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Hygrothermal study of a wine cellar and analysis of passive cooling systems for its energy retrofitting

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Abstract

Spain is the third largest producer of wine worldwide. This field represents a very important branch for the country on the environmental, social and economic level, nationally and internationally. At the same time, the environmental conditions of our planet nowadays require an exceptional attention to the construction field in terms of emissions. It is becoming more and more spread the concept of a Zero Energy Building, namely the construction of buildings that require a meagre or null additional energy intake. This thesis combines these two vital fields with the aim of improving the energy efficiency of wine cellars in terms of air-conditioning, for the monitorization of relative humidity and temperature, whose value is essential that remains constant for a proper wine aging.

Among few wine cellars suitable for this study, was chosen the one that seemed more appropriate, located in Peñafiel, nearby Valladolid in the D.O. Ribera del Duero, one of the country's quality regions of the production of wine.

The first analysis required in the development of this study would be the examination of four sensors, arranged in a vertical row in the middle of the cellar, which detect the relative humidity and the temperature of the environment. These four sensors - which at the beginning of this study had already provided measurements for one year - were located in such position in order to draw attention to the layering of air, which, as previous studies show, increases in the summer period for the warming of the roof, fact that will require a significant awareness during the next steps of the study.

By means of plans, sections, elevations and similar, we proceeded with the 3D modelling of the building in the energy simulation software DesignBuilder, in which there will be collected all the details about the construction and the climatization systems.

Once the model is filled with all the available information, it begins the validation part: it is essential to verify the correspondence between the data taken from the sensors and the simulated data, in order to be able to rely on the model during the last part of the study.
The stage by which the work gets to an end, which as well represents the purpose of this thesis, is the investigation of passive systems solutions in order to bring the requested comfort by reducing drastically the energy expenses, increasing in such a way the efficiency of the building.

Keywords: wine cellar, passive system, hygrothermal analysis, energy simulation, DesignBuilder.

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List of Abbreviations

ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
AD	Average Deviation
BAPV	Building Applied PhotoVoltaic
BIM	Building Information Modeling
BIPV	Building Integrated PhotoVoltaic
CV(RMSE)	Coefficient of Variation of the Root Mean Square Error
HVAC	Heating Ventilation Air Conditioning
D.O.	Demoninación de Origen
IPMVP	International Performance, Measurement and Verification Protocol
ISO	International Organization for Standardization
LAI	Leaf Area Index
MBE	Mean Bias Error
MR1	Machinery Room 1
MR2	Machinery Room 2
NMBE	Normalized Mean Bias Error
nZEB	nearly Zero Energy Building
PCM	Phase Change Material
PV	PhotoVoltaic
R^2 or CD	Coefficient of Determination
RH	Relative Humidity
S_02	Sensor at 0,2m
S_15	Sensor at 1,5m
S_30	Sensor at 3,0m
S_45	Sensor at 4,5m
SD	Standard Deviation

TIT1	Thermal Insulation Thickness 1
TIT2	Thermal Insulation Thickness 2
TIT3	Thermal Insulation Thickness 3
TS1	Targeted Simulation 1.0
TS2	Targeted Simulation 2.0
TS3	Targeted Simulation 3.0
U-value	Thermal Transmittance
ZEB	Zero Energy Building

Chapter 1

Overview of the study

1.1 Justification

This study aims to bring energetic solutions on multiple fronts. On one side there is the hygrothermal condition of the wine cellar, hence, the quality of the wine produced by the winery object of the study. On the other side there is the concept of creating certain comfort conditions in a peculiar environment, such as the wine cellar, without resorting to the use of HVAC (Heating, Ventilation and Air-Conditioning) energy-powered systems but thanks to the implementation of passive systems.
The compelling part about these two factors is that the first one is supposed to increase the incomes of the winery, making it produce finer wine, the second one is supposed to improve the energy savings, reducing the energy expenses and their cost. Therefore, both are aiming to bring economic benefits to the winery, and lastly, but not of less importance, to the environment.
The importance of such study lays on the fact that it outlines how it does not take much effort to create a building that is both financially convenient and sustainable.

1.2 Objectives

This thesis investigates different passive system solutions that promote the construction of low-energy buildings in the agronomy sector. Particularly, it focuses on the study of a wine cellar used for the ageing of red wine. Such process requires specific hygrothermal conditions throughout the year, which very often translates into high energy consumption for the climatization of the environment. The main purpose is to find a guidance and recommendations for the correct design of wine cellars that would ensure the achievement of the wine comfort conditions without restoring to massive amount of energy.
At the beginning of the year 2018, four sensors were located inside the wine cellar at

three different heights, in such a way to be able to monitor also the vertical delta temperature, and one sensor was located outside to register the external temperatures that truly characterized that year.
The first part of the study would be the collection of the experimental data and the pursuit of a monitoring system that would help understand the goodness or badness of the hygrothermal situation inside the wine cellar. A substantial part of the thesis will focus on the percentage of the days per year during which the comfort conditions for wine are satisfied. Concluded the data analysis, the next step would be the creation of a digital model in the DesignBuilder software in order to shape a truthful configuration, behaving as similar to the reality as possible, on which will be developed the last part of the study, the implementation of passive systems for the energetic improvement of the building.
The aim is to find passive solutions applicable to the case that best suit the winery to guarantee effectively the comfort conditions required.

1.3 Structure

The introduction will open up with some knowledge about the culture of wine in Mediterranean countries like Spain, and the economy concerning. A short section will explain as well about the fermentation process and the wine ageing optimal conditions for red wine, the most sensible among the many wine kinds, and the one produced in the winery studied. Shortly, some typical winery constructions will be reviewed as well.
Later on, a chapter is dedicated to an overview of the passive cooling systems, divided essentially in vertical envelopes and roofs. It will be explained how they work, which are their best applications on building retrofitting and the improvements they bring to the energy efficiency of the construction.
The fourth chapter contains all the information related to the winery object of study, such as the locality, the climate of the region, the building composition and layout, with plants, sections, elevations and envelope stratifications.
Finally, the essential part of the thesis, its development, divided in three chapters:

1. Analysis: the study starts with the analysis of the experimental data collected by the five sensors during the year 2018 inside the wine cellar of the winery and on the outdoor. The analysis contains annual, seasonal, monthly and daily studies of the data.

2. DesignBuilder: the second part of the study is the realization of the building model on the DesignBuilder software. This resulted to be the most difficult

part of the thesis due to the validation process. Indeed, many fundamental data for the energy simulation were not provided by the winery, probably for the lack of information about the construction design.

3. Passive Systems: once the model has been validated, the next step would be the implementation of passive systems for the retrofitting of the building, with the consequently energy simulation to detect the most suitable passive cooling strategy for the winery in question, and to determine the efficiency improvement brought to the building.

The thesis ends with the exposition of the conclusions and future investigations.

Chapter 2

Introduction

2.1 Wine

Wine has always represented an essential element on the table in few European countries like Spain, Italy and France, since millenniums ago. Nowadays the wine market is one of the most valuable in terms of international food trade. Europe is the main worldwide producer of wine: between 2013 and 2017 the average annual production was of 168 million hectoliters, accounting for almost a 75% of exports to the developed countries all over the world, such as USA, China, Argentina - just talking about the main consumers. [4] As many agricultural processes, the wine production requires a massive energy intake, estimated at over 105PJ per year, emitting nearly 16 million tonnes of CO_2, values that are not considering the expenses due to the bottle making and transportation (data referred to the year 2005). [5]
At the same time, the actual conditions of our planet nowadays are such that a prompt intervention on every area is necessary. Considering that the construction industry is one of the most influent fields in terms of energy expenses, both on the level of materials production, the process of construction and the costs necessary for the maintenance and usage for the livability of the environment, it is everyday more spread the concept of a sustainable architecture, founded on the implementation of passive systems or active systems demanding energy to renewable energy sources. It's the concept of *ZEB* or *nZEB* constructions, acronyms for *Zero Energy Building* or *nearly Zero Energy Building.* As the latest report on sustainable constructions, published by the European Commision, affirms, one of the main goals is to lower the need of energy for heating and cooling buildings. This can be achieved by implementing, during the first stages of building design, highly insulated envelopes, air tightness in the openings and heat recovery on ventilation. [6] All these aspects regard profusely the wine production field, especially in the ageing stages where

it is required a constant temperature which, as reported in section 2.3.1 and 5.1.2, oscillates from 5°C to 18°C, values that in many of the most wine-productive regions are very difficult, not to say impossible, to maintain without a cooling system.
This is exactly why in the past, since centuries B.C., wine was stored underground, where the many layers of the earth build a perfect environment for the ageing of wine, keeping low and quite constant temperatures the year round, even in the warmest countries, such as Spain, and a high level of relative humidity, generally recommended around the 80%, needed in order to maintain under control wine evaporation.
Because of the high inertia that the ground provides to the envelopes of these subterranean cellars, many of them are still in use nowadays. A vast collection is present in the central areas of Spain, around its capital Madrid, in the regions of Castilla la Mancha, Rioja and most importantly Ribera del Duero, the D.O. region where this thesis is centered on.
Based on the same characteristics, many underground, basement and ground-covered wine cellars have been constructed in the last decades, all of them taking advantages of the same fundamental property: high inertia. The winery subject of this work is of quite recent construction, and on the contrary of what would be best for energy saving, environment preservation and also company business, it is an above the ground building.

2.2 The Fermentation Process

This thesis aims to study the environmental conditions kept in the selected wine cellar and tries to understand if the data obtained with the monitorization held throughout the year satisfy the values of temperature and relative humidity needed for a fine wine ageing. In order to understand better why the values found are or are not appropriate for this purpose, some basic knowledge on the fermentation process and the production of wine is exposed.
As notoriously known, red wine is produced only from red grapes. The *must* of the grapes has always the same grey-green color – both for red grapes and white grapes – and certainly not reddish. Indeed, the substances that have the ability to tint wine red are contained in the skin. The properties of these substances vary according to the type of grape and the climate conditions they grow in. [7]
When the grapes are ripe, the *harvest* begins. This process can be done by hand or mechanically. The use of machines facilitates the harvest but brings damages to the vineyard and the taste of wine, giving it a metallic taste. For these reasons wine

makers prefer to harvest by hand, being this way more delicate on the grapes and the land. Indeed, the harvest is one of the fundamental moments in the wine making process: the moment the grapes are picked determines the acidity, the sweetness and in general the flavor of wine.
Once the harvest is done, the grapes are sent to the winery to be de-stemmed. This is a decisive moment for the sweetness and delicacy taste of wine, because the polyphenols present in the sprig of grapes are very acid and bitter, and if kept inside the grapes they would give the wine an unwanted harsh taste. Thus, it is important to be vary careful during this stage because if the stem is broken inside the grapes it will release very astringent and bitter substances.[8]
Once the grapes are de-stemmed, the pressing process can start. In the past men and women did this manually by stomping the grapes with their feet, nowadays this process is usually performed mechanically, improvement that brought massive sanitary gains.
The outcome is the must, which now is ready to start the fermentation process that will transform it in red wine.
Contrary to what the majority thinks, the difference between red wine and white does not lay on the color of grapes used to produce them. What distinguishes the two types of wine is the primary fermentation, which in red wines is carried out including the grapes skin, containing tannins, which are responsible for its dark color. In the white wines, instead, the skin is separated from the flesh and the must keeps the grey-green color of the pulp.
The primary fermentation process – due to the yeast present in the grapes – transforms the grape juice into wine by turning the sugar present in the fruit into alcohol and carbon dioxide.
This process is brought out inside steel tanks filled in with must, grapes skin and stems. The chemical reactions tend to increase the temperature of the tanks, which makes it very important to keep it under control and around 25°C and 30°C – red wine fermentation temperature. Higher temperatures lead to higher loss of coloring substances and tannins, implying a more delicate wine, while sturdy wines come from lower temperature fermentations.
Depending on the variety of the grapes used and on the kind of wine willing to obtain, the fermentation could last from few days, as for the more delicate wines, to one month, as for the robust ones.
To obtain more sugary wines, the must is taken to the next step before every bit of fructose is transformed into alcohol.
Once fermentation is over, *clarification* begins: solids corps as yeast cells, skin and

tannins are removed by fining or filtration. This is another extremely delicate step since an excessive extraction of polyphenol could produce particularly bitter wines, with undesirable taste.
After the clarification, the secondary fermentation starts. This process is highly important in the production of red wines since the lactic acid produced in this stage is softer and more delicate than the malic acid produced during the primary fermentation.
Throughout this time, wine is usually kept inside wood barrels – often oak wood – which give wine some extra flavor. Using wood containers allows air to filtrate inside the barrels and oxygenate the wine, affecting positively its maturation. Nevertheless, sometimes the secondary fermentation is brought out into stainless-steel tanks.
The final step is the ageing of wine, which could be done inside the stainless-steel tanks or inside the oak barrels. Ageing wine in contact with wood would give it smoother and rounder flavor, increasing its oxygenation as well.
Still, the winemaker could decide to bottle wine and sell it with no further ageing.[9]

2.3 Optimal conditions for wine ageing

The maturation of wine refers to a stage that involves different processes, as clarification, secondary fermentation, as seen in the previous paragraph. During this phase of the wine making process, wine is generally kept inside wood barrels, just like in the wine cellar studied. This kind of storage of wine allows it to be in contact with air and thus, being oxygenated, resulting in a better wine quality. After a certain amount of time, wine is bottled and left in the wine cellar under specific environmental conditions. This stage is called ageing.
In the next two paragraphs are explained the optimal conditions for the maturation and ageing of red wine, the only kind produced in the winery subject of study. This knowledge will allow us to understand better the goodness of the data and how to improve in a further stage the winery conditions in terms of energy savings.

2.3.1 Red Wine

The two crucial parameters to keep under control during wine maturation and wine ageing, are *temperature* and *relative humidity*, specifically low temperature and high relative humidity. Further than that, there are other variables to take into account, such as vibrations, or light. Indeed, ultraviolet rays have the ability to deteriorate the organic particles present in wine, resulting in a degradation of its taste. This is why, for common knowledge, wine cellars are cool and dark, thus, usually underground. There is a vast quantity of literature concerning the environmental conditions that should be kept inside wine cellars for the proper wine ageing. In the next lines are shown few of them.

Troost[10] says temperature should be kept between 12°C and 15°C with a relative humidity between 86% and 98%, and thinks that wine cellars reaching 20°C are not adequate for wine conservation, while Bondiac[11] sustains lower temperatures, between 10°C and 12°C, saying nothing about relative humidity, similarly to Hidalgo Togores[12] that refers to an interval of 9°C-12°C and a 70%-80% of relative humidity. Marescalchi[13] favors different intervals depending on the years passed from the bottling: 15°C - 20°C for the first year and 4°C-12°C for the followings. Rankine[14] suggests to keep temperature between 13°C and 18°C, while Vogt[15] recommends to keep it around 12°C and never above 15°C, encouraging to keep the annual oscillation always below 6°C. SEPSA sustains the importance of a constant temperature variating from 8°C to 14°C, maintaining temperature always above 4°C and below 25°C. Cortés[16] aims for a temperature between 8°C and 11°C and a relative humidity oscillating between 65% and 80%. Anta[17] says its preferable a constant temperature between 8°C and 12°C, just as Muñoz Ochoa[18], who expresses also about relative humidity, considering appropriate when varying between 45% and 80%, while Ough[19] recommends little higher values, between 10°C and 15°C, still affirming that extremely high values easily bring to a degradation of wine taste. Pérez and Gervás[20] say that the interval should be different according to the season, claiming it to be between 10°C and 12°C in winter and between 16°C and 18°C in summer, and never during the year above these values. Ribéreau-Gayon[21] and Yravedra[22] consider no internvals but only a 20°C limit, as Christaki and Tzia[23] that require instead a 12°C limit. Foulonneau[24] recommends keeping it between 11°C and 14°C. Zamora[25] allows a wider interval between 10°C and 18°C.

Even though every author reports different temperature intervals, it is commonly recognized that temperatures higher than 18°C-20°C can damage wine by accelerating its ageing to a speed that turns it into vinegar. At the same time, temperatures too low, generally below 4°C-5°C, cause wine to age too slowly.
It is generally agreed that high values of relative humidity are necessary for a convenient wine storage more on a economical point of view rather than on a quality level – when we say that "a bottle of wine tastes like cork", we are unconsciously referring to the *Armillaria mellea* grown inside the cork, which happens in cold and

Table 2.1: Wine comfort conditions by author

Author	**Year**	**Temperature**	**Relative Humidity**
Muñoz Ochoa	1955	8-12°C	45-80%
Marescalchi	1965	first year: 15-20°C following years: 4-12°C	-
Cortés	1968	8-11°C	65-80%
Vogt	1971	12-15°C ΔT = 6°C	-
Bondiac	1980	10-12°C	-
Troost	1985	12-15°C always < 20°C	86-98%
Anta	1992	8-12°C	-
Ough	1996	10-15°C	
Pérez and Gervás	1998	10-12°C in winter 16-18°C in summer	-
Ranking	1999	13-18°C	-
Christaki and Tzia	2002	always < 12°C	
Hidalgo Togores	2003	9-12°C	70-80%
Zamora	2003	10-18°C	-
Yravedra	2003	always < 20°C	-
Ribéreau-Gayon	2003	always < 20°C	-
Foulonneau	2004	11-14°C	-

wet environments. But, even though a high relative humidity could cause the growth of fungus, it is necessary in other to avoid relevant wine losses by evaporation.

2.4 Types of wineries

Nowadays the diversity of wine cellar constructions is wide all around the world. From the most ancient caves, dating back to the Roman Empire, to the most modern constructions designed by the ultimate archistars, one could find any kind of winer constructiony to this day.
From Plinio il Vecchio to Vitruvio, from Palladio to our days, the wineries were always supposed to be underground in order to preserve the comfort conditions that require low constant temperature.

Back then keeping the building to a low constant temperature was quite difficult, not to say impossible. Nowadays, after millenniums of development and discoveries, it is possible to keep the indoor temperature at 18°C while the outdoor averages around 35°C or more. This is the reason why many architects forgot about passive strategies to guarantee the wanted conditions without resorting to massive energy consumption.
While residential houses or working spaces need to guarantee the human comfort conditions, which adjust to the season, around 20°C during winter, and around 26°C during summer, wine cellars require a low constant temperature the year round. With no passive cooling strategies, the energy demand of such buildings would increase to unreasonable amounts, as it is. Nowadays, many of the newest wineries are designed mainly to leave their sign on the land they are built on. They become an icon that follows the brand, with the only function of being impressed on the buyer's mind. What is left aside is the vast, heterogeneous and complex set of functions these buildings have to guarantee. It is also for such reasons that in one of the countries with the largest and finest production of wine, Italy, it was published the CasaClima Wine protocol, a quality certification developed to promote the sustainability of wineries. Beside the energy efficiency and sustainability standards of the building itself, the attention goes to a low environmental impact process of the production of wine and the ability to reduce to a minimum the resources used.[26]

In this chapter are shown the principal types of wineries that were classified on the Ph.D. thesis of Mazarrón in 2010, titled "Estudio de las condiciones interiors de las bodegas subterránea en España, como modelo de eco-construcción".
The classification concerns the type of construction, without referring to materials and types of envelope:

(a) *Above-the-ground*: the wine cellar is located above the ground as the whole winery, similarly to industrial constructions. Some of these wineries opt for air-conditioning systems, that provide for cooling and humidification, in order to keep the indoor conditions adequate to the ageing of wine.

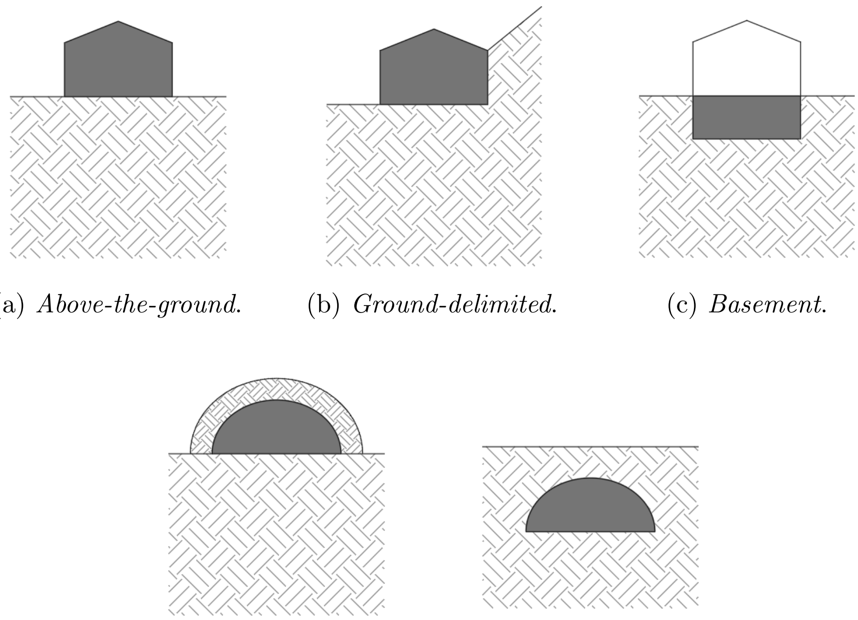
(b) *Ground-delimited*: some of the vertical envelopes of the wine cellars are in contact with the ground. The thermal inertia due to the direct contact with the earth helps reducing the energy consumption to keep low indoor temperatures.

(c) *Basement*: the wine cellar usually is located below the winery. The machinery rooms, the offices and all the other spaces not meant for the wine ageing are located above the ground as any industrial construction, acting as the top envelope for the wine cellar, surrounded on all the other sides by the ground.

(d) *Ground-covered*: the wine cellar is located at ground level, but its envelope is completely covered with ground to increase the thermal inertia and ease the fulfillment of the wine comfort conditions.

(e) *Underground*: this is the most ancient type pf wine cellar. The first one of this kind was found in Armenia and it dates to 4000 BC. The comfort conditions are easily kept thanks to the ground thermal inertia.

The wine cellar object of the study is of the kind (a), above-the-ground. Surely enough, without a finely insulated envelope, the winery would require a massive amount of energy intake in order to keep the indoor environment at the wine comfort conditions. Poor insulation and lack of air-conditioning would cause a dramatic decrease of the wine quality.



(a) *Above-the-ground.* (b) *Ground-delimited.* (c) *Basement.*

(d) *Ground-covered.* (e) *Underground.*

Figure 2.1: Different types of wineries

Chapter 3

Passive Systems

More than one third of the energy consumption in the developed countries nowadays is due to building's energy request. In view of these circumstances, it becomes of vital importance the implementation of constructive systems that aim to reduce the energy demand, due especially to heating, ventilation and air-conditioning systems (HVAC).
The envelope of a building is the principal reason of thermal exchange with the environment, therefore it is the main element to take into consideration during the energy design or the energy renewal of a building. A weakly insulated or poorly designed envelope massively influences the heat gain during the hot period and heat loss during the cold period. It is therefore essential to study every possible way of thermally regulating a building in order to achieve the comfort conditions for the human being – or any other necessity, such as food conservation, or indeed, wine ageing – and to reduce the superfluous energy consumption.[27]
The human genius has always found solutions depending on the climate conditions he was facing, making virtue of necessity. The most striking example would be the ingenious construction in which Persians produced ice in the arid and extremely hot land that is the Dash-e Lut desert.

So, how come that a couple of millenniums ago, when there was no electricity nor air-conditioning systems, Persians could get a refreshing ice-cream in extreme weather conditions, while we can barely build a comfort environment without resorting to massive amounts of energy intakes?

The truth is that with every important discovery, and with the continuous improvement of the living conditions, the human being has become lazier and lazier. We tend to minimize the physical effort and physical discomfort resulting in great energy consumers to who the critical environmental conditions come as last and least important issue to be worrying about. Building engineers and architects have a crucial role at this time, being the ones that could bring that 39% of energy consumption to a nearly 0%, just as the latest European report on sustainable construction says [6], naming the new generation of sustainable buildings *nZEB*, standing for *nearly Zero Energy Buildings*. The solution lays on the passive systems.

A passive system is an assembly of natural and architectural components which converts solar energy into usable or storable heat without mechanical power.

As delineated in the section 5.1.3, the analysis of data shows the unsatisfied comfort conditions during the hottest period of the year, being Summer and part of Autumn. Therefore, the passive system solutions that best fit this case study are the ones aiming to cool down the internal environment.
Passive cooling strategies are the ones that prevent heat gains inside the building, and the parameters that should be kept under control are the envelope's insulation, the radiative shading of the external surfaces of the building, such as roofs and vertical envelopes, and surfaces properties, such as colour, reflectiveness. [36]
Indeed, the internal environment exchanges heat with the exterior through the envelope, by conduction, convection and radiation. Reducing these three factors, largely depending on the external walls and roof conditions, also the internal temperature would decrease considerably. In other words, it becomes of vital importance to lower down the envelope temperature.
On this purpose, in the next paragraphs will be listed and analyzed various passive systems solutions, in order to have, later on, a precise and transparent idea of which systems could best fit the winery studied.
The passive systems will be divided into two principal categories:

- Vertical envelopes
- Roofs

3.1 Vertical envelopes

3.1.1 Ventilated façade

The simplest and probably most known passive system in the category of vertical envelope is certainly the ventilated façade, a type of light façade whose peculiarity is having an air gap separating the most external coating layer from the bearing

structure. On the contrary of many traditional vertical envelopes, the air gap is not sealed between the two layers of the wall, but it opens to the external environment with various hiatuses conveniently located, usually at the top and at the bottom of the coating tile.
The most sophisticated fastening systems are realized with steel anchorages sunk in the bearing structure, and spaced from it to create the air gap, equipped with earthquake bearing systems that allow the façade to move in four directions during the phenomenon.
Generally, the air gap ranges from 5cm to 15cm of width. It has been demonstrated that the larger the air gap, the higher the energy savings during the hot seasons, due to a greater passage of air.
The suspended coating layer, also know as second skin, is responsible for shielding the bearing structure from the atmospheric agents, such as rain, and just as importantly, for shading the envelope from the sun radiation. Indeed, studies show how the energy savings due to such passive system increase as the sun radiation on the building façade increases in turn. The operating principle consists on the air flowing inside the cavity at a lower temperature than the coating layer, warmed up by solar radiation, which with a static air cavity would transfer the heat by convection to the internal envelope, and consequently, to the internal environment. The opened gap, instead, guarantees a continuous flow of fresher air, reducing the heat exchange between external and internal environment.
This fact also explains why ventilated façades are adopted only on those parts of the buildings southern exposed – for what concerns the northern hemisphere.
It is true, though, that a continuous air flow prevents the formation of interstitial condensation, most commonly observed on the northern exposed façades.
It has been proven that a typical summer cooling energy savings of 40% can be achieved with a carefully designed ventilated wall, making the double skin façade one of the best options in managing the interaction between the outdoors and the internal spaces.[28][29]

3.1.2 Green walls

Similarly, to ventilated façades, green walls act as a shielding skin on the coating layer of the envelope.
A green wall can essentially be realized in three different ways:

- The first kind is basically a vertical garden. It is made of a soil substrate of certain thickness hold vertically by grids attached to the bearing layer of the envelope;

- Another kind, shown in Fig.3.2, is kind of a story-garden, made with plants vases located at a vertical distance averaging between 20cm and 1m, in each of which grow some plants;
- The last kind is more of a double skin, made of a vertical grid running over the entire wall, on which climbing plants grow, creating during time a second green skin of the building.

The choice of a green wall system is usually carried out in urbanized areas where green spaces are not frequent, and the urban heat island issue is vast and impending. This is due to the fact that the insertion of green surfaces in urban canyons allow to reduce the UHI effect by shading the building heat-absorbing surfaces, lowering in turn the temperature on the surroundings.

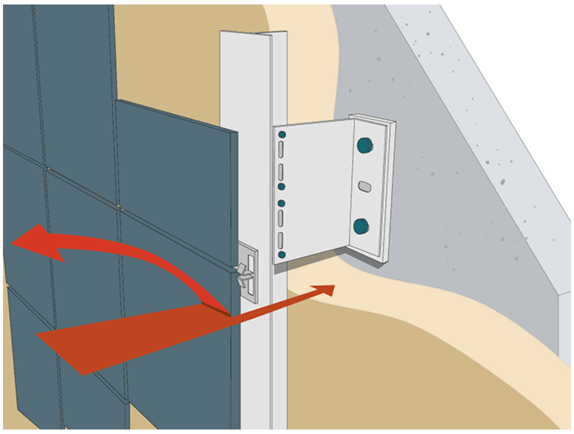
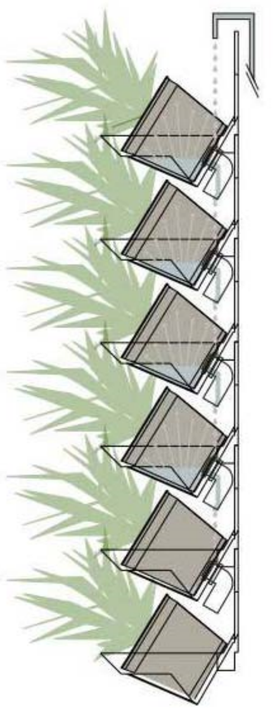


Figure 3.1: Operating principle of the ventilated façade.

Nevertheless, as this passive system founds its basis together with the ventilated façade, the implementation of such green walls will reduce the temperature on the external layer of the envelope thanks to the shading generated by the vegetation. Furthermore, with evapotranspiration, extensive amounts of solar radiation can be converted into latent heat, which, once again, avoids the rise in temperature of the coating layer.[30] The straightforward consequence of a lower temperature of the external surface is the reduction of heat exchange between the external and the internal environment, resulting into way lower heat gains during the warmer seasons. Just as for ventilated façades, this translates into energy savings due to a minor need of cooling systems to work.
Additionally to the ventilated façades, green walls can benefit of the mass property they have because of the presence of soil. The soil substrate can act as a thermal mass, lowering the temperature peaks and attenuating the temperature oscillations, resulting in more constant conditions of the internal environment. Furthermore, the soil acts as well as an insulating layer, increasing the thermal transmittance value of the envelope.
As better explained in the section 3.2.2, green walls and green roofs show better energy improvements in non-insulated or poorly insulated buildings. This is why they are commonly used as a retrofitting alternative.

(a) *Green wall with vertical soil substrate.*



(b) *Vase piled green wall.*

(c) *Double skin climbing wall.*

Figure 3.2: Different types of green walls

3.1.3 Photovoltaic walls

With the economic development of the latest decade, the seek of a more comfortable living and working environment has become largely spread, especially in those

country where weather conditions are extreme. In areas like Hong Kong, a 54% of the total energy demand is required by buildings, and at least half of it is due to air-conditioning systems.
For regions with such a climate, the more appropriate passive system would be one that reduces the heat gain, maybe by shading the envelope, and at the same time produces energy destined to power the cooling systems.
We are talking about a ventilated façade constituted by panels made of photovoltaic cells. This system is called PV walls and there are two common applications:

- BIPV (Building Integrated Photovoltaic), considers the replacement of the coating layer with photovoltaic cells that become strictly integrated in the envelope. This is the common application for buildings of new construction;

- BAPV (Building Applied Photovoltaic), considers the addition of an external layer made of photovoltaic panels, spaced from the existing coating layer in order to create an air duct. This is an application for the retrofitting of existing buildings.

A BAPV wall reduces the heat gain of the internal environment by shading the envelope from the direct sun radiation, and by cooling the external layer thanks to the air flux circulating in the duct. It has been demonstrated that such a wall can reduce the PV module's temperature by 15°C and thus increase its energy output by 8%. Also, the shading effect due to the PV cladding and the waste heat removed by the air flow, reduce the peak of temperature by over 20°C compared with a normal wall, resulting in a considerable reduction of cooling loads for the air-conditioning system, powered by the shading layer itself.
In clear days, the heat flux is reduced during daytime thanks to the shading of PV modules, and at nighttime because the building's envelope does not exchange heat by radiation with the cold sky.
Such a system not only helps to create a more comfortable internal environment, just like the others already reviewed, but, as well provides for a significant part of the energy needed to reach the comfort conditions.
An experimental analysis developed in Hong Kong showed that the heat gain can be reduce of over 50% on façades exposed to any direction – except North – and that the best air gap width is of 6cm.[31]

3.1.4 Phase Change Materials

Another passive system that is being implemented more and more often for the passive cooling of the building, both in new constructions and in retrofitting, is the solution based on Phase Change Materials (PCM): materials with a solid-liquid phase change which are capable to store heat and release it.
Phase Change Materials (PCMs) are often combined with gypsum board, plaster, concrete or other materials in order to increase the thermal storage capacity of ceilings, walls and floors. By completing a phase transition between solid and liquid they can absorb large quantities of latent heat. The high latent heat storage capacity of these materials works to effectively increase thermal mass which can help to moderate interior temperatures and improve comfort conditions. PCMs are frequently used to reduce the need for mechanical cooling, peak load shifting and improving solar energy utilization.
Latent heat storage takes place by phase transition of the storage material. When heat is transferred to the storage material, melting takes place at a specific and almost constant temperature, or phase change temperature. After this stage, further increase of heat results in an addition of sensible heat storage. This heat then dissipates by solidification of the storage material. Regularly, for building applications solid-liquid phase change is used since it presents high energy density and no volume expansion problems.
PCM can be incorporated in buildings either as passive or active systems. In passive design approach the PCM is incorporated into the building construction and elements as an integrate-design. Enhancing the benefits of sunlight to reduce heating requirements or reducing energy need for cooling by minimizing heat gains in summer are principal objectives of integrated design.
An appropriate passive design by means of PCM can provide long term energy efficiency, thermal comfort, stabilization of indoor air temperature and a reduction of the use and size of the HVAC systems. Commonly, in passive design approach for building applications the PCM is incorporated into the building envelope as an integrated material into building walls, roofs, floors, slabs, fenestration, insulation, façade, and shading systems.

3.2 Roofs

Roofs represent a big slice on the global energy balance of a building. Their influence could reach a 60% of the total heat gain, or loss, in one-story buildings, such as the winery studied. Thus, their correct and focused design is essential to lower the energy demand of the entire construction and to guarantee the thermal comfort in the attic spaces.

3.2.1 Ventilated roofs

Exactly how the ventilated façade is the most known passive system among vertical envelopes, the ventilated roof is the most known among the roofing passive systems.
With the same internal layering, the ventilated roof carries also a water barrier layer as last layer before the ventilation gap. Ventilated roofs age further back than ventilated façades, because traditionally they were easier to realize since the cavity could be completed with two series of wooden listels set perpendicular to each other and one on top of the other. Nowadays ventilated roofs are as well constructed similarly to ventilated façades in order to improve the air flow around the cavity.

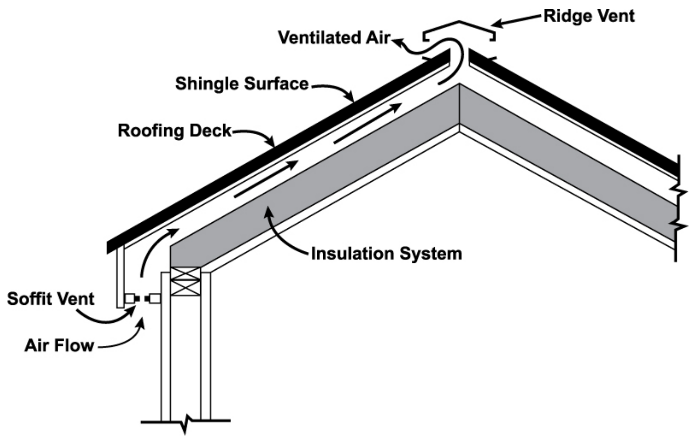


Figure 3.3: Sketch of a ventilated roof

Studies show how the inclination of the ventilated cavity influences the percentage of energy saving: as the angle decreases, as to stay, the cavity tilts toward the horizontal, the percentage of energy saving decreases, too, going from a over 40% on ventilated façades, to a 23% on ventilated roofs.[28]
Still, since, as mentioned before, roofs have a huge influence on the global heat balance of buildings, particularly the one-story constructions, and generally the attic spaces, a focused design or renewal of the covering envelope becomes of crucial relevance.

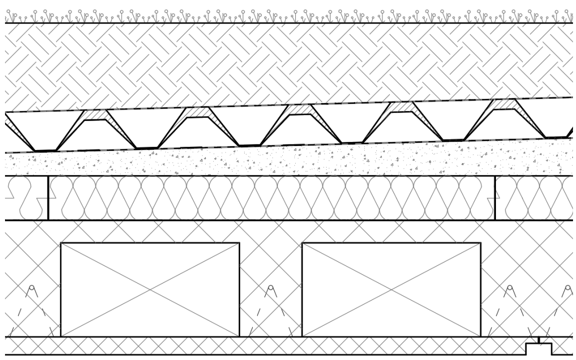
3.2.2 Green roofs

Another roofing passive system that is becoming more and more popular lately is the green roofing.
A green roof is nothing more than a traditional roof made with a concrete slab, covered on top with different layers that together create a proper garden: a waterproofing

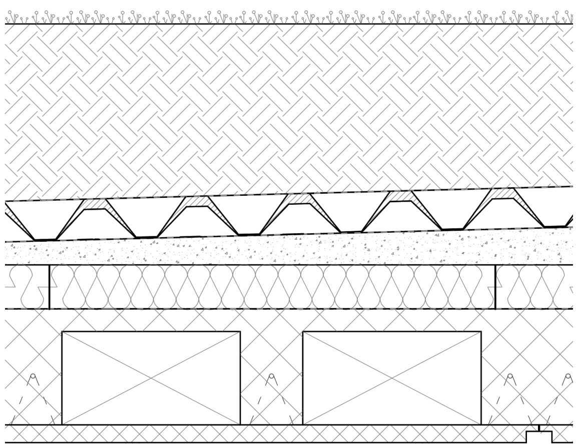
membrane to avoid infiltration inside the building, a growing medium made of soil, and a vegetation layer.
Based on the type and width of these two last layers, a green roof could be divided into two categories:

- *Extensive* green roofs (Fig.3.4(a)) have a thinner substrate layer and generally the only vegetation that grows on them is sedum or lawn. This type of green roof is generally quite light and does not need any further strengthening of the bearing structure. For this reason, extensive green roofs are suitable for building retrofitting;[32]

- *Intensive* green roofs (Fig.3.4(b)) represent instead higher additional loads because of the thicker layer of substrate, which, therefore, allows the growth of bigger and higher vegetation, such as proper trees and shrubs.[32]



(a) *Detail of an extensive green roof.*



(b) *Detail of and intensive green roof.*

Figure 3.4: The two categories of green roofs

Green roofs are considered a passive system because of the shading effect they have on the external roof surface. While a traditional roof can reach temperatures of

30°C higher than the external temperature, green roofs can actually reduce it. It was studied that green roofs cool as successfully as a roof with a bright white surface of an equivalent *albedo*, ratio of total reflected to incident radiation, of 0,7÷0,85, while a traditional clay tile roof can average around 0,1÷0,2.[32]
A bibliographic study showed that generally, in a Mediterranean, desertic or tropical climate, green roofs reduce considerably the energy demand due to cooling systems in the hot summer days. This is due to the scarce amount of heat transferred to the internal environment, equivalent to less than a 2% of the total heat reaching the green roof, since a 58% is lost by evapotranspiration, a 30% by radiative exchange with the surroundings and a 10% was estimated to be lost by photosynthesis effects.[32]
On the contrary, in winter the foliage temperature is lower than the soil temperature. This is due to the heat exchange by radiation between the foliage and the sky, which averages around -55°C, while the soil is covered and protected. Thus, compared to traditional roofing, green roofs reduce heat losses in the cold seasons since the air in direct contact with the most external surface happens to be warmer.
Still, it was found that during the sunny winter days, green roofs act negatively on the heat balance for the shading that the vegetation produces on the roof's surface, which hence is not warmed up.
In general, one of the green roofs' benefits, beside energy savings, is the reduction of extreme temperature oscillation, improving the roof's longevity by limiting the thermal stress otherwise applied to roofing membranes.
By reviewing some literature on green roof, it was found that the amount of energy savings during the hot periods largely depend on many factors. The type of vegetation growing on it is one of them. A thick and dense vegetation (high value of *Leaf Area Index* (LAI), high albedo ratio, dense vegetation coverage) guarantees a better shading, reducing the solar radiation.[33]
As mentioned before, green roofs could represent a valid solution on the retrofitting of old buildings with bad or null insultations. It was indeed studied that green roofs show better results on non-insulted buildings, acting also as an insulating layer themselves, and that thicker the soil substrate, greater the insultation. While on well insulated and carefully designed modern buildings (at least as they should be), the percentage of energy savings due to the addiction of a green roof is practically irrelevant.[34]
It is anyway important to underline that because of the substantial mass of the soil, green roofs act also as a thermal mass, delaying and attenuating the peak temperatures and stabilizing the internal conditions the year round.

3.2.3 Photovoltaic roofs

Roofs account for an important amount of heat gain/loss, especially in buildings where the percentage of envelope corresponding to the roof is high.
This type of passive system is not very known by the non-specialists of the sector for its shading features. It is mostly applied, also by individual residential owners, for the conversion of radiative energy into usable energy for powering the building. What most people do not know is the capability they have of reducing the heat gain through the roof, which in hot seasons represents the greater heat gain of the building – in one story buildings. The application of such passive system brings energy savings for the reduction of heat gain, bringing on its own a more comfortable environment, and for providing energy to the building, for instance for air-conditioning the spaces. In one story buildings, this type of passive system is more effective on roofs than on façades, due to the better exposition to the sun they have.

