The effect of high thermal insulation on high thermal mass: Is the dynamic behaviour of traditional envelopes in Mediterranean climates still possible?

Original
The effect of high thermal insulation on high thermal mass: Is the dynamic behaviour of traditional envelopes in Mediterranean climates still possible? / Stazi, Francesca; Bonfigli, Cecilia; Tomassoni, Elisa; DI PERNA, Costanzo; Munafo', Placido. - In: ENERGY AND BUILDINGS. - ISSN 0378-7788. - ELETTRONICO. - 88:(2015), pp. 367-383. [10.1016/j.enbuild.2014.11.056]

Published
DOI:10.1016/j.enbuild.2014.11.056

The effect of high thermal insulation on high thermal mass: is the dynamic behaviour of traditional envelopes in Mediterranean climates still possible?

Francesca Stazi [a,*], Cecilia Bonfigli [a], Elisa Tomassoni [a], Costanzo Di Perna [b], Placido Munafò [a]

[a] Dipartimento di Ingegneria Civile, Edile e Architettura (DICEA), Facoltà di Ingegneria, Università Politecnica delle Marche, Via Brecce Bianche, 60131 Ancona, Italy
[b] Dipartimento di Ingegneria Industriale e Scienze Matematiche, Facoltà di Ingegneria, Università Politecnica delle Marche, Via Brecce Bianche, 60131 Ancona, Italy

*** Corresponding Author**
Eng. Francesca Stazi, Assistant Professor
Università Politecnica delle Marche, Facoltà di Ingegneria, DICEA
Via Brecce Bianche, 60131 Ancona, Italy
f.stazi@univpm.it
Tel.: +39 071 2204783
Mobile: +39 328 3098217
Fax: +39 071 2204378

Abstract

The paper aims at studying the effect of both high thermal insulation and high thermal mass techniques in buildings' dynamic behaviour in Mediterranean climates. The two techniques can lead to conflicting requirements when considering winter and summer conditions, or even high daily temperature ranges. Therefore, the best solution for the summer can be the worst solution for the winter. Therefore, it is necessary to identify insulation measures that conserve the mass' dynamic behaviour.

Experimental investigations were carried out on a single-family house to characterize the behaviour of its walls with different thermal inertia. Thermal simulations made it possible to explore different retrofit configurations also including dynamic strategies. The solutions were compared on comfort, energy savings and global cost.

The study shows that the most suitable intervention is the maximization of the internal heat capacity and the introduction of an external insulation layer sealed in wintertime and ventilated in summer, thus maintaining the existing massive envelope's seasonal dynamic behaviour by alternatively maximising thermal barrier effect and heat loss. Considering this, the authors introduced a recently patented dynamic system that reduces both summer discomfort levels and consumption of about 20 % and 43 % respect to the worst retrofit solution.

Key words: optimal building envelope, energy efficient retrofitting, energy saving, comfort, global cost, dynamic thermal insulation.

DOI: 10.1016/j.enbuild.2014.11.056

1 Introduction

The energy saving regulations developed on the last years have focused their attention on the problem of heating consumption reduction (common to all European countries) without considering that in hot summer Mediterranean climates the predominant need is to guarantee comfort during the warm period.

That has brought, even in warmer countries as in Italy, the imposition of transmittance limit values, stationary or periodic parameter. So, even in such climates, lightweight and super-insulated building envelopes have been adopted in new constructions. Moreover, in existing buildings retrofit considerable thicknesses of insulation layer were placed either on the external or internal side of the wall, regardless of the relative position between mass and thermal insulation. However many authors have already shown that different insulation-mass configurations differently impact on both heating - cooling consumptions and indoor comfort with a different and often opposite effect on the various aspects. The optimal stratigraphy varies based on the considered operational conditions (intermittent use [1], continuous use [2]), climate (extreme climate or with variable temperature range [3]) and the specific analysed aspect between energy efficiency [4, 5], comfort [6-8] or costs [9, 10].

So that the better choice identification is still an open question and it could result to be with internal insulation (in studies focused on winter performance [1, 11]), external insulation (in studies focused on summer performance [2, 12-16]), insulation placed on both sides of the wall [1, 9, 17, 18]. Very rarely studies have been performed on a multidisciplinary simultaneous evaluation of the different aspects.

Focusing on the summer comfort optimization is established in literature that high thicknesses insulation layers, imposed by energy savings standards, whatever their position, act as a thermal barriers avoiding the heat loss with overheating risks, demonstrating the important role of the thermal mass in all climate [19, 20 - 22]. In hot summer Mediterranean climate building envelopes with heavy “storing” masses that dynamically adapt to seasonal variations was found to be preferable. The traditional architectures are an example of a very close relationship with the specific climate because they have dynamically adapted to the external environment without the use of the systems but through the adoption of passive strategies such as high massive envelopes [23-25] and natural cross ventilation [26].

For new and retrofitted envelopes, various authors demonstrated that dynamic configurations should be preferred: not insulated walls [6, 23]; walls with seasonal deactivation of the insulation layer [28, 29]; walls with recently developed dynamic finishing materials (PCM) [30]. Between the abovementioned solutions, some are not suited for both summer and winter period (not insulated solutions); the dynamic insulation is mainly designed to enhance the indoor ventilation rather than maximize the dynamic behaviour of the massive layers of the envelope that should be a priority in the retrofit of existing massive envelopes; PCM materials are a solution working on the latent heat storage rather than on the interaction between natural ventilation and mass. Another solution to enhance the dynamic interaction with the environment is the ventilated external insulation layer that consists in an external insulation separated from the internal massive wall by a channel that can be either ventilated in summer or closed in winter should resolve the posed question. The system was originated in Northern Europe with various patents [31-33] but has been rarely applied owing to its installation complexity and the poor winter thermal performance of the air vents, which are generally made of thin aluminium plates. For this reason, our research group has studied a pre-assembled system with air vents made of insulating material (registered trademark MUnSTa®) [34]. This type of system could improve the dynamic behaviour of the inner mass but no studies in literature were performed on performance quantification.

In summary, various authors highlighted the overheating risk of the super-insulated envelopes newly introduced by the energy saving standards, but the quantification of the benefices (on comfort, consumptions and global cost) of restoring the dynamic behaviour of the mass through the introduction of a ventilated layer is still lacking.

The paper aims at studying the effect of both high thermal insulation and high thermal mass techniques in the dynamic behaviour of buildings in Mediterranean climates also considering natural ventilation (cross and interposed in the building elements).

A multidisciplinary study was carried out including: an experimental investigation on a traditional detached building; analytical simulations of comfort level and energy consumptions to define the most beneficial mutual position between mass and insulation and check the effect of the introduction of natural ventilated cavities on the external envelope; global cost comparison between different scenarios; integrated evaluation between the various aspects (comfort, energy saving, global cost).

2 Phase, tools and methods

2.1 Phases

The research was carried out through experimental activities and analytical simulations according to the following phases:

- on-site monitoring during summer and intermediate season on four rooms (two at the ground floor and two at the first floor), characterised by different envelope inertia so as to assess the thermal performance and to obtain real data to compare with simulation values;
- dynamic simulations and model calibration through comparison with measured values;
- parametric analysis on the virtual model to extend the study for different seasons and to assess the comfort levels and energy saving potential of different retrofit scenarios.

2.2 The case study

The case study [Fig.1] is a single-family house located in the central Italy near the Adriatic coast (latitude 43° 27', longitude 13° 37'), characterized by 1647 degree-days. The building is a typical example of traditional rural architecture built up at beginning of the 900 (around the 1920) and the first floor had been completed after the war with a different constructive technology. It consists in a volume of two storeys above ground level (S/V ratio = 0.69), with its longitudinal axis inclined clockwise about 45° with respect to the north-south direction. The ground floor has a high thermal inertia solid-bricks masonry wall (thickness: 42 cm), while the first floor has a low thermal inertia semisolid-brick (called “occhialoni”) masonry wall (thickness: 25cm). The ground floor is made up by a concrete slab directly laid above the ground level; the floors on the first level and roof are reinforced brick-concrete slabs. The building has small size windows equipped with wooden frames and single glazing.

The thermal characteristics of each envelope component are reported in Tabs. 1 and 2 (Scheme 0).

2.3 Experimental study

The present paper report the experimental data from two monitoring campaigns conducted from July 27 to August 2 and September 9 to 19, in order to record data on the behaviour of the walls at the two building levels.

Two south-facing rooms have been monitored [Fig. 2]: one at the ground floor and one at the first floor. Since the boundary conditions of the two rooms are completely different the acquired data were useful both for model calibration and for a separate assessment of the two wall's behaviour rather than for a direct comparison.

Both monitoring activities involved the following investigations according to ISO 7726:2002 [35]:

- Outdoor environmental conditions: a weather station with a global radiometer, a combined sensor for wind speed and direction and a thermohygrometer with a double screen anti-radiation was used;
- Indoor climate conditions: two indoor microclimate stations that included a thermohygrometer and thermo-resistors with a tolerance according to IEC 751 were used;
- Envelope performance: dataloggers coupled to thermoresistances, with tolerance in accordance with IEC 751, were used to measure the internal and external surface temperatures of the walls.

The accuracy provided by the manufacturer for the used probes is shown below:

- thermoresistances (surface temperatures and air temperatures): 0.15 ° C (at 0 ° C);
- thermohygrometer: 0,15 ° C (at 0 ° C); UR 2 % (5-95 %, 23 ° C);
- global radiometer: 0.5 % m.v. + 5 W/m^2;
- wind direction: 5°;
- wind velocity: 2.5 % m.v./reading;

Datalogger accuracy is 3 % m.v./reading.

2.4 Methods of thermal analysis

Analytical simulations of the thermal behaviour were carried out using EnergyPlus dynamic software. The model was calibrated through comparison with monitored values. The real outdoor environmental conditions measured during the experimental phases (a new epw file for EnergyPlus simulation was generate) and the specific data of occupancy conditions (air infiltration, ventilation schedules and internal loads) were set on the model. So the correspondence between the monitored and calculated values could be checked.

The obtained model reproduces with a good approximation the observed values, as shown, as an example, in the graph relating to the comparison of the south wall surface temperatures at the ground floor (Fig. 3).

Using the calibrated model parametric variations were carried out by changing the insulation layer position (external or internal) within the horizontal and vertical stratigraphy (ground floor slab, roof, walls) in order to obtain, from the "as built" model two insulated envelopes respectively characterized by high or low internal inertia.

2.4.1 Retrofit scenarios

The retrofit measures were combined according to the following scenarios (Tabs. 1, 2 and 3):

- *as built* scenario: ground floor (G_0), roof (R_0), walls (W_0) and windows as in the "as built" situation;
- *SCHEME 0*: in the *as built* scenario (G_0 R_0 W_0) the glazed area is increased until reaching the minimum health standards [36] and achieving an overall 9% of window-to-wall ratio (against a 7% of window-to-wall ratio of the as built scheme); the glass-frame system performance is also improved ($U \leq 2 W/m^2K$ [37]);
- *SCHEME 1*: starting from Scheme 0 a retrofit on the ground floor and roof was implemented by assuming two type of solutions:

a. *High Capacity floors*: the insulating material is placed on the side facing outward thus leaving high mass on the inner side;

b. *Low Capacity floors*: the insulating material is placed on the internal face of the floors;

- *SCHEME 2*: the previous scenario (Schema 1) is completed by introducing the insulation layer also on the external walls assuming three solutions:

a. *High Capacity building*: the insulating material is applied in the outer side of the vertical envelope by positioning it adjacent to the existing wall;

b. *High Capacity vented building*: the insulating material is applied in the outer side of the vertical envelope leaving a cavity that could be alternatively closed (in the cold period) or vented (in the hot period through openable vents);

c. *Low Capacity building*: the insulating material is applied on the inner side of the vertical building envelope.

- *SCHEME 3*: new lightweight wooden building envelope typical of a constructive practice increasingly used in Italy.

- *SCHEME 4:* improvement of the worst case (Scheme 2c) through the introduction of a massive inner finish [37] characterized by a good heat capacity accumulation properties.
- *SCHEME 5:* further optimization of the preferable solution (namely Scheme 2b) with the introduction of a ventilation layer even in the roof slab and the elimination of the attic floor.

Different insulation layer thicknesses and materials were used in the configurations in order to provide the same stationary and periodic thermal transmittance [37]. The main difference between the walls is the thermal inertia on the inner side represented by the parameter of internal areal heat capacity defined by European standard EN ISO 13786:2008 [39]. On the table, the limits imposed (or suggested) for each parameter are also reported.

Between the abovementioned schemes, the Scheme 2b introduced a dynamic insulation system. Thanks to an air gap introduced between the external insulation layer and the internal mass (walls or roof) and the introduction of openable vents, the envelope is able to dynamically adapt to the external climate with two configurations, ventilated during the summer (vents open) and air-tight in winter (vents closed).

The authors patented a system to enhance the vents performance and to simplify the realization [34]. The system involves the use of two types of panels defined "normal panels" and "special panels". Both of them consist of an outer insulating layer (n. 1 and n. 2 in Fig. 4) spaced from the internal massive wall (or floor) thanks to the use of cubical spacers (made by the same insulating material) thus creating an air gap (Fig. 4 with number 3). The anchorage of the panels to the massive support occurs as a normal external insulation, i.e. with adhesive and mechanical anchors both placed in correspondence of the spacers. The opening / closing of the ventilation channel takes place through vents positioned in the inferior/superior "special panels". These vents (Fig. 4 with number 4) are made of insulating material (shaped in a suitable manner), equipped with seals (the same used for windows) and handled by an electronic device similar to that used for the rolling shutters (n. 5 in Fig. 4). The system could also be completed with sensors for automatic opening based on external temperature.

The "special panels" come on site ready for installation previously provided with the following elements: spacers, vents and electronic system (powered by electric cables or batteries) for vents opening, expanded metal mesh coupled with insect mesh at the openings (n. 7 in Fig. 4), vertical elements of insulating material to avoid thermal bridges (n. 6 in Fig. 4).

The ventilated solution was simulated through EnergyPlus AirFlowNetwork tool [40]. The cavity was modelled as a separate zone adjacent to the room and provided with vents placed on the bottom and on the top. Based on the airflow network method, this simulation model is assumed to mimic the airflow driven by buoyancy and by wind pressure.

2.4.2 Energy and comfort analysis

Dynamic thermal simulations with EnergyPlus software were performed to evaluate walls thermo-physical parameters, internal comfort conditions and energy consumptions.

