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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

2 The energy saving regulations developed on the last years have focused their attention on the problem of
3 heating consumption reduction (common to all European countries) without considering that in hot summer
4 Mediterranean climates the predominant need is to guarantee comfort during the warm period.
5 That has brought, even in warmer countries as in Italy, the imposition of transmittance limit values,
6 stationary or periodic parameter. So, even in such climates, lightweight and super-insulated building
7 envelopes have been adopted in new constructions. Moreover, in existing buildings retrofit considerable
8 thicknesses of insulation layer were placed either on the external or internal side of the wall, regardless of the
9 relative position between mass and thermal insulation. However many authors have already shown that
10 different insulation-mass configurations differently impact on both heating - cooling consumptions and
11 indoor comfort with a different and often opposite effect on the various aspects. The optimal stratigraphy
12 varies based on the considered operational conditions (intermittent use [1], continuous use [2]), climate
13 (extreme climate or with variable temperature range [3]) and the specific analysed aspect between energy
14 efficiency [4, 5], comfort [6-8] or costs [9, 10].

15 So that the better choice identification is still an open question and it could result to be with internal
16 insulation (in studies focused on winter performance [1, 11]), external insulation (in studies focused on
17 summer performance [2, 12-16]), insulation placed on both sides of the wall [1, 9, 17, 18]. Very rarely
18 studies have been performed on a multidisciplinary simultaneous evaluation of the different aspects.
19 Focusing on the summer comfort optimization is established in literature that high thicknesses insulation
20 layers, imposed by energy savings standards, whatever their position, act as a thermal barriers avoiding the
21 heat loss with overheating risks, demonstrating the important role of the thermal mass in all climate [19, 20 -
22 22]. In hot summer Mediterranean climate building envelopes with heavy “storing” masses that dynamically
23 adapt to seasonal variations was found to be preferable. The traditional architectures are an example of a
24 very close relationship with the specific climate because they have dynamically adapted to the external
25 environment without the use of the systems but through the adoption of passive strategies such as high
26 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 $43^{\circ} 27'$, longitude $13^{\circ} 37'$), 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/m²;

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 ($U \leq 2W/m^2K$ [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 τ and
 197 it can be written as:

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

199 where: $C_G(\tau)$ represents the global cost referred to starting year τ_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 τ_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°C
284 when the windows are open (black dotted line) and an overheating until to 3.5°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

396 improvement of the thermal performance of the existing glazed surface. The same phenomenon, however,
397 causes a slight increase in summer consumption.

398 Compared to the previous scenario, the ground floor and roof slabs insulation (Scheme 1) reduces the winter
399 consumptions down to about 106 kWh/m²/year for a continuous system operation and to about 81
400 kWh/m²/year for intermittent use, regardless of the reciprocal position (external or internal) between the
401 insulation layer and the supporting structure. The further insulation of the walls (Scheme 2) results in a
402 significant reduction in primary energy winter consumption by placing the insulation on the outer side, with
403 almost similar performance between the traditional insulating system and the vented one. The latter solution
404 is slightly better because of the higher thermal resistance due to the addition of a (not vented in winter
405 period) air cavity.

406 Compared to these two interventions the low inertia retrofit and the wooden technology have higher
407 consumptions (both around 41 kWh/m²/year for continuous ignition and 33 kWh/m²/year for intermittent
408 ignition).

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

412 The analysis of summer consumptions shows that the insulation interventions proposed in Scheme 1 and 2
413 (insulation of windows, roof, ground floor, walls) worsens the "as built" condition in all studied
414 configurations. In this season, the benefit of adopting a ventilated solution respect to a traditional insulation
415 layer is higher than those observed in winter, since it allows a dynamic behaviour of the inner mass through
416 the ventilation of the internal gap. Moreover, there are 8 kWh/m²/year difference between this preferable
417 vented solution and worst Low Capacity solution because the insulating layer placed on the inner side causes
418 overheating phenomena. The same problem does not seem to affect the lightweight wooden building that
419 presents consumption values more close to the ventilated insulation system.

420 The introduction of the inner massive finish reduces the summer consumption of internal insulated wall of
421 about 2 kWh/m²/year (from 30 to 28) while the totally vented solution reduces the consumption down to 17
422 kWh/m²/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_{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

476 semisolid brick walls with low thermal inertia on the first floor. Moreover analytical variation were realized
477 to compare the two walls under the same boundary conditions.

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

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

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

494 The results proved that the introduction of an insulation layer on the internal side is the worst intervention
495 but, having to necessarily choose it to maintain the external aesthetic wall appearance, it is important to
496 adopt a massive finishing panel on the internal side. Moreover the results highlighted that the better solution
497 envisages the adoption of a ventilated envelope in order to alternatively maximize the thermal barrier effect
498 and the heat loss. In this way it is possible to resolve the conflicting requirements which are typical of
499 climates with both seasonal and daily high temperature ranges. For that reason an innovative (recently
500 patented) system was proposed. It is characterized by an external super insulation layer spaced from the
501 internal wall by an air gap that can be alternatively sealed in winter and ventilated in summer. The
502 combination of the proposed dynamic strategies (daily natural ventilation, inner mass, vented external wall)
503 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

