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The dual influence of the envelope on the thermal performance of conditioned and unconditioned buildings

Abstract

Cities are progressively widening, incorporating rural and industrial zones and, at the same time, largest cities often need conversion of entire neighbourhoods. The transformation of large areas, through the introduction of energy-efficient buildings, quickly provides economic and social benefits. The current technologies for building energy-saving offer wide technical solutions range mainly developed for residential buildings. Nevertheless, the current literature lacks enough studies on envelope effectiveness in non-residential sectors, where indoor conditions are considerably different from residential.

In this context, the paper aims at assessing the influence of five architectural characteristics on the energy performances in a case-study food-processing building. 576 building configurations are analyzed for six different intended use (0°C-24°C) in conditioned and unconditioned scenarios. The performances of the different building configurations are expressed in terms of energy need (conditioned scenario) and thermal discomfort (unconditioned scenario). Results reveal that energy building performances are connected to temperature ranges and the same building envelope characteristic can show positive or negative contribution according to the simulated scenario. Finally, for both scenarios, the most influential architectural characteristics have been identified and evaluated. The paper proposes a methodology for building en-

ergy assessment for the transformation of existent industrial food-processing buildings in urban and suburban areas.

Keywords: neighborhood transformation, building design, energy simulation, energy performance, agricultural facility, envelope performances

1. Introduction

Since the last century, the urbanization has increased in all regions [1, 2, 3] and in several densely populated areas, such as Europe, the urban sprawl has involved industrial and rural zones, located once out of the city borders and now incorporated in the new urban areas [4, 5]. The inclusion of rural and industrial facilities in the urban fabric rises an important issue concerning the sustainability and the compatibility of the activities carried out in these buildings with the urban environment [6, 7]. In any case, from both social and environmental points of view, the abandon of these buildings and agglomerations can drive to urban degradation [8]. Therefore, to adapt buildings to the new intended uses, in several cases they undergo processes of transformation such as reuse, rehabilitation [9] regeneration [10] or even demolition [11]. When the demolition is not allowed nor feasible, the indoor activities can go through deep changes: from industrial to residential, commercial, food storage, etc [12].

The modification of the intended uses drives to several issues, one of which concerns the restored-building energy efficiency. In fact, the original structures were built with energy efficiency criteria for a different use (or without criteria at all) and their conversion can bring to inefficiency issues in particular for indoor heating and cooling. Moreover, the well-known data

about the impact of building sector in the overall energy consumption (approximately 40% of energy consumption and 36% of CO₂ emissions in the EU [13]) pushed, among the others, the European Commission and then the Member States to promulgate stricter and stricter laws to improve the thermal performances of new and restored buildings also encouraging the exploitation of renewable energy sources [14, 15, 16, 17, 18].

The goal of the energy consumption reduction has been mainly sought in two ways: the first aims at reducing the energy need and the second at replacing (a quota of) the energy provided by fossil fuel source with renewable sources.

The first path encouraged the study of more efficient and sustainable solutions for the building envelopes, in particular on materials, orientation optimization, sun shadings, glazing, building geometry and other architectural characteristics [19]. The second allowed development and applications in solar, wind or ground energy exploitation (e.g. photovoltaic, solar panel, geothermal, etc.) [20, 21]. The wide technical solution range and the increasing diffusion of thermal simulations in design, has driven also to the development of new methods for the energy need calculation, [22] and more reliable software.

Hence, the problem of the use conversion in the building sector can take advantage of the synergy between the innovation coming from the new technologies and the solutions provided by the development for energy software assessment [23].

Furthermore, also due to more and more precise calibration and validation processes of energy models [24, 25, 26, 27], the gap between theoretical

assessment and real values of the parameters of interest (e.g. heat flux, indoor temperature trends, energy consumptions etc.) could be reduced. Another impulse to the research has been given by software that can handle multiple energy simulations, elaborate the results and help the designers to optimize the design process. For example, the combination of EnergyPlus [28] and Matlab [29] has proved to return high quality results managing huge number of simulations allowing the user to test different scenarios with limited effort [30].

The literature on building sector innovation involved, especially, the upgrading interventions of residential and business structures, or in general, those with permanent human occupancy. A limited number of studies assessed the potential efficiency of the most widespread energy-saving solutions in the context of industrial buildings [31, 32, 33, 34, 35, 36, 37] such as the food and agrifood processing sector that shows a remarkable energy use [38, 39, 40]. In some cases, the solutions proved to be more efficient than in residential sector [17], and this aspect can drive to favourable solution even in case of building conversion. Even if not comparable with residential, the agrifood processing buildings exhibit relevant energy need mainly due to lighting, hot water production, food transformation phases and indoor thermal conditioning. The latter plays a fundamental role for food safety and food quality that often require specific temperature and humidity conditions in order to guarantee food preservation, all this representing a high cost for the farms in both economic and environmental terms [41, 17].

As matter of fact, for most of the available technical solutions, optimized for residential purposes, the efficacy has not been largely tested yet on in-

dustrial building needs.

The cheese factories or food storage facilities having use compatible with the urban environment) can be considered typical examples since require low temperature ranges, from 0°C to 8°C, all year long, or again the storehouse groceries where the packaged food is usually stored at room temperature (around 20°C-22°C) since designed for the human presence too.

This study aims at testing the effectiveness of some envelope characteristics (wall, roof, glazing, orientation and sun shading) referring to six different temperature ranges (TRs), selected to cover a wide temperature band (from 0°C to 24°C) and different years, in both conditioned and unconditioned scenarios.

In other words, it aims at investigating if a single building configuration shows good performances in all the thermal ranges and for both scenarios or, on the contrary, if the efficiency of a single configuration depends on the selected temperature range and/or scenario. To achieve this result, the present work is based on the following steps:

- assessing the correlation of the architectural solution efficacy in conditioned and unconditioned scenarios;
- studying and assessing the correlation between the building thermal performance and the outdoor environment (yearly average temperature) for each temperature range;
- evaluating the influence of each architectural characteristic on the thermal behaviour in both scenarios and for all the temperature ranges.

The methodology is applied to an existent building located in Italy and

selected as representative case study.

The results on the building thermal behaviour are evaluated assessing the influence of temperature ranges (see Section 3.1) and the influence of architectural characteristics and typologies (see Section 3.2). The study is based on dynamic energy simulations performed with EnergyPlus and Matlab and the main outcomes are elaborated and provided according to performance indicators based on thermal energy need (for conditioned scenarios) and thermal discomfort (for unconditioned scenarios). The outcomes of the present work, even if referred to a selected case study, can be considered representative for the definition of a methodology that should be adopted in the preliminary phases of the conversion or transformation process of agrifood urban complex in order to evaluate the possible benefits of the transformation and drive the decision-making and transformation process.

2. Materials and methods

2.1. Architectural characteristics and typologies

From a theoretical point of view, in a study aiming at identifying the optimal building characteristics, the possible variables are in a copious number. On the other hand, the literature shows the most effective interventions concern the building envelope and its components, including sun protection systems such as shading walls [42]. As a consequence, in order to consider the various intervention strategies, the present paper considers the following building architectural characteristics: external wall typology (w), roof typology (r), opening glazing typology (g), presence or absence of shading system (s) and geographical building orientation (o). In order to investigate

and quantify the effect of each architectural characteristic on the building thermal behaviour, different possible typologies for the same characteristic have been selected. Obviously, the energy performance can be remarkably affected by other building characteristics (such as the building dimensions, surface/volume ratio, proportions, glaze/wall ratio, etc.). However, those characteristics are mainly set according to other design criteria, needs or regulations and cannot be easily changed for energy saving design or retrofit interventions aimed at only improving the thermal behaviour. In order to provide sound results for a wide range of buildings, as better explained later, a case-study - representative in terms of shape, volume proportions, glaze/wall ratio - has been considered in this work.

Hence, in the rest of the paper the label "*architectural characteristic*" identifies a building envelope component or system (such as wall, roof, etc.), whereas the label "*typology*" refers to a configuration of the architectural characteristic and related thermal values. In the following sub-sections both architectural characteristics and typologies are deeper detailed and are selected according to Torreggiani et al. [43].

2.1.1. External walls

The present study considers six different external walls. The different wall typologies have been selected among both existent and some currently available on the European area market. Moreover, they were identified in order to consider different thermal performance combinations (e.g. thermal transmittance, time shift, surface mass). A label from *w01* to *w06* was assigned to each investigated wall typology. The main properties of external wall typologies investigated here are summarized in Table 1. The walls stock

adopted here is as follows:

- *w01*: full clay brick-lime mortar masonry, 12 cm thick, typical wall of existent construction widespread in the traditional Italian countryside. It is characterised by very high transmittance, high mass and very low time shift;
- *w02*: light weight concrete brick-cement mortar brickwork, 26 cm thick, typical of existent buildings, widespread in Italian countryside but also in industrial facilities in the last decades of the past century. The wall is characterised by high transmittance and low time shift;
- *w03*: wood cross laminated timber (CLT) panels, 22 cm thick, with transmittance and time shift in compliance with requirements of Italian regulations on heated rooms in new buildings;
- *w04*: hollow clay brick masonry, 25cm thick, plus 11 cm thick EPS insulating material. It has low transmittance and low time shift;
- *w05*: reinforced concrete (RC) walls, 20 cm thick, characterized by high transmittance and high time shift;
- *w06*: high performance wall built with light weight concrete blocks, 26 cm thick, plus an external 50 cm thick straw-bale layer.

The external walls characterised by labels #01 and #02 do not respect current Italian law requirements [44] and are typical and representative of the aboveground agricultural and industrial buildings in the case study area [45].

In Table 1, the layers composing the six wall structures are listed together with their main thermal properties (materials are listed starting from

the external layer). The values of t : thickness; λ : conductivity; ρ : density; c : specific heat in Table 1 refer to the single layer, where all the layers contribute to identify the thermal characteristics. The thermal characteristics of the whole package are then shown by means of the most common thermal performance indicators. The first is the steady-state thermal transmittance U (i.e. the rate of heat transferred through from one side to the other side material in a reference surface). As an example, according to current Italian law [44] for new heated buildings in the climatic area of the case study, U must be lower than $0.34 \text{ Wm}^{-2}\text{K}^{-1}$. So, $w03$, $w04$ and $w06$ only respect this prescription.

Another important indicator is the decrement factor F_a (defined as the ratio between modulus of the periodic thermal transmittance Y_{mn} , in the 24h, and the steady-state thermal transmittance U). It represents an attenuation index of the thermal flux through the wall. F_a lower than 0.15 is considered excellent for the Italian law [46]. It is correlated to the time shift Φ [47], defined as the temporal difference - usually expressed in hours - between the time in which the maximum temperature is recorded on the external surface and the time in which is recorded in the internal surface of the architectural element. Values of Φ close to 12h are considered as excellent for the Italian law [46]. The periodic thermal transmittance Y_{mn} is defined as the complex amplitude of the density of heat flow rate through the surface of the component adjacent to zone m (external), divided by the complex amplitude of the temperature in zone n (internal) when the temperature in zone m is kept constant [47]. Currently, for the Italian law, only the steady-state transmittance is considered for the calculation of wall characteristics, but terms calculated

from Y_{mn} (i.e. F_a and Φ) play an important role in the building thermal behaviour especially for cooling [48] and for this reason in the present work, more thermal performance indicators have been used for the selection of the different wall typologies. The plaster and strawbales are directly exposed to the sun, their solar absorptance is set respectively 0.65 and 0.5.

2.1.2. Roof

Similarly, for the external walls, for the roof structure six different roof typologies have been identified and adopted in the study. The choice followed the same criteria as for external walls and, in this case, a label r was assigned to each typology:

- $r01$: RC hollow slab, 20 cm thick, characterised by very high transmittance and very low time shift;
- $r02$: RC hollow, slab 25 cm thick, characterised by high transmittance and low time shift;
- $r03$: RC hollow slab, 25 cm thick, plus insulation layer 13-cm thick. Transmittance and time shift meet Italian law prescription for heated rooms in new buildings;
- $r04$: RC hollow, slab 20 cm thick, plus insulating material 12-cm thick in order to obtain a system with low transmittance and low time shift;
- $r05$: wooden slab: high transmittance and high time shift;
- $r06$: typical of high-performance construction, 18-cm of fibre-wood insulation is added to solution $r02$ so to reach a low transmittance and high time shift roofing surface.