The inside surface temperatures of the vertical walls, the operative temperatures and internal comfort of the two south-facing rooms (model calibrated with measures) have been examined during summer and intermediate season. The summer comfort was assessed with the adaptive model considering the category II, as indicated in standard UNI EN 15251:2008 [41], and the hours of discomfort (percentage of hours outside the range) were compared.

In addition, the consumptions were calculated in order to compare the energy saving provided by each retrofit scenario. The introduction of a summer mechanical cooling system (as an alternative to the base scenario with natural ventilation) was assumed to find out summer consumptions. Since summer cooling is achieved by electrical power with low efficiency and winter heating by high efficiency fossil fuel, to make these two different forms of energy comparable, the consumptions were calculated in terms of primary energy by using two different conversion factors (1 for fossil fuel and 2.17 for electric energy, as defined by AEEG in EEN 3/08 [42]).

To ensure that the study was not influenced by the specific use of the heating system, or a specific profile of daily ventilation (as set in the calibrated virtual model), all the parametric variations were carried out considering the following assumptions:

- internal gains profile fixed according to UNI TS 11300-1 table 9 [42];

- two heating operation programs: intermittent or continuous from November 1 to April 15 as established by Italian law [44] for zone D, with a set point of 20 ° C. The intermittent heating was switched on for a total of 12 h per day [44] distributed according to the following time slots: 6.00 a.m. - 10.00 a.m., 12.00 a.m. - 16.00 p.m., 18.00 p.m. - 22.00 p.m.;
- ventilation rate is set to 0.3 air change rate per hour (ach) during the winter period (UNI/TS 11300-1) while in the summer a continuous profile set to 1.5 ach was considered according to UNI 10375 [43];
- summer cooling system with a set-point of 26 ° C.

2.4.3 Method of global costs evaluation

Finally an economic analysis according to the procedure described in the UNI EN 15459 [46] by using the global cost methodology was carried out. The whole cost is determined by summing up the global costs of initial investment costs, periodic and replacement costs, annual costs and energy costs and subtracting the global cost of the final value. The global cost is directly linked to the duration of the calculation period τ and it can be written as:

$$C_G(\tau)= C_I + \sum_j \left[\sum_{i=0}^{\tau} \left(C_{a,i}(j) \cdot R_d(i)\right) - V_{f,\tau}(j)\right] \qquad (1)$$

where: $C_G(\tau)$ represents the global cost referred to starting year τ_0, C_I is the initial investment cost, $C_{a,i}(j)$ is the annual cost for component j at the year i (maintenance, replacement and running costs), $R_d(i)$ is the discount rate for year i, $V_{f,\tau}(j)$ is the final value of component j at the end of the calculation period (referred to the starting year τ_0).

With regard to initial investment cost (C_I)**:** the unit prices for products, including both furniture and application, were established from the current Italian pricelist. In particular the DEI pricelist [47] for the buildings recovery, renovation and maintenance was consulted. In order to evaluate the cost related to the innovative vented solution, additional costs respect to a traditional external insulation layer were applied due to : deeper wall mechanical fasteners, additional insulating material and workmanship for the spacers supply and installation, electronic system for vents opening and expanded metal mesh that were pre-assembled in the special panel. The prices were obtained from market companies and considering the system as if it was industrially produced rather than handcrafted.

With regard to the annual costs for components ($\boldsymbol{C_a}$) it consists of maintenance and replacement costs (C_m) and operation cost (C_o). Only the maintenance costs of energy system were considered (2.75% of the investment costs related to heating and cooling systems). The timing for replacement of systems and building components were acquired from the Annex A of EN 15459 (as shows in Table 4) considering the same cost adopted for the initial investment. The operational costs for heating and cooling were obtained by multiplying the useful energy demands with the respective tariff (0.087 €/kWh for natural gas and 0.2 €/kWh for electricity after tax) [48].

With regard to the discount rate ($\boldsymbol{R_d}$): in order to refer the costs to the starting year the real discount rate is used

$$\boldsymbol{R_d(p)} = \left(\frac{1}{1+R_R/100}\right)^p \qquad (2)$$

where: $\boldsymbol{R_R}$ is the real interest rate and $\boldsymbol{p}$ is the timing of the considered costs (i.e. number of years after the starting year).

With regard to the final value for each component ($\boldsymbol{V_f}$), it is determined by straight-line depreciation of the initial investment until the end of the calculation period and referred to the beginning of the calculation period.

All the relevant input data are shown in Table 4.

Afterwards the different cost components have been grouped into three categories: costs related to the building envelope, costs related to heating and cost related to cooling. See Table 5.

3 Results on summer comfort

3.1 As built

Fig. 5 shows the results of the monitored external climatic conditions. The period was characterized by mostly sunny conditions with external temperatures daily varying between 33 ° C during the day and 20 ° C during the night in the first three days (27-30 July). These could be considered typical summer season conditions. On July 31 there was a sudden drop of temperature values down to 26 ° C during the day and to about 16 ° C at night. The relative humidity shows an almost uniform trend between 30 % and 70 %.

Fig. 6 reports the external and internal surface and air temperatures recorded during the summer experimental campaign at the two building levels.

The monitored rooms have the same exposure (southern side) but present external walls with different inertia (solid bricks masonry and semisolid bricks masonry) and different elevations (ground floor and first floor).

The *external surface temperatures* reach their minimum value at around 5:00 a.m. in both walls with lower values (about 2 ° C) recorded in the first floor lightweight wall. In the following hours, with the solar radiation rising, the external surface temperatures increase, with the same trend for the two walls (since they have the same external plaster finishing) reaching the maximum at about 11:00 a.m., with higher values (about 2 ° C) for the low inertia wall. The difference could be ascribed to a different outgoing heat flux for the two walls.

The *internal surface temperatures* show different fluctuations at the two levels with a maximum daily range of about 4 ° C for lightweight wall and 1.5 ° C for the massive ones. Moreover, the two curves have a different slant: the massive wall surface temperature increases slowly and the maximum value is kept for a long time (about 12 hours: from 11.00 a.m. to 00.00 p.m.); the low inertia wall surface temperature rises more quickly and, as soon as the maximum value was reached (about 7 hours after recording the maximum value on the outside surface), it suddenly decreases.

The different walls behaviour is a consequence of different both walls inertia and radiative contributions of the rooms internal surfaces: at the ground floor there is a great contribution of heat dispersion through the lower floor, while at the first floor there are higher heat gains from the roof.

To analyse the impact of natural cross ventilation on each wall, a comparison between 29 July (open windows) and 30 July (closed windows) was realized.

When the windows are open (hatched area) the internal air temperatures (continuous lines) at two levels are equal because of the inlet of outside air, with values down to 25 °C in the first hours of the morning and of about 31 °C during the central hours of the day. The values instead differ with closed windows (whole day of 30 July). During the night, the values are higher than in the open configuration reaching 28 °C at the ground floor and 29 °C at the first floor. During the day, in the former low temperatures are maintained (29 °C) so lowering the values of about 2 °C respect to a vented ground floor, differently in the upper floor there is a thermal overheating (about 1°C) respect to open configuration.

This difference depends on the radiative contribution of the other constructive elements that are much reduced with open windows while causes an overheating at the first floor and overcooling at ground floor with closed windows.

A dynamic simulation, starting from calibrated model through the measured data on the two floors, was carried out by placing the two walls at the same building level (ground floor) to assess how much those dissimilarities are related to the different boundary conditions. In a subsequent variation, the heat flow through the ground floor was also eliminated by imposing an adiabatic layer in order to make the result independent from the selected storey and highlight the contribution due solely to the different envelope masses. Internal loads programs have been used according to the standard recommendations [43] and a typical summer day (July 29) was chosen for the evaluation also varying the windows opening (always open or always closed).

The study of air temperatures at the ground floor (Fig. 7-a) confirms what founded with measures in the as built situation, in which the closing of windows determines a reduction in temperatures fluctuations with lower daily values and higher night time values than in the naturally vented environment. Nevertheless the low nocturnal values in vented room, combined with the storing effect of the two walls (higher for the massive one), determines that the surface temperatures are lower for the open configuration than in the closed one through the day (Fig. 7-b,c). The internal surface temperatures are very slightly influenced by windows opening or closing for both the massive wall and the light-weight one because of the great incidence of the ground floor heat dispersions.

For both walls the introduction of an adiabatic ground floor causes the curve upwards translation of 2.5 ° C when the windows are open (black dotted line) and an overheating until to 3.5 ° C with closed windows (dashed grey line). The closing of the windows determines slightly higher surface temperatures on lightweight envelope for his lower inertia.

A different fluctuation due mainly to the different inertia is highlighted by comparing the two walls temperature trends.

3.2 Retrofit measures

A set of dynamic simulations were performed from June to September to compare the comfort level for the different envelope solutions. Table 6 shows the discomfort hours due to overheating and overcooling calculated according to UNI EN 15251:2008 [41], on two floors considering a continuously natural vented environment.

As resulted from the summer monitoring the "as built" condition is characterized by overcooling (about 378 hours) at the ground floor for the heat dispersion towards the ground, and by overheating on the first floor (128 hours). The windows thermal performance optimization and the simultaneous increasing of the glazed surface (Scheme 0), slightly reduce the ground floor overcooling (from 378 to 246), while increase the first floor overheating hours (from 128 to 144).

The insulation of ground floor and roof slabs (Scheme 1) causes (regardless the insulation position) a considerable reduction of the overcooling discomfort hours both at the ground floor and first floor (with values down to 0 - 4), but increases the overheating phenomena at both building levels with a slightly preferable comfort levels if adopting the external insulation. This confirms the results obtained in Fig. 10 (adiabatic layer).

The previous scenarios (Scheme 1) were improved with the subsequent insulation of the vertical walls (Scheme 2). The results demonstrate that the improvement or worsening of the comfort conditions strictly depends in this case on the adopted insulation solution (exterior, ventilated or interior). The high capacity building envelope characterized by external insulation layer worsens comfort levels (compared to the previous Scheme 1) by increasing the overheating discomfort hours both on the ground floor (from 130 to 193) and on the first floor (from 227 to 356). The insulation material applied on the inner side causes very high discomfort level due to overheating almost tripling the discomfort hours on the ground floor (from 183 to 542) and on the upper floor (from 281 to 655). Differently from the other two solutions, the ventilated insulation system ensures a clear improvement of the indoor thermal comfort conditions in both storey by reducing the discomfort hours down to 85 on the ground floor and 160 on the first floor. This system is the only insulation configuration of the entire building, which enhances the comfort conditions. It takes advantage by cold nocturnal air that in this wall flows adjacent to the inner mass with a cooling effect.

The newly built lightweight wooden envelope (Scheme 3) has a behaviour comparable to the low internal capacity building with 428 overheating hours on the ground floor and 518 on the first floor.

The introduction of a massive clay panel as internal finishing in the low massive wall (Scheme 4) determines a discomfort hours reduction. The values decrease down to 329 hours at the ground floor and 463 hours on the first floor (from an initial value respectively of 542 and 655) bringing values more close to the High Capacity building.

The study of discomfort hours over the entire season for the totally vented configuration by introducing a ventilation layer even in the roof slab (Scheme 5) demonstrates that this solution allows further reduction in discomfort hours over the entire season reaching a minimum value of 72 hours at the ground floor and 93 hours at the first floor, about 17 % reduction respect to the worst case (Low Capacity building).

The study of the internal surface temperatures during the hottest summer week (July 20 to 26) for the main schemes (Scheme 0, 2 and 3) is reported in Fig. 8 and 9.

Fig. 8 shows the results obtained for the retrofit of the whole envelope (floor and wall) at the ground floor level. This graph confirms the previous comfort results, since all retrofit interventions result in an increase of the internal temperatures respect to the initial "as built" situation. The ventilated system values stand lower than the other interventions curves. The thermal behaviour of such system strictly depends from the temperature difference between the outside air and the air within the channel, which is the main driving force for the stack effect activation inside the cavity (as established in literature [49]). The study of the air velocity values inside the channel highlights that the ventilation is effectively activated when the channel air temperature considerably exceeds the outside air temperature value: this happens (shaped area between dotted lines) during the whole day and particularly in night-time for most of the represented period with typical summer temperatures conditions, while the ventilation is not effective on extremely hot days (July 22 to 25). The benefits of adopting a vented system respect to a traditional external insulation could be quantified in a reduction of 2 ° C in typical summer days and of only 0,5 ° C on days with extremely high temperatures.

The graph regarding temperature trends on the first floor (Fig. 9) shows that the same considerations of the lower level can be adopted. Moreover at this level the adoption of a naturally ventilated insulation layer is preferable also with respect to the existing (not insulated) wall since the low inertia of the wall at this level make an insulation intervention more important for its thermal barrier effect (and the consequent reduction of the surface temperature fluctuations). In the extremely hot days (July 22 to 25), and in general in extreme climates, the primarily required building envelope performance is to block the incoming heat flow. That is why the interventions with external insulation result to be preferable than the not insulated "as built" wall.

4 Results on intermediate season comfort

4.1 As built

Fig. 10 shows the results of the monitored weather conditions. The period was quite variable, with sunny or slightly cloudy days (September 9 to 13), characterized by daily temperatures ranging between 26 ° C and 16 ° C, and rainy days (September 14 to 19) where temperatures are more variable with maximum value of about 19 ° C (September 16).

The relative humidity values show an increasing trend from 40 % to over 90 % in rainy days.

The same comparison developed in the summer phase between massive and lightweight walls was carried out in a mid-season, when the high daily temperature range allows to better appreciate the thermal mass dynamic nature.

Fig. 11 reports the external and internal surface temperatures recorded during the experimental campaign in the intermediate season at the two building levels on the south exposure.

The *external surface temperature* of the heavy wall presents maximum values of about 4 ° C higher than the low inertia wall (except in rainy and cloudy days in which the temperatures are nearly equal) showing a different behaviour than that recorded during the summer, when the maximum value was higher for the light weight wall. At night, however, the behaviour of the two walls is unchanged compared to the summer monitoring, with minimum values lower for the lightweight wall (about 2 ° C).

The *internal surface temperatures* of the solid brick masonry are higher than those recorded for the semi-solid brick wall, showing an opposite behaviour than that detected during the summer. Nevertheless there is still a greater stability of massive wall temperatures (daily temperature range of about 2 ° C) with respect to the light weight wall (diurnal temperature variation of about 4 ° C). The different behaviour of the two walls is due to the specific capability of preserving the summer stored heat and the different response to the seasonal variations.