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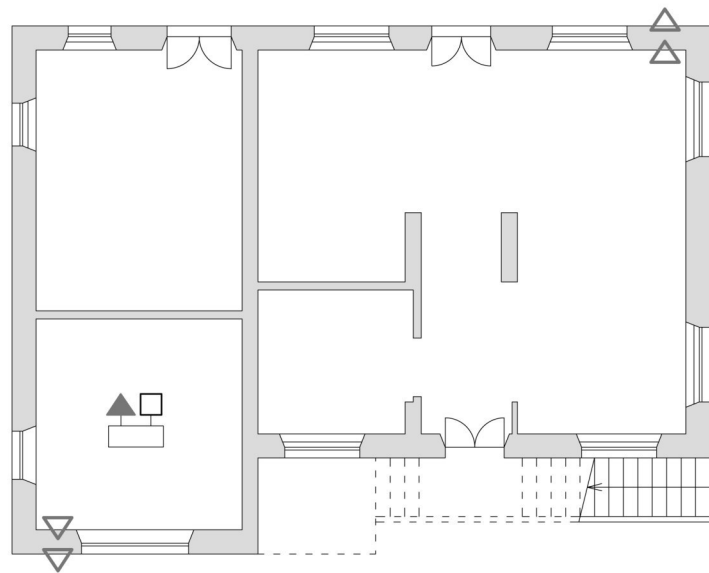
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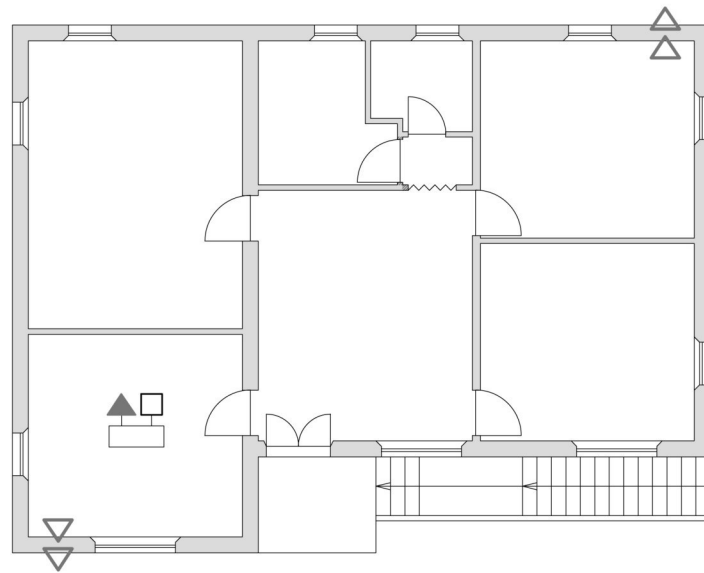
- Fig. 1. External view of the case study.
- Fig. 2. Plans indicating the measuring instruments.
- Fig. 3. Calibration of the simulation model by comparison with the measured data.
- Fig. 4. Construction details.
Climatic data recorded in the summer monitoring: air temperature, relative humidity and global solar radiation.
- 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



