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

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## **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.

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# 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].



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

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

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

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

## 55    **2    Phase, tools and methods**

### 56    *2.1 Phases*

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

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

### 65    *2.2 The case study*

66    The case study [Fig.1] is a single-family house located in the central Italy near the Adriatic coast (latitude  
67    43° 27', longitude 13° 37'), characterized by 1647 degree-days. The building is a typical example of  
68    traditional rural architecture built up at beginning of the 900 (around the 1920) and the first floor had been  
69    completed after the war with a different constructive technology. It consists in a volume of two storeys above  
70    ground level (S/V ratio = 0.69), with its longitudinal axis inclined clockwise about 45° with respect to the  
71    north-south direction. The ground floor has a high thermal inertia solid-bricks masonry wall (thickness: 42  
72    cm), while the first floor has a low thermal inertia semisolid-brick (called “occhialoni”) masonry wall  
73    (thickness: 25cm). The ground floor is made up by a concrete slab directly laid above the ground level; the  
74    floors on the first level and roof are reinforced brick-concrete slabs. The building has small size windows  
75    equipped with wooden frames and single glazing.

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

## 77    2.3 *Experimental study*

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

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

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

- 86    - Outdoor environmental conditions: a weather station with a global radiometer, a combined sensor for wind  
87    speed and direction and a thermohygrometer with a double screen anti-radiation was used;
  - 88    - Indoor climate conditions: two indoor microclimate stations that included a thermohygrometer and thermo-  
89    resistors with a tolerance according to IEC 751 were used;
  - 90    - Envelope performance: dataloggers coupled to thermoresistances, with tolerance in accordance with IEC 751,  
91    were used to measure the internal and external surface temperatures of the walls.
- 92    The accuracy provided by the manufacturer for the used probes is shown below:
- 93    - thermoresistances (surface temperatures and air temperatures): 0.15 ° C (at 0 ° C);
  - 94    - thermohygrometer: 0,15 ° C (at 0 ° C); UR 2 % (5-95 %, 23 ° C);
  - 95    - global radiometer: 0.5 % m.v. + 5 W/m<sup>2</sup>;
  - 96    - wind direction: 5°;
  - 97    - wind velocity: 2.5 % m.v./reading;
- 98    Datalogger accuracy is 3 % m.v./reading.

## 99    2.4 *Methods of thermal analysis*

100    Analytical simulations of the thermal behaviour were carried out using EnergyPlus dynamic software.  
101    The model was calibrated through comparison with monitored values. The real outdoor environmental  
102    conditions measured during the experimental phases (a new epw file for EnergyPlus simulation was

103 generate) and the specific data of occupancy conditions (air infiltration, ventilation schedules and internal  
104 loads) were set on the model. So the correspondence between the monitored and calculated values could be  
105 checked.

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

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

#### 112 2.4.1 Retrofit scenarios

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

- 114 - *as built* scenario: ground floor ( $G_0$ ), roof ( $R_0$ ), walls ( $W_0$ ) and windows as in the “as built” situation;
- 115 - *SCHEME 0*: in the *as built* scenario ( $G_0$   $R_0$   $W_0$ ) the glazed area is increased until reaching the minimum  
116 health standards [36] and achieving an overall 9% of window-to-wall ratio (against a 7% of window-to-wall  
117 ratio of the as built scheme); the glass-frame system performance is also improved ( $U \leq 2 \text{ W/m}^2\text{K}$  [37]);
- 118 - *SCHEME 1*: starting from Scheme 0 a retrofit on the ground floor and roof was implemented by assuming  
119 two type of solutions:
  - 120 a. *High Capacity floors*: the insulating material is placed on the side facing outward thus leaving high mass on  
121 the inner side;
  - 122 b. *Low Capacity floors*: the insulating material is placed on the internal face of the floors;
- 123 - *SCHEME 2*: the previous scenario (Schema 1) is completed by introducing the insulation layer also on the  
124 external walls assuming three solutions:
  - 125 a. *High Capacity building*: the insulating material is applied in the outer side of the vertical envelope by  
126 positioning it adjacent to the existing wall;
  - 127 b. *High Capacity vented building*: the insulating material is applied in the outer side of the vertical envelope  
128 leaving a cavity that could be alternatively closed (in the cold period) or vented (in the hot period through  
129 openable vents);

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

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

132 in Italy.

133 - *SCHEME 4*: improvement of the worst case (Scheme 2c) through the introduction of a massive inner finish

134 [37] characterized by a good heat capacity accumulation properties.

135 - *SCHEME 5*: further optimization of the preferable solution (namely Scheme 2b) with the introduction of a

136 ventilation layer even in the roof slab and the elimination of the attic floor.

137 Different insulation layer thicknesses and materials were used in the configurations in order to provide the

138 same stationary and periodic thermal transmittance [37]. The main difference between the walls is the thermal

139 inertia on the inner side represented by the parameter of internal areal heat capacity defined by European

140 standard EN ISO 13786:2008 [39]. On the table, the limits imposed (or suggested) for each parameter are also

141 reported.

142

143 Between the abovementioned schemes, the Scheme 2b introduced a dynamic insulation system. Thanks to an

144 air gap introduced between the external insulation layer and the internal mass (walls or roof) and the

145 introduction of openable vents, the envelope is able to dynamically adapt to the external climate with two

146 configurations, ventilated during the summer (vents open) and air-tight in winter (vents closed).

147 The authors patented a system to enhance the vents performance and to simplify the realization [34]. The

148 system involves the use of two types of panels defined "normal panels" and "special panels". Both of them

149 consist of an outer insulating layer (n. 1 and n. 2 in Fig. 4) spaced from the internal massive wall (or floor)

150 thanks to the use of cubical spacers (made by the same insulating material) thus creating an air gap (Fig. 4

151 with number 3). The anchorage of the panels to the massive support occurs as a normal external insulation,

152 i.e. with adhesive and mechanical anchors both placed in correspondence of the spacers. The opening /

153 closing of the ventilation channel takes place through vents positioned in the inferior/superior "special

154 panels". These vents (Fig. 4 with number 4) are made of insulating material (shaped in a suitable manner),

155 equipped with seals (the same used for windows) and handled by an electronic device similar to that used for

156 the rolling shutters (n. 5 in Fig. 4). The system could also be completed with sensors for automatic opening

157 based on external temperature.

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

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

#### 166 *2.4.2 Energy and comfort analysis*

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

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

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

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

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

185 - two heating operation programs: intermittent or continuous from November 1 to April 15 as established by  
 186 Italian law [44] for zone D, with a set point of 20 ° C. The intermittent heating was switched on for a total of  
 187 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  
 188 p.m., 18.00 p.m. - 22.00 p.m.;

189 - ventilation rate is set to 0.3 air change rate per hour (ach) during the winter period (UNI/TS 11300-1) while  
 190 in the summer a continuous profile set to 1.5 ach was considered according to UNI 10375 [43];

191 - summer cooling system with a set-point of 26 ° C.

#### 192 2.4.3 Method of global costs evaluation

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

$$198 \quad C_G(\tau) = C_I + \sum_j \left[ \sum_{i=0}^{\tau} (C_{a,i}(j) \cdot R_d(i)) - V_{f,\tau}(j) \right] \quad (1)$$

199 where:  $C_G(\tau)$  represents the global cost referred to starting year  $\tau_0$ ,  $C_I$  is the initial investment cost,  $C_{a,i}(j)$  is  
 200 the annual cost for component  $j$  at the year  $i$  (maintenance, replacement and running costs),  $R_d(i)$  is the  
 201 discount rate for year  $i$ ,  $V_{f,\tau}(j)$  is the final value of component  $j$  at the end of the calculation period (referred  
 202 to the starting year  $\tau_0$ ).

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

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

218 With regard to the discount rate ( $R_d$ ): in order to refer the costs to the starting year the real discount rate is  
 219 used

$$220 \quad R_d(p) = \left( \frac{1}{1+R_R/100} \right)^p \quad (2)$$

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

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

226 All the relevant input data are shown in Table 4.

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

### 229 **3 Results on summer comfort**

#### 230 *3.1 As built*

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



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

238 The monitored rooms have the same exposure (southern side) but present external walls with different inertia  
239 (solid bricks masonry and semisolid bricks masonry) and different elevations (ground floor and first floor).  
240 The *external surface temperatures* reach their minimum value at around 5:00 a.m. in both walls with lower  
241 values (about 2 °C) recorded in the first floor lightweight wall. In the following hours, with the solar  
242 radiation rising, the external surface temperatures increase, with the same trend for the two walls (since they  
243 have the same external plaster finishing) reaching the maximum at about 11:00 a.m., with higher values  
244 (about 2 °C) for the low inertia wall. The difference could be ascribed to a different outgoing heat flux for  
245 the two walls.

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

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

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

257 When the windows are open (hatched area) the internal air temperatures (continuous lines) at two levels are  
258 equal because of the inlet of outside air, with values down to 25 °C in the first hours of the morning and of  
259 about 31 °C during the central hours of the day. The values instead differ with closed windows (whole day of  
260 30 July). During the night, the values are higher than in the open configuration reaching 28 °C at the ground  
261 floor and 29 °C at the first floor. During the day, in the former low temperatures are maintained (29 °C) so  
262 lowering the values of about 2 °C respect to a vented ground floor, differently in the upper floor there is a  
263 thermal overheating (about 1°C) respect to open configuration.

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

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

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

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

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

### 289 3.2 Retrofit measures

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

294 As resulted from the summer monitoring the "as built" condition is characterized by overcooling (about 378  
295 hours) at the ground floor for the heat dispersion towards the ground, and by overheating on the first floor  
296 (128 hours). The windows thermal performance optimization and the simultaneous increasing of the glazed  
297 surface (Scheme 0), slightly reduce the ground floor overcooling (from 378 to 246), while increase the first  
298 floor overheating hours (from 128 to 144).

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

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

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

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

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

326

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

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

342 The graph regarding temperature trends on the first floor (Fig. 9) shows that the same considerations of the  
343 lower level can be adopted. Moreover at this level the adoption of a naturally ventilated insulation layer is

344 preferable also with respect to the existing (not insulated) wall since the low inertia of the wall at this level  
345 make an insulation intervention more important for its thermal barrier effect (and the consequent reduction of  
346 the surface temperature fluctuations). In the extremely hot days (July 22 to 25), and in general in extreme  
347 climates, the primarily required building envelope performance is to block the incoming heat flow. That is  
348 why the interventions with external insulation result to be preferable than the not insulated “as built” wall.

## 349 **4 Results on intermediate season comfort**

### 350 *4.1 As built*

351 Fig. 10 shows the results of the monitored weather conditions. The period was quite variable, with sunny or  
352 slightly cloudy days (September 9 to 13), characterized by daily temperatures ranging between 26 ° C and 16  
353 ° C, and rainy days (September 14 to 19) where temperatures are more variable with maximum value of  
354 about 19 ° C (September 16).

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

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

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

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

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

370 is due to the specific capability of preserving the summer stored heat and the different response to the  
371 seasonal variations.

