, it is obtained flakes with inside microscopic cells of air, which determine the heat transfer resistance. The cellulose flakes were applied by specialized personnel. The flakes were directly insufflated in the construction site, without the presence of additive. By this method the fiber fills all interstice of the construction and guarantees a good air tightness performance. The production of panels consists in the addition of 5-10% of polyester fiber to the fiber flakes. The addition makes the panel elastic, compact and easily workable.

**Use:** the material is ideal for the insulation of empty cavities for masonry walls and timber structure with a thick above the 10 cm. The material is also indicated for the filling of cavities with deteriorated or

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insufficient insulation. The cellulose can be subjected to assessment with the formation of empty cavities. For this reason, after several weeks is necessary to control the result and eventually to proceed with the addition of more cellulose material. The cellulose panels are used in cavities of timber structure, in false ceilings, in underfloors and ceilings. The panels are cut with a knife or a disc saw and they should be laid horizontally and in a dry place.

**Health risk:** the materials generally don’t contain harmful substances. During the manufacturing process fine dust can arise, which can provoke irritations to the respiratory tracks. The laying of the panels is clean however, also releases small quantity of dust.

**Environmental impact:** the cellulose flakes is reusable and recyclable. In case of moisture absorption the flakes can be extracted through aspiration, allowed to dry and again insufflated. The intact panels can be reutilized. To facilitate the transport the cellulose is compressed and packed in sacks. The insufflation process provokes a volume increment of about 8 times the original volume, due to the air, which is incorporated.

**EU Fire Classification:** Class E (EN 13501-1)

**Average unit price:** 100-350 (€/m³) (Benedetti et alii, 2010) + local pricelist of Bolzano

**Roof structure:**

The intervention for the roof insulation improvement, according to the conservation experts, consists in the addition of 25 cm of thermal insulation with a thermal conductivity of 0,042 W/mK (11 cm between the wood beams and 14 cm under the beams), due to obtain for the roof a total thermal transmittance of about 0,17 W/m²K. The analysis for the heating load reduction with Energy Plus conducted by the Eurac team recommends a further 5 cm of thermal insulation, so that the heating energy demand of the building can be further reduced (Eurac, 3ENCULT, 2013).

After a study of the five available materials, the choice fell on a thermal insulation with wool fiber. The choice is based principally on the good thermal properties of the material. Besides its good conducibility, the material possesses a high specific heat, which permits for example, the heat storage during the summer warm days and its release during the nights. Another aspect determinant for the choice of this type of thermal insulation is its good compatibility with the roof timber structure, considering that both derived from the same raw material: the interaction between supporting structure and insulation are optimized, given that both are characterized by an equivalent behavior in relation to humidity and breathability.
Figure 56 Room 51 – Roof Insulation Improvement – Mean Air Temperature

Figure 56 shows the internal air temperature trend between the two models. The internal air temperature increases after the addition of wood fiber thermal insulation on the roof. The “room 51” in “WG Roof WoodFiber” model reaches an internal temperature of about 33.3 °C, while in the “WG AirTight” model, the highest temperature is equal to 32.8 °C. For both models the highest temperature value was calculated on 12th July at 15:00 o’clock. More than 72% of temperature divergence overtakes 0.5 °C in the month of July.

The increment of the temperature after the thermal insulation application on the roof is legitimate, considering that for this part of the analysis the windows and chimneys are closed and the air infiltration was reduced. The following thermal insulation additions to the building presumably will lead to a further temperature increment, which should be contained in an acceptable rate to avoid a building overheating in the summer period.

Cellar Floor and Floor on the Ground:

The floor on the ground has a thermal transmittance of 2.66 W/m²K\(^{21}\), while the cellar ceiling has a thermal transmittance of about 1.03 W/m²K. The experts recommended to insert in the floors 12 cm of thermal insulation with a minimal thermal conductivity of about 0.035 W/mK (Eurac, 3ENCULT, 2013).

Non hygroscopic material are chosen for the insulation of the cellar floor. The EPS is completely waterproof and the Expanded Perlite used for the cellar floor is a waterproof type commonly applicable

\(^{21}\) To the floor on the ground a layer of XPS (Benedetti et alii, 2010) thermal insulation is added.
for interfloor insulation. The rest of materials are humidity sensible and also preferably not usable for this type of construction:

- EPS Expanded Polystyrene \((\lambda=0.036 \text{ W/mK})^{22}\)
- Expanded Perlite \((\lambda=0.052 \text{ W/mK})^{23}\)

The Expanded Perlite used for the floor insulation has in this case a higher conductivity value than the EPS. A bit more high temperature simulation results with the EPS (negative value on Figure 58) case are expected: the thermal fluxes related to EPS from the room GF_4 to the cellar (when the room temperature is higher than the cellar temperature) is lesser than the Expanded Perlite flux.

The chosen materials are added in the model and both simulated for the calculation of the internal temperatures. The comparison of the results together with the cost and health risk evaluation will be useful for the predilection of one insulation type with respect to the other.

- Room temperatures

A better comprehension of the thermal insulation behavior is possible by observing the temperature trend in the room model called “GF_4” adjacent the cellar room.

![GF_4 - Cellar Insulation Comparison - Mean Air Temperature [C] - July](image)

Figure 57 GF_4 – Cellar Insulation Comparison - Mean Air Temperature - July

Figure 57 shows a quite equivalent behavior in term of temperature by both insulation materials. Minimal temperature divergences are observed (Figure 58).

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22 Source: www.polisud.com/eps.php
Figure 58 GF_4 - EPS / Expanded Perlite - Temperature divergence $\Delta T$ [C]

- **Costs**

The EPS costs between 50 and 250 €/m³ and the Expanded Perlite between 100 and 250 €/m³. Consequently for a thickness of 12 cm thermal insulation the price for the EPS results between 6 and 30 €/m² and for the Expanded Perlite is between 12 and 30 €/m². Furthermore, it is assumed that the laying of both materials in the cellar floor occurs after the removal of its old paving structure for an area of circa 106 m². Excluding the installation costs the minimal prices result equal to 5300 € for the EPS and 10600 € for the Expanded Perlite.

- **Health Risk**

The EPS and the Expanded Perlite generally don’t reveal negative effects to the human health. Attendions are to pay only during the manufacturing process for both material types.

<table>
<thead>
<tr>
<th>Room Peak Temperature [C]</th>
<th>Price [€]</th>
<th>Health Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS</td>
<td>33.6</td>
<td>5300</td>
</tr>
<tr>
<td>Expanded Perlite</td>
<td>33.5</td>
<td>10600</td>
</tr>
</tbody>
</table>

| 04/16 | 04/20 | 04/24 | 04/28 | 05/02 | 05/06 | 05/10 | 05/14 | 05/18 | 05/22 | 05/26 | 05/30 | 06/03 | 06/07 | 06/11 | 06/15 | 06/19 | 06/23 | 06/27 | 06/31 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  |

Table 14 EPS / Expanded Perlite: Factor Comparison

24 The removal of the old paving structure don’t cause any damages from the point of view of the conservation, considering that the paving structure dates at the refurbishment works of the ’50/60 years and it is in poor conditions.
Considering the minimal divergence temperature between the different materials in front of their large price difference, the choice is felled on the EPS thermal insulation.