Ground floor



First floor



weather station



1 high-thermal sensor



2 wind speed and direction sensor



3 pyranometer



indoor station



air temperature

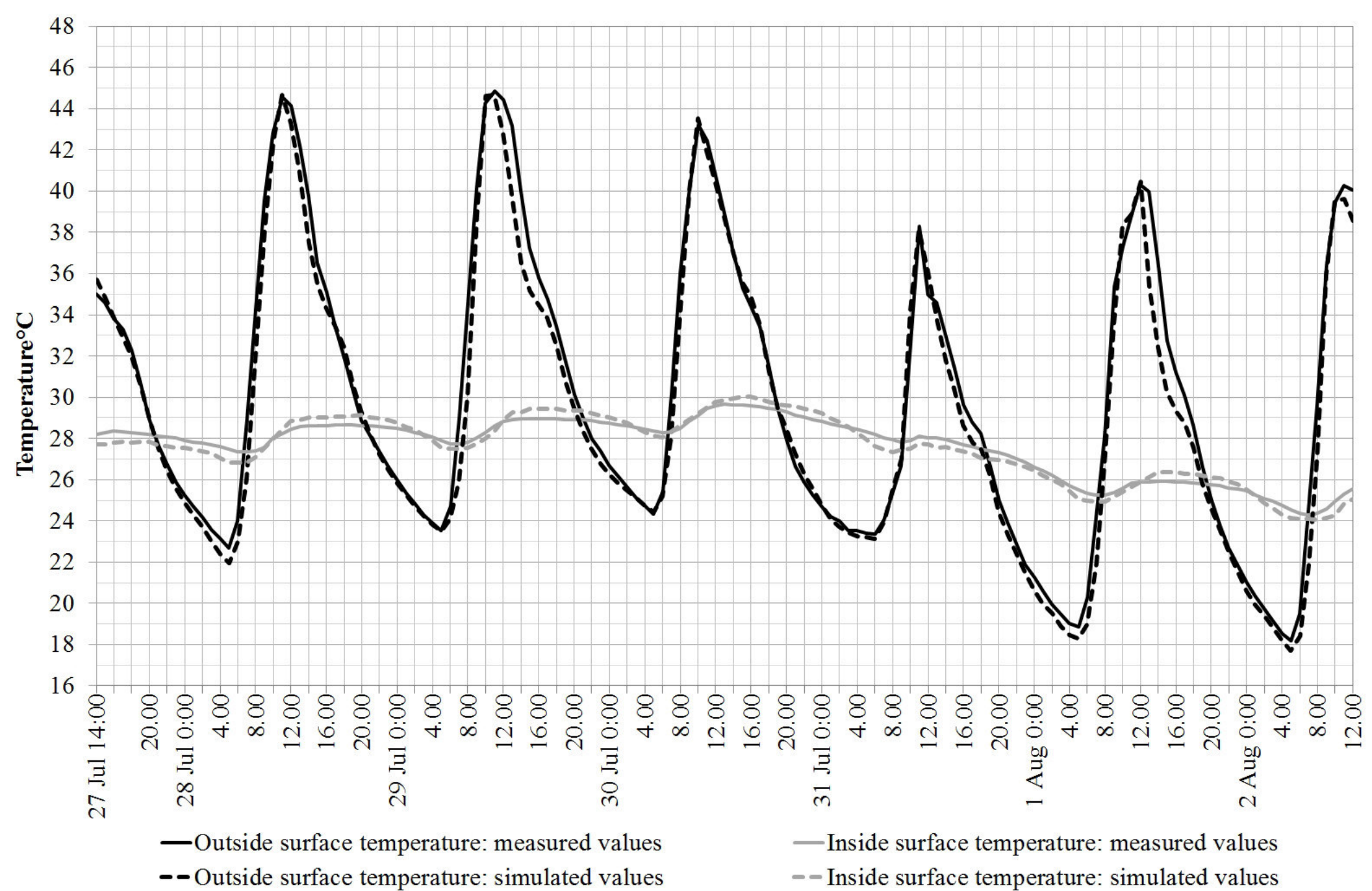


relative humidity



surface thermoresistance



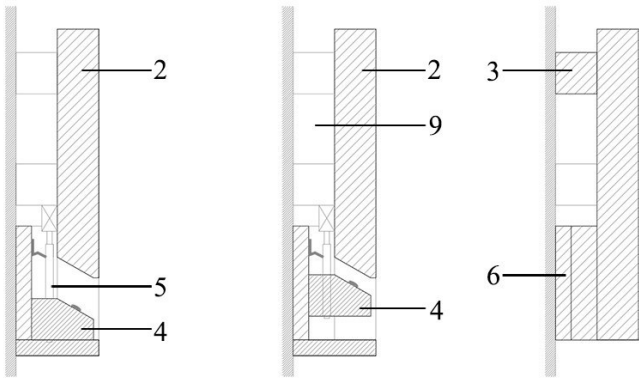
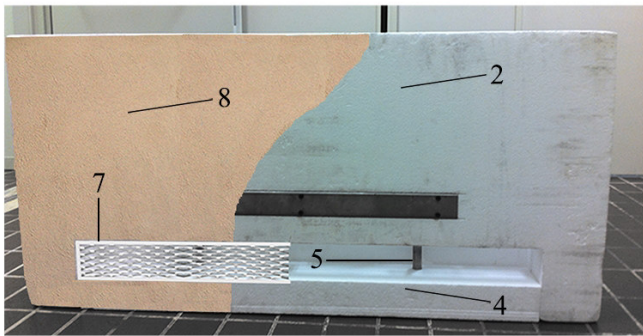
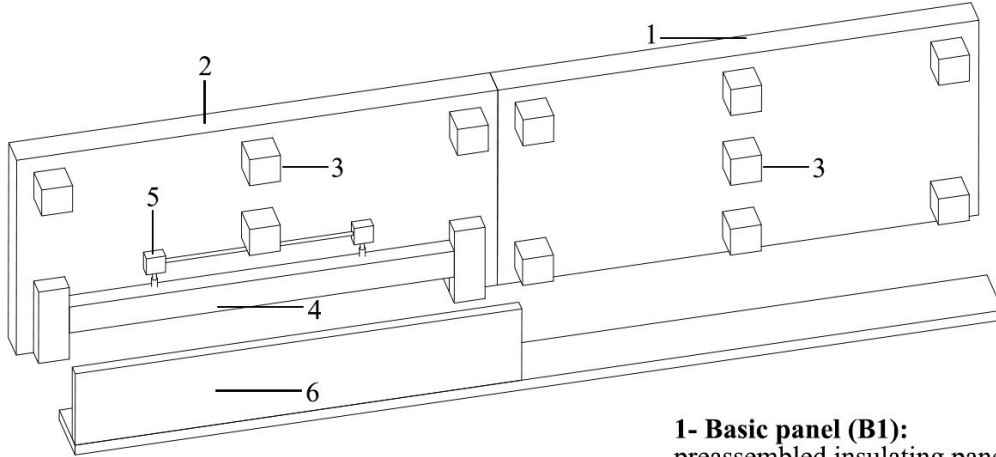


A - EXISTING SUPPORTING WALL



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: elements made by insulating material installed to create the ventilation duct.