4.2 Retrofit measures

The configurations belonging to the Scheme 2, with high internal mass (High Capacity building) and low internal mass (Low Capacity building) were compared during the two intermediate seasons (spring and autumn). The vented solution curve was not reported since, having in the selected period the vents closed), the values were almost coincident with the traditional external insulation solution.

During the spring season (Fig. 12-a) different phases could be identified. A first phase (March 1 to 5) in which both walls are still affected by the typical winter behaviour (heated room) since the heating system was recently turned off (on March 1 for this simulation). The operative temperatures have the same minimum values while the room with an internal insulated envelope is characterized by greater maximum values (1.5-2 ° C). A second phase (March 5 to 17) when the room with lightweight envelope undergoes a sudden lowering in operative temperature values because the heating effect is finished and the outside temperatures are still low. In the third phase (March 17 to entire hot season) the rising of the outside temperatures determines an immediate overheating of the interior space of the low capacity building (with maximum values of 2.5-3 ° C higher than the other solution).

In autumn (Fig. 12-b) an inverted behaviour is shown. While in spring (and for the whole summer) the room with lightweight wall presents peaks of overheating, at the end of the hot period (September – October) the external air temperature drop, causes especially for this solution the internal gradual reduction of the operative temperatures (up to 3 ° C less than the massive wall), with an unfavourable behaviour for the approaching of the cold season.

5 Consumptions

Table 7 shows the consumptions evaluation in terms of primary energy for both heating and cooling demand. The results show that glazed surface enlargement and its thermal optimization (from *"as built"* configuration to Scheme 0) lead to a heating consumption reduction for both continuous and intermittent operation (about 8 % in the first case and 7 % in the second). This is due to the increase of solar gains and the simultaneous improvement of the thermal performance of the existing glazed surface. The same phenomenon, however, causes a slight increase in summer consumption.

Compared to the previous scenario, the ground floor and roof slabs insulation (Scheme 1) reduces the winter consumptions down to about 106 kWh/m^{2}year for a continuous system operation and to about 81 KWh/m^{2}year for intermittent use, regardless of the reciprocal position (external or internal) between the insulation layer and the supporting structure. The further insulation of the walls (Scheme 2) results in a significant reduction in primary energy winter consumption by placing the insulation on the outer side, with almost similar performance between the traditional insulating system and the vented one. The latter solution is slightly better because of the higher thermal resistance due to the addition of a (not vented in winter period) air cavity.

Compared to these two interventions the low inertia retrofit and the wooden technology have higher consumptions (both around 41 kWh/m^{2}year for continuous ignition and 33 kWh/m^{2}year for intermittent ignition).

The adoption of the internal massive finishing (Scheme 4) slightly reduces winter consumption of the low inertia solution (about 2 %). Moreover, the totally vented solution (Scheme 5) presents minimum consumptions values saving up to 18 % for heating respect to the worst case outcome.

The analysis of summer consumptions shows that the insulation interventions proposed in Scheme 1 and 2 (insulation of windows, roof, ground floor, walls) worsens the "as built" condition in all studied configurations. In this season, the benefit of adopting a ventilated solution respect to a traditional insulation layer is higher than those observed in winter, since it allows a dynamic behaviour of the inner mass through the ventilation of the internal gap. Moreover, there are 8 kWh/m^{2}year difference between this preferable vented solution and worst Low Capacity solution because the insulating layer placed on the inner side causes overheating phenomena. The same problem does not seem to affect the lightweight wooden building that presents consumption values more close to the ventilated insulation system.

The introduction of the inner massive finish reduces the summer consumption of internal insulated wall of about 2 kWh/m^{2}year (from 30 to 28) while the totally vented solution reduces the consumption down to 17 kWh/m^{2}year.

In order to explain the different performances achieved by the lightweight wooden envelope respect to the vented insulation (its higher winter consumptions and similar summer ones) a comparative study of the operative temperatures was carried out.

Fig. 13-a reports the result obtained during the cold season adopting a continuous operating system with 20 ° C set point. The comparison shows that the greater heating consumptions of the lightweight solution (dark line) respect to the massive one (grey line) are due to more marked temperature fluctuations and lower minimum values so that a greater heat amount have to be supplied by the heating system to reach the set point value.

Fig. 13-b reports the summer temperature temperatures with natural ventilation. The results show that in the room with ventilated insulation (grey line) the temperature fluctuations are consistently maintained close to the set point values (thus requiring less energy if introducing a cooling system). In the room with a lightweight wooden envelope (dark line) there is more heat to remove (for many temperature peaks) but if adopting a cooling plant, than it would be often switched off because the high fluctuations lead to temperatures often below the set-point value of 26 ° C. Therefore in the massive case the plant is continuously turned on but a limited heat amount has to be subtracted from the rooms while in the lightweight case there is an intermittent ignition (remaining off for part of the day both in June and in September) with more work for the cooling system in the operation time slots and high discomfort levels for the high temperature fluctuations (as also stressed in the comfort section).

6 Global cost assessment

The global cost assessment in relation to the overall energy performance was carried out for the different retrofit interventions.

The graph (Fig. 14) shows the global cost for the scenario in which both heating and cooling system are included (the same internal comfort conditions between the various solutions are imposed), and the case in which the only heating system is used (excluding the final histograms quote), adopting a summer natural ventilation. In the latter case, the different retrofit solutions are characterized by different summer comfort levels evaluated as the percentage of discomfort hours over the entire season (dashed line).

The interventions related to the single building element improvement (windows, floors) are not convenient for the high cost related to winter heating. The internal insulation of the entire building, characterized by low internal capacity ($LC_{building}$), is not cost effective being characterized by higher global costs than the other solutions and by high summer discomfort levels. The preferable systems are found to be those with external traditional insulation and with ventilated insulation which have a similar global cost but the second solution guarantees lower discomfort levels if choosing to adopting a passive cooling strategy.

The removal of the slab separating the first floor space from the attic determines an increase in the building envelope global cost for the additional cost of slab demolition. Nevertheless, the global cost of the building configuration with ventilated insulation applied both to walls and roof is the lowest one because even if characterized by a greater initial investment it guarantees very lower summer consumption resulting to be cost-effective by a global evaluation. Moreover if adopting a summer passive cooling (thus excluding the superior histogram quote), this last solution, despite characterized by a higher global cost, presents optimal indoor thermal comfort conditions.

In an overall evaluation, the adoption of a ventilation layer only for the vertical wall ($HC_{vented\ building}$) rather than for the whole envelope (total vented solution) seems to be preferable if adopting a passive cooling strategy because of the lower investment and similar comfort conditions.

7 Conclusions

The presented work deals with the effect of the super-insulation applied to an existing massive traditional envelopes, on comfort, consumption and global costs, and the efficacy of dynamic strategies, such as natural ventilation (cross and interposed in the building elements) and optimization of inner layer inertial properties, to recover the thermal mass dynamic nature.

As established in literature the new energy saving standards determine the overheating of the internal environment during the summer by imposing high insulation thicknesses. Nevertheless, very rarely studies on the solution of this problem through the introduction of natural ventilation both in the internal environment and interposed in external envelope layers was performed.

In the first phase of the present research an experimental study was performed on a single-family traditional house in the central Italy characterized by high thermal inertia solid brick masonry at the ground floor and semisolid brick walls with low thermal inertia on the first floor. Moreover analytical variation were realized to compare the two walls under the same boundary conditions.

Regarding the behaviour of the thermal mas, the study made it possible to collect real data in the two building storeys, investigate the strong relation between room position / exposure and internal temperatures and to stress different daily fluctuations mainly due to the specific thermal inertia. It was also found a double trend inversion between walls with different inertia at the two extremities of the hot season that determines a continuously lower performance for the lightweight solution.

Regarding the dynamic interaction between mass and natural ventilation it was possible to demonstrate that the natural ventilation is capable to reduce the overheating at the first floor and overcooling at the ground floor. Moreover it has low incidence on the mass behaviour if the wall is placed in an environment with high thermal dispersion (0.5 °C), while it is very effective if the wall is in a super-insulated and overheated room (reduction down to 1 - 1.5 °C on surface temperature). The deactivation of the natural ventilation determines slightly higher surface temperatures in the case of lightweight envelopes (0.5 °C).

In the second phase of the study, analytical assessments under dynamic conditions were carried out for various building envelope configurations, new and subsequent to retrofit interventions, characterized by different thermal inertia levels and evaluating the introduction of a natural ventilation layer. Differently from other studies the solutions were compared through an integrated evaluation of different aspects (energy saving, indoor comfort and global costs).

The results proved that the introduction of an insulation layer on the internal side is the worst intervention but, having to necessarily choose it to maintain the external aesthetic wall appearance, it is important to adopt a massive finishing panel on the internal side. Moreover the results highlighted that the better solution envisages the adoption of a ventilated envelope in order to alternatively maximize the thermal barrier effect and the heat loss. In this way it is possible to resolve the conflicting requirements which are typical of climates with both seasonal and daily high temperature ranges. For that reason an innovative (recently patented) system was proposed. It is characterized by an external super insulation layer spaced from the internal wall by an air gap that can be alternatively sealed in winter and ventilated in summer. The combination of the proposed dynamic strategies (daily natural ventilation, inner mass, vented external wall) ensures: optimum comfort conditions during the summer (improving by approximately 20 % the levels of comfort than the worst outcome solution), winter and summer energy saving (respectively reduced up to 17 % and up to 43 % respect to the worst case) and a lower global cost despite the higher initial investment.

Bibliografia

[1] M. Lj. Bojić, D.L. Loveday, The influence on building thermal behaviour of the insulation/masonry distribution in a three-layered construction, Energy and Buildings 26 (1997) 153-157.

[2] E. Kossecka, J. Kosny, Influence of insulation configuration on heating and cooling loads in a continuously used building, Energy and Buildings 34 (2002) 321-331.

[3] Y. Huang, J. Niu, T. Chung, Study on performance of energy-efficient retrofitting measures on commercial building external walls in cooling-dominant cities, Applied Energy 103 (2013) 97-108.

[4] S. Ferrari, Building envelope and heat capacity: re-discovering the thermal mass for winter energy saving, in: Conference proceedings: “Building low energy cooling and advanced ventilation technologies in the 21st century”, September, 2007, Crete island, Greece. p.346-351.

[5] N. Aste, A. Angelotti, M. Buzzetti, The influence of external walls thermal inertia on the Energy performance of well insulated buildings, Energy and Buildings 41 (2009) 1181-1187.

[6] D. M. Ogoli, Predicting indoor temperatures in closed buildings with high thermal mass, Energy and Buildings 35 (2003) 851-862.

[7] C. A. Balaras, The role of thermal mass on the cooling load of buildings. An overview of computational methods, Energy and Buildings 24 (1996) 1-10.

[8] V. Cheng, E. Ng, B. Givoni, Effect of envelope color and thermal mass on indoor temperatures in hot humid climate, Solar Energy 78 (2005) 528-534.

[9] S. A. Al-Sanea, M. F. Zedan, Improving thermal performance of building walls by optimizing insulation layer distribution and thickness for same thermal mass, Applied Energy 88 (2011) 3113-3124.

[10] G. Kumbaroğlu, R. Madlener, Evaluation of economically optimal retrofit investment options for energy savings in buildings, Energy and Buildings 49 (2012) 327-334.

[11] P. T. Tsilingiris, Wall heat loss from intermittently conditioned spaces – The dynamic influence of structural and operational parameters, Energy and Buildings 38 (2006) 1022-1031.

[12] P. T. Tsilingiris, Parametric space distribution effects of wall heat capacity and thermal resistance on the dynamic thermal behavior of walls and structures, Energy and Buildings 38 (2006) 1200-1211.

[13] S. A. Al-Sanea, M. F. Zedan, Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential, Applied Energy 89 (2012) 430-442.

[14] K. Gregory, B. Moghtaderi, H. Sugo, A. Page, Effect of thermal mass on the thermal performance of various Australian residential constructions systems, Energy and Buildings 40 (2008) 459-465.

[15] J. Zhou, G. Zhang, Y. Lin, Y. Li, Coupling of thermal mass and natural ventilation in buildings. Energy and Buildings 40 (2008) 979-986.

[16] F. Stazi, C. Di Perna, P. Munafò, Durability of 20-year-old external insulation and assessment of various types of retrofitting to meet new energy regulations, Energy and Buildings 41 (2009) 721-731.

[17] H. Asan, Effects of Wall's insulation thickness and position on time lag and decrement factor, Energy and Buildings 28 (1998) 299-305.

[18] K. J. Kontoleon, D. K. Bikas, The effect of south wall's outdoor absorption coefficient on time lag, decrement factor and temperature variations, Energy and Buildings 39 (2007) 1011-1018.

[19] R. S. McLeod, C. J. Hopfe, A. Kwan, An investigation into future performance and overheating risks in Passivhaus dwellings, Building and Environment 70 (2013) 189-209.

[20] R. Lindberg, A. Binamu, M. Teikari, Five-year data of measured weather, energy consumption, and time-dependent temperature variations within different exterior wall structures, Energy and Buildings 36 (2004) 495-501.

[21] A. Norén, J. Akander, E. Isfält, The effect of Thermal Inertia on Energy Requirement in a Swedish Building – Results Obtained with Three Calculation Models. Low Energy and Sustainable Buildings 1 (1999) 1-16.

[22] C. Di Perna, F. Stazi, A. Ursini Casalena, M. D'Orazio, Influence of the internal inertia of the building envelope on summertime comfort in buildings with high internal heat loads, Energy and Buildings 43 (2011) 200-206.

[23] S. Martin, F. R. Mazarron, I. Canas, Study of thermal environment inside rural houses of Navapalos (Spain): the advantages of reuse buildings of high thermal inertia, Construction and Building Materials 24 (2010) 666-676.

[24] N. Cardinale, G. Rospi, A. Stazi, Energy and microclimatic performance of restored hypogenous buildings in south Italy: The "Sassi" district of Matera, Building and Environment 43 (2010) 94-106.

[25] Z. Yilmaz, Evaluation of Energy efficient design strategies for different climatic zones: Comparison of thermal performance of buildings in temperate-humid and hot-dry climate, Energy and Buildings 39 (2007) 306-316.

[26] A. Gagliano, F. Patania, F. Nocera, C. Signorello, Assessment of the dynamic thermal performance of massive buildings, Energy and Buildings 72 (2014) 361-370.

[27] S. Martin, F. R. Mazarron, I. Canas, Study of thermal environment inside rural houses of Navapalos (Spain): the advantages of reuse buildings of high thermal inertia, Construction and Building Materials 24 (2010) 666-676.