To allow a comparison between the achieved thermal conditions after each improvement step, the behavior in term of temperature for the “room 51” is illustrated.

Figure 59 shows an increment of the internal air temperature after a subsequent insulation of another building construction part. With the basement insulation, the maximal temperature rose from 33.3 °C to 33.9 °C on 12th July at 15:00 o'clock.

“Portici” Floor:

The “Portici” floor in the state of the art presents a thermal transmittance of about 0.437 W/m²K (Eurac, 3ENCULT, 2013). The conservator experts recommended the substitution of the actual sand filling with 18 cm of thermal insulation and an additional 3 cm of insulation above the floor.

The zone to isolate is on the North side of the building and cover the passage of the “Portici”. The external part of the floor has an arch structure and for facilitate its insulation a flexible filling material with a conducibility is required. The EPS present principally a stiff structure and isn’t taken into consideration. The other four thermal insulation types are suitable for the purpose and in sum they are the following:

- Cellulose
- Wood Fiber
- Perlite
The chosen materials are added in the model and both simulated. The comparison of the results may be useful for the predilection of one insulation type with respect to the other. A better comprehension is possible by observing the temperature trend in the room model called “F1_1”, which is oriented to the “Portici” street.

<table>
<thead>
<tr>
<th>Thermal Insulation Type</th>
<th>Conductivity [W/m K]</th>
<th>Density [kg/m³]</th>
<th>Specific Heat [J/Kg K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose Fiber²⁵</td>
<td>0.040</td>
<td>40</td>
<td>1600</td>
</tr>
<tr>
<td>Wood Fiber</td>
<td>0.038</td>
<td>70</td>
<td>2000</td>
</tr>
<tr>
<td>Perlite²⁶</td>
<td>0.042</td>
<td>155</td>
<td>2000</td>
</tr>
<tr>
<td>Rock Wool²⁷</td>
<td>0.052</td>
<td>100</td>
<td>1000</td>
</tr>
</tbody>
</table>

*Table 15 Portici Floor - Thermal Insulation Properties*

![F1_1 - Portici Thermal Insulation Comparison - Mean Air Temperature [°C] - July](image)

*Figure 60 F1_1 Portici Thermal Insulation Comparison – Mean Air Temperature – July*

²⁵ Source: www.homatherm.com (Day Accessed: 10.05.2014)
²⁶ Source: www.perlite.it (Day Accessed: 10.05.2014)
²⁷ Source: Cristina Benedetti, Peter Erlacher et alii, Materiali Isolanti - Le guide pratiche del master CasaClima, Brunico: Bozen-Bolzano University Press, 2010
Figure 60 shows an equivalent behavior of the different insulation materials. For this reason it is possible to privilege the two materials with a higher heat specific and also a bigger heat storage capacity, well appreciated in the summer period. The two insulation types are the Cellulose Fiber and the Wood Fiber.

<table>
<thead>
<tr>
<th>Material Origin</th>
<th>Price [€/m²]</th>
<th>Health Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegetable</td>
<td>21 - 73.5</td>
<td>not spotted</td>
</tr>
<tr>
<td>Wood Fiber</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegetable</td>
<td>31.5 - 63</td>
<td>not spotted</td>
</tr>
</tbody>
</table>

Table 16 Cellulose and Wood Fiber factor comparison

After a study of the two available materials, the choice fell on a thermal insulation with wool fiber. Both have good thermal properties, however the wood fiber is characterized by a better behavior in term of humidity. The cellulose in presence of humidity lose considerably its thermal properties. Furthermore it is to consider that the cellulose after a first installation through insufflation can be subjected to assessment with the formation of empty cavities and consequently is required a second addition of cellulose materials.

In July, with the improvement of Portici thermal insulation with Wood Fiber, the internal temperatures of room F1_1 reaches a maximum value of about 33.7 °C. Without the improvement the temperature is equal to 33.0 °C (Figure 61).
To allow a comparison between the achieved thermal conditions after each improvement step, the behavior in term of temperature for the “room 51” is illustrated. The room 51 don’t reveals any relevant temperature differences. The insulation of the Portici floor has no evident effects on the room 51, due to the long distance between the two rooms. In July, the maximum temperature difference achieves a value of about 0.1 °C. The maximum internal temperature calculated in “WG Portici WoodFiber” model is equal to 34.0 °C (Figure 62).

![Room 51 - Portici Thermal Insulation Improvement - Mean Air temperature [C] - July](image)

**Figure 62 Room 51 – Portici Thermal Insulation Improvement – Mean Air Temperature - July**

**WINDOW REPLACEMENT**

In the “WINDOW REPLACEMENT” sub-chapter it will be treated the topics of thermal transmittance and glazing factor, considering that the part of the air infiltration through discontinuity of the building envelope was already discussed in the AIRTIGHTNESS sub-chapter. Three types of window/glass system would be considered and in Energy Plus simulated: the existing windows and two types of windows with improved thermal properties. After that, the simulation results were analysed and compared in order to justify the choice of the adopted window/glass system in the “total improved” model, which is successively used for the analysis of the ventilation strategies.

As mentioned above, the major part of the original windows are not of historic value form conservator’s point of view and should be replaced, reproducing the aesthetic of a historic window. In particular, the new windows should hold high energy efficient properties and answer to the heritage demands of the building. Through the study concerning the typical and historic local windows conducted by window developer and producer, building physicist, architect and conservator, the two window characteristics
which should be adopted were defined: the original proportion between glass area and sash bars and window frame and the optic appearance of original historic glazing.

In absence of drawings related to the original historic window, window prototypes based on a “classic” (coupled) window in terms of function, division and proportion were developed. The developed concept separates the demands and functions into two layers: one outer layer for the reproduction of the original historic window and an inner layer for high energy efficiency. In total two prototypes were developed by the EURAC researchers. The last developed prototype is a triple glazing with a horizontal impost and four window sashes (2 above, 2 below). The triple glazing (2/8/2/8/2) has the same thickness of a common double glazing. The use of this very thin triple glazing made it possible that the frame proportion became fragile and the optic from inside becomes very similar to a double glazing. (Eurac, 3ENCULT, 2014)

![Last window prototype installed in the Weigh-house](image)

The existing windows with a high thermal transmittance were compared with windows with an improved thermal transmittance and g-factor.

<table>
<thead>
<tr>
<th>Existing Window</th>
<th>Improved Window</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box type window</td>
<td>Double Glazing</td>
</tr>
<tr>
<td>Single glazing</td>
<td>Argon</td>
</tr>
<tr>
<td>GAS type</td>
<td>Air</td>
</tr>
<tr>
<td>$U_g$ [W/m²K]</td>
<td>2.70</td>
</tr>
<tr>
<td>$U_l$ [W/m²K]</td>
<td>2.50</td>
</tr>
<tr>
<td>g-factor</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Table 17 $U$- and g-values (Eurac, 3ENCULT, 2014)

---

28 Source: Eurac, 3ENCULT, 2014
Figure 64 shows thermal conditions inside the room 51 for each considered window system.

No important different temperature trends are illustrated. The graphic shows that when the external temperatures are higher than the internal temperatures the “WG Coupled Single Glazing” reveals higher temperatures than the other two cases. While, when the external temperature are lesser than the internal temperatures a contrary effect is calculated. In July, the “WG Coupled Single Glazing” case reveals a maximum temperature of about 34.0 °C, the “WG Double Glazing” reveals a maximum temperature of about 33.7 °C and the “WG Triple Glazing” of about 33.5 °C.