#### 372 4.2 Retrofit measures

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

377 During the spring season (Fig. 12-a) different phases could be identified. A first phase (March 1 to 5) in  
378 which both walls are still affected by the typical winter behaviour (heated room) since the heating system  
379 was recently turned off (on March 1 for this simulation). The operative temperatures have the same  
380 minimum values while the room with an internal insulated envelope is characterized by greater maximum  
381 values (1.5-2 ° C). A second phase (March 5 to 17) when the room with lightweight envelope undergoes a  
382 sudden lowering in operative temperature values because the heating effect is finished and the outside  
383 temperatures are still low. In the third phase (March 17 to entire hot season) the rising of the outside  
384 temperatures determines an immediate overheating of the interior space of the low capacity building (with  
385 maximum values of 2.5-3 ° C higher than the other solution).  
386 In autumn (Fig. 12-b) an inverted behaviour is shown. While in spring (and for the whole summer) the room  
387 with lightweight wall presents peaks of overheating, at the end of the hot period (September – October) the  
388 external air temperature drop, causes especially for this solution the internal gradual reduction of the  
389 operative temperatures (up to 3 ° C less than the massive wall), with an unfavourable behaviour for the  
390 approaching of the cold season.

### 391 5 Consumptions

392 Table 7 shows the consumptions evaluation in terms of primary energy for both heating and cooling demand.  
393 The results show that glazed surface enlargement and its thermal optimization (from “as built” configuration  
394 to Scheme 0) lead to a heating consumption reduction for both continuous and intermittent operation (about  
395 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<sup>2</sup>/year for a continuous system operation and to about 81 kWh/m<sup>2</sup>/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<sup>2</sup>/year for continuous ignition and 33 kWh/m<sup>2</sup>/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<sup>2</sup>/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<sup>2</sup>/year (from 30 to 28) while the totally vented solution reduces the consumption down to 17 kWh/m<sup>2</sup>/year.

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

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

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

## 441 **6 Global cost assessment**

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

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



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

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

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

## 465 **7 Conclusions**

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

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

474 In the first phase of the present research an experimental study was performed on a single-family traditional  
475 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 mass, 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 ( $0.5\text{ }^{\circ}\text{C}$ ), while it is very effective if the wall is in a super-insulated and overheated room (reduction down to  $1 - 1.5\text{ }^{\circ}\text{C}$  on surface temperature). The deactivation of the natural ventilation determines slightly higher surface temperatures in the case of lightweight envelopes ( $0.5\text{ }^{\circ}\text{C}$ ).

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

504 comfort than the worst outcome solution), winter and summer energy saving (respectively reduced up to 17  
505 % and up to 43 % respect to the worst case) and a lower global cost despite the higher initial investment.  
506

## 507 **Bibliografia**

- 508 [1] M. Lj. Bojić, D.L. Loveday, The influence on building thermal behaviour of the insulation/masonry  
509 distribution in a three-layered construction, *Energy and Buildings* 26 (1997) 153-157.
- 510 [2] E. Kossecka, J. Kosny, Influence of insulation configuration on heating and cooling loads in a  
511 continuously used building, *Energy and Buildings* 34 (2002) 321-331.
- 512 [3] Y. Huang, J. Niu, T. Chung, Study on performance of energy-efficient retrofitting measures on  
513 commercial building external walls in cooling-dominant cities, *Applied Energy* 103 (2013) 97-108.
- 514 [4] S. Ferrari, Building envelope and heat capacity: re-discovering the thermal mass for winter energy  
515 saving, in: Conference proceedings: "Building low energy cooling and advanced ventilation  
516 technologies in the 21<sup>st</sup> century", September, 2007, Crete island, Greece. p.346-351.
- 517 [5] N. Aste, A. Angelotti, M. Buzzetti, The influence of external walls thermal inertia on the Energy  
518 performance of well insulated buildings, *Energy and Buildings* 41 (2009) 1181-1187.
- 519 [6] D. M. Ogoli, Predicting indoor temperatures in closed buildings with high thermal mass, *Energy and*  
520 *Buildings* 35 (2003) 851-862.
- 521 [7] C. A. Balaras, The role of thermal mass on the cooling load of buildings. An overview of  
522 computational methods, *Energy and Buildings* 24 (1996) 1-10.
- 523 [8] V. Cheng, E. Ng, B. Givoni, Effect of envelope color and thermal mass on indoor temperatures in  
524 hot humid climate, *Solar Energy* 78 (2005) 528-534.
- 525 [9] S. A. Al-Sanea, M. F. Zedan, Improving thermal performance of building walls by optimizing  
526 insulation layer distribution and thickness for same thermal mass, *Applied Energy* 88 (2011) 3113-  
527 3124.
- 528 [10] G. Kumbaroğlu, R. Madlener, Evaluation of economically optimal retrofit investment options for  
529 energy savings in buildings, *Energy and Buildings* 49 (2012) 327-334.
- 530 [11] P. T. Tsilingiris, Wall heat loss from intermittently conditioned spaces – The dynamic influence of  
531 structural and operational parameters, *Energy and Buildings* 38 (2006) 1022-1031.
- 532 [12] P. T. Tsilingiris, Parametric space distribution effects of wall heat capacity and thermal resistance on  
533 the dynamic thermal behavior of walls and structures, *Energy and Buildings* 38 (2006) 1200-1211.
- 534 [13] S. A. Al-Sanea, M. F. Zedan, Effect of thermal mass on performance of insulated building walls and  
535 the concept of energy savings potential, *Applied Energy* 89 (2012) 430-442.
- 536 [14] K. Gregory, B. Moghtaderi, H. Sugo, A. Page, Effect of thermal mass on the thermal performance of  
537 various Australian residential constructions systems, *Energy and Buildings* 40 (2008) 459-465.

- 538 [15] J. Zhou, G. Zhang, Y. Lin, Y. Li, Coupling of thermal mass and natural ventilation in buildings.  
539 Energy and Buildings 40 (2008) 979-986.
- 540 [16] F. Stazi, C. Di Perna, P. Munafò, Durability of 20-year-old external insulation and assessment of  
541 various types of retrofitting to meet new energy regulations, Energy and Buildings 41 (2009) 721-  
542 731.
- 543 [17] H. Asan, Effects of Wall's insulation thickness and position on time lag and decrement factor,  
544 Energy and Buildings 28 (1998) 299-305.
- 545 [18] K. J. Kontoleon, D. K. Bikas, The effect of south wall's outdoor absorption coefficient on time lag,  
546 decrement factor and temperature variations, Energy and Buildings 39 (2007) 1011-1018.
- 547 [19] R. S. McLeod, C. J. Hopfe, A. Kwan, An investigation into future performance and overheating risks  
548 in Passivhaus dwellings, Building and Environment 70 (2013) 189-209.
- 549 [20] R. Lindberg, A. Binamu, M. Teikari, Five-year data of measured weather, energy consumption, and  
550 time-dependent temperature variations within different exterior wall structures, Energy and  
551 Buildings 36 (2004) 495-501.
- 552 [21] A. Norén, J. Akander, E. Isfält, The effect of Thermal Inertia on Energy Requirement in a Swedish  
553 Building – Results Obtained with Three Calculation Models. Low Energy and Sustainable Buildings  
554 1 (1999) 1-16.
- 555 [22] C. Di Perna, F. Stazi, A. Ursini Casalena, M. D'Orazio, Influence of the internal inertia of the  
556 building envelope on summertime comfort in buildings with high internal heat loads, Energy and  
557 Buildings 43 (2011) 200-206.
- 558 [23] S. Martin, F. R. Mazarron, I. Canas, Study of thermal environment inside rural houses of Navapalos  
559 (Spain): the advantages of reuse buildings of high thermal inertia, Construction and Building  
560 Materials 24 (2010) 666-676.
- 561 [24] N. Cardinale, G. Rospi, A. Stazi, Energy and microclimatic performance of restored hypogenous  
562 buildings in south Italy: The "Sassi" district of Matera, Building and Environment 43 (2010) 94-106.
- 563 [25] Z. Yilmaz, Evaluation of Energy efficient design strategies for different climatic zones: Comparison  
564 of thermal performance of buildings in temperate-humid and hot-dry climate, Energy and Buildings  
565 39 (2007) 306-316.
- 566 [26] A. Gagliano, F. Patania, F. Nocera, C. Signorello, Assessment of the dynamic thermal performance  
567 of massive buildings, Energy and Buildings 72 (2014) 361-370.
- 568 [27] S. Martin, F. R. Mazarron, I. Canas, Study of thermal environment inside rural houses of Navapalos  
569 (Spain): the advantages of reuse buildings of high thermal inertia, Construction and Building  
570 Materials 24 (2010) 666-676.
- 571 [28] F. Stazi, A. Vegliò, C. Di Perna, P. Munafò, Experimental comparison between 3 different  
572 traditional wall constructions and dynamic simulations to identify optimal thermal insulation  
573 strategies, Energy and Buildings 60 (2013) 429-441.

574 [29] M. S. E. Imbabi, A passive–active dynamic insulation system for all climates, *International Journal*  
575 *of Sustainable Built Environment* 1 (2012) 247-258.

576 [30] D. Zhou, C. Y. Zhao, Y. Tian, Review on thermal energy storage with phase change materials  
577 (PCMs) in building applications, *Applied Energy* 92 (2012) 593-605.

578 [31] H. Bartodziej, Method of heat flow control through an external wall of building and wall assembly  
579 for execution of this method, WO00/60183A1, 2000 (Patent).

580 [32] G. Anmelder, Fassadenwärme-Dämm-Verbundsystem, DE102004001601A1, 2005 (Patent).

581 [33] R. Güldenpfenning, Verfahren Herstellung wärmegeämmter Putzfassaden, DE3238445A1, 1984  
582 (Patent).

583 [34] Patent MI2011A001317, Modulo per cappotto e cappotto.

584 [35] International standard UNI EN ISO 7726:2002, Ergonomics of the thermal environment—  
585 instruments for measuring physical quantities.

586 [36] Decreto Ministeriale 5 Luglio 1975, modificazioni alle istruzioni ministeriali 20 giugno 1896  
587 relativamente all'altezza minima ed ai requisiti igienico sanitari principali dei locali d'abitazione.

588 [37] <http://www.bioterraitalia.com/>

589 [38] Decreto Legislativo 19 agosto 2005, n.192, Attuazione della direttiva 2003/91/CE relativa al  
590 rendimento energetico nell'edilizia.

591 [39] International standard UNI EN ISO 13786:2008, Thermal performance of building components -  
592 Dynamic thermal characteristics - Calculation methods.

593 [40] DOE, EnergyPlus 7.0 Input/Output Reference: The encyclopedic Reference to EnergyPlus Input and  
594 Output, U.S. Department of Energy, 2011.

595 [41] European standard UNI EN 15251:2008, Indoor environmental input parameters for design and  
596 assessment of energy performance of buildings addressing indoor air quality, thermal environment,  
597 lighting and acoustics.

598 [42] EEN 3/08 deliberation. Conversion factor of kWh in petroleum equivalent tons connected to energy  
599 efficiency certificates. Authority for Electric Energy and Gas (AEEG). 2008.