[28] F. Stazi, A. Vegliò, C. Di Perna, P. Munafò, Experimental comparison between 3 different traditional wall constructions and dynamic simulations to identify optimal thermal insulation strategies, Energy and Buildings 60 (2013) 429-441.

[29] M. S. E. Imbabi, A passive–active dynamic insulation system for all climates, International Journal of Sustainable Built Environment 1 (2012) 247-258.

[30] D. Zhou, C. Y. Zhao, Y. Tian, Review on thermal energy storage with phase change materials (PCMs) in building applications, Applied Energy 92 (2012) 593-605.

[31] H. Bartodziej, Method of heat flow control through an external wall of building and wall assembly for execution of this method, WO00/60183A1, 2000 (Patent).

[32] G. Anmelder, Fassadenwärme-Dämm-Verbundsystem, DE102004001601A1, 2005 (Patent).

[33] R. Güldenpfenning, Verfahren Herstellung wärmegedämmter Putzfassaden, DE3238445A1, 1984 (Patent).

[34] Patent MI2011A001317, Modulo per cappotto e cappotto.

[35] International standard UNI EN ISO 7726:2002, Ergonomics of the thermal environment—instruments for measuring physical quantities.

[36] Decreto Ministeriale 5 Luglio 1975, modificazioni alle istruzioni ministeriali 20 giugno 1896 relativamente all'altezza minima ed ai requisiti igienico sanitari principali dei locali d'abitazione.

[37] http://www.bioterraitalia.com/

[38] Decreto Legislativo 19 agosto 2005, n.192, Attuazione della direttiva 2003/91/CE relativa al rendimento energetico nell'edilizia.

[39] International standard UNI EN ISO 13786:2008, Thermal performance of building components - Dynamic thermal characteristics - Calculation methods.

[40] DOE, EnergyPlus 7.0 Input/Output Reference: The encyclopedic Reference to EnergyPlus Input and Output, U.S. Department of Energy, 2011.

[41] European standard UNI EN 15251:2008, Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.

[42] EEN 3/08 deliberation. Conversion factor of kWh in petroleum equivalent tons connected to energy efficiency certificates. Authority for Electric Energy and Gas (AEEG). 2008.

[43] UNI/TS 11300-1:2008, Prestazioni energetiche degli edifici–Parte 1: Determinazione del fabbisogno di energia termica dell'edificio per la climatizzazione estiva ed invernale.

[44] D.P.R. 26 agosto 1993, n. 412, Regolamento recante norme per la progettazione, l'installazione, l'esercizio e la manutenzione degli impianti termici degli edifici ai fini del contenimento dei consumi di energia, in attuazione dell'art. 4, comma 4, della L. 9 gennaio1991, n. 10.

[45] National standard UNI 10375:2011, Calculation method of the indoor temperature of a room in the warm period.

[46] International standard UNI EN 15459:2008, Thermal performance of buildings - Economic evaluation procedure for energy systems in buildings.

[47] Prezzi informativi dell'edilizia: Recupero Ristrutturazione Manutenzione. DEI Tipografia del genio civile (2013).

[48] AEEG elaboration on Eurostat data for domestic consumers. 2012.

[49] P. Brunello, F. Peron, Modelli per l’analisi del comportamento fluidodinamico delle facciate ventilate, Fisica Tecnica Ambientale (1996) 313-324.

Fig. 1. External view of the case study.

Fig. 2. Plans indicating the measuring instruments.

Fig. 3. Calibration of the simulation model by comparison with the measured data.

Fig. 4. Construction details.

Climatic data recorded in the summer monitoring: air temperature, relative umidity and global solar radiation.

Fig. 5. Climatic data recorded in the summer monitoring: air temperature, relative umidity and global solar radiation.

Fig. 6. External and internal surface temperatures and mean air temperatures recorded in two south-facing rooms, one at the ground floor (heavy masonry wall) and one at the first floor (lightweight wall), under different natural ventilation conditions.

Fig. 7. Effect of windows opening on the wall's performance at the ground floor during a typical summer day: air temperature of the as built condition (a); internal surface temperatures of the massive wall (b) and lightweight wall (c), even adopting an adiabatic ground slab.

Fig. 8. Southern walls internal surface temperatures at the ground floor. Comparison between the different insulations interventions.

Fig. 9. Southern walls internal surface temperatures at the first floor. Comparison between the different insulations interventions.

Fig. 10. Results of monitoring in the mid season: internal and external surface temperatures in the southern rooms, one at the ground floor (with heavy masonry wall) and one at the first floor (with lightweight wall).

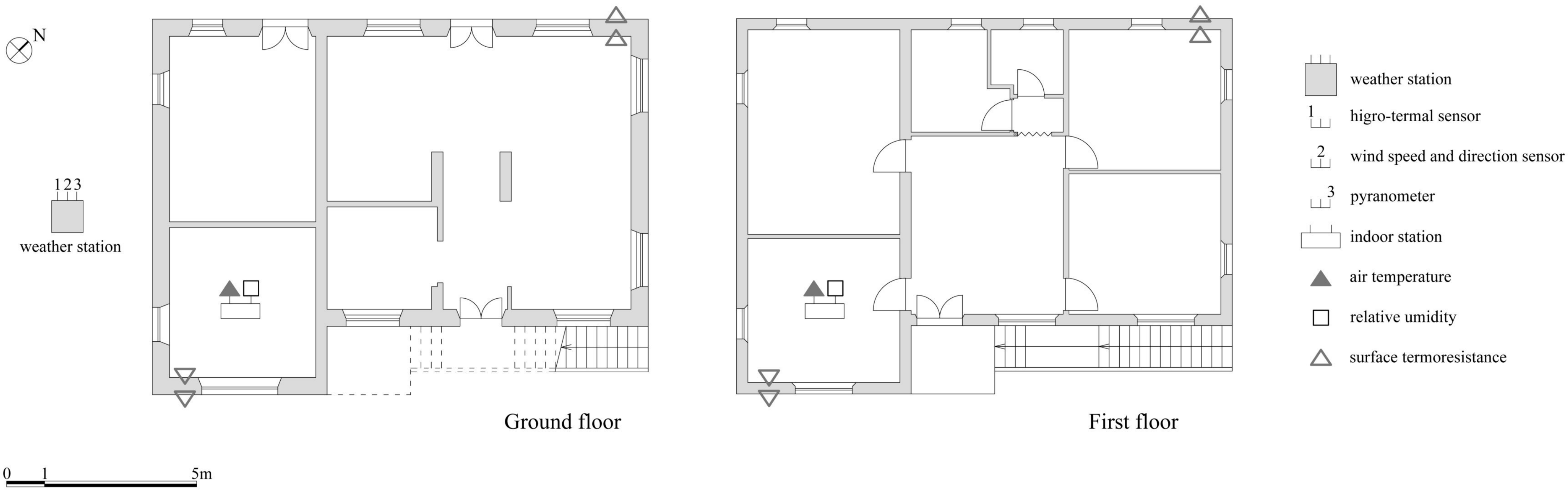
Fig. 11. Results of monitoring in the mid season: internal and external surface temperatures in the northern rooms, one at the ground floor (with heavy masonry wall) and one at the first floor (with lightweight wall).

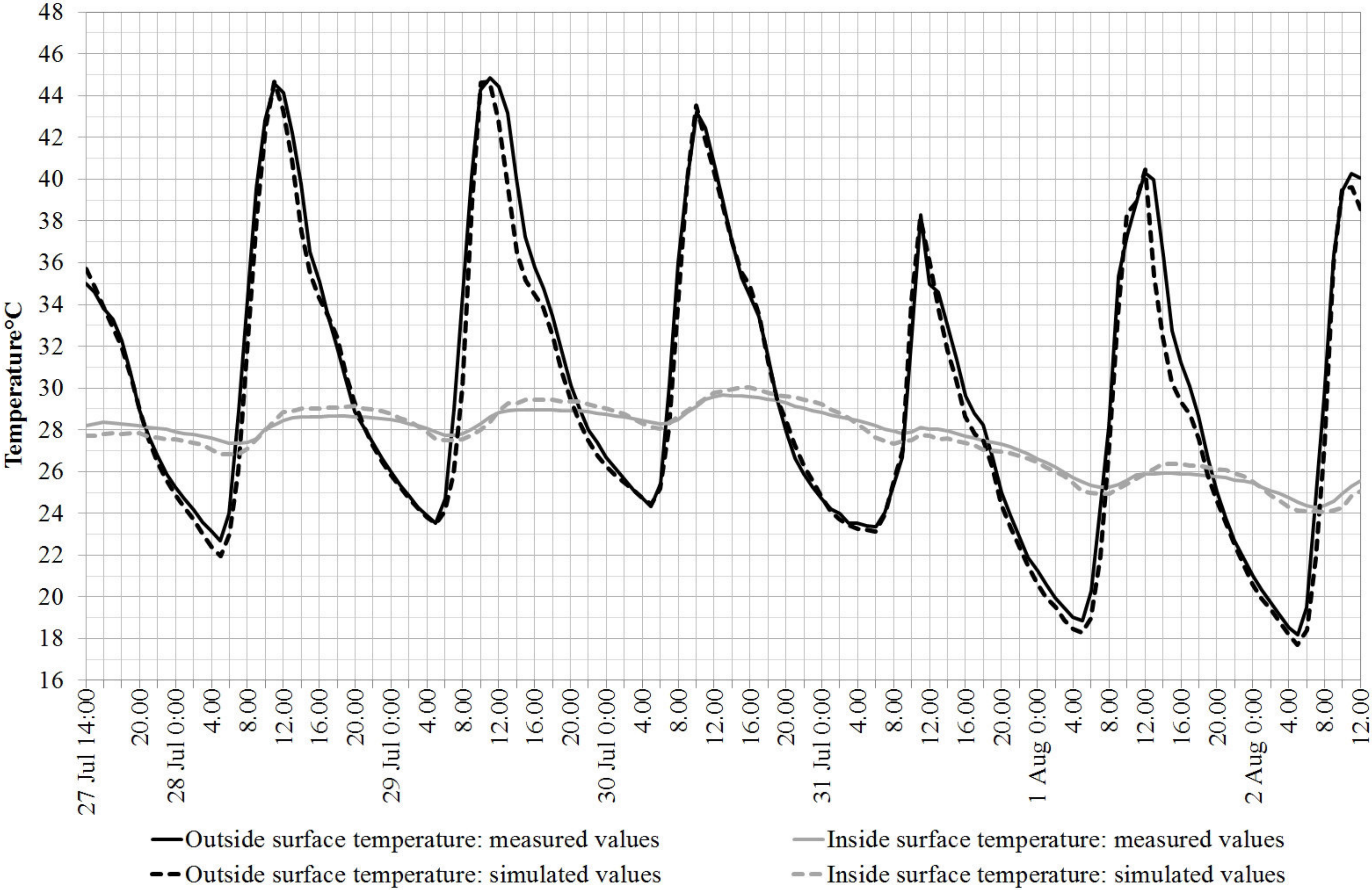
Fig. 12. Operative temperatures in the moderate months. Comparison between the High Capacity building and Low Capacity building in March – April (a) and in September – October (b).

Fig. 13. Comparison between the ground floor operative temperatures of the High Capacity Vented building and the New Wooden building during the summer (a) and winter (b) season.

Fig. 14. Combined assessment of the global cost, energy performance and thermal comfort of the different examined scenarios.

Measuring instruments

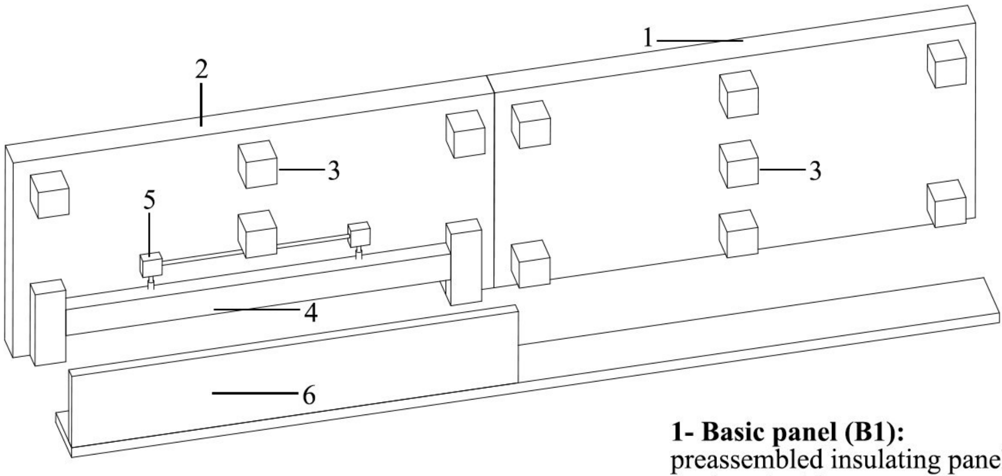


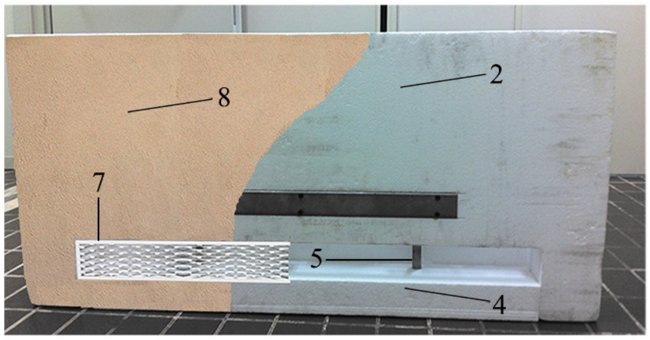

Temperature°C
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
27 Jul 14:00
20:00
28 Jul 0:00
4:00
8:00
12:00
16:00
20:00
29 Jul 0:00
4:00
8:00
12:00
16:00
20:00
30 Jul 0:00
4:00
8:00
12:00
16:00
20:00
31 Jul 0:00
4:00
8:00
12:00
16:00
20:00
1 Aug 0:00
4:00
8:00
12:00
16:00
20:00
2 Aug 0:00
4:00
8:00
12:00
Outside surface temperature: measured values
Outside surface temperature: simulated values
Inside surface temperature: measured values
Inside surface temperature: simulated values

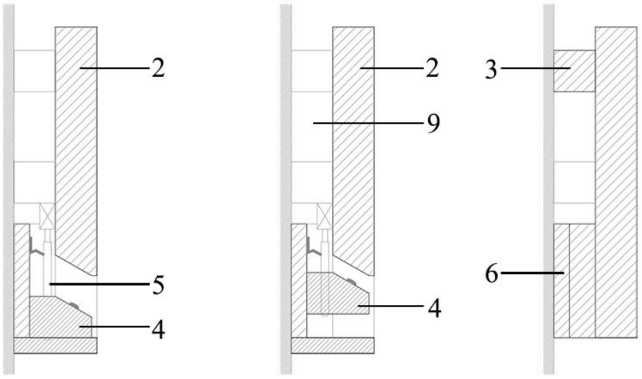
A - EXISTING SUPPORTING WALL

EXISTING SUPPORTING WALL made of SOLID BRICKS (A1) at the first floor and HOLLOW BRICKS called "*occhialoni*" (A2) at the second floor.