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

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

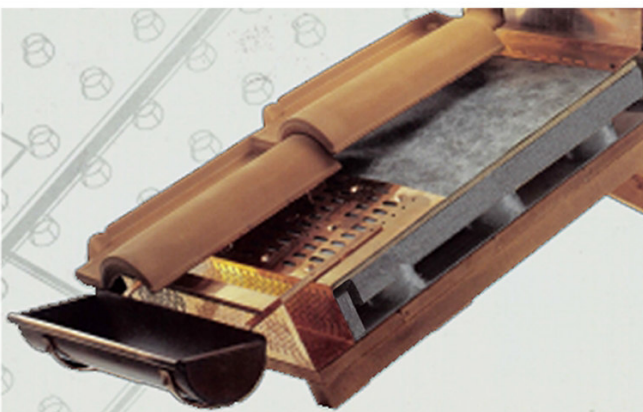
6- Thermal bridge correction

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

8- External plaster coating

9- Vented cavity

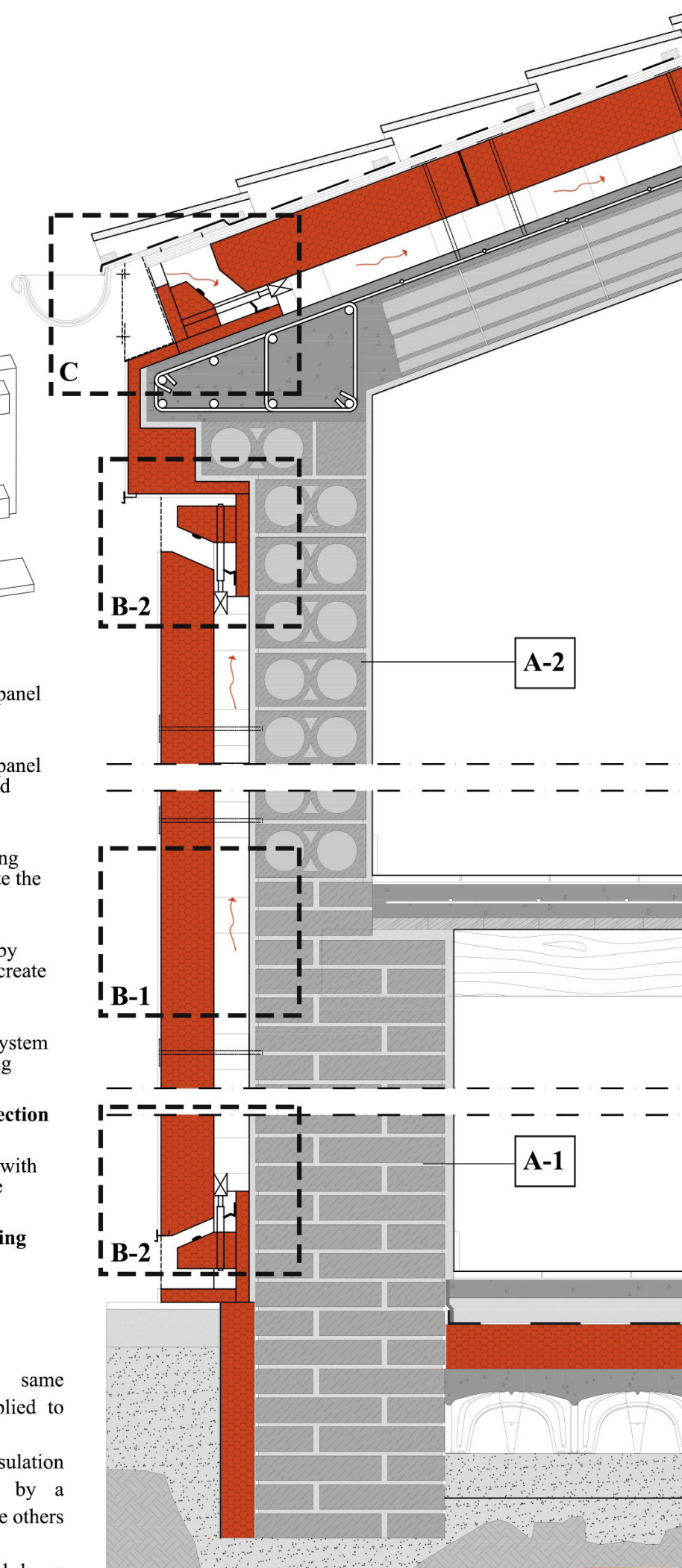
C - MUnStA® SYSTEM APPLIED TO THE ROOF



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

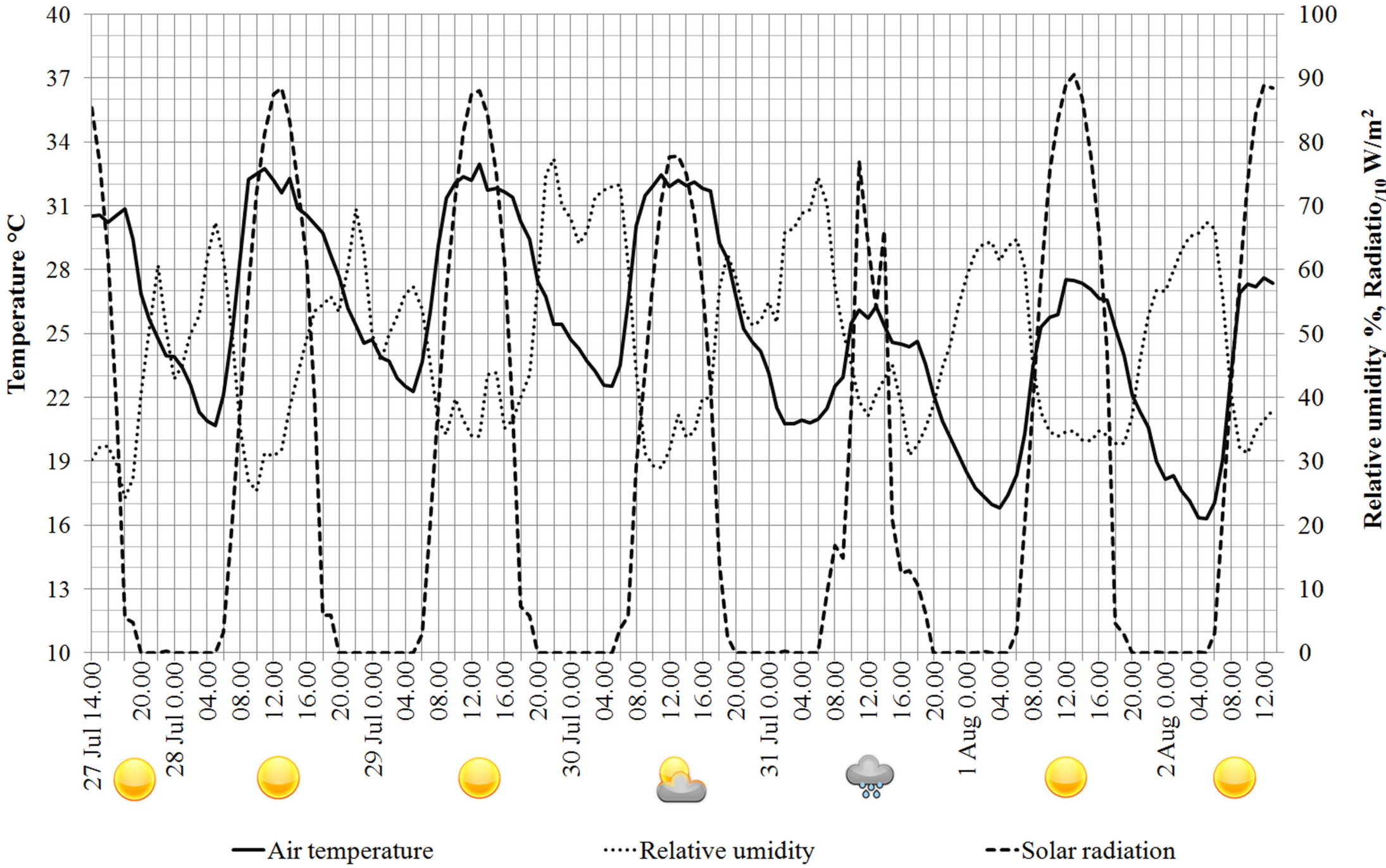
The outer side of the insulation panel will be covered by a waterproof layer and by the other necessary finishing layers.