600 [43] UNI/TS 11300-1:2008, Prestazioni energetiche degli edifici–Parte 1: Determinazione del fabbisogno  
601 di energia termica dell'edificio per la climatizzazione estiva ed invernale.

602 [44] D.P.R. 26 agosto 1993, n. 412, Regolamento recante norme per la progettazione, l'installazione,  
603 l'esercizio e la manutenzione degli impianti termici degli edifici ai fini del contenimento dei consumi  
604 di energia, in attuazione dell'art. 4, comma 4, della L. 9 gennaio 1991, n. 10.

605 [45] National standard UNI 10375:2011, Calculation method of the indoor temperature of a room in the  
606 warm period.

607 [46] International standard UNI EN 15459:2008, Thermal performance of buildings - Economic  
608 evaluation procedure for energy systems in buildings.

609 [47] Prezzi informativi dell'edilizia: Recupero Ristrutturazione Manutenzione. DEI Tipografia del genio  
610 civile (2013).

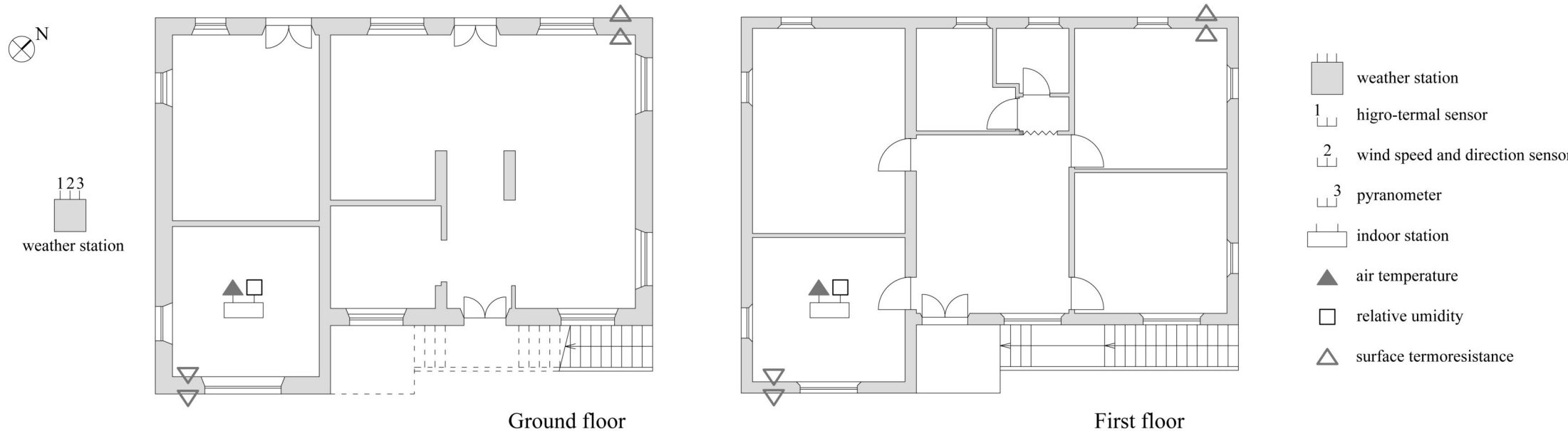
- 611 [48] AEEG elaboration on Eurostat data for domestic consumers. 2012.
- 612 [49] P. Brunello, F. Peron, Modelli per l'analisi del comportamento fluidodinamico delle facciate
- 613 ventilate, Fisica Tecnica Ambientale (1996) 313-324.

- 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.
- Fig. 5. Climatic data recorded in the summer monitoring: air temperature, relative humidity 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.

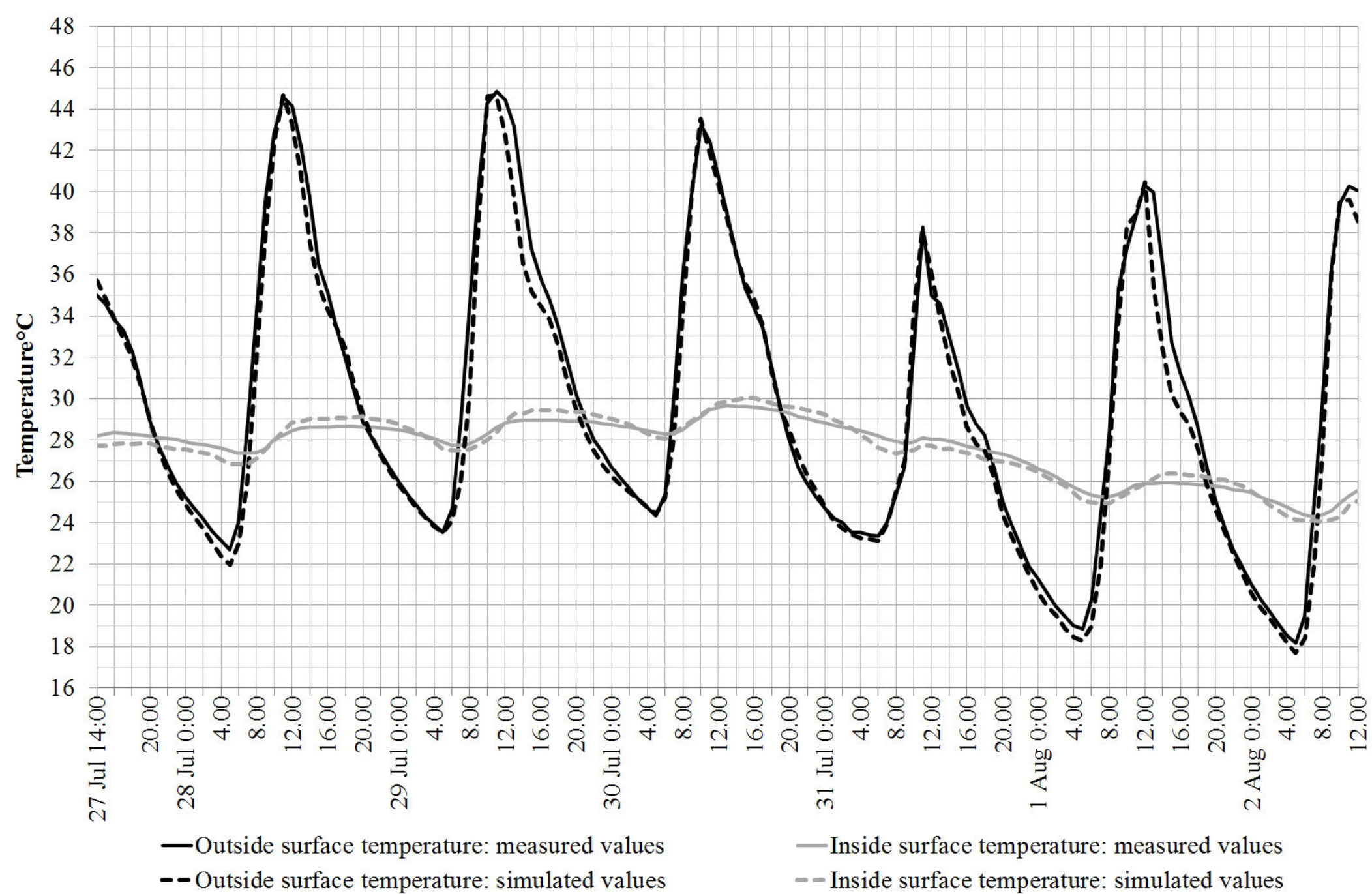




Measuring instruments



0 1 5m



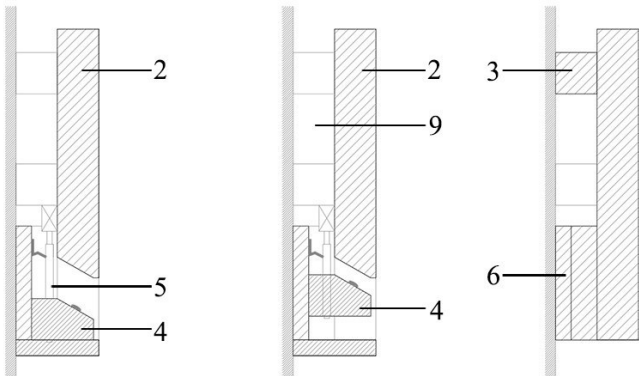
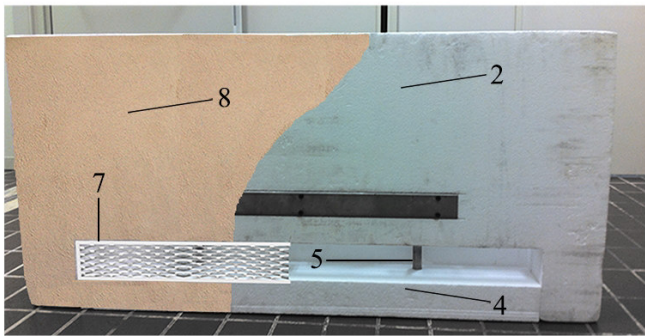
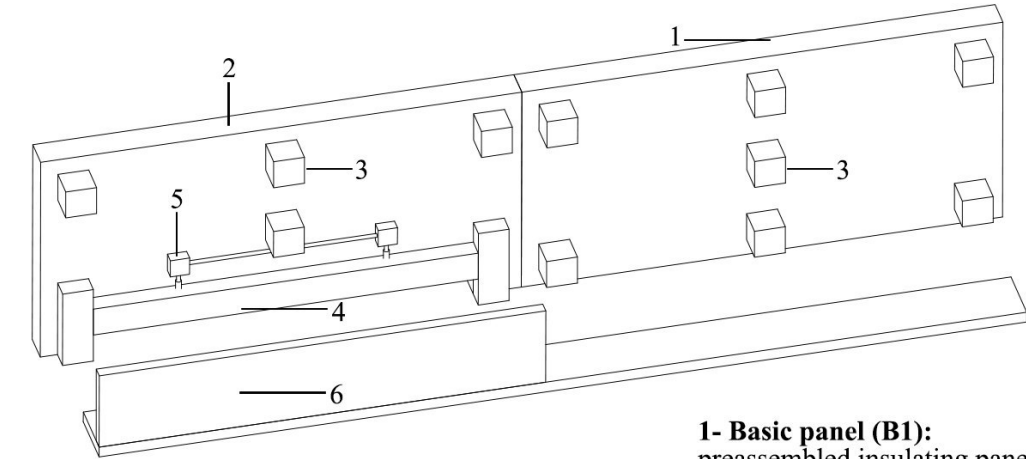


**A - EXISTING SUPPORTING WALL**



E X I S T I N G  
S U P P O R T I N G    W A L L  
made of SOLID BRICKS  
(A1) at the first floor and  
H O L L O W    B R I C K S  
called “occhialoni” (A2)  
at the second floor.