B - MUnSTa® SYSTEM APPLIED TO THE WALL







1- Basic panel (B1):
preassembled insulating panel equipped with spacers.

2- Special panel (B2):
preassembled insulating panel equipped with spacers and moving system.

3- Spacers:
elemnts made by insulating material installed to create the ventilation duct.

4- Ventilation opening:
movable elements made by insulating material wich create the ventilation openings.

5- Electrical system:
preassembled electrical system for the ventilation opening handling.

6- Thermal bridge correction

7- Perforated sheet:
perforated sheet coupled with insect mesh to protect the ventilation openings.

8- External plaster coating

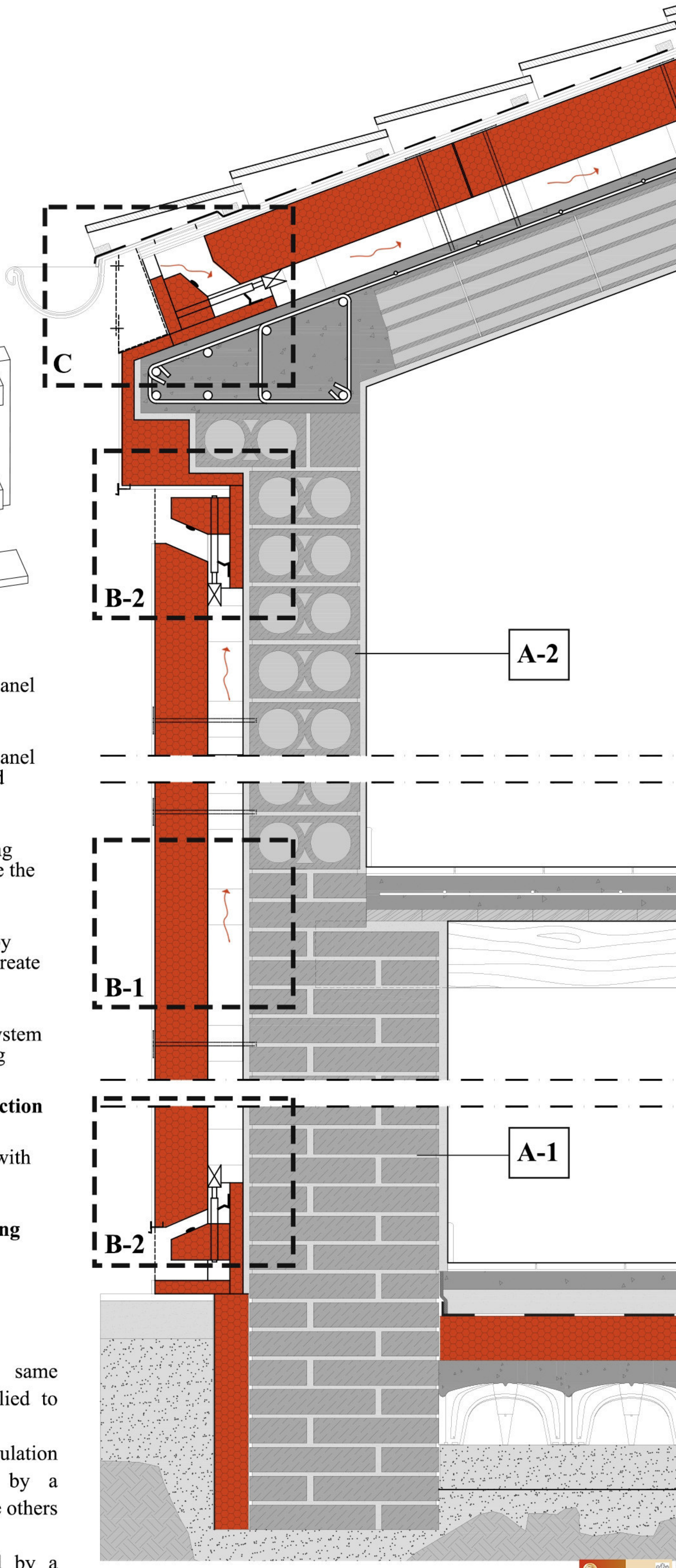
9- Vented cavity

C - MUnSTa® SYSTEM APPLIED TO THE ROOF

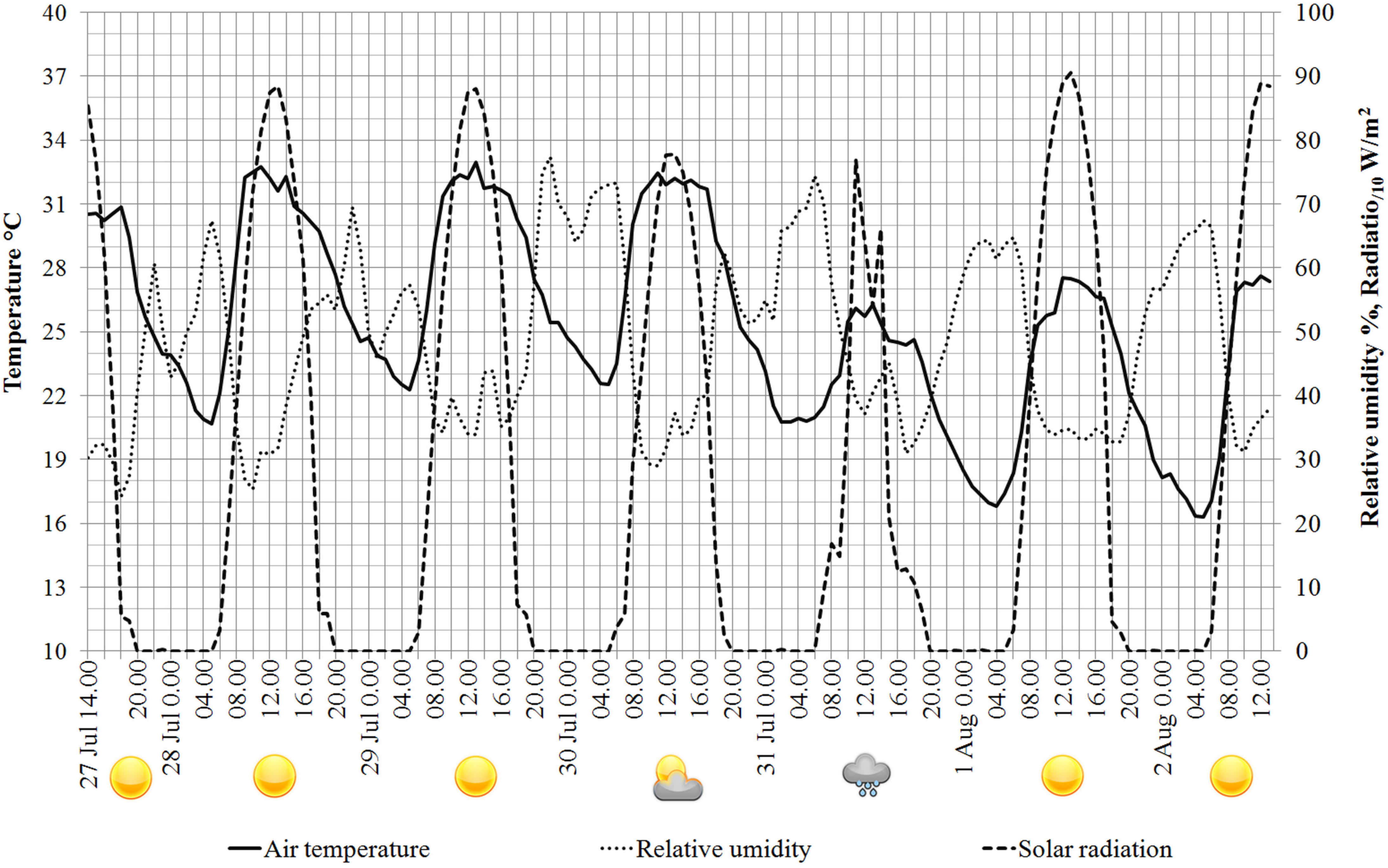
The system has the same components as those applied to the wall.

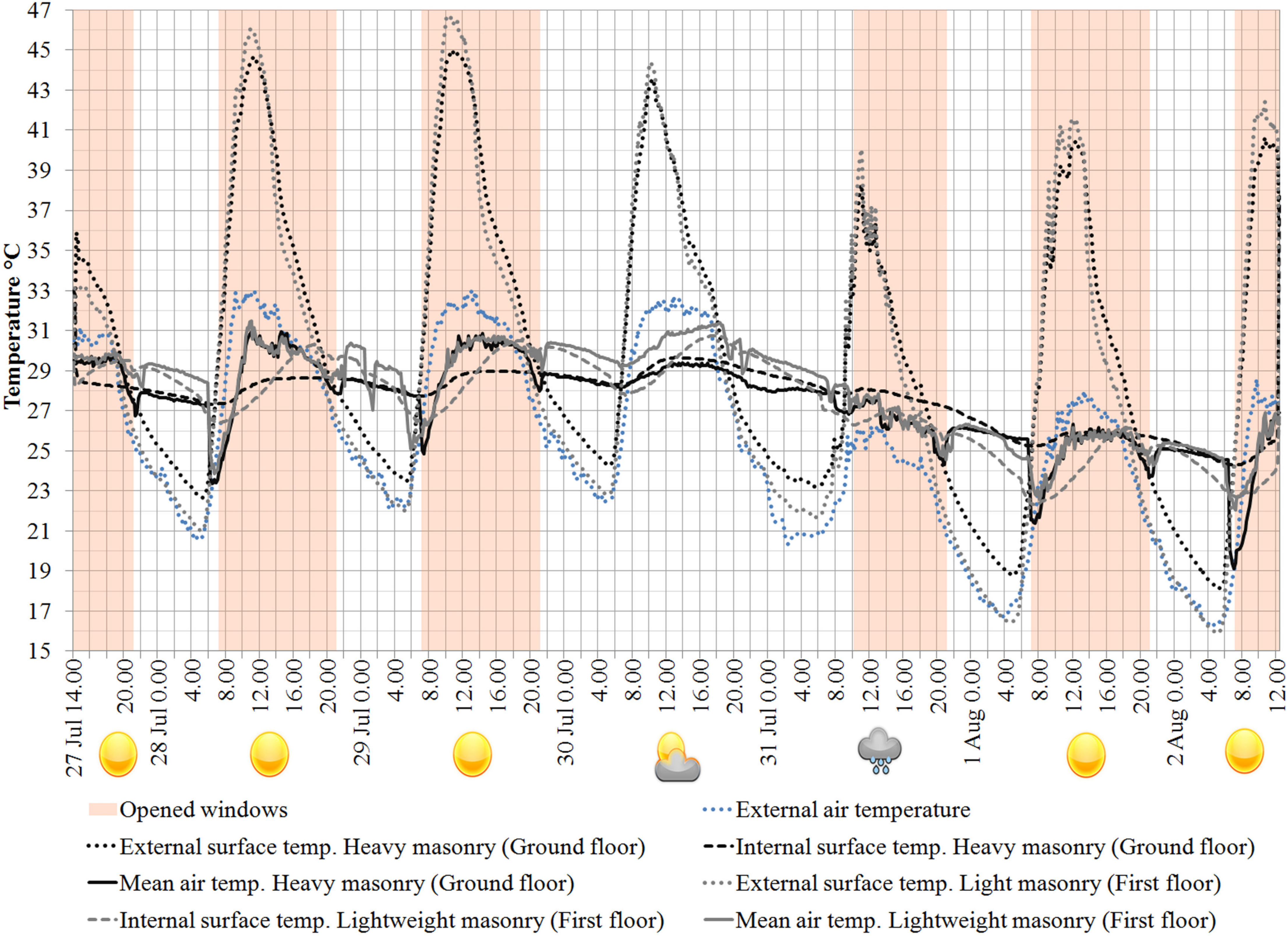
The outer side of the insulation panel will be covered by a waterproof layer and by the others necessary finishing layers.

The system is completed by a gutter and perforated sheet which allows the air inlet to the ventilation duct.