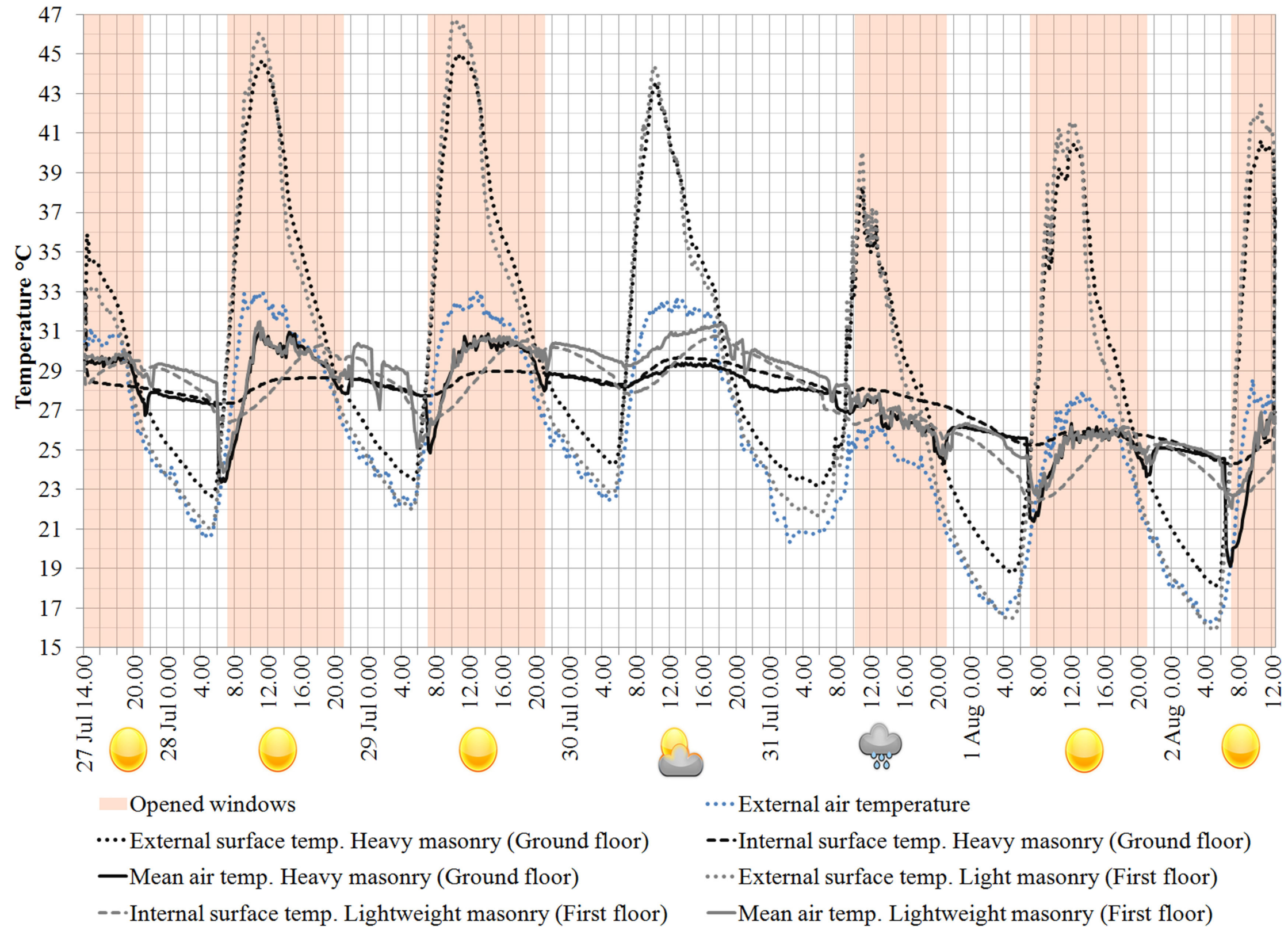
The system is completed by a gutter and perforated sheet which allows the air inlet to the ventilation duct.

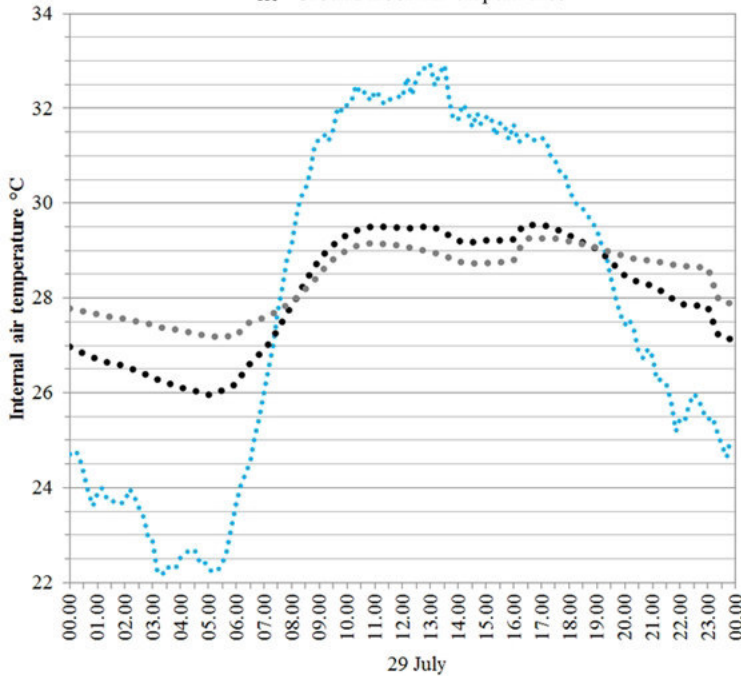
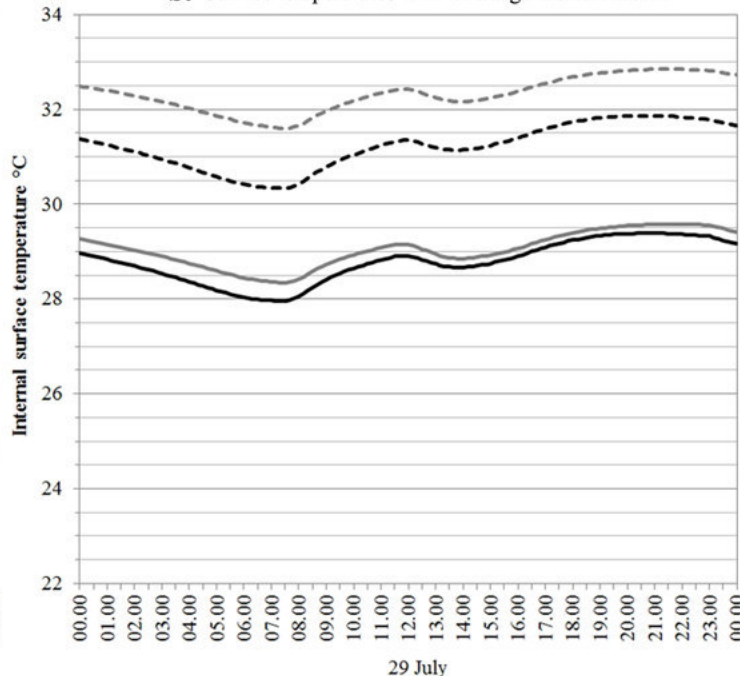
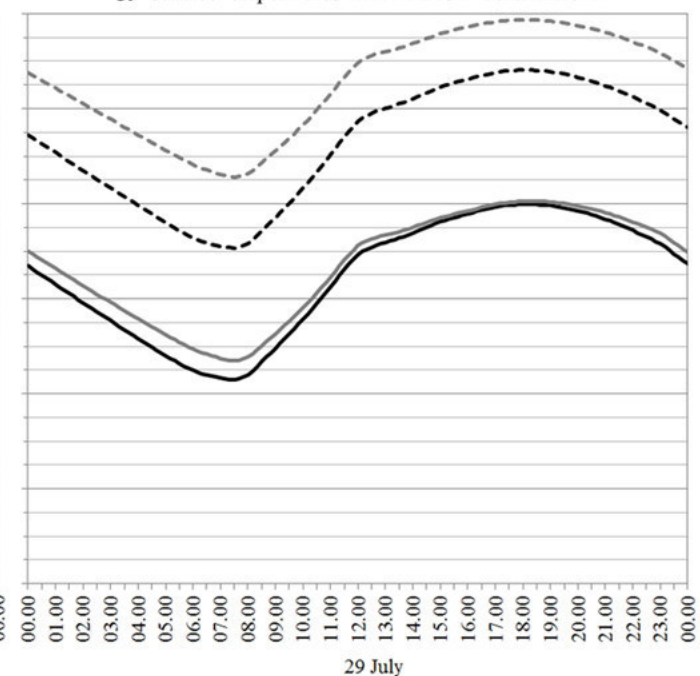