**B - MU<sub>n</sub>STa® 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.

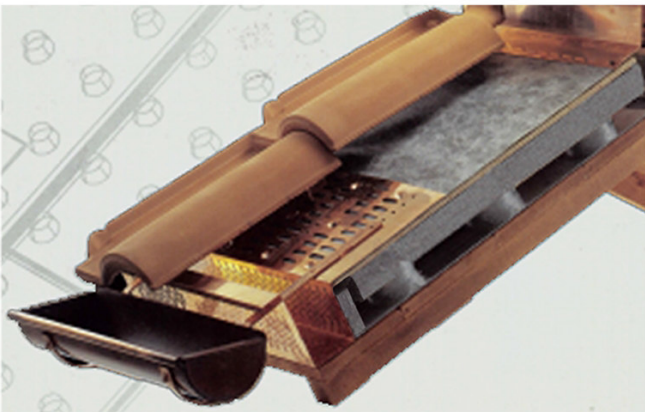
**6- Thermal bridge correction**

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

**8- External plaster coating**

**9- Vented cavity**

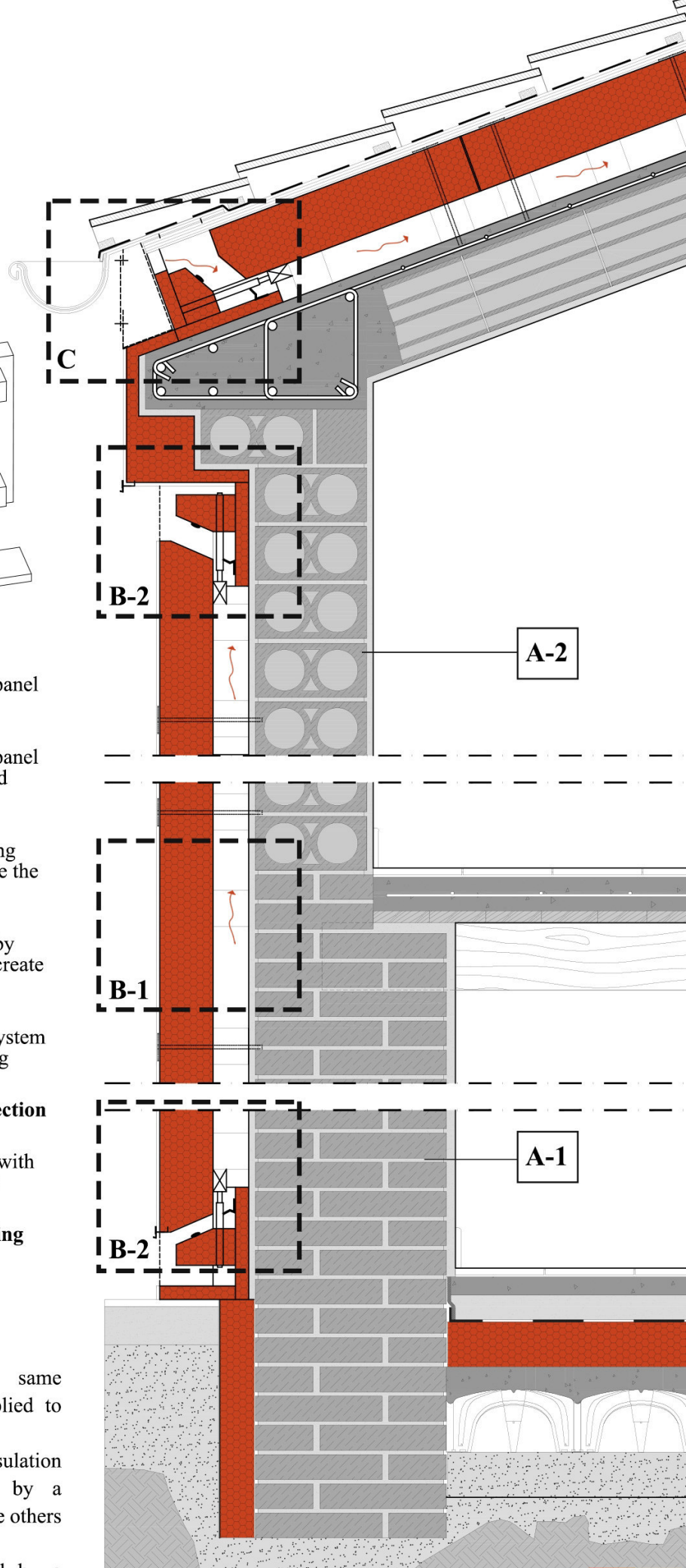
**C - MU<sub>n</sub>STa® SYSTEM APPLIED TO THE ROOF**



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.

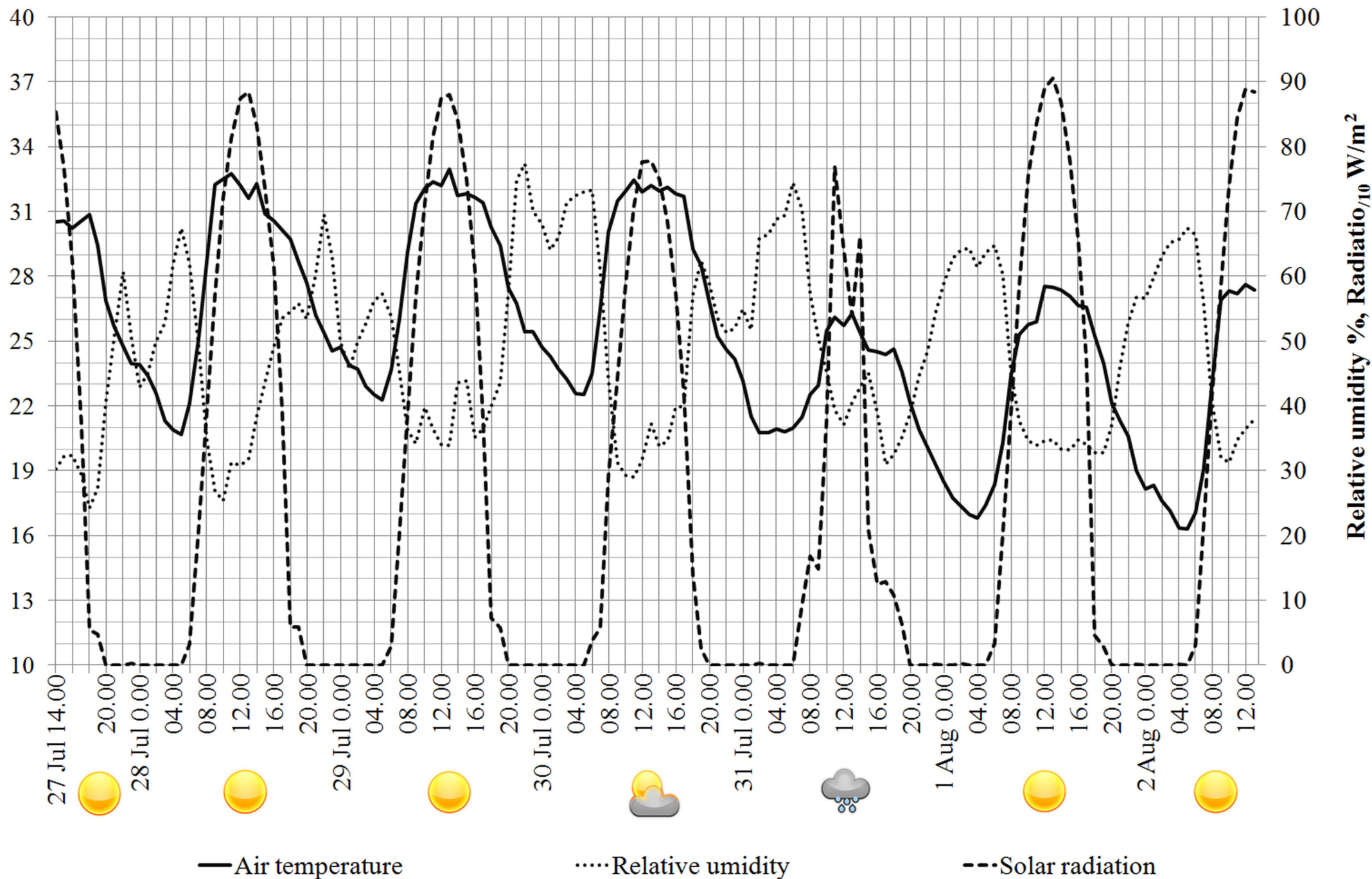


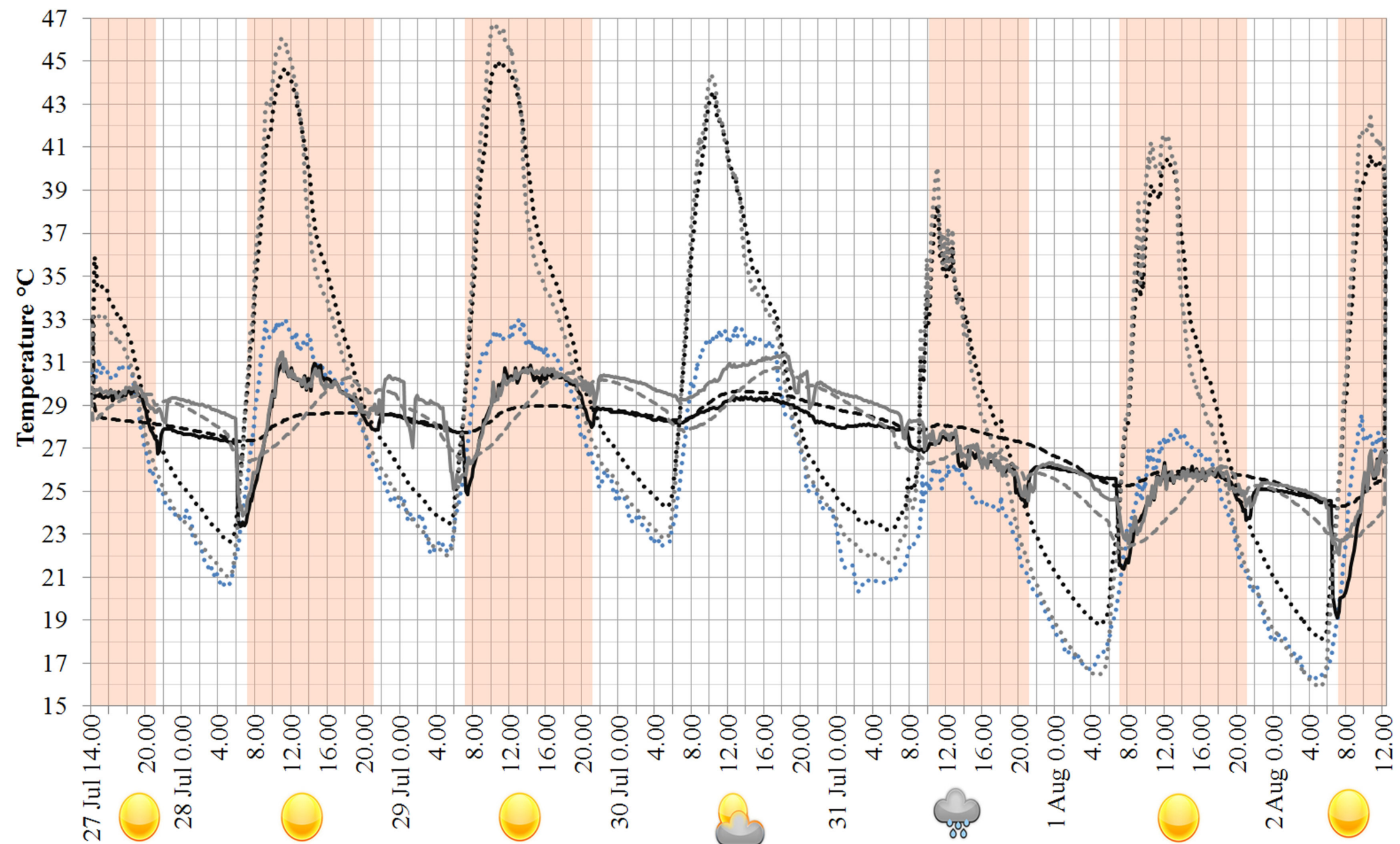
**DINAMIC INSULATION**  
**application to wall and roof**