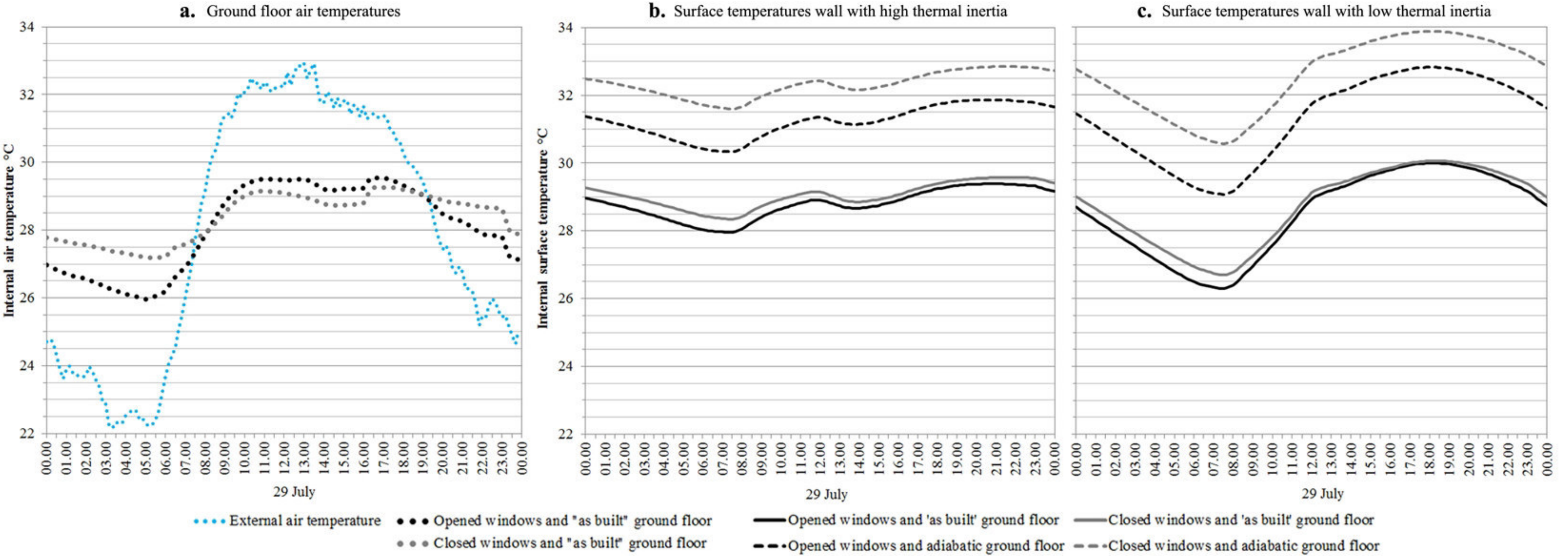


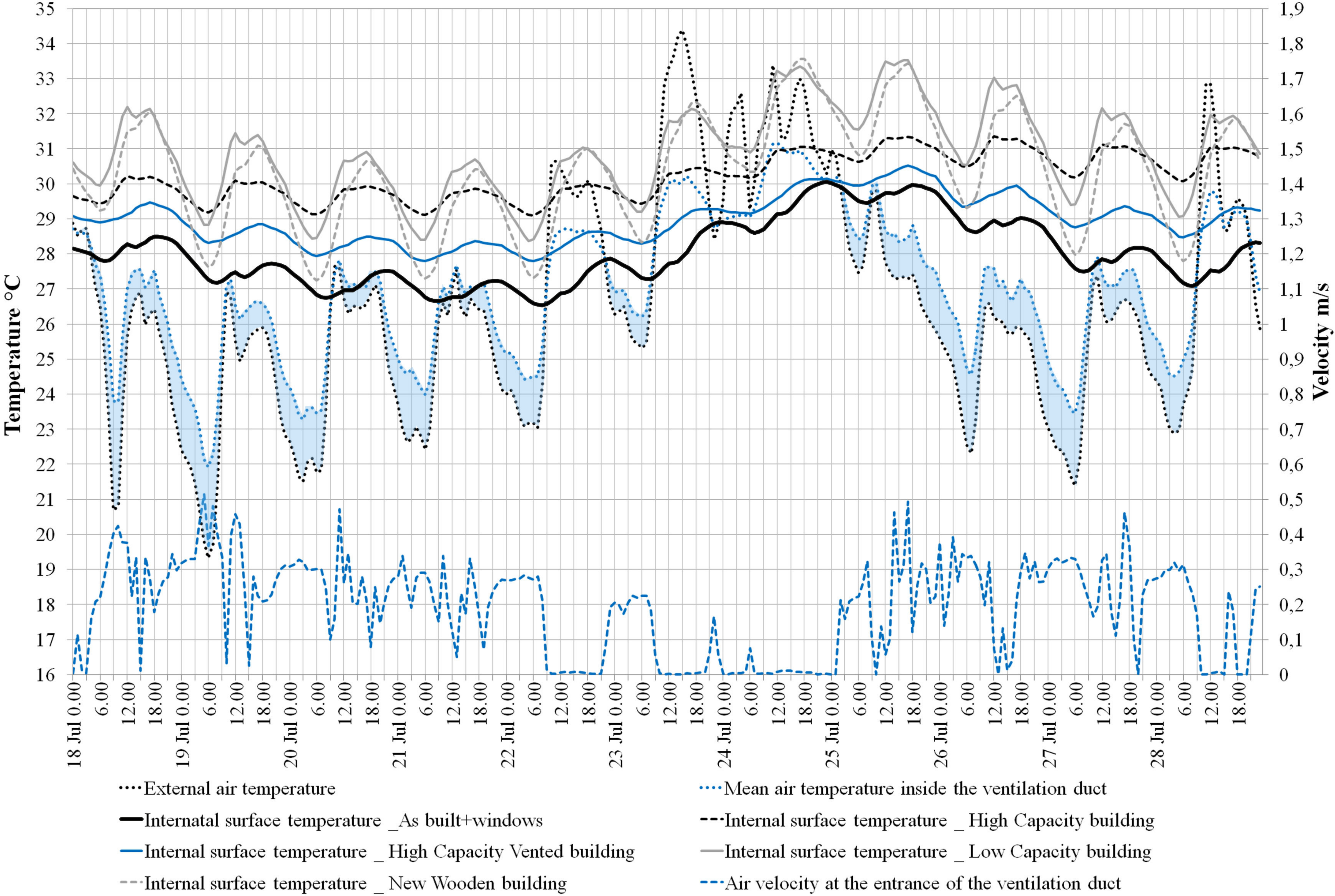
DINAMIC INSULATION
application to wall and roof

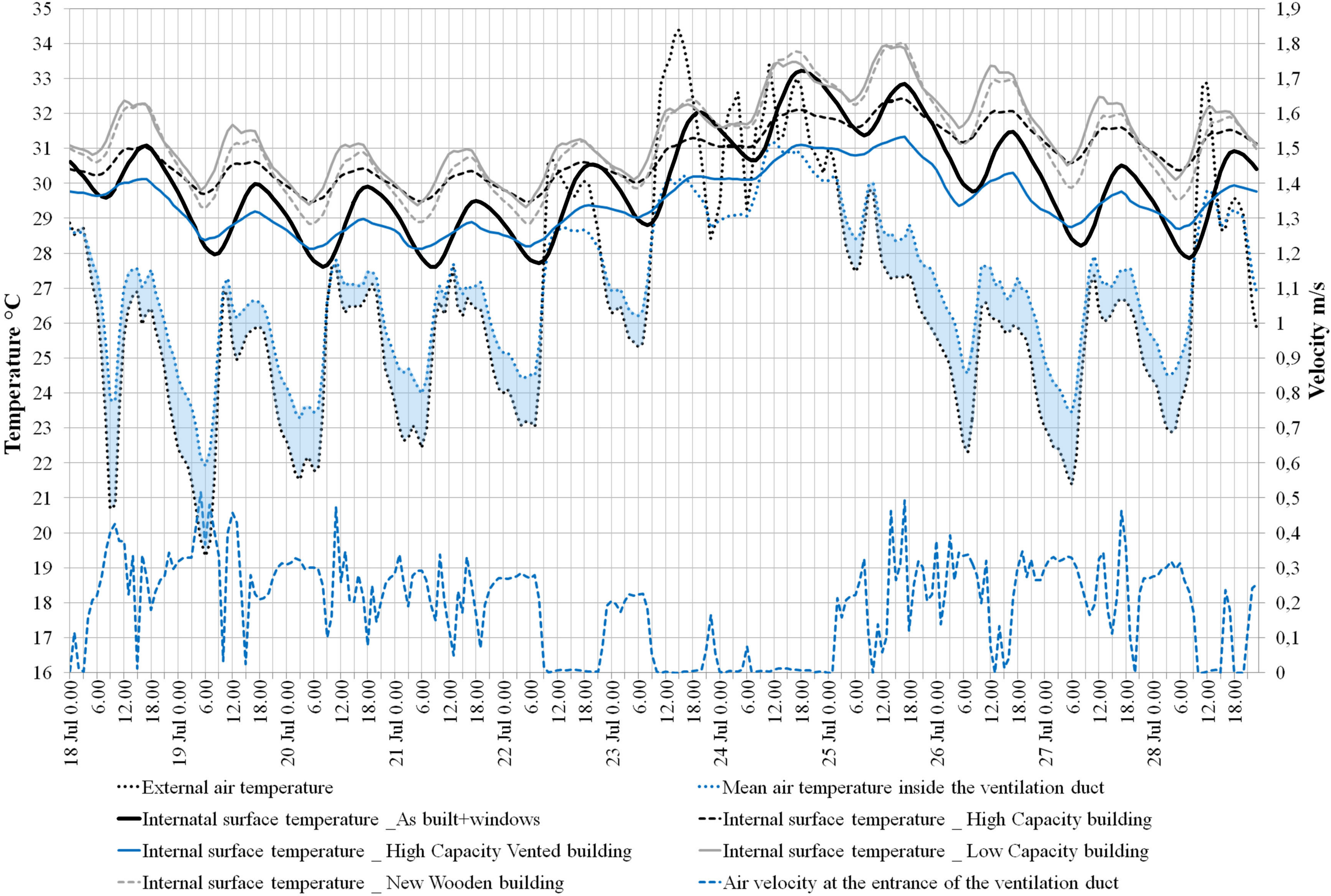

Temperature °C
Relative umidity %, Radiatio$_{10}$ W/m^2
40
37
34
31
28
25
22
19
16
13
10
100
90
80
70
60
50
40
30
20
10
0
27 Jul 14.00
20.00
28 Jul 0.00
04.00
08.00
12.00
16.00
20.00
29 Jul 0.00
04.00
08.00
12.00
16.00
20.00
30 Jul 0.00
04.00
08.00
12.00
16.00
20.00
31 Jul 0.00
04.00
08.00
12.00
16.00
20.00
1 Aug 0.00
04.00
08.00
12.00
16.00
20.00
2 Aug 0.00
04.00
08.00
12.00
Air temperature
Relative umidity
Solar radiation