DINAMIC INSULATION
application to wall and roof



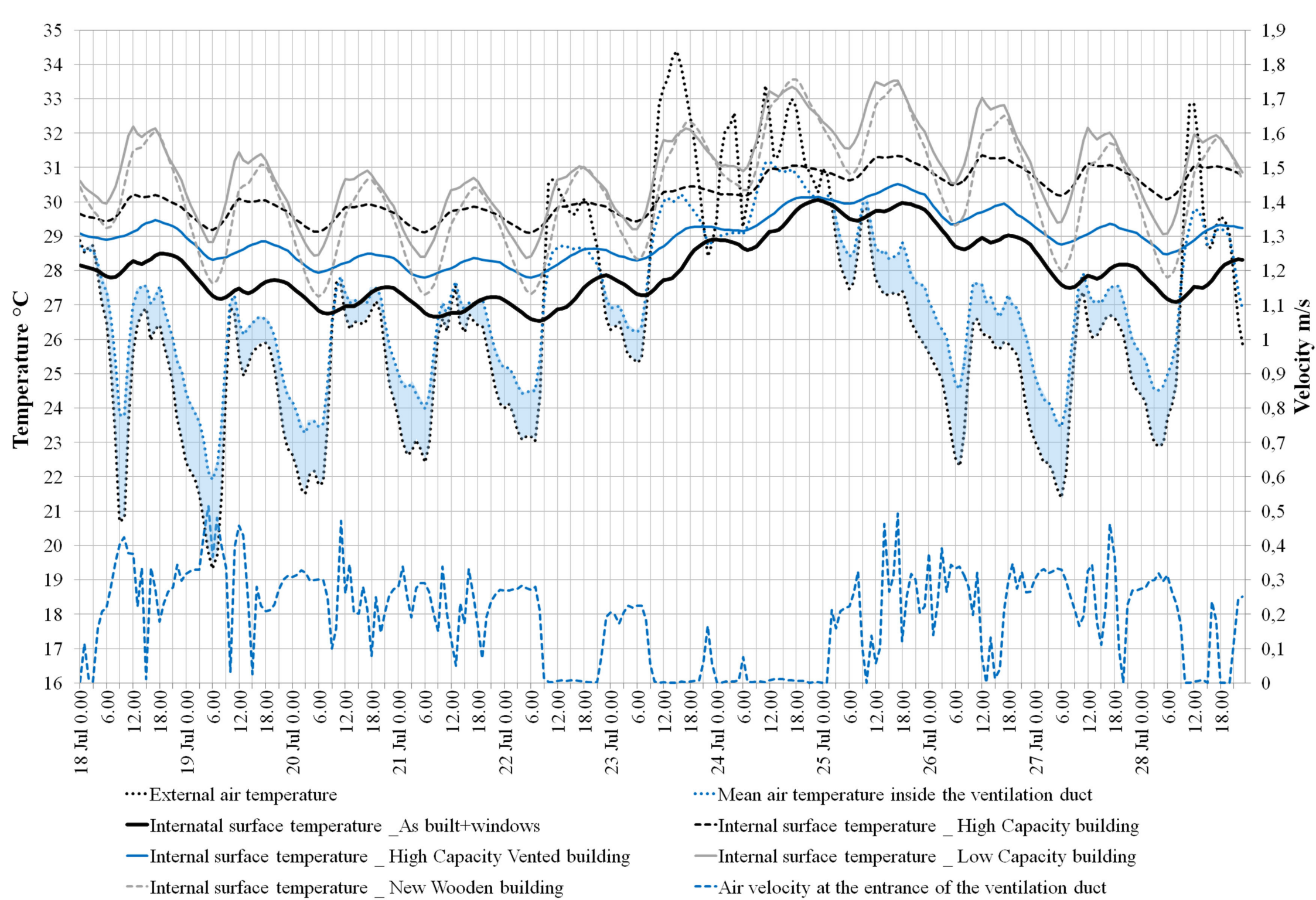


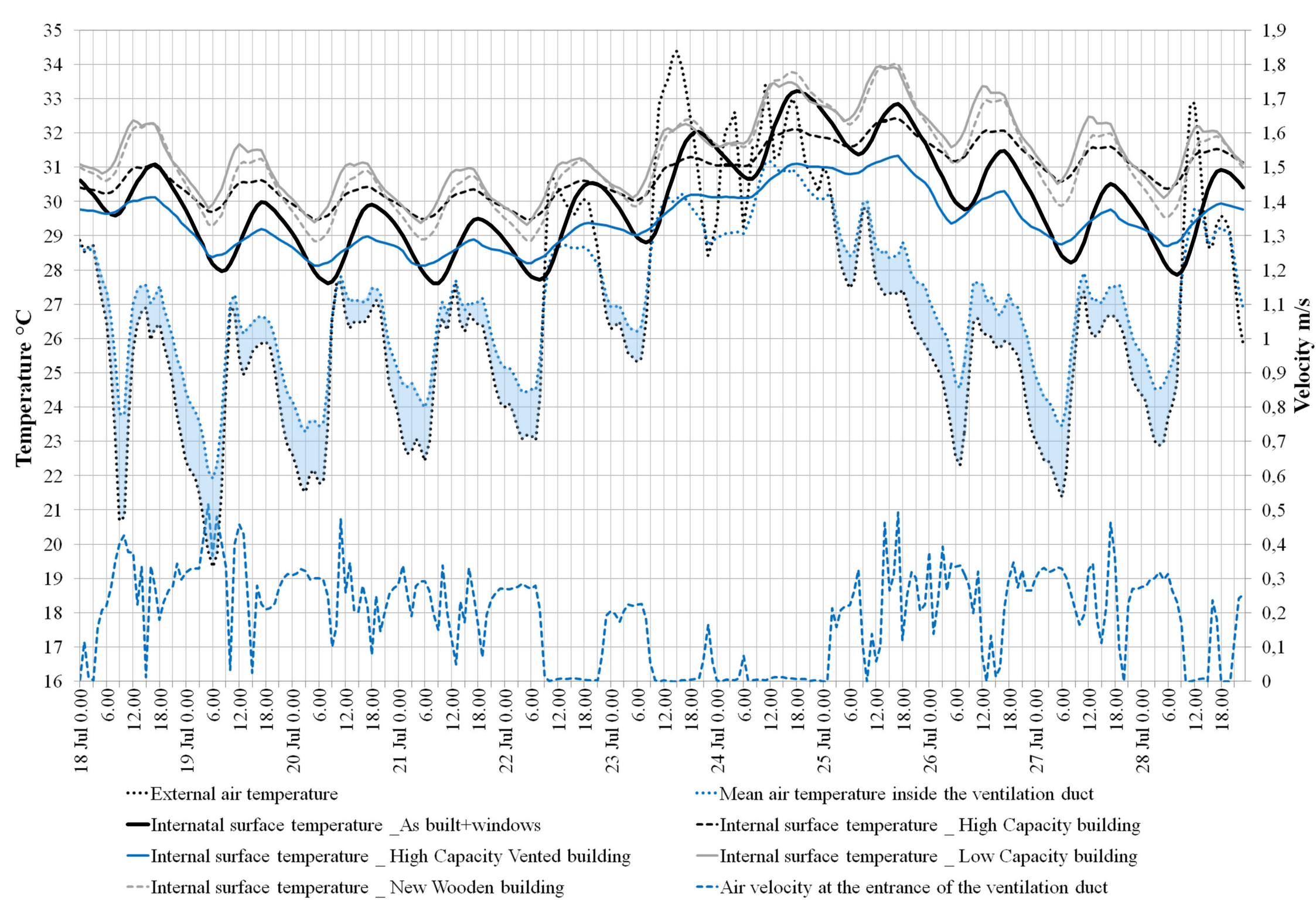


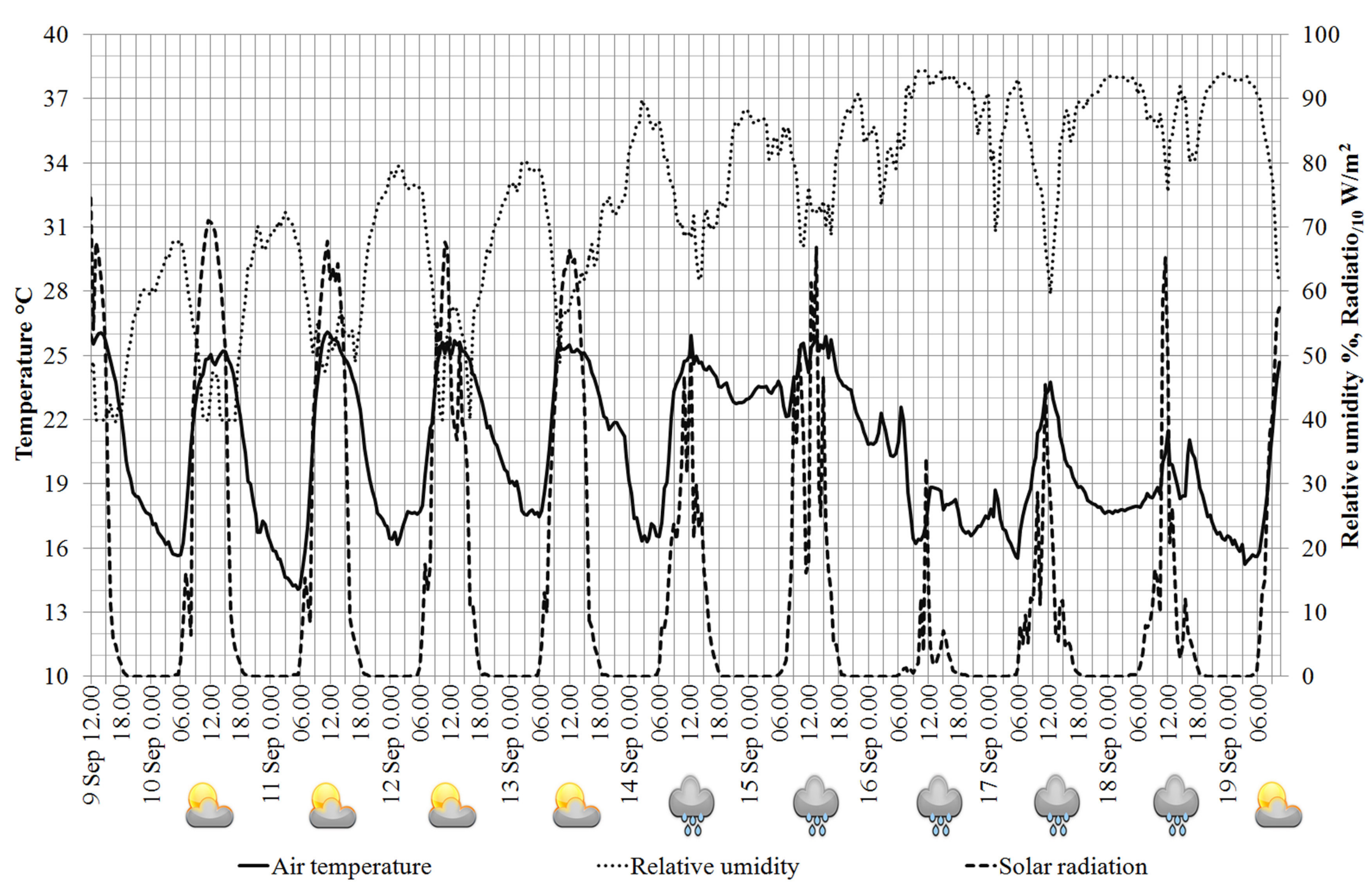