Temperature °C





Opened windows

External surface temp. Heavy masonry (Ground floor)

Mean air temp. Heavy masonry (Ground floor)

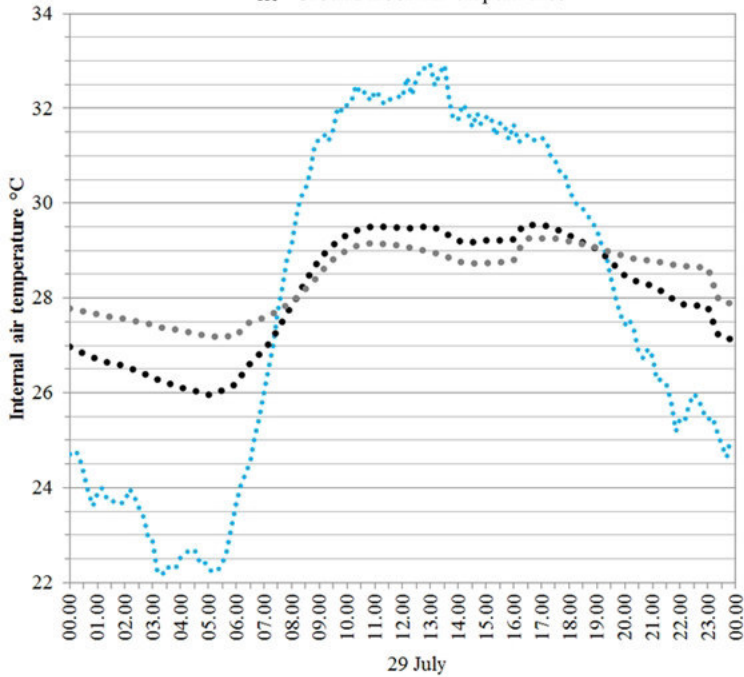
Internal surface temp. Lightweight masonry (First floor)

External air temperature

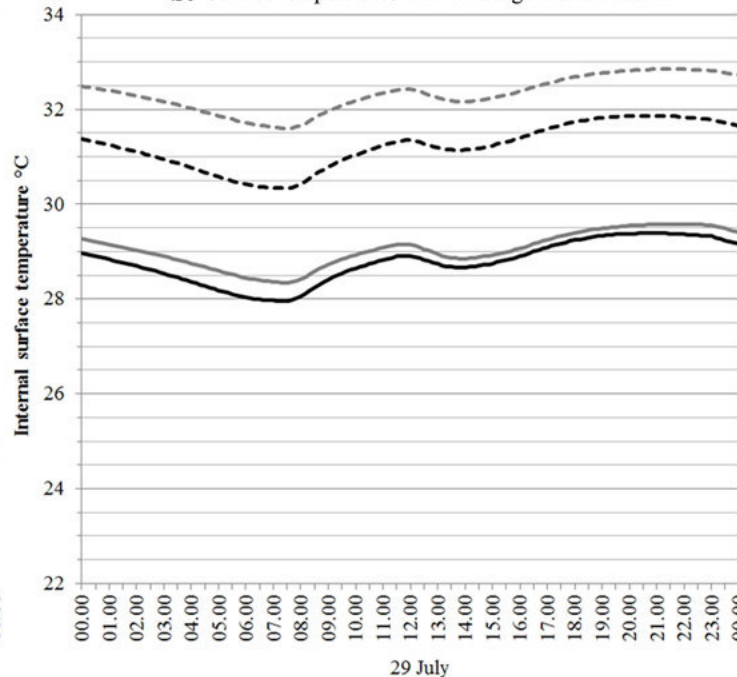
Internal surface temp. Heavy masonry (Ground floor)

External surface temp. Light masonry (First floor)

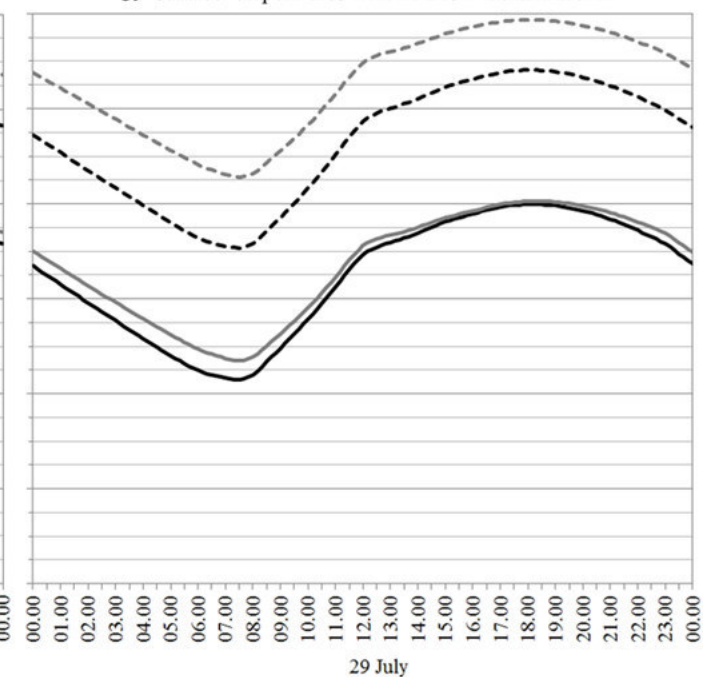
Mean air temp. Lightweight masonry (First floor)

**a.** Ground floor air temperatures

External air temperature  
 Opened windows and "as built" ground floor  
 Closed windows and "as built" ground floor

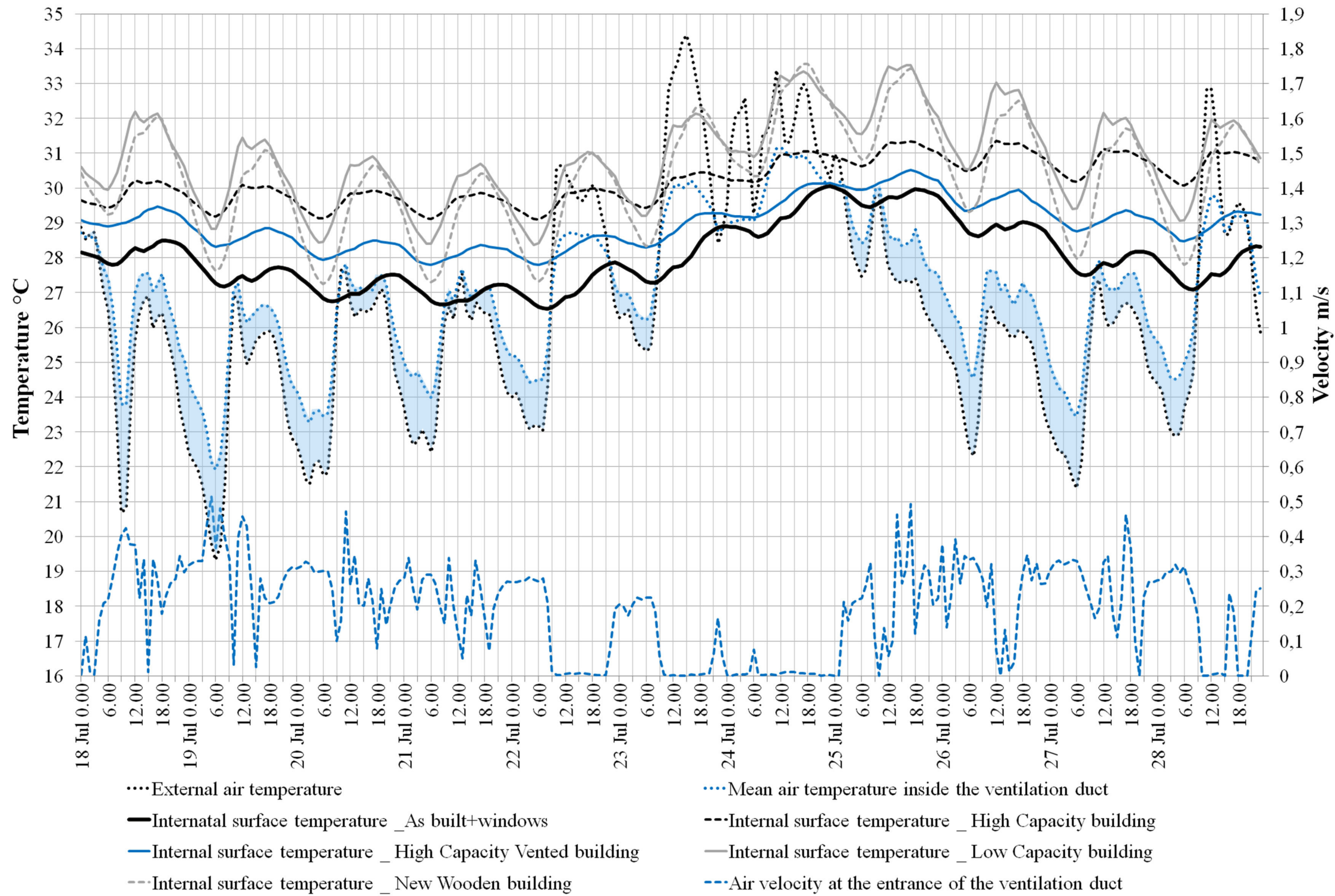
**b.** Surface temperatures wall with high thermal inertia