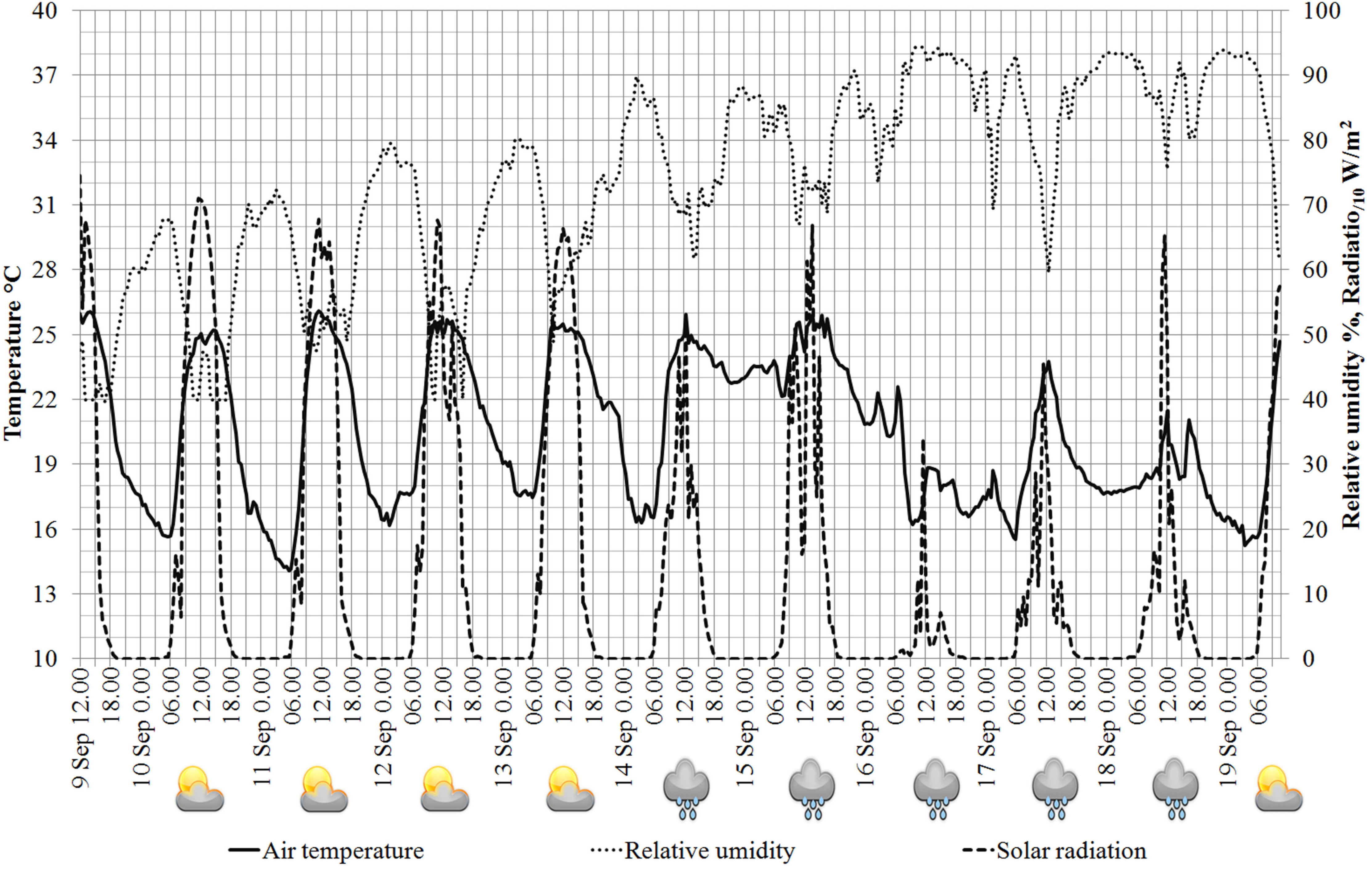


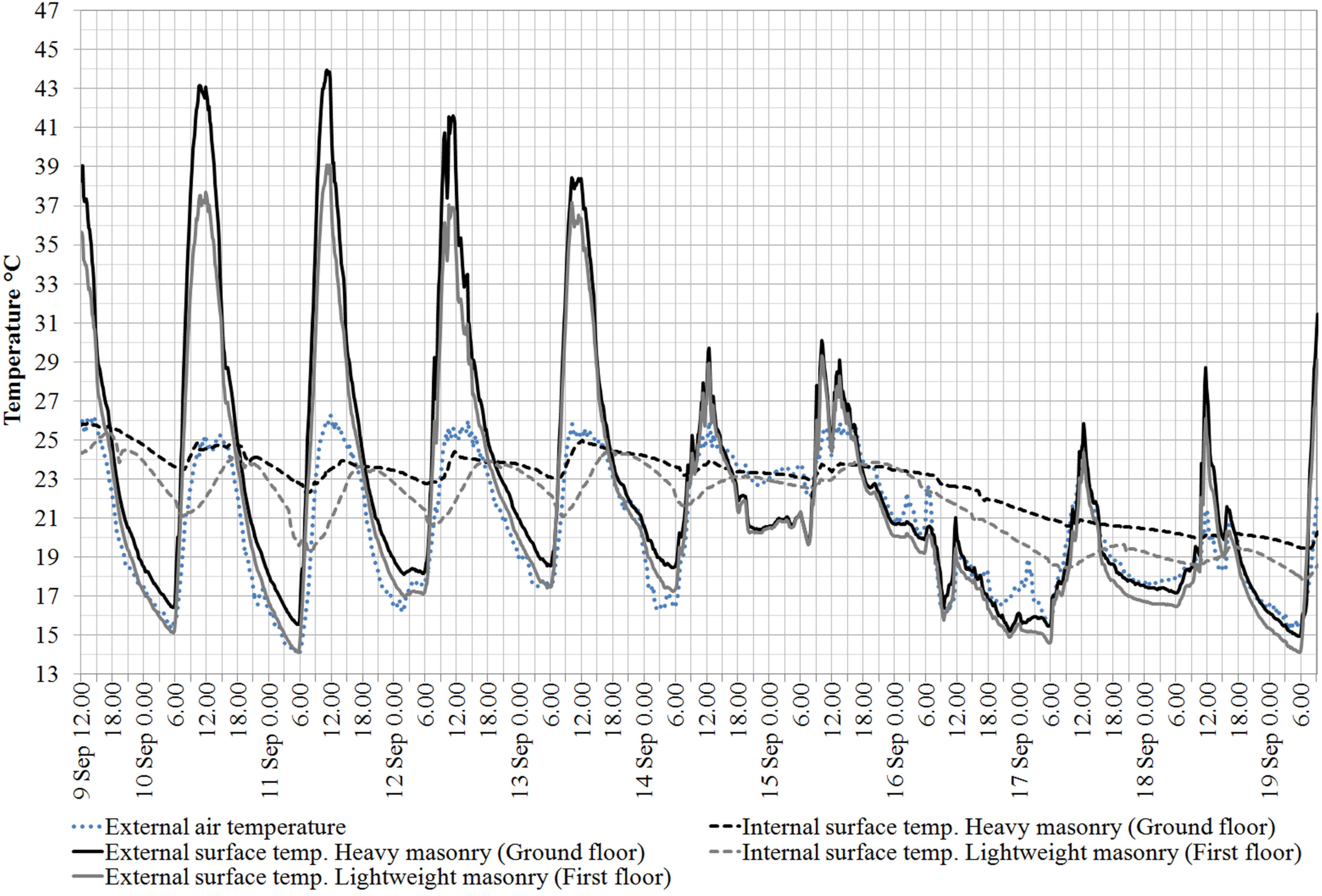
Temperature °C
47
45
43
41
39
37
35
33
31
29
27
25
23
21
19
17
15
27 Jul 14.00
20.00
28 Jul 0.00
4.00
8.00
12.00
16.00
20.00
29 Jul 0.00
4.00
8.00
12.00
16.00
20.00
30 Jul 0.00
4.00
8.00
12.00
16.00
20.00
31 Jul 0.00
4.00
8.00
12.00
16.00
20.00
1 Aug 0.00
4.00
8.00
12.00
16.00
20.00
2 Aug 0.00
4.00
8.00
12.00
Opened windows
External air temperature
External surface temp. Heavy masonry (Ground floor)
Internal surface temp. Heavy masonry (Ground floor)
Mean air temp. Heavy masonry (Ground floor)
External surface temp. Light masonry (First floor)
Internal surface temp. Lightweight masonry (First floor)
Mean air temp. Lightweight masonry (First floor)

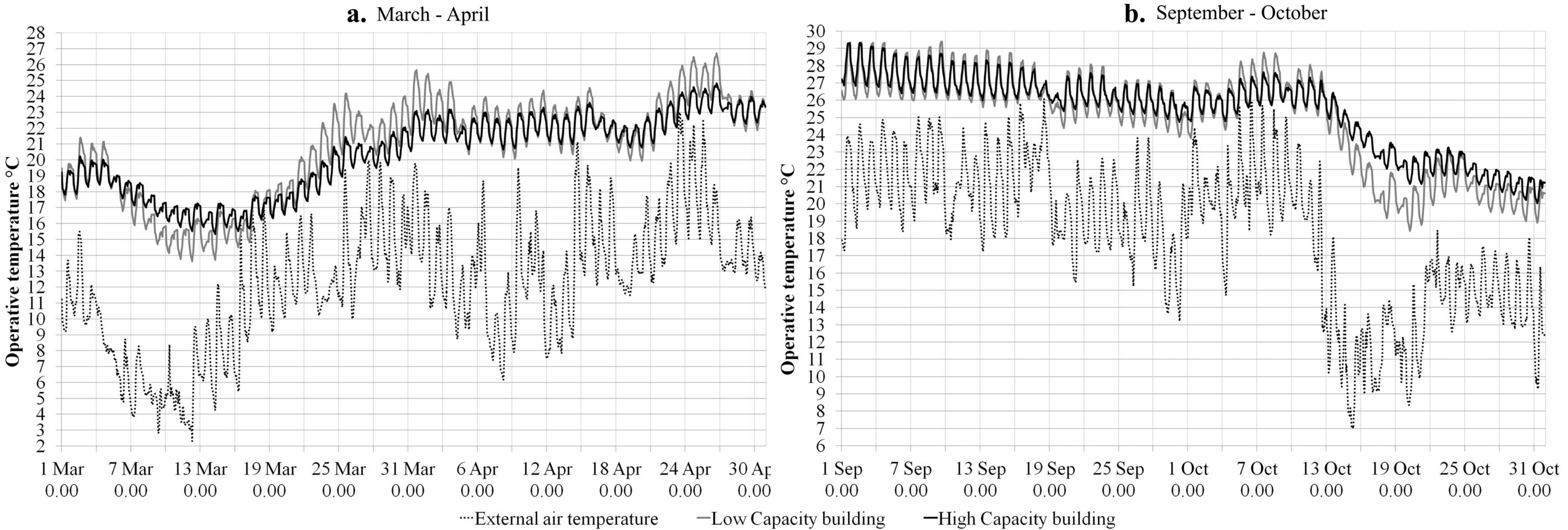

a. Ground floor air temperatures
b. Surface temperatures wall with high thermal inertia
c. Surface temperatures wall with low thermal inertia
Internal air temperature °C
Internal surface temperature °C
34
32
30
28
26
24
22
00.00
01.00
02.00
03.00
04.00
05.00
06.00
07.00
08.00
09.00
10.00
11.00
12.00
13.00
14.00
15.00
16.00
17.00
18.00
19.00
20.00
21.00
22.00
23.00
00.00
29 July
External air temperature
Opened windows and "as built" ground floor
Closed windows and "as built" ground floor
Opened windows and 'as built' ground floor
Closed windows and 'as built' ground floor
Opened windows and adiabatic ground floor
Closed windows and adiabatic ground floor

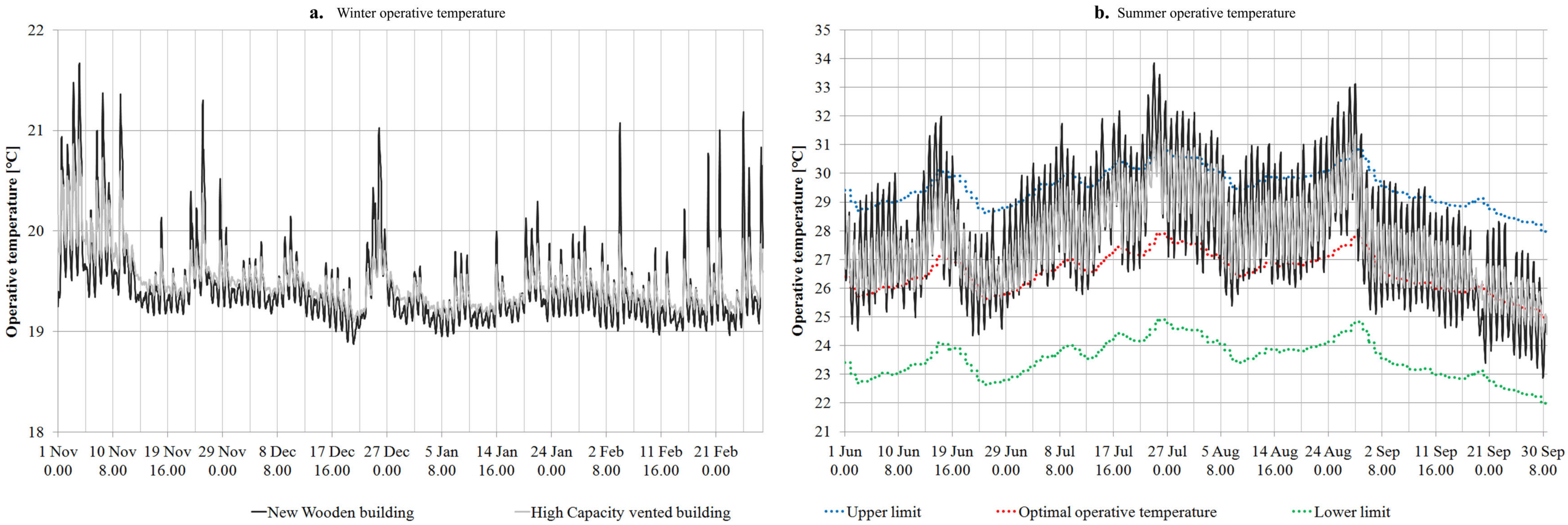

Temperature °C
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
Velocity m/s
1,9
1,8
1,7
1,6
1,5
1,4
1,3
1,2
1,1
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
18 Jul 0.00
6.00
12.00
18.00
19 Jul 0.00
20 Jul 0.00
21 Jul 0.00
22 Jul 0.00
23 Jul 0.00
24 Jul 0.00
25 Jul 0.00
26 Jul 0.00
27 Jul 0.00
28 Jul 0.00
External air temperature
Mean air temperature inside the ventilation duct
Internatal surface temperature _As built+windows
Internal surface temperature _ High Capacity building
Internal surface temperature _ High Capacity Vented building
Internal surface temperature _ Low Capacity building
Internal surface temperature _ New Wooden building
Air velocity at the entrance of the ventilation duct

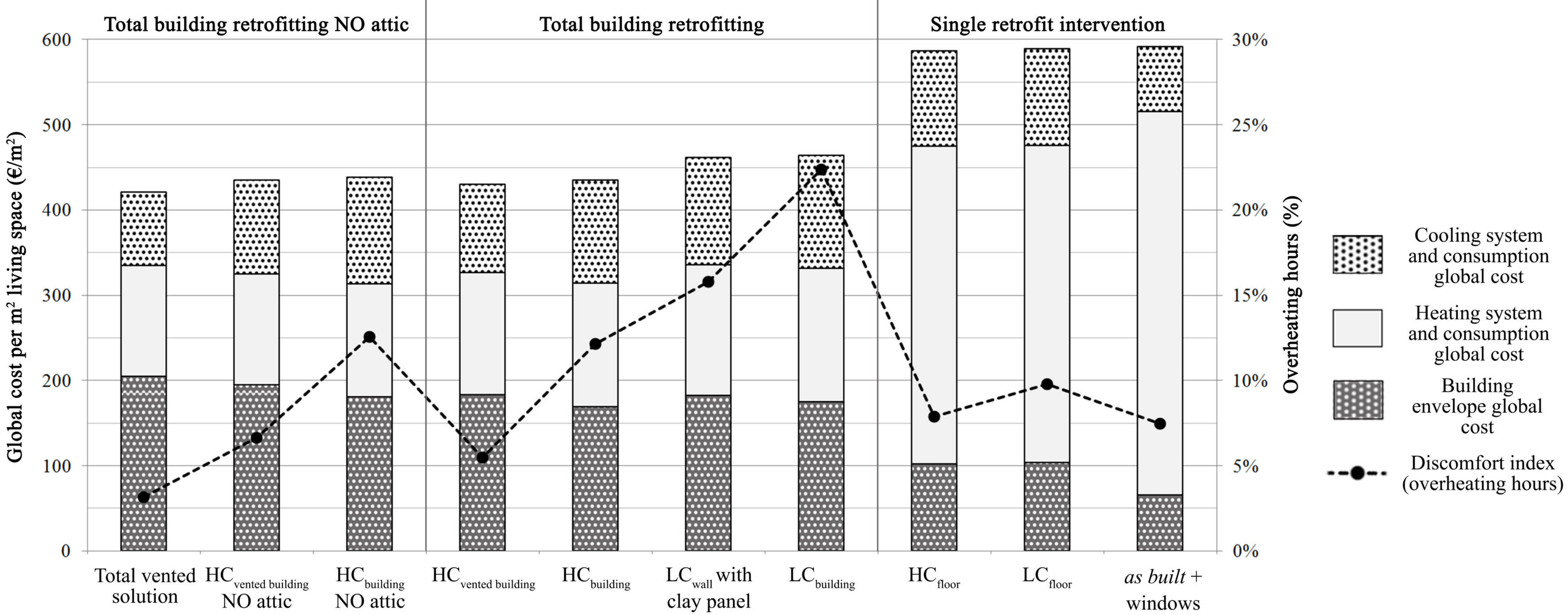

Temperature °C
Velocity m/s
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
1,9
1,8
1,7
1,6
1,5
1,4
1,3
1,2
1,1
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
18 Jul 0.00
6.00
12.00
18.00
19 Jul 0.00
6.00
12.00
18.00
20 Jul 0.00
6.00
12.00
18.00
21 Jul 0.00
6.00
12.00
18.00
22 Jul 0.00
6.00
12.00
18.00
23 Jul 0.00
6.00
12.00
18.00
24 Jul 0.00
6.00
12.00
18.00
25 Jul 0.00
6.00
12.00
18.00
26 Jul 0.00
6.00
12.00
18.00
27 Jul 0.00
6.00
12.00
18.00
28 Jul 0.00
6.00
12.00
18.00
External air temperature
Mean air temperature inside the ventilation duct
Internatal surface temperature _As built+windows
Internal surface temperature _ High Capacity building
Internal surface temperature _ High Capacity Vented building
Internal surface temperature _ Low Capacity building
Internal surface temperature _ New Wooden building
Air velocity at the entrance of the ventilation duct