a. Ground floor air temperatures**b.** Surface temperatures wall with high thermal inertia**c.** Surface temperatures wall with low thermal inertia

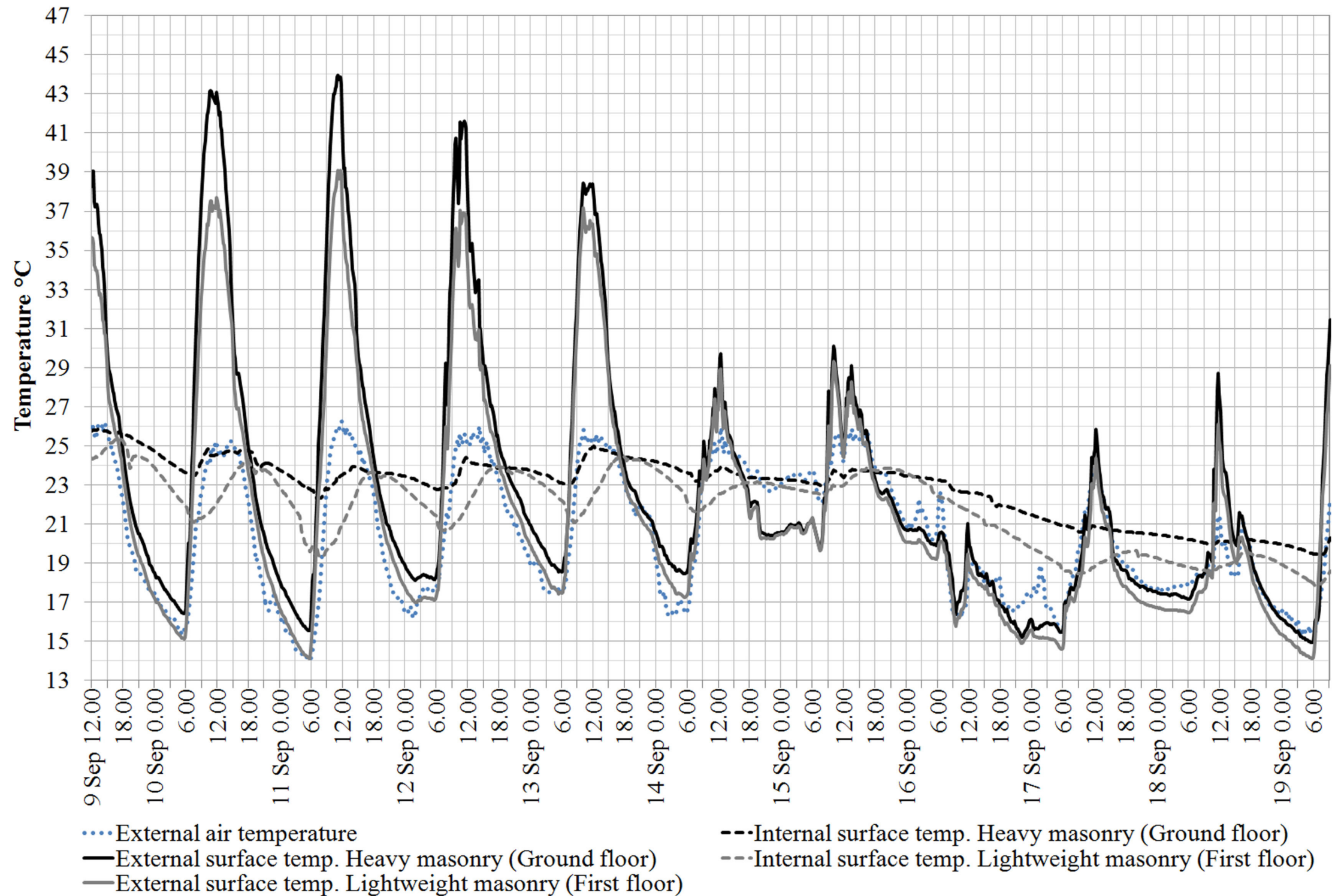
●●● External air temperature
 ●●● Opened windows and "as built" ground floor
 ●●● Closed windows and "as built" ground floor