In the summer period, no relevant temperature differences are calculated. However, Eurac team estimated, that an adoption of a triple glazing system permits a relevance energy consumption reduction during the heating period (the reduction is also linked to the airtightness improvement of the windows). For this reason a window replacement with a triple glazing system is convenient.

Always taking into consideration the “As is State” model as reference model, all improvement works up here analyzed have led to a general increase in the internal temperature of the room 51. The purpose of the next step, i.e. the addition of a shading system for the windows of the building aspire to a temperature reduction.
SHADING SYSTEM

In the 50’/60’ years, the Weigh-house was equipped with a solar shading system composed of traditionally shutters with orientable slats. At the actual state, considering also the disrepair of the building, only few windows are equipped with the shutters, the rest is devoid of them.

For the model in Energy Plus, an external shutter is taken into consideration. After that, the shutter is replaced with a shading system with the same thermal properties, but placed behind the windows in the inside part of the building. The two common types of shading system are added for the estimation of the effects on the thermal condition inside the rooms that each of them generates. More deeply the aim is to verify, in which rate their adoption can contribute to the reduction of the inside temperature in summer periods, when the external temperature are extreme elevated.

According to the analysis of the environmental outside temperature of Bolzano and the internal thermal condition of the building, the closing of the shading elements is set for the hours between 11:00 and 15:00 in the period from 1st June till 30th September. Precisely the shading elements should be closed when the solar radiation on the window surface overtakes the 400 W/m² (value estimated after the examination of the data result).

![Solar Radiation Rate per Area (W/m²)(Hourly) - Window(W32)](image)

Figure 65 Solar Radiation Rate per Area on Window W32
EXTERNAL SHUTTERS

The shutters are traditionally made of wood, however nowadays they are also produced with other different materials, like PVC, aluminum with thermal insulation, etc.

Figure 66 Window Detail (Source: Eurac, 3ENCULT, 2013)

Figure 66 shows the original shutters of the Weigh-house, where the underlying part is formed by orientable slats. In detail it is illustrated a window without shading elements, however equipped with hinges for their installation. For the simulation, the slats are oriented with an angle of 45 degree when the shutters are closed, in order to permit a part of natural daylighting.

The External Shutter solution is compared with internal blind with the same thermal properties. The aim is to observe, which effect the blind position has on the internal temperatures.

![Figure 67 Room 51 – Window Shading System Comparison – Mean Air Temperature – 09th September](Image)
The adoption of external window shading system contributes to a minimal reduction of the internal temperature. It could be possible, that with a lower angular aperture of the slats the temperature decrease is greater (Figure 67).

INDOOR TEMPERATURE RELATED TO THE ENERGY EFFICIENCY IMPROVEMENT

Figure 68 and Figure 69 compare the temperature trend of “room 51” between the “WG As is State” and the total improved model, called “WG ExBlind”. From a maximum internal temperature of 32.3 °C in the “WG As is State” case the temperature reaches a value of 33.4 °C in the “WG ExBlind” case.

---

**Figure 68 Room 51 Energy Efficiency Improvement – Mean Air Temperature**

**Figure 69 Room 51 Energy Efficiency Improvement – Mean Air Temperature - July**
Figure 70 shows the temperature percentage includes in fixed temperature range for all the analyzed models of the energy efficiency part: from the “WG As is State” model to the “WG ExlBlind” model. In July, the energy efficiency improvement works lead to an increase of the room 51 temperatures. By each intervention to the building envelope the temperature percentage above 30 °C rose. Only the addition of external blind reduced lightly the temperatures. For the “WG As is State” model a quite 40% of temperatures above 30 °C is calculated. While for the WG “ExBlind” more than 90% is calculated.

![Figure 70 Room 51 Energy Efficiency Improvement – Mean air temperature range](image)
6.4. Ventilation strategies

The choices adopted for the energy efficiency improvement of the building envelope take to an increase of the internal air temperatures. Through ventilation strategies is observed in which degree the cooling load is reduced and successively an analysis of the internal thermal comfort of the Weigh-house is conducted. Together with the thermal comfort analysis a brief study of air quality is done. At first, natural ventilation inside the building is allowed. The air flows through different openings, like windows and chimneys. After that a ventilation hybrid solution that combine natural and mechanical system is treated.

![Ventilation strategies analysis procedure](image)

The ventilation concept developed in this thesis will refer not to all thermal zones, but only to those zones, which are used as integral part of the ventilation system (Basement_1 and Chimneys) or are ideally used as museum exposed area (First and Second Floor Zones). The interested Thermal Zones are underlined in Table 18:

<table>
<thead>
<tr>
<th>THERMAL ZONE NAME</th>
<th>Basement</th>
<th>Ground floor</th>
<th>First Floor</th>
<th>Second floor</th>
<th>Top floor</th>
<th>Chimney</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Basement</td>
<td>GF_1</td>
<td>F1_1</td>
<td>F2_1</td>
<td>TF_1</td>
<td>Chimney1</td>
</tr>
<tr>
<td></td>
<td>Ground floor</td>
<td>GF_2</td>
<td>F1_2</td>
<td>F2_2</td>
<td>TF_2</td>
<td>Chimney2</td>
</tr>
<tr>
<td></td>
<td>Ground floor</td>
<td>GF_3</td>
<td>F1_3</td>
<td>F2_3</td>
<td>TF_3</td>
<td>Chimney3</td>
</tr>
<tr>
<td></td>
<td>Ground floor</td>
<td>GF_4</td>
<td>F1_4</td>
<td>F2_4</td>
<td>TF_8</td>
<td>Chimney4</td>
</tr>
<tr>
<td></td>
<td>Ground floor</td>
<td>GF_5</td>
<td>F1_5</td>
<td>F2_5</td>
<td>Chimney5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>room 30</td>
<td>F2_7</td>
<td>room 45</td>
<td>Chimney6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>room 32</td>
<td>F2_11</td>
<td>room 46</td>
<td>Chimney7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>room 33</td>
<td>room 50</td>
<td>Chimney8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>room 34</td>
<td>room 51</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 18 Thermal zones for ventilation strategies
6.4.1. Natural Ventilation

The analysis of natural ventilation starts from the total improved model explained in the Energy Efficiency Improvement chapter. To the model are associated several ventilation modality, controlled by the Schedule object of EnergyPlus software. This approach allows the comparison of the model behavior according to the different ventilation modality:

- **NO Ventilation (WG NO Vent)**: windows and chimneys remain closed. The model corresponds to the total improved model explained in the Energy Efficiency Improvement chapter. It is used as “reference” model in order to evaluate the effects on the internal conditions by adopted ventilation modalities.

- **Ventilation through chimneys (WG OpenedCH)**: air flows through always open chimneys, i.e. the natural ventilation mode is always active.