Table 1: Main wall typologies properties, where: t : thickness [m]; λ : conductivity [$W(mK)^{-1}$]; ρ : density [kgm^{-3}]; c : specific heat [$J(kgK)^{-1}$]; U : thermal transmittance [$Wm^{-2}K^{-1}$]; F_a : decrement factor; Φ : time shift [h]; m : surface mass [kgm^{-2}].

| Wall # | Material component | t | λ | c | ρ | U | F_a | Φ | m |
|--------|-----------------------|-------|-----------|-------|--------|------|-------|--------|-----|
| w01 | Plaster | 0.015 | 0.700 | 1400 | 900 | 2.60 | 0.76 | 3.91 | 234 |
| | Bricks | 0.120 | 0.700 | 1600 | 830 | | | | |
| | Plaster | 0.015 | 0.700 | 1400 | 900 | | | | |
| w02 | Plaster | 0.015 | 0.700 | 1400 | 900 | 1.26 | 0.31 | 9.69 | 328 |
| | Light-weight concrete | 0.260 | 0.450 | 1100 | 1100 | | | | |
| | Plaster | 0.015 | 0.700 | 1400 | 900 | | | | |
| w03 | Plaster | 0.015 | 0.700 | 1400 | 900 | 0.29 | 0.14 | 12.34 | 141 |
| | Heavy polystyrene | 0.080 | 0.035 | 120 | 1350 | | | | |
| | CLT panel | 0.220 | 0.220 | 500 | 1650 | | | | |
| w04 | Plaster | 0.015 | 0.700 | 1400 | 900 | 2.60 | 0.76 | 3.91 | 234 |
| | Light polystyrene | 0.080 | 0.360 | 1200 | 1000 | | | | |
| | Hollow brick masonry | 0.260 | 0.500 | 900 | 1000 | | | | |
| | Plaster | 0.015 | 0.700 | 1400 | 900 | | | | |
| w05 | Plaster | 0.015 | 0.700 | 1400 | 900 | 2.43 | 0.17 | 10.72 | 906 |
| | RC Walls | 0.360 | 1.800 | 12400 | 1000 | | | | |
| | Plaster | 0.015 | 0.700 | 1400 | 900 | | | | |
| w06 | Strawbales | 0.500 | 0.110 | 1000 | 1500 | 0.19 | 0.02 | 22.77 | 378 |
| | Plaster | 0.015 | 0.700 | 1400 | 900 | | | | |
| | Light-weight concrete | 0.260 | 0.450 | 1100 | 1100 | | | | |
| | Plaster | 0.015 | 0.700 | 1400 | 900 | | | | |

Table 2 collects the properties of the six roof typologies with the main thermal values of both materials and package. The reported properties are the same as for walls and again the construction layers (materials) are listed starting from the outer. The wood-based structural wall and structural roof (i.e. *w03* and *r05*) have been introduced in the stock since these materials gained an increasing importance in the building construction market thanks to their seismic and thermal characteristics [49]. Even though they are mainly applied in conditioned buildings, they can significantly affect the thermal performance also in unconditioned buildings, especially if they are introduced in the context of thermal upgrading interventions on existent poor performance structures. The roof tiles are directly exposed to the sun, their solar absorptance is set to 0.7.

2.1.3. Opening glazing

As far as the opening glazing is concerned, two typologies were considered:

- *gLP* (low performance glazing): characterized by simple-glazed window, with glazing transmittance $U_g=6 \text{ Wm}^{-2}\text{K}^{-1}$ and air infiltration value equal to 0.5 changes per hour. This is typical of existent buildings.
- *gHP* (high performance glazing): constituted by a double-glazed window, with $U_g=2.2 \text{ Wm}^{-2}\text{K}^{-1}$, and air infiltration value equal to 0.3 changes per hour, in accordance to UNI 13300 regulation [50] and Italian laws [46] for conditioned buildings. This last represents a high level of performance corresponding to modern glazing systems.

The introduction in the work of two glaze typologies, reflecting opposite

combinations of thermal performances, allows the numerical estimation of maximum benefits (in terms of energy saving or reduction of temperature discomfort) achievable with a glazing substitution intervention. Since, the window surface can represent a relevant percentage of the whole façade, even in agricultural and industrial buildings, the thermal performance of the glazed system could play a major role on the whole thermal response of the structure.

2.1.4. *Shading system*

The solar radiation could represent a positive or negative factor for the building thermal behaviour, as function of the season and indoor desired temperature. As matter of fact, during the colder months solar radiation can help to reduce heating consumption, while during the warmer months, typically increases the cooling need. In this work, a sun-shading wall, built close to external walls, was introduced. The shading green wall is composed of a steel grid structure covered by *Parthenocissus tricuspidata*, a seasonal climbing plant. The wall is located 3 m far from the external walls. In the numerical simulation, two different cases (i.e. typologies) were considered:

- *sON*: sun-shading wall is present and then considered in the analyses. The transparency has been taken into account according to month-by-month leaf coverage [51];
- *sOF*: sun-shading wall is not present.

2.1.5. *Building orientation*

The building orientation is an aspect not always considered as a variable in thermal analysis, even though it can play a remarkable role in certain cli-

matic scenarios for building energy need [52, 53]. Therefore, in the present work, four different orientations have been considered applying at the actual building orientation, labelled *o01*, three progressive counter clockwise 90° rotations so obtaining orientations *o02*, *o03* and *o04*.

2.2. Definition of the ideal Temperature Ranges (TRs)

One of the scopes of the work is to analyse if effective solutions related to some temperature ranges (identified as optimal for some types of production/conservation food industry processes), can be effective for other thermal ranges and/or compatible with human presence as well.

So, in the present paper, six target temperature ranges have been selected according to different needs. Their ranges are typical of food preservation and ageing.

- *TR1*: 0°C-4°C, considered the optimal temperature slot for keeping fresh cheese [54] and in general all the foods to be conserved in the refrigerator cell.
- *TR2*: 4°C-8°C is the optimal temperature for the processing techniques of fresh fruit and vegetables.
- *TR3*: 8°C-12°C suitable for second fermentation of classical method wines,
- *TR4*: 12°C-16°C suitable for the conservation of white wines
- *TR5*: 16°C-20°C suitable for the conservation and ageing of red wines
- *TR6*: 20°C-24°C referred to storehouse groceries usually storing food at room temperature, compatible with human presence.

It is worth to note, that the definition of suitable temperature ranges for wine ageing has been carried out through a comparative analysis based on the scientific literature. Even though the scientific literature excludes the possibility to define an ideal temperature range for all the wine types and qualities, the chosen ranges can be considered suitable and reliable [55, 56, 57].

The TR adopted in the study are summarized in Table 3.

By considering all the six ranges, the study covers a large temperature band (from 0°C to 24°C) to widely investigate the building thermal behaviour. For the analyses, the ranges are considered in both conditioned and unconditioned buildings. They are used, in fact, as reference for discomfort calculation (as later explained) in unconditioned buildings, and as thermostat set points for (heating and cooling) in conditioned buildings.

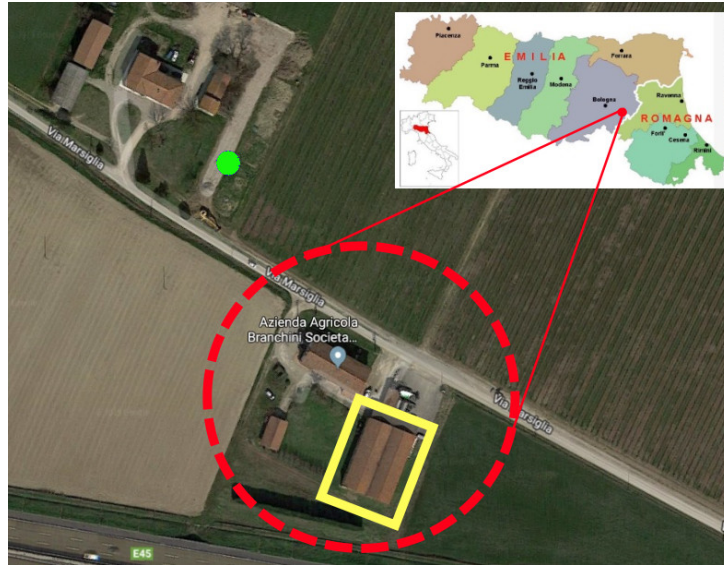
2.3. Description of the case study building

The case study building, adopted for the energy analyses of the present work, is a winery located in Bologna countryside more and more incorporated in the metropolitan area (see Figure 1a). The building (see Figure 1b) is currently used for winemaking and storage before final sales. It has an in-plane rectangular shape, with main axis 32° North-East oriented. The longitudinal and transverse dimensions are respectively 27.75 m and 18.50 m (see Figure 2). The double-arched transverse section has variable minimum height of 5.30 m and maximum 7.00 m. Six columns with 5.55 m spacing, fully infilled, are located along the main axis and they divide the internal volume into two symmetrical wings: the North-East wing hosts the wine-making process while the South-West area is currently used to stor-

age bottled wine. The structure is built with traditional materials with low energy performance.

The perimeter walls and the inner infilled walls are 32-cm-thick concrete brick panels plastered with cement-based mortar. The horizontal structure, covering the work volume, is represented by a 30-cm-thick RC slab while the arched roof is built with a non-insulated RC slab. Five single glazed windows are located on the North-East wall, two metallic doors are located on both the two shorter façades. On the North-West façade a canopy protects the delivery area. The indoor volume is naturally ventilated and furthermore no air-conditioning or ventilation system are present. The case study is a typical precast building and is representative of Italian agrifood and industrial buildings for volume, dimensions, proportions, materials, window/wall ratio and shape.

With reference to the architectural characteristics/typologies defined in the previous sub-sections, the structure is built with *w02* wall typology, *r02* roof typology and has low performance glazing (*gLP*). Currently, there is no sun protection system (*sOF*) and for the sake of simplicity the 32° North-East orientation of the main building dimension was defined as orientation reference *o01* of the present paper. The orientation *o02*, *o03*, *o04* resulted then oriented respectively of 122°, 212° and 302° North-East. In the simulations, the introduction of the sun shading system will protect two sides of the building corresponding to storage area where the most temperature-sensitive products are stored.

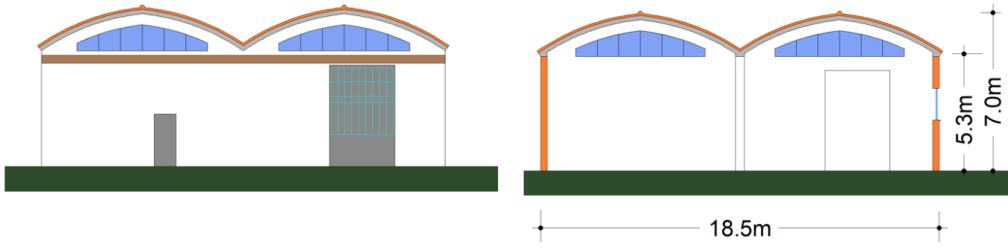


(a) View of the farm with particular of the winery investigated. The green dot indicates the weather station location



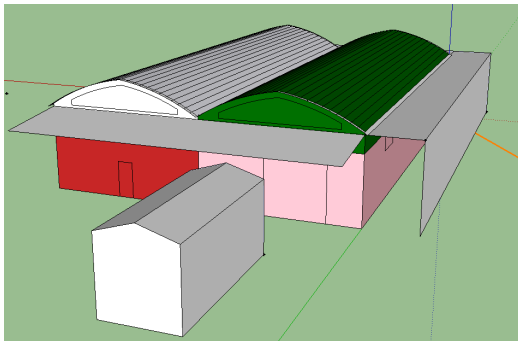
(b) North view of the winery

Figure 1: General views of the case-study building

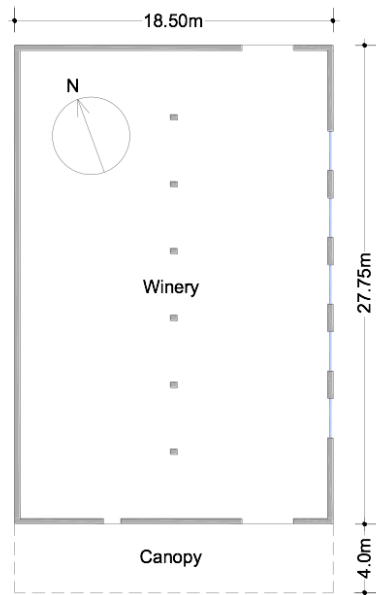


(a) Frontal view of the winery.

(b) Vertical section of the winery



(c) Thermal zoning of the investigated building



(d) Plan view of the winery

Figure 2: Case-study building details

2.4. Energy modelling

The increasing interest of the research in the field and the growing number of applications where energy saving strategies play a major role in the design phase [58, 59], has driven the development and the diffusion of software for building energy modelling. Nowadays, several programs are available to simulate energy needs and consumptions. For this work, a base energy model was created using EnergyPlus [28], then all the variations to the base model were generated using specific Matlab codes. The integration between Matlab and EnergyPlus was used also to automatically manage simulations and result analyses, returning both building indoor temperature and energy consumption trends. The case study building modelling was calibrated and validated in a previous study [57] in the unconditioned scenario, allowed to use a reliable energy model for the simulations and the parametric studies described in the following section.

For the present work, all the possible combinations from 6 walls, 6 roofs, 4 building orientations, 2 glazing and 2 sun-shading typologies were analysed obtaining a total of 576 different building models. Then, each building combination has run in both conditioned and unconditioned scenarios and for two different years used as reference for outdoor environmental conditions. Thus, 2304 simulations were performed ($576 \text{ models} \times 2 \text{ scenarios} \times 2 \text{ yearly series}$) and their outcomes analysed.