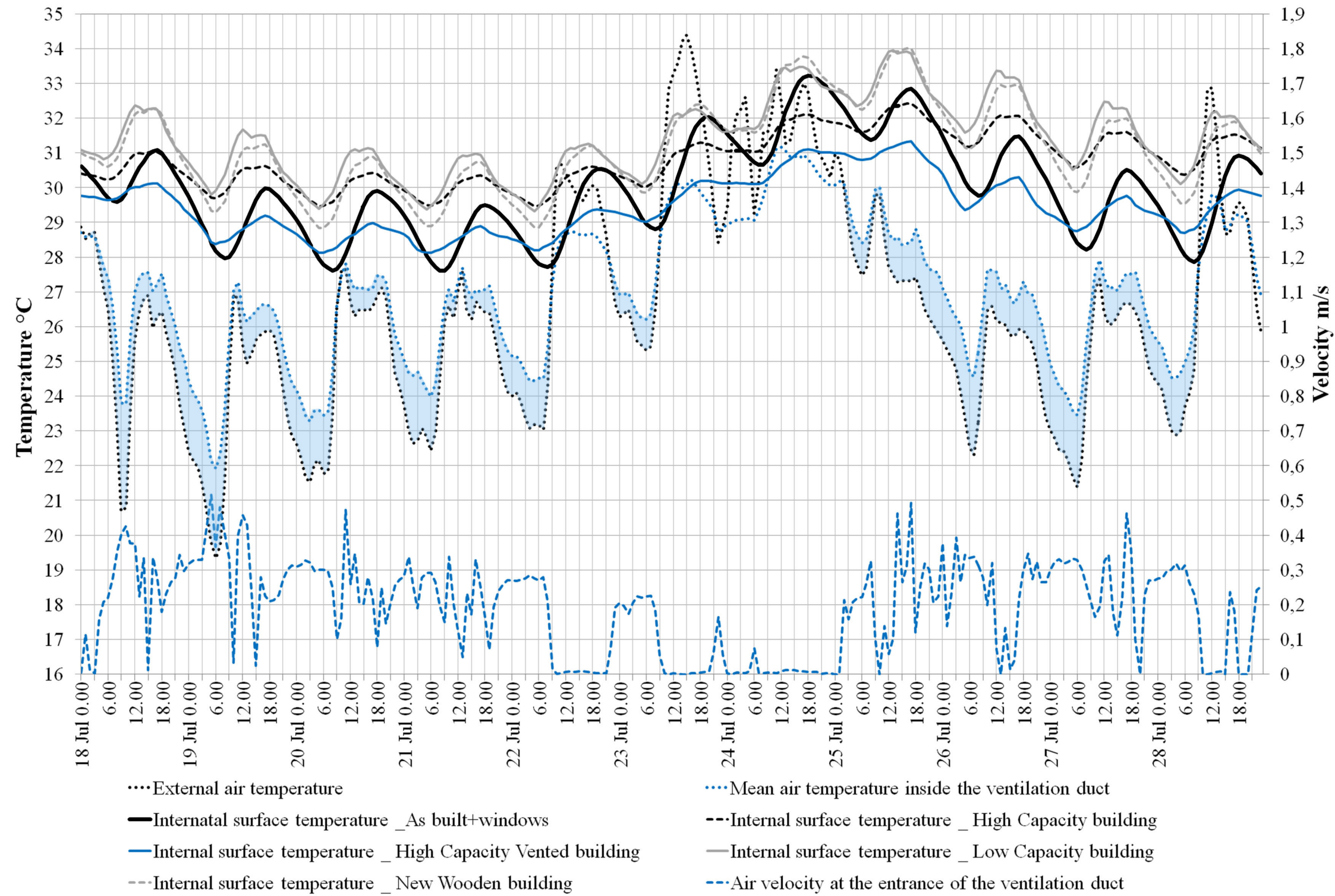
Opened windows and 'as built' ground floor  
 Closed windows and 'as built' ground floor

**c.** Surface temperatures wall with low thermal inertia

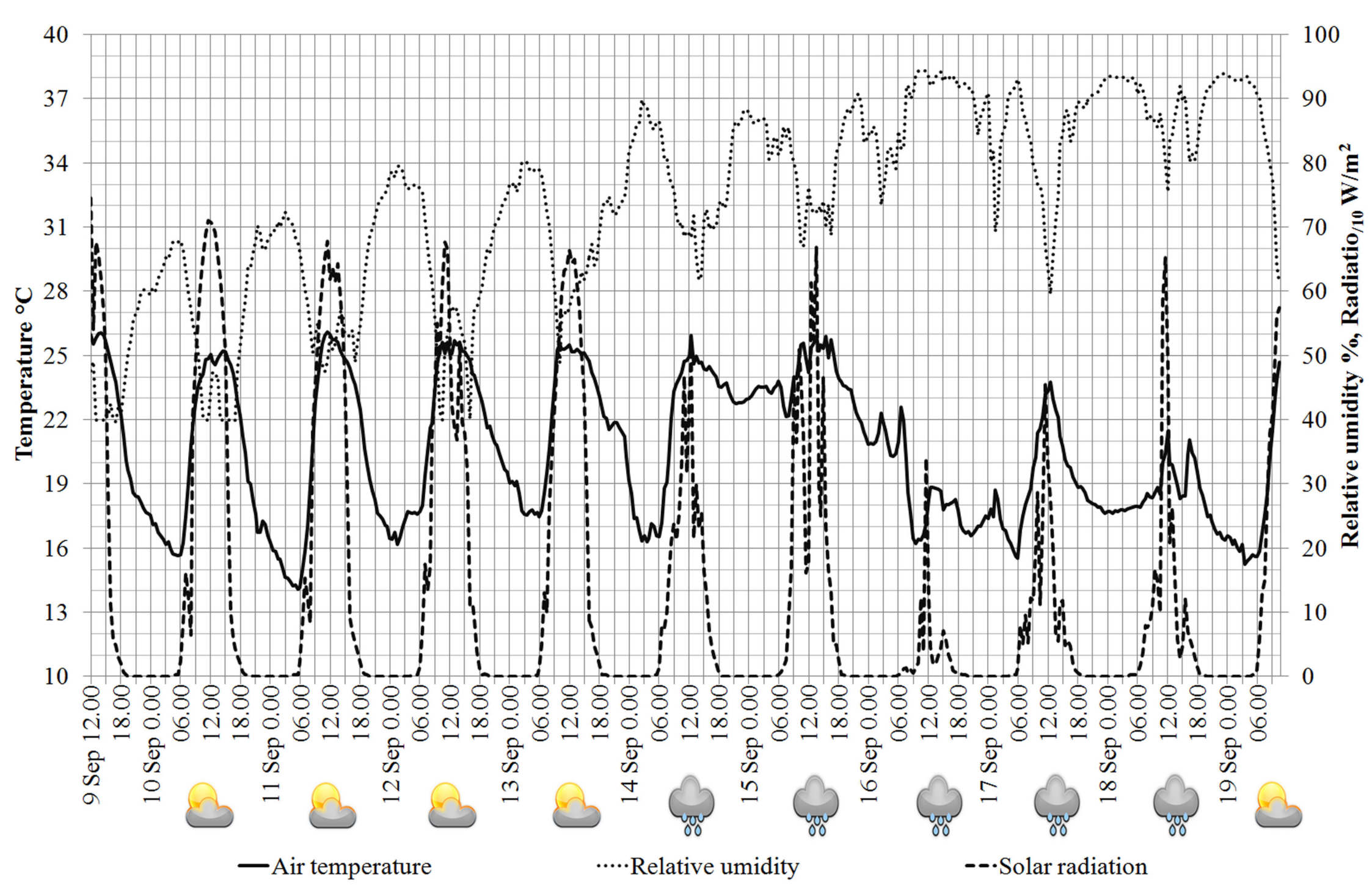
Opened windows and adiabatic ground floor  
 Closed windows and adiabatic ground floor