- **Ventilation through windows (WG OpenedWD)**: air flows through window openings. The windows are inwards open in tilt position with an open factor of 0.3. The external windows allow the ventilation inside the building for all 24 hours of the day (All Day Ventilation), but only when the air temperature of the thermal zone respects fixed conditions. In contrary case the windows are considered closed.

\[ T_{\text{zone}} > T_{\text{out}} \text{ and } T_{\text{zone}} > T_{\text{set}} \]

where \( T_{\text{set}} \) varies in function of the time:

<table>
<thead>
<tr>
<th>Time Period</th>
<th>( T_{\text{set}} ) [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:00 - 23:00</td>
<td>25</td>
</tr>
<tr>
<td>23:00 - 8:00</td>
<td>22</td>
</tr>
</tbody>
</table>

*Table 19 Window Temperature control*

- **Ventilation through windows and chimneys**: the air flows through windows and chimney openings according to the before mentioned control mode. In this case the ventilation is distinguished by the time in which the ventilation is allowed.

  - **All Day Ventilation (WG AllDayVent)**: Venting allowed from 0:00 to 24:00
  - **Night Ventilation (WG NightVent)**: Venting allowed from 23:00 to 8:00 a.m.

- **Ventilation through windows and thermal chimneys (WG ThermCH AllDayVent)**: the air flows through windows and chimneys with the same modality explained in “Ventilation through windows and chimneys” in “AllDay Ventilation” case. The only difference consists in the type of the considered chimneys. The word “Thermal” emphasizes the fact that to the chimney wall was applied an absorber wall. The absorber wall is characterized by a glazing surface with a high solar transmittance.

Two rooms of the building were analyzed: the Room 51 and the room F2_2. The two zones are situated on the second floor of the building. The Room 51 is composed by an external wall surface oriented to the South and a second wall surface oriented to the West. The West façade is shaded by the adjacent building. The room F2_2 is also composed by a façade oriented to the South, while the second façade
is oriented to the East. Both zones are allowed by a chimney. The chimney of the Room 51 is called Chimney 2 and the one of the room F2_2 is called Chimney 7.

The comparison between the two Thermal Zones is made to observe their behavior in term of temperature and relative humidity of air in function of their different location inside the building. The simulation results are showed in the following figures.

**TEMPERATURE COMPARISON BETWEEN ROOM 51 AND F2_2**

![Figure 72 Location of room 51 and F2_2 with related chimneys](image)

![Figure 73 Room 51 – Ventilation Methods - Average Indoor Temperature [C]](image)
For the Room 51 and F2_2 the average air temperature trend is similar: no relevant differences are visible (Figure 73 and Figure 74). In July and August with greater external air temperature than the other period of the year, high zone temperature levels are registered when the ventilation inside the building is absent or minimized (“WG NOVent” and “WG OpenedCH” cases). The adoption of a ventilation strategy through window openings allows a consistent building cooling load reduction. For both cases, during the months of June, July and August the temperatures are above 23 °C. In April the temperatures are included between 19 and 21 °C. In “WG NOVent” and “WG OpenedCH” cases, peaks of temperature are visible during the warmer months, especially in July and August. While for both cases in April and May the average temperature value is close to that of the other cases. The reason for this phenomenon is caused by the controls set in EnergyPlus for the openings. These controls are closely related to temperature values of the zone and from the outside. The opening configurations are the following:

April:
- WG NOVent: Chimney closed and windows closed
- WG OpenedCH: chimney opened and windows closed
- WG AllDayVent: Chimney opened and windows generally closed due to internal temperatures

July:
- WG NoVent: Chimney closed and windows closed
- WG OpenedCH: chimney opened and windows closed
- WG AllDayVent: Chimney opened and windows generally opened

This means that chimney opening contributes only minimally to the cooling load reduction. The window openings are the real responsible for the thermal improvement conditions.
AIR RELATIVE HUMIDITY COMPARISON BETWEEN ROOM 51 AND F2_2

Starting from the ventilation through the chimneys, Figure 75 and Figure 76 show a generally air relative humidity (RH) reduction. Only in the month of April, the air RH in the “WG OpenedWD” case is elevated as in the “WG NOVent” case. This is explained by the fact that the windows remain closed, due to external temperatures and imposed temperature controls (T_set).

It is observed that even if the two rooms are placed in different location inside the building, the temperatures of room 51 compared with those of F2_2 have approximately an equivalent trend. The same occurs with the relative humidity.

From here on, a more detailed analysis will be performed for the room 51. The different ventilation modality in term of temperature are compared.
VENTILATION MODE COMPARISON BETWEEN “WG OpenedCH” AND “WG OpenedWD”

In the months of April and May until the first half of May, the zone in both cases presents similar temperature values (Figure 77). More precisely, the “WG OpenedCH” case reveals slightly lower temperatures than the other case. These temperature values are achieved considering the chimney openings always opened for the “WG OpenedCH” case. While windows in the “OpenedWD” case are generally closed, according to the external and zone thermal conditions. In April, the average temperatures do not exceed 21.1 °C in the “WG OpenedWD” and 20.0 °C in “WG OpenedCH”.

![Room 51 - OpenedCH / OpenedWD - Mean Air Temperature [C] - from 16th April to May](image)

*Figure 77 Room 51 – Mean Air Temperature – from 16th April to May*

In summer period, i.e. from mid-June until late September the temperature differences of the room 51 between the two cases are relevant. The most temperature differences between the two cases are calculated in July and August, when the average external temperatures are higher than the other months. The generated air flow through windows allows a greater cooling load reduction of the house than the chimney case. This is explained by the fact that the small number of chimneys permit a lesser air infiltration. In July, in “WG OpenedWD” case the maximum air temperature achieves a value of about 27.3 °C, while for “WG OpenedCH” case the maximum air temperature is equal to 32.5 °C (Figure 78).
VENTILATION MODE COMPARISON BETWEEN “WG AllDayVent”, “WG OpenedCH” AND “WG OpenedWD”

Figure 78 Room 51 – WG OpenedCH / WG OpenedWD – Mean Air Temperature – July and August

Figure 79 Room 51 – WG OpenedCH + WG OpenedWD + WG AllDayVent – Mean Air Temperature – July and August

Figure 79 shows air temperature behaviour of the zone combining the before mentioned two ventilation modality. The air temperature trend for the “WG AllDayVent” case follows principally the temperature...
trend of the case “WG OpenedWD”. In fact, the most contribution for the cooling load reduction of the building is due to the opening of the windows and not to the chimneys openings. In the “WG AllDayVent” case, the average temperature for the month of July achieves a value of 24.0 °C, while in August of 23.5 °C.

VENTILATION MODE COMPARISON BETWEEN “WG AllDayVent” AND “WG NightVent”

Within a few days of July, Figure 80 evidences more high temperatures in the “NightVent” case than the “AllDayVent” case, while in the other months the temperature trend shows no considerable differences in both cases. In the “NightVent” case, the window are not controlled by temperature conditions and remain always closed from 8:00 a.m. to 23:00. While in the “AllDayVent” case the windows are closed only when the zone temperature is lower than external temperature and Set Temperature. According to these conditions, in July the windows remain opened more frequently and thereby the internal temperature differences between the two cases is more evident. The following graphic demonstrates what was mentioned before.
The percentage of temperature included in the range between 25 °C and 28 °C is increased by 10% for the NightVent case. As a consequence the percentage of temperature included in the range between 23 °C and 25 °C decreased by 9% (Figure 81).