The EnergyPlus software works with garbage in-garbage out standard, entailing the refinement of input data and the verification of the model outcomes are two crucial points. The model of the case-study building, calibrated and validated on experimental data [36, 57] was selected as reference

for generating all the other combinations. The building model is subdivided in four different thermal zones: the wine making area, the wine-storage area going from ground level to 4.50 m of height, and other two zones, having the same in-plane division of the previous, but starting from the level 4.50 m until the roof structure (see Figure 2c). The shading surfaces are made by vertical (5 m high, located 3m far from the building walls) and horizontal green surfaces. The latter connect the vertical green walls to the building walls along the south-western and north-western sides. Further details are given in the Appendix A.4

Then, a specific *ScheduleObject* was created to control the transmittance according to the seasonal foliar coverage over the year. Specifically, the transmittance coefficient varies from 0.15 of the summer to 0.90 of the winter, taking into account both the foliar coverage and the steel trussed structures.

Since the aim of the study is the assessment of the envelope performance, all internal loads and masses have been excluded since they are different for each intended use and sensibly affect the thermal behaviour, as demonstrated in Benni et al. [35].

The ground temperatures are based on the data collected during the on-site experimental monitoring campaign [60, 61, 41, 38]. Scripts elaborated through Matlab software eased the creation of the 576 models. Every model has its specific label in the form: $wXXrXXoXXXgXXsXX$, where wXX , rXX , $oXXX$, gXX , sXX follows the nomenclature previously described. The base model has the label $w02r02o032gLPsOF$ since it has wall $w02$, roof $r02$, orientation 32° NE, with low performance windows and no sun shading system. The models described here have been used for time-history energy

analyses in both unconditioned and conditioned scenarios. The increment time step used in the analyses was one hour. The conditioned scenario has been obtained by introducing in the model the presence of an ideal heating-cooling system able to guarantee the indoor temperature of the volumes (1) and (3) in Figure 2c inside the desired range.

2.5. External temperature history (model input)

Obviously, the thermal performance of any building, is largely influenced by the outdoor environmental conditions such as temperature, humidity, rainfall, snowfall, etc. therefore the same building will provide every year different thermal responses if unconditioned, or different energy needs if thermostat set points are present. In particular, previous studies [57] showed that one of the conditions that mostly affects the discomfort is the yearly average temperature. Since the study aims to assess the thermal performance of a building in a specific site, in order to have reliable indications, the study adopts data recorded in the proximity of the structures.

Several weather files are currently available for energy simulations. Nevertheless, the closest weather file available on EnergyPlus site is located 32 km North from the farm (Bologna airport) in a very different environment condition (urbanised area) [62]. To cope with this problem, the installation of a meteorological station in the farm allowed to create weather files based on the records of the real outdoor environmental characteristics. Further details are given in the Appendix A. In particular, two years have been selected for the present work: 2007 (code: y07) and 2013 (code: y13), since:

- they have closer annual average temperature ($T_{2007}=13.95^{\circ}\text{C}$ and $T_{2013}=14.17^{\circ}\text{C}$)

similar to the yearly average temperature of the site, i.e. 13.7°C, of the last 20 years [63];

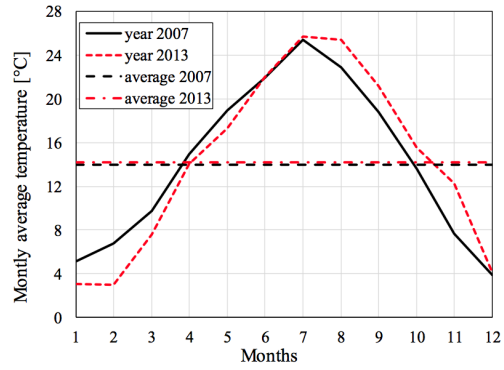
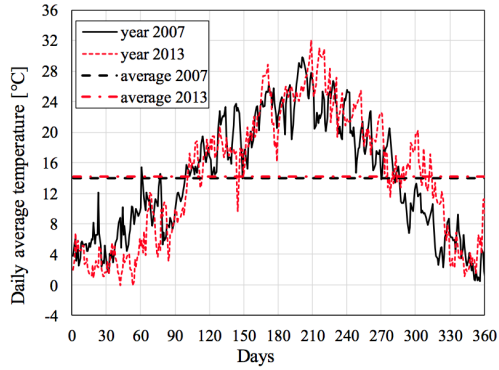
- they are based on the data collected by the farm weather station;
- their seasonal trends are different since August-December in 2013 was warmer than in 2007 and vice versa for January-May period.

Figures 3a and 3b show the daily average temperature trends for 2007 and 2013 and the monthly average temperature trends. The difference between the two years is highlighted by the temperature distributions and also by the solar horizontal radiation (see Figures 3c-3d).

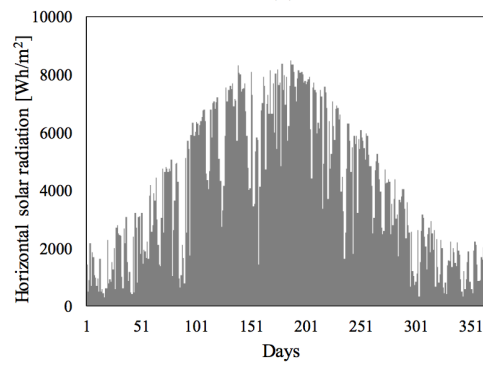
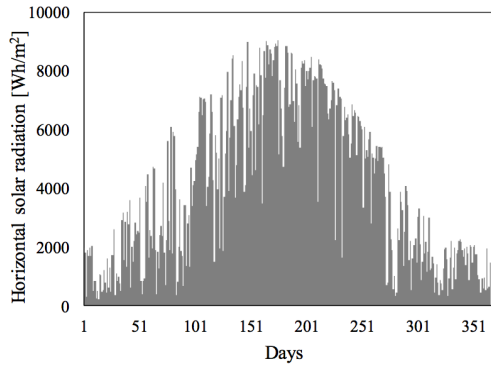
The Kolmogorov Smirnov test on the temperatures rejects the null hypothesis ($P=0.677$) that the two data sets have the same distribution; their dissimilarity index is equal to 0.125. Even though a certain temperature trend is expected for a specific site, considering only one year for the simulations could be not sufficient to suitably estimate the energy behaviour of a building during its lifetime, since uncertainty on seasonal effects are neglected. In the present paper, by comparing the outcomes from the two different years, the characteristics that influence the most the building thermal behaviour are identified.

2.6. Building performance indicators (model output)

The thermal analysis for conditioned buildings is usually based on few indicators such as thermal energy need (meaning the theoretical energy needed to maintain the temperature within a prescribed temperature range) or energy consumption (both usually expressed in kWh).



(a) Daily average temperature for 2007 and 2013 years (b) Monthly average temperature for 2007 and 2013 years



(c) Daily total horizontal solar radiation for 2007 (d) Daily total horizontal solar radiation for 2013

Figure 3: Details on the climatic data used in the numerical simulations

The first is commonly used for sizing the heating and cooling systems, the latter drives directly to economical assessment of operating cost due to thermal energy need, taking into account also the system efficiency and heat distribution. Since the work aims at analysing the influence of the envelope on building thermal behaviour, systems are excluded and therefore the energy demand is taken as reference result for the conditioned scenario. Under this light, the energy demand can be considered as the energy consumptions of an ideal system with efficiency coefficient equal to 1 and with no power limitation.

The energy need (hereinafter called EN) necessary to keep the indoor temperature was automatically returned by the EnergyPlus simulations. On the other hand, the building models in unconditioned scenario can be assessed comparing the indoor temperature with respect to the temperature range threshold. As above said, temperature and humidity play a fundamental role in food conservation and production phases but is not possible establish, in general for all the building uses, an optimal humidity level. Therefore, in the work, the temperature was the only parameter used as reference for the building thermal behaviour assessment. A specific indicator based on the concept of thermal discomfort, has been used. According to Barbaresi et al. [57], the discomfort level (DL) assesses how much the indoor temperature gets out of the desired range. The indicator, DL , is expressed in degree hours [dh] and was calculated as follows:

$$DL = |DL_-| + |DL_+| \quad (1)$$

where:

$$DL_- = \sum_{i=1}^n \delta_- \cdot (t_{min} - t_i) \quad (2a)$$

$$DL_+ = \sum_{i=1}^n \delta_+ \cdot (t_{max} - t_i) \quad (2b)$$

$$\delta_- = \begin{cases} 1 & \text{if } T_i < T_{min} \\ 0 & \text{if } T_i > T_{min} \end{cases} \quad (3a)$$

$$\delta_+ = \begin{cases} 1 & \text{if } T_i > T_{max} \\ 0 & \text{if } T_i < T_{max} \end{cases} \quad (3b)$$

and where T_{min} , T_{max} are the temperature range lower and upper limits. In this way, the total annual discomfort level DL of the building is the sum of the discomfort level for the excessive temperatures (i.e. DL_+) and defect temperatures (i.e. DL_-). The DL_+ is the sum of all the hourly differences between the indoor temperature of simulation T_i and the upper limit of the temperature comfort range T_{max} , when the indoor temperature from the simulation exceeds the upper range threshold. The DL_- , on the opposite, is the sum of all the hourly differences between the lower limit of the temperature comfort range T_{min} and the temperature from simulation T_i when the indoor temperature from simulation is lower than the lower range threshold.

The total annual thermal energy need (EN) and the total annual discomfort level (DL) will be used in the following sections as reference for the assessment of the thermal performance of a building model and for their comparison. It is to remember that, in general, these measures are not an

intrinsic property of the building, since their values are determined also by the outdoor weather conditions. The use of two different years in the simulations will enable to evaluate also the robustness of these two indicators at the building scale.

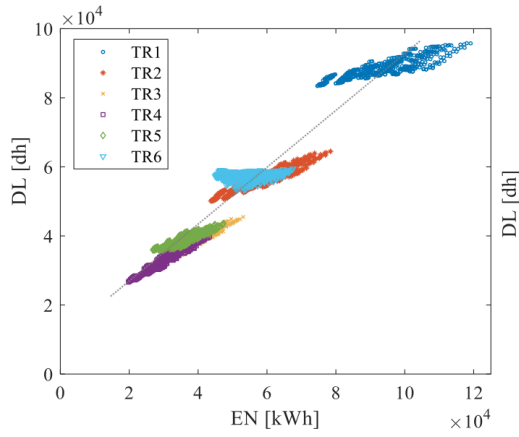
3. Results and Discussion

This section presents the main results of the energy simulations performed and, from their analysis, the most important observations are reported in order to address the main findings.

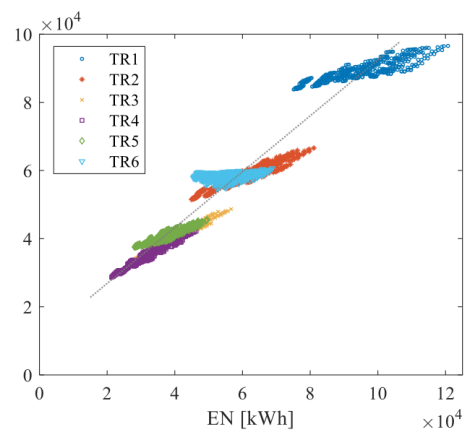
3.1. Influence of temperature range on building thermal behaviour

The first investigation concerned the influence of the adopted temperature range on the thermal performance of the building. Figure 4 shows the comparison between the values of EN (in abscissa) and DL (in ordinate) as obtained for each analysed model in both the conditioned and unconditioned scenarios. Each dot corresponds to the performances of a single building configuration for a specific thermal range in both scenarios, conditioned (EN) and unconditioned (DL). The six different markers refer to the six different temperature ranges (TRs) considered in the work. Obviously, every data cloud contains 576 points (equivalent to the number of building models). Following the same labels adopted above, from $TR1$ to $TR6$, the temperature range varies from 0°C - 4°C to 20°C - 24°C . Figure 4a and 4b refers respectively to 2007 and 2013 performances.

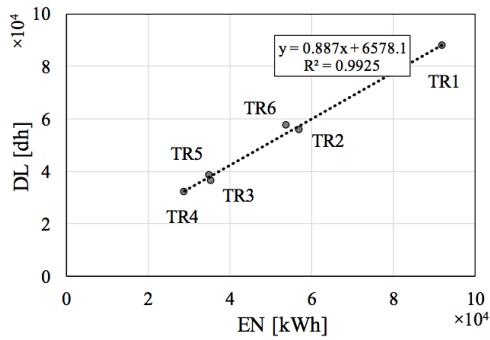
A first preliminary consideration is related to the position, in the graph EN - DL , of the clouds. The position of $TR1$ data cloud in Figure 4b suggests that for the 0°C - 4°C temperature range the highest energy consumptions (i.e.