Temperature °C
40
37
34
31
28
25
22
19
16
13
10
Relative umidity %, Radiatio$_{10}$ W/m^2
100
90
80
70
60
50
40
30
20
10
0
9 Sep 12.00
18.00
10 Sep 0.00
06.00
12.00
18.00
11 Sep 0.00
06.00
12.00
18.00
12 Sep 0.00
06.00
12.00
18.00
13 Sep 0.00
06.00
12.00
18.00
14 Sep 0.00
06.00
12.00
18.00
15 Sep 0.00
06.00
12.00
18.00
16 Sep 0.00
06.00
12.00
18.00
17 Sep 0.00
06.00
12.00
18.00
18 Sep 0.00
06.00
12.00
18.00
19 Sep 0.00
06.00
Air temperature
Relative umidity
Solar radiation


Temperature °C
47
45
43
41
39
37
35
33
31
29
27
25
23
21
19
17
15
13
9 Sep 12.00
18.00
10 Sep 0.00
6.00
12.00
18.00
11 Sep 0.00
6.00
12.00
18.00
12 Sep 0.00
6.00
12.00
18.00
13 Sep 0.00
6.00
12.00
18.00
14 Sep 0.00
6.00
12.00
18.00
15 Sep 0.00
6.00
12.00
18.00
16 Sep 0.00
6.00
12.00
18.00
17 Sep 0.00
6.00
12.00
18.00
18 Sep 0.00
6.00
12.00
18.00
19 Sep 0.00
6.00
External air temperature
External surface temp. Heavy masonry (Ground floor)
External surface temp. Lightweight masonry (First floor)
Internal surface temp. Heavy masonry (Ground floor)
Internal surface temp. Lightweight masonry (First floor)


a. March - April
b. September - October
Operative temperature °C
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
1 Mar 0.00
7 Mar 0.00
13 Mar 0.00
19 Mar 0.00
25 Mar 0.00
31 Mar 0.00
6 Apr 0.00
12 Apr 0.00
18 Apr 0.00
24 Apr 0.00
30 Ap 0.00
1 Sep 0.00
7 Sep 0.00
13 Sep 0.00
19 Sep 0.00
25 Sep 0.00
1 Oct 0.00
7 Oct 0.00
13 Oct 0.00
19 Oct 0.00
25 Oct 0.00
31 Oct 0.00
External air temperature
Low Capacity building
High Capacity building


a. Winter operative temperature
Operative temperature [°C]
22
21
20
19
18
1 Nov 0.00
10 Nov 8.00
19 Nov 16.00
29 Nov 0.00
8 Dec 8.00
17 Dec 16.00
27 Dec 0.00
5 Jan 8.00
14 Jan 16.00
24 Jan 0.00
2 Feb 8.00
11 Feb 16.00
21 Feb 0.00
New Wooden building
High Capacity vented building
b. Summer operative temperature
Operative temperature [°C]
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
1 Jun 0.00
10 Jun 8.00
19 Jun 16.00
29 Jun 0.00
8 Jul 8.00
17 Jul 16.00
27 Jul 0.00
5 Aug 8.00
14 Aug 16.00
24 Aug 0.00
2 Sep 8.00
11 Sep 16.00
21 Sep 0.00
30 Sep 8.00
Upper limit
Optimal operative temperature
Lower limit



	Total vented solution	$HC_{\text{vented building}}$ NO attic	HC_{building} NO attic	$HC_{\text{vented building}}$	HC_{building}	LC_{wall} with clay panel	LC_{building}	HC_{floor}	LC_{floor}	*as built* + windows	
hezating+cooling	51	58	64	60	66	70	72	131	131	143	**Primary energy demand (kWh/m² year)**
heating	34	34	35	38	38	40	41	106	106	129	

Table 1. Thermal characteristics of each studied envelope.

	STANDARD [39] / SUGGESTED [22] limits	**SCHEME 0**	**SCHEME 1 and 2**		**SCHEME 3**
	Ground floor	As built Ground floor **(G_0)**	High Capacity Ground floor **(HC_{ground})**	Low Capacity Ground floor **(LC_{ground})**	New Wooden building Ground floor **(NW_{ground})**
		Gravel 12 cm Cast concrete 30 cm Tiles 2 cm	Lightweight concrete 10 cm Air 30 cm Reinforced cast concrete 30 cm EPS insulation 10 cm Lightweight concrete 10 cm Tiles 2 cm	Lightweight concrete 10 cm Air 30 cm Cast concrete 11 cm Lightweight concrete 10 cm EPS insulation 10 cm Tiles 2 cm	Lightweight concrete 10 cm Reinforced cast concrete 30 cm Cast concrete 14 cm Glass wool insulation 6 cm Tiles 2 cm
Thermal transmittance. *U* (W/m^{2}K)	0.34	1.44	0.3	0.3	0.30
Periodic thermal transmittance *Yie* (W/m^{2}K)	< 0.20	0.19	0.01	0.01	0.01
Internal areal heat capacity *k1* (kJ/m^{2}K)	Suggested ≥ 50	62	62	41	30
	Roof	As built Roof **(R_0)**	High Capacity Roof **(HC_{roof})**	Low Capacity Roof **(LC_{roof})**	New Wooden building Roof **(NW_{roof})**
		Roof tiles 2 cm Cast concrete 6 cm Brick-concrete slab 18cm Internal plaster 1.5 cm	Roof tiles 2 cm EPS insulation 13 cm (Ventilated cavity 8 cm)[d] Cast concrete 4 cm Brick-concrete slab 18 cm Internal plaster 1.5 cm	Roof tiles 2 cm Cast concrete 4 cm Brick-concrete slab 18 cm Mineral wool insulation 13 cm Internal plaster coating 0.5 cm	Roof tile 2 cm Wood fiber insulation 8 cm XLAM 13 cm Glass wool insulation 5 cm Gypsum plasterboard 1.25 cm
Thermal transmittance *U* (W/m^{2}K)	0.26	1.91	0.24 (0.23)[d]	0.24	0.24
Periodic thermal transmittance *Yie* (W/m^{2}K)	< 0.20	0.90	0.03	0.03	0.02
Internal areal heat capacity *k1* (kJ/m^{2}K)	Suggested ≥ 50	75	66	20	17
	Wall	As built Wall **(W_0)**	High Capacity Wall **(HC_{wall})**	Low Capacity Wall **(LC_{wall})**	New Wooden building Wall **(NW_{wall})**
		External plaster 1.5 cm Solid brick 42 cm[a] (Semisolid brick 25 cm)[b] Internal plaster 1.5 cm	External plaster coating 0.5 cm EPS insulation 12 cm (Ventilated cavity 8 cm)[c] Plaster 1.5 cm Solid brick 42 cm Internal plaster 1.5 cm	External plaster 1.5 cm Solid brick 42 cm Internal plaster 1.5 cm Mineral wool insulation 12 cm Gypsum plasterboard 1.25 cm (Clay panel 2.2 cm)[c]	External plaster coating 1.5 cm Wood fibre insulation 8 cm XLAM 9.7 cm Glass wool insulation 5 cm Gypsum plasterboard 1.25 cm Gypsum plasterboard 1.25 cm
Thermal transmittance *U* (W/m^{2}K)	0.29	1.35[a] (1.11) [b]	0.25 (0.24)[c]	0.25	0.25
Periodic thermal transmittance *Yie* (W/m^{2}K)	< 0.12	0.18[a] (0.42) [b]	0.01	0.01	0.03
Internal areal heat capacity *k1* (kJ/m^{2}K)	Suggested ≥ 50	66[a] (58) [b]	63	16 (30)[c]	26

[a], [b] **a** correspond to the as built wall at the ground floor, **b** correspond to the as built wall at the first floor

[c] Introduction of a ventilated layer behind the external wall insulation: High Capacity Vented Wall (Scheme 2b)

[b] Introduction of a ventilated layer behind the external roof insulation: High Capacity Vented Wall (Scheme 4)

[c] Introduction of a inner massive finish (Scheme 5)

Table 2. Thermal properties of the main materials of the external envelope.

	λ [W/mK]	c [J/kgK]	ρ [kg/m^3]
External / internal plaster	0.900	1000	1900
External plaster coating	0.700	1000	1000
Gypsum plasterboard	0.250	1000	900
Clay panel	0.047	1000	1300
EPS insulation	0.036	1480	35
Mineral wool insulation	0.036	840	175
Wood fibre insulation	0.049	2100	265
Glass wool insulation	0.040	670	40
Solid brick	0.780	940	1500
Semisolid brick	0.360	840	1100
XLAM	0.130	1600	500

Table 3. Scheme of the studied scenarios

	WINDOWS		**GROUND**	**ROOF**	**WALL**
as built	WWR 7% U≈ 5 W/m^{2}K		G_0	R_0	W_0
SCHEME 0	WWR 9% U≈ 2 W/m^{2}K		G_0	R_0	W_0
SCHEME 1	WWR 9% U≈ 2 W/m^{2}K	a.	High (HC_{ground})	High (HC_{roof})	W_0
		b.	Low (LC_{ground})	Low (LC_{roof})	W_0
SCHEME 2	WWR 9% U≈ 2 W/m^{2}K	a.	High (HC_{ground})	High (HC_{roof})	High (HC_{wall})
		b.	High (HC_{ground})	High (HC_{roof})	Vented ($HC_{vented\ wall}$)
		c.	Low (LC_{ground})	Low (LC_{roof})	Low (LC_{wall})
SCHEME 3	WWR 9% U≈ 2 W/m^{2}K		Wood	Wood	Wood
SCHEME 4	WWR 9% U≈ 2 W/m^{2}K		Low (LC_{ground})	Low (LC_{roof})	High (Massive inner finish)
SCHEME 5	WWR 9% U≈ 2 W/m^{2}K		High (HC_{ground})	Vented ($HC_{vented\ roof}$)	Vented ($HC_{vented\ wall}$)

Table 4. Input data for the economic analysis.

INPUT DATA				
Parameter	**Value**	**Comments/Source**		
Starting year for calculation	2013	according to Annex I of EU regulation		
Calculation period	30 years			
Interest rate	4%	real		
ASSUMED LIFETIMES OF BUILDING ELEMENTS				
Parameter	**Value**	**Comments/Source**		
Insulation (thermal protection)	50 years	UNI EN 15459 [46]		
Window	30 years			
Heating system	20 years			
Cooling system	15 years			
ENERGY PRICES				
Parameter	**Value**	**Comments/Source**		
Natural gas	0.087€/kWh	VAT and taxes excluded		
Electricity	0.2 €/kWh			
Energy price development	2.8%	real		
SPECIFIC COST [€/m^2] (VAT excluded)				
Ground floor	$\mathbf{HC}_{\mathbf{floor}}$ and $\mathbf{LC}_{\mathbf{floor}}$: 22.43			
Roof	$\mathbf{HC}_{\mathbf{roof}}$: 39.33	$\mathbf{HC}_{\mathbf{vented\ roof}}$: 53.76	$\mathbf{LC}_{\mathbf{roof}}$: 42.22	
Wall	$\mathbf{HC}_{\mathbf{wall}}$: 53.12	$\mathbf{HC}_{\mathbf{vented\ wall}}$: 67.26	$\mathbf{LC}_{\mathbf{wall}}$: 48.78	$\mathbf{LC}_{\mathbf{wall\ with\ clay\ panel}}$: 56.13
Attic floor removal	20.20			

Table 5. Specific costs associated to the three categories: building envelope, heating and cooling

		BUILDING ENVELOPE (€)				**HEATING (€)**				**COOLING (€)**			
		C_I	C_m	C_o	V_f	C_I	C_m	C_o	V_f	C_I	C_m	C_o	V_f
SCHEME 0		12,791	3,944	-	-3,944	1,827	2,447	84,499	-1,127	3,200	2,722	9,638	-789
SCHEME 1	a.	20,841	3,944	-	-4,936	1,827	2,447	69,542	-1,127	3,200	2,722	16,644	-789
	b.	21,226	3,944	-	-4,984	1,827	2,447	69,240	-1,127	3,200	2,722	17,053	-789
SCHEME 2	a.	35,730	3,944	-	-6,773	1,827	2,447	25,150	-1,127	3,200	2,722	18,431	-789
	b.	38,867	3,944	-	-7,160	1,827	2,447	24,727	-1,127	3,200	2,722	15,048	-789
	c.	34,608	3,944	-	-6,634	1,827	2,447	25,296	-1,127	3,200	2,722	18,891	-789
SCHEME 4		43,347	3,944	-	-7,397	1,827	2,447	22,114	-1,127	3,200	2,722	13,608	-789
SCHEME 5		36,240	3,944	-	-6,836	1,827	2,447	24,864	-1,127	3,200	2,722	17,961	-789

Table 6. Evaluation of thermal comfort with the *Method of Percentage outside the range* (Annex F – Method A) and the *Method of Degree hours* criteria (Annex F – Method B). Comparison between the "as built" condition and the other alternative solutions.

DISCOMFORT INDEX					
SCHEME		Hours of overheating		Hours of overcooling	
		Ground floor	First floor	Ground floor	First floor
	as built	0	128	378	83
SCHEME 0	*as built*+ windows	0	144	246	75
SCHEME 1	HC_{floor}	130	227	0	4
	LC_{floor}	183	281	4	6
SCHEME 2	$HC_{building}$	193	356	0	0
	$HC_{vented\ building}$	85	160	0	0
	$LC_{building}$	542	655	0	0
SCHEME 3	$NW_{building}$	428	518	0	0
SCHEME 4	Inner massive finish	329	463	0	0
SCHEME 5	Totally vented solution	72	93	0	0

Table 7. Winter and summer primary energy demand for the “as built” case and the alternative solutions under various system operation profiles.

SCHEME		WINTER CONSUMPTIONS		SUMMER CONSUMPTIONS
		Continuous heating energy consumption (kW$_p$/m^2 year)	Intermittent heating energy consumption (6:00-10:00, 12:00-16:00, 18:00-22:00) (kW$_p$/m^2 year)	Continuous cooling energy consumption (kW$_p$/m^2 year)
	"as built"	138.62	102.88	14.18
SCHEME 0	*"as built"*+ windows	128.71	95.95	14.57
SCHEME 1	HC$_{floor}$	105.93	81.07	25.15
	LC$_{floor}$	105.47	80.82	25.77
SCHEME 2	HC$_{building}$	38.31	30.93	27.86
	HC$_{vented\ building}$	37.67	30.35	22.19
	LC$_{building}$	41.22	33.34	30.69
SCHEME 3	NW$_{building}$	40.79	32.42	24.89
SCHEME 4	Inner massive finish	40.33	32.61	28.18
SCHEME 5	Totally vented solution	33.69	27.41	17.30