VENTILATION MODE COMPARISON BETWEEN “WG NOVent” AND “WG NightVent”

Through a night ventilation strategy the internal temperature decreased considerably (Figure 82). The solar heat stored into the wall, is released during the night, when the window are opened. From a maximum internal temperature of about 33.4 °C (13th July at 18:00) in the “WG NOVent” case the temperatures reached a value of 27.8 °C in the “WG NightVent” case (calculated on 11th July at 15:00).
COMPARISON BETWEEN WG AllDayVent (WITH “NORMAL” CHIMNEYS) AND WG ThermCH AllDayVent

From the conservation point of view, the construction of thermal chimneys is not allowed. However, in the present work the thermal chimney case is taken into consideration, for evaluation of possible thermal benefits.

The purpose of a thermal chimney adoption was thought to increase the cooling effect. In this case its adoption to the structure takes to an opposite effect, i.e. to a little temperature increase (Figure 83). In the model, the chimney is considered as a thermal zone adjacent room 51. The absorbed surface added to the “normal” chimney raises the chimney zone temperature and as a consequence warmer air flows into the room. The solution which provided the thermal chimney may be discarded.
THERMAL COMFORT ANALYSIS

The percentage of thermal comfort satisfaction is calculated using the simulation results in EnergyPlus according to the EN 15251. The Adaptive Method considers the dependence of the thermal comfort in function of the operative and external temperature.

According to the simulation results, through a natural ventilation strategy (Excluding “WG OpenedCH”) it is possible to reach an optimal thermal condition inside the zone in the months of June, July, August and September (Figure 84). For these months the calculated operative temperature values entry with a rate of above 95% in the range of Category I: in July and August a quite 100% is reached. In the month of April, an almost total absence of Category I thermal satisfaction percentage is observed, due to the law temperatures inside the zone. The “WG NOVent” case reveals a percentage above the 70% only in the month of Mai, while in the other cases the percentage decreases near 0%.

The Category II of the Adaptive Method increases the temperature range, where the thermal comfort is considered satisfied. That means that the percentage of unsatisfied occupants can be slightly more elevated than the Category I. Figure 85 shows a generally improvement of thermal comfort conditions inside the building. According to Category II, an evident improvement of percentage satisfaction in April for the case “WG NOVent” and “WG OpenedWD” is observed (in this month the windows remains generally closed).
According to Category III, a further increase in the percentage of satisfaction is obtained. Excluding April and the “WG NOVent” and “WG OpenedCH” cases, good thermal conditions inside the room are reached for all the other months (Figure 86).

Comparing the three graphics the following assertions are deduced:

- Thermal comfort conditions are achievable with the adoption of natural ventilation strategies through windows.
- In the warmer months already in Category I the thermal comfort is satisfied.
April is the most critical month. An optimal thermal comfort is not satisfied, thereby the percentage of satisfied occupants is lesser than to the other months. By observing the room air temperature of April, the "problem" can be solved informing the occupants of the inconvenience. They can thus provide to an appropriate clothing, depending on their sense of well-being.

**AIR CHANGE ANALYSIS**

According to the developed Airflownetwork controls sets, the air change rate of the room 51 is analyzed. The norm EN 15251:2007 prescribes, in case of natural ventilation, the minimum air change rate value that should be guaranteed in a non-residential building.

- During un-occupied hours: 2 ach before the occupancy
- During occupied hours: min 0.1 to 0.2 l/s,m²

Figure 87 shows that during occupied hours the minimum air change rate is not respected. An insufficient air change rate compromises the concentration of pollutants in the air and thereby the risk of problem health could increase. However, it is to be taken into consideration, that these air change rate values are the results of a simulation conducted with determined Airflownetwork control sets. The venting inside the building is controlled in function of the external temperature and internal temperature. That means, that with other ventilation mode or controls type different air change rate values could be obtained, and maybe it could be arrived to a different conclusion.
THERMAL COMFORT WITH AIR CHANGE RATE (MODEL NAME: WG Natural AllDay)

Acting on the window control, the achievement of a minimum Air Change Rate inside the room 51 is trying to be obtained. Some windows on the first and second floor are imposed always open with a reduced open factor, independent of the external and internal thermal conditions. The windows, which remain always open are illustrated in Figure 88. The opening of the other windows remains linked to the internal and external temperature conditions.

![Figure 88 Constant Opened Windows: First Floor (A.) and Second Floor (B.)](image)

The first axis on Figure 89, on the left, show the ACH trend, while the second axis on the right indicates the internal air temperatures. Through the lecture of the graphic, it is visible that the minimum air change rate can be guaranteed for a good part of the two days. However, the internal temperatures achieve values above the values of the “WG AllDayVent” case. The slight temperature increment in the new case could lead to a decrease of the thermal comfort inside the building.

![Figure 89 Room 51 – Air Change Rate and Air Temperature](image)
In May, April and October, due to the not so warm external conditions the room temperatures are low and as a consequence the thermal comfort for Category I, II and III is not guaranteed or only for a few percentage satisfied. In July and August indeed, the thermal comfort is satisfied with a percentage of circa 100% in the Category II of the Adaptive Method (Figure 90). Comparing the results with the previous results obtained in the “AllDayVent” case (Figure 91), a general slightly decrease is visible, due to the new window control setting.
Many other window control settings could be imposed to the model, and always, the response of the model will be different. In this case, acceptable values of ACH are reached, without decreasing significantly the levels of thermal comfort inside the building than the previous calculated percentages.

In the following paragraph, an alternative method for the temperature reduction of the rooms is studied. Thinking about climate change, the problem of the constant outdoor temperature increasing in the province of Bolzano (Zebisch et alii, 2011) is a sensible theme. For this reason, a ventilation system concept that permits room temperature reduction in the torrid periods is developed. The work restrictions imposed on the listed building have led to the choice of a system, which is the least invasive as possible. A geothermal cooling system requires soil excavations for the pipe installation and for this reason was discarded. At the end it was decided to use a ventilation system that exploits the “cool reservoir” of the Weigh-house cellar.

### 6.4.2. Hybrid Ventilation

Through the temperature monitoring of the two cellar floors it was detected that the cellar temperature in summer is relatively constant and independent from the outside temperature. During the day it remains about 10 Kelvin colder than in the rooms upstairs on the 1st floor (Eurac, 3ENCULT, 2013). This temperature difference was decisive for the development of the house hybrid ventilation system concept. The mechanical part may be composed of a ventilation system with a recovery unit that exchanges and cools down the supply air of the upper floors with the cool air from the "cooling reservoir" of the cellar. In this case, the base will not be ventilated and must be climatically separated from the above floors.

![Figure 92 Hybrid Ventilation Concept](image-url)
RECOVERY SYSTEM

The creation of the hybrid ventilation concept is achievable in Energy Plus through different ways. In this case, for the analysis of the cooling load reduction in the building, it was considered to operate in term of energy. Basically with energy transfer equation, it was determined the exchanged energy in time function between the basement and the rooms of the first and second floor.

\[ \dot{Q} = \dot{m} \cdot c_p \cdot \Delta T \ [W] \]

where:
- \( \dot{Q} \) = Exchanged Thermal Power (“Hourly Exchanged Energy”)
- \( \dot{m} \) = air mass flow [Kg/s]
- \( c_p \) = Specific Heat [J/Kg K]
- \( \Delta T \) = Temperature difference [K]

\( \dot{Q} \) represents the energy exchanged through an ideal Heat Exchanger device in time function. It is directly proportional to mass flow, specific heat and temperature difference. The ideal energy exchanged should be multiplied with an efficiency factor, which corresponds to the efficiency of the Heat Exchanger device. The following picture shows the simplified hybrid system concept developed in terms of energy.

![Figure 93 Hybrid Ventilation System in terms of Energy](image)

Hypothesis:
- \( \dot{m}_{in} = \dot{m}_{out} \) : the air mass flow that flows inside the building is equal the outgoing air mass flow
- \( \dot{m}_{zone} = \dot{m}_{basement} \) : the air mass flow of the zone is equal than the basement air mass flow
- \( T_{zone} > T_{basement} \) : the zone temperature is higher than the basement temperature
The EnergyPlus object that permits to work in terms of energy is the object “Energy Management System” (EMS). The Energy Management System provides high-level, supervisory control to override selected aspects of EnergyPlus modeling. A small and simple programming language called EnergyPlus Runtime Language (Erl) is used to describe the control algorithms (EnergyPlus, EMS, 2013).

The first step of the EMS Application is to define the variables of the Erl program. There are global and local variables and the global variable have to be unique. Global variable can be used across Erl programs and always refer to the same instance of a particular variable. Local variable can be used only within a given Erl program. Erl programs have eight types of variables. For the purpose of the simulation, it will be used the following variable types (EnergyPlus, EMS, 2013):

- **Sensor**: each EnergyManagementSystem:Sensor input declares a user-defined variable and maps it to a variable elsewhere in EnergyPlus (via output variables). Variables so declared have global scope and are used to get time-varying input data from elsewhere in the EnergyPlus model. In this case the Sensors are the Zone Mean Air Temperature and the Outdoor Temperature.

- **Actuator**: each EnergyManagementSystem:Actuator input object declares a user-defined Erl variable and maps it to a variable elsewhere in EnergyPlus. Variables so declared have global scope and are used to set control results elsewhere in the EnergyPlus model. In this case the Component type uses as Actuator is the “Other Equipment” object. For each zone of the first and second floor an “Other Equipment” object is inserted.

- **Global variable**: EnergyManagementSystem:GlobalVariable input objects are used to declare variables with a user-defined name and global scope. Global variables can be used to store intermediate results that span across Erl programs. These variables are global only within Erl and not with respect to code elsewhere in Energy Plus.

- **Internal variable**: Each EnergyManagementSystem:InternalVariable input object declares a user-defined Erl variable and maps it to a variable elsewhere in Energy Plus. Variables so declared have global scope and are used to get static input data from elsewhere in Energy Plus. As internal variable are declared the Volume [m$^3$] and the floor Area [m$^2$] of each room of the first and second floor.
After the variable definition, the Erl algorithms were created using the objects EMS:Program and EMS:Subroutine. Figure 94 shows the algorithm concept:

The structure of the Erl program has been realized in this form for simplify the comprehension of the algorithm text. Through the main program the subroutine “Variable_Definition” is called. The subroutine contains all sensors and internal variables of each room, necessary for the “Hourly Exchanged Energy” and “mass flow” calculation. The utilized formulas for the “Hourly Exchanged Energy” and “mass flow” calculation are included in the “Heat Exchanger” program, which is called from the “Variable_Definition” subroutine. The “Heat Exchanger” program is repeated until all the rooms above the basement are analyzed (LOOP creation). Practically each room exchanges energy (through an ideal Heat Exchanger device) with the cellar in relation to the imposed boundary conditions.

In addition to the “Hourly Exchanged Energy” calculation, the mass flow is used to determine the power consumed from an ideal fan. The ideal fan supplies the air coming from the Heat Exchanger device inside the rooms. The energy consumption of the fan is calculated through the following formula (EnergyPlus, Eng.Ref., 2013):

\[ Q_{\text{fan}} = \frac{m \cdot \Delta P}{\eta \cdot \rho_{\text{air}}} \ [W] \]
where:

\[ \dot{Q}_{\text{fan}} = \text{Fan Power [W]} \]
\[ \Delta P = \text{fan design pressure increase [Pa]} \]
\[ \dot{m} = \text{air mass flow [Kg/s]} \]
\[ \rho_{\text{air}} = \text{air density at standard conditions [Kg/m}^3\text{]} \]

The planning of a complete HVAC with its pipe path is complex and requires great resources of time. For this reason, a fan with an ideal pipe path is considered, just to indicate the possible energy consumptions of the mechanical ventilation system, related to the proposed Hybrid Ventilation Concept. The pipe path corresponds in this case to a closet circuit formed from four straight pipes and four angular pipes with an angle of 90 degrees. Along the analysed circuit it is to supposed a several number of canalizations (equal to the number of the rooms), which supplies air into the rooms.

![HVAC, Ideal pipe path](image)

The pressure difference \( \Delta P \) for the \( \dot{Q}_{\text{fan}} \) calculation was determined with the use of the following formulas:

- Angular pipe
  \[ \Delta P = \frac{\xi * \rho * v^2}{2} \text{ [Pa]} \]

- Straight pipe
  \[ \Delta P = \frac{\lambda * L * \rho * v^2}{d_i * 2} \text{ [Pa]} \]

Where:

- \( L \) = pipe length [m]
- \( \xi \) = Zeta value [-]

29 Source: http://www.schweizer-fn.de/stroemung/druckverlust/druckverlust.php#druckverlustrohr (Day Accessed: 18.03.2014)
30 Source: http://www.schweizer-fn.de/stroemung/druckverlust/druckverlust.php#druckverlustrohr (Day Accessed: 18.03.2014)
\[ v = \text{flow rate [m/s]} \]
\[ \lambda = \text{pipe friction coefficient [-]} \]
\[ d_i = \text{pipe diameter [m]} \]
\[ \rho = \text{density [Kg/m}^3\text{]} \]

**BOUNDARY CONDITIONS**

The air is supplied inside the rooms only according to fixed boundary conditions. Through the Erl program the air is supplied into the rooms when the following three conditions are respected:

- The room temperature is higher than the basement temperature (Erl: \( T_i > T_{\text{Basement}} \))
- The room temperature is higher than 25° C (Erl: \( T_i > 25^\circ\text{C} \))
- The external temperature is higher than 25°C (Erl: \( T_{\text{Out}} > 25^\circ\text{C} \))

In order to understand how the hybrid ventilation concept works is necessary to evaluate the boundary conditions fixed in the EMS object with the boundary conditions imposed in the AirflowNetwork.

According to the AirflowNetwork the room windows are open when:

- \( T_{\text{zone}} > T_{\text{external}} \)
- \( T_{\text{zone}} > T_{\text{set}} \)

According to the EMS the mechanical ventilation system works when:

- \( T_{\text{zone}} > T_{\text{Basement}} \)
- \( T_{\text{zone}} > 25^\circ\text{C} \)
- \( T_{\text{external}} > 25^\circ\text{C} \)

So that it is possible to have three possible different scenarios:

- Ventilation through windows
- Ventilation through windows and mechanical system
- Ventilation through mechanical system

For example:

<table>
<thead>
<tr>
<th>( T_{\text{zone}} )</th>
<th>( T_{\text{external}} )</th>
<th>( T_{\text{set}} )</th>
<th><strong>Ventilation Art</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>24</td>
<td>25</td>
<td>through windows</td>
</tr>
<tr>
<td>27</td>
<td>26</td>
<td>25</td>
<td>through windows and mechanical system</td>
</tr>
<tr>
<td>27</td>
<td>28</td>
<td>25</td>
<td>through mechanical system</td>
</tr>
</tbody>
</table>

*Table 20 Hybrid System – Example of Ventilation Art*

The hybrid ventilation system is added to the “WG Natural AllDay” model (the new model name is “WG Hybrid AllDay”). The simulations are conducted for two different cases: the first case considers the
ventilation inside the building through windows and mechanical system. While in the second case only the mechanical system is activated (“WG Hybrid NOVent”). With the last ventilation art it is possible to observe, if the cellar “cooling reservoir” is able to improve the thermal comfort, when due to some external factor the windows should remain closed.

Through the graphic in Figure 96 the period of Heat Exchanger activation is visible. The blue line represents the temperature trend of the room 51, when all windows and chimneys are closed and the Heat Exchanger is activated (“WG Hybrid NOVent”). The orange line represents the temperature trend, when the natural and mechanical system are both in function (“WG Hybrid AllDay”). In July the cellar temperatures reach a maximal value of about 25.7 °C in the first case and a value of about 24.2 °C in the “Hybrid AllDay” case. The maximal cellar temperature in the case without the mechanical system was equal to 20.6 °C.
Figure 97 shows that when the Hybrid ventilation system is in function, i.e. natural and mechanical ventilation are allowed, a generally slightly temperature decrease is observed than the case with only natural ventilation. When natural ventilation strategy is permitted the use of “cooling reservoir” of the cellar through mechanical system is limited.

![Room 51 - Natural / Hybrid Ventilation - Mean Air Temperature [C] - July](image)

*Figure 97 Room 51 Hybrid System - Mean Air Temperature – July*
Figure 98 shows the temperature trend of the room 51, when no ventilation through the windows and chimneys is allowed and the Heat Exchanger is activated. A decrease of the temperature in the month of July is observed and the reached maximal temperature difference is equal to 2.2 °C.

In July, the heat exchanger allows a relative important temperature decrease, when the windows and chimneys are closed. While, the benefits with the heat exchanger together with the ventilation through the external openings are not so relevant (Figure 99).

Figure 98 Hybrid System with Closed Openings Mean Air Temperature – July

Figure 99 Room 51 – Natural and Hybrid Ventilation – Average indoor Temperature
Figure 100 shows the energy mechanical system consumption for both cases.

![Hybrid System - Energy Consumption [kW]](image)

**Figure 100 Hybrid System – Energy Consumption (kW)**

July is the month with the most energy consumption. The calculated consume value amounts to 72.41 kW. Each month energy consumption is multiplied with electricity price according to the AEEG (Authority for Electricity gas and water supply system) to observe the total effective costs per kWh.

<table>
<thead>
<tr>
<th>Period</th>
<th>Energy Hybrid System Consumption [kW]</th>
<th>Energy Hybrid System Consumption [€/kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AllDay Ventilation</td>
<td>NOVent</td>
</tr>
<tr>
<td>April (from 14th)</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Mai</td>
<td>0.86</td>
<td>8.88</td>
</tr>
<tr>
<td>June</td>
<td>19.82</td>
<td>40.60</td>
</tr>
<tr>
<td>July</td>
<td>54.73</td>
<td>72.41</td>
</tr>
<tr>
<td>August</td>
<td>26.97</td>
<td>52.20</td>
</tr>
<tr>
<td>September</td>
<td>0.00</td>
<td>18.24</td>
</tr>
<tr>
<td>October (til 14th)</td>
<td>0.00</td>
<td>1.59</td>
</tr>
<tr>
<td><strong>TOT [€/kWh]</strong></td>
<td><strong>16.55</strong></td>
<td><strong>31.35</strong></td>
</tr>
</tbody>
</table>

*Table 21 Hybrid System – Energy Consumption and Costs*

For the complete cooling period, a cost maximum cost of circa 32 € is calculated (Table 21), when the mechanical part of the ventilation system is in function and the external openings are closed.

### 6.5. Difficulties on the model construction

The construction of the Weigh-house model in Energy Plus requires a good knowledge of the software, due to its not so intuitive graphic interface. The Sketch-Up Plug-In has simplified the drawing of the building, where the surfaces were realized through the selection of apposite commands, however the construction of the Weigh-house model has required particular attentions with a considerable employing...
of time. In particular, difficulties are met during the realization of the chimneys and the development of mechanical ventilation part for the hybrid system.

These difficulties are justified in the fact that for the study of the building behavior through a model, it necessary to find a compromise between the reality and mathematical modelling. Often the model doesn’t represent exactly the geometry of the considering building, due to technical and drawing restrictions. For these reasons, often the engineer or architect is forced to apply changes, which, however, shouldn’t influence the success of the work.

Changes are made to the location of the chimneys into the rooms and to the chimneys geometry. The chimneys were inserted in the construction, for the analysis of their contribute on the thermal comfort conditions and each of them were considered as a singular Thermal Zone. Originally a rectangular shape to the Chimney Thermal Zone was attributed, however the choice of the shape didn’t allow the simulation running, caused by a “Non_Convex” error response. The type of error is associated to how the beam solar radiation entering a zone through exteriors windows. In this case, the solar distribution in Energy Plus model was considered setting the instruction “FullInteriorAndExterior” and that means that (EnergyPlus. I/O Ref., 2013):

- exterior shadowing from window and door reveals is calculated
- shadow patterns on exterior surfaces caused by detached shading, wings, overhangs, and exterior surfaces of all zones are computed
- the amount of beam radiation falling on each surface in the zone, including floor, walls and windows, by projecting the sun’s rays through the exterior windows is considered

Energy Plus calculates the distribution of short-wave radiation in the interior of each thermal zone. The amount of this radiation consists in radiation absorbed on the inside face of opaque surfaces, absorbed in the glass and shading device layers of the zone’s exterior and interior windows, transmitted through the zone’s interior windows to adjacent zones, and at last transmitted back out of the exterior windows.

The most common non-convex zone is an L-shaped zone (Figure 101).

**Convex Definition:** any straight line passing through the zone intercepts at most two surfaces

![Convex zones](image)

![Non-Convex zones](image)

*Figure 101 Example of Convex and Non-Convex zones*[^1]

[^1]: Source: EnergyPlus, I/O Ref. 2013, pp.17
To overcome the problem the geometry of the chimney was modified in a triangular shape with an equivalent area and in some case also the location was changed.

Another difficulty encountered during the model construction regards the development of the Hybrid ventilation system of the Weigh-house. As already mentioned the mechanical part of the hybrid system was made through the use of the Energy Plus object called “Energy Management System” (EMS). However, at the beginning was supposed to create a mechanical system composed by a Heat Exchanger and related Fans through the AirflowNetwork object. The concept behind its development was the same than the EMS, i.e. to exploit the cellar thermal potential for the cooling load reduction of the upstairs rooms.

The creation of a HVAC system in Energy Plus needs the definition of AirflowNetwork components, like heat exchanger, fan, ducts, etc. Each component possesses an “Inlet” and “Outlet” node. The node is the point at which fluid properties are evaluated and represent the point of connection with the related components, which are linked together to create various loops within the simulation. Loops are realized by defining these loops and also defining the components on the loops. The following figure shows an example of the loop-node concept.

![Figure 102 Example node diagram](image)

If the AirflowNetwork object is used, the definition of an external node is necessary. In this case, the studied system concept don’t provide an external node and the thermal exchange happen between the internal room air and the cellar air. As consequence, a “trick” in Energy Plus for the running of the HVAC system simulation was trying to find. After many efforts, another method for the analysis of the cooling load reduction was taken into consideration, i.e. the use of EMS method.

All the encountered difficulties during the realization of the model were useful to learn the limits of Energy Plus software and to realize how the development of an HVAC system requires time and very

---

good knowledge and experience in the mechanical ventilation field. Although interesting, for this case was preferable the use of a method that allowed the resolution of the proposed scope efficiently and also in a reasonable time.
7.0. Conclusion

In the present work, cooling load reduction by ventilation strategies of the Weigh-house of Bolzano during summer period is presented. The Weigh-house is a historical building dating from the XIII century and consist in a massive structure. Because of its constructive characteristics, the study of energy efficiency improvement solutions for the building envelope and ventilation strategies required the use of dynamic simulation tool. The reference model (As is State model), i.e. the one that represents the building in the current state, is realized thanks to the collection of a big amount of data, collected through several on-site inspections and tests, such as the blower door test, U-value measurement with thermo-flux meters, indoor environment monitoring, IR evaluation. All theoretical analysis were performed with the dynamic simulation software EnergyPlus.

Before starting the energy efficiency improvement process on the model envelope, a validation consisting in a simple comparison between the indoor air temperature coming from the software EnergyPlus and Therakles was done. The comparison results on the indoor temperatures showed acceptable differences, presumably due to different calculation method of solar gains on the transparent surfaces and sun path. This hypothesis has been formulated by performing simulations on a model devoid of windows and successively on one with windows. When only the opaque surfaces are considered, the maximum temperature divergence did not exceed 0.4 °C and over 70% of hourly temperature differences was lower the 0.1 °C. While considering the room with the glass surfaces the results were less promising, but still acceptable. The maximum temperature divergence between the two software’s is equal to 1.5 °C with only ca. 7% of hourly temperature differences are between 1.0 and 1.5 °C. Most of temperature divergences are registered in July and August, when the solar radiation that meets the transparent surfaces is higher. A more in-depth comparative validation was worth investigating; however a longer time would be necessary to study the different implemented theoretical approaches employed by the developers for describing the building energy behavior and solving the mathematical equations.

The analysis of the energy efficiency improvement through retrofit actions on building envelope, was conducted to verify if the common interventions, thought for the heating period, are compatible also with the cooling period needs. The results show that airtightness and thermal insulation improvement and windows replacement led to an acceptable indoor temperature increase. A comparison between reference and energy efficiency improved models reveals a maximal temperature increment of about 1.2 °C in the month of July. From a maximum of 32.3 °C by the reference model the temperature achieve a value of 33.5 °C. While, the adoption of external shutter to the windows on the first and second floor of the building did not show a relevant indoor temperature drop.

Having evaluated that the solutions on the building face both winter and summer energy issues, the cooling load reduction of the Weigh-house is analyzed by different ventilation strategies: the natural ventilation through windows and chimney openings, and the hybrid ventilation, namely the case of integration of the natural and the mechanical ventilation systems. Regarding natural ventilation strategies, through adjusting of window and chimney openings, the results show that windows give the
most contribute on the cooling load reduction. The number and size of chimneys already placed inside the building led to a minimal drop in temperature. Furthermore, it was observed that a simultaneous controlled air infiltration through window and chimney openings contributes to an immediate indoor temperature decrease compared to the no-ventilation case, where all openings are considered closed. For example, comparing NO-ventilation with window night ventilation case, in July, from an average indoor temperature of 31.5 °C with closed openings, it was calculated a decreasing to a value of about 24.3 °C.

Simulation results also showed that night ventilation is a good solution for the cooling load reduction, but do not guarantee the minimum ACH rate during occupied hours required by the standard EN 15251 for non-residential building. While, a controlled air infiltration through windows during all the day permits the achievement of the minimum ACH rate, but take to a slightly decrease of thermal comfort satisfaction percentage (according to EN 15251 – Adaptive method) compared to the window night ventilation. Anyway, for both cases a percentage of almost 100% in Category III is reached from May to September. Only April resulted a “critic” month with a law percentage of thermal comfort satisfaction, because of too low temperatures. In this case will be useful to advise occupants to wear heavier or take into consideration the adoption of a heating system.

Eventually, with regard to the hybrid ventilation system concept developed with heat flux equation, interesting observations can be done. According to the EnergyPlus weather data and setting controls, the results show that the use of “cooling reservoir” of the cellar for the cooling load reduction of the upper rooms is necessary when the chimney and windows openings are closed. While, when controlled air infiltration through windows and chimneys is allowed, the utility of the heat recovery system is less meaningful. The reason is that natural ventilation alone, take to a drop in temperature sufficient to guarantee an optimal indoor thermal comfort and thereby the mechanical system does not operate. As consequence, the highest energy consumption of the mechanical system was calculated when the all chimney and window openings are closed. For example, in July the energy consumption reaches its maximum of 72.4 kW. In total, during all simulated period (from 16th April to 14th October), the estimated energy price according to AEEG (Authority for Electricity gas and water) is of 31.35 €. In conclusion the adoption of this type of heat recovery system could be used in the circumstance in which weather conditions or external factors – e.g. air pollutants – forced the closing of the external openings.

These are the topics treated in the present work. It would be surely interesting to extend the analysis of the issue object of the present study. Smart windows and chimney openings control by means of actuators and more control settings for the natural ventilation strategies definitely represent the future studies to undertake with the aim of thermal comfort optimization.

Even if, EnergyPlus simulation software is an extensively tested tool, an empirical validation of the models could be required, in particular for the historic, high-mass, variable moist wall, buildings. The comparison of the obtained results with the actual monitored data coming from a real building, will be used for a later model calibration. However, it can be considered reliable enough to trust in the obtained
achievements, and their possible further applications. Analyzing the output data, it is possible to assert that for the Weigh-house, cooling load reduction by natural ventilation strategies is achievable.
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11.0. Bibliography of Standards

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