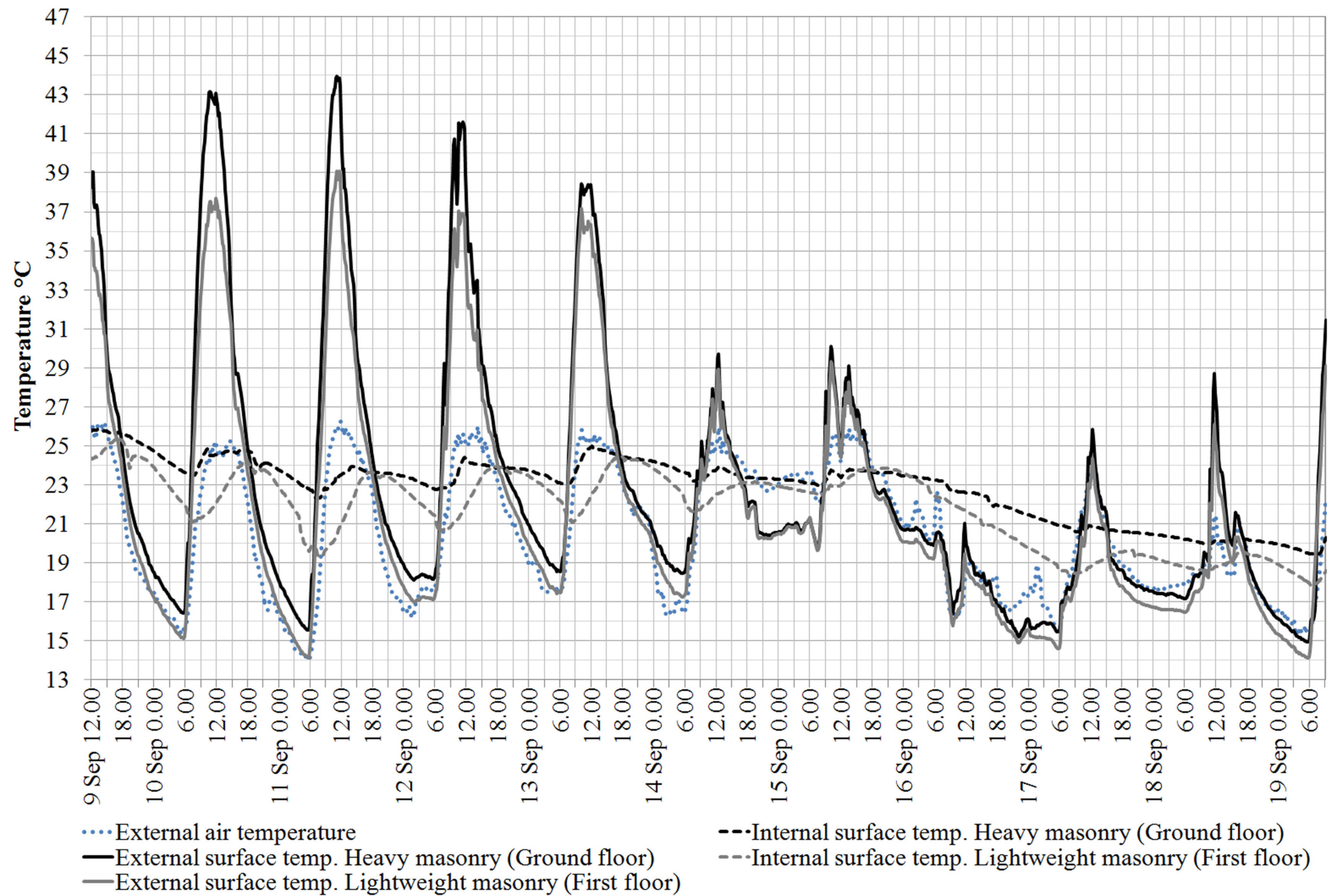




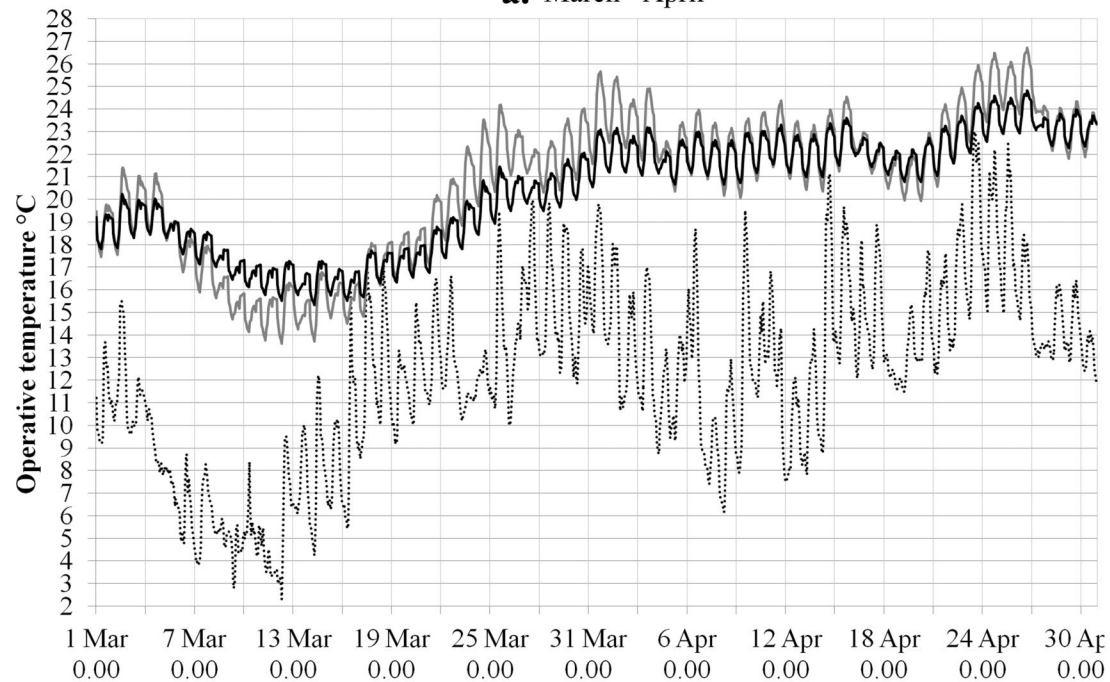




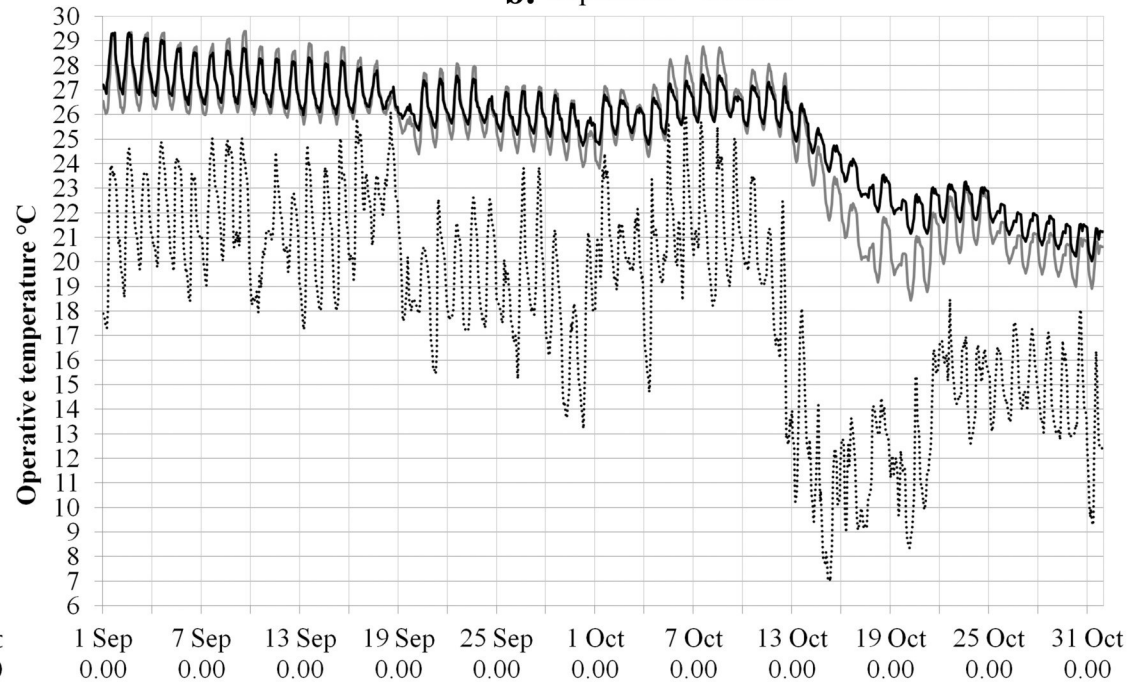




**a.** March - April

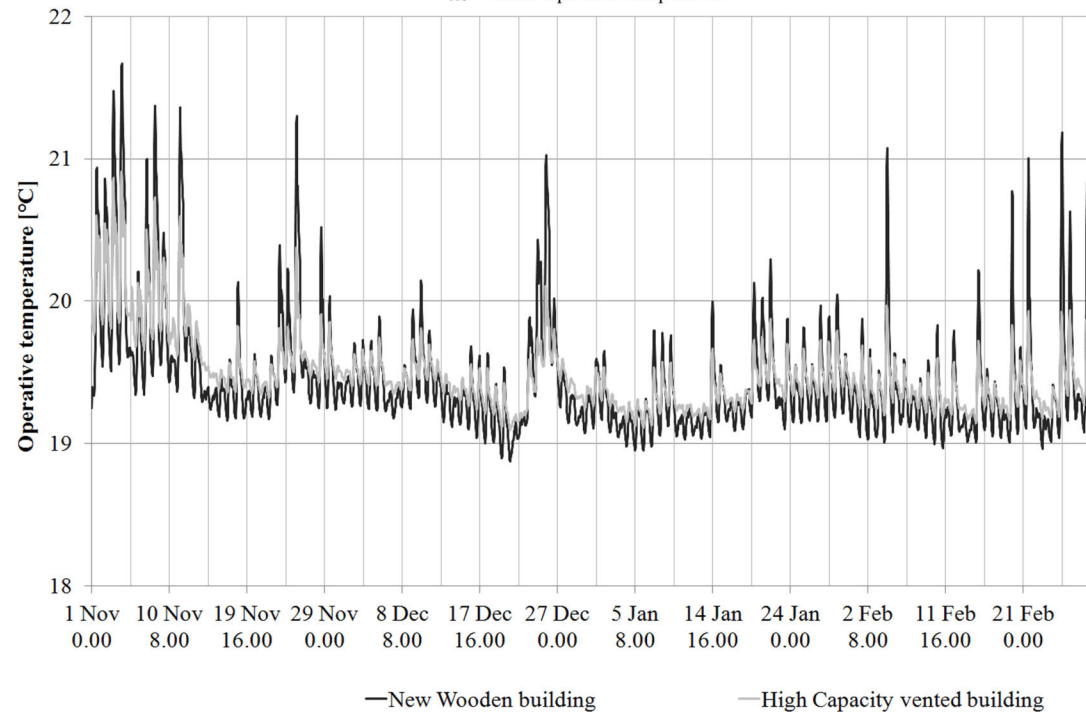


**b.** September - October

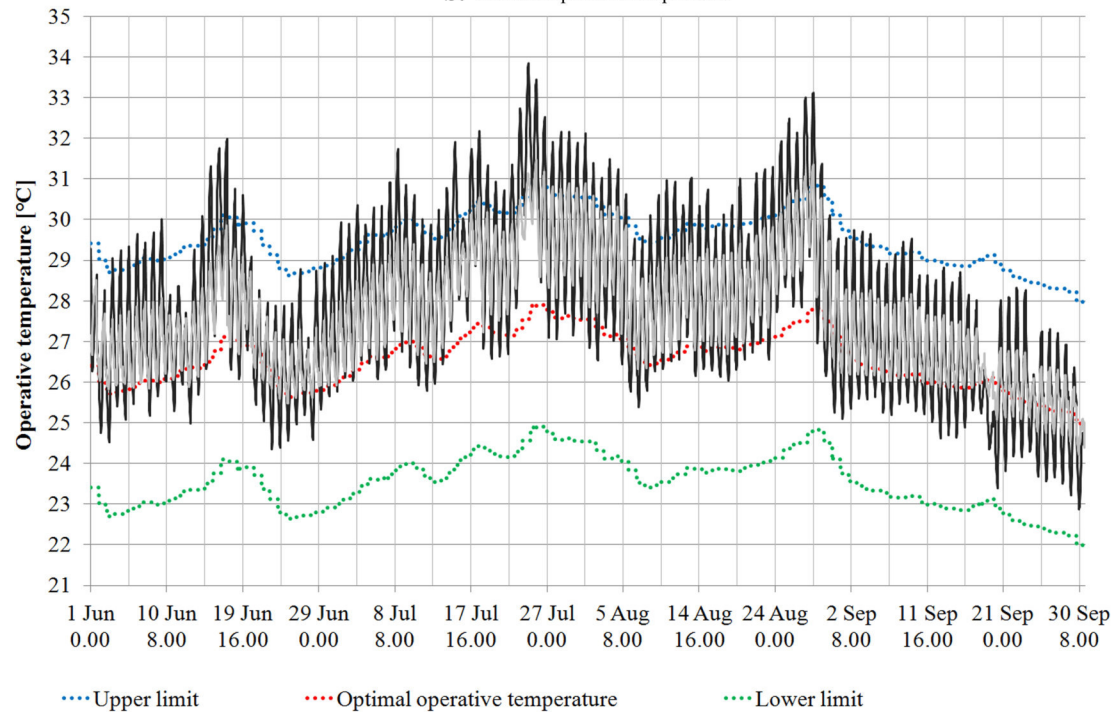


.....External air temperature    —Low Capacity building    —High Capacity building