3.2.4 Reflective roofs

The heat gain through roofs can be of particular relevance in the global energy balance of one-story buildings. The solar radiation incident on every envelope surface can be absorbed, reflected and transmitted to the interior of the building, largely influencing the thermal conditions of the internal environment. Roof are directly exposed for most of the daytime to solar radiation, which, during the hot seasons, can bring the roof's surface to warm up to 30÷40°C above the external air temperature.[35] Surely, the climate conditions are widely responsible for the influence, on the global heat balance of the building, of solar radiation incident on the envelope surface. Nonetheless, a finely studied combination of reflection, transmission and emission coefficients can improve the energy savings both in hot and cold seasons, in all those countries with sunny days and clear nights.
Reflective roofs can be considered a passive system because of their high albedo value.

The albedo of a surface is the ratio of reflected to total incident solar radiation.

Thus, higher the albedo value, higher the reflection of solar radiation, and lower the consequent heat absorption. A high albedo value is typical of light surfaces; thus, the reflective roofs passive system consists of painting the roof's surface with a white varnish or implementing white materials for the coating layer in the construction phase. Light colored surfaces have a reflection coefficient close to 1, which means

that their absorption and transmission coefficients approach 0, implying the absence of surface warm up due to sun radiation, and a consequent absence of heat transfer toward the internal environment.
On the contrary, dark surfaces present reflection and transmission coefficients with very low values and an absorption coefficient tending toward 1, reaching this value only in ideal black bodies.
Implementing the reflective roof design means increasing the envelope reflection coefficient, rising the abledo value from a 0,1 to much higher values, oscillating around 0,8÷0,9. Lower the reflective coefficient, lower the heat absorbed by the surface, lower the heat transferred to the internal environment by conduction. This means that lower the heat gains, higher the comfort and lower the cooling loads on the air-conditioning system.
Many experimental analyses have been carried out for many decades. It has been proven that with high reflective roofs the reduction in cooling peak power can reach the 30÷40% and in cooling energy the 40÷50%. Also, normal dark colored surfaces reflect 20% of the incoming light, reflective dark colored surfaces 40% and light-colored surfaces reflect up to 80%.[36]
The main disadvantage of this type of passive system is the glare the surfaces provoke for their light bright color. It is also necessary to keep a constant maintenance of the roof in order to keep the surface clean and bright.
As seen for the other passive systems, the energy savings are more evident in buildings with no insulation layer.
Reflective roofs not only decrease the heat gains during sunny days, they also prevent the heat losses in clear nights. Dark surfaces would exchange energy by radiation with the sky, releasing important amounts of heat.
Thus, on the contrary of many other passive systems already described, reflective roofs grant energy savings both in hot seasons, preventing heat gains, and in cold seasons, preventing heat losses.

Chapter 4

Object of the study

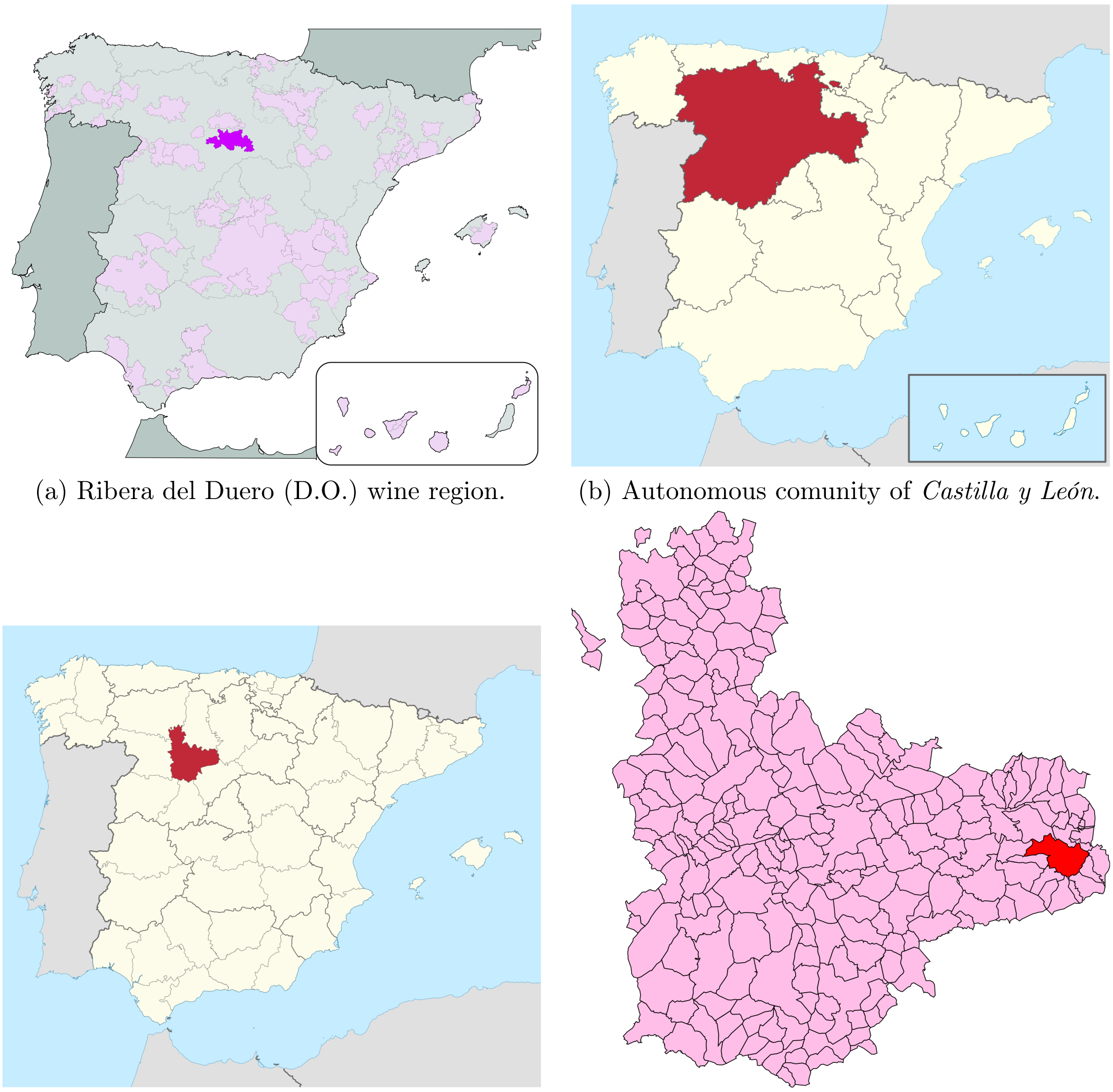
4.1 The Locality

The winery is located just outside *Peñafiel* (Fig.4.1(d)), a small town in the province of *Valladolid* (Fig.4.1(c)), in the autonomous community of *Castile and León* (Fig.4.1(b)). This area, known as *Ribera del Duero* (Fig.4.1(a)), is one of the eleven quality regions for the production of wine in Spain and one of the most important *Denominación de Origen (DO)*.

4.2 The Climate

As reported on the *Documento Básico (DB)* of the *Código Técnico*, the area of Valladolid, thus Peñafiel, stands in the E1 climatic zone. At an elevation of 753m above sea level, Peñafiel experiences hot summers Mediterranean climate: very hot and dry summers with mild and wet winters. In summer the maximum temperature oscillates around 30°C, while during the winter time -1°C is the lowest it gets.
The following diagram displays how many days per month reach certain temperatures.

The winery studied was equipped, during the examined year, with an external sensor that detected a maximum temperature of almost 37°C in summer, and a minimum temperature of almost -6°C in winter.
The graph in Fig.4.3 shows the monthly number of sunny, partly cloudy, overcast and precipitation days. Days with less than 20% cloud cover are considered as sunny, with 20-80% cloud cover as partly cloudy and with more than 80% as overcast.



(a) Ribera del Duero (D.O.) wine region.

(b) Autonomous comunity of *Castilla y León*.

(c) Province of *Valladolid*.

(d) Locality of *Peñafiel* in the province of *Valladolid*.

Figure 4.1: Localization of the winery

The graph in Fig.4.4 shows on how many days per month certain precipitation amounts are reached.

The dominant winds in the locality of Valladolid blow toward two principal direction: North-East and South-West. The following graph (Fig.4.6) shows the number of hours that the winds blow in the indicated direction during a year.

The following graph (Fig.4.5) shows the days per month during which the wind reaches a certain speed.

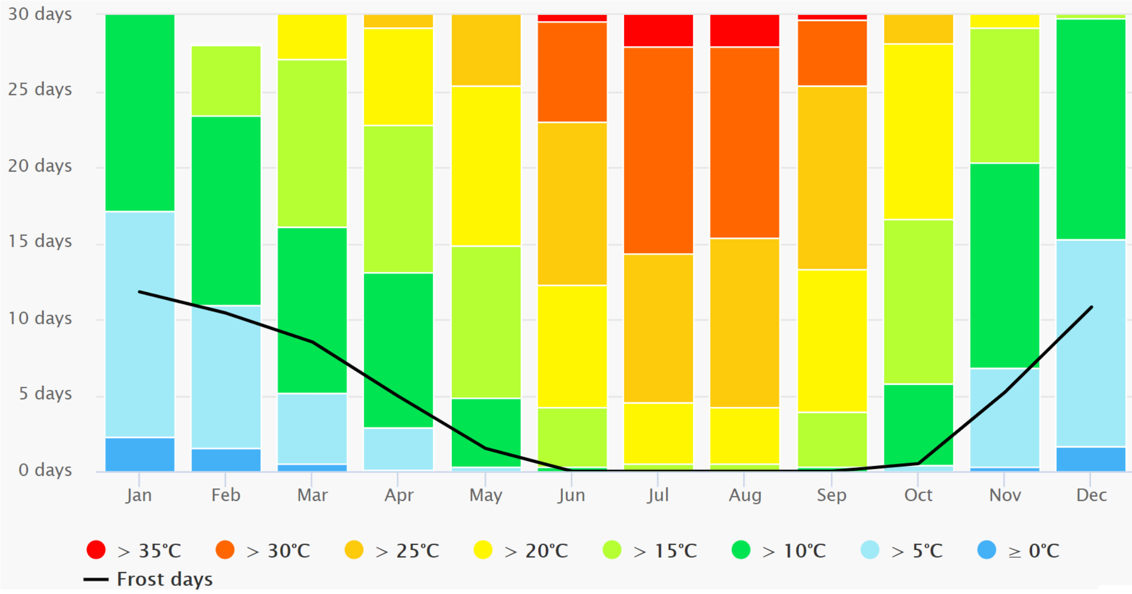


Figure 4.2: Average number of days per month during which certain temperatures are reached

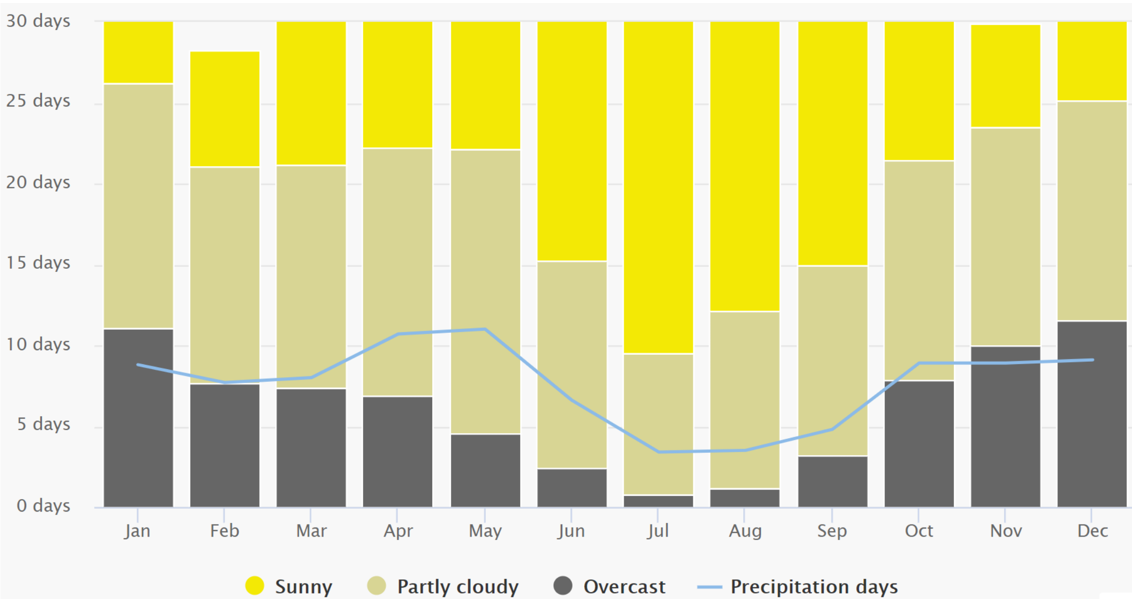


Figure 4.3: Average number of sunny, partly cloudy, overcast and precipitation days during each month

4.3 The Building

4.3.1 The Body

The building has a rectangular form with sides of 39,3m and 17,3m, and is composed essentially by two main blocks:

- The bigger one, of dimensions 17,3m x 32,85m and 8m high, reports the access

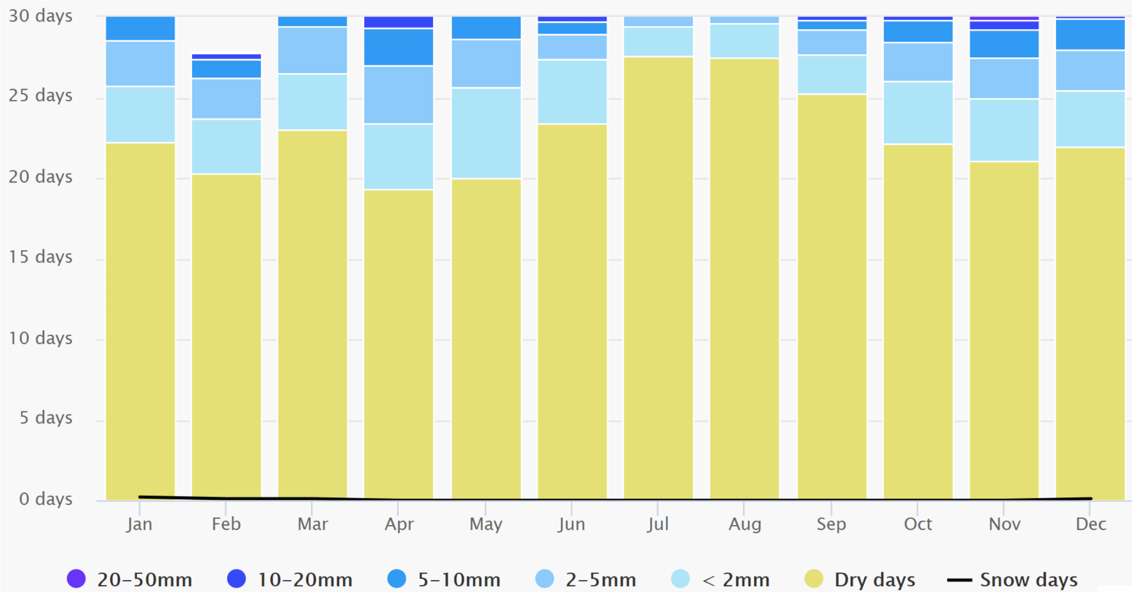


Figure 4.4: Average precipitation per month

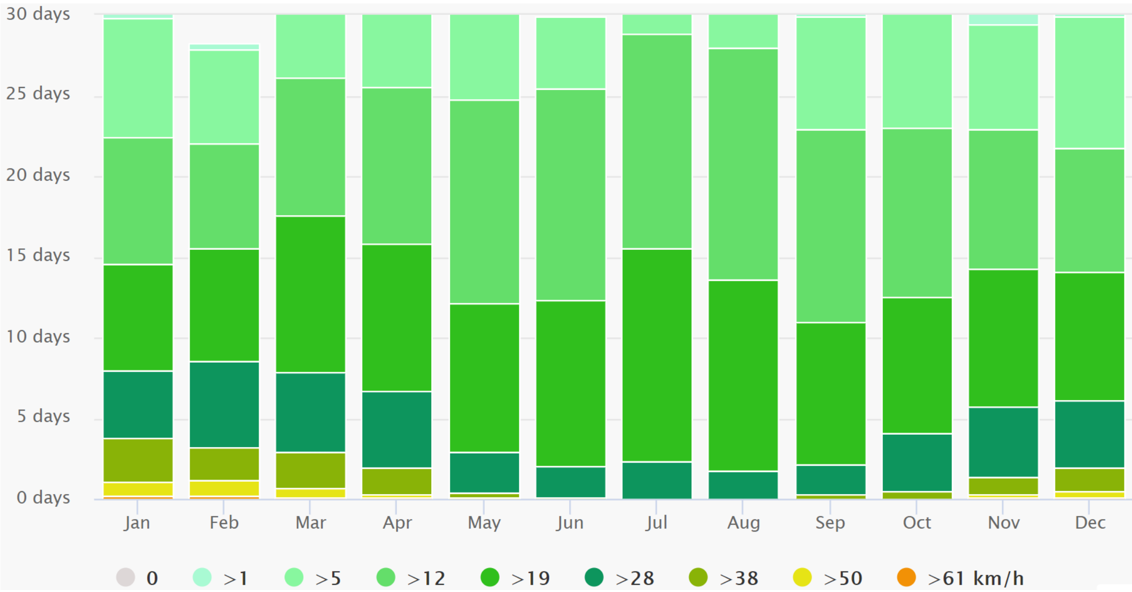


Figure 4.5: Average number of days during which certain wind speeds are reached

to the structure, located on the main façade north-east oriented. This block is divided in three areas: just behind the entrance we could find the office area, divided in two floors; the office area allows the access to the second part of this block, the wine cellar where wine barrels are stored for the fermentation process; this part is directly connected to the machinery room, where the fermentation takes place in the specific machines and wine is bottled at the end of the process.

- The smaller one is located on the back of the building, facing south-west toward

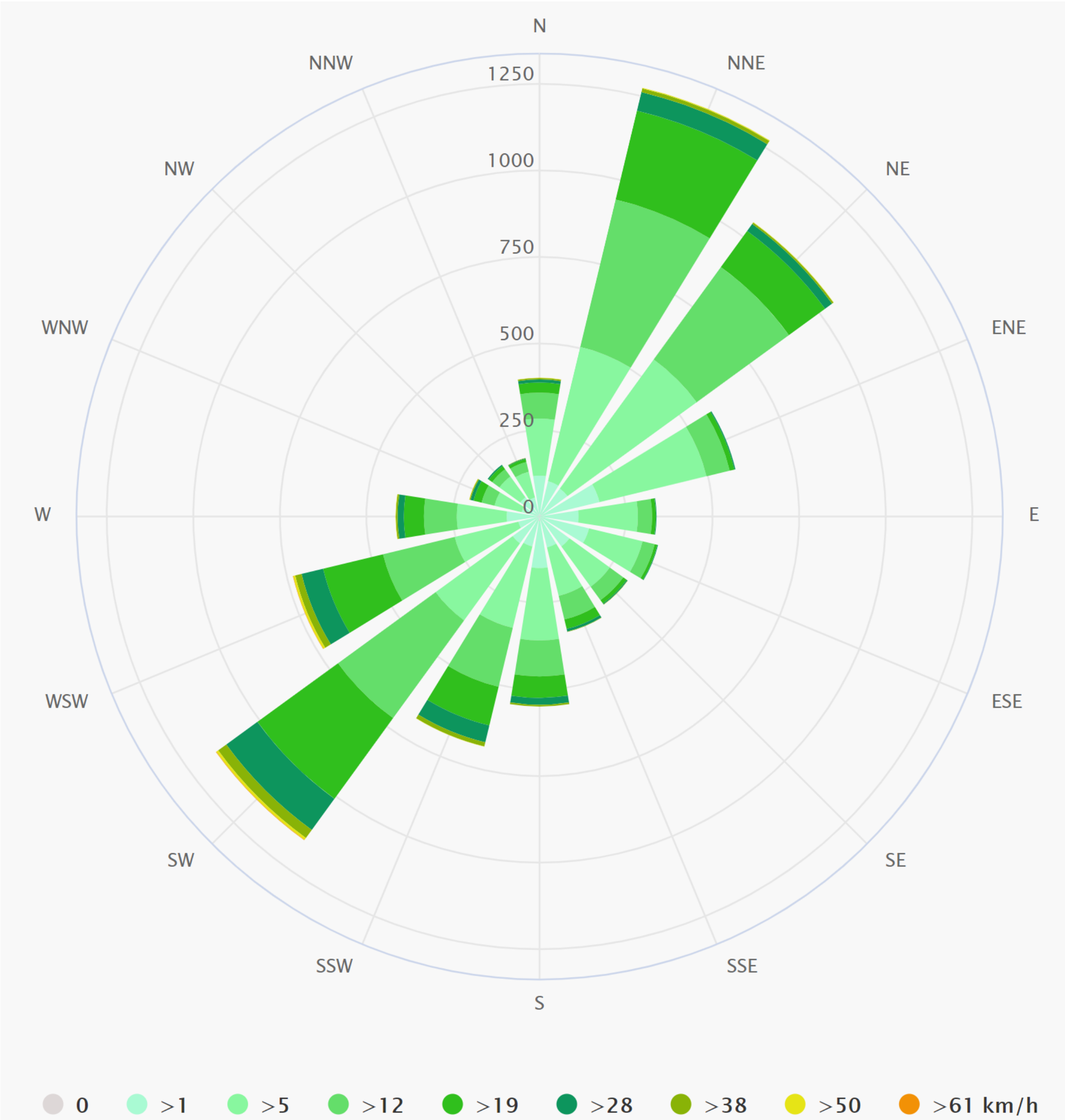


Figure 4.6: Direction and intensity of dominant winds in the region of Valladolid

the vineyard and is entirely occupied by the machinery room; it has dimensions of 17,3m x 6,45m and it is 7m high.

Sections, plans and elevations can be found at the bottom of the document in Appendices, on page 113:

- Sections: Appendix H on page 128

The principal façade of the building slightly deviates from the North-South axis by an angle of 12°, as shown in Fig.4.7.

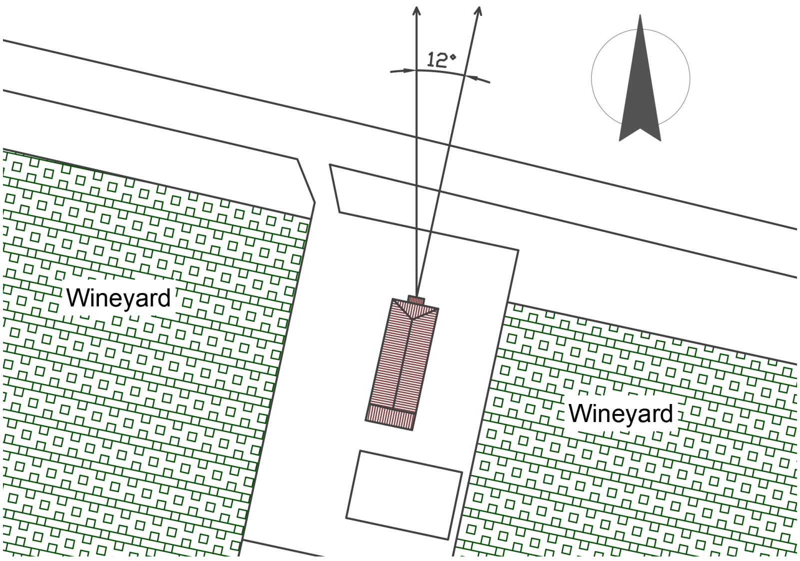


Figure 4.7: Angle of deviation from the North of the winery

4.3.2 The Envelope

In the chapter 8.1 on page 113, are reported the sections, together with their information, of the envelopes and the internal partitions:

- Vertical Envelope (VE_01): Appendix A on page 114;
- Vertical Envelope - back part (VE_02): Appendix B on page 116;
- Vertical Partition (VP_01): Appendix C on page 118;
- Horizontal Envelope - ground floor - office area (HE_01): Appendix D on page 120;
- Horizontal Envelope - ground floor - wine cellar and machinery room (HE_02): Appendix E on page 122;
- Horizontal Partition - interstorey floor (HP_01): Appendix F on page 124;
- Oblique Envelope (OE_01) :: Appendix G on page 126.

Chapter 5

Analysis

This thesis studies the data taken from four sensors that have been detecting temperature and relative humidity of the wine cellar for one whole year. Each sensor registered values every 30 minutes, providing 17 520 values of temperature and 17 520 values of relative humidity each one.
The reason why were required four sensors instead of one only is because, for a complete analysis, it is advisable to study also the air temperature stratification in the cellar. To do so, the sensors were positioned at different heights on the same vertical row (Fig.5.2 and 5.3) in the middle of the wine cellar (Fig.5.1):

1. Sensor OM_7189: at 0,2m from the ground;
2. Sensor OM_7156: at 1,5m from the ground;
3. Sensor OM_7144: at 3m from the ground;
4. Sensor OM_7167: at 4,5m from the ground.

Previous studies highlighted the fact that temperature is basically constant on any horizontal plane. For this reason, were used only four sensors positioned on a vertical axis: each one would register the values of temperature and relative humidity relative to its level, considered to be constant on the whole horizontal surface.[1][37]

To ease the identification of the sensors, we decided to replace their default identification code with one reffering to the height it is positioned at:

1. S_02 stands for OM_7189
2. S_15 stands fro OM_7156;
3. S_30 stands fro OM_7144;

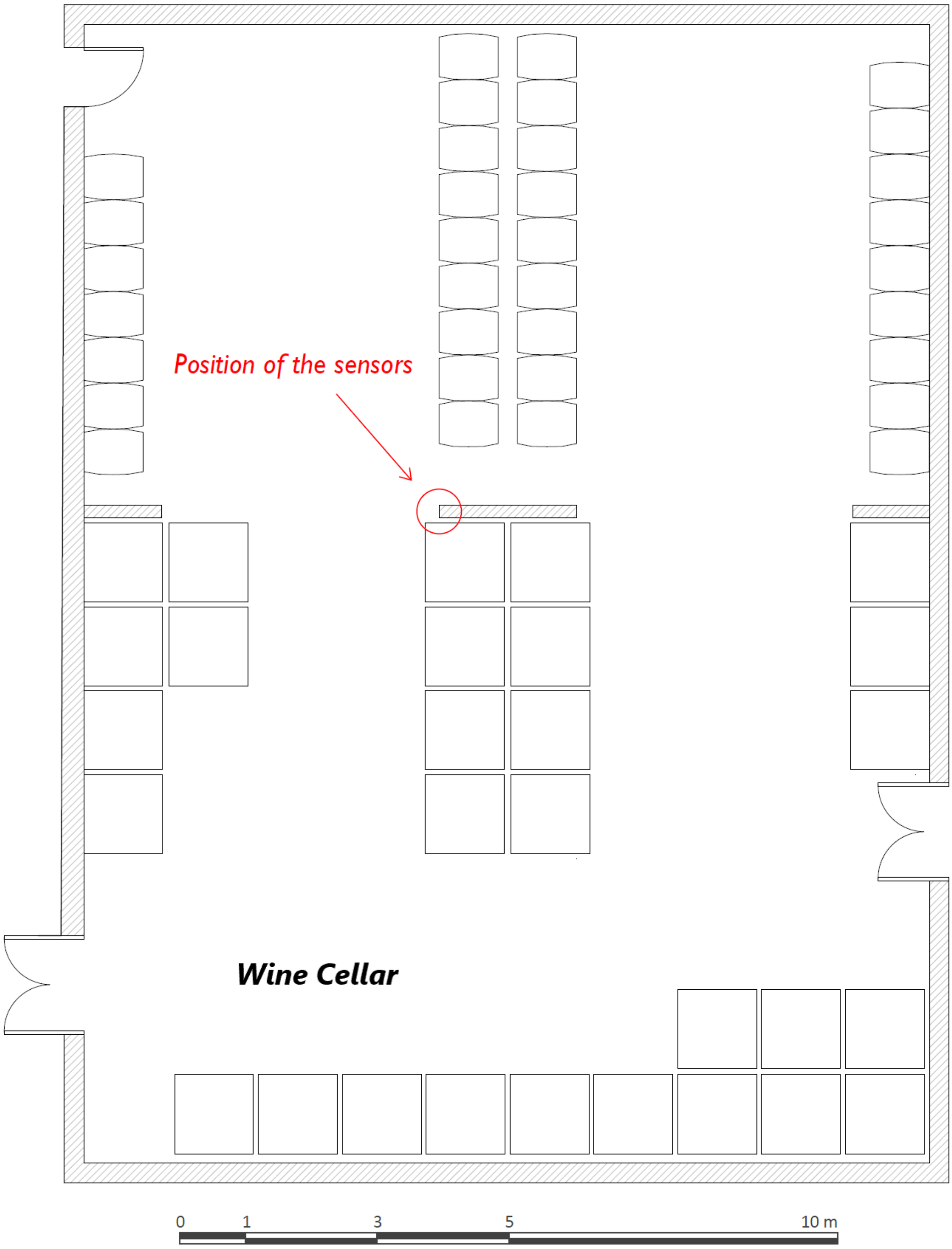


Figure 5.1: Position of the sensors in the wine cellar

4. S_45 stands fro OM_7167.

The sensors used are OM-92 Series (Fig.5.4), by Omega, an Italian company specialized in the production of thermo-sensors. The OM-92 Series are portable, battery operated, temperature and humidity data loggers. The logging is performed at a user configurable rate which is software selectable, and in this case corresponding to 30 minutes. These sensors are equipped with a software application for the

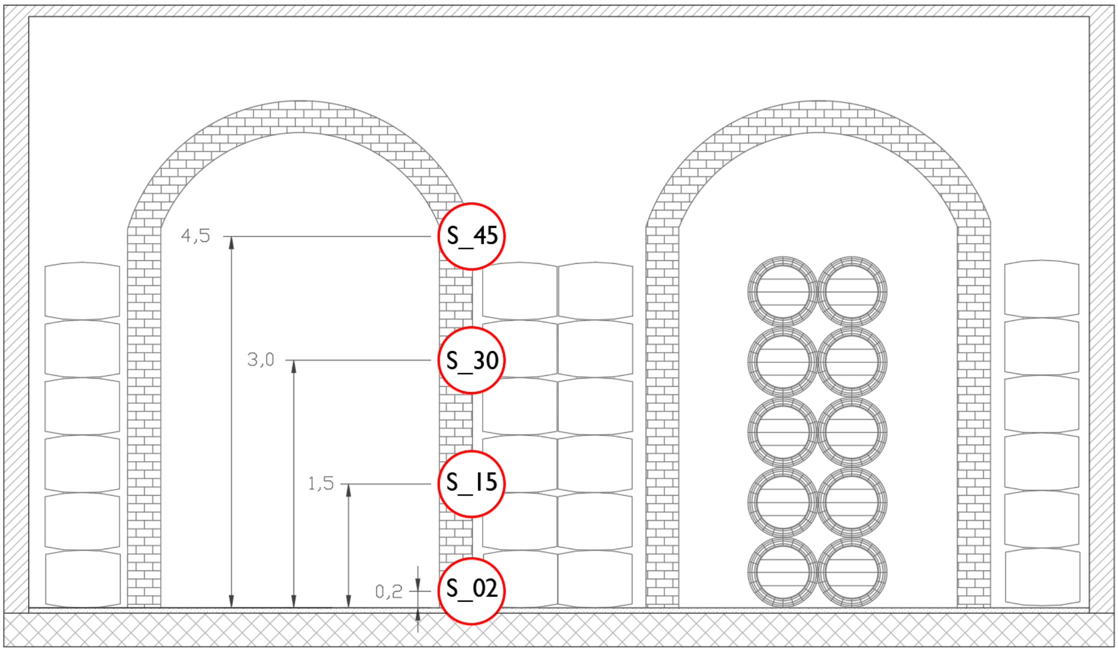


Figure 5.2: Vertical distribution of the sensors in the wine cellar. Measurements in meters

extraction of data of spreadsheets (*.csv* extention file). Here are reported some basic specifications:

- Temperature
  - Range: -30°C ÷ 80°C
  - Resolution: 0,01°C
  - Accuracy: ±0,3°C from 5°C to 60°C, ±2,0°C on the rest of the interval
- Relative Humidity
  - Range: 0 ÷ 100%
  - Resolution: 0,01%
  - Accuracy: ±3% from 20% to 80%, ±5% on the rest of the interval

Since DesignBuilder works with a database of hourly weather data that backdates the year 2002, a new weather template was necessary in order to accomplish a neat simulation of the behavior of the internal conditions of the winery. This implies the urgency of simulating with the weather data effectively registered in the year of the simulation, thus, the need of an exterior sensor that would record the external temperatures.
The sensor chosen for this purpose is a Hobo Pro v2 (Fig.5.5(a)) that registers

Figure 5.3: Vertical distribution of the sensors in the wine cellar

temperature and relative humidity, specifically for outdoor environments. It is indeed waterproof and equipped with a protective shield for solar radiations and bad weather conditions (Fig.5.5(b)).

(a) *Sensor Hobo Pro v2, temperature and relative humidity data logger*

(b) *Solar shield for the Hobo Pro v2 sensor*

Figure 5.5: External sensor

Here are reported some basic specifications:

- Temperature
  - Range: -40°C ÷ 70°C
  - Resolution: 0,02°C at 25°C
  - Accuracy: ±0,21°C from 0°C to 50°C
- Relative Humidity
  - Range: 0 ÷ 100% (exposure to conditions below -20°C or above 95% RH may temporarily increase the maximum RH sensor error by an additional 1%)
  - Resolution: 0,05%
  - Accuracy: ±2,5% from 10% to 90%, ±5% on the rest of the interval

Figure 5.4: Sensor OM-92, temperature and relative humidity data logger

The sensor was located inside the protective shield and hung outside the winery at a height of approximatedly 2m from the ground on the wall of an external hut (Fig.5.6).

5.1 Data analysis

5.1.1 Data acquisition

The output of the sensors' software application is an .csv file with two spreadsheets, one for *temperature* (T) and one for *relative humidity* (RH). In each spreadsheet

(a) *Position of the external sensor* (b) *Position of the externa hut*

Figure 5.6: External sensor hung on a wall of the external hut

there are seven columns:

1. Date (day/month/year);
2. Time (hour:minute:second) – taken every half hour;
3. External temperature/relative humidity;
4. Internal temperature/relative humidity at the height of 0,2m;
5. Internal temperature/relative humidity at the height of 1,5m;
6. Internal temperature/relative humidity at the height of 3,0m;
7. Internal temperature/relative humidity at the height of 4,5m.

Since the values of temperature and relative humidity are automatically registered by the four sensors every half hour, each sensor throughout the year records 17 520 values of temperature and 17 520 values of relative humidity. This means that we are facing a total of 140 160 values of internal conditions.

In order to be able to effectively use them, separating the values present in the *Date* column into *Day* and *Month* was necessary. Doing so it would be possible at a later stage to create many spreadsheets containing tables organized by *Day*, *Month*, *Season*, and so on, and study the trend of the environment conditions inside the wine cellar.
Once the Date column was split into the *Day* and *Month* columns, from the Insert section were crated two *Pivot Tables*, one for temperature and one for relative humidity, each one made of five columns:

1. Month;

2. Monthly Mean Value of the sensor at the height of 0,2m;

3. Monthly Mean Value of the sensor at the height of 1,5m;

4. Monthly Mean Value of the sensor at the height of 3,0m;

5. Monthly Mean Value of the sensor at the height of 4,5m.

Table 5.1: Monthly mean values of internal temprature provided by each sensor

Internal Temperature				
Month	**S_02** (°C)	**S_15** (°C)	**S_30** (°C)	**S_45** (°C)
1	14,5653	14,4842	14,5387	14,6054
2	12,7978	12,5784	12,4783	12,3947
3	11,5603	11,2468	11,1350	11,1113
4	12,5076	12,7251	12,9576	13,3207
5	15,1164	15,7861	16,1627	16,5579
6	17,4848	18,5448	19,1199	19,7048
7	20,6062	21,9305	22,6662	23,3948
8	21,8489	23,1729	23,7717	24,3001
9	21,4266	22,1874	22,5344	22,8618
10	18,0990	18,2653	18,3334	18,3240
11	16,7177	16,6468	16,7183	16,8177
12	15,8921	15,7533	15,7748	15,7847
Total	16,5775	16,9730	17,2141	17,4647

The characteristic of these Pivot Tables (Tab.5.1 and Tab.5.2) is that each row is the result of the average executed on another series of values, the daily average, executed, in turn, with the values collected every half hour by the sensors.
Thus, the next step would be arranging these daily values in 12 spreadsheets, one per each month, in the same Excel file. This fix would make it easier to create other tables in the future, such as the Seasonal spreadsheets.

5.1.2 Chart configuration

Comfort Zone To appreciate if the values fell into the acceptable range, it was previously drawn a *Comfort Zone* in each psychrometric chart (Fig.5.7).
Studying the wine literature, was concluded that a temperature oscillating between 5°C and 18°C has no harm on the wine, and that a high relative humidity, above

Table 5.2: Monthly mean values of internal relative humidity provided by each sensor

Internal Relative Humidity				
Month	**S_02** (%)	**S_15** (%)	**S_30** (%)	**S_45** (%)
1	77,8686	78,2984	77,7730	77,2561
2	74,3166	75,4835	75,9080	76,0115
3	77,3425	79,1903	79,8211	79,8490
4	85,8267	84,8680	83,7328	82,3024
5	88,2312	84,4959	82,5039	80,7149
6	88,8420	83,4345	80,6936	78,3438
7	69,4572	62,9710	59,0407	56,0336
8	77,5738	72,3247	70,7677	69,3682
9	69,5166	66,3203	65,2106	63,9487
10	65,3929	64,1940	63,6604	63,4329
11	74,9920	74,8518	74,2788	74,1175
12	78,5332	78,7861	78,3614	78,3499
Total	77,3221	75,4133	74,2813	73,2735

60%, avoids wine loss during its ageing.
In the Fig.5.7 are shown ass well some harmful effects caused by a change in the optimal conditions for wine ageing:

- An increase of temperature inside the wine cellar for a long period of time would cause a loss of quality of the wine, giving it rather a vinegar taste. Indeed, the winery studied, using the same must from which wine is elaborate, produces vinegar, letting it age outside the wine cellar, where temperature and relative humidity conditions are far distant from the Comfort Zone;

- On the contrary, a decrease of temperature for a long period of time would decelerate the ageing process causing the necessity of a longer period of storage, stealing space for new wine bottling every year;

- A dry environment would increase the chances of evaporation of wine, with a consequently wine loss. By definition a satured air does not permit the evaporation of any liquid, which is why wine makers favor a wet environment, even if this implies the risk of growth of funguses, such as the *Armillaria mellea*.

As the last two circumstances refer to an economic issue for the winery, the first one concerns the quality of the product.

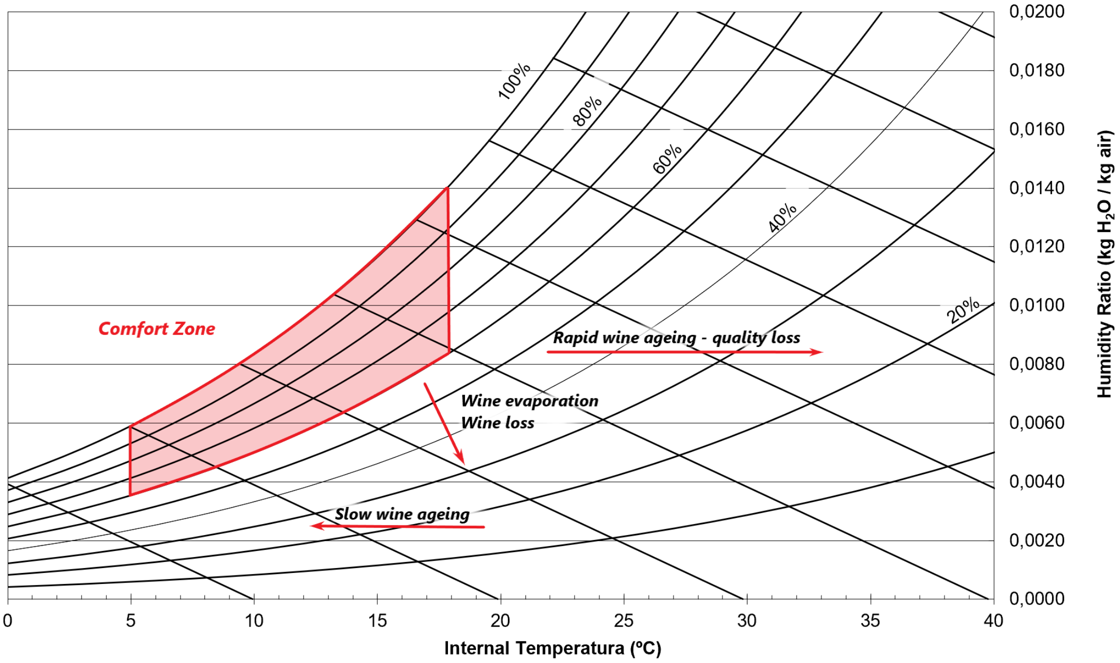


Figure 5.7: Comfort Zone in terms of *temperature* and *relative humidity* for a proper wine ageing

Keeping a low temprature will therefore be the leading matter in the further development of energetic solutions for the building, with the aim of reducing its energy intakes and bringing the product back to the excellence that has made the region famous.

Get Psyched! The psychrometric charts were generated thanks to the Get Psyched! software released by the kW Engineering company, and free downloadable from their website. Among the many features that the package allows to personalize, there is also the altitude, which directly influences the atmospheric pressure. Thus, inserting the *Altitude* at 753m - above sea level - and setting the *Atmospheric Pressure* function, the program automatically calculates a 92 364 Pa value.

5.1.3 Annual analysis

The first study of these data concerned the annual behavior of the climatic conditions inside the wine cellar. The experimental data were collected in the graph shown in Fig.5.8. At first glance we can observe a substantial fluctuation of temperature conditions throughout the year, with a difference of 15°C from Winter to Summer.

The graph shows that the internal temperature follows, being slightly attenuated, the external conditions. It is clear how at least for one third of the time, temperature does not lay inside the comfort zone.
Furthermore, carefully observing, we can notice a clear air stratification, with temperature differences that grow wider as approaching the hot season. The graph outlines the influence of solar radiation on the roof surface and the meager amount of thermal insultation among the roof layers:

- During Summer the data show higher temperatures close to the ceiling, with substantial daily fluctuations that become slightly more constant as the height decreases. We can see indeed how the S_02 sensor reports very few oscillations. This depends on the solar radiation, very intense during the hot, sunny season, that warms up the roof to extremely high temperatures. The heat transfer is massive due to a poor thermal insulation, thus huge heat amounts are transferred to the internal environment by conduction.

- During the colder seasons, such as Autumn and Winter, the data show a reduced air stratification, and highlight how the higher temperatures now appear at the lowest sensor, the S_02. Daily fluctuations are lowered, too. During these months solar radiation is less intense, and the roof surface is not as warmed up as before. On the contrary, the outside temperature is quite low and due to poor thermal insulation, once again, heat transfer is massive, resulting in lower internal temperatures close to the ceiling, and slightly higher as approaching the floor.

5.1.4 Seasonal analysis

Four graphs were created, one for each sensor, showing the daily average of temperature and relative humidity of the 365 days of the year. In order to understand better which resulted to be the most critical months for the wine comfort in the wine cellar, the data were separated into the four seasons.
The seasons were considered as follows:

- Spring: from 21st March to 20th June

- Summer: from 21st June to 20th September

- Autumn: from 21st September to 20th December

- Winter: from 21st December to 20th March

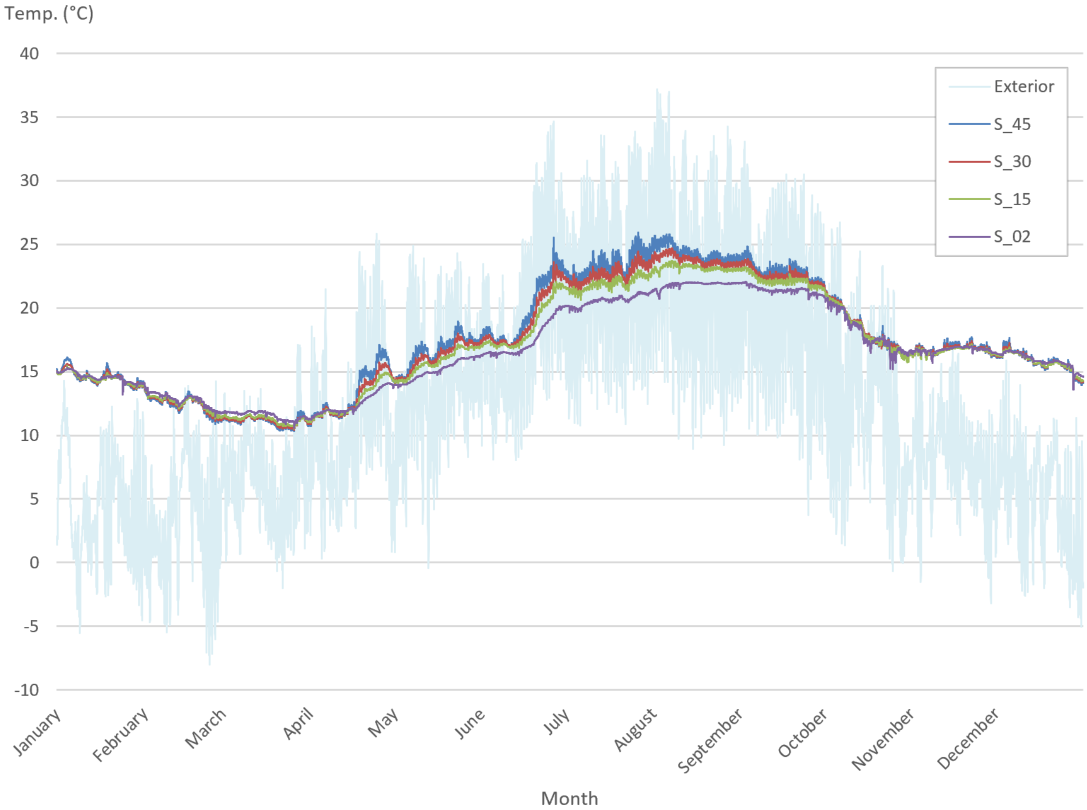


Figure 5.8: Continuous trend of temperature during the whole year examined, for the four internal sensors and the external one

The graphs showed that for about one third of the monitored year, the comfort conditions needed for a correct wine ageing were not satisfied.

Furthermore, we observe a slightly difference in the data depending on the position of the sensors, namely, on the height at which the data were registered. To highlight this difference, two tables (Tab.5.3 and Tab.5.4), containing the percentage and the number of days with satisfied comfort condition for the four sensors, are reporter.

As the tables show, Winter is the only season whose conditions satisfy the wine comfort for the whole time, even though this analysis examines only the daily average. In other words, the comfort conditions may be satisfied every day, but we don't surely know if they are satisfied thought out each day. A further analysis will bring light over this issue.
Unexpectedly, the second season that mostly satisfies the comfort conditions is Spring, with values very close to 100%. We can observe a slightly difference though, among the four sensors: the number of comfort-satisfied days decreases as the height increases, varying from a 100% for the lowest sensor, to an 88% for the highest one.

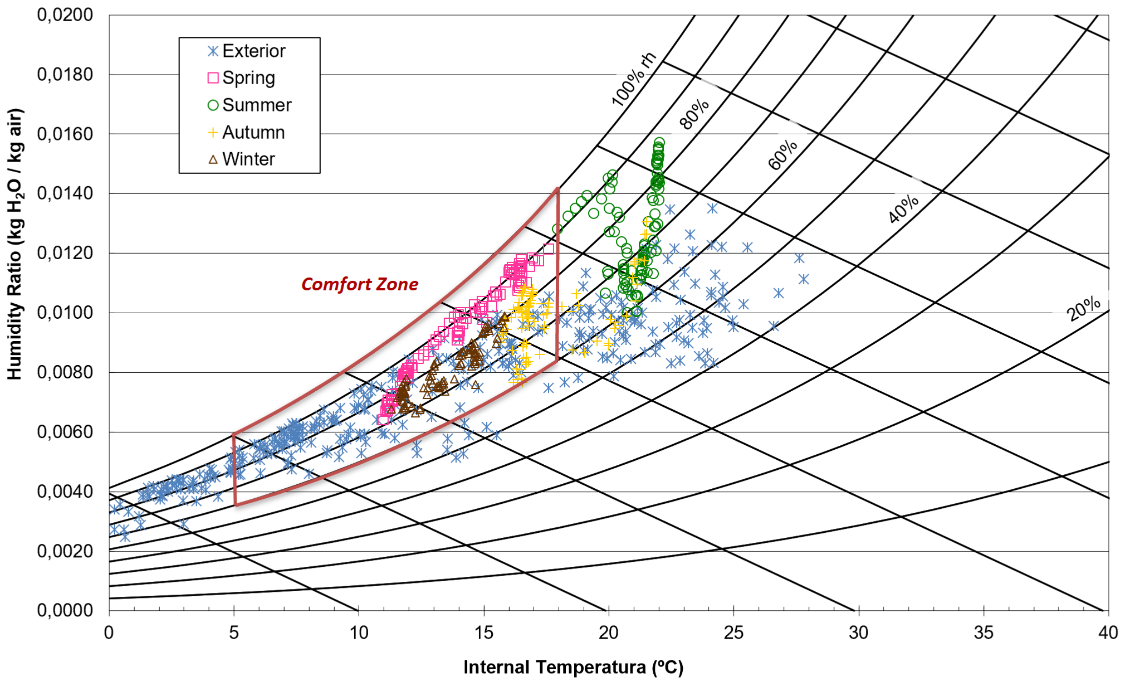


Figure 5.9: Seasonal graph with the data provided by the S_02 sensor

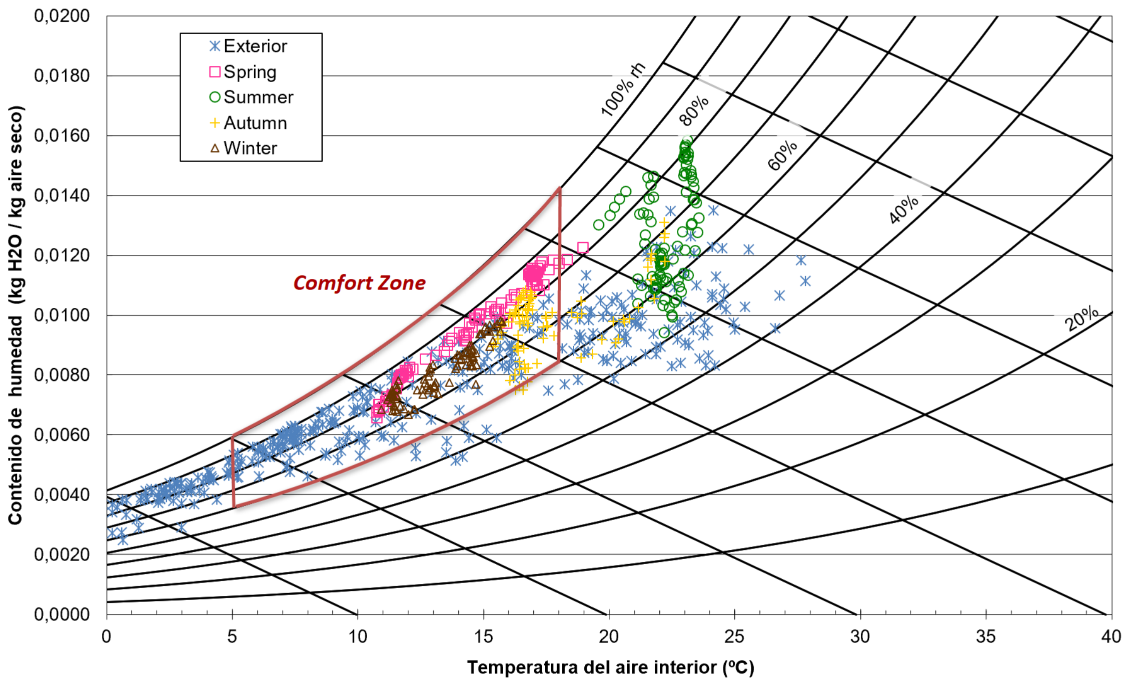


Figure 5.10: Seasonal graph with the data provided by the S_15 sensor

It is clear that the wine cellar is facing a quite substantial air stratification as approaching the hot season. The eleven days discerning the lowest and the highest sensors reveal a rising temperature close to the ceiling, underlining a relevant influence of the warm roof due to solar radiation.

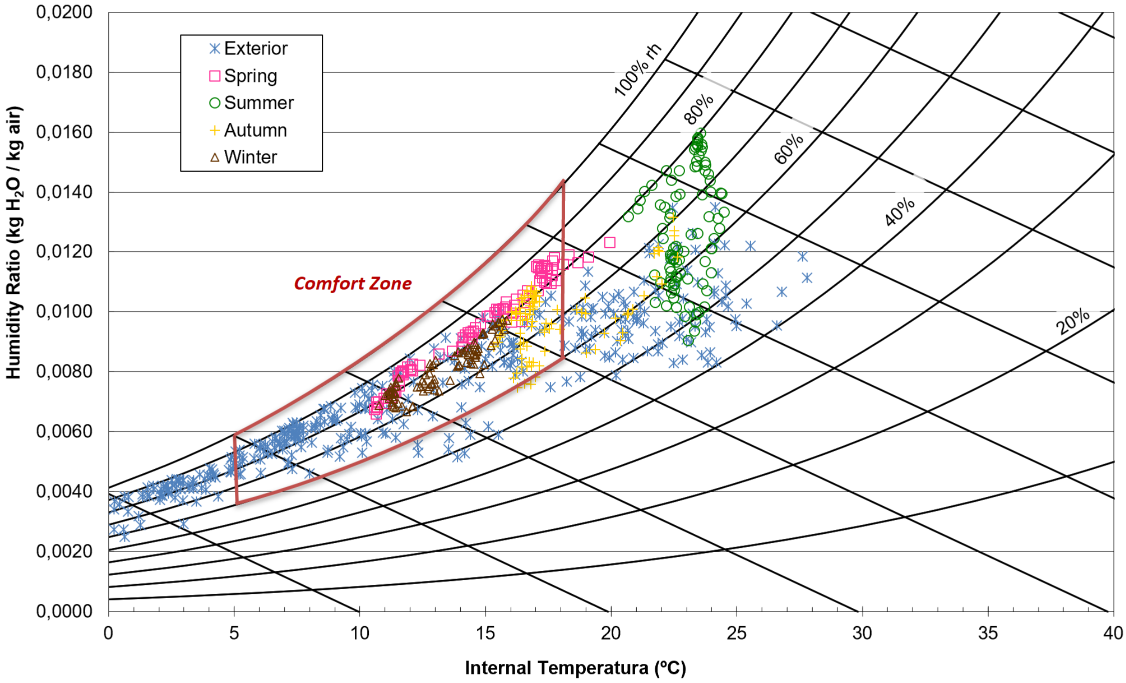


Figure 5.11: Seasonal graph with the data provided by the S_30 sensor

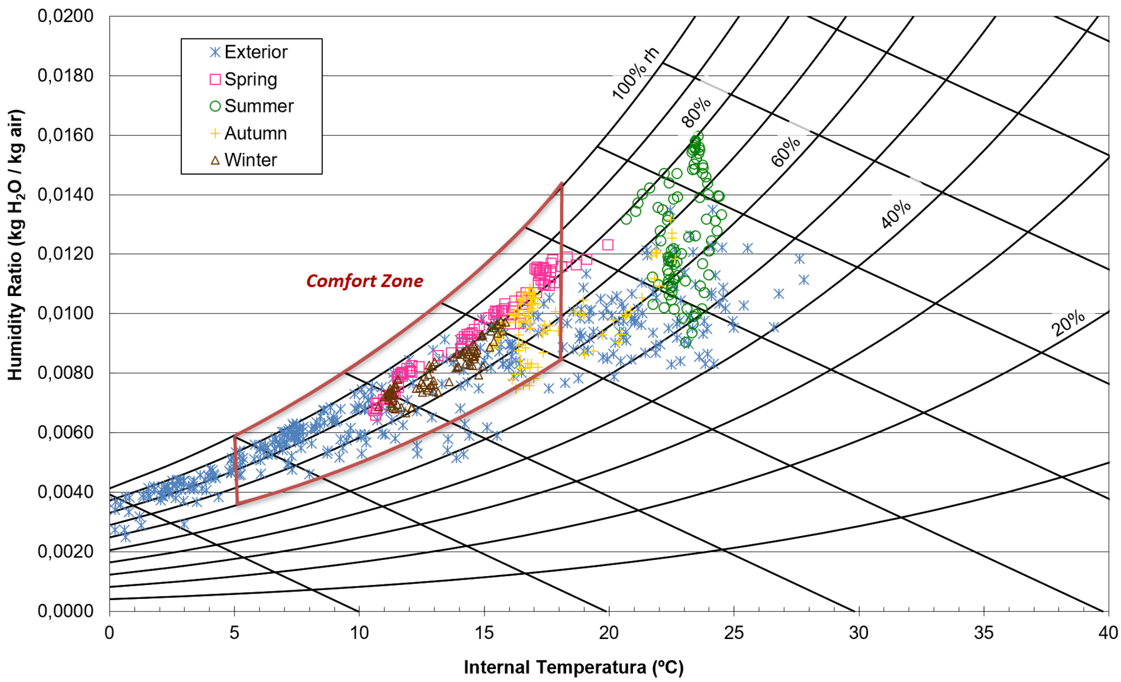


Figure 5.12: Seasonal graph with the data provided by the S_45 sensor

In Autumn the comfort conditions are satisfied for about two thirds of the time. Once again, the results highlight an air stratification causing a difference of five days of satisfied comfort conditions between the lowest and the highest sensor.

As predictable, Summer is the most critical season, with only one day of satisfied

Table 5.3: Amount of days that satisfy the comfort conditions - by percentage and by number - for the senors S_02 and S_15

	Num. of days per season	Amount of days with *satisfied comfort conditions*			
		S_02		S_15	
		Percent.	Num.	Percent.	Num.
Spring	92	100%	92	97%	89
Summer	92	1%	1	0%	0
Autumn	91	73%	66	70%	64
Winter	90	100%	90	100%	90
Total Num. of days	365	62,8%	249	66,58%	243

Table 5.4: Amount of days that satisfy the comfort conditions - by percentage and by number - for the sensors S_30 and S_45

	Num. of days per season	Amount of days with *satisfied comfort conditions*			
		S_30		S_45	
		Percent.	Num.	Percent.	Num.
Spring	92	95%	87	88%	81
Summer	92	0%	0	0%	0
Autumn	91	69%	63	67%	61
Winter	90	100%	90	100%	90
Total Num. of days	365	65,7%	240	63,77%	232

comfort conditions. With this analysis it is not possible to appreciate the air stratification in such a period, but as Spring and Autumn highlight, we can expect a critical rising temperature as moving upward.

5.1.5 Monthly analysis

More specifically, it is reported a monthly analysis showing the average values of temperature and relative humidity for each month of the year. In order to understand the reliability of these averages, we add to each value its *Standard Deviation* (Tab.5.5 and Tab.5.6). This function will give us an idea of how the *daily averages* are distributed around the *monthly average*. Later on, a further analysis will explain how the experimental values, collected every 30 minutes, are distributed around the daily average.

Table 5.5: Standard Deviation from the monthly mean values of temperature and relative humidity for the sensors S_02 and S_15

	S_02		**S_15**	
	Temp. (°C)	**RH** (%)	**Temp.** (°C)	**RH** (%)
January	14,57 ± 0,36	77,86 ± 2,37	14,48 ± 0,40	78,29 ± 2,39
February	12,79 ± 0,54	74,31 ± 3,56	12,58 ± 0,57	75,48 ± 3,29
March	11,56 ± 0,29	77,34 ± 2,48	11,25 ± 0,27	79,19 ± 2,15
April	12,51 ± 0,87	85,83 ± 3,37	12,73 ± 1,24	84,87 ± 1,74
May	15,12 ± 0,78	88,23 ± 2,48	15,79 ± 0,96	84,50 ± 1,82
June	17,48 ± 1,34	88,84 ± 2,23	18,54 ± 1,79	83,43 ± 2,72
July	20,61 ± 0,39	69,46 ± 7,70	21,93 ± 0,47	62,97 ± 7,48
August	21,85 ± 0,22	77,57 ± 6,58	23,17 ± 0,19	72,32 ± 7,24
September	21,43 ± 0,27	69,52 ± 5,57	22,19 ± 0,42	66,32 ± 4,97
October	18,10 ± 1,45	65,39 ± 6,40	18,27 ± 1,57	64,19 ± 5,57
November	16,72 ± 0,18	74,99 ± 6,00	16,65 ± 0,21	74,85 ± 6,03
December	15,89 ± 0,57	78,53 ± 3,77	15,75 ± 0,64	78,79 ± 3,44

Table 5.6: Standard Deviation from the monthly mean values of temperature and relative humidity for the sensors S_02 and S_15

	S_30		**S_45**	
	Temp. (°C)	**RH** (%)	**Temp.** (°C)	**RH** (%)
January	14,53 ± 0,47	77,77 ± 2,26	14,60 ± 0,58	77,25 ± 2,48
February	12,47 ± 0,60	75,91 ± 3,30	12,39 ± 0,65	76,01 ± 3,31
March	11,14 ± 0,28	79,82 ± 1,96	11,11 ± 0,34	79,85 ± 2,07
April	12,96 ± 1,50	83,73 ± 1,61	13,32 ± 1,84	82,30 ± 2,75
May	16,16 ± 1,07	82,50 ± 2,16	16,56 ± 1,20	80,71 ± 2,84
June	19,12 ± 2,11	80,69 ± 3,92	19,70 ± 2,42	78,34 ± 5,11
July	22,67 ± 0,60	59,04 ± 8,38	23,39 ± 0,81	56,03 ± 9,06
August	23,77 ± 0,35	70,77 ± 7,57	24,30 ± 0,57	69,37 ± 7,82
September	22,53 ± 0,51	65,21 ± 4,82	22,86 ± 0,62	63,95 ± 4,97
October	18,33 ± 1,58	63,66 ± 4,98	18,32 ± 1,54	63,43 ± 5,06
November	16,72 ± 0,24	74,28 ± 5,96	16,82 ± 0,30	74,12 ± 5,99
December	15,77 ± 0,68	78,36 ± 3,13	15,78 ± 0,75	78,35 ± 3,02

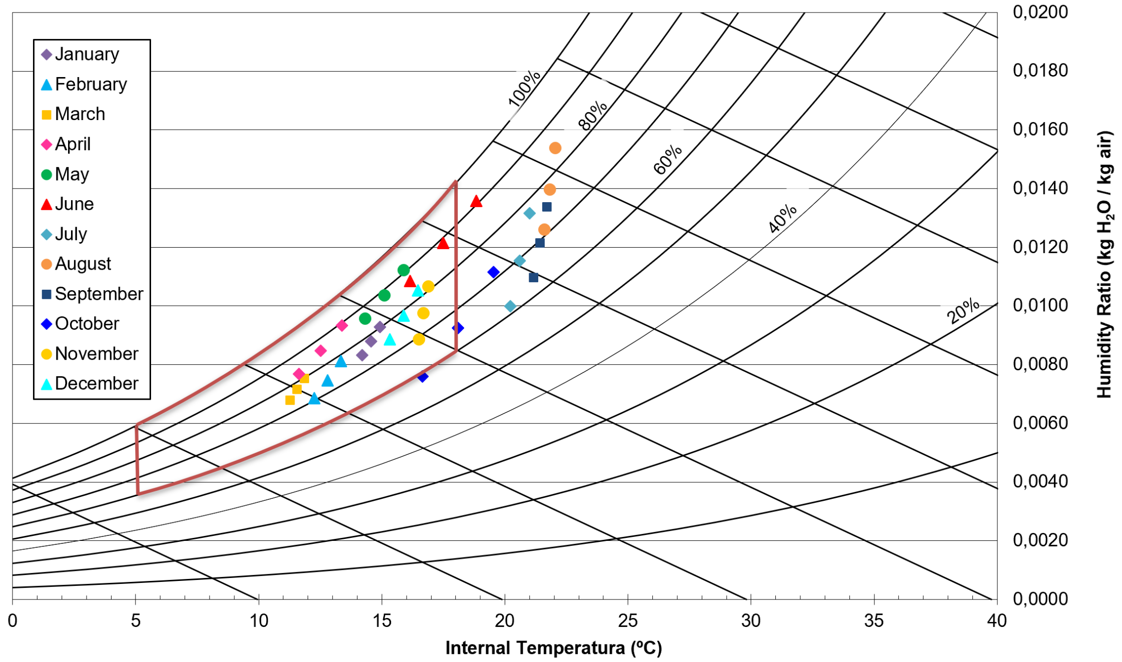


Figure 5.13: Monthly mean values and relative standard deviation for the sensor S_02

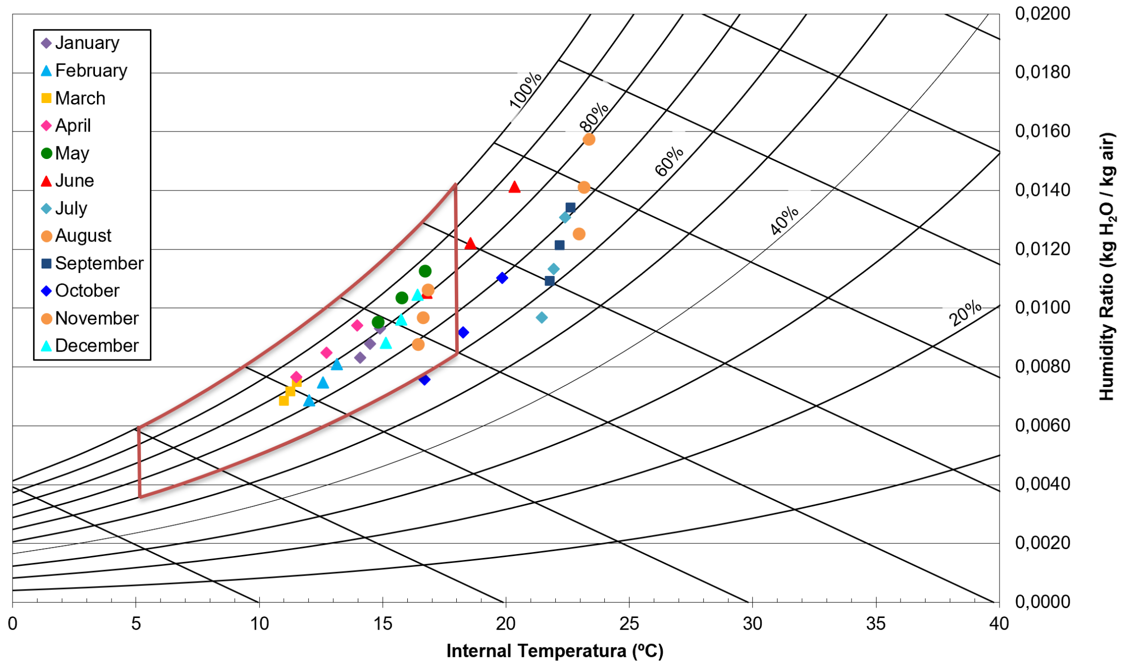


Figure 5.14: Monthly mean values and relative standard deviation for the sensor S_15

At first glance we notice that the Standard Deviation increases during the hot season, as expected, with the highest values corresponding to June, both for temperature and relative humidity.

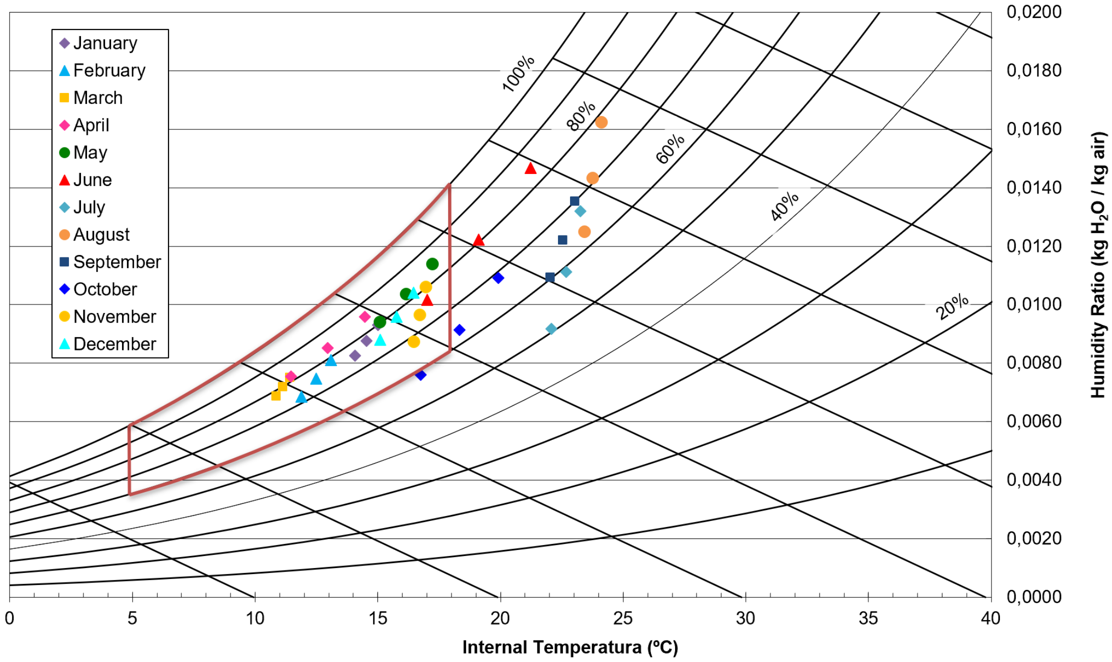


Figure 5.15: Monthly mean values and relative standard deviation for the sensor S_30

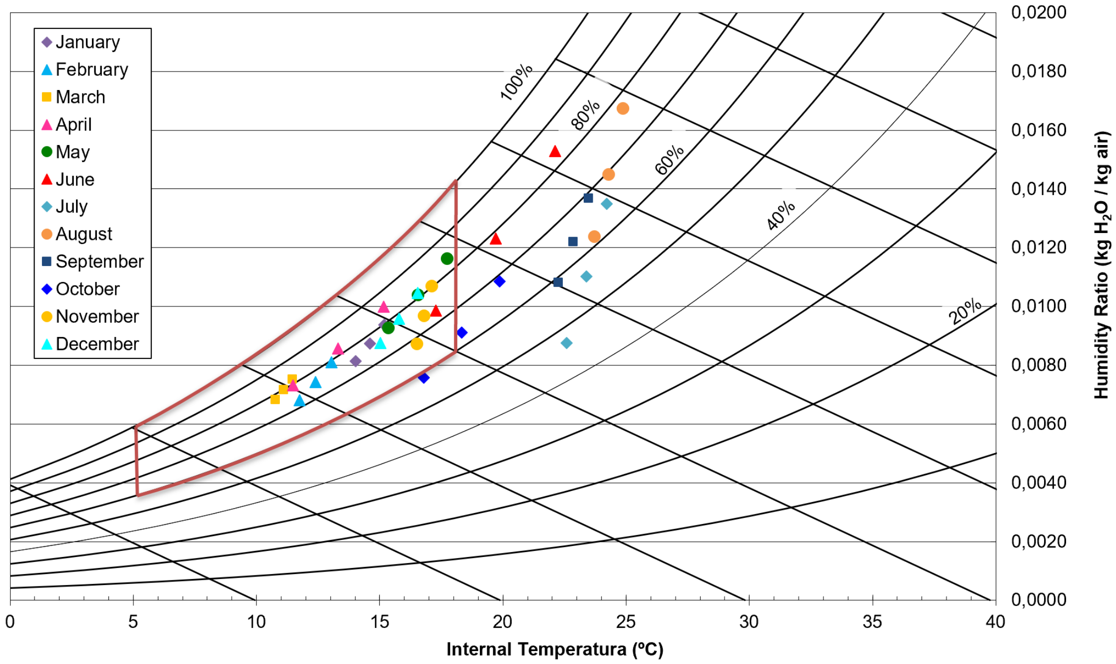


Figure 5.16: Monthly mean values and relative standard deviation for the sensor S_45

Indeed, this means that there is a larger variation of temperature, and relative humidity, during those transitional months passing from one season to another, like April, June and October, suggesting a massive influence of the solar radiation on the

envelope of the building.
Reviewing deeply these values, we notice that besides increasing during the year, the Standard Deviation increases as well with the height, reaching the highest value at 4,5m from the ground. Once again, the results show the important influence of the convection heat exchange with the warm roof, heated by the beating sun during the hottest and sunniest time of the year.

A careful analysis of the experimental data is essential also to understand where to intervene in the last stage of this thesis, concerning the implementation of passive systems solutions aiming to reduce the energy intake of the building, particularly of the wine cellar, needed to keep temperature and relative humidity as constant as possible and inside the comfort zone, essential to obtain a much better wine quality. The results obtained so far are showing the necessity of shading the envelope, particularly the roof, from the sun radiation. This would likely implicate the insertion of a ventilated façade and a ventilated roof that beside shading the envelope, will permit a continuous passage of fresh air that, by convection, will cool down the surface.

The graph displayed in Fig.5.17 shows how temperature varies with height during the year. As the tables display, the month that presents the highest Standard Deviation, namely, the widest temperature variation, is June, with ΔT ranging from 4°C to almost 7°C as the height increases. March and November, instead, show very little variation: temperature is maintained quite constant (1°C of maximum ΔT) in the entire environment, mostly at 1,5m from the ground.
Strangely, close to these two cold months in the graph we find the hottest month of the year as well, August. The data show that during August the temperature is kept quite constant, with its smallest variation at 1,5m from the ground, and the widest at 4,5m height, close to the ceiling, fact presumably due to the proximity to the roof exposed to solar radiation for an extended period of time.
It is important to underline, though, that a small variation, synonym of constant temperature, does not mean that the comfort conditions are satisfied. Indeed, even if the ΔT ranges close to 1°C, the average temperature oscillates around 23°C, far away from the comfort zone, especially if we consider that we are analysing daily averages.

5.1.6 Daily analysis

To better study the temperature behavior, were analyzed also the daily fluctuations of the two most significant days in the year: the hottest, and the coldest. Since

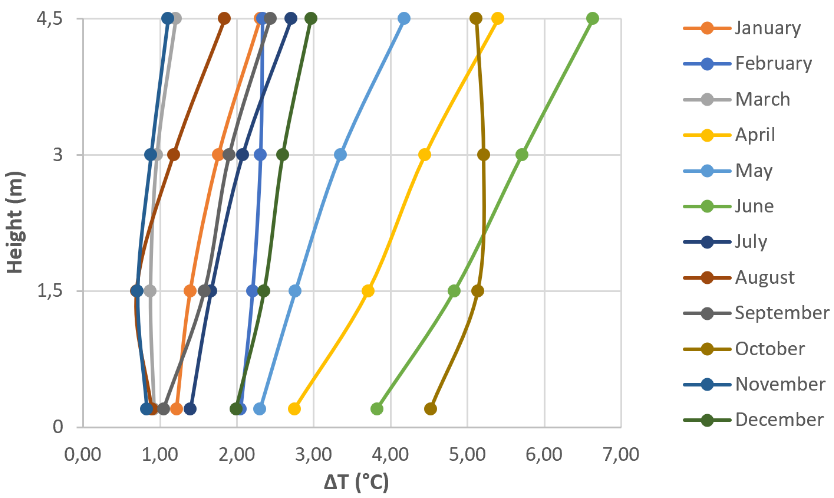


Figure 5.17: Variation of temperature during each month at different heights

during the year of measurements it was located also a sensor on the outside of the building to register the external temperatures, it resulted possible to get an accurate response: it was created another pivot table in which it was calculated the average temperature of each day of the year, and by a *Maximum* and *Minimum* function were determined the hottest and the coldest day of 2018 in Peñafiel:

- Hottest day: 3rd August, with an average temperature of 27,8°C;
- Coldest day: 9th January, with an average temperature of -1,7°C.

Table 5.7: Highest daily mean values of temperature for the four sensors

	S_02	**S_15**	**S_30**	**S_45**
Date	14th August	7th August	7th August	7th August
Daily Mean Temp. (°C)	22,0132	25,5663	24,5025	25,3911

Table 5.8: Lowest daily mean values of temperature for the four sensors

	S_02	**S_15**	**S_30**	**S_45**
Date	26th March	25th March	25th March	25th March
Daily Mean Temp. (°C)	10,9712	10,7424	10,5809	10,5058

Executing the same analysis with the internal temperatures, what came up was that the highest and lowest internal temperatures do not correspond with the hottest and coldest day of the year.

As shown in the table the highest internal temperatures appear to be on the 7th

August for the sensors at 1,5m, 3,0m, 4,5m, while for the sensor at 0,2m the highest temperature appears on the 14th August.
The most reasonable answer to this scenario is the inertia of the envelope, for which the heat due to solar radiation, convection and conduction is transferred to the inside of the building with a certain delay.
Similarly, the lowest temperatures emerge on the 25th March for the upper sensors, while on the 26th of the same month for the sensor placed at the lowest height.
As could be notice at first glance from the tables, temperature increases with height during the hottest day, while decreases during the coldest. This fact is due to the temperature of the roof, which heats up in summer for the intensive solar radiation, while cools down in winter for the continuous radiative heat exchange with the sky, and the meagre solar radiation tipical of this season.
The air stratification is quite substantial during summer, where at a height difference of only 2m shows a 3°C delta.

However, it was decided to develop a daily study on the coldest and on the hottest day of the year, in other words, were considered the data corresponding to the external lowest and highest temperatures:

- The hottest day (3rd August)
  - Maximum of 36,769°C;
  - Minimum of 16,725°C.
- The coldest day (9th January)
  - Maximum of 1,994°C;
  - Minimum of -5,511°C.

Two graphs were carried out with these informations, shown in the Fig.5.18 and Fig.5.19.
Analyzing the two charts, we can notice a huge difference in the distribution of the data.
On the coldest day of the year, the temperature is rather constant, oscillating between 14°C and 15°C, and with a relative humidity ranging from 60% to 80%. The comfort conditions are kept the whole time.
On the hottest day of the year, instead, the temperature values are widely oscillating from one sensor to another, even if each one shows quite narrow range. The S_02 sensor registered values oscillating from 20°C to 21,5°C, the S_15 from 22°C to 23°C,

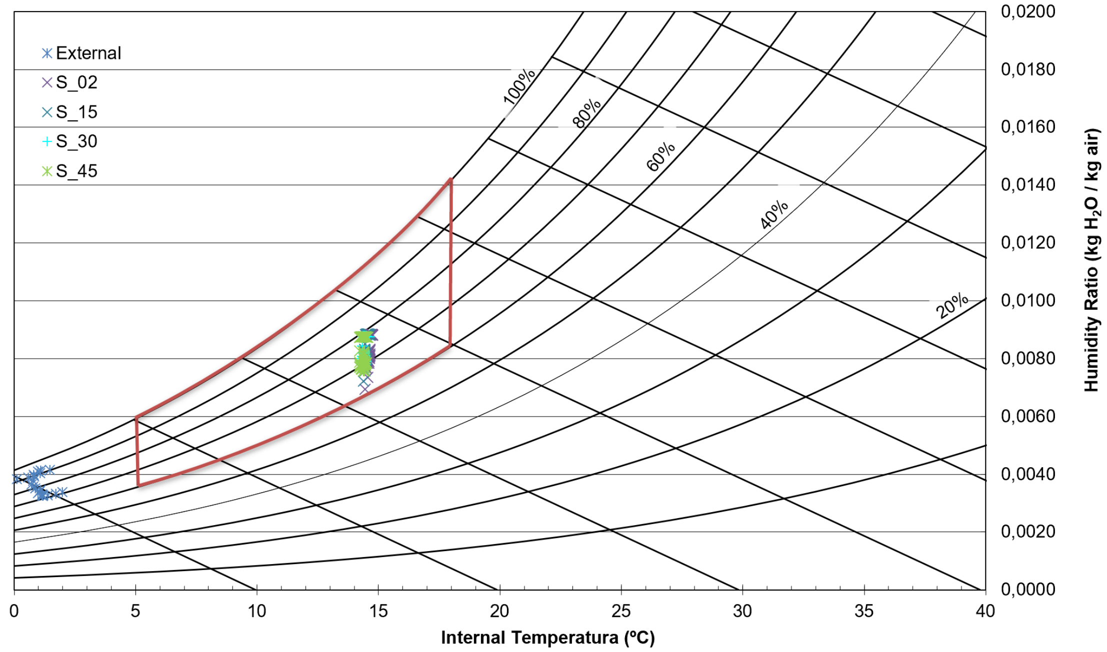


Figure 5.18: Daily distribution of the coldest day of the year for the four sensors and the external conditions

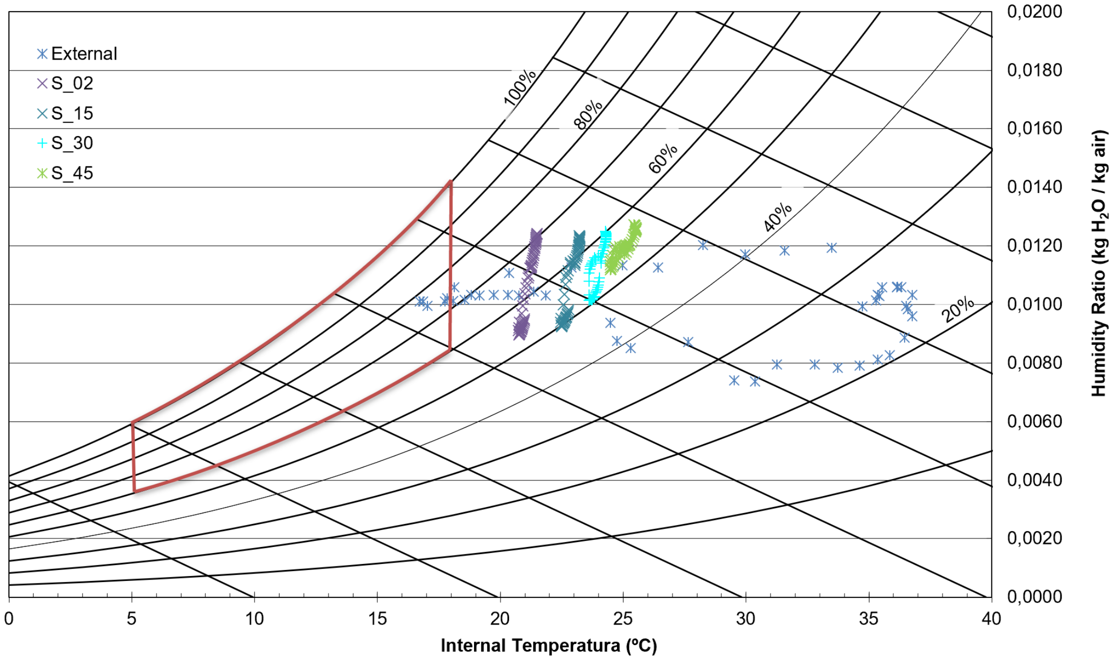


Figure 5.19: Daily distribution of the hottest day of the year for the four sensors and the external conditions

the S_30 from 23°C to 24°C, and the S_45 from 24°C to over 25°C.

Such air stratification can be observed also in Fig.5.20, where we can notice a substantial difference among the temperatures registered by the four sensors. On the contrary, it is interesting to notice that on the coldest day of the year (Fig.5.21), the air stratification is basically inconsequential, nonetheless, the highest temperatures appear to be registered by the lowest sensor, the S_02. Once again, the analysis shows the colossal influence of the roof's thermal insulation.

The values lay substantially away from the comfort zone, not satisfying the relative humidity conditions either, ranging from a 70% to a 50%, which means that, beside the bad quality outcome, there is a high chance of wine losses by evaporation. Once again, this last analysis underlines the necessity of an envelope rehabilitation, with particular attention given to the roofing part.

Analyzing more deeply the daily fluctuations, by calculating the standard deviation for every day of the year of each one of the four sensors, came up that, accordingly to the monthly analysis, the day with largest fluctuation of temperature is the 26th June, for the S_15, S_30 and S_45 sensors. At 4,5m from the ground the highest temperature appears to be 25,52°C at 17:00 and the lowest 22,31°C at 9:00. The lowest sensor, S_02, shows, as always, a little exception, displaying the largest temperature fluctuation in December. Results are shown in Tab.5.9.

Table 5.9: Largest temperature fluctiations (ΔT and Standard Deviation) over the year for each sensor

	S_02	**S_15**	**S_30**	**S_45**
Date	28th December	26th June	26th June	26th June
ΔT (°C)	1,90	1,17	2,06	3,22
Average ± SD (°C)	14,67 ± 0,67	21,21 ± 0,39	22,36 ± 0,65	23,54 ± 0,94

During the later stage, concerning the evaluation of the DesignBuilder model, it was decided to realize a continuous trend graph in order to evaluate the cooling planning of the wine cellar. Both the hottest and the coldest day of the year graphs showed a continuous trend with no fluctuations. Whilst this fact reflects the normality during Winter, it is extremely bizarre during Summer. The continuous trend indeed, implies no sudden fluctuation of temperature, thus, no cooling system activation whatsoever.
Such information made us realize that, even if in the wine cellar there is an HVAC system installed, the winery owners never turn it on, not even during the hot season, when external temperatures reach almost 37°C and the internal conditions lay rather far away from the comfort zone.

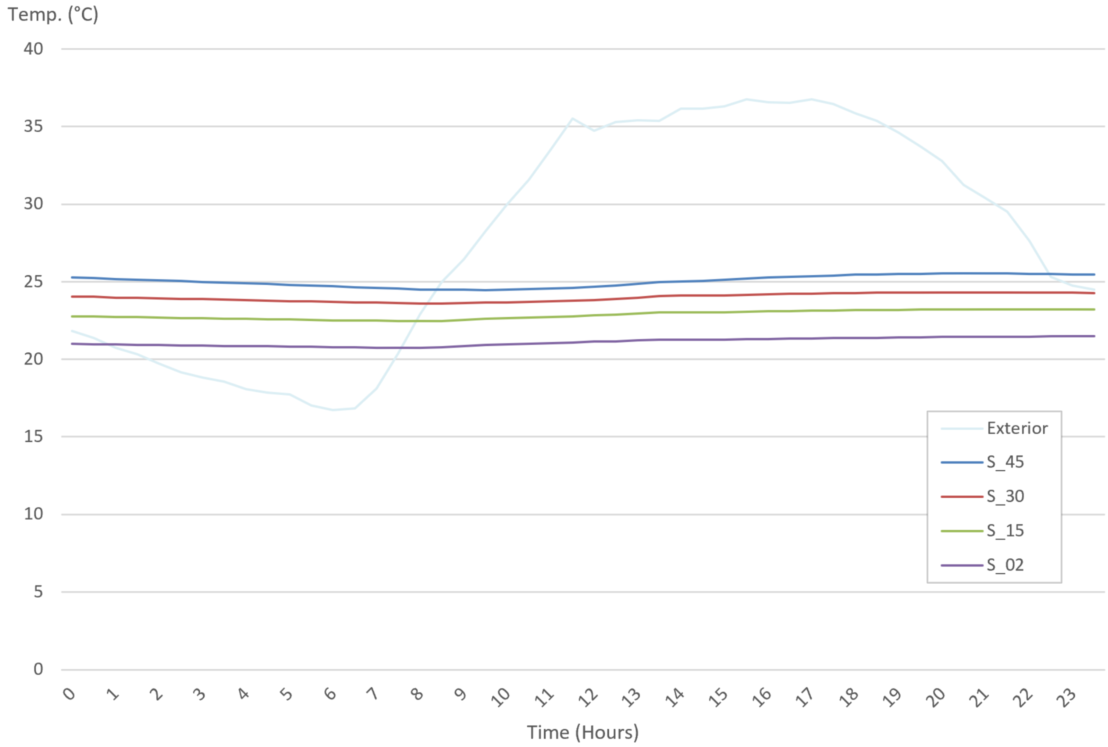


Figure 5.20: Continuous trend of the hottest day of the monitorized year (3rd August)

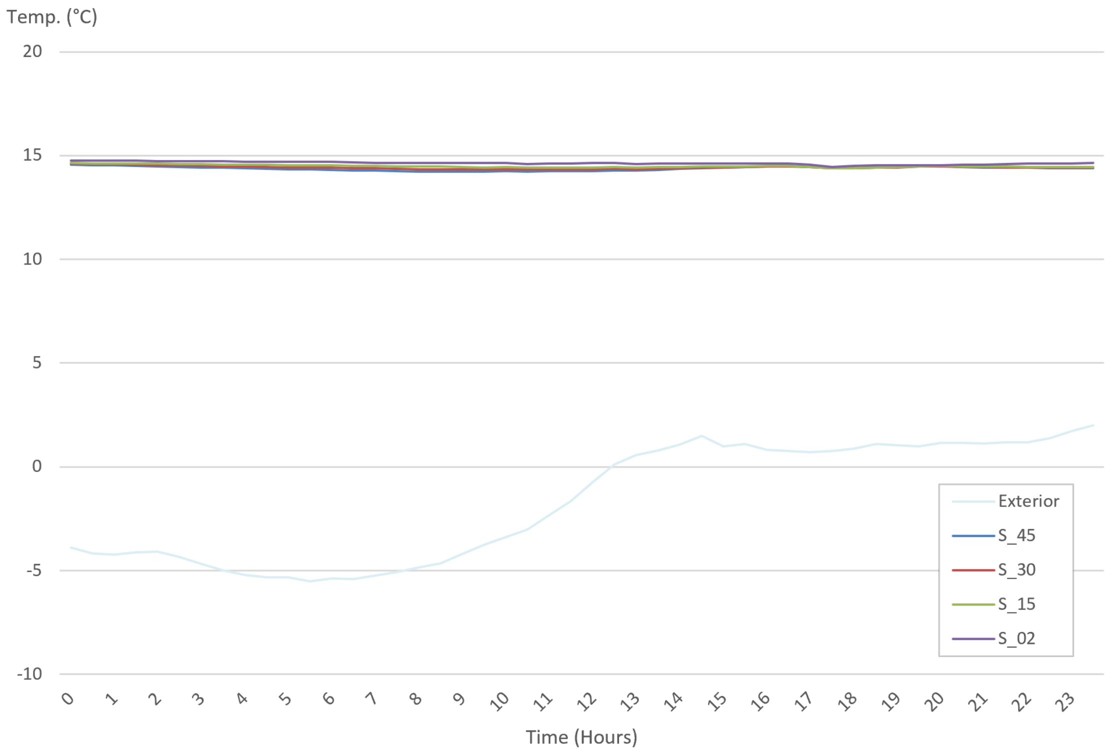


Figure 5.21: Continuous trend of the coldest day of the monitorized year (9th January)

Such analysis cleared up as well the doubts that came up in the seasonal analysis whether the comfort conditions are satisfied throughout the day or not.
We can see that both during the coldest and the hottest day of the year, temperature does not float excessively, on the contrary, stays quite constant. This fact implies that we can relate on the daily average of temperature whether they lay inside or outside the comfort zone.

5.1.7 Comments

With the seasonal analysis it was possible to understand the general conditions of temperature and relative humidity during the year, arranging two tables (Tab.5.3 and Tab.5.4) with the percentage of days that show satisfied comfort conditions for the ageing of wine. It was discovered that Summer is the most critical season, with 0%, or 1% for the lowest sensor, of days within the comfort zone, followed by Autumn, showing satisfied comfort conditions for two thirds of the time. Spring and Winter do not show particular issues, with a 100% almost in every sensor.
The annual analysis showed that hygrothermal conditions fall inside the comfort zone for about two thirds of the year (Fig.5.8). Beside that, such analysis revealed an air stratification on horizontal planes, coherently with some literature findings. This fact gave the hint to examine more deeply the difference among the outcome of the four sensors. Some graphs were delineated showing the vertical ΔT by month (Fig.5.17) and day (Fig.5.20). The results show the considerable influence of the solar radiation on the roof surface, especially during the hot, sunny seasons, like Summer. Further analysis were carried out on the Standard Deviation of the temperature conditions during the whole year (Tab.5.5 and Tab.5.6). The results showed that the worst conditions appear in June, with a daily fluctuation that overtakes 3°C and a monthly fluctuation that almost reaches 7°C, both calculated at 4,5m from the ground (Fig.5.17).

Chapter 6

Model creation and validation

6.1 EnergyPlus and DesignBuilder

EnergyPlus is an autonomous software for the dynamic thermal simulation of the building system with all its supplemental devices, such as the HVAC, lighting, electrical systems and many others. It is essentially the calculator that gives as output all the energy consumptions, the temperatures and the thermal exchanges related to the building.
Since EnergyPlus is a programming software, not very intuitive to use, it was equipped with an external graphical interface software to make it more user-friendly, DesignBuilder.[38]
With DesignBuilder the user can create his own 3D model and assign to each component of the building the respective characteristics, such as dimensions, shapes, materials, thermal systems, heat gains, and so on.
EnergyPlus was developed by the United States Department of Energy (USDOE) as second generation software after the great success that arised DOE-2 (USDOE e-Lawrence Berkley National Laboratory) and BLAST (Building Loads Analysis and System Thermodynamics) released by the US Army Corps of Engineers and the University of Illinois Champaign, in 1970s, after the energetic crisis, intended to be used by building engineers and architects aiming to reduce the energy consumption of buildings, as the American energy usage statistics reveal it to be dominant.[39]
Like its parent programs, EnergyPlus is an energy analysis and thermal loads simulation program, based on a user's description of a building from the perspective of the building's physical make-up. The EnergyPlus outputs are the heating and

cooling loads necessary to maintain the wanted setpoint conditions inside the studied environment. EnergyPlus has inherited many features present in their parents' programs, BLAST and DOE-2, as, just for naming two among the many, the sub-hourly user-definable time steps, the ASCII text-based weather input and output files, as we will later talk about.
EnergyPlus is not a user interface, it is intended to be the simulation engine around which a third party interface can be wrapped. Inputs and outputs are simply ASCII codes that a GUI (Graphical User Interface) can depict. Among the many GUIs developed in the years, DesignBuilder differs from others. EnergyPlus was included into DesignBuilder with the aim of allowing the user to bring about energetic simulations with not particular technical knowledge.[39]
DesignBuilder was purposely designed around EnergyPlus to consent the insertion of the right input necessary for this one to calculate. Similarly to BIM softwares like Revit, DesignBuilder contains various archives with packages of construction materials, coating materials, glasses, solar shields, equipped with all their thermal properties. This feature, among the many, make DesignBuilder a unique software tool to create and evaluate building designs.[40]

6.2 Degree of confidence

In order to understand how well the virtual energy model reflects the reality, it is necessary to resort to the use of various indexes that determine the degree of confidence of the model. This aspect of the building energy evaluation has been largely studied and after a bibliographic research it was found that the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) has set some limits to define the goodness of the energy models.

With reference to the International Performance Measurement and Verification Protocol (IPMVP) [41] and the ASHRAE Guideline 14 [42], following are shown the indexes used for the validation of the model object of the present study.

6.2.1 Mean Bias Error (MBE) and Average Deviation (AV)

The Mean Bias Error is the average of the errors of a sample space. Generally it is a good indicator of the overall behaviour of the simulated data with regards to the regression line of the sample. However, tha main problem with this index is that it is subject to cancellation errors where the sum of positive and negative vaues could reduce the value of MBE. [43]

$$MBE = \frac{\sum_{i=1}^{n}(m_i - s_i)}{n} \tag{6.1}$$

Where:
m_i = measured value;
s_i = simulated value;
n = number of measured data points.

For obvious reasons this index was not used. However, in order to estimate the mean difference between the simulated temperature and the experimental temperature, the formulation was slightly modified to obtain the Average Deviation:

$$AV = \frac{\sum_{i=1}^{n}|(m_i - s_i)|}{n} \tag{6.2}$$

Where:
m_i = measured value;
s_i = simulated value;
n = number of measured data points.

6.2.2 Normalized Mean Bias Error ($NMBE$)

The Normalized Mean Bias Error is, as its name says, the normalization of the MBE index that is used to scale the results of MBE, making them comparable. It quantifies the MBE index by dividing it by the average of the measured values ($\overline{m}$), giving the global difference between the real values and the predicted ones. [43]

$$NMBE = \frac{1}{\overline{m}} \cdot \frac{\sum_{i=1}^{n}(m_i - s_i)}{n - p} \times 100(\%) \tag{6.3}$$

Where:
m_i = measured value;
s_i = simulated value;
n = number of measured data points;
p = is the number of adjustable model parameters, which, for calibration purposes, is suggested to be zero.
The NMBE is also subject to cancellation errors; consequently, the use of this index alone is not recommended.

6.2.3 Coefficient of Variation of the Root Mean Square Error ($CV(RMSE)$)

The Coefficient of Variation of the Root Mean Square Error measures the variability of the errrors between measured and simulated values. It is not subject to cancellation errors, hence, ASHRAE Guidelines [42] and IPMVP [41] use it with $NMBE$ to verify the accuracy of the models. [43]

$$CV(RMSE) = \frac{1}{\overline{m}} \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n-p}} \times 100(\%) \tag{6.4}$$

Where:
m_i = measured value;
s_i = simulated value;
n = number of measured data points;
p = is the number of adjustable model parameters, which, in this cae it is suggested to be one.

6.2.4 Coefficient of Determination (R^2)

The Coefficient of Determination is the proportion between the variability of the data and the goodness of the model, it indicates how close the simulated values are to the regression line of the measured values. It is another statistical index commonly used to measure the uncertainties of the models. It is limited between 0,00 and 1,00 where the upper value means that the simulated values match the measured ones perfectly, while the lower one indicates that there is no correlation between measured and simulated values. [43]

$$R^2 = \left(\frac{n \cdot \sum_{i=1}^{n}(m_i \cdot s_i) - \sum_{i=1}^{n} m_i \cdot \sum_{i=1}^{n} s_i}{\sqrt{(n \cdot \sum_{i=1}^{n} m_i^2 - (\sum_{i=1}^{n} m_i^2)^2) \cdot \sum_{i=1}^{n} s_i^2 - (\sum_{i=1}^{n} s_i^2)^2)}} \right)^2 \tag{6.5}$$

Where:
m_i = measured value;
s_i = simulated value;
n = number of measured data points.

The Tab.6.1 summarizes the limits imposed by the ASHRAE Guideline 14 and the IPMVP for the validation of energy models.

Table 6.1: Limits imposed by the ASHRAE Guideline 14 and the IPMVP

Data Type	Index	ASHRAE Guideline 14	IPMVP
Monthly	$NMBE$	5	20
	$CV(RMSE)$	15	-
Daily	$NMBE$	10	5
	$CV(RMSE)$	30	20
-	R^2	>75	>75

In the next part of this chapter, will be discussed the structure of the model and the changes introduced for its validation.
Following, a layout of the winery (Fig.6.1) will clarify the disposition of the different areas that will be spoken off in this chapter.

Figure 6.1: Layout of the winery

6.3 Location, Region

In order to create a virtual 3D model that would reflect the reality, or in other words, a model whose envelopes and systems behave just as they behaved in the year 2018 - the year monitored - it was necessary to insert the weather data, measured that year by the external sensor, inside the computational systems of EnergyPlus. This means substituting the weather data available on EnergyPlus for the region the winery is located in, Valladolid, which date back to the year 2002.
Furthermore, it was fundamental the use of the external sensor because the weather

data available on EnergyPlus are registered indeed in Valladolid, the largest city close to Peñafiel, which is still almost 60km away from the winery, thus simulating with such data wouldn't result very accurate.
Hence, it was created a .epw file containing the hourly weather data of the year 2018 registered in Peñafiel, just beside the winery as shown in Chapter 5 in Fig. 5.6 on page 36. Such file was then inserted in the DesignBuilder software, together with the overall location data such as, altitude, latitude, longitude, atmospheric pressure, among the many (Fig.6.2*(b)*).

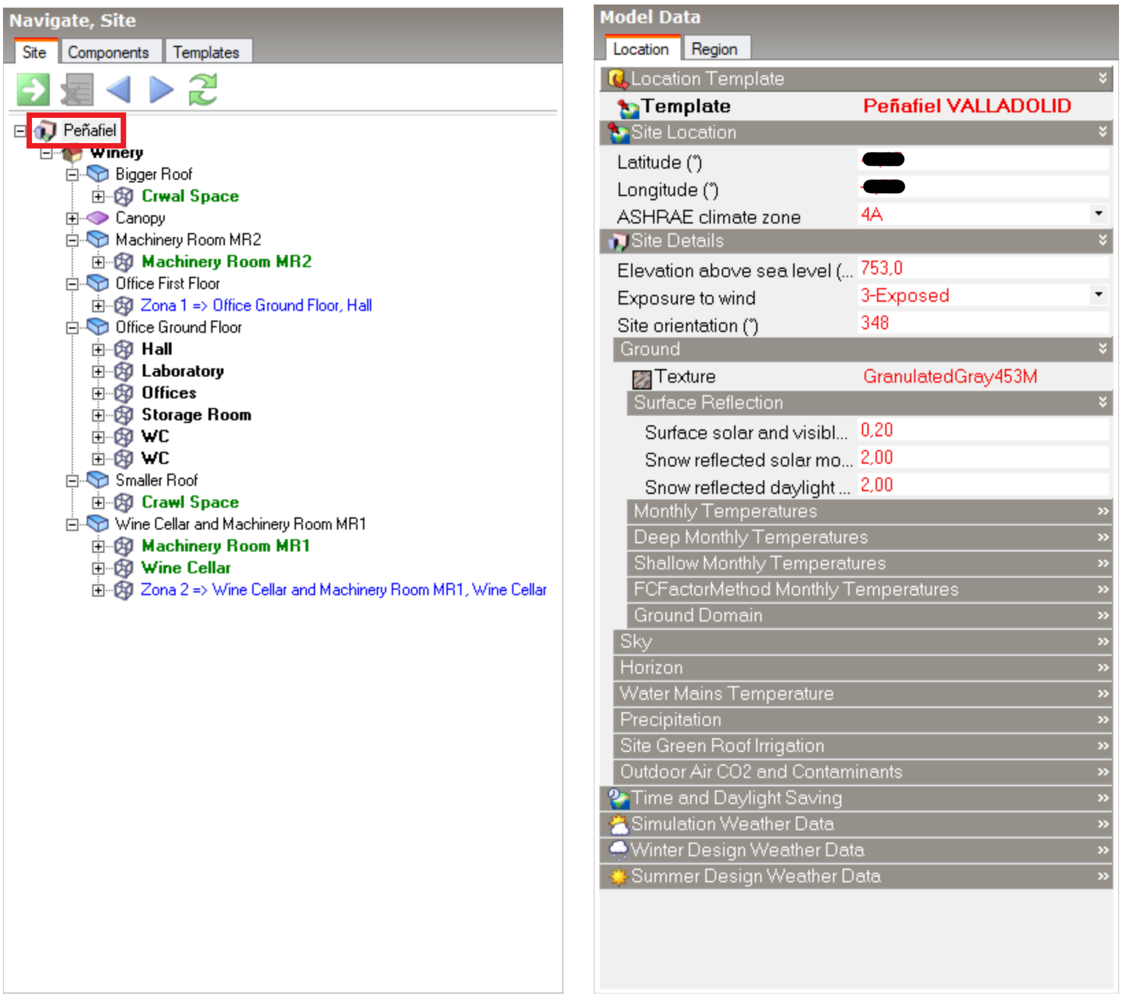
Selecting *Peñafiel* in the *Navigate, Site* section (Fig.6.2*(a)*), the *Model Data* box related to the *Location* and to the *Region* pops out on the left part of the screen (Fig.6.2*(b)*). Selecting the *Peñafiel VALLADOLID* template, the *Location templates Data* box opens (Fig.6.3*(a)*), from which we can reach, through *Simulation weather* section, the *Hourly weather Data* box and the .epw file (Fig.6.3*(b)*). This file should be stored in ProgramData > DesignBuilder > Weather Data.

6.4 Winery

Selecting *Winery*, in the *Navigate, Site* section, another *Model Data* box opens on the left part of the screen. The sections are not related anymore to the *Region* and the *Location*, but to the features of the building, such as *Construction*, *Activity*, *HVAC*, and so on, as shown in the Fig.6.4*(b)*.
Since not every room of the winery has the same function, nor the same features, as there are offices and wine cellars, storage rooms and machinery rooms, the characteristics of the envelopes and, just to name one, the occupancy, must be assigned to each *Zone* of the building, by selecting *Machinery Room*, *Offices First Floor*, *Wine Cellar*, an so on (Fig.6.4*(a)*).

In the next part will then be exposed the features and the characteristics of each zone of the winery.

The information about the construction, the activity, the climatization and others, received at the beginning of this study, have been partly confirmed and partly denied by the manager of the winery during an interview carried out at the winery on the site inspection (13^{th} May 2019), where it was also possible to investigate the building and take the pictures that fill this thesis.



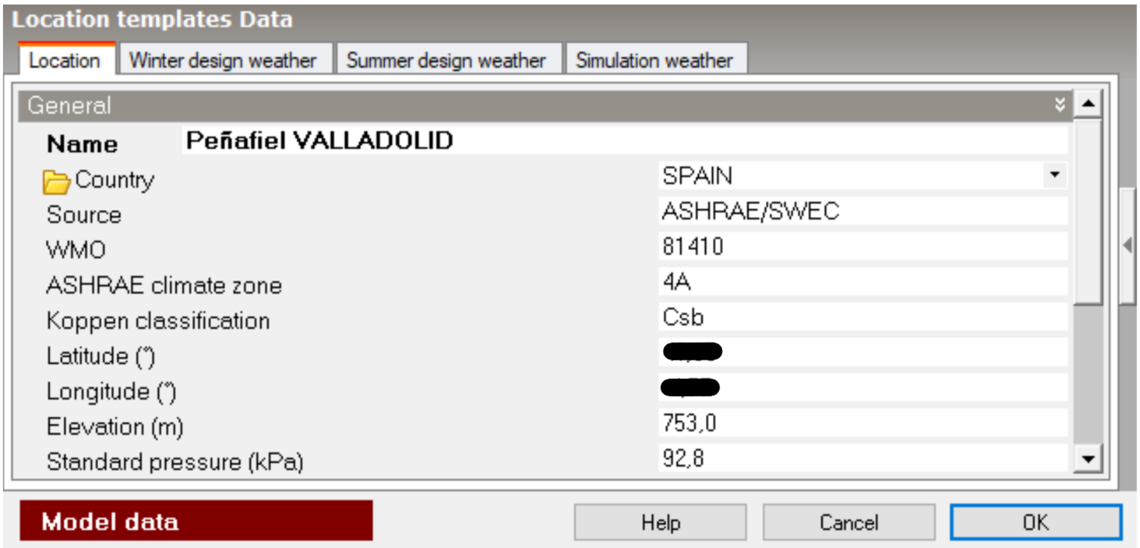
(a) *Navigate, Site: Peñafiel* (b) *Location: template and general info*

Figure 6.2: Site Location settings

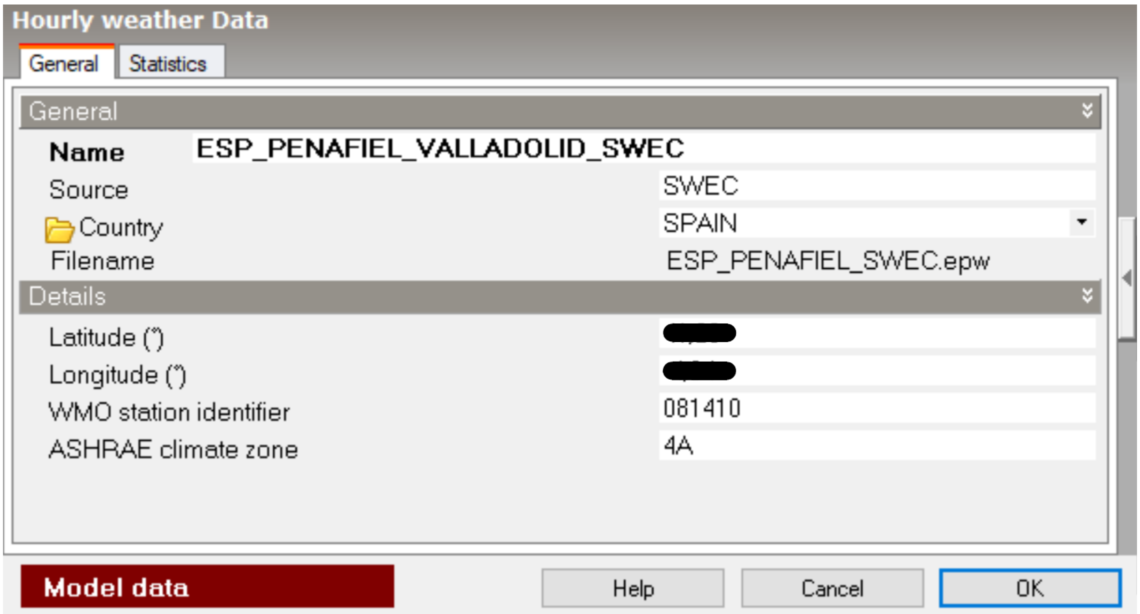
6.4.1 Construction

As seen in section 4.3.2 on page 30, the winery presents:

- Two types of vertical envelopes;
- Two types of horizontal envelopes;
- One type of horizontal partition;
- One type of oblique evelope;
- One type of false ceiling;
- One type of vertical partition.



(a) *Location templates Data*

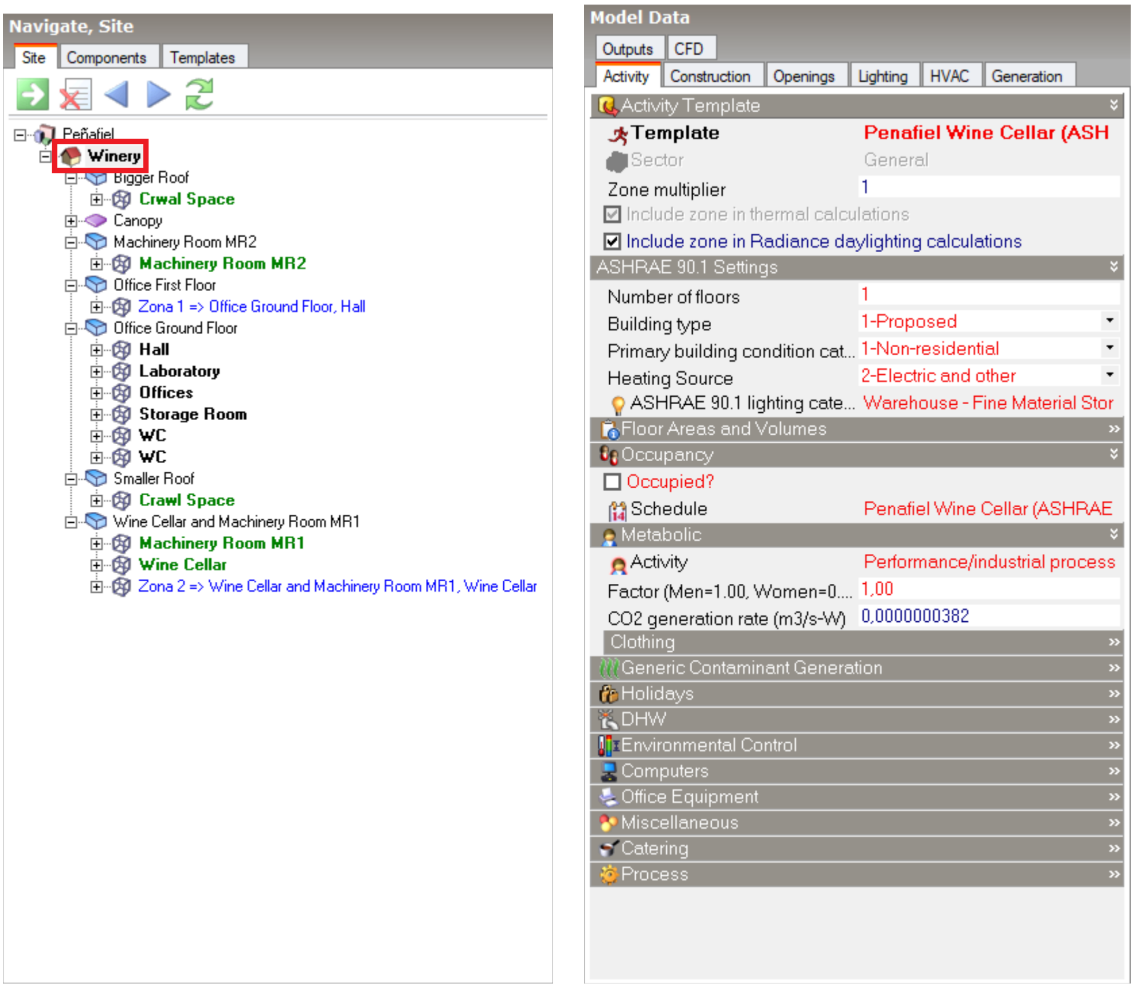


(b) *Hourly weather Data*

Figure 6.3: Site Location settings

These eight elements have been assigned to each construction component of the winery, by clicking on the *Construction* section of the *Model Data* box, as shown in Fig.6.4*(b)*.

Following, are shown the characteristics of each part of the building as seen from DesignBuilder.



(a) *Navigate, Site: Winery* (b) *Building: template, general and specific info*

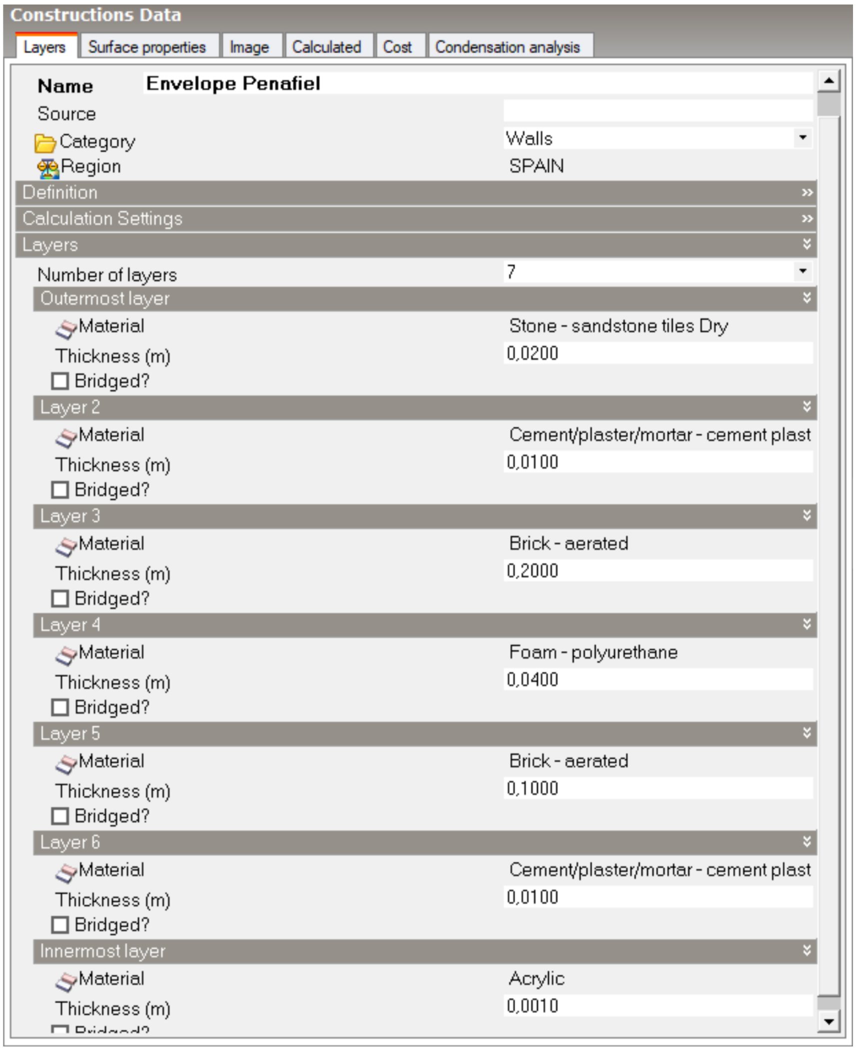
Figure 6.4: Building settings

Vertical Envelope (VE_01) Reported in DesignBuilder as *Envelope Peñafiel* (Fig.6.5). See Appendix A on page 114 for more information.

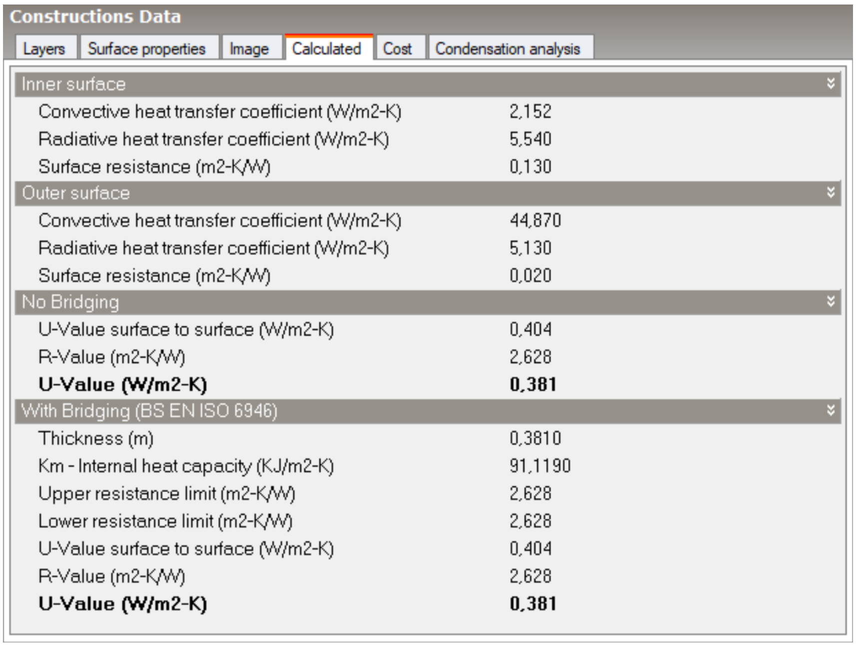
Vertical Envelope - back part (VE_02) Reported in DesignBuilder as *Envelope Peñafiel (back part)* (Fig.6.6). See Appendix B on page 116 for more information.

Vertical Partition (VP_01) Reported in DesignBuilder as *Partition Peñafiel* (Fig.6.7). See Appendix C on page 118 for more information.

Ground Floor - Wine Cellar and Machinery Room: (HE_01) Reported in DesignBuilder as *Ground Floor Peñafiel (Wine Cellar)* (Fig.6.8). See Appendix D on page 120 for more information.

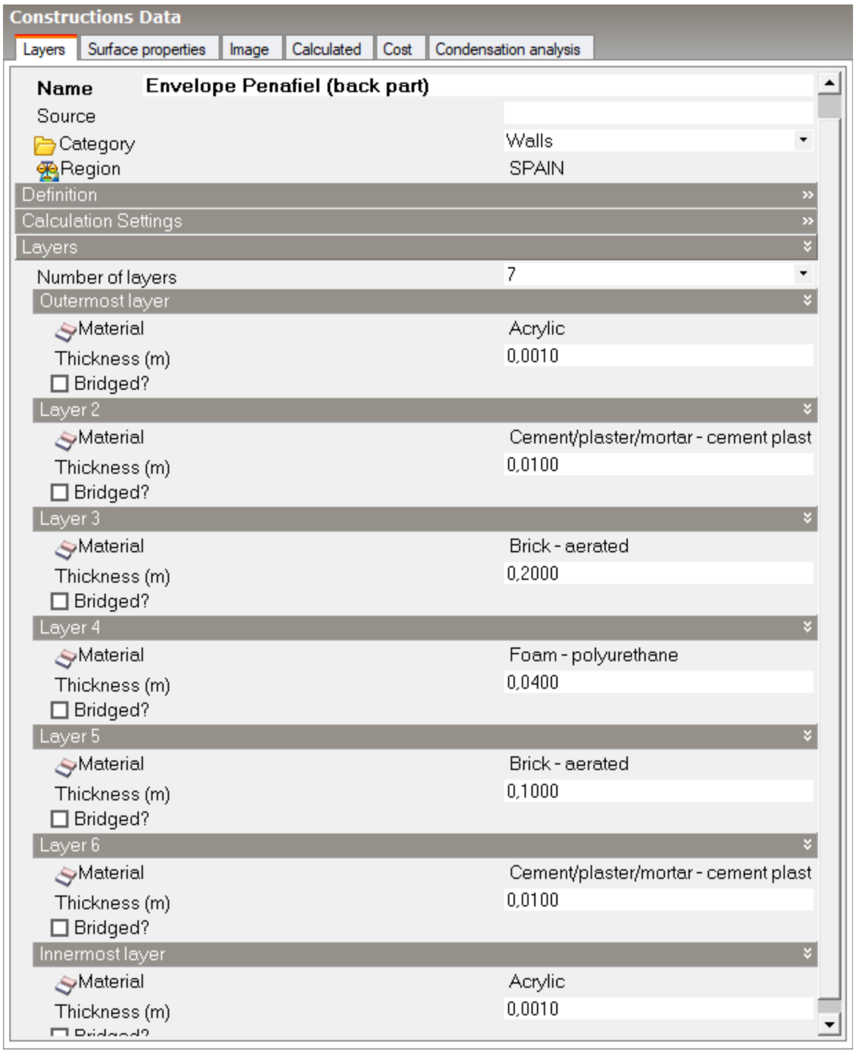


(a) *Layers*

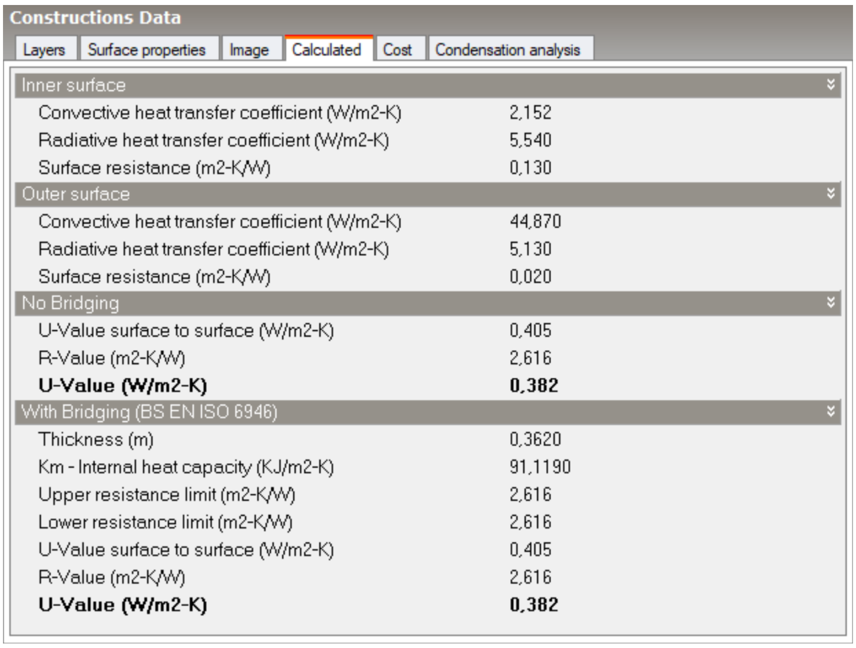


(b) *Calculations*

Figure 6.5: Vertical Envelope

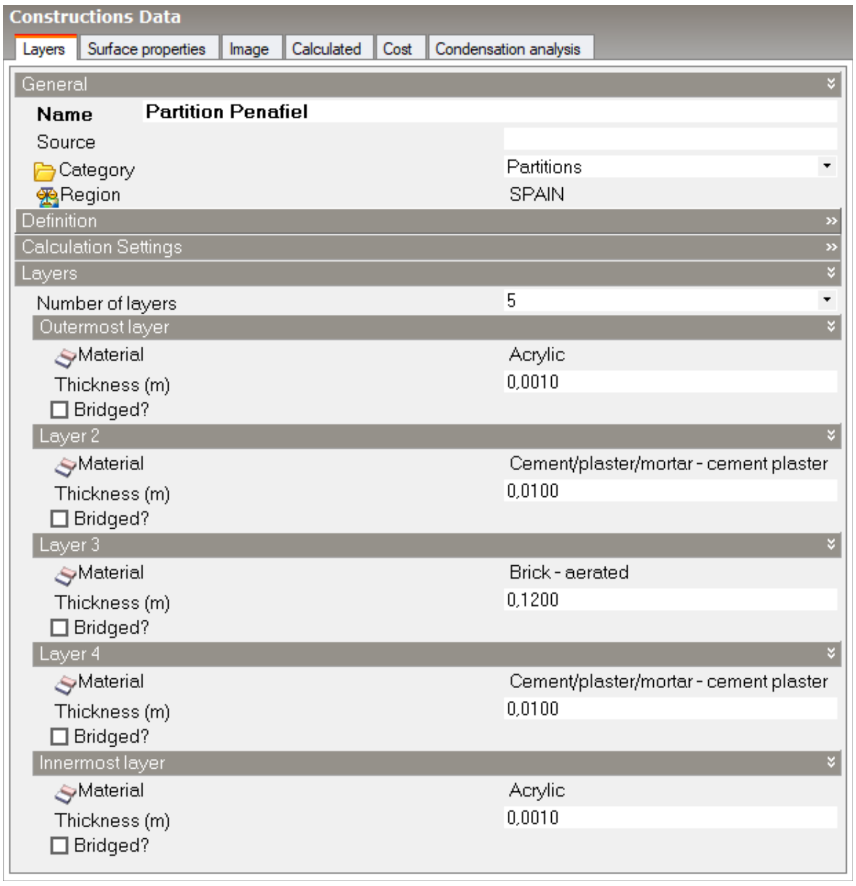


(a) *Layers*

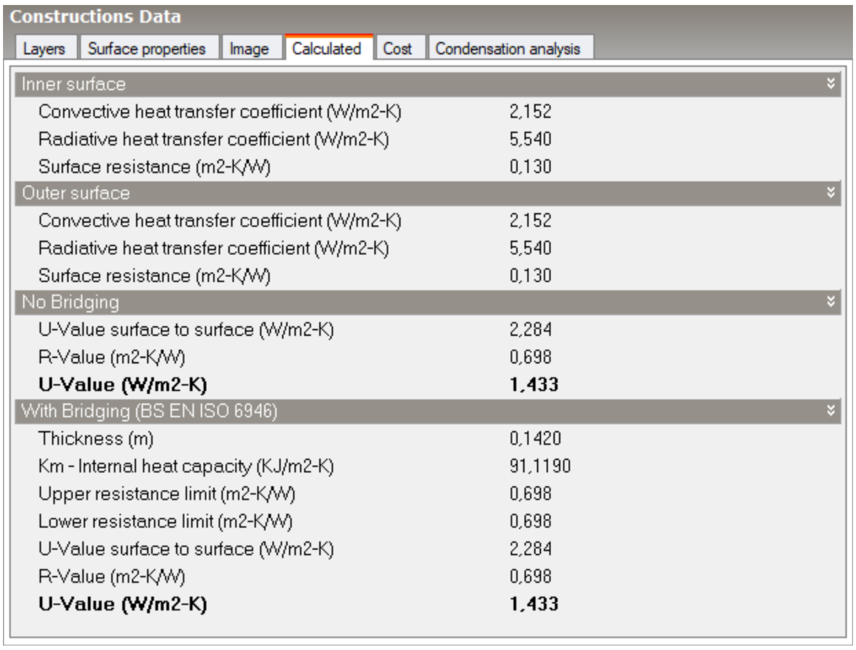


(b) *Calculations*

Figure 6.6: Vertical Envelope

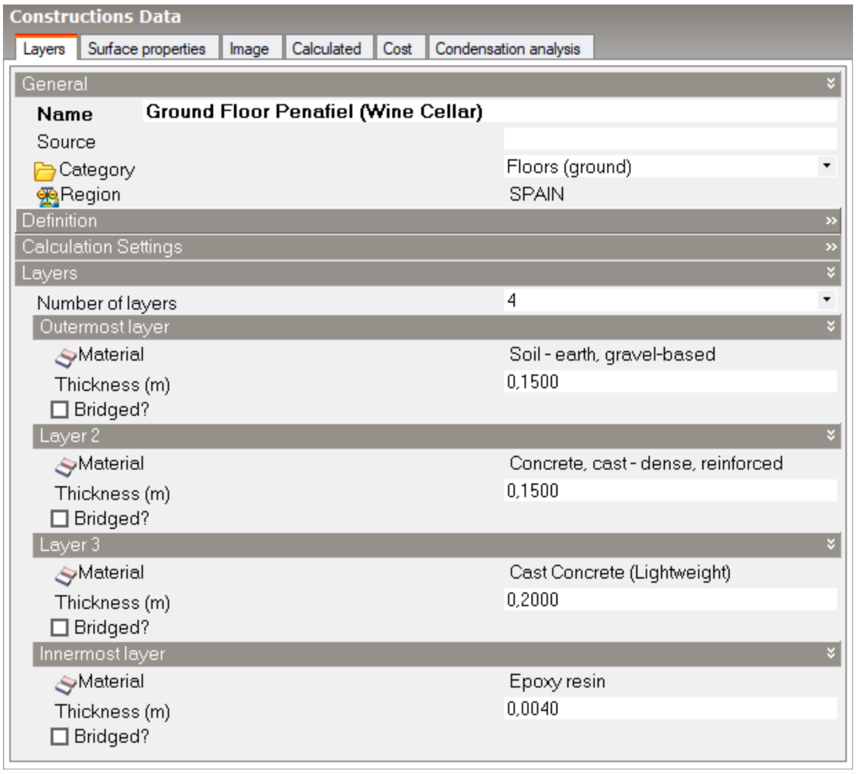


(a) *Layers*

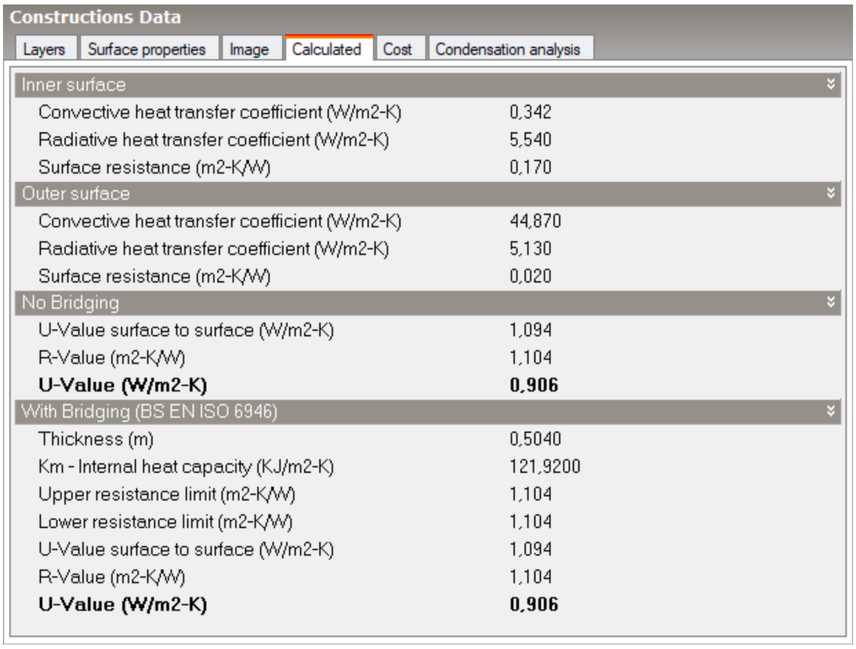


(b) *Calculations*

Figure 6.7: Vertical Partition



(a) *Layers*



(b) *Calculations*

Figure 6.8: Ground Floor - Wine Cellar and Machinery Room

Ground Floor - Office Area: (HE_02) Reported in DesignBuilder as *Ground Floor Peñafiel (Offices)* (Fig.6.9). See Appendix E on page 122 for more information.

Interstorey Floor - Office Area: (HP_01) Reported in DesignBuilder as *Interstorey Floor Peñafiel (Offices)* (Fig.6.10). See Appendix F on page 124 for more information.

Roof (OE_01) Reported in Designuilder as *Roof Peñafiel* (Fig.6.11). See Appendix G on page 126 for more information.

Linear Thermal Brigdes and Junctions As it was not possible to relate to detailed plans and sections, to the linear thermal bridges and junctions present in the winery were assigned default values already present in DesignBuilder, which are the based on BRE IP 1/06 values degraded by the greater of 0.04 W/mK or 50%. [44]

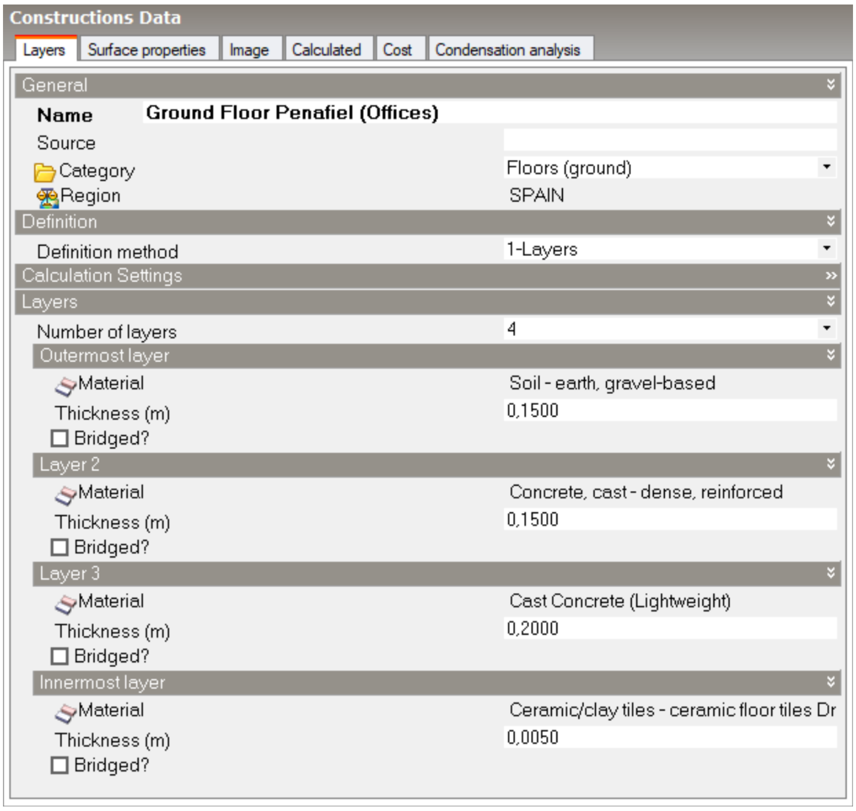
6.4.2 Activity

Analyzing the human activity and the funcioning of electric machineries inside the building is fundamental to estimate the warmth that the occupants and the equipments release to the internal environment, which translates into heat gains burdening on the energy balance of the each thermal zone and those surrounding.

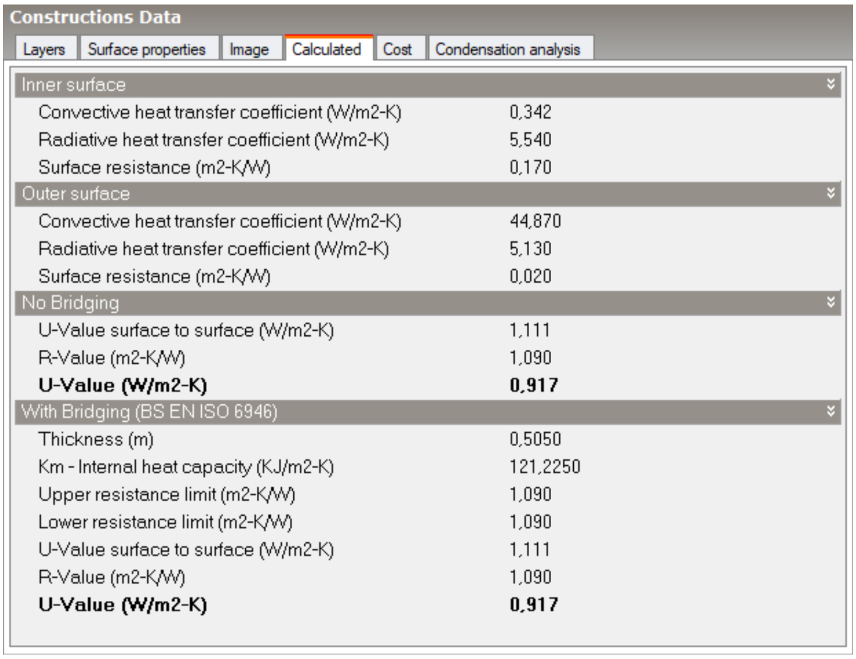
Occupancy In order to evaluate correctly the heat gains due to occupants, it is necessary to know the number of people that generally occupy the different areas of the winery, and their metabolic rate.
The inspection at the winery made it possible to figure out the number of people that normally work in the different thermal zones and their usual time schedule. With these basic information it was possible to start filling the virtual model with the specific factors[1]:

- Three women in the *Offices* area:
  - Type of work: Office activities – Typing
  - Metabolic Rate: 117 W/person

[1] The *Metabolic Rate* and *Metabolic Factor* values contanied in DesignBuilder are retreived from the CIBSE (Chartered Institution of Building Services Engineers)

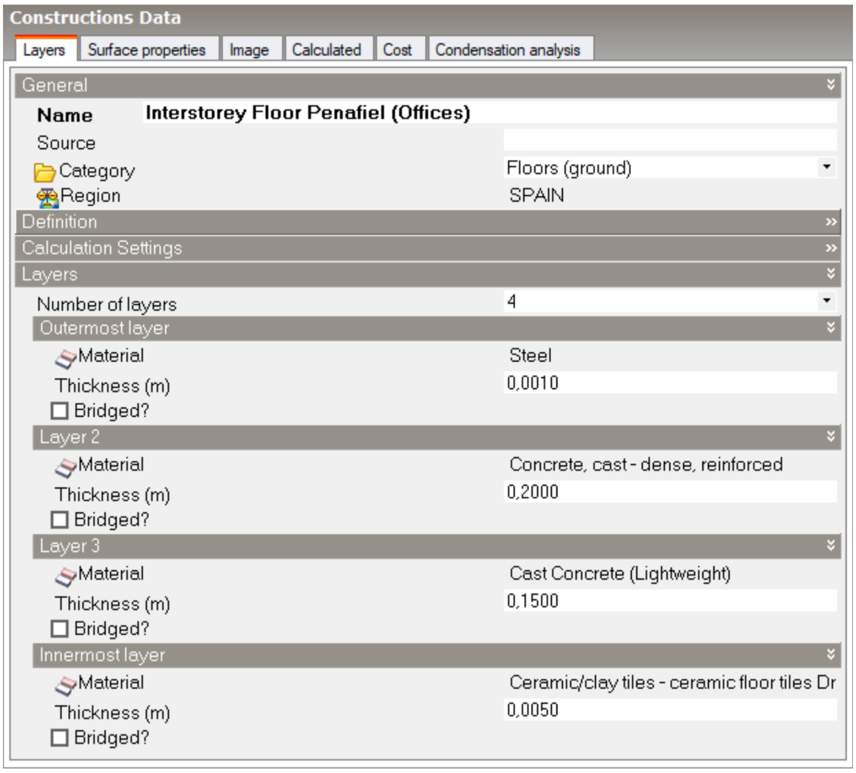


(a) *Layers*

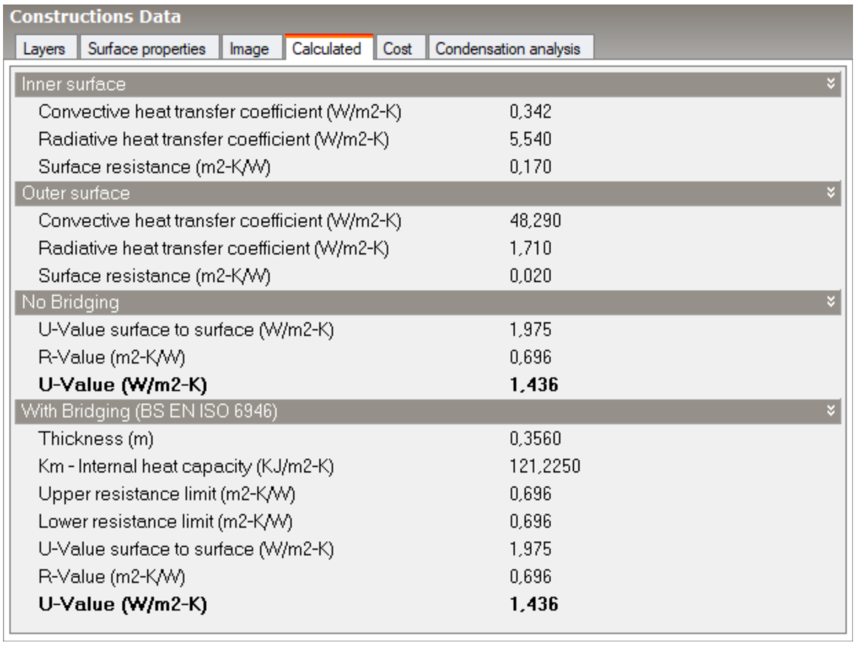


(b) *Calculations*

Figure 6.9: Ground Floor - Office Area

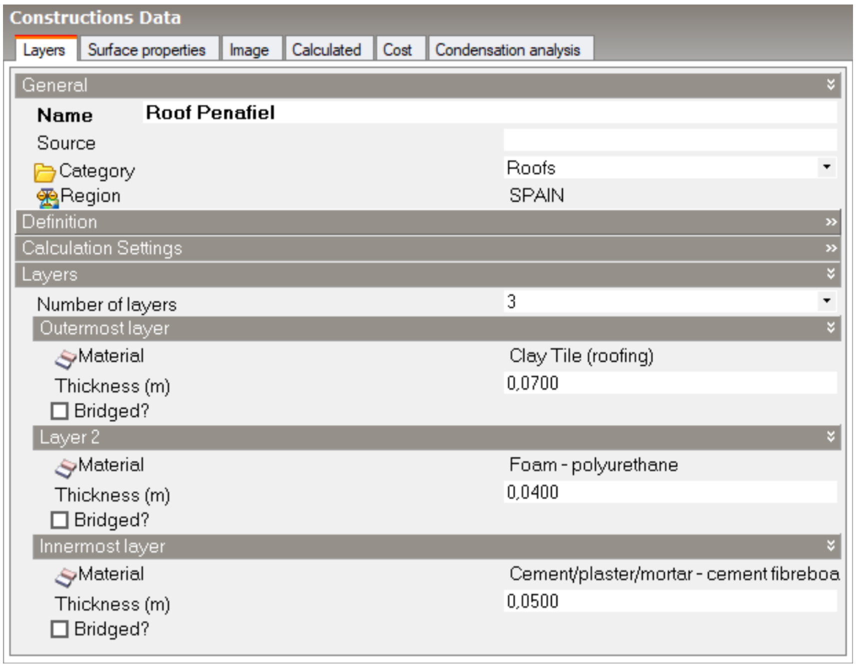


(a) *Layers*

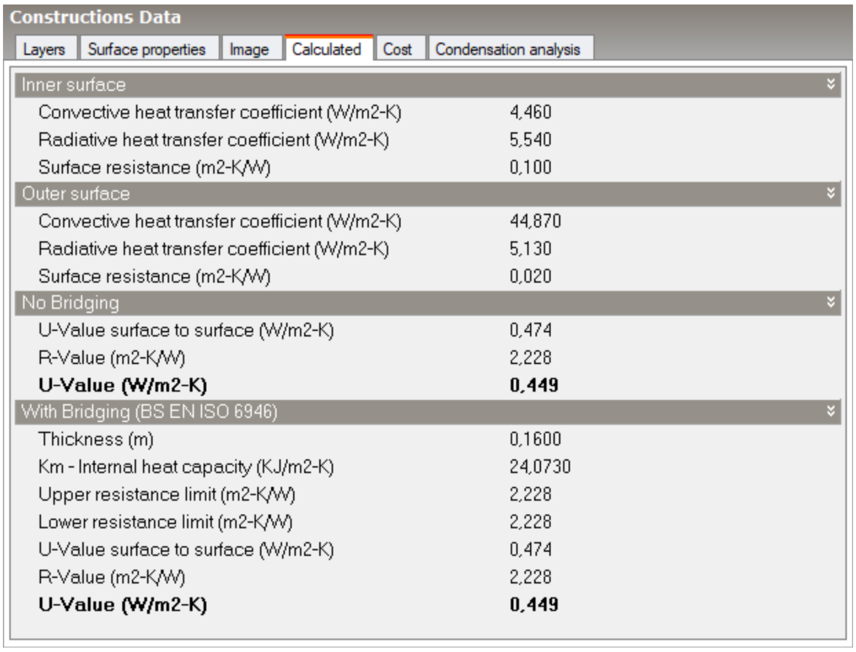


(b) *Calculations*

Figure 6.10: Interstorey Floor - Office Area



(a) *Layers*



(b) *Calculations*

Figure 6.11: Roof

  - Metabolic Factor: 0,85

- Two men in the *Office First Floor* area:
  - Type of work: Office activities – Typing
  - Metabolic Rate: 117 W/person
  - Metabolic Factor: 1

- Two men in the *Machinery Room (MR1)*:
  - Type of work: Miscellaneous occupational – General manual work and light exercise
  - Metabolic Rate: 250 W/person
  - Metabolic Factor: 1

The working hours are the same for every employee: 9:00 - 14:00 / 16:00 - 19:00 during the week days. The winery normally remains closed during the weekend, except for occasional events, such as wine tasting, carried out in the Office First Floor. Since they are just sporadic, it was decided not to include them in the annual schedule.

Computers and Office Equipment From the ASHRAE *Handbook of Fundamentals* were retreived some information about the heat gain originating from the computers and the office equipment, such as printers, fax machines and photocopiers. The Handbook suggests to consider a thermal contribution to the energy balance of:

- 5,4 W/m^2 for environments with low occupancy rate (around 15,5 m^2/work station)
- 10,8 W/m^2 for environments with medium occupancy rate (around 11,6 m^2/work station)

Thus, it was considered a medium occupancy rate for the Offices area and a low occupancy rate for the Office First Floor area.

Miscellaneous The ASHRAE Handbook suggests to consider for environments with heavy machinery, such as the Machinery Rooms of the winery, values of heat gains ranging between 50 W/m^2 and 220 W/m^2.
This value varies quite signifincantly during the year due to the different stages of the production of wine. A year, indeed, witnesses the alternation of the fermentation

phase, lasting about 4 months and involving an intese use of the fermentation machineries, and a period of less internse work for the equipment, during which the bottling and the relocation of the wine from a storage to another take place.
The uncertainties related to the heat gains originating in the machinery room demanded a meticulous study of the temperature distibution during the whole year. Accordingly, this value was determined in a second moment.

Lighting Since the information about the lighting equipment barely existed, it was decided to select the most appropriate template from the default ones available on DesignBuilder, corresponding to

- Building-Specific Space, Warehouse, Fine Material storage 10 W/m^2 (retreived from *Common Space Types, Table 9.6.1, ASHRAE 90.1-2010*) for the Wine Cellar and the Machinery Rooms;
- Common Space, Office - Enclosed, 11.9 W/m^2 (retreived from *Common Space Types, Table 9.6.1, ASHRAE 90.1-2010*) for the Offices and other areas.

HVAC One of the main reasons that led to the winery inspection was the HVAC system. From the report received from the winery manager at the beginning of the study, it emerged the fact that the temperature inside the wine cellar is controlled by an HVAC system that keeps the environment inside certain prefixed values.
Nontheless, from the experimental analysis developed as first step of the investigation, it became clear that the HVAC system was not functioning (see section 5.1.6 on page 53), at least in the year 2018 when the experimental data were collected.
As most important factor in the analysis, the first question asked to the manager during the inspection was indeed about the wine cellar HVAC system. As expected, the answer revealed that the heating-cooling system had not been working for the past couple of years.
If on one side such circumstance is just horrifying for the wine kept ageing inside the wine cellar, on the other hand it confirmed that the analysis carried out up to that moment was correct.
Hence, the only HVAC systems, working, in the winery are the ones in the Offices (one Fan Coil unit) used to keep warm the working spaces, and two in the Hall (two Fan Coil units).
Since the winter is quite sharp in the Ribera del Duero region, the winery personnel prefers to keep the heating on the whole time in the Offices, even at night and in the weekends, during the winter months, which means from November through March. It is clearly off during summer, from June to September, while it is on during office

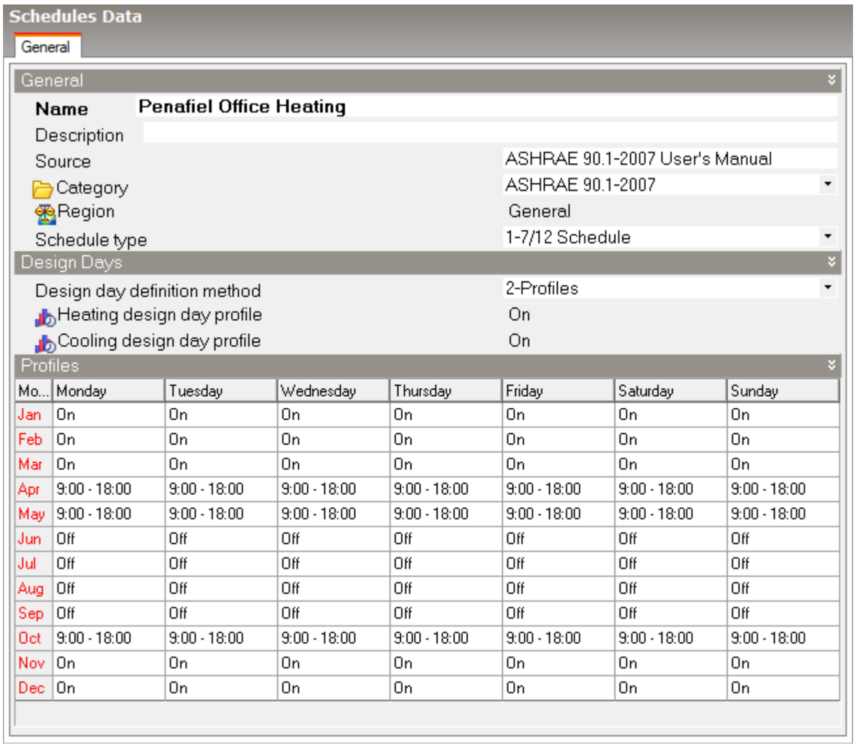
hours in April, May and October (Fig.6.12*(a)*).
In order to avoid the temperature to decrease too much in the Wine Cellar during winter, the manager prefers to keep the heating on during the coldest months also in the Hall (Fig.6.12*(b)*).
The heating is clearly off in the Storage Room and in the *WCs*.
Since the information about the Fan Coil units present in the building were meagre, it was decided to select a default template, adjusting the Heating Schedule as outlined previously.
It was also considered a Natural Ventilation schedule, imaging that the personnel opens the windows only half an hour per day during July and August, since the area is quite ventilated, and the offices are exposed North. Anyway, the Offices and the Wine Cellar are not even adjacent, thus the presence or absence of a meagre ventilation, such as the one chosen, would not affect the temperature profile of the Wine Cellar. Once again, all the technical information were taken from the defaults template, ASHRAE 90.1 Occupancy – Offices.

Openings As mentioned previously, the windows in the winery are generally kept closed, also those in the wine cellar. The only substantial opening occurs for three months, February, March and April, when the garage door of the Machinery Room is kept completely open during working hours for general operations of the production of wine, such as transportation, bottling, etc. The time schedule is shown in Fig.6.14.

6.5 The Validation

Once the model was created and completed with all the construction information, the validation part begun.
DesignBuilder is programmed to simulate different temperatures: Air Temperature, Radiant Temperature and Operative Temperature. The one selected to be compared with the experimental profile was the *Operative Temperature*, defined as a uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment.[45][46][47][48] It is indeed called as well Dry Resultant Temperature or just Resultant Temperature.

The first simulations realized were only test simulations, developed just to bring



Schedules Data
General

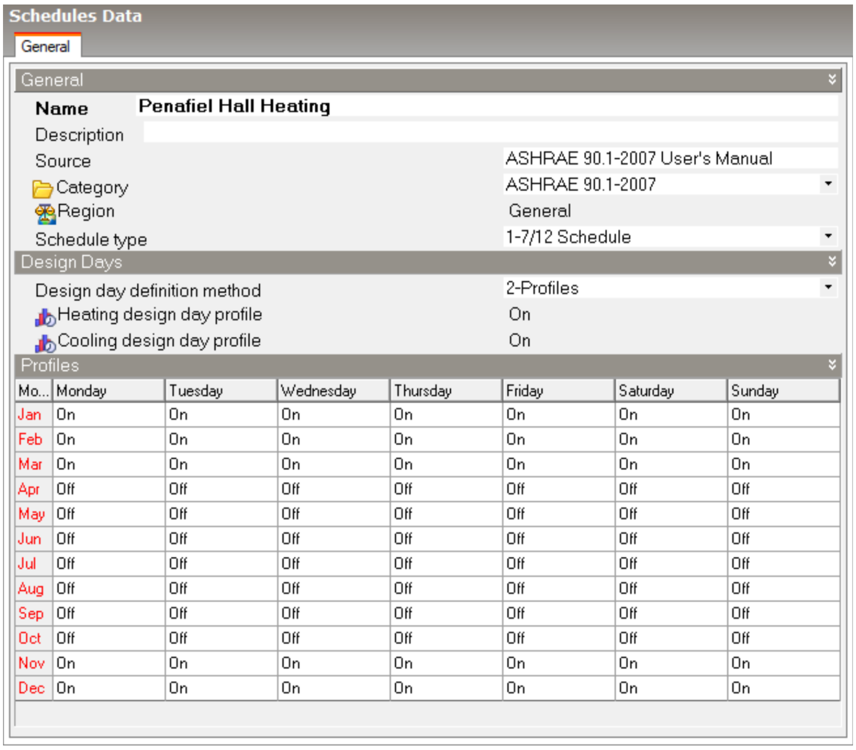
General
Name: Penafiel Office Heating
Description:
Source: ASHRAE 90.1-2007 User's Manual
Category: ASHRAE 90.1-2007
Region: General
Schedule type: 1-7/12 Schedule

Design Days
Design day definition method: 2-Profiles
Heating design day profile: On
Cooling design day profile: On

Profiles

Mo...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	On	On	On	On	On	On	On
Feb	On	On	On	On	On	On	On
Mar	On	On	On	On	On	On	On
Apr	9:00 - 18:00	9:00 - 18:00	9:00 - 18:00	9:00 - 18:00	9:00 - 18:00	9:00 - 18:00	9:00 - 18:00
May	9:00 - 18:00	9:00 - 18:00	9:00 - 18:00	9:00 - 18:00	9:00 - 18:00	9:00 - 18:00	9:00 - 18:00
Jun	Off	Off	Off	Off	Off	Off	Off
Jul	Off	Off	Off	Off	Off	Off	Off
Aug	Off	Off	Off	Off	Off	Off	Off
Sep	Off	Off	Off	Off	Off	Off	Off
Oct	9:00 - 18:00	9:00 - 18:00	9:00 - 18:00	9:00 - 18:00	9:00 - 18:00	9:00 - 18:00	9:00 - 18:00
Nov	On	On	On	On	On	On	On
Dec	On	On	On	On	On	On	On

(a) Offices *heating schedule*



Schedules Data
General

General
Name: Penafiel Hall Heating
Description:
Source: ASHRAE 90.1-2007 User's Manual
Category: ASHRAE 90.1-2007
Region: General
Schedule type: 1-7/12 Schedule

Design Days
Design day definition method: 2-Profiles
Heating design day profile: On
Cooling design day profile: On

Profiles

Mo...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	On	On	On	On	On	On	On
Feb	On	On	On	On	On	On	On
Mar	On	On	On	On	On	On	On
Apr	Off	Off	Off	Off	Off	Off	Off
May	Off	Off	Off	Off	Off	Off	Off
Jun	Off	Off	Off	Off	Off	Off	Off
Jul	Off	Off	Off	Off	Off	Off	Off
Aug	Off	Off	Off	Off	Off	Off	Off
Sep	Off	Off	Off	Off	Off	Off	Off
Oct	Off	Off	Off	Off	Off	Off	Off
Nov	On	On	On	On	On	On	On
Dec	On	On	On	On	On	On	On

(b) Hall *heating schedule*

Figure 6.12: *Offices* and *Hall* Heating schedule

the simulated profile as close as possible to the experimental one, by assigning very

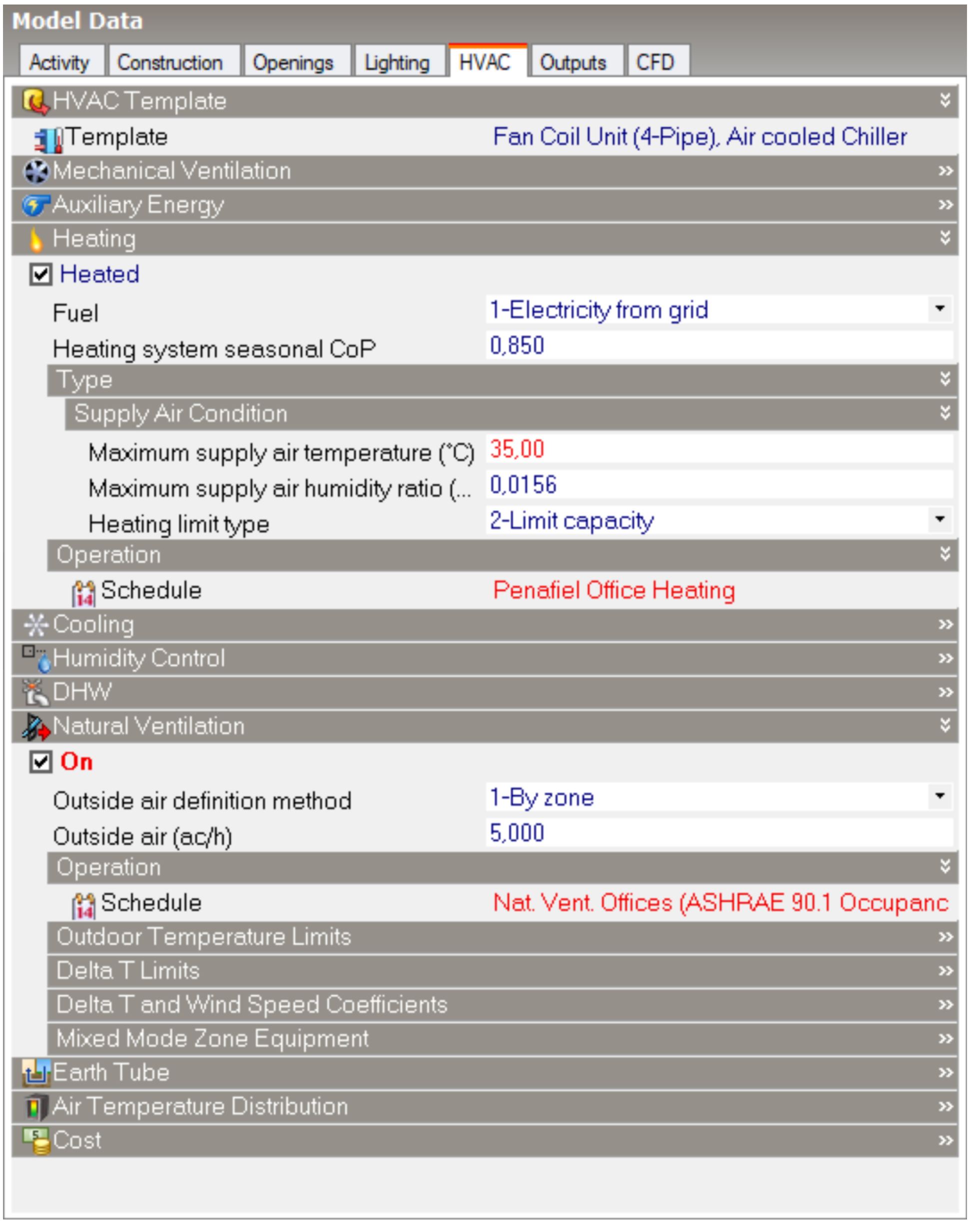
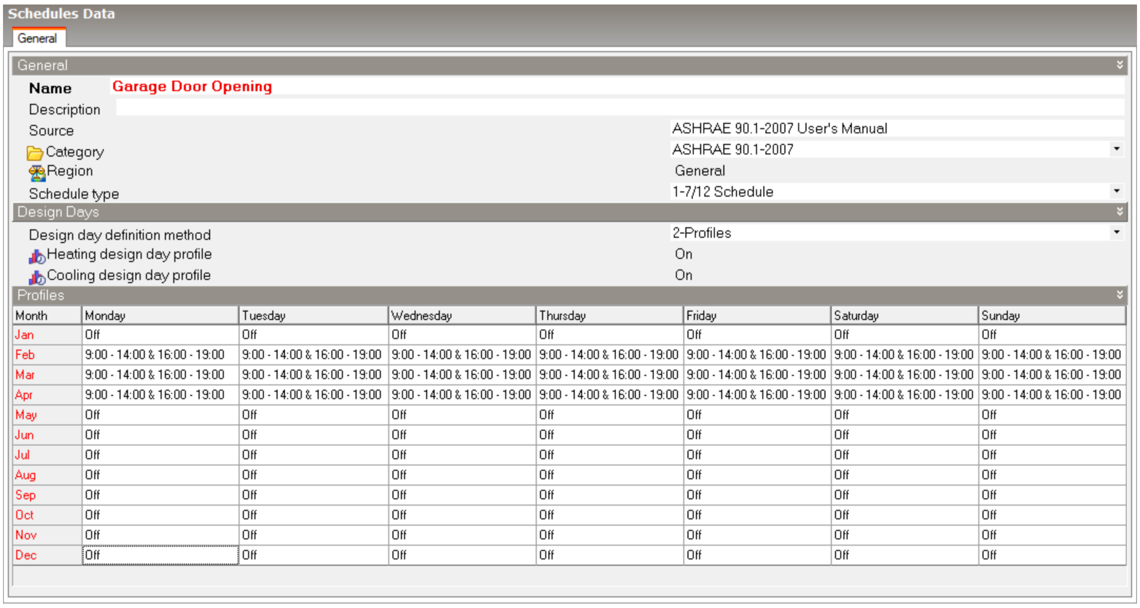


Figure 6.13: *Offices* and *Hall* HVAC system chacarcteristics

generic values to those aspects that most affect the simulation, such as infiltrations and heat gains.
Finally, arrived at an acceptable trend, it started the thoughtful part, the targeted simulation.

6.5.1 Targeted Simulation 1.0

The only factors left to adjust in the model were then infiltrations, heat gains caused by the machineries in the two Machinery Rooms, and heat gains caused by the



Schedules Data

General

General

Name	Garage Door Opening
Description	
Source	ASHRAE 90.1-2007 User's Manual
Category	ASHRAE 90.1-2007
Region	General
Schedule type	1-7/12 Schedule

Design Days

Design day definition method	2-Profiles
Heating design day profile	On
Cooling design day profile	On

Profiles

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	Off	Off	Off	Off	Off	Off	Off
Feb	9:00 - 14:00 & 16:00 - 19:00	9:00 - 14:00 & 16:00 - 19:00	9:00 - 14:00 & 16:00 - 19:00	9:00 - 14:00 & 16:00 - 19:00	9:00 - 14:00 & 16:00 - 19:00	9:00 - 14:00 & 16:00 - 19:00	9:00 - 14:00 & 16:00 - 19:00
Mar	9:00 - 14:00 & 16:00 - 19:00	9:00 - 14:00 & 16:00 - 19:00	9:00 - 14:00 & 16:00 - 19:00	9:00 - 14:00 & 16:00 - 19:00	9:00 - 14:00 & 16:00 - 19:00	9:00 - 14:00 & 16:00 - 19:00	9:00 - 14:00 & 16:00 - 19:00
Apr	9:00 - 14:00 & 16:00 - 19:00	9:00 - 14:00 & 16:00 - 19:00	9:00 - 14:00 & 16:00 - 19:00	9:00 - 14:00 & 16:00 - 19:00	9:00 - 14:00 & 16:00 - 19:00	9:00 - 14:00 & 16:00 - 19:00	9:00 - 14:00 & 16:00 - 19:00
May	Off	Off	Off	Off	Off	Off	Off
Jun	Off	Off	Off	Off	Off	Off	Off
Jul	Off	Off	Off	Off	Off	Off	Off
Aug	Off	Off	Off	Off	Off	Off	Off
Sep	Off	Off	Off	Off	Off	Off	Off
Oct	Off	Off	Off	Off	Off	Off	Off
Nov	Off	Off	Off	Off	Off	Off	Off
Dec	Off	Off	Off	Off	Off	Off	Off

Figure 6.14: Garage door opening schedule

heating in the Hall – and actually also in the Offices, but as already mentioned, since the Wine Cellar and the Offices area are not even adjacent, a slightly change of heating schedule in the Offices wouldn't affect the temperature profile in the Wine Cellar.

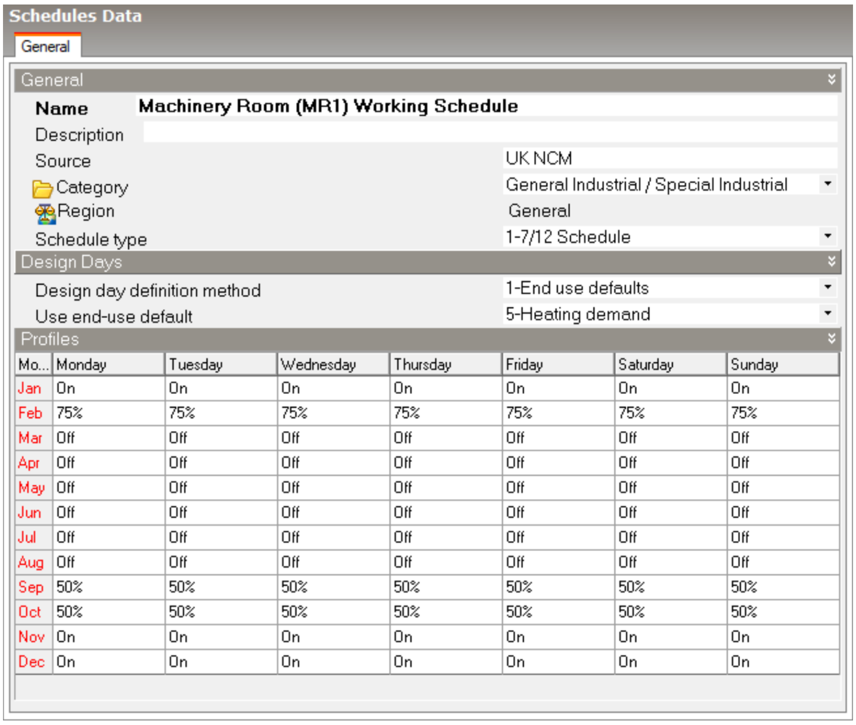
Concluded the test simulations, the model was left with the following characteristics:

- Infiltrations: 0,3 ac/h;
- Miscellaneous: heat gains produces by the machineries in the Machinery Rooms
  - Machinery Room MR1: Fig.6.15
  - Machinery Room MR2: Fig.6.16
- Hall heating schedule: Fig.6.17

With the information collected, it was developed the first targeted simulation, for the sake of brevity will be expressed as TS1 from now on. On a spreadsheet were collected the daily averages of the 365 days of the year 2018 registered by each sensor, the four inside the wine cellar and the one outside the winery.

The results are shown in Tab.6.2. From Tab.6.1 we can see that not every index satisfies the limits imposed by the ASHRAE Guideline 14 and by the IPMVP. The IPMVP, indeed, imposes to the *NMBE* to stay at least below 5, for a daily analysis.

Likewise, the AD value is above 1°C. Taking a look at Fig.6.18, the first fact that appears very clear from the graphs is that the profiles of the experimental temperatures are substantially more constant than the simulated one.



Schedules Data

General

General

Name: Machinery Room (MR1) Working Schedule

Description:

Source: UK NCM

Category: General Industrial / Special Industrial

Region: General

Schedule type: 1-7/12 Schedule

Design Days

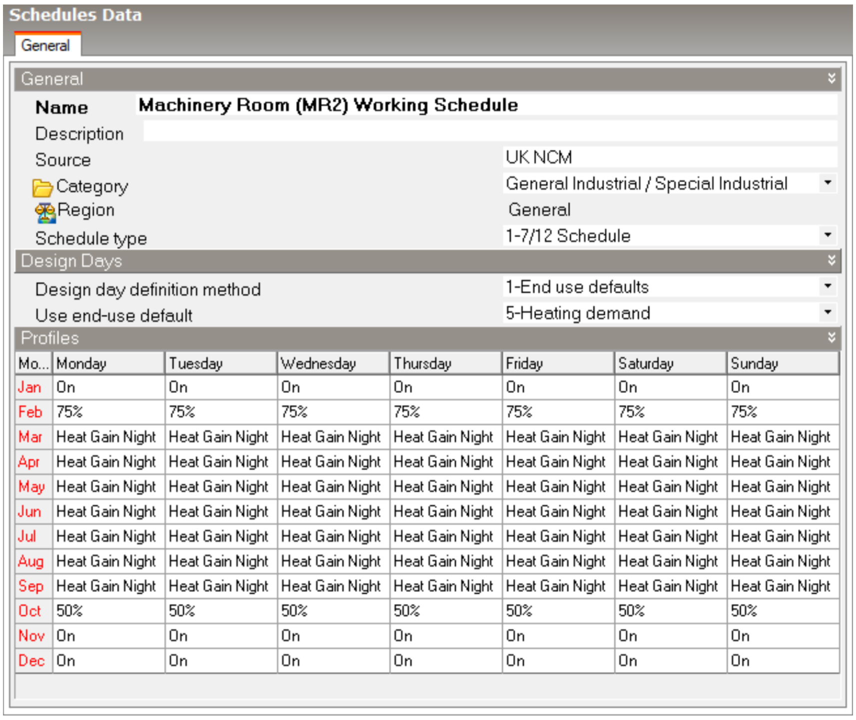
Design day definition method: 1-End use defaults

Use end-use default: 5-Heating demand

Profiles

Mo...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	On	On	On	On	On	On	On
Feb	75%	75%	75%	75%	75%	75%	75%
Mar	Off	Off	Off	Off	Off	Off	Off
Apr	Off	Off	Off	Off	Off	Off	Off
May	Off	Off	Off	Off	Off	Off	Off
Jun	Off	Off	Off	Off	Off	Off	Off
Jul	Off	Off	Off	Off	Off	Off	Off
Aug	Off	Off	Off	Off	Off	Off	Off
Sep	50%	50%	50%	50%	50%	50%	50%
Oct	50%	50%	50%	50%	50%	50%	50%
Nov	On	On	On	On	On	On	On
Dec	On	On	On	On	On	On	On

Figure 6.15: Working schedule in the Machinery Room (MR1)



Schedules Data

General

General

Name: Machinery Room (MR2) Working Schedule

Description:

Source: UK NCM

Category: General Industrial / Special Industrial

Region: General

Schedule type: 1-7/12 Schedule

Design Days

Design day definition method: 1-End use defaults

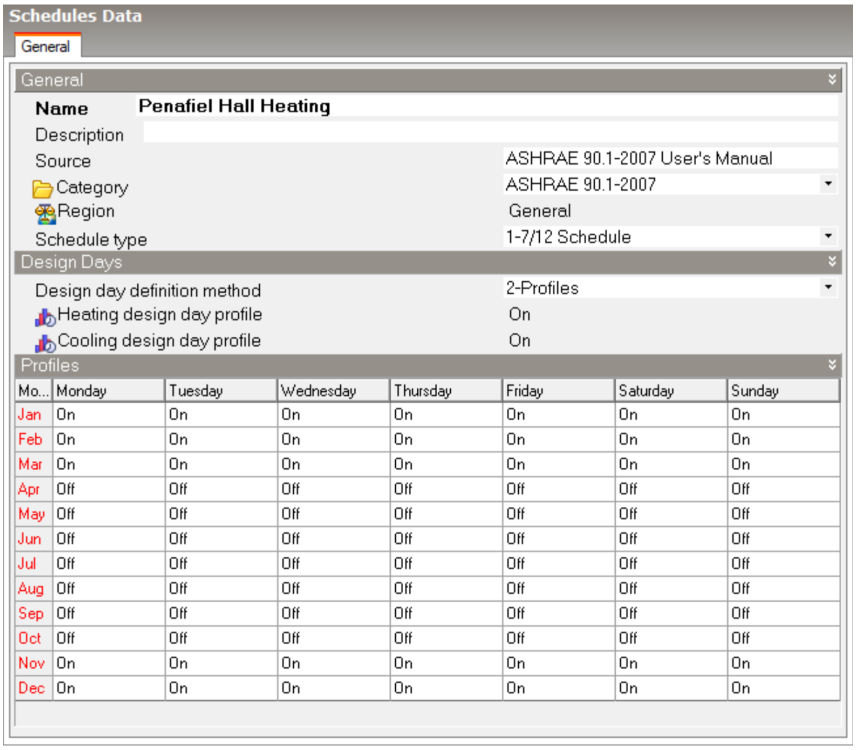
Use end-use default: 5-Heating demand

Profiles

Mo...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	On	On	On	On	On	On	On
Feb	75%	75%	75%	75%	75%	75%	75%
Mar	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night
Apr	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night
May	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night
Jun	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night
Jul	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night
Aug	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night
Sep	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night	Heat Gain Night
Oct	50%	50%	50%	50%	50%	50%	50%
Nov	On	On	On	On	On	On	On
Dec	On	On	On	On	On	On	On

Figure 6.16: Working schedule in the Machinery Room (MR2)

An explanation of such behavior could be the absence of thermal mass in the virtual model that would simulate the presence of about 700 barrels of 250l of wine. Because of its thermal inertia, wine tends to keep the temperature constant inside the wine



Schedules Data

General

General

Name Penafiel Hall Heating
Description
Source ASHRAE 90.1-2007 User's Manual
Category ASHRAE 90.1-2007
Region General
Schedule type 1-7/12 Schedule

Design Days

Design day definition method 2-Profiles
Heating design day profile On
Cooling design day profile On

Profiles

Mo...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	On	On	On	On	On	On	On
Feb	On	On	On	On	On	On	On
Mar	On	On	On	On	On	On	On
Apr	Off	Off	Off	Off	Off	Off	Off
May	Off	Off	Off	Off	Off	Off	Off
Jun	Off	Off	Off	Off	Off	Off	Off
Jul	Off	Off	Off	Off	Off	Off	Off
Aug	Off	Off	Off	Off	Off	Off	Off
Sep	Off	Off	Off	Off	Off	Off	Off
Oct	Off	Off	Off	Off	Off	Off	Off
Nov	On	On	On	On	On	On	On
Dec	On	On	On	On	On	On	On

Figure 6.17: Heating schedule in the *Hall*

Table 6.2: TS1 indexes results

	AD (°C)	***NMBE***	***CV(RMSE)***	R^2
TS1	1,09	5,24	7,27	0,96

cellar, resulting in a flatter temperature profile.
For such reasons, the first adjustment that should have been made was indeed the creation of a thermal mass.

Thermal Mass It was first created a *Component Block* to which were assigned the appropriate characteristics, as shown in Fig.6.20. It was then developed another simulation, but the data did not vary a bit, they kept the same numbers up to the fifth decimal.

It was then decided to attempt a different way, trying to build a *Virtual Partition* to which were assigned wine characteristics (Fig.6.21), just as previously, and the maximum thickness allowed, 3 m. Again, it was developed another simulation and once more, the data did not slightly vary.

It was decided to give up on this solution, and the adjustments moved on to the examinations of the energy balance diagrams.

Another aspect quite notable on the TS1 is that the simulated temperature is

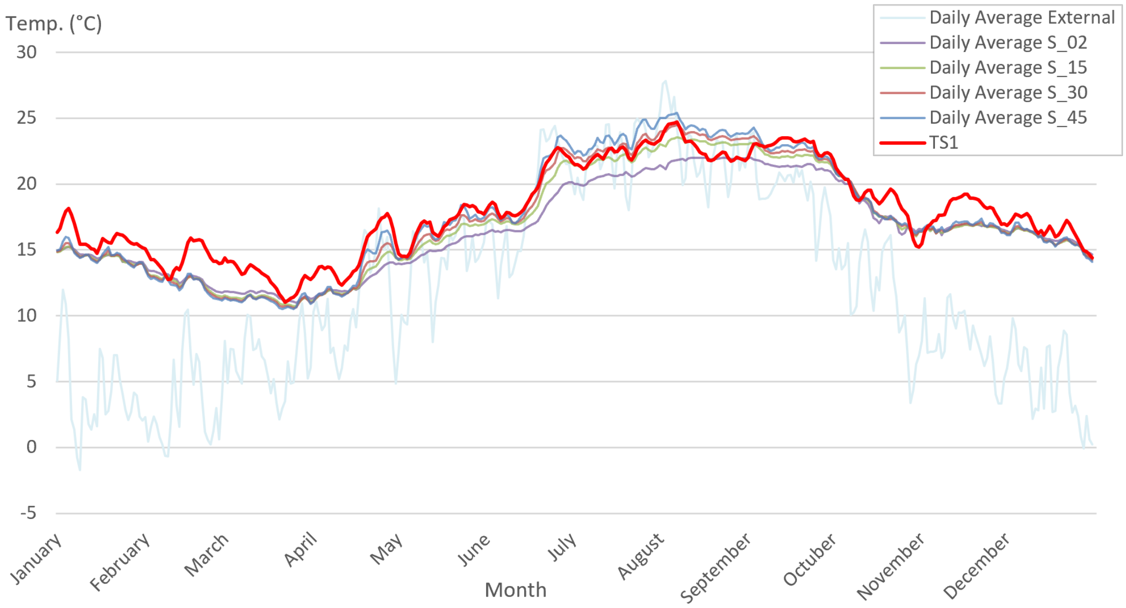


Figure 6.18: TS1 profile compared to the experimental temperatures

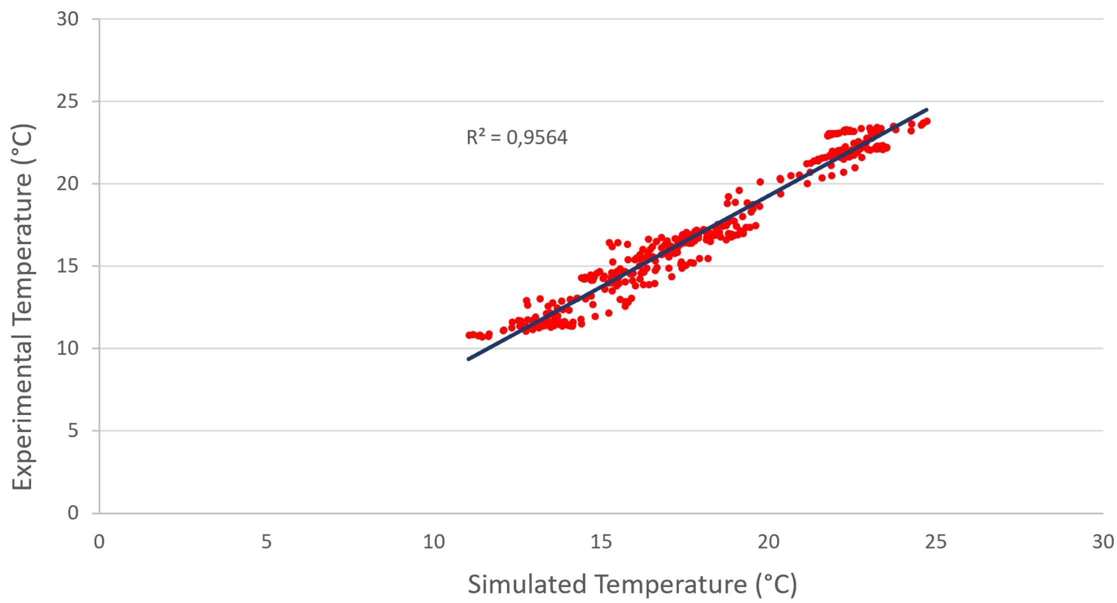


Figure 6.19: Coeff. of Determination - TS1

generally higher than the experimental one. This could be caused by an unreasonably high amount of heat gains, not coherent to the actual ones.

Heat Gains In the test simulations were assigned to the heat gains caused by the machineries diminishingly values, from $200W/m^2$, downward. Reached the TS1, the

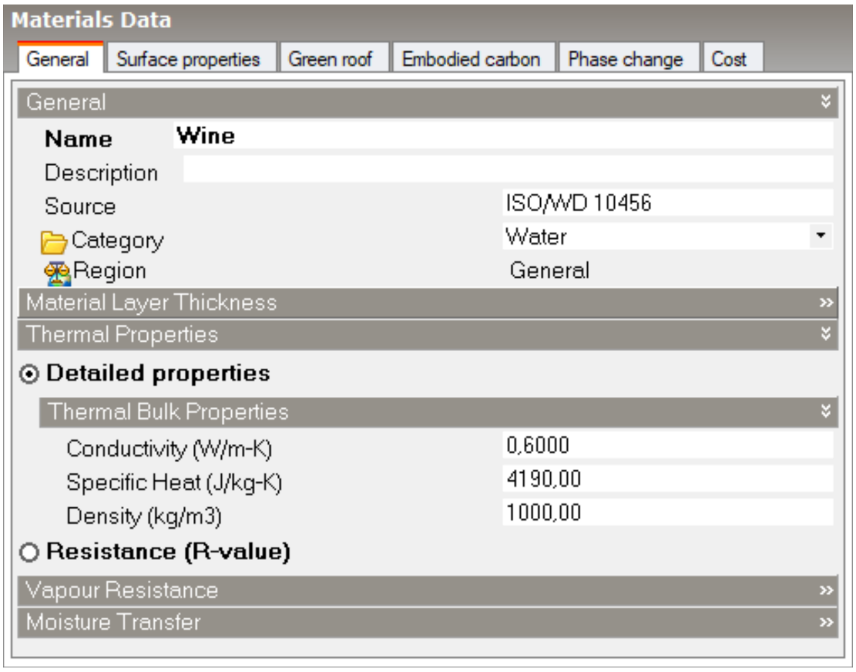


Figure 6.20: Wine characteristics assigned to the *Component Block*

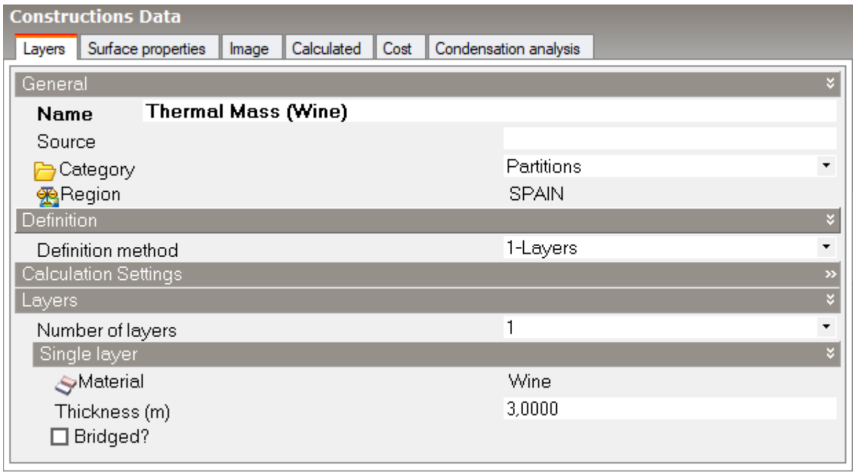


Figure 6.21: Wine characteristics assigned to the *Virtual Partition*

value was corresponded to $75W/m^2$ for the Machinery Room MR1, and $25W/m^2$ in the Machinery Room MR2, but as mentioned previously, such values did not reflect the reality for the major part of the year.

Accordingly to what expressed by the winery manager, the only months with an intense use of the machineries are those related to the fermentation of wine, which correspond to January, February, October, November and December. Hence it was decided to leave the heat gains at $75W/m^2$ and $25W/m^2$ for that period, bearing in mind the fact that it could have been changed in a second moment.

Regarding the other months of the year, it was considered that the day of the

inspection at the winery was a normal labor day, in other words, the heat gains produced on the 13th of May were more or less the same produced every other day of the remaining months. Hence, since the heat gains that day appeared quite insignificant, it was decided to set them to a null value the rest of the months.
Thus, the heat gains were divided in *On* and *Off*, with only three exceptions:

- September and October: the fermentation machineries are not in use, but the production of wine has started, with the harvest and the pressing of the grapes, thus it was considered a 50% of the prefixed value ($75W/m^2$);
- February: this is the month of passage from the fermentation process to the movement of wine in barrels and other containers. Since it is not possible to establish different schedule in different moments of the month, it was considered a constant 50% of the prefixed value, even if such solution does not correspond to reality, as can be seen in the graph.

For what concerns the Machinery Room MR2, the same considerations have been acknowledged, with one slightly difference.
During the inspection the manager outlined how every night the lift truck is charged in the Machinery Room MR2. For such matter, instead of setting the heat gains Off from March to September, they have been assigned the schedule shown in Fig.6.22.
The general schedule is shown in Fig.6.16.

Still the model could be improved, the R^2 should at least be higher than 0,9 and the Average Deviation should be lower than 1,0°C.
It was then decided to extract from DesginBuilder the Energy Balance graphs in order to understand from which part of the building occurred the major heat losses or heat gains (Fig.6.23).

By looking at the graph in Fig.6.18 appears clear how the simulated profile is generally higher than the four experimental ones relative to the four sensors. It is understandable, considering the trends shown in Fig.6.23, how the Wine Cellar reproduced in the virtual model receives too many heat gains from the surrounding thermal zones – being the partitions the only source from which the Wine Cellar could be warmed up. For such reasons it was decided to bring the heat gains, caused by the machineries in the adjacent room, from $75W/m^2$ to a value of $50W/m^2$. Such changes brought to the next simulation.

Moreover, it is also important to notice that the air stratification is probably

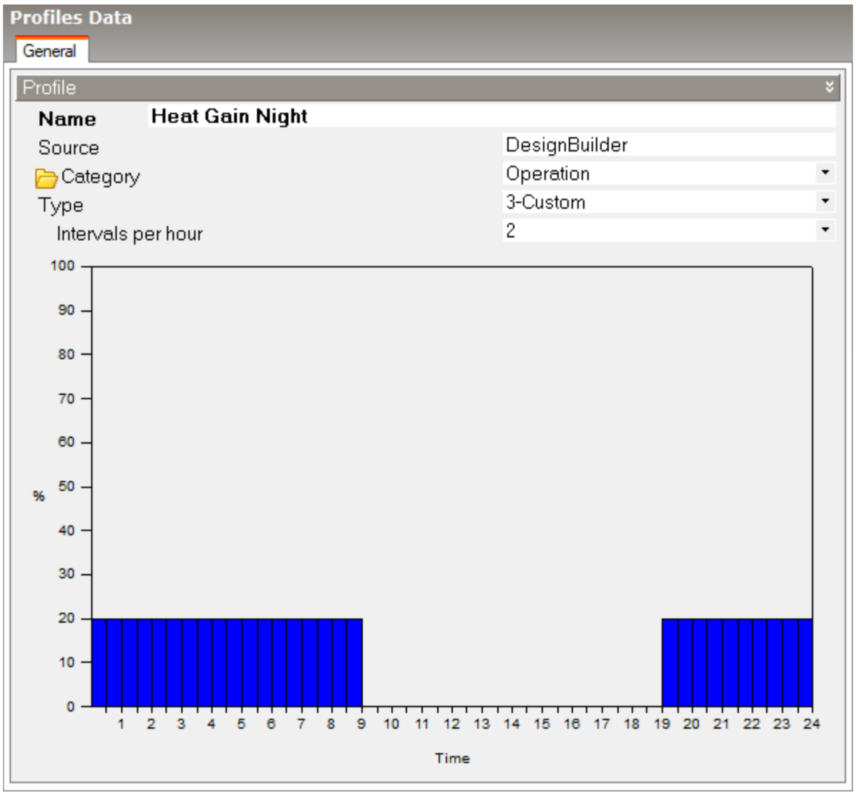


Figure 6.22: Night heat gains schedule of the smaller machinery room

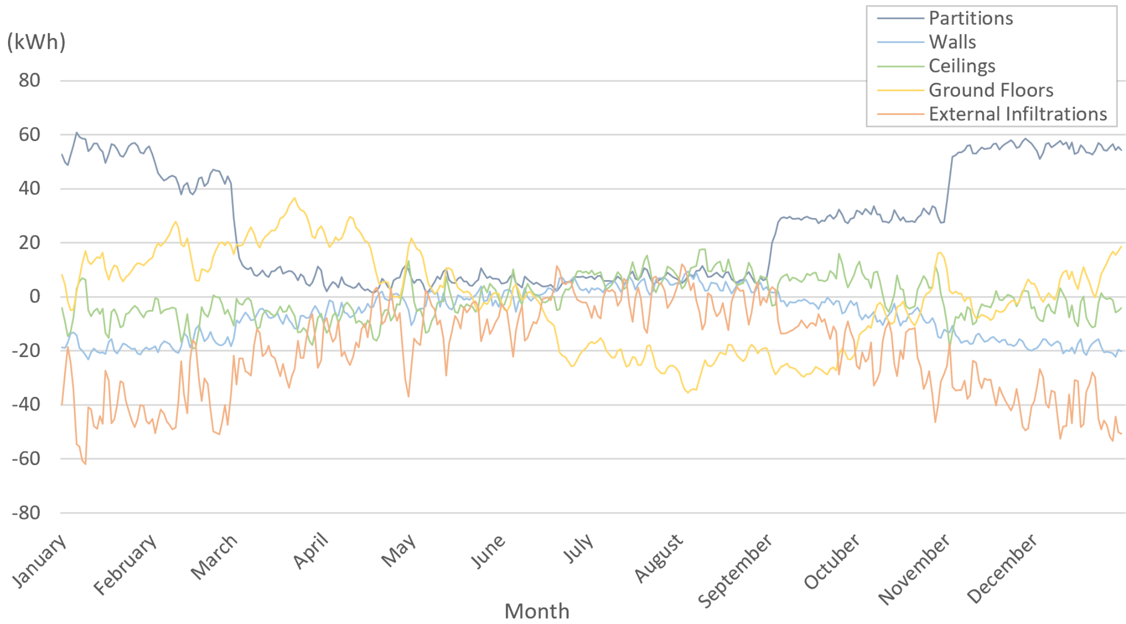


Figure 6.23: Energy Balance - heat gains and heat losses - TS1

caused by two factors. On one hand, as already mentioned in the data analysis, it is caused by the sun radiation warming up or cooling down the roof depending on the season. On the other hand the delta temperature probably depends also on the

influence of the ground floor that, as commented previously, warms up the wine cellar during winter and cools it down during summer.
This theory is reinforced by the fact that temperature does not oscillates during the 24h period in summer, in other words, temperature is not influenced by solar radiation incident on the roof during the day, nor by the irradiative exchange with the sky at night (see Fig.5.20).

6.5.2 Targeted Simulation 2.0

After diminishing the heat gains caused by the machineries in the Machinery Room MR1, the results improved, as shown in Tab.6.3.
Still, looking at the graph in Fig.6.24 can be noticed that the simulated profile is

Table 6.3: TS2 indexes results

	AD (°C)	***NMBE***	***CV(RMSE)***	R^2
TS2	0,85	1,88	6,12	0,94

still quite distant from the experimental temperatures in the months of February and March.
The only adjustments admissible at this point would be the schedule of the heating

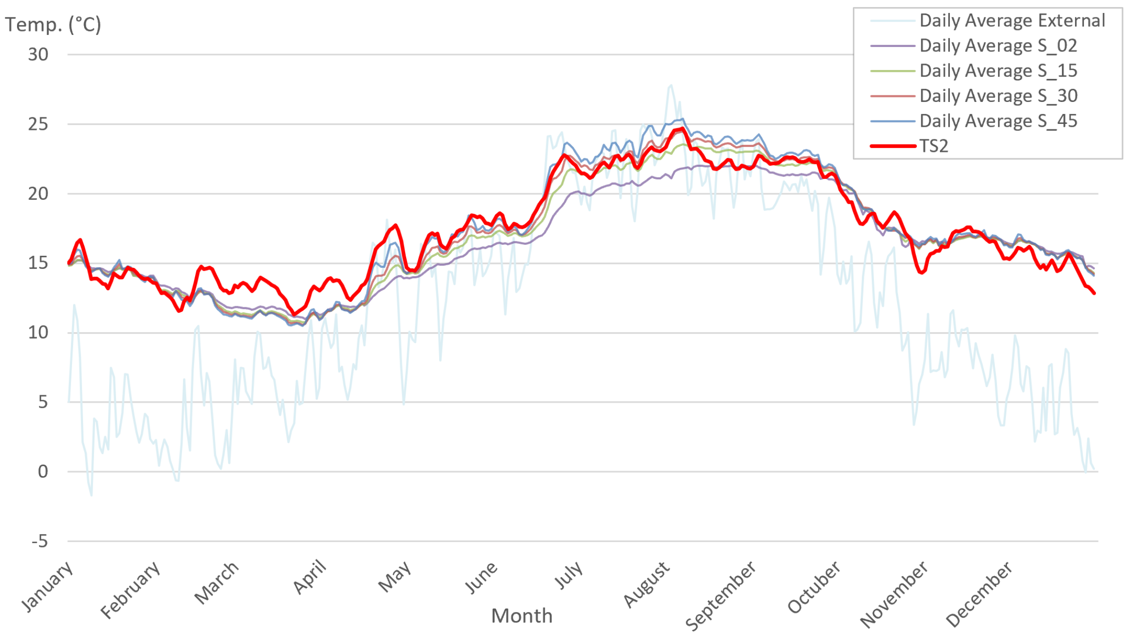


Figure 6.24: TS2 profile compared to the experimental temperatures

in the Hall, since it remains the factor with most uncertainties.

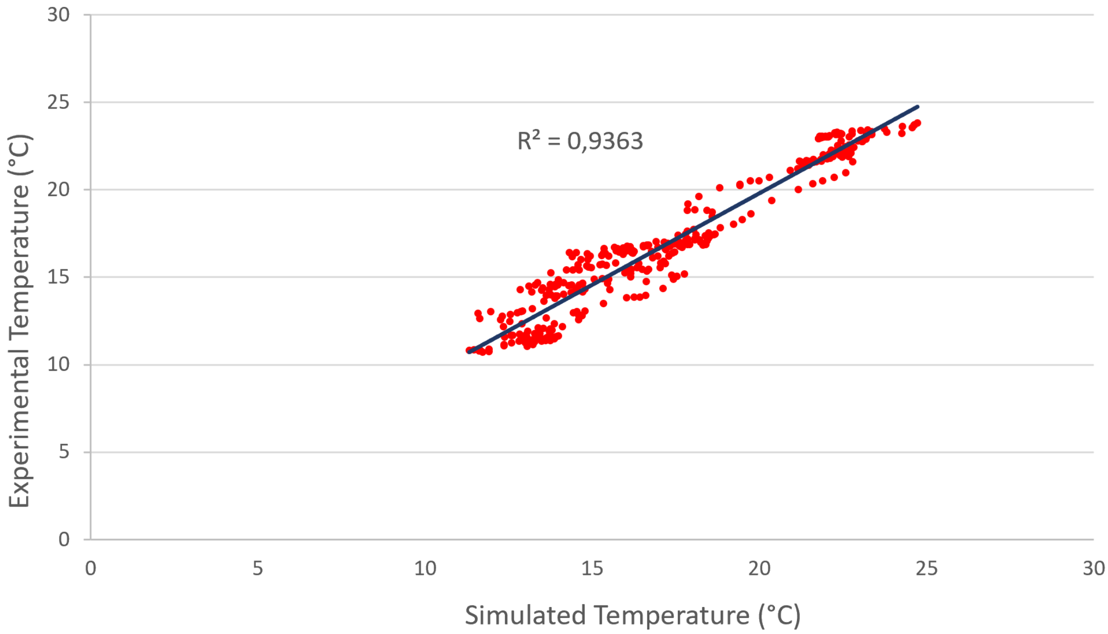


Figure 6.25: Coeff. of Determination - TS2

Furthermore, once again the graph in Fig.6.26 suggests that the only heat gain in the Wine Cellar could be received, in the winter months, by the those partitions adjacent either to the Machinery Room MR1 or to the Hall.
Since there is no reason to think that the Working Schedule of the Machinery Room MR1 is not coherent to what already considered, the only option left is to change indeed the heating schedule in the Hall.

6.5.3 Targeted Simulation 3.0

These last adjustments finally gave the model credibility, with a Coeff. of Determination equal to 0,95 and an average deviation of 0,72°C. The *NMBE* was decresed considerably too, while the *CV(RMSE)* value has remained low.
Surely, the model is not perfect and never will, but it could anyway be improved.

Table 6.4: TS3 indexes results

	AD (°C)	***NMBE***	***CV(RMSE)***	R^2
TS3	0,72	0,40	5,22	0,95

As already mentioned, all those fluctuations still quite evident the graph in Fig.6.27 are not actually present in the experimental profiles. The inclusion of a thermal mass would probably decrease the rather costant – even though oscillating – error

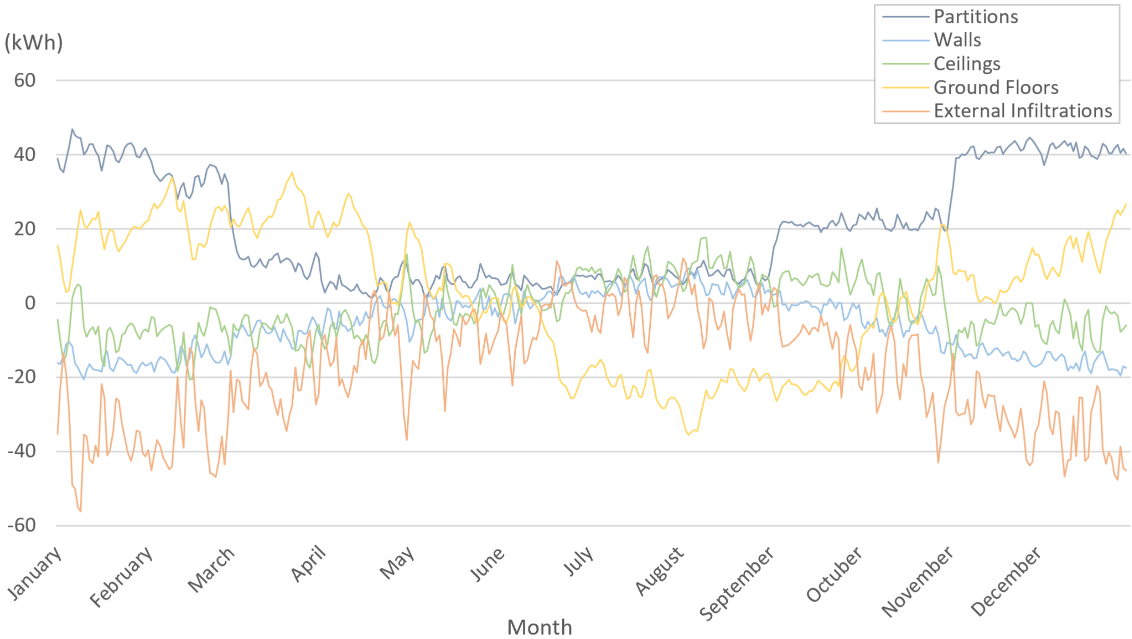


Figure 6.26: Energy Balance - heat gains and heat losses - TS2

caused by its absence.

Otherwise, the model could be now considered Validated and fairly accurate and

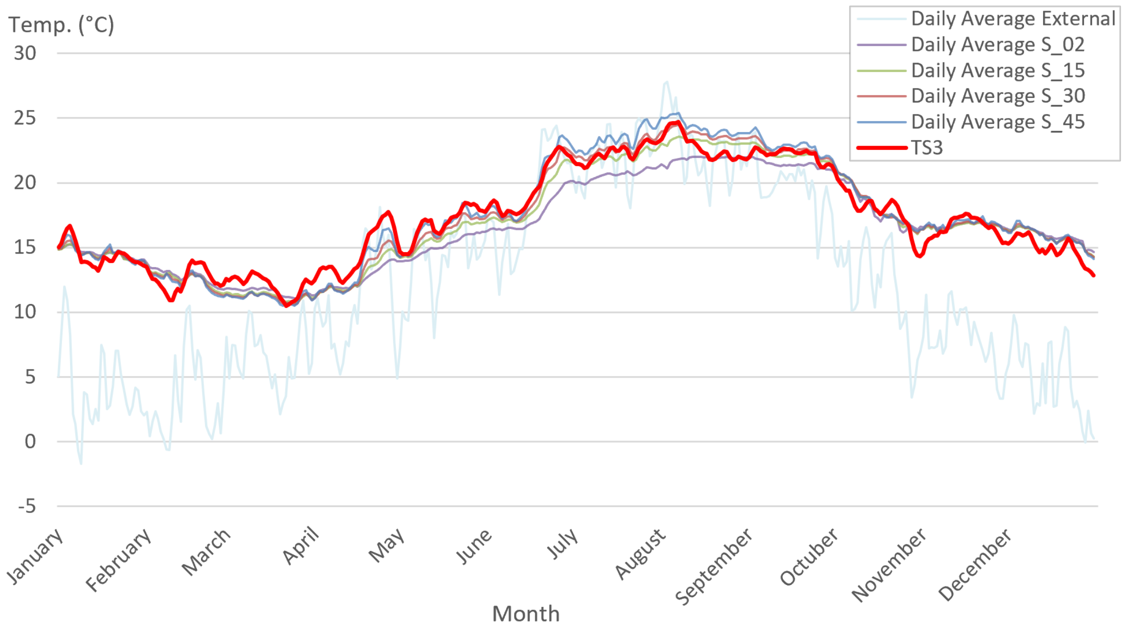


Figure 6.27: TS3 profile compared to the experimental temperatures

trustworthy to be used as base model for the next step of this study, the implementation of passive systems.

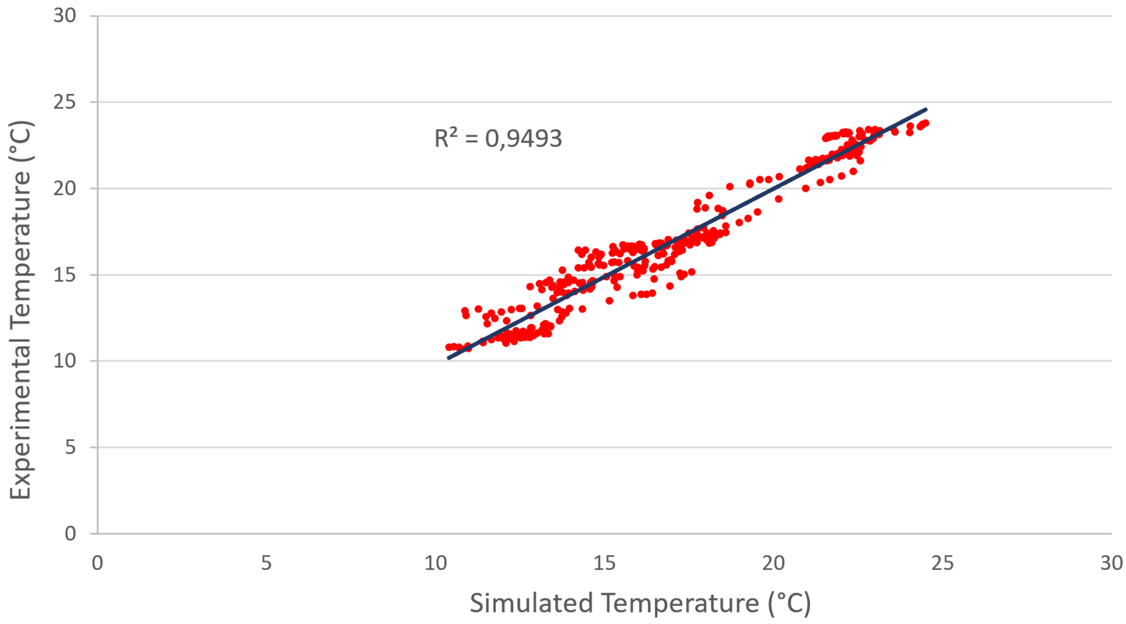


Figure 6.28: Coeff. of Determination - TS3

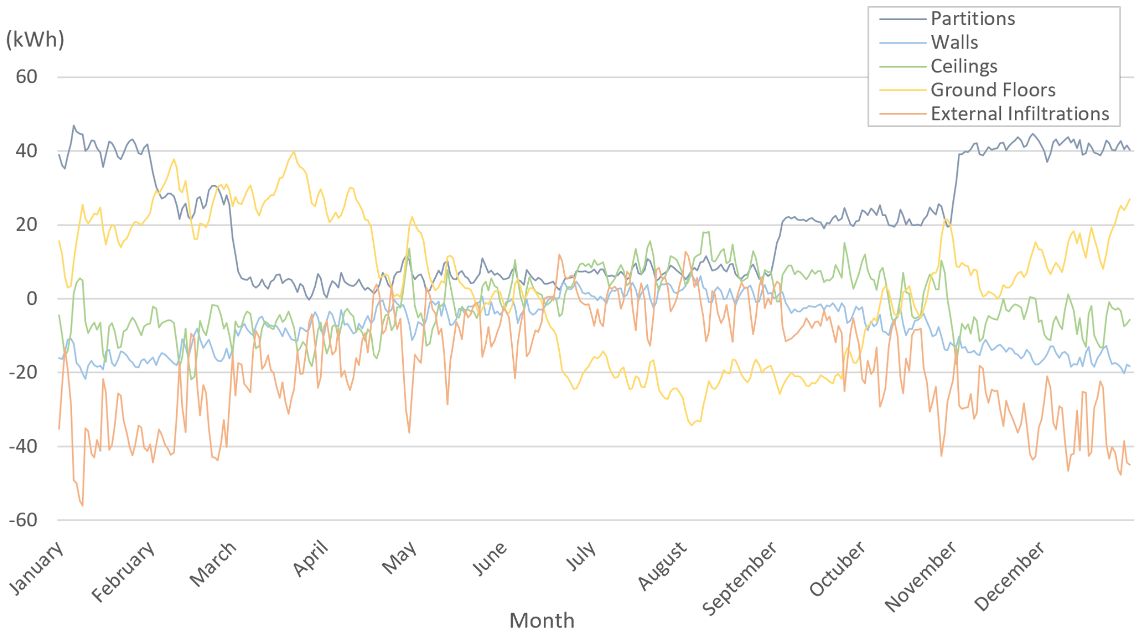


Figure 6.29: Energy Balance - heat gains and heat losses - TS3

6.5.4 Comments

From the three graphs (Fig.6.18, Fig.6.24 and Fig.6.27) we can see how the model simulates temperature oscillations that are not so evident in the experimental profiles. We can suggest that those frequent fluctuations of temperature are caused by the absence of a thermal mass that simulates the 700 barrels of wine, as this is the only variable that could not be simulated.

Indeed, it was also tried to increase the width of thermal insulation on the vertical envelopes and of the roof, but the only result was a general increase of temperature and a slightly reduction of the fluctuations.
Taking a careful look at the graph in Fig.6.29, we can notice that the fluctuations due to the partitions are stepped distributed in the months of January, February, September, October and December, namely, those to which were assigned the non-null values of heat gains due to the Machinery Rooms working schedule. As such results are not properly reflecting the reality – we could imagine that the machinery heat gains change more gradually from a month to another – there is still nothing that could be done to improve the results, since DesignBuilder does not permit a day-by-day schedule, and since the information about the heat gains are quite a wild card. Indeed, these values were assigned only by looking at the ASHRAE Handbook that suggests considering such values for particular industrial activities, comparable to those run in the Machinery Rooms.

For what concerns the heat gains and losses through the envelope of the building, we can see how the direct contact with the ground floor has a positive impact on the temperature inside the Wine Cellar. Indeed, if for the human comfort a ground floor construction with no thermal insulation would be just terrible, for a Wine Cellar that needs to keep the temperature around the 15°C seems just perfect. Indeed, the ground temperature is more and more constant as the depth increases, and at about 3 – 4 m depth the temperature varies around 14 – 16°C. It is true that the winery's foundations reach the 1,6 m depth, but it is as well true that the ground under the building does not report the same heat exchange with the open-air environment as the ground that surrounds the winery. Indeed, the ground under the winery, not being in contact with the open-air, does not exchange heat by convection nor by irradiation with the sky, thus, its temperature stays more constant and does not decrease during the cold months. As well, during summer, the ground under the winery is not warmed up by solar radiation, and its temperature does not reach high values, but stays quite fresh and removes some heat from the winery above.

Furthermore, the high thermal inertia of the ground floor, constituted by layers of concrete, explains why the Wine Cellar is heated up in winter and cooled down in summer. Indeed, the ground slab accumulates heat during summer and releases it slowly to the internal environment of the Wine Cellar once the temperature starts to decrease. During winter the heat accumulated is released to the internal environment, whose temperature now is substantially lower, and the ground slab gradually cools down. During summer, the opposite happens, the ground slab, now entirely cooled down, absorbs heat from the internal environment whose temperature now is quite high, as shown in the analysis.

From the ceiling and the vertical envelopes, the heat exchange is more moderate throughout the year. This could be justified by the presence of thermal insulations in both the construction components. The greater influence of the ground floor with respect to the walls and the ceilings is partly due to the difference of Thermal Transmittance between the three components. As shown in Fig.6.5, the external envelope has a U-value of 0,381 W/m^2K, in Fig.6.8 the ground floor reports an U-value of 0,906 W/m^2K, and in Fig.6.11 it is reported the U-value of the roof, equal to 0,449 W/m^2K. This substantial difference could be the reason why the Wine Cellar exchanges much more heat with the ground than with the external environment.
As predictable, the heat exchanges are negative during winter, meaning that heat is extracted from the internal environment, which cools down, while they are positive in summer, meaning that the winery is heated up. Both these effects are negative for the wine comfort since the winery should be warmed up a little during winter and cooled down during summer in order to reach the hygrothermal conditions required.

From the graph in Fig.6.29 we can see how the heat gains due to the external infiltrations follow the external temperature trend. It was considered that the reason of the fluctuations of the simulated temperature profile could be caused by an excessive amount of infiltrations, but as it was increased the airtightness in other to flatter the profile, it was noticed that the fluctuations stayed the same.
After this last attempt it was realized that there are several combinations of the construction airtightness, the amount of heat gains caused by the machineries, the openings schedules, and many other factors, that return very similar temperature profiles. From the results shown in Tab.6.4 it was decided that the accuracy of the present model is acceptable for the purpose defined at the beginning of this study.

The next step is indeed the research of suitable passive systems that would fairly improve the comfort conditions of the Wine Cellar. More specifically, the graph in Fig.6.27 and the Seasonal Analysis reported in section 5.1.4 show the urgency of decreasing the temperature during summer, at least of $6-7$°C.
From the graph in Fig.6.4 it is quite evident how there are very few heat gains during the hot months that warm up the Wine Cellar. Indeed, on the contrary of

what was thought before, it is quite difficult to find a passive system suitable for the building in question, that would decrease the internal temperature of more than 15°C with respect to the external one. Nonetheless, passive systems such as ventilated or green roofs, ventilated or green facades, were developed and studied to keep the human comfort conditions, which during the hot season usually report an internal temperature few degrees lower than the external one, as the human body considerably acclimates to the surrounding environment. The purpose of the study was indeed to find a sustainable way to keep the internal temperature below 18°C the whole year.

Chapter 7

Implementation of passive systems

From the analysi appeared clear that the first interventions to be made on the winery construction system regarded the roof. The data analysis outlined how the heat transfer through the roof had major impact on the hygrothermal conditions of the wine cellar, showing a great vertical delta temperature, with values increasing at the higher sensor during summer and decreasing during winter.

Hence, the first attempts pointed toward the modification of the roof structure.

7.1 Insulation

The simplest and commonest passive system is the thermal insulation. This last part of the thesis begun with a study of the most adequate thickness and position of a thermal insulator. Three attempts were carried out of three Thermal Insulation Thicknesses positioned on the innermost surface of the pitched roof:

1. TIT1: 5cm;
2. TIT2: 15 cm;
3. TIT3: 25cm.

7.1.1 TIT1

The first try involved the addition of 5cm of thermal insulator on internal surface of the pitched roof.
Following are reported the characteristics of the insulation layer (in Tab.7.1) and the pitched roof envelope (in Tab.7.2).

Table 7.1: Characteristics of the thermal insulation material

Material	**Conductivity** (W/mK)	**Thickness** (m)	**Resistivity** (m^2K/W)
Polyurethane foam	0,028	0,05	1,79

Table 7.2: U-value of the pitched roof envelope before and after the thermal insulation addition

U-value of the *old* pitched roof (W/m^2K)	**U-value of the *new* pitched roof** (W/m^2K)
0,449	0,249

It is reported in Fig.7.1 the temperature profile that would be registered throughout the year if the pitched roof had an additional thermal insulation layer of 5cm of polyurethane foam.

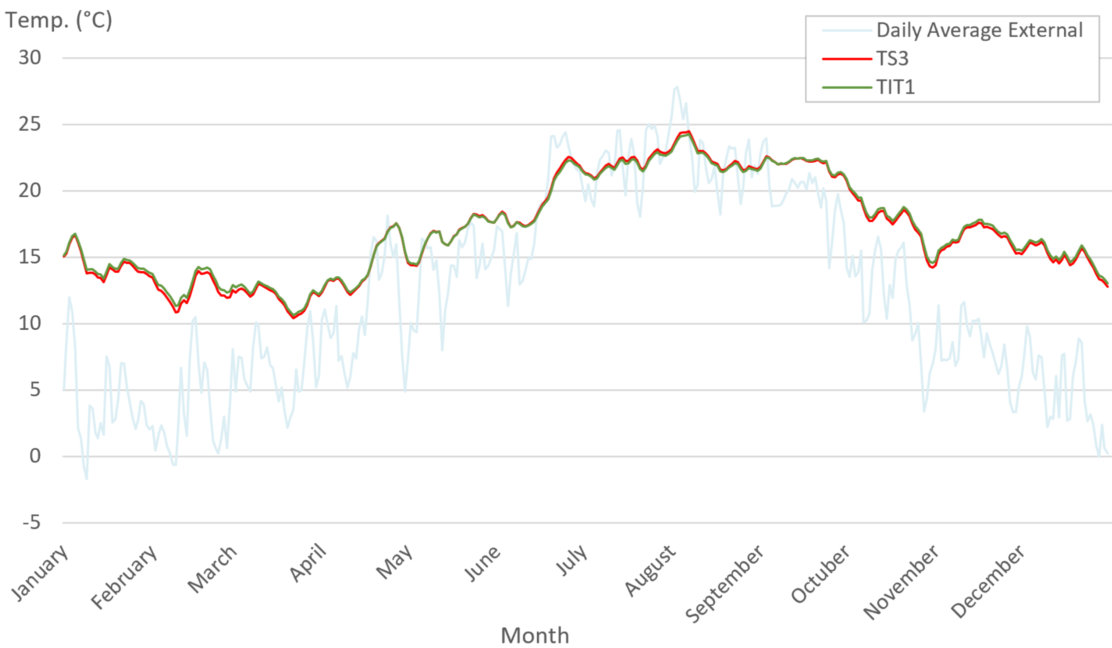


Figure 7.1: Temperature profile of the first attempt of thermal insulation - I1

Since the addition of an extra insulation layer did not report much difference in the temperature profile, it was decided to increase the thickness of the thermal insulation layer to see to what extent the wine comfort conditions could be improved with such a passive systems solution.

7.1.2 TIT2

Thus, the thermal insulation thickness was increased to 15cm, and left in the same position.
Following are reported the characteristics of the insulation layer (in Tab.7.3) and the pitched roof envelope (in Tab.7.4).

Table 7.3: Characteristics of the thermal insulation material

Material	**Conductivity** (W/mK)	**Thickness** (m)	**Resistivity** (m^2K/W)
Polyurethane foam	0,028	0,15	5,36

Table 7.4: U-value of the pitched roof envelope before and after the thermal insulation addition

U-value of the *old* pitched roof (W/m^2K)	**U-value of the *new* pitched roof** (W/m^2K)
0,449	0,132

It is reported in Fig.7.2 the temperature profile that would be registered throughout the year if the pitched roof had an additional thermal insulation layer of 15cm of polyurethane foam.

Again, we can see that the temperature profile generated by the addition of 15cm of polyurethane foam does not vary substantially from the temperature profile of the actual situation. Indeed, the maximum they differ of is 0,82°C.
As the internal conditions are improving, it was decided to keep increasing the thermal insulation thickness and see the outcome.

7.1.3 TIT3

The third attempt brought the thickness of additional thermal insulation layer to 25cm.
Following are reported the characteristics of the insulation layer (in Tab.7.5) and the pitched roof envelope (in Tab.7.6).

From the graph in Fig.7.4 we can see how the temperature attenuation registered by this last application is less evident than in the passage from I1 to I2. The temperature profile generated by the addition of 25cm of thermal insulator differs

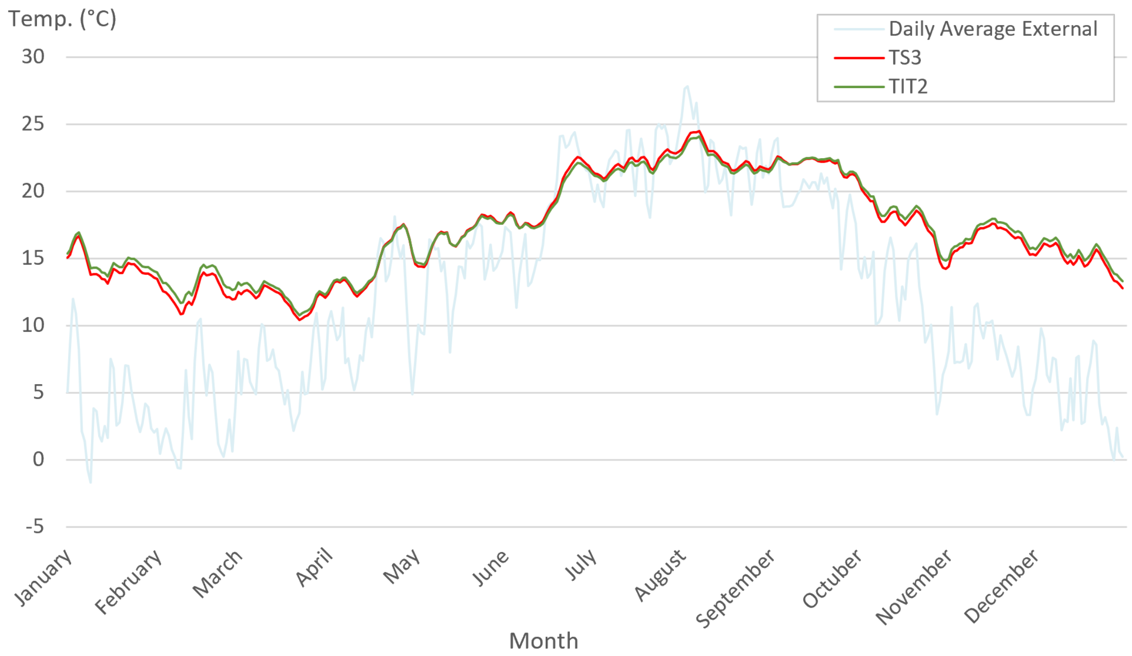


Figure 7.2: Temperature profile of the second attempt of thermal insulation - I2

Table 7.5: Characteristics of the thermal insulation material

Material	Conductivity (W/mK)	Thickness (m)	Resistivity (m^2K/W)
Polyurethane foam	0,028	0,25	8,93

Table 7.6: U-value of the pitched roof envelope before and after the thermal insulation addition

U-value of the *old* pitched roof (W/m^2K)	U-value of the *new* pitched roof (W/m^2K)
0,449	0,09

from the temperature profile of the actual situation for a maximum of 0,93°C, only 0,11°C less than I2.

7.1.4 Comments

The last simulation was carried out knowing that such passive solution would never be applicable, for a matter of cost-effective. If we look at the graph in Fig.7.4 we notice how the curve thickness – temperature reduction is formed by two segments characterized by substantially different slopes. The graph outlines how after a certain thickness the thermal insulator loses gradually its effectiveness. This means that even by increasing the additional thickness to unreasonably high values, such as

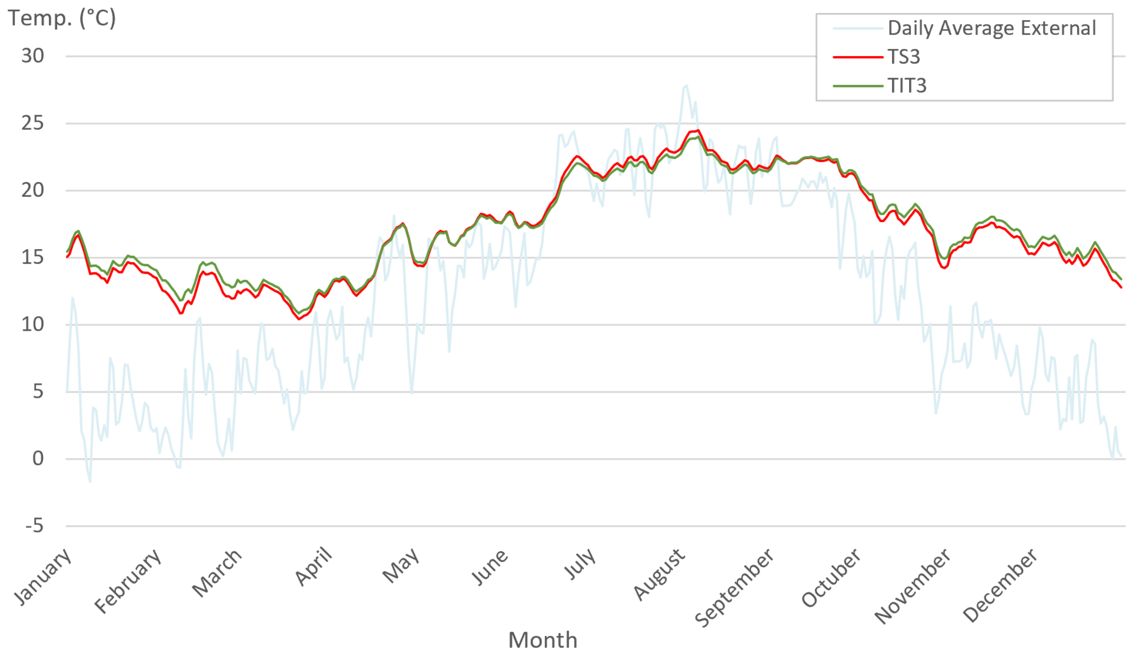


Figure 7.3: Temperature profile of the third attempt of thermal insulation - I3

30cm, we would not obtain the desired result of decreasing the temperature during the summer period of about 6 – 7 °C, especially because the largest temperature variations are registered in winter, when the wine cellar is, hence, warmer due to the additional insulation.

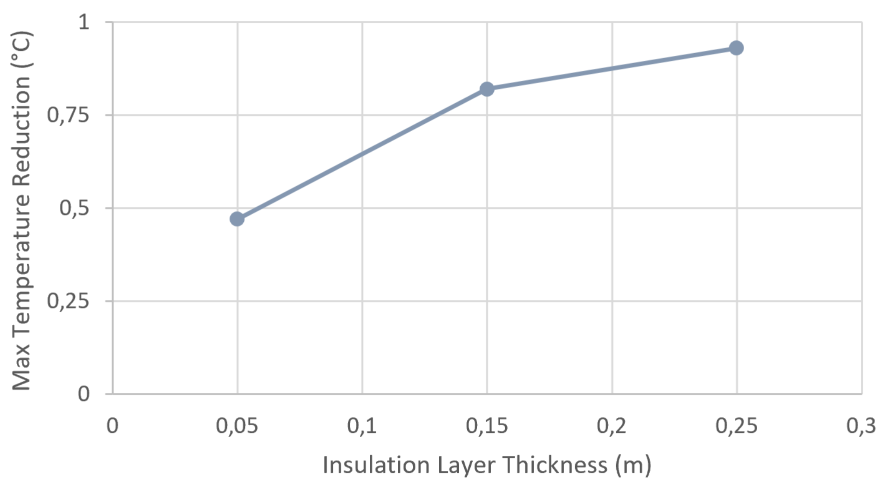


Figure 7.4: Insulator thickness and maximum temperature reduction - I3

7.2 Ventilated envelopes

As the two main insulating passive systems did not show the desired results, it was decided to try with the passive cooling. The most common solution for a passive cooling system is the ventilated envelope, being a pitched roof or a vertical envelope. Computing a ventilated envelope with DesignBuilder is no easy task. The procedure used to model such a passive cooling system is explained below:

1. The ventilated air layer is processed by DesignBuilder as a cavity. In order to create such cavity, internal partitions are drawn at 5cm from the innermost surface of the external envelope. To such partitions are assigned the characteristics of the external envelope. Doing so, the outermost layer becomes the double skin (see Fig.7.5 (c) and Fig.7.6).

2. The cavity is now to DesignBuilder another thermal zone. In order to let the software compute it as a ventilated layer it is necessary to set the Zone type on the Activity tab to *3-Cavity* at zone level in the cavity zone (see Fig.7.5 (a) and Fig.7.6). This causes the following further changes to be made to the model:

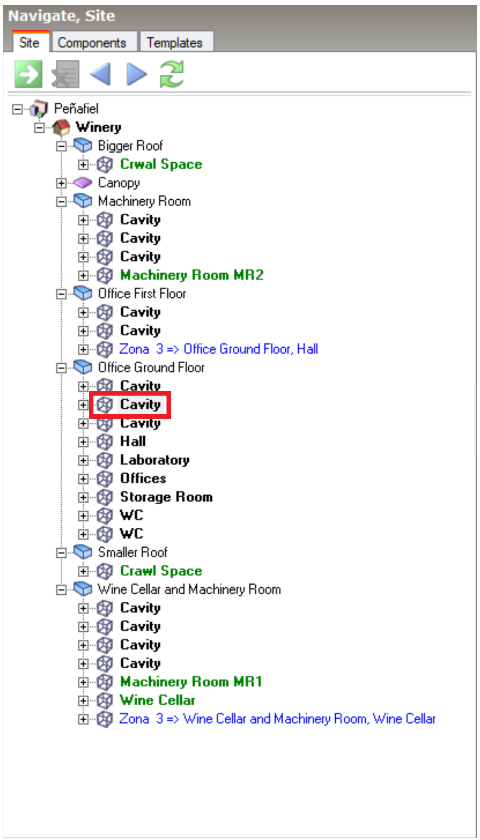
    (a) The zone is set as unoccupied by loading <None> Activity, HVAC and Lighting template data (see Fig.7.5 (b)).

3. The air tightness of the cavity is set to the maximum allowed value, 5ac/h, in order to simulate the openings present on the ventilated facades.

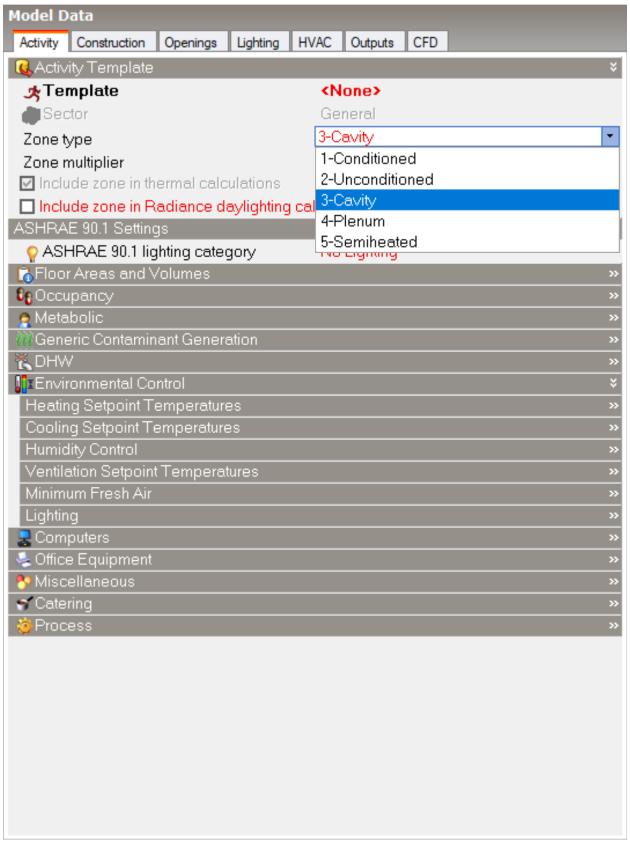
4. From the ISO 6946:2007(E) - Annex B [49] it was retrieved the value of the convective coefficient for vertical ventilated façade with a upward heat flow – which is the most common in naturally ventilated facades. This Convective Heat Transfer Coefficient, $h_c = 5,0 W/m^2 K$, was set on the Internal Surface of the double skin from the Construction Data tab.

The ventilated facade was implemented on the whole building minus on the facade exposed north.

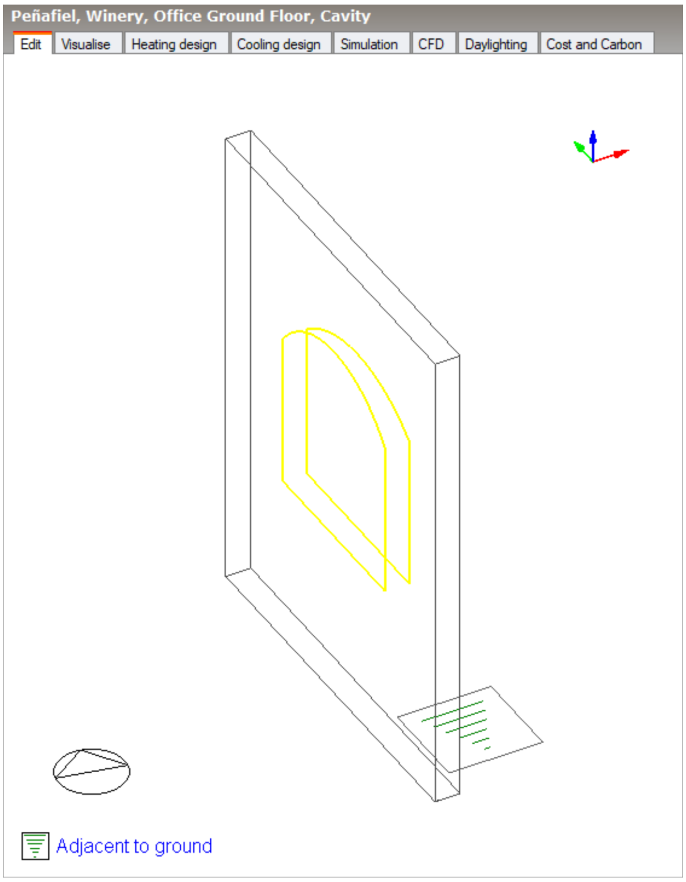
For what concerned the roof, the same considerations could not be made, because, unlike the vertical envelope, the double skin for the roof could not be drawn. Hence, it was decided to modify the construction characteristics of the pitched roof and of the false ceiling, considering that this would be the most similar solution to a ventilated roof.
The procedure is explained below:



(a) *Navigate, Site: Cavity*



(b) *Model Data: Zone type: 3-Cavity*



(c) *3D view of a cavity*

Figure 7.5: Cavity settings

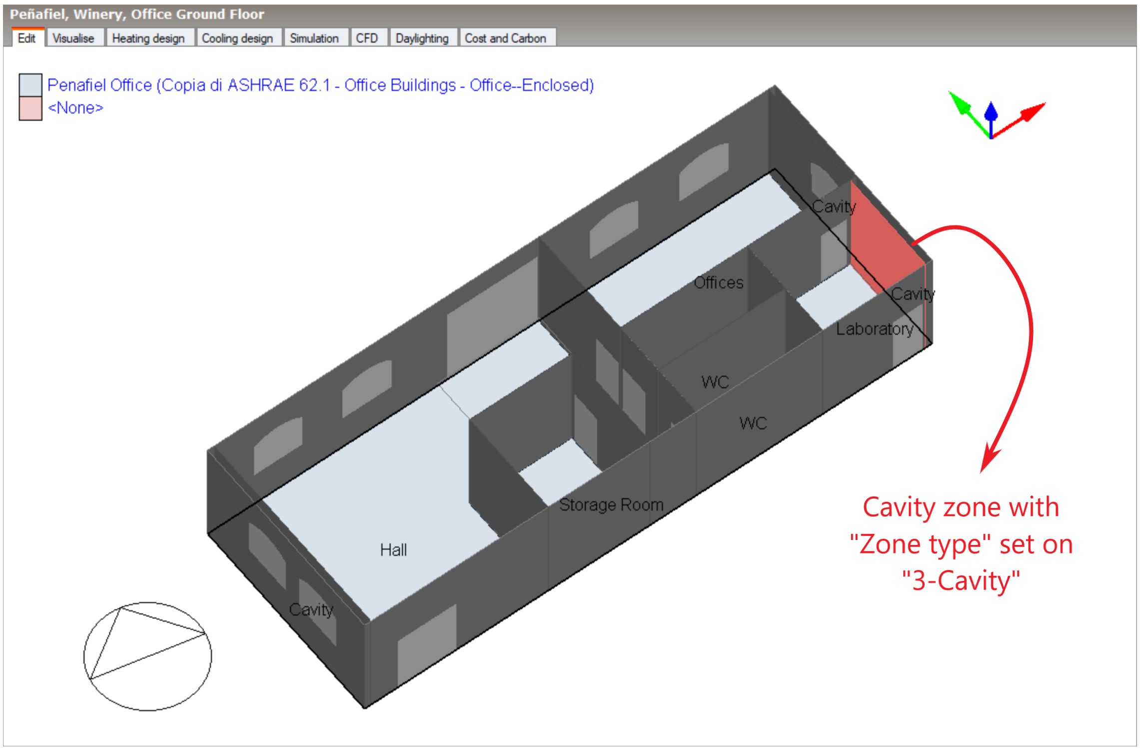


Figure 7.6: Insulator thickness and maximum temrature reduction - I3

1. To the pitched roof it was allocated only a layer of roofing tiles;

2. To the false ceiling it was allocated the stratification that belonged to the pitched roof, minus the roofing tiles;

3. The crawl space created between the pitched roof and the false ceiling was converted into a Cavity, as for the vertical envelope. To such cavity it was assigned the highest value allowed of air tightness: 5ac/h;

4. As the roof is inclined by 10° only, from the ISO 6946:2007(E) - Annex B it was retrieved the value of the convective coefficient for ventilated envelopes with a horizontal flow. This Convective Heat Transfer Coefficient, $h_c = 2,5W/m^2K$, was assigned to the Internal Surface of the pitched roof from the Construction Data tab.

The ventilated roof was implemented on the whole building. It was decided to try three different solutions: ventilated roof, ventilated façade and ventilated façade with roof. The results are shown in Fig.7.7. As we can see, the effect obtained is exactly the opposite of the one desired. Instead of decreasing the internal temperature during summer, it was decreased only during winter, when the internal temperature is oscillating precisely around the optimum temperature for wine ageing.

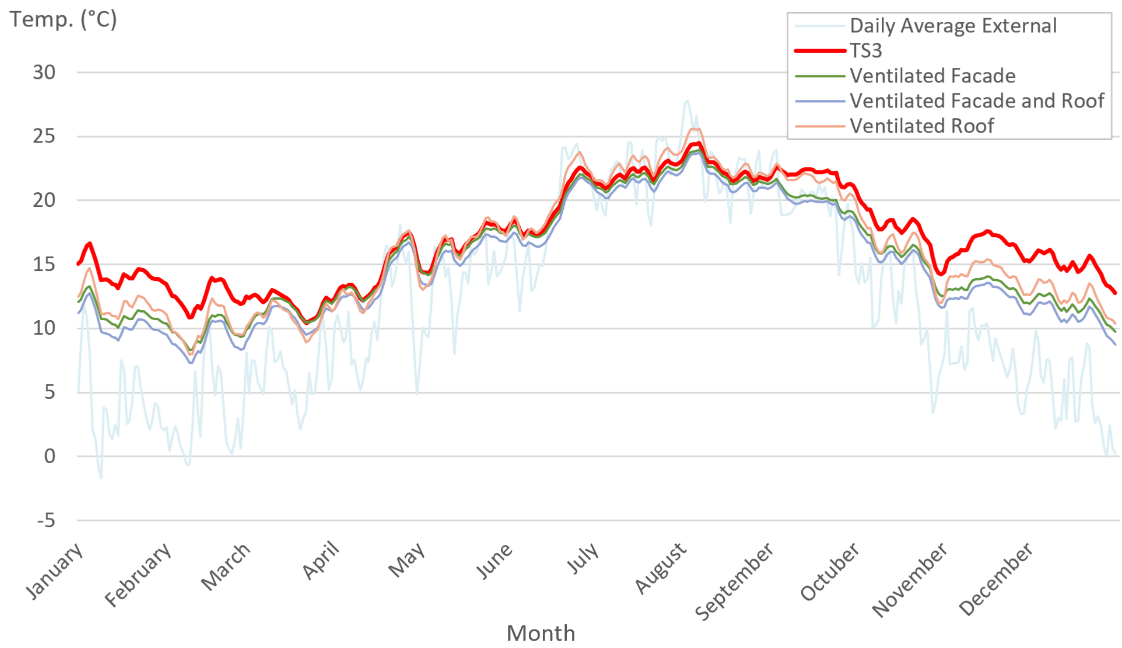
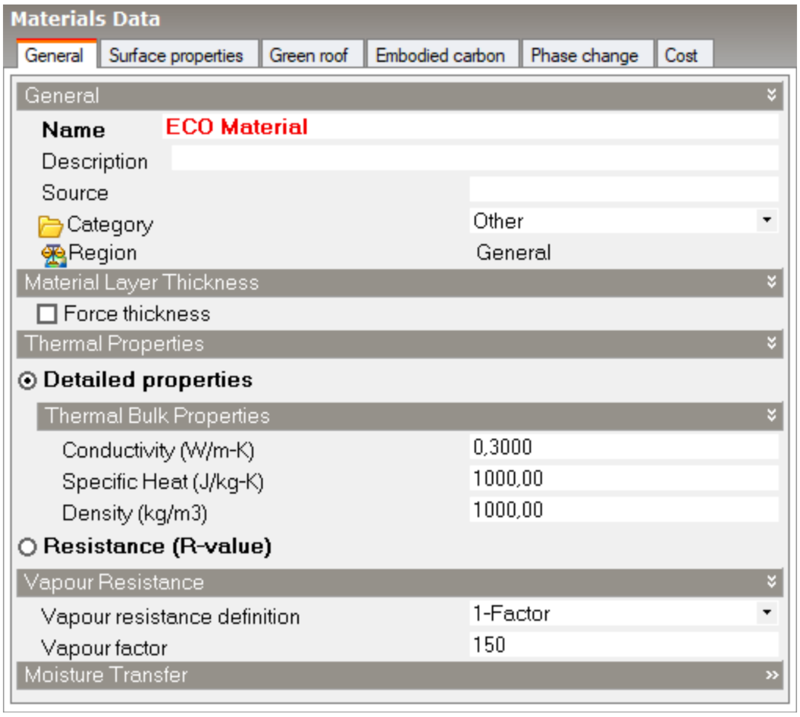


Figure 7.7: Temperature profile of the implementation of the ventilated enevelopes

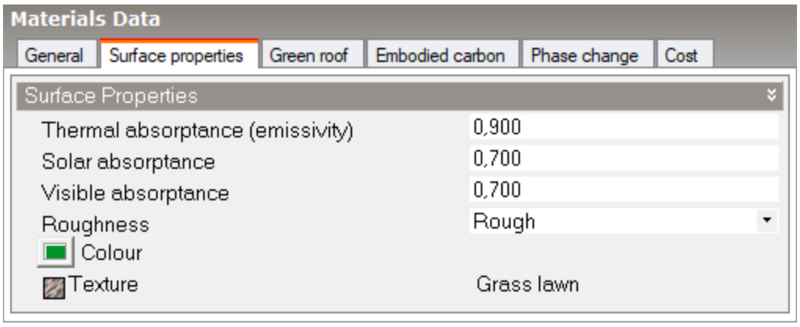
We can see, anyhow, that the largest effects are caused by the combination of ventilated roof and ventilated façade, which reports anyway temperatures that reach almost the 24°C in summer.
Thereby, neither this passive solution reports good outcomes, and it is consequently not recommended for an energy retrofitting.

7.3 Green envelopes

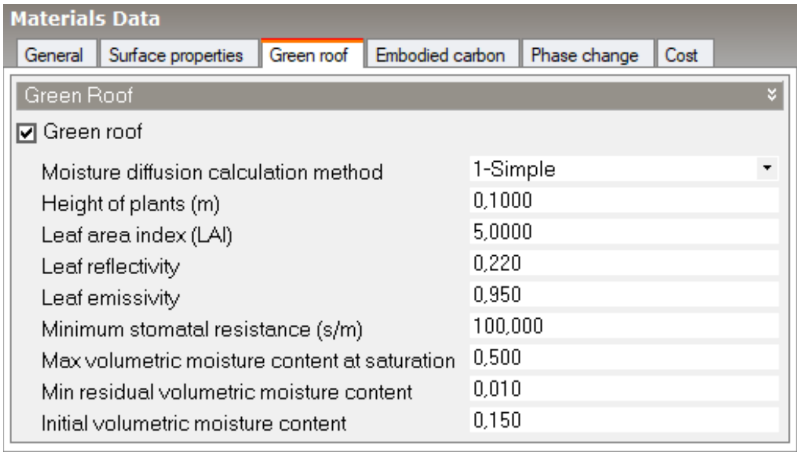
Green roofs are a combination of the two passive systems studied so far. On one hand they act as a thermal insulator, increasing the thermal inertia of the building as well. On the other hand, it acts as a solar shield thanks to the plants and leaves shading the envelope.
In order to model a green façade or a green roof in DesignBuilder, it is only necessary to add a layer on the outermost surface of the envelope. Indeed, DesignBuilder has in its database an ECO Material that simulates this type of passive system. All its characteristics are reported in Fig.7.8. Both for the vertical envelope and for the roof it was chosen an height for the plants of 10cm, with no bushes nor trees. [50] As shown in Fig.7.9 the effect of the green envelope is a general increase of temperature throughout the year. This passive solution has a major effect in winter, where it reaches a temperature increase of 1°C, and in summer the wine cellar is not cooled down either. Once again, this type of energy retrofitting is not reccomended.



(a) *ECO material characteristics*



(b) *Surface properties*



(c) *Green roof settings*

Figure 7.8: Green roof ECO material data

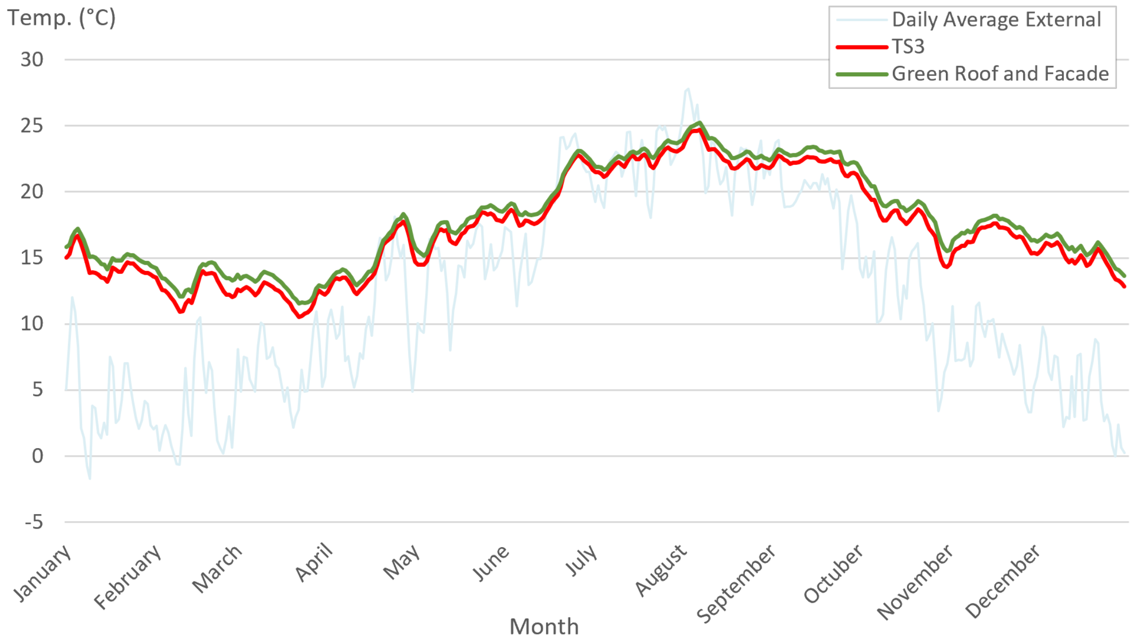


Figure 7.9: Profile temperature of the green envelope passive solution

7.4 Phase Change Materials

Come to this point is became clear that the missing element to the winery's envelopes was not the thermal insulation nor the solar screening of the envelope.
Considering that the commonest constructions of the wineries, of today as of yesterday, are underground constructions, the missing element to the envelopes of the winery studied, cloud be the thermal inertia.
As seen in Chapter 3, thermal inertia nowadays could be realized thanks to the newest technologies of the Phase Change Materials (PCMs).
Hence, it was decided to try this passive solution, implementing a layer of different PCMs to the vertical envelopes and to the false ceiling of the building. Three distinct PCMs were used, differing from one another for the melting point. Their characteristics were retreived from a list of PCMs contained in the DesignBuilder's database. In Tab.7.7 are sown their characteristics, while in Fig.7.10 are shown the enthalpy curves of the three different PCMs.

As we can see from the graph, the temperature profiles related to the three distinct PCMs do not differ from one another, although the melting points chosen are very various.
Unlike the other passive systems implemented previously, the use of PCMs gives back a constant decrease of temperature throughout the year, around 0,3°C. This fact tells us that, on one hand the PCMs are correctly working, increasing the thermal inertia of the building. On the other hand, this passive solution is not implementable

Table 7.7: The three types of PCMs implemented

BioPCM® Name	**Melting Point** (°C)	**Density** (kg/m^3)	**Specific Heat** (J/kgK)	**Thickness** (m)
M182/Q18	18	235	1970	0,0371
M51/Q23	23	235	1970	0,0208
M91/Q29	29	235	1970	0,0742

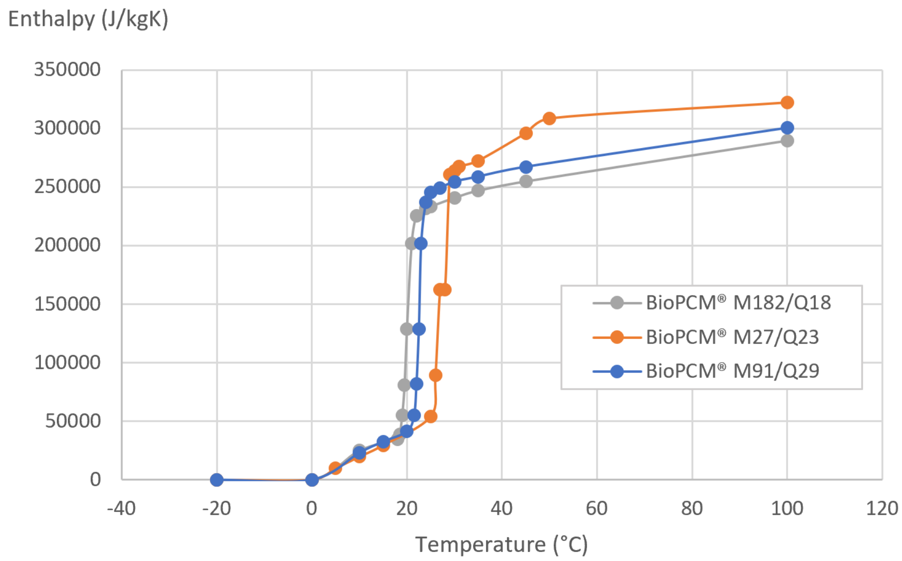


Figure 7.10: Enthalpy curves of the three PCMs

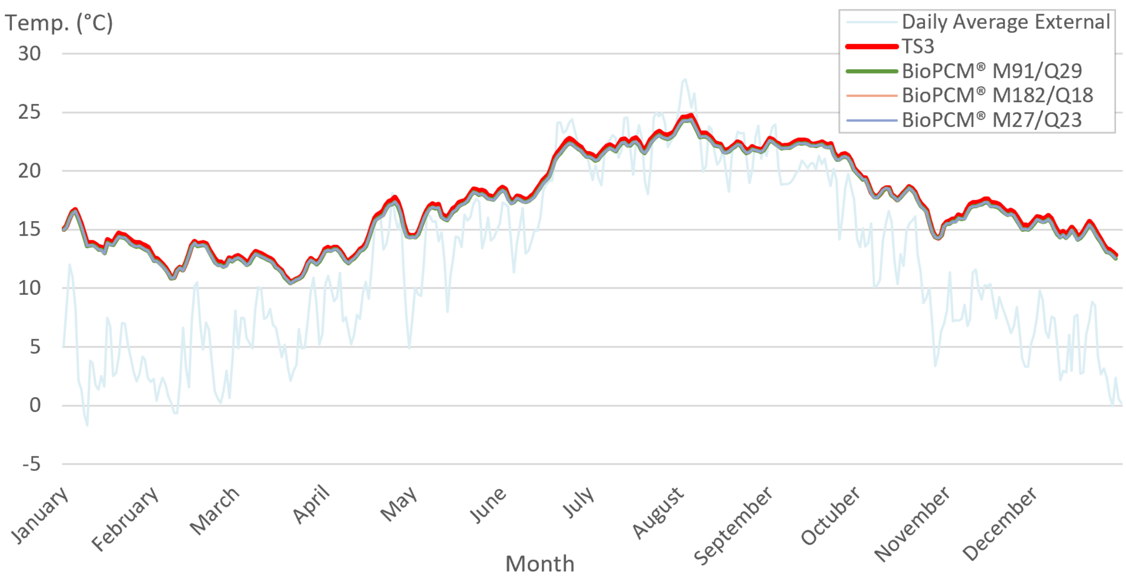


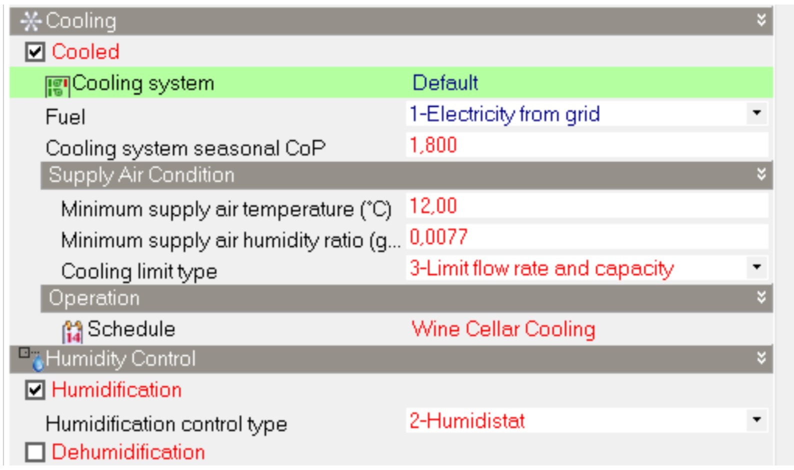
Figure 7.11: Temperature profile of the PCM implementation

for a reason of cost-effective, and because, even after trying very different PCMs, the temperature profile of the winery does not decrease more than 0,3°C.

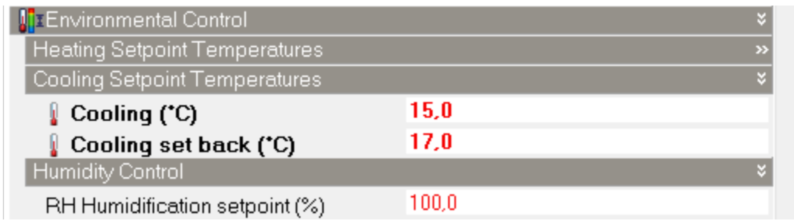
This confirms what was already foreseen in section 6.5.4, that it is very unlikely to find a passive system that would decrease the winery's temperature in the summer period more than what the actual envelope is already doing: with an external temperature that reaches the 35°C, the wine cellar is however kept under 25°C.
The only advisable solution now appears to be a mechanical cooling during the hot season, powered by photovoltaic panels.

7.5 Photovoltaic panels

The results of the passive systems investigated so far left no choice but the implementation of air conditioning systems during the hottest period. It was hence imagined resorting to a cooling system powered by photovoltaic panels located on the roof, where they would absorb larger amount of energy during the sunny summer days, corresponding to the ones that need air conditioning the most.
Thus, to the validated model was added the cooling system, with the characteristics showed in Fig.7.12 *(a)* and Fig.7.12 *(b)*. The air conditioning schedule is set "On" the whole year, because the cooling system is set to be working only above a certain temperature.



(a) *CoolingHVAC*



(b) *CoolingActivity*

Figure 7.12: Cooling settings

The results are shown in Fig.7.13 and in Fig.7.14. We can see how temperature is kept inside the comfort zone the whole time.
This passive cooling solution appears to be the best retrofitting option among the many passive systems analyzed for the winery studied, and since the winery is already equipped with an HVAC system, the implementation of photovoltaic panels is strongly recommended .

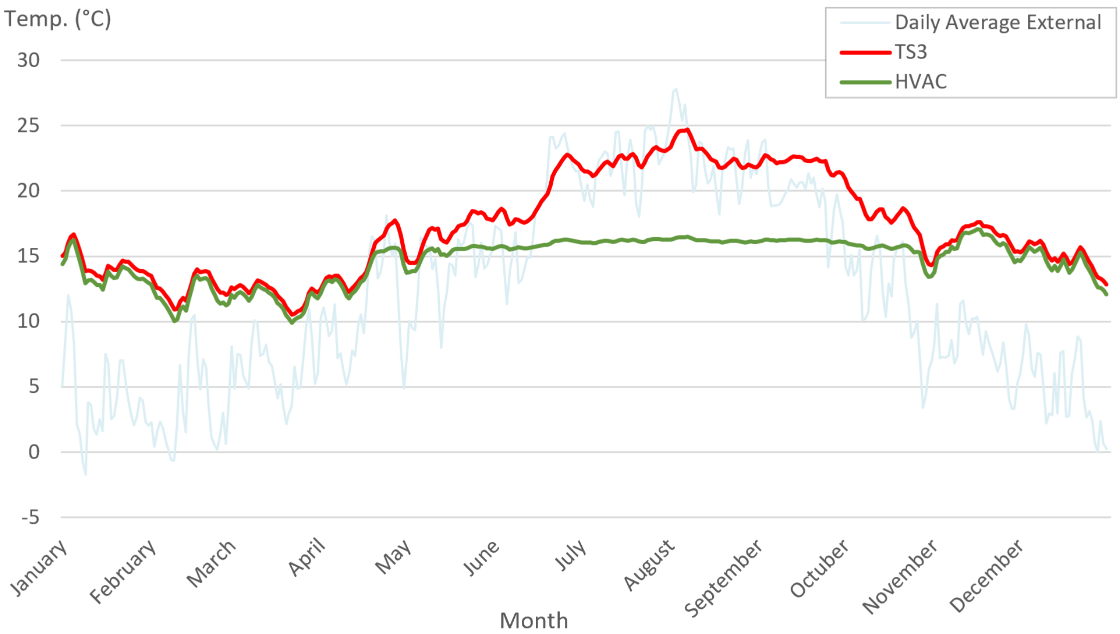


Figure 7.13: Winery's temperature trend with the implementation of HVAC powered by photovoltaic cells

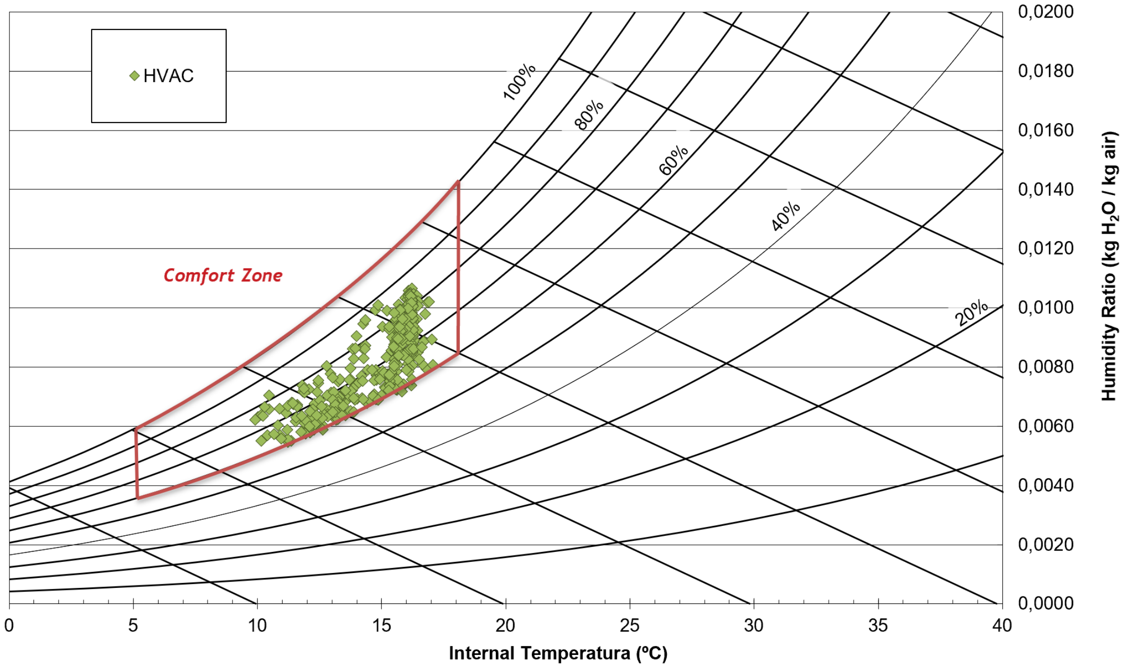


Figure 7.14: Winery's hygrothremal conditions with the implementation of HVAC powered by photovoltaic cells

Chapter 8

Conclusions

The study started with the analysis of the experimental data, registered by the five sensors – four inside the Wine Cellar and one outside the building – in the year 2018. After a previous bibliographic research among the wine comfort condition for a proper wine ageing, it was created the test chart, reporting the Comfort Zone, that would have been used to verify whether the experimental data fell inside the acceptable Temperature-Relative Humidity range.
The seasonal analysis showed how summer is the worst season for wine with a 0% of satisfied comfort conditions, followed by autumn, then spring, and finally winter, with a 100% of satisfied comfort conditions.
The monthly analysis outlined instead the vertical delta temperature for every month, showing that April, May, June and October, rather transitional months, report the highest variations.
Finally, the daily analysis demonstrated how the conditioning system inside the Wine Cellar had not been used for the monitored year, as then it had been confirmed by the winery manager. It showed as well the great influence of the roof in the heat exchanges with the surrounding environment – causing likewise a substantial vertical delta temperature during the hot season – displaying how the highest sensor registers the lowest temperatures in winter and the highest in summer.
The study continued with the creation of a virtual 3D model on DesignBuilder. In order to guarantee a correct simulation, the weather data registered by the external sensor were collected and inserted in the software as a new weather database specific for the area.
The model was then filled will the known information about the construction characteristics, the occupancy, the activity, and others. The unknow information were thoughtfully assumed or given prefixed values acquired from norms, like the ASHRAE Handbook, on which EnergyPlus is based.

Were first implemented three different thicknesses of thermal insulator on the innermost surface of the pitched roof. Such passive system revealed itself to be not implementable for a matter of cost-effective.
It was they tried to implement the ventilated envelope passive cooling. Again, three different solutions were examined: the ventilated vertical envelope, the ventilated roof and the combination of both. These three solutions showed greater influence with respect to the thermal insulator, but still they had no great effect of the summer internal conditions of the wine cellar.
After having excluded thermal insulation and ventilated envelopes, it was decided to try a combination of the two, the green envelope. This indeed, should behave both as a thermal insulator for the soil layer added to the envelope, and as a ventilated layer for the leaves that shade the envelope. On the contrary of the suppositions, this passive cooling solution resulted only in a constant increase of temperature over the whole year.
Reached these results, the idea was that the building needs an increase of thermal inertia in order to cool down. Were then implemented three different PCMs – varying for the melting points. The result was completely the opposite of the green envelope: temperature decreased constantly throughout the year. Still, the temperature reduction was too meagre to let this solution be applicable, also for a matter of cost-effective. The only
option appeared now the implementation of photovoltaic panels to power the HVAC system already present in the wine cellar. After implementing the simplified version of an HVAC system on DesignBuilder, the results showed the applicability of this solution.
Hence, it could be concluded that the passive cooling solution that best fits this case study is the implementation of photovoltaic panels on the roof of the winery, were they get the most of the sun during those months that most require their use.
Since the winery is already equipped which an HAVC system, the photovoltaic panels appear to be a convenient solution also for a matter of cost-effective.
Anyhow, as the PCMs results show, an increase of thermal inertia of the building envelope would improve the comfort conditions for the wine ageing. The problem is that the thermal inertia provided by the PCMs is not enough to keep the temperature under certain values even in summer. It should be, indeed, comperable with the therma inertia grant by the soil in an underground building. This is why it is anyway recommended to build wine cellars under the ground level, or as seen in section 2.4, implement a thick layer of earth soil on the envelope of the building to simulate an underground construction.

8.1 Future Investigations

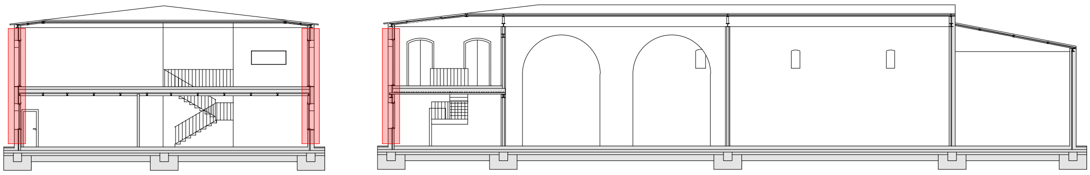
Given longer time, the first aspect to analyze would be the cost evaluation of the photovoltaic panels implementation, together with their technical characteristics to understand what type and the number of panels needed to power the HVAC system already present in the winery. As importantly, it should be developed an analysis to understand where these panels should be positioned to be most efficient, especially for a matter of temperature stratification.

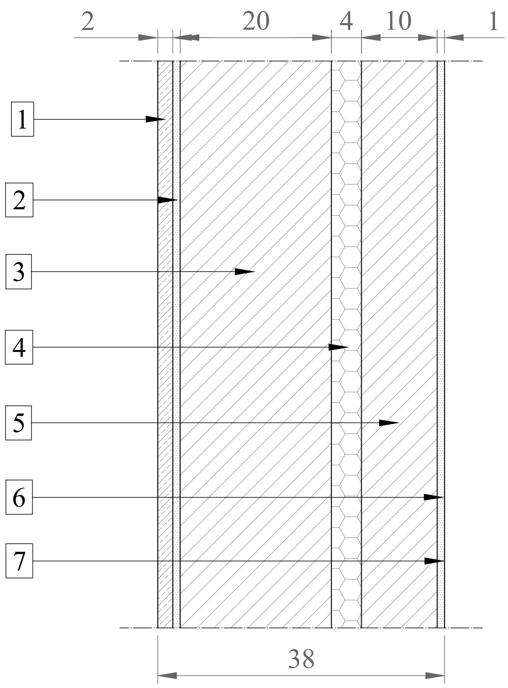
The study could follow with a specific analysis of the energy savings due to the implementation of the photovoltaic panels. During the winery inspection were listed all the machineries working throughout the year, with their time schedule and the energy they need to work. All these data could be inserted in the DesignBuilder model in order to simulate a realistic energy consumption, and evaluate the energy expenses before the installation of the photovoltaic panels, and after.

Appendices

Appendix A

Vertical Envelope VE_01





Layer	**Width** [cm]	**Material**	**Thermal Conductivity (h)** [W/mK]
1	2	Sandstone panels	1,2
2	1	Mortar - cement plaster	0,72
3	20	Aerated brick	0,3
4	4	Polyurethane foam	0,028
5	10	Aerated brick	0,3
6	1	Mortar - cement plaster	0,72
7	0,1	Acrylic varnish	0,2

		Theraml Transmittance (U) [W/mq^{2}K]
Total	38,1	0,381

Thermo-Hygrometric study of a wine cellar in the Spanish region Ribera del Duero

Relators: Marco Perino

Co-relators: Cesar Porras Amores, Carmen Vina

Author: Maria Giulia Gagliardini

Scale 1:10

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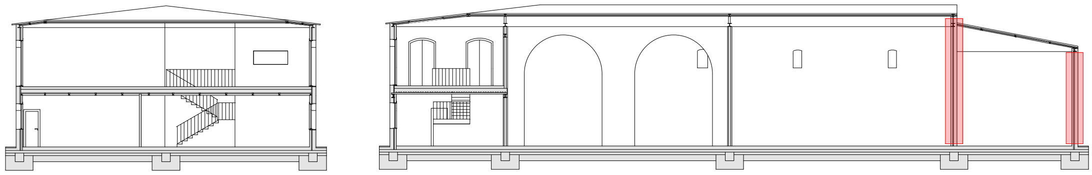
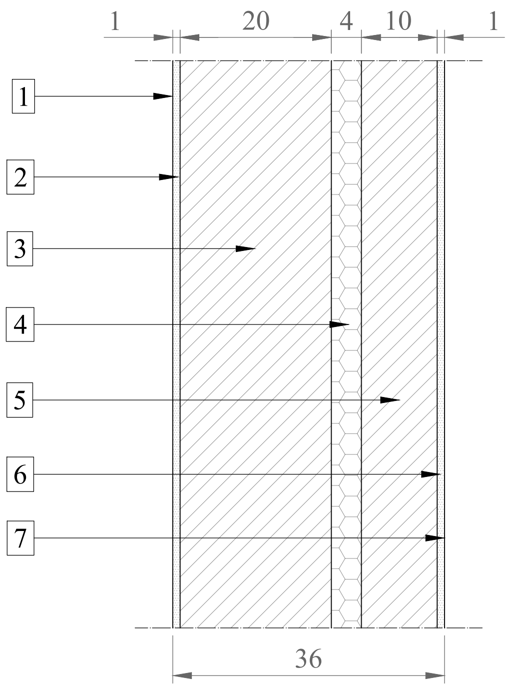
Vertical
Envelope
VE_01

Appendix B

Vertical Envelope VE_02





Layer	**Width** [cm]	**Material**	**Thermal Conductivity (h)** [W/mK]
1	0,1	Acrylic varnish	0,2
2	1	Mortar - cement plaster	0,72
3	20	Aerated brick	0,3
4	4	Polyurethane foam	0,028
5	10	Aerated brick	0,3
6	1	Mortar - cement plaster	0,72
7	0,1	Acrylic varnish	0,2

		Theraml Transmittance (U) [W/mq^{2}K]
Total	36,2	0,382

Thermo-Hygrometric study of a wine cellar in the Spanish region Ribera del Duero

Relators: Marco Perino

Co-relators: Cesar Porras Amores, Carmen Vina

Author: Maria Giulia Gagliardini

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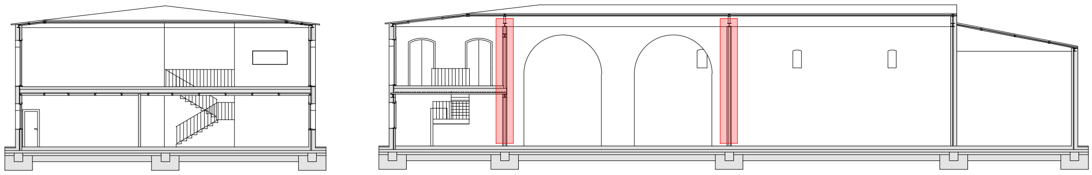
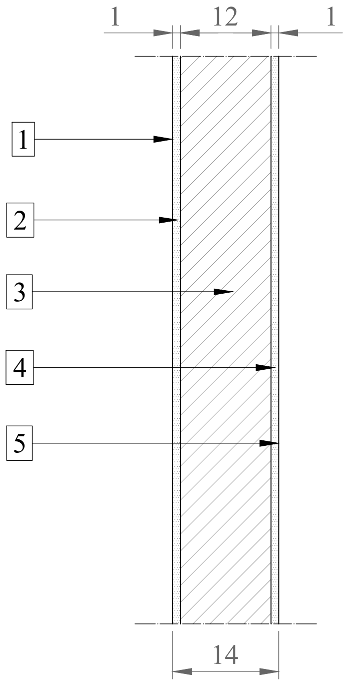
Vertical Envelope
VE_02

Appendix C

Vertical Partition VP_01





Layer	Width [cm]	Material	Thermal Conductivity (h) [W/mK]
1	0,1	Acrylic varnish	0,2
2	1	Mortar - cement plaster	0,72
3	10	Aerated brick	0,3
4	1	Mortar - cement plaster	0,72
5	0,1	Acrylic varnish	0,2

		Theraml Transmittance (U) [W/mq^{2}K]
Total	14,2	1,433

Thermo-Hygrometric study of a wine cellar in the Spanish region Ribera del Duero

Relators: Marco Perino
Co-relators: Cesar Porras Amores, Carmen Vina
Author: Maria Giulia Gagliardini

Scale 1:10

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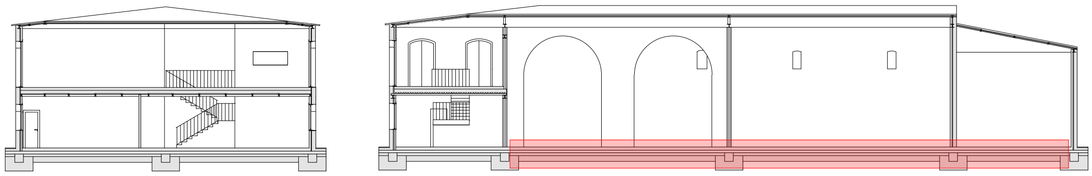
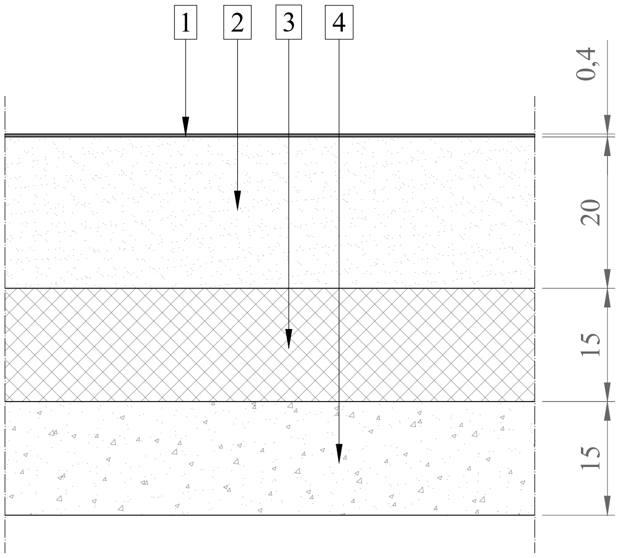
Vertical Partition
VP_01

Appendix D

Horizontal Envelope HE_01





Layer	Width [cm]	Material	Thermal Conductivity (h) [W/mK]
1	0,4	Epoxy resin	0,2
2	20	Cast concrete (lightweight)	0,38
3	15	Reinforced concrete	1,9
4	15	Gravel-based soil	0,52

		Theraml Transmittance (U) [W/mq^{2}K]
Total	50,4	0,906

Thermo-Hygrometric study of a wine cellar in the Spanish region Ribera del Duero

Relators: Marco Perino
Co-relators: Cesar Porras Amores, Carmen Vina

Scale 1:10

Author: Maria Giulia Gagliardini

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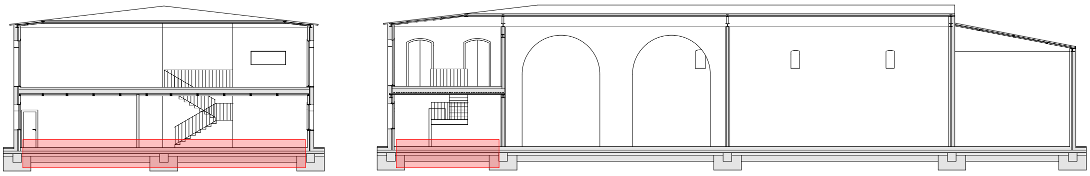
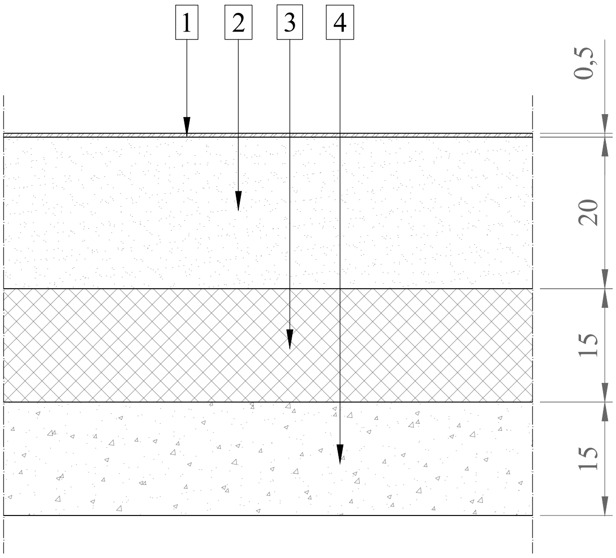
Horizontal Envelope
HE_01

Appendix E

Horizontal Envelope HE_02





Layer	Width [cm]	Material	Thermal Conductivity (h) [W/mK]
1	0,5	Ceramic tiles	0,8
2	20	Cast concrete (lightweight)	0,38
3	15	Reinforced concrete	1,9
4	15	Gravel-based soil	0,52

		Theraml Transmittance (U) [W/mq^{2}K]
Total	50,5	0,917

Thermo-Hygrometric study of a wine cellar in the Spanish region Ribera del Duero

Relators: Marco Perino

Co-relators: Cesar Porras Amores, Carmen Vina

Author: Maria Giulia Gagliardini

Scale 1:10

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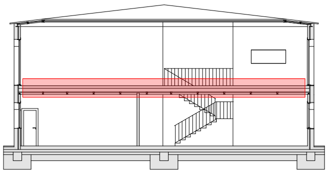
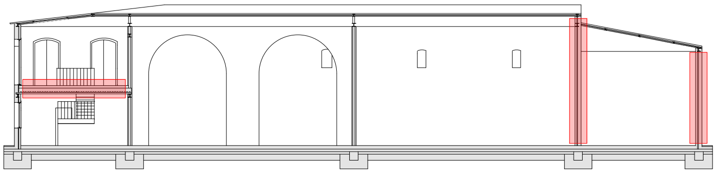
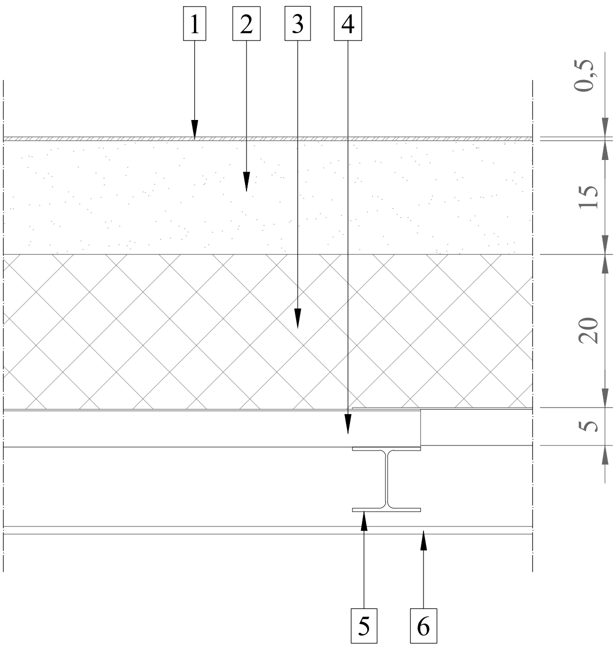
Horizontal Envelope
HE_02

Appendix F

Horizontal Partition HP_01







Layer	Width [cm]	Material	Thermal Conductivity (h) [W/mK]
1	0,5	Ceramic tiles	0,8
2	15	Cast concrete (lightweight)	0,38
3	20-25	Reinforced concrete	1,9
4	0,01	Corrugated sheet (steel)	50
5	-	Secondary beam HE (steel)	-
6	-	False ceiling	-

		Theraml Transmittance (U) [W/mq^{2}K]
Total	35,6	1,436

Thermo-Hygrometric study of a wine cellar in the Spanish region Ribera del Duero

Relators: Marco Perino

Co-relators: Cesar Porras Amores, Carmen Vina

Author: Maria Giulia Gagliardini

Scale 1:10

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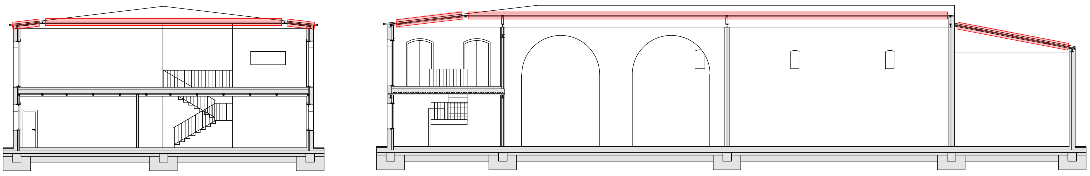
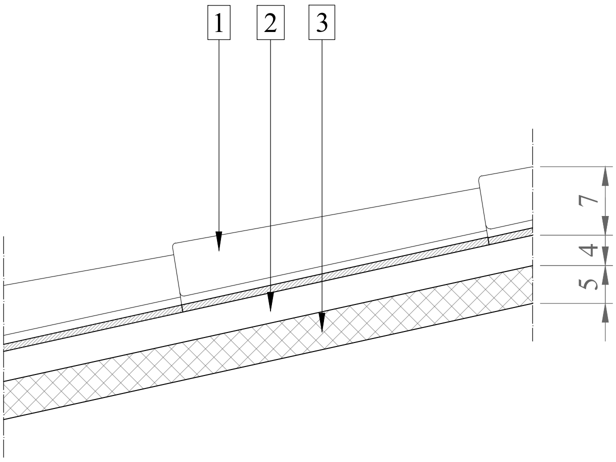
Horizontale
Partition
HP_01

Appendix G

Oblique Envelope OE_01





Layer	Width [cm]	Material	Thermal Conductivity (h) [W/mK]
1	7	Clay tile	1
2	4	Polyurethane foam	0,028
3	5	Cement fiberboard	0,082
		Theraml Transmittance (U) [W/mq^{2}K]	
Total	16	0,449	

Thermo-Hygrometric study of a wine cellar in the Spanish region Ribera del Duero

Relators: Marco Perino

Co-relators: Cesar Porras Amores, Carmen Vina

Author: Maria Giulia Gagliardini

Scale 1:10

A.A.2018/2019

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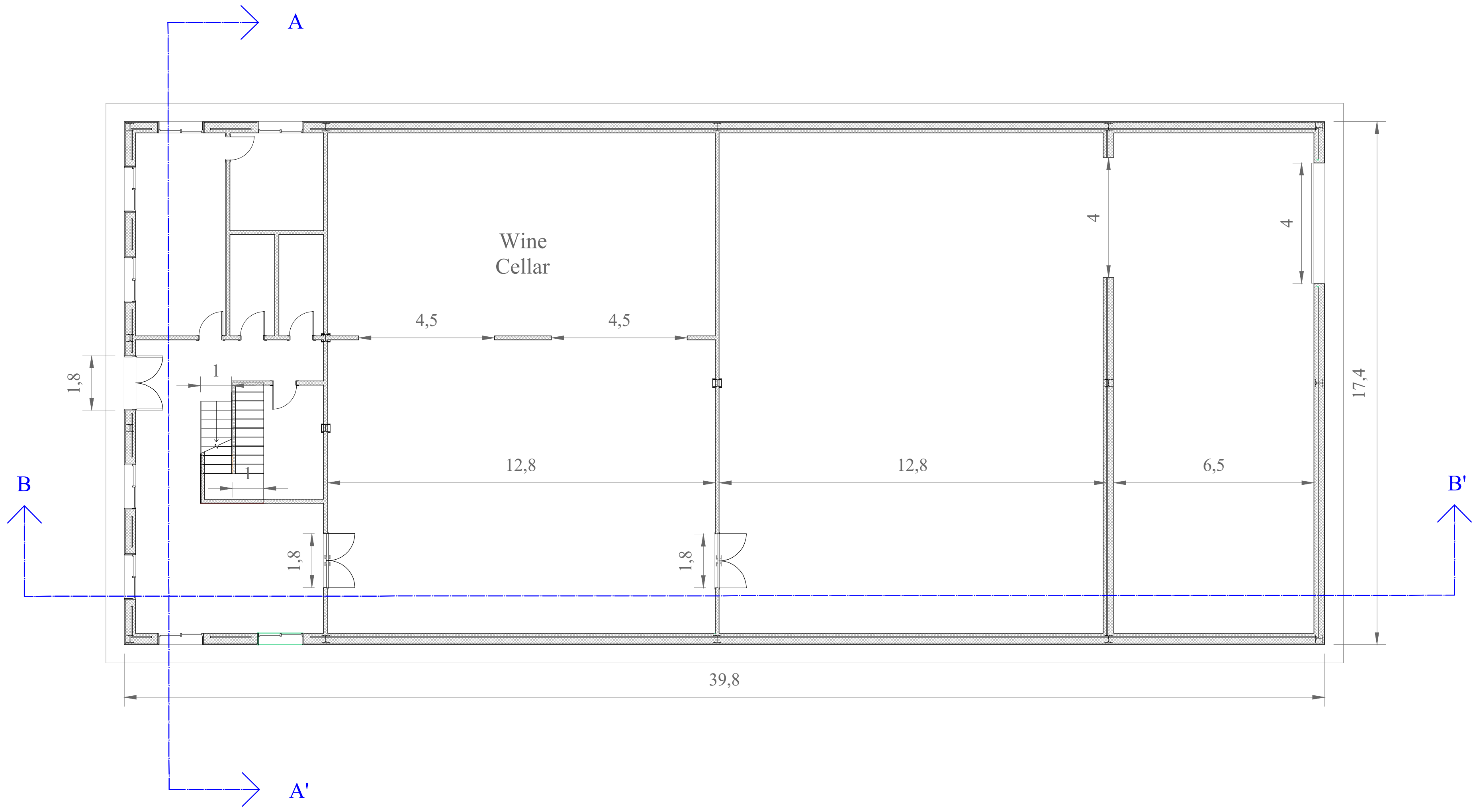
Oblique
Envelope
OE_01

Appendix H

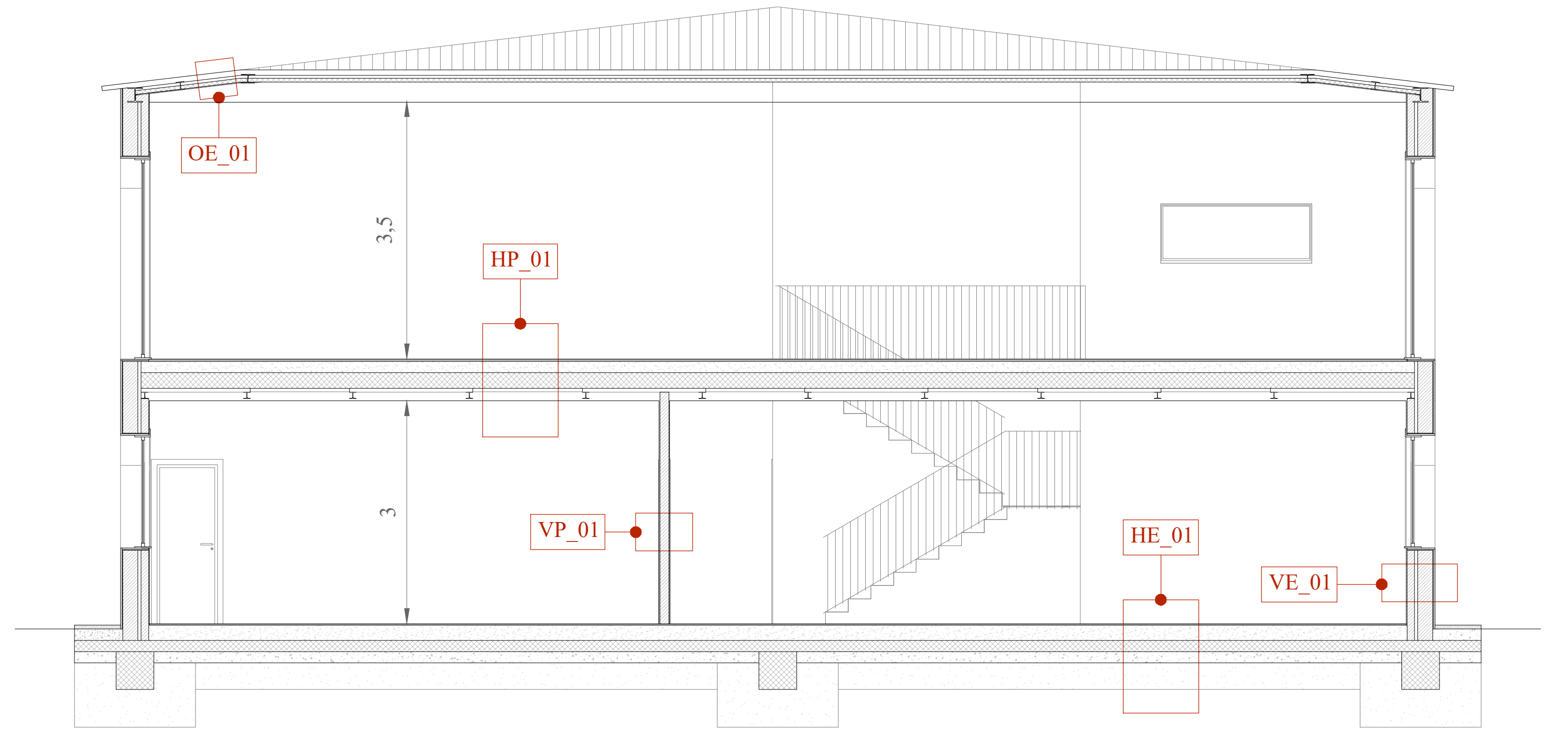
Sections

Annex Horizontal Envelope HE_01	Thesis of Master's Degree in Building Engineering **Politecnico di Torino** Trabajo Fin de Master M.I.T.E. (Master en Innovacion Tecnologica de la Edificacion) **Universidad Politecnica de Madrid**	A.A. 2018/2019	*Thermo-Hygrometric study of a wine cellar in the Spanish region Ribera del Duero* Relators: Marco Perino Co-relators: Cesar Porras Amores, Carmen Vina Author: Maria Giulia Gagliardini Scale 1:100

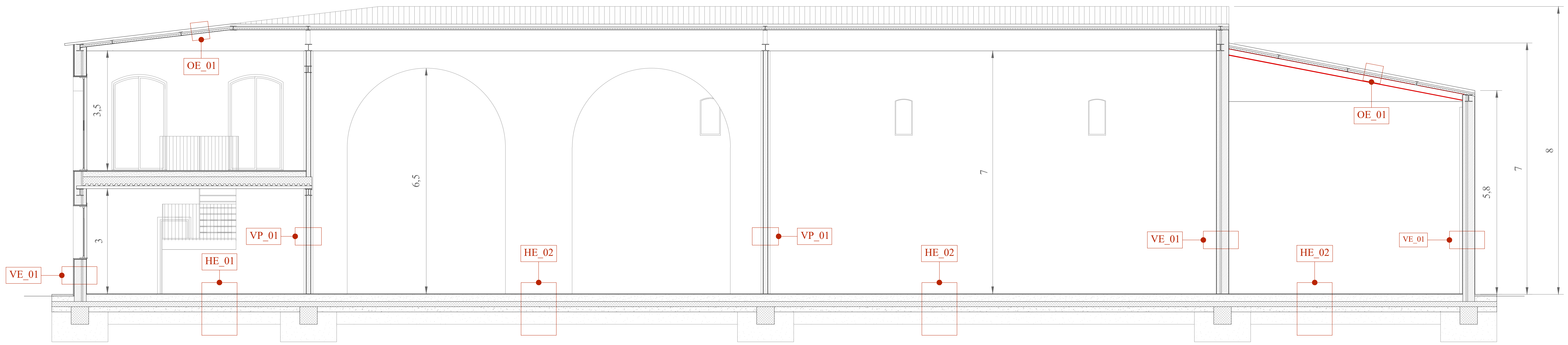
Plan Ground Floor
Scale 1:200



Section A-A'
Scale 1:100



Section B-B'
Scale 1:100



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Acknowledgements

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