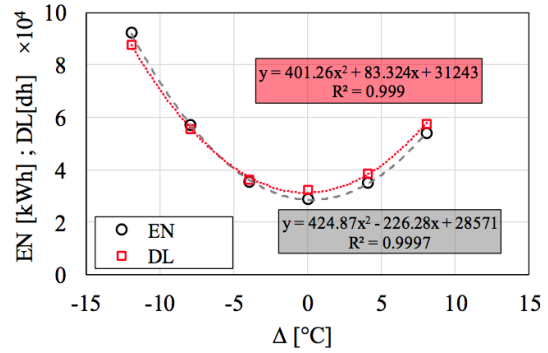
(a) Comparison of EN and DL indicators for the six TRs for year 2007



(b) Comparison of EN and DL indicators for the six TRs for year 2013



(c) Position in the EN - DL plane of the median values obtained for each TR for year 2007



(d) Plot of the consumption EN and DL median values obtained for each TR for with respect the Δ value of each TR for year 2007.

Figure 4: Influence of the temperature range (TR) on the building performances

74 000-120 000 kWh) and the largest discomfort level (i.e. 82 000-97 000 dh) per year, are expected. Meaning that, for the case study and geographical site at hand, the food-processing activities requesting $TR1$ will results the most burdensome. Following analogous reasoning, the $TR2$, $TR3$ and $TR4$ clouds progressively reduce both EN and DL indicators up to 20 000-42 000 kWh and 27 000-40 000 dh respectively. The values of EN and DL increase again for $TR5$ and $TR6$.

In the Figure 4c, the TR clouds are represented by their EN and DL medians for the years 2007 exhibiting aligned values in the EN - DL plane. This testifies that in general, if the medians are considered representative of the whole TR set, EN and DL indicators increment in analogous way according to the TR variation due to the strong dependence on the indoor temperature.

So, as expected, the TRs with the lowest energy demand and lowest discomfort are those closer to yearly average temperature in the site. For the sake of clarity, Figure 4d shows the trend of EN and DL (median value), for year 2007, versus the parameter Δ , calculated as difference between the central value of each TR and the annual average temperature of the site equal to $13.95^{\circ}C$ for 2007 (see Table 3). It is worth to note as for Δ values closer to zero (i.e. the $TR4$) both EN and DL indicators reach the minimum, and more interesting, the global trend is essentially parabolic. The coefficient of determination R^2 of the fitting equation is practically unitary for both DL and EN and then the equations are substantially exact.

Moreover, for a TR with low value of Δ , limited increments of energy consumptions and discomfort are expected with respect to the minimum, but

at the opposite, exponential increases of the consumptions are to imagine as long as Δ increases. For example, for the investigated case, if $\Delta=4^{\circ}\text{C}$ (i.e. *TR3* and *TR5*), an increment of 10-15% with respect to minimum is expected for discomfort and consumption, while for $\Delta=8^{\circ}\text{C}$ (i.e. *TR2* and *TR6*) and 12°C (*TR1*) the indicators become 190% and 300% compared to the minimum.

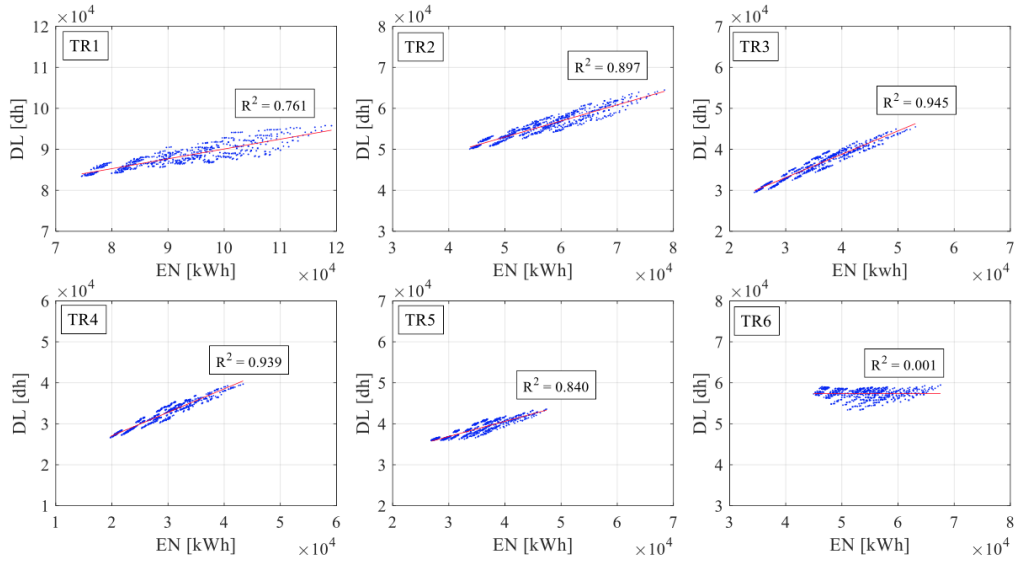
The practical consequence is that the expected performance of the building will result practically the same for two *TRs* having Δ with same absolute value but opposite sign. From the knowledge of the parabolic equations $DL = DL(\Delta)$ and $EN = EN(\Delta)$, the expected DL and EN could be simply defined on the basis of the desired optimal indoor temperature (that is connected to the intended use).

Under this light, if a modification affects the required indoor temperature (as frequently occurs changing the intended use), an immediate assessment of the DL and EN variations is simple to achieve.

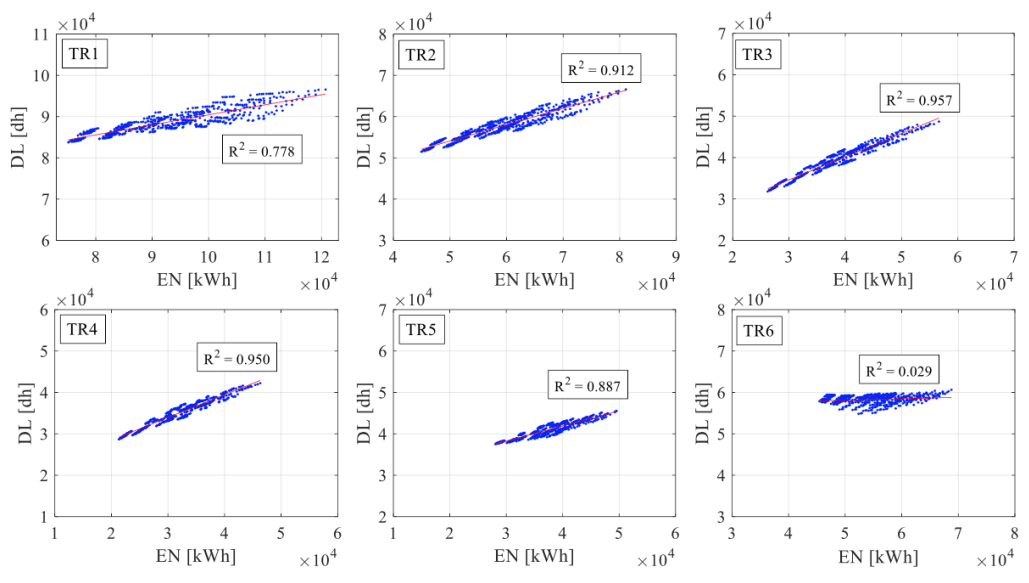
This tool allows the owner to calculate the new building performance as a Δ value function. Analogous conclusions can be drawn considering year 2013. They confirm these outcomes, but are not reported here for the sake of brevity.

After these preliminary considerations, it is interesting to analyse more in depth the data distribution of each *TR*. Figure 5 reports the results of the same building in terms of EN vs DL annual values, simulated in the two different scenarios (i.e. conditioned and unconditioned). Figure 5a and 5b show respectively the results of 2007 and 2013.

The graphs evidence a good correlation between EN and DL from *TR2*



(a) Year 2007



(b) Year 2013

Figure 5: Scatter plot of the EN vs. DL indicators for the six temperature ranges (TRs)

to $TR4$ ($R^2 > 0.85$), confirming that a combination of architectural characteristics will provide good (or bad) performance in both unconditioned and conditioned scenarios. The correlation appears weaker for $TR1$ and $TR5$ and then fall down moving from $TR5$ to $TR6$ going from values around 0.8 to practically 0.

In order to better investigate the reason of the big leap of R^2 in the last TR , three further temperature ranges were added to the study. They were labelled TRa , TRb and TRc . They progressively move from $TR5$ to $TR6$ since they respectively consider 17°C-21°C, 18°C-22°C and 19°C-23°C temperature ranges. The plot of R^2 vs the TR central temperatures is reported in Figure 6 for both 2007 and 2013 years. It also considers the value of the further ranges TRa - TRc discussed above.

It seems worth to note that, for the case investigated here, R^2 has a smoothed trend that rapidly decreases after temperature around 18°C.

This evidence results interesting since the optimal ranges for human occupancy are typically located on the right portion of the graph, exactly where the R^2 rapidly tend to zero. Differently to Figure 4d, the graph in Figure 6 shows an absence of symmetry with respect to Δ . This outcome testifies as the central values of the clouds medians are strongly related to Δ values whereas their dispersion is not. In order to better understand the trend of $TR6$, this specific temperature range was investigated with more detail in the following Section.

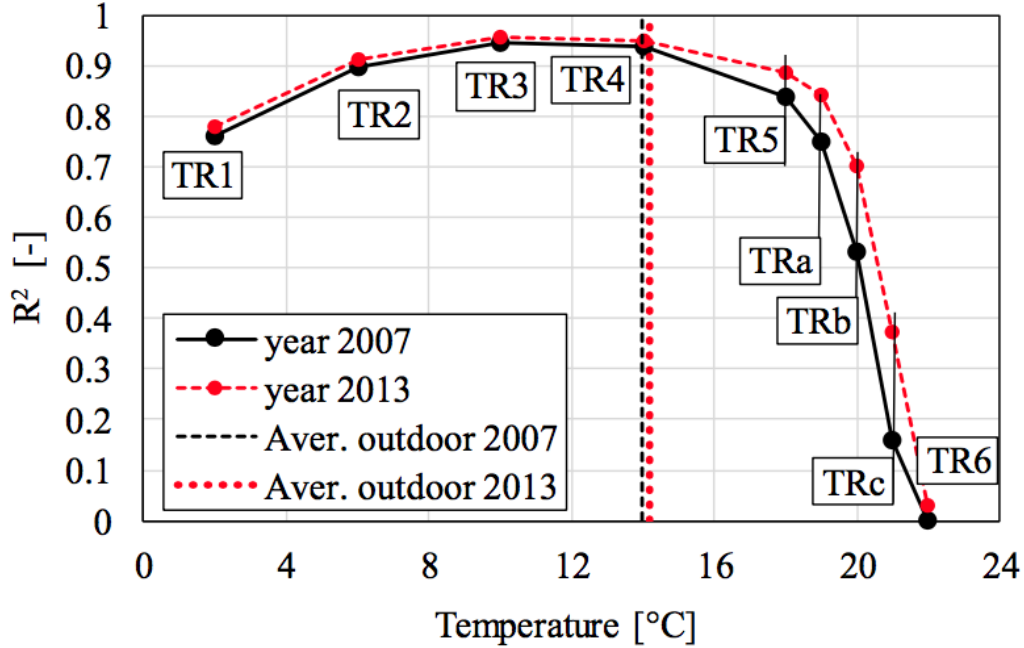


Figure 6: Graphs of the coefficient of determination R^2 calculated for $EN-DL$ data clouds from $TR1$ to $TR6$ and the three further TRs added to the study (i.e. TRa , TRb and TRc). The R^2 values are plotted with in abscissa the central temperature the TR . The vertical lines in the figure indicate the average temperature of the year (black for 2007 red for the 2013).

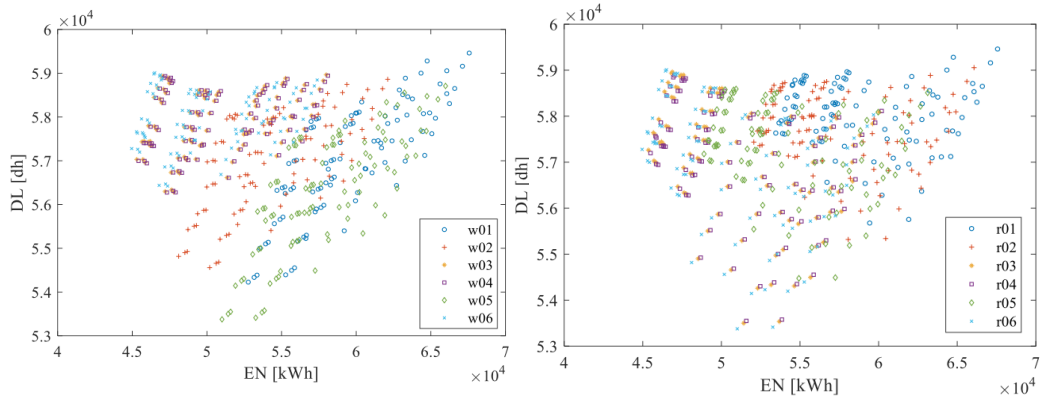
3.2. The influence of architectural characteristics and typologies on building thermal behaviour

Consequently, the paper assesses the effects of different architectural characteristics and typologies combinations on the thermal behaviour of the case study building. In this context, the architectural characteristics, that mostly affect the thermal behaviour, are identified. This aspect will be thoroughly discussed in this Section. Figure 7 shows the scatter plot related to $TR6$ (TR with the largest dispersion for both EN and DL performance indica-

tors). Each subfigure is related to a single architectural characteristic (wall, roof, etc.) and the different markers highlight the different typologies (such as $w01$, $w02$, etc. in Figure 7a). Some relevant information can be deduced from this figure: as example, Figures 7d and 7e highlight how some characteristics are more effective in one scenario than in the other: in Figures 7d, switching from gHp to gLP produces small variations for unconditioned scenario and on the contrary, worsen remarkably the performance of the building for the conditioned scenario. Similarly, in Figure 7e the absence of shading entails relevant improvements in unconditioned scenario and small variations in the conditioned one.

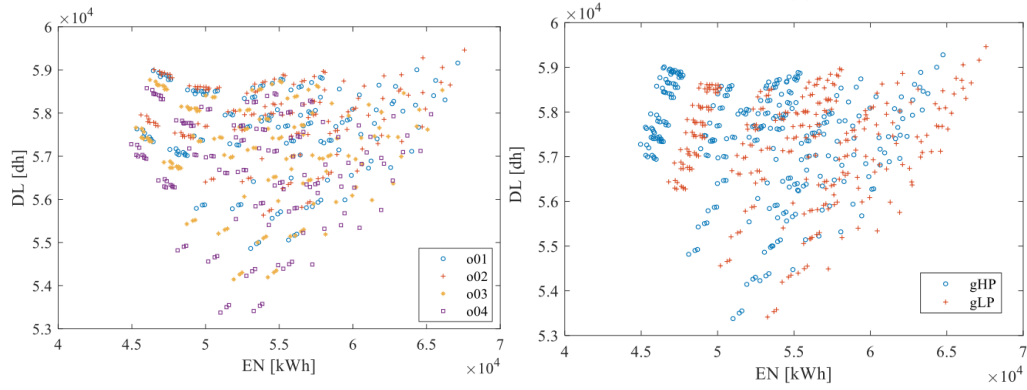
To better understand this phenomenon, centroids (median values) of each typology were reported in Figure 8 for year 2007. The Figure 8a shows the centroids for $TR4$, i.e. (TR with highest R^2) while Figure 8b displays the range $TR6$ (TR with lowest R^2). In the former, all centroids of the same architectural characteristic are aligned along first-third quarters entailing that solutions with good performance for the unconditioned scenario have good performance for the conditioned scenario and vice versa. On the contrary, some typologies of $TR6$, such as walls, can improve performances for unconditioned scenario and at the same time worsen the conditioned scenario performances (compared to the average).

Then, our educated guess to explain this effect is related to the architectural characteristic properties such as thermal lag or surface density. These can explain the absence of correlation in some temperature ranges, e.g. $TR6$, since the substitution of an architectural characteristics could produce different effects if the building is conditioned or not. These aspects will be object



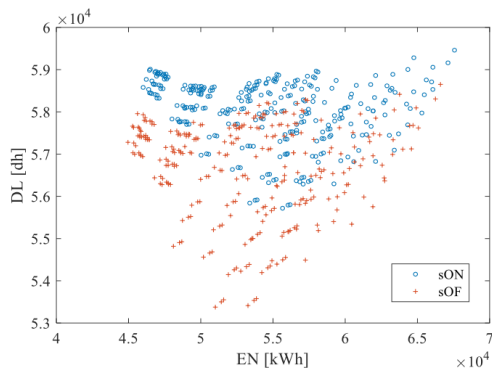
(a) Wall

(b) Roof



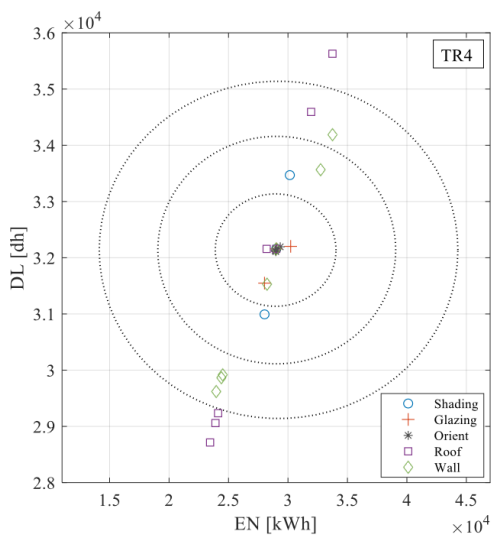
(c) Orientation

(d) Glazing

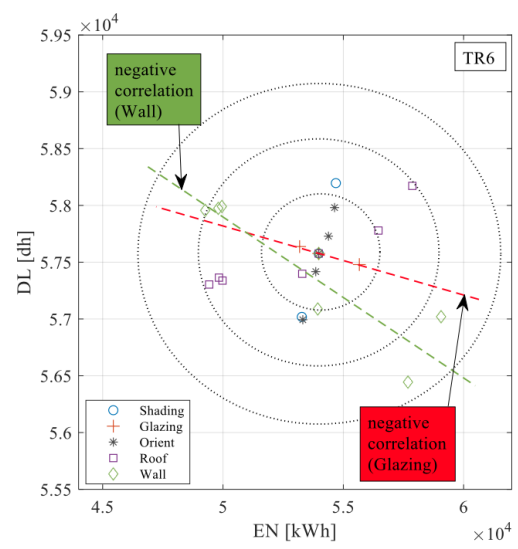


(e) Shading

Figure 7: Comparison of EN vs. DL indicators for temperature $TR6$. Each subfigure shows, with different markers, the points belonging to different typologies of a specific architectural characteristic



(a) TR4



(b) TR6

Figure 8: Position in the plane $EN-DL$ of the typology centroids (median values) for year 2007

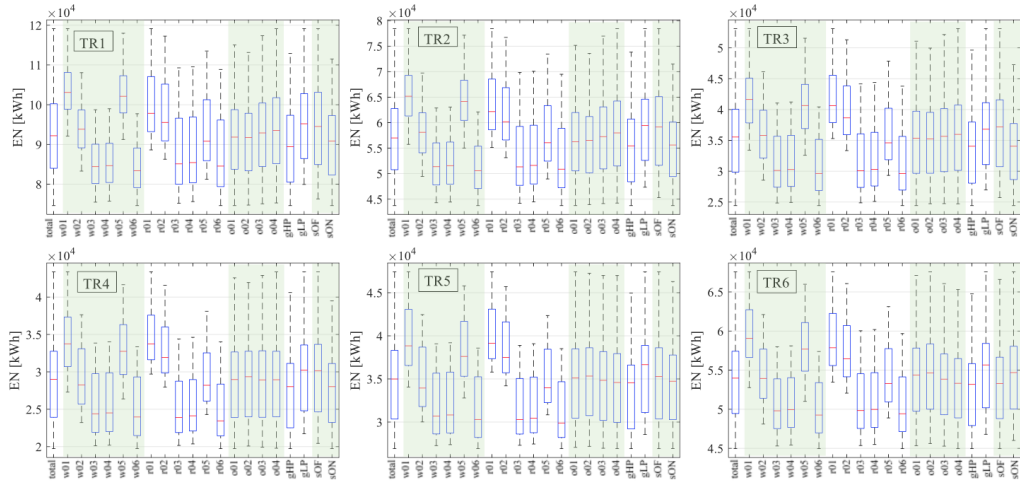
of future investigations. Low correlation of the cloud points in *EN-DL* graphs is an unexpected outcome, since it means that the same combination of architectural characteristics provides an opposite contribution if applied in conditioned or unconditioned scenario. This finding has practical consequences in energy retrofitting interventions, entailing that the strategy for building performance improvements must be carefully selected as a function of the desired indoor temperature. This could limit in a drastic way the number of effective solutions to adopt in a design. Some technical interventions could not improve building performance in some *TRs* while they result very effective in others. So, in this context, is not possible to generalize a hierarchy of the interventions or find criteria valid for each *TR* since every range has its own peculiarities depending on building characteristics.

Furthermore, to identify and then quantify, for each *TR*, the architectural characteristics that mostly affect the energy performance of the models, an in-depth statistic data elaboration was adopted. Results have been depicted as boxplots reported in Figures 9 and 10. Figures 9a and 9b exhibit, for 2007, respectively the *EN* and *DL* annual distributions of the data set, related to each of the 20 typologies, belonging to the 5 different architectural characteristics. In each Subfigure, the first boxplot on the left is related to the total data set. The typologies of the same architectural characteristics are highlighted by means of the vertical green and white strips. On each box, the central red mark indicates the median, the bottom and top edges of the box indicate the 25th (quartile 1: *Q1*) and 75th (quartile 3: *Q3*) percentiles, respectively. The whiskers extend to the most extreme data points, outliers excluded. Then, the outliers were identified as the values falling outside

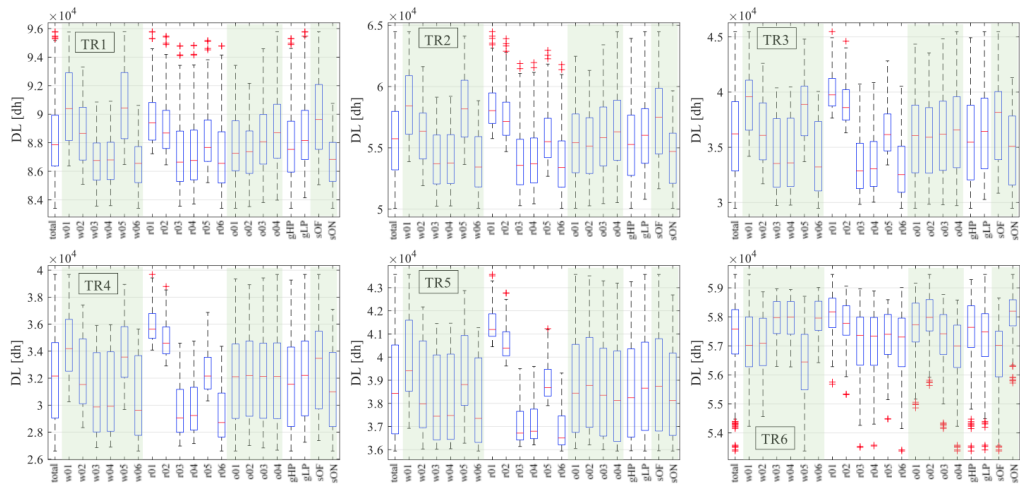
the range from $Q1 - 1.5IQ$ and $Q3 + 1.5IQ$ where $IQ = Q3 - Q1$ is the interquartile distance. The outliers are plotted individually using the red '+' symbol.

These choice for the graphs can help to visually identify the typologies that affect the most the performances by analysing the interquartile distance IQ . As a representative example, $r01$ of $TR5$ in Figure 9b is taken (this boxplot shows the performances of all models containing $r01$ when $TR5$ is set). Boxplot shows that any solution containing $r01$ would be higher than 40500 dh regardless the other typologies chosen in the model, and 50% of all models containing $r01$ (see interquartile $Q3-Q1$) returns performance in a very limited range (41000 dh - 42000 dh). Under this light, the interquartile distance can be taken as reference for the influence of the single typology on building thermal behaviour: the smaller the interquartile distance, the higher the influence.

Tables 4 and 5 show the values, for every typology, for the TRs , for the different scenarios (unconditioned and conditioned respectively) for year 2007, of the interquartile range normalized to total median ($IQ/med_{tot}100$ [%]); the values are in percentage. The med_{tot} is the median of all the 576 models. As far as the conditioned scenario is concerned, the typologies showing the major influence are $w01$, $w02$, $w05$, $r01$, $r01$, $w01$ respectively from $TR1$ to $TR6$. Totally different is the unconditioned scenario where the roof typology $r01$ exhibits the lowest value for all TRs except $TR1$ and $TR6$ governed by $w06$ (wall) and sON (added shading system). By the evaluation of the IQ , useful considerations can be drawn on the most influential typology or even architectural characteristic, even though this parameter is not able to provide

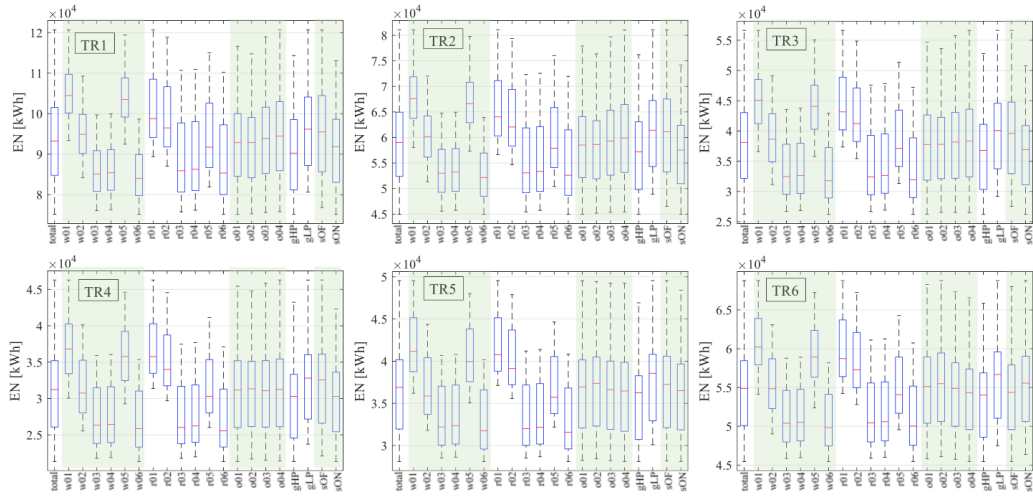


(a) *EN* indicator

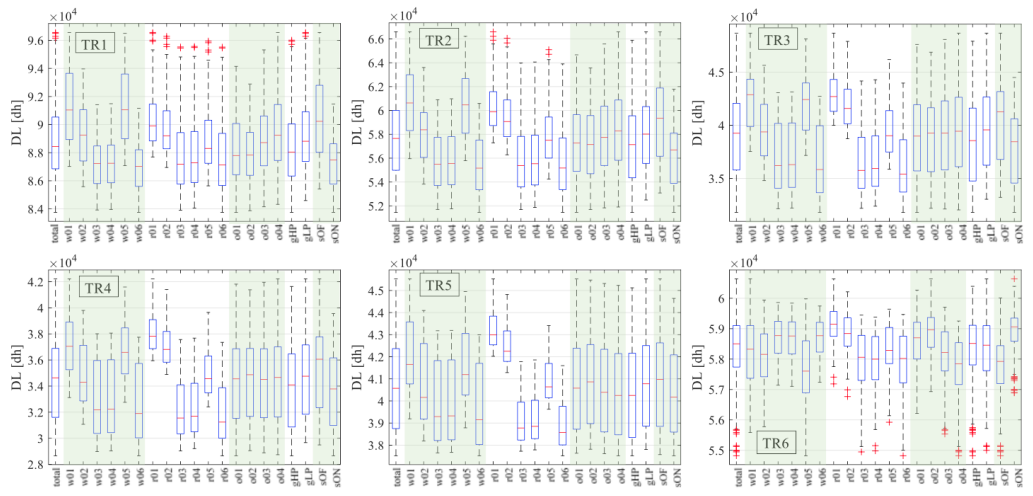


(b) *DL* indicator

Figure 9: Boxplot representation for the six *TRs* for the year 2007



(a) *EN* indicator



(b) *DL* indicator

Figure 10: Boxplot representation for the six *TRs* for the year 2013

information on the positive or negative effect of the typology/architectural characteristic.

Therefore, to exactly establish the positive or negative influence of a typology on the energy performance, the deviation among median values has been used.

Table 6 and 7 report the deviations among typologies' medians and the median of all simulations, for each typology of every TR , for year 2007, respectively in the conditioned and the unconditioned scenarios. The values are normalized to total median and expressed in percentage ($(med_{typology} - med_{tot})/med_{tot} \times 100$ [%]). The sign of the value in Tables 6 and 7 defines if the introduction of a certain typology produces positive or negative effects, in a specific TR . Both the information provided by Tables 4, 5, 6 and 7 will help to define the most effective interventions, providing a general view of the effects of a typology in a specific temperature range and scenario.

Remarkably, by moving from the conditioned to the unconditioned scenario, the introduction of a specific typology could produce different effects (see for example the different sign for $w06$ in $TR6$ for conditioned and unconditioned scenario). Furthermore, by the analysis Tables 6 and 7 emerges that in an unconditioned scenario, $w06$ could help to improve the energy performances if applied in a building having an optimal temperature in the ranges from $TR1$ to $TR5$, while on the contrary could results useless or even detrimental if applied in the $TR6$. Similar results can be found by considering the year 2013 confirming the general validity of the outcomes.

Finally, in order to assess the influence of the building characteristics on the thermal behaviour, the standard deviations of the medians of each char-

acteristic were calculated. In fact, the higher the standard deviation, the higher the influence of the characteristic on the building thermal behaviour. Specifically, Figure 11 shows the standard deviation of the medians for each architectural characteristic in all TRs for conditioned (Figure 11a) and unconditioned (Figure 11b) scenarios in 2007.

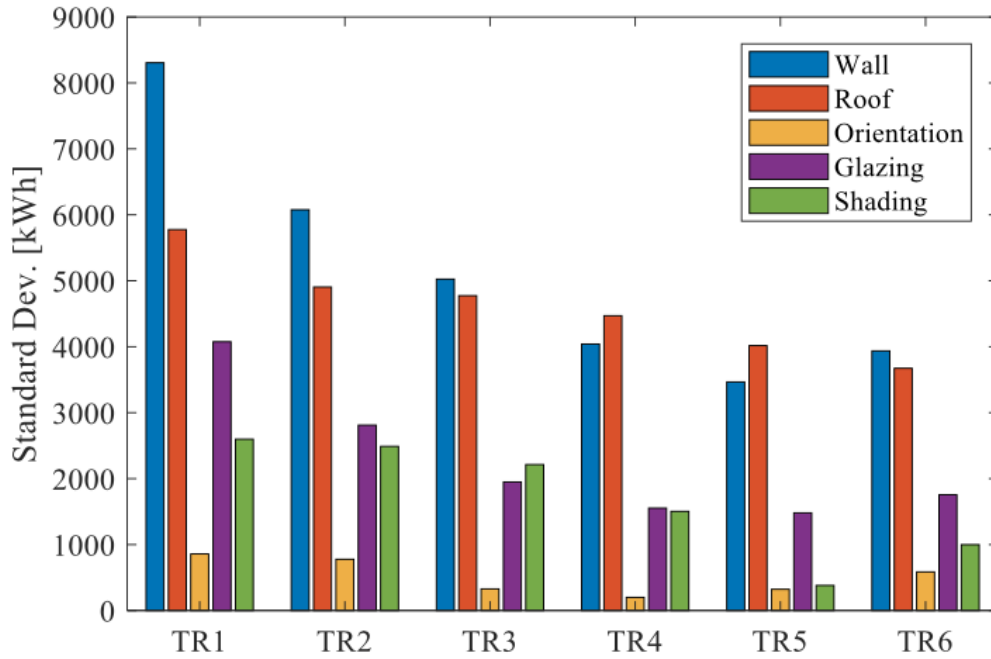
The values of the coefficient of variation (CoV), expressed in percentage, are reported in Table 8 for completeness reasons, for both years 2007 and 2013 and for the two different scenarios. They were calculated as the standard deviation of the medians of the typologies of the same characteristic, divided by the total median (med_{tot}) $\times 100$ [%]. In conditioned buildings, walls and roof always are the most relevant characteristics, in unconditioned buildings, besides walls and roof, also the shading plays an important role in the building thermal behaviour, in particular in $TR1$ where appears the most effective characteristic.

This outcome highlights how the influence of each characteristic is affected in a significant way also by the chosen temperature range and by the scenario, confirming those input data should be carefully taken into account during the design phase overall when changes of intended use are considered.

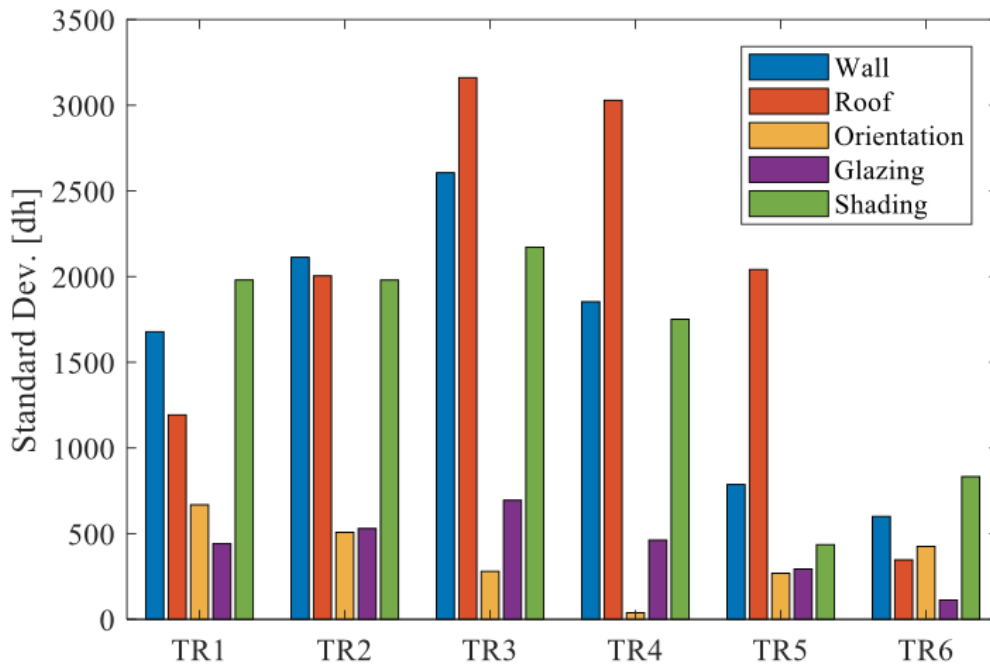
4. Conclusions

In order to guarantee an optimal usage of energy resources, the future building envelopes should be carefully selected as a results of an optimization process that guarantees the achievement of the required energy performances.

The present paper investigates the effects of some architectural characteristics of the building envelope on the thermal performance of the building



(a) *EN* scenario



(b) *DL* scenario

by means of thermal energy analyses on the model of a non-residential building selected as case study. Five architectural characteristics were considered, i.e. walls, roof, orientation, glazing and solar shading, and for each architectural characteristic different typologies were analysed, allowing the creation of 576 different building models obtained by combining the twenty typologies selected. Then energy simulations were run for six different optimal temperature ranges (TR) from 0°C-4°C to 20°C-24°C in two different situation, by considering a conditioned scenario and an unconditioned scenario. The considered temperature ranges were selected among those typical in some agrifood processes or in food conservation.

A huge quantity of numerical results were theoretically available after the simulations, but in order to define simple parameters for measuring and comparing the performances of different models, the main outcomes were provided, in the present work, in terms of performance indicators based on energy need (i.e. EN for conditioned scenario) and thermal discomfort (i.e. DL for unconditioned scenario). The use in the simulations of meteorological input data of two different years (i.e. 2007 and 2013) enabled to evaluate also the robustness of these two indicators at the building scale.

As first we observed that TR with the lowest energy demand and lowest discomfort are those closer than yearly outdoor average temperature at the site. Considering the parameter Δ , calculated as difference between the central value of each TR and the annual average temperature of the site, for Δ values closer to zero both EN and DL indicators score the minimum, and more interesting, the global trend of EN and DL is essentially parabolic with Δ and centred on $\Delta = 0$. Moreover, for a TR with low value of Δ ,

energy consumptions and discomfort limited increments are expected with respect to the minimum, but on the contrary, exponential increase of the consumptions are to imagine as long as Δ increases. From the knowledge of the fitting parabolic equations of EN and DL , if a change of the intended use that requiring different indoor temperature in the building is planned, an immediate assessment of the increment/decrement of DL an EN is simple to achieve just from the knowledge of Δ . Then, it was observed that from $TR1$ to $TR5$, a good correlation among EN and DL substantially exists. For $TR6$ (i.e. the range from 20°C to 24°C), the correlation disappeared. In order to better investigate the reason of the big leap of correlation in the last TR , three further temperature ranges were added to the study and an in-depth statistical analyses were adopted as tool. It was visible how some characteristics affect the building thermal behaviour being more effective in one scenario than in others.

Further, for $TR6$, some typologies, such as walls, can improve performances for unconditioned scenario and at the same time worsen the conditioned scenario performances. So, for example, it could occur that by changing the typology of walls respect to a specific model, the performance of the building improves working in unconditioned scenario, whereas worsen if the operating in a conditioned scenario. This explains the absence of correlation in some temperature ranges. In the context of an energy retrofiting interventions design, this last outcome entails that the strategy to improve the performance of a building must be carefully selected as a function of the optimal indoor temperature requested by the processes in the building reducing in a drastic way the number of effective solutions to adopt in a

design.

Finally, simple statistical analyses defined the most influential typologies and architectural characteristics on the thermal performances of the building. Remarkably, the introduction of a specific typology could produce very different and sometimes ambivalent effects by moving from the conditioned to the unconditioned scenario. This outcome highlights how the influence of each characteristic/typology is affected in a significant way by the chosen temperature range and by the scenario, confirming those input data should be carefully taken into account during the design phase overall when changes of intended use are considered.

The outcomes of the present work, even if referred to a case study, should be considered for the definition of a methodology that could be applied to the buildings located involved in conversion, incorporation and transformation process, for a preliminary assessment of the possible benefits and to drive the future decision-making process of cities development.

Table 2: Main roof typologies where: t : thickness [m]; λ : conductivity [$W(mK)^{-1}$]; ρ : density [kgm^{-3}]; c : specific heat [$J(kgK)^{-1}$]; U : thermal transmittance [$Wm^{-2}K^{-1}$]; F_a : decrement factor; Φ : time shift [h]; m : surface mass [kgm^{-2}].

| Roof # | Material component | t | λ | c | ρ | U | F_a | Φ | m |
|--------|--------------------|-------|-----------|------|--------|------|-------|--------|-----|
| r01 | Roof tiles | 0.030 | 2.000 | 2700 | 1260 | | | | |
| | Hollow slab | 0.200 | 0.800 | 1000 | 600 | 2.01 | 0.73 | 4.70 | 302 |
| | Plaster | 0.015 | 0.700 | 1400 | 900 | | | | |
| r02 | Roof tiles | 0.040 | 0.700 | 1800 | 830 | | | | |
| | Hollow slab | 0.250 | 0.800 | 1000 | 600 | 1.66 | 0.50 | 6.83 | 293 |
| | Plaster | 0.015 | 0.700 | 1400 | 900 | | | | |
| r03 | Roof tiles | 0.040 | 0.700 | 1800 | 830 | | | | |
| | Fiber wood panels | 0.130 | 0.039 | 160 | 2100 | 0.25 | 0.12 | 14.98 | 314 |
| | Hollow slab | 0.250 | 0.800 | 1000 | 600 | | | | |
| | Plaster | 0.015 | 0.700 | 1400 | 900 | | | | |
| | | | | | | | | | |
| r04 | Roof tiles | 0.040 | 0.700 | 1800 | 830 | | | | |
| | Light polystyrene | 0.120 | 0.040 | 20 | 1350 | 0.29 | 0.36 | 7.75 | 304 |
| | Hollow slab | 0.250 | 0.800 | 1000 | 600 | | | | |
| | Plaster | 0.015 | 0.700 | 1400 | 900 | | | | |
| | | | | | | | | | |
| r05 | Roof tiles | 0.040 | 0.700 | 1800 | 830 | | | | |
| | Fiber wood panels | 0.120 | 0.150 | 1000 | 2500 | 0.92 | 0.20 | 12.08 | 213 |
| | Plaster | 0.015 | 0.700 | 1400 | 900 | | | | |
| r06 | Roof tiles | 0.040 | 0.700 | 1800 | 830 | | | | |
| | Fiber wood panels | 0.180 | 0.039 | 160 | 2100 | 0.19 | 0.06 | 18.38 | 322 |
| | Hollow slab | 0.250 | 0.800 | 1000 | 600 | | | | |
| | Plaster | 0.015 | 0.700 | 1400 | 900 | | | | |
| | | | | | | | | | |

Table 3: Temperature ranges (*TRs*) considered in the present work. * Δ represents the difference between the central value of each TR and the annual average temperature of the site (13.95°C and 14.17°C respectively for 2007 and 2013).

| | TR1 | TR2 | TR3 | TR4 | TR5 | TR6 |
|-------------------------------|---------|---------|---------|---------|---------|---------|
| Range [$^{\circ}C$] | 0-4 | 4-8 | 8-12 | 12-16 | 16-20 | 20-24 |
| Average value [$^{\circ}C$] | 2 | 6 | 10 | 14 | 18 | 22 |
| Year 2007 | | | | | | |
| $\Delta[^{\circ}C]^*$ | -11.95 | -7.95 | -3.95 | 0.05 | 4.05 | 8.05 |
| q (intercept) | 66097.7 | 33362.9 | 16032.3 | 15593.5 | 25780.7 | 57308.7 |
| m (slope) | 0.23984 | 0.39265 | 0.56925 | 0.57316 | 0.37047 | 0.00076 |
| R_{adj}^2 | 0.7609 | 0.8974 | 0.9455 | 0.9387 | 0.8404 | 0.0017 |
| Year 2013 | | | | | | |
| $\Delta[^{\circ}C]^*$ | -12.17 | -8.17 | -4.17 | -0.17 | 3.83 | 7.83 |
| q (intercept) | 66125.8 | 34307.9 | 17791.5 | 17472.7 | 27306.9 | 56513.8 |
| m (slope) | 0.24302 | 0.39533 | 0.56058 | 0.5492 | 0.36466 | 0.03288 |
| R_{adj}^2 | 0.7779 | 0.9124 | 0.9572 | 0.9502 | 0.8866 | 0.0292 |

Table 4: Interquartile ranges for typology of every TR , for 2007 in the unconditioned scenario. The values are normalized to total median and expressed in percentage ($IQ/med_{tot}100[\%]$).

| Typology | $TR1$ | $TR2$ | $TR3$ | $TR4$ | $TR5$ | $TR6$ | TRa | TRb | TRc |
|----------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Unconditioned (2007) | | | | | | | | | |
| $w01$ | 10.00 | 13.96 | 20.39 | 22.87 | 18.61 | 11.29 | 16.77 | 14.27 | 12.50 |
| $w02$ | 10.32 | 13.77 | 21.85 | 25.5 | 19.70 | 11.64 | 16.88 | 14.92 | 12.78 |
| $w03$ | 10.74 | 14.47 | 23.24 | 27.03 | 20.15 | 11.79 | 17.82 | 15.5 | 13.57 |
| $w04$ | 10.70 | 14.45 | 23.27 | 27.06 | 20.16 | 11.76 | 17.8 | 15.53 | 13.57 |
| $w05$ | 10.16 | 13.84 | 20.17 | 22.97 | 18.18 | 11.52 | 16.31 | 13.95 | 12.03 |
| $w06$ | 10.81 | 14.56 | 23.31 | 27.02 | 20.09 | 11.9 | 17.79 | 15.44 | 13.57 |
| $r01$ | 15.02 | 17.44 | 21.56 | 20.53 | 16.42 | 12.35 | 15.37 | 14.28 | 13.37 |
| $r02$ | 15.48 | 18.00 | 22.23 | 21.22 | 16.85 | 12.14 | 15.70 | 14.65 | 13.33 |
| $r03$ | 18.01 | 20.28 | 24.45 | 23.67 | 18.42 | 12.95 | 17.04 | 15.31 | 13.74 |
| $r04$ | 17.93 | 20.19 | 24.47 | 23.67 | 18.44 | 12.96 | 17.11 | 15.38 | 13.8 |
| $r05$ | 16.63 | 19.11 | 23.5 | 22.21 | 17.68 | 12.62 | 16.24 | 14.72 | 13.38 |
| $r06$ | 18.16 | 20.41 | 24.48 | 23.84 | 18.47 | 12.95 | 17.14 | 15.32 | 13.76 |
| $o01$ | 16.26 | 20.07 | 28.35 | 30.21 | 22.98 | 14.94 | 20.18 | 18.27 | 16.40 |
| $o02$ | 15.70 | 19.34 | 27.77 | 30.22 | 22.47 | 15.45 | 20.51 | 18.40 | 16.67 |
| $o03$ | 17.31 | 21.33 | 28.77 | 30.65 | 22.77 | 14.40 | 19.88 | 17.70 | 15.75 |
| $o04$ | 18.02 | 22.34 | 29.8 | 30.19 | 22.78 | 14.05 | 20.05 | 17.30 | 15.50 |
| gHP | 18.22 | 21.57 | 27.88 | 29.65 | 21.17 | 14.67 | 18.77 | 16.94 | 15.49 |
| gLP | 17.73 | 21.06 | 28.23 | 30.33 | 22.22 | 15.25 | 19.49 | 17.63 | 16.15 |
| sOF | 19.71 | 23.61 | 30.49 | 31.06 | 23.56 | 14.55 | 21.11 | 18.45 | 16.29 |
| sON | 16.22 | 18.73 | 25.55 | 27.14 | 21.42 | 14.87 | 19.53 | 17.5 | 16.08 |

Table 5: Interquartile ranges for typology of every TR , for 2007 in the unconditioned scenario. The values are normalized to total median and expressed in percentage ($IQ/med_{tot}100[\%]$).

| Typology | $TR1$ | $TR2$ | $TR3$ | $TR4$ | $TR5$ | $TR6$ | TRa | TRb | TRc |
|--------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Conditioned (2007) | | | | | | | | | |
| $w01$ | 5.39 | 8.54 | 12.51 | 11.94 | 7.98 | 2.98 | 6.68 | 5.09 | 3.77 |
| $w02$ | 4.21 | 6.71 | 14.24 | 14.94 | 9.76 | 2.84 | 7.32 | 5.06 | 3.03 |
| $w03$ | 2.96 | 7.16 | 17.14 | 18.28 | 9.54 | 1.91 | 6.85 | 4.47 | 2.30 |
| $w04$ | 2.97 | 7.14 | 17.07 | 18.31 | 9.59 | 1.96 | 6.91 | 4.49 | 2.34 |
| $w05$ | 5.27 | 8.32 | 12.38 | 11.67 | 7.85 | 3.32 | 6.90 | 4.91 | 3.75 |
| $w06$ | 2.87 | 7.36 | 17.36 | 18.36 | 9.50 | 1.74 | 6.82 | 4.29 | 2.18 |
| $r01$ | 3.00 | 4.46 | 6.89 | 5.72 | 2.53 | 1.76 | 1.68 | 1.33 | 1.35 |
| $r02$ | 3.04 | 4.86 | 7.59 | 6.17 | 2.70 | 1.77 | 1.74 | 1.24 | 1.52 |
| $r03$ | 4.01 | 6.65 | 11.34 | 9.89 | 3.22 | 2.86 | 1.85 | 1.72 | 2.29 |
| $r04$ | 3.96 | 6.57 | 11.24 | 9.84 | 3.32 | 2.86 | 1.92 | 1.65 | 2.29 |
| $r05$ | 3.31 | 5.75 | 9.25 | 7.30 | 3.00 | 2.39 | 1.75 | 1.36 | 1.82 |
| $r06$ | 4.09 | 6.76 | 11.53 | 10.13 | 3.25 | 2.91 | 1.78 | 1.77 | 2.35 |
| $o01$ | 3.99 | 8.6 | 16.93 | 17.16 | 9.90 | 2.33 | 7.03 | 4.19 | 2.74 |
| $o02$ | 3.38 | 8.16 | 16.4 | 17.32 | 10.11 | 1.88 | 7.11 | 4.27 | 2.75 |
| $o03$ | 3.96 | 8.61 | 17.3 | 17.29 | 9.87 | 2.38 | 6.88 | 4.82 | 2.84 |
| $o04$ | 4.30 | 8.78 | 17.73 | 17.45 | 10.17 | 2.54 | 7.06 | 4.77 | 2.97 |
| gHP | 4.06 | 8.82 | 18.68 | 18.3 | 9.93 | 2.50 | 6.96 | 4.44 | 2.60 |
| gLP | 3.92 | 8.00 | 17.64 | 17.23 | 9.93 | 2.57 | 7.13 | 4.82 | 2.92 |
| sOF | 5.17 | 9.59 | 17.03 | 17.9 | 10.38 | 2.73 | 7.76 | 4.96 | 2.97 |
| sON | 3.11 | 7.33 | 17.24 | 17.08 | 9.26 | 1.56 | 6.65 | 4.08 | 2.11 |

Table 6: Deviations among typologies median and total median, for each typology of every TR , for year 2007 in conditioned scenario. The values are normalized to total median and expressed in percentage ($(med_{typology} - med_{tot})/med_{tot}100[\%]$).

| Typology | $TR1$ | $TR2$ | $TR3$ | $TR4$ | $TR5$ | $TR6$ | TRa | TRb | TRc |
|--------------------|-------|--------|--------|--------|--------|-------|--------|--------|-------|
| Conditioned (2007) | | | | | | | | | |
| $w01$ | 11.81 | 14.35 | 17.14 | 16.32 | 10.99 | 9.42 | 10.43 | 9.53 | 9.41 |
| $w02$ | 1.77 | 1.94 | 0.73 | -2.66 | -3 | -0.07 | -2.21 | -1.69 | -0.74 |
| $w03$ | -8.43 | -9.88 | -15.25 | -15.91 | -12.28 | -7.73 | -10.71 | -9.71 | -8.72 |
| $w04$ | -8.17 | -9.54 | -14.82 | -15.51 | -11.92 | -7.45 | -10.38 | -9.4 | -8.44 |
| $w05$ | 10.76 | 12.53 | 14.36 | 12.87 | 7.47 | 6.87 | 6.98 | 6.57 | 6.97 |
| $w06$ | -9.54 | -11.28 | -16.63 | -17.39 | -13.42 | -8.74 | -11.8 | -10.7 | -9.72 |
| $r01$ | 6.12 | 9.07 | 14.29 | 16.3 | 11.83 | 7.2 | 10.6 | 8.98 | 7.9 |
| $r02$ | 3.61 | 5.57 | 8.72 | 10.11 | 7.18 | 4.6 | 6.32 | 5.39 | 4.91 |
| $r03$ | -7.69 | -9.94 | -15.4 | -17.62 | -13.46 | -7.68 | -11.66 | -10.23 | -8.82 |
| $r04$ | -7.33 | -9.45 | -14.73 | -16.85 | -12.96 | -7.41 | -11.22 | -9.87 | -8.52 |
| $r05$ | -1.5 | -1.64 | -2.65 | -2.78 | -2.89 | -1.27 | -2.37 | -2.1 | -1.66 |
| $r06$ | -8.29 | -10.73 | -16.64 | -19.17 | -14.58 | -8.43 | -12.71 | -11.15 | -9.64 |
| $o01$ | -0.38 | -1.32 | -0.58 | -0.12 | 0.32 | 0.75 | -0.08 | 0.84 | 1.19 |
| $o02$ | -0.5 | -0.8 | -0.83 | 1.17 | 0.96 | 1.22 | 1.29 | 1.69 | 1.78 |
| $o03$ | 0.76 | 0.45 | 0.3 | -0.28 | -0.44 | -0.23 | -0.52 | -0.58 | -0.16 |
| $o04$ | 1.43 | 1.73 | 1.2 | -0.22 | -1.16 | -1.22 | -1.18 | -1.49 | -1.24 |
| gHP | -2.99 | -2.72 | -4.2 | -3.38 | -1.24 | -1.47 | -1.25 | -1.45 | -1.46 |
| gLP | 3.26 | 4.25 | 3.56 | 4.19 | 4.75 | 3.13 | 4.41 | 3.69 | 3.27 |
| sOF | 2.52 | 3.75 | 4.61 | 3.95 | 0.8 | -1.3 | 0.25 | -0.44 | -0.96 |
| oON | -1.46 | -2.42 | -4.2 | -3.38 | -0.74 | 1.32 | -0.02 | 0.58 | 1.25 |

Table 7: Deviations among typologies median and total median, for each typology of every TR , for year 2007 in unconditioned scenario. The values are normalized as in previous table

| Typology | $TR1$ | $TR2$ | $TR3$ | $TR4$ | $TR5$ | $TR6$ | TRa | TRb | TRc |
|----------------------|-------|-------|--------|--------|-------|-------|-------|-------|-------|
| Unconditioned (2007) | | | | | | | | | |
| $w01$ | 2.88 | 4.8 | 9.3 | 6.32 | 2.53 | -0.97 | 1.61 | 1 | 0 |
| $w02$ | 0.91 | 1.11 | -0.37 | -1.95 | -1.18 | -0.85 | -0.78 | -0.29 | -0.43 |
| $w03$ | -1.26 | -3.65 | -7.41 | -7.13 | -2.57 | 0.69 | -1.16 | -0.09 | 0.43 |
| $w04$ | -1.21 | -3.54 | -7.25 | -6.97 | -2.49 | 0.72 | -1.09 | -0.04 | 0.43 |
| $w05$ | 2.93 | 4.36 | 7.38 | 4.38 | 0.99 | -1.97 | 0.12 | -0.28 | -0.99 |
| $w06$ | -1.49 | -4.14 | -8.28 | -7.89 | -2.82 | 0.66 | -1.32 | -0.22 | 0.49 |
| $r01$ | 1.74 | 4.11 | 9.76 | 10.79 | 7.18 | 1.03 | 5.73 | 4.31 | 2.13 |
| $r02$ | 0.93 | 2.54 | 6.58 | 7.58 | 5.09 | 0.35 | 4 | 3.08 | 1.32 |
| $r03$ | -1.39 | -3.89 | -9.28 | -9.63 | -4.47 | -0.37 | -2.87 | -1.56 | -1.33 |
| $r04$ | -1.26 | -3.65 | -8.75 | -9.09 | -4.26 | -0.41 | -2.75 | -1.52 | -1.33 |
| $r05$ | -0.22 | -0.42 | -0.18 | 0 | 0.64 | -0.31 | 0.68 | 0.68 | -0.05 |
| $r06$ | -1.49 | -4.2 | -10.19 | -10.71 | -5.02 | -0.47 | -3.21 | -1.79 | -1.43 |
| $o01$ | -0.69 | -0.59 | -0.41 | -0.15 | 0.02 | 0.26 | 0.19 | 0.17 | 0.34 |
| $o02$ | -0.56 | -1.07 | -0.84 | 0.12 | 0.89 | 0.7 | 0.94 | 0.87 | 0.8 |
| $o03$ | 0.24 | 0.16 | -0.08 | -0.09 | -0.21 | -0.28 | -0.14 | -0.63 | -0.28 |
| $o04$ | 0.95 | 1.02 | 0.97 | -0.1 | -0.79 | -1.01 | -0.59 | -1.2 | -0.96 |
| gHP | -0.37 | -0.84 | -2.08 | -1.89 | -0.5 | 0.11 | -0.28 | -0.13 | 0.05 |
| gLP | 0.34 | 0.5 | 0.63 | 0.14 | 0.58 | -0.17 | 0.3 | 0.16 | -0.16 |
| sOF | 2.01 | 3.16 | 5.37 | 4.08 | 0.8 | -0.97 | 0.14 | -0.42 | -1.07 |
| sON | -1.17 | -1.86 | -3.11 | -3.62 | -0.81 | 1.08 | -0.16 | 0.34 | 0.62 |

Table 8: Coefficient of variation of the medians of each characteristic for both the scenarios.

The values are expressed in percentage

| characteristic | <i>TR1</i> | <i>TR2</i> | <i>TR3</i> | <i>TR4</i> | <i>TR5</i> | <i>TR6</i> | <i>TRa</i> | <i>TRb</i> | <i>TRc</i> |
|----------------------|-------------|--------------|--------------------|--------------|--------------|-------------|--------------|-------------|-------------|
| Conditioned (2007) | | | | | | | | | |
| Wall | 9.01 | 10.66 | 14.14 | 13.93 | 9.90 | 7.29 | 8.94 | 8.16 | 7.76 |
| Roof | 6.27 | 8.60 | 13.43 | 15.41 | 11.48 | 6.80 | 10.08 | 8.72 | 7.63 |
| Orientation | 0.93 | 1.36 | 0.92 | 0.69 | 0.92 | 1.09 | 1.05 | 1.42 | 1.35 |
| Glazing | 4.42 | 4.93 | 5.49 | 5.35 | 4.23 | 3.25 | 4.01 | 3.64 | 3.35 |
| Shading | 2.82 | 4.37 | 6.23 | 5.18 | 1.09 | 1.85 | 0.19 | 0.73 | 1.56 |
| Unconditioned (2007) | | | | | | | | | |
| Wall | 1.91 | 3.79 | 7.2 | 5.76 | 2.05 | 1.04 | 1.04 | 0.45 | 0.54 |
| Roof | 1.36 | 3.6 | 8.73 | 9.42 | 5.31 | 0.60 | 3.87 | 2.64 | 1.54 |
| Orientation | 0.76 | 0.91 | 0.77 | 0.12 | 0.70 | 0.74 | 0.64 | 0.91 | 0.76 |
| Glazing | 0.5 | 0.95 | 1.92 | 1.44 | 0.76 | 0.19 | 0.41 | 0.21 | 0.15 |
| Shading | 2.25 | 3.55 | 6.00 | 5.45 | 1.13 | 1.45 | 0.21 | 0.54 | 1.19 |
| Conditioned (2013) | | | | | | | | | |
| Wall | 9.24 | 10.92 | 14.53 | 14.51 | 10.40 | 7.69 | 9.48 | 8.70 | 8.13 |
| Roof | 6.28 | 8.43 | 12.81 | 14.19 | 10.79 | 6.91 | 9.66 | 8.61 | 7.69 |
| Orientation | 0.84 | 1.09 | 0.75 | 0.38 | 1.08 | 0.9 | 1.46 | 1.52 | 1.15 |
| Glazing | 4.48 | 5.1 | 6.08 | 5.69 | 4.42 | 3.43 | 4.21 | 4.04 | 3.69 |
| Shading | 2.77 | 4.32 | 4.93 | 5.14 | 1.42 | 1.53 | 0.3 | 0.49 | 0.95 |
| Unconditioned (2013) | | | | | | | | | |
| Wall | 1.98 | 4.04 | 7.5 | 6.16 | 2.45 | 0.74 | 1.57 | 0.85 | 0.30 |
| Roof | 1.34 | 3.55 | 8.14 | 8.34 | 4.74 | 0.83 | 3.77 | 2.66 | 1.65 |
| Orientation | 0.80 | 0.91 | 0.48 | 0.46 | 0.65 | 0.85 | 0.81 | 0.79 | 0.66 |
| Glazing | 0.61 | 1.08 | 1.82 ⁵² | 1.36 | 0.92 | 0.07 | 0.85 | 0.59 | 0.1 |
| Shading | 2.19 | 3.26 | 5.06 | 4.65 | 1.4 | 1.38 | 0.45 | 0.37 | 1.03 |

Appendix A. Modelling

The present Appendix A reports details on energy modelling.

Appendix A.1. Thermal zoning

The thermal zones have been defined following a procedure described in [61]. This procedure is based on a preliminary temperature survey as follows. Several sensors are placed in a room recording for a variable period. Collected data are elaborated and used to thermally zone the room, according to a parameter called ARV (Acceptability Reference Value) that represents the acceptable temperature tolerance (meaning that two temperatures, whose difference is smaller than this value, are considered equivalent). The ARV should be defined based on the research goals and required precision. This method, applied to case study, is widely explained in Barbaresi et al. [57]; specifically 19 sensors were installed, recording temperature and humidity every 30 minutes, for one month in summer and one in winter. Data have been elaborated using an ARV of 2 °C (value defined analyzing the scientific literature) and finally the resulting thermal zone are:

- north-eastern zone below 4m height wine-storage area;
- south-western zone below 4m height wine-making area;
- zone above 4m height.

The latter zone was further divided in two zones also for geometrical reasons, creating four thermal zones as depicted in Figure 2c. For their division, *AirWallObjects* were used as described in Barbaresi et al. [64].

In the actual configuration, the wine conserved in the storage area is totally bottled (unconditioned containers), on the contrary, in the wine-making area the wine is stored into tanks and fermenters (conditioned containers). Therefore, the wine kept in the storage area is affected by the indoor temperature trends, entailing that extreme conditions can spoil the wine ageing and conservation. For this reason, the result analysis is applied solely to the storage area.

Appendix A.2. Ground modelling

In such buildings, characterized by large floor surface, the building-ground mutual influence [65] must be properly modelled. To take into account this effect, a fictitious thermal zone (10 m deep) has been created, according to Mazarrón et al. [32], in order to calculate the heat exchange between the ground and the floor.

Appendix A.3. Weather data

Due to the importance of the outdoor environmental conditions, the main weather meters have been recorded directly on site by means of a set of weather stations installed close to winery. Two weather stations (Davis Vantage Vue and PCE-FWS 20N) were installed 2 meters distant from each other and 100 m far from the winery (see Figure 1a). The stations' characteristics are described in the Table A.1 The collected data have been elaborated, compared to those recorded by a station belonging to the net of Regional Environment Protection Agency, ARPAAE [63], located 2 km far from the winery, and finally used to create the weather file. In this way, a weather

file reporting precise environmental data, could be used allowing accurate simulations.

Table A.1: Main weather stations' characteristics

| | PCE-FWS 20N | | Davis Vantage Vue | |
|-------------------|-------------|----------|-------------------|----------|
| | Resolution | Accuracy | Resolution | Accuracy |
| Temperature [°C] | 0.1 | ±1 | 0.1 | ±0.3 |
| Rel. humidity [%] | 1 | ±4 | 1 | ±2 |
| Pressure [hPa] | 0.1 | ±3 | 0.1 | ±1 |
| Rainfall [mm] | 0.3 | ±1 | 0.2 | ±0.2 |
| Wind speed [m/s] | 0.1 | ±1 | 0.5 | ±1 |

Appendix A.4. Sun-shading wall

In the models, external solar shading surfaces are located out of the building and are made up of climbing plants, such as vine plants, whose effects are deeply reported in the scientific literature [66, 52, 67]. Structures are thought as a metal wireframe structure with a seasonal climbing vegetation and are modelled in EnergyPlus as *ShadingSurfaceObjects* with solar transmittance value equal to 1.0 (meaning all the sunlight can pass through the surface).

A *ScheduleObject* has been applied to the solar transmittance to simulate the seasonal leaves coverage. According to detailed studies and to Susorova et al. [51], the leaf and surface structure coverage was set from 15% in winter to 0.95% in summer (in accordance with the *ScheduleObject* that varies from 0.85 to 0.05). This solution allows maximum solar radiation during winter

and minimum during summer.

Appendix A.5. Thermal energy need

The aim of the paper is to assess the incidence of main envelope characteristics on the building energy performance, according to different temperature setpoints. For this reason, the other variables that mainly affect the energy need and that do not directly affect the envelope thermal behavior have been set equal for all the models. Specifically, the heating cooling systems have been not introduced and the simulations return ideal thermal loads in terms of energy and power necessary to keep the indoor temperature within the thermostat setpoints (loads usually used for system sizing). The ideal thermal load can be considered as the energy provided by an ideal system with limitless power, infinite precision and 100% efficiency. Otherwise, if a heating/cooling system was implemented, the final energy need would have been affected also by the system performance and heat distribution consumptions. Besides, the thermal loads (people, equipment, lighting) can differ for the intended use and building owner choices. Therefore, among all the possible configurations, the one with lower thermal loads was chosen for all the models. In fact, a food-storage building usually has no permanent internal systems, lighting or people, hence the internal heat gain is set equal to 0 in all simulations.

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