**a.** Winter operative temperature



**b.** Summer operative temperature





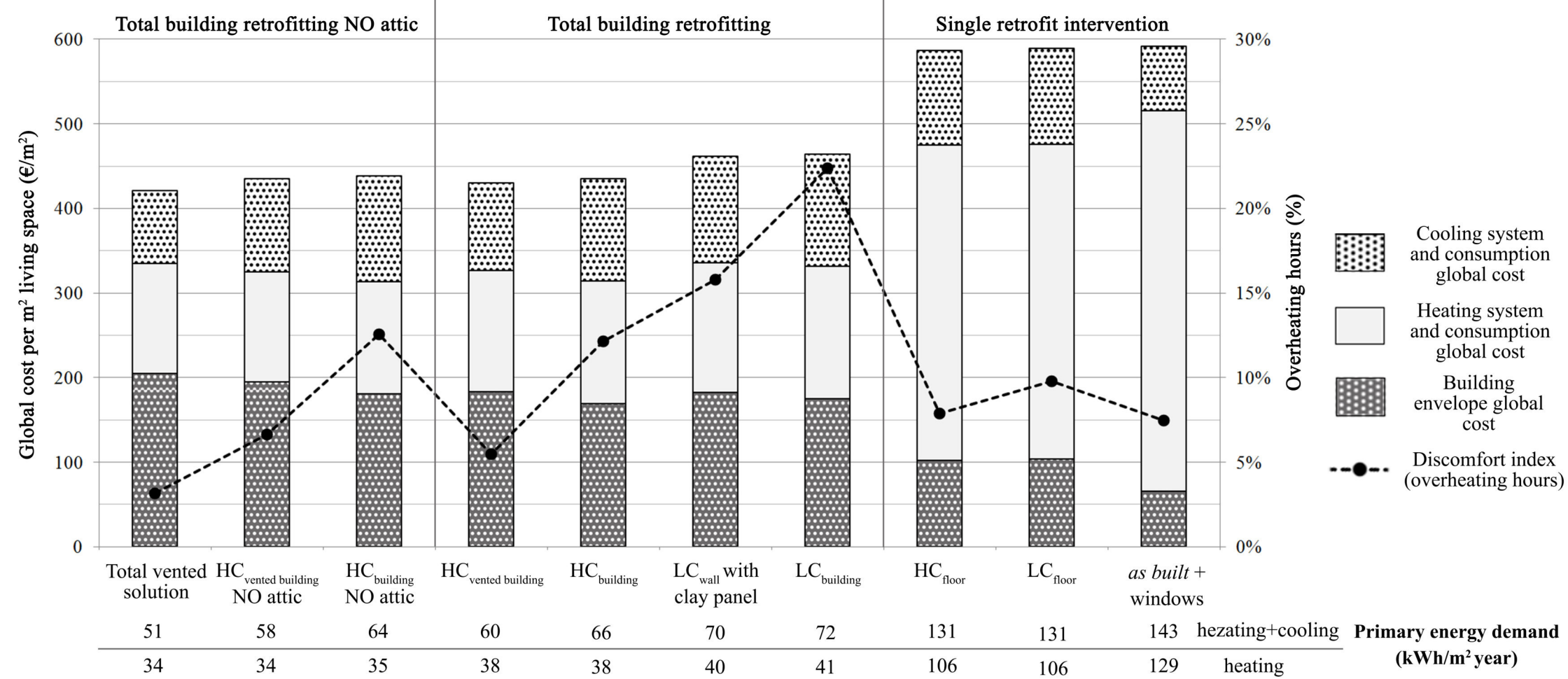


Table 1. Thermal characteristics of each studied envelope.

	STANDARD [39] / SUGGESTED [22] limits	SCHEME 0	SCHEME 1 and 2		SCHEME 3
		As built Ground floor ( <b>G<sub>0</sub></b> )	High Capacity Ground floor ( <b>HC<sub>ground</sub></b> )	Low Capacity Ground floor ( <b>LC<sub>ground</sub></b> )	New Wooden building Ground floor ( <b>NW<sub>ground</sub></b> )
Ground floor		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 <sup>2</sup> K)	0.34	1.44	0.3	0.3	0.30
Periodic thermal transmittance $Y_{ie}$ (W/m <sup>2</sup> K)	< 0.20	0.19	0.01	0.01	0.01
Internal areal heat capacity $kI$ (kJ/m <sup>2</sup> K)	Suggested $\geq 50$	62	62	41	30
		As built Roof ( <b>R<sub>0</sub></b> )	High Capacity Roof ( <b>HC<sub>roof</sub></b> )	Low Capacity Roof ( <b>LC<sub>roof</sub></b> )	New Wooden building Roof ( <b>NW<sub>roof</sub></b> )
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) <sup>d</sup> 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 <sup>2</sup> K)	0.26	1.91	0.24 (0.23) <sup>d</sup>	0.24	0.24
Periodic thermal transmittance $Y_{ie}$ (W/m <sup>2</sup> K)	< 0.20	0.90	0.03	0.03	0.02
Internal areal heat capacity $kI$ (kJ/m <sup>2</sup> K)	Suggested $\geq 50$	75	66	20	17
		As built Wall ( <b>W<sub>0</sub></b> )	High Capacity Wall ( <b>HC<sub>wall</sub></b> )	Low Capacity Wall ( <b>LC<sub>wall</sub></b> )	New Wooden building Wall ( <b>NW<sub>wall</sub></b> )
Wall		External plaster 1.5 cm Solid brick 42 cm <sup>a</sup> (Semisolid brick 25 cm) <sup>b</sup> Internal plaster 1.5 cm	External plaster coating 0.5 cm EPS insulation 12 cm (Ventilated cavity 8 cm) <sup>c</sup> 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) <sup>c</sup>	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 <sup>2</sup> K)	0.29	1.35 <sup>a</sup> (1.11) <sup>b</sup>	0.25 (0.24) <sup>c</sup>	0.25	0.25
Periodic thermal transmittance $Y_{ie}$ (W/m <sup>2</sup> K)	< 0.12	0.18 <sup>a</sup> (0.42) <sup>b</sup>	0.01	0.01	0.03
Internal areal heat capacity $kI$ (kJ/m <sup>2</sup> K)	Suggested $\geq 50$	66 <sup>a</sup> (58) <sup>b</sup>	63	16 (30) <sup>c</sup>	26

<sup>a</sup>, <sup>b</sup> <sup>a</sup> correspond to the as built wall at the ground floor, <sup>b</sup> correspond to the as built wall at the first floor<sup>b</sup> Introduction of a ventilated layer behind the external roof insulation: High Capacity Vented Wall (Scheme 4)<sup>c</sup> Introduction of a ventilated layer behind the external wall insulation: High Capacity Vented Wall (Scheme 2b)<sup>c</sup> Introduction of a inner massive finish (Scheme 5)

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

	$\lambda$ [W/mK]	$c$ [J/kgK]	$\rho$ [kg/m <sup>3</sup> ]
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
<i>as built</i>	WWR 7% $U \approx 5 \text{ W/m}^2\text{K}$		$G_0$	$R_0$	$W_0$
<b>SCHEME 0</b>	WWR 9% $U \approx 2 \text{ W/m}^2\text{K}$		$G_0$	$R_0$	$W_0$
<b>SCHEME 1</b>	WWR 9% $U \approx 2 \text{ W/m}^2\text{K}$	a.	High ( $HC_{\text{ground}}$ )	High ( $HC_{\text{roof}}$ )	$W_0$
		b.	Low ( $LC_{\text{ground}}$ )	Low ( $LC_{\text{roof}}$ )	$W_0$
<b>SCHEME 2</b>	WWR 9% $U \approx 2 \text{ W/m}^2\text{K}$	a.	High ( $HC_{\text{ground}}$ )	High ( $HC_{\text{roof}}$ )	High ( $HC_{\text{wall}}$ )
		b.	High ( $HC_{\text{ground}}$ )	High ( $HC_{\text{roof}}$ )	Vented ( $HC_{\text{vented wall}}$ )
		c.	Low ( $LC_{\text{ground}}$ )	Low ( $LC_{\text{roof}}$ )	Low ( $LC_{\text{wall}}$ )
<b>SCHEME 3</b>	WWR 9% $U \approx 2 \text{ W/m}^2\text{K}$		Wood	Wood	Wood
<b>SCHEME 4</b>	WWR 9% $U \approx 2 \text{ W/m}^2\text{K}$		Low ( $LC_{\text{ground}}$ )	Low ( $LC_{\text{roof}}$ )	High (Massive inner finish)
<b>SCHEME 5</b>	WWR 9% $U \approx 2 \text{ W/m}^2\text{K}$		High ( $HC_{\text{ground}}$ )	Vented ( $HC_{\text{vented roof}}$ )	Vented ( $HC_{\text{vented wall}}$ )



Table 4. Input data for the economic analysis.

INPUT DATA				
Parameter	Value		Comments/Source	
Starting year for calculation	2013			
Calculation period	30 years		according to Annex I of EU regulation	
Interest rate	4%		real	
ASSUMED LIFETIMES OF BUILDING ELEMENTS				
Parameter	Value		Comments/Source	
Insulation (thermal protection)	50 years			
Window	30 years		UNI EN 15459 [46]	
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 [€/m²] (VAT excluded)				
Ground floor	HC <sub>floor</sub> and LC <sub>floor</sub> : 22.43			
Roof	HC <sub>roof</sub> : 39.33		HC <sub>vented roof</sub> : 53.76	LC <sub>roof</sub> : 42.22
Wall	HC <sub>wall</sub> : 53.12	HC <sub>vented wall</sub> : 67.26	LC <sub>wall</sub> : 48.78	LC <sub>wall with clay panel</sub> : 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 <sub>I</sub>	C <sub>m</sub>	C <sub>o</sub>	V <sub>f</sub>	C <sub>I</sub>	C <sub>m</sub>	C <sub>o</sub>	V <sub>f</sub>	C <sub>I</sub>	C <sub>m</sub>	C <sub>o</sub>	V <sub>f</sub>
<b>SCHEME 0</b>		12,791	3,944	-	-3,944	1,827	2,447	84,499	-1,127	3,200	2,722	9,638	-789
<b>SCHEME 1</b>	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
<b>SCHEME 2</b>	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
<b>SCHEME 4</b>		43,347	3,944	-	-7,397	1,827	2,447	22,114	-1,127	3,200	2,722	13,608	-789
<b>SCHEME 5</b>		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
	<i>as built</i>	0	128	378	83
<b>SCHEME 0</b>	<i>as built</i> + windows	0	144	246	75
<b>SCHEME 1</b>	HC <sub>floor</sub>	130	227	0	4
	LC <sub>floor</sub>	183	281	4	6
<b>SCHEME 2</b>	HC <sub>building</sub>	193	356	0	0
	HC <sub>vented building</sub>	85	160	0	0
	LC <sub>building</sub>	542	655	0	0
<b>SCHEME 3</b>	NW <sub>building</sub>	428	518	0	0
<b>SCHEME 4</b>	Inner massive finish	329	463	0	0
<b>SCHEME 5</b>	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	Intermittent heating energy consumption (6:00-10:00, 12:00-16:00, 18:00-22:00)	Continuous cooling energy consumption
		(kW <sub>p</sub> /m <sup>2</sup> year)	(kW <sub>p</sub> /m <sup>2</sup> year)	(kW <sub>p</sub> /m <sup>2</sup> year)
	<i>"as built"</i>	138.62	102.88	14.18
<b>SCHEME 0</b>	<i>"as built"</i> + windows	128.71	95.95	14.57
<b>SCHEME 1</b>	HC <sub>floor</sub>	105.93	81.07	25.15
	LC <sub>floor</sub>	105.47	80.82	25.77
<b>SCHEME 2</b>	HC <sub>building</sub>	38.31	30.93	27.86
	HC <sub>vented building</sub>	37.67	30.35	22.19
	LC <sub>building</sub>	41.22	33.34	30.69
<b>SCHEME 3</b>	NW <sub>building</sub>	40.79	32.42	24.89
<b>SCHEME 4</b>	Inner massive finish	40.33	32.61	28.18
<b>SCHEME 5</b>	Totally vented solution	33.69	27.41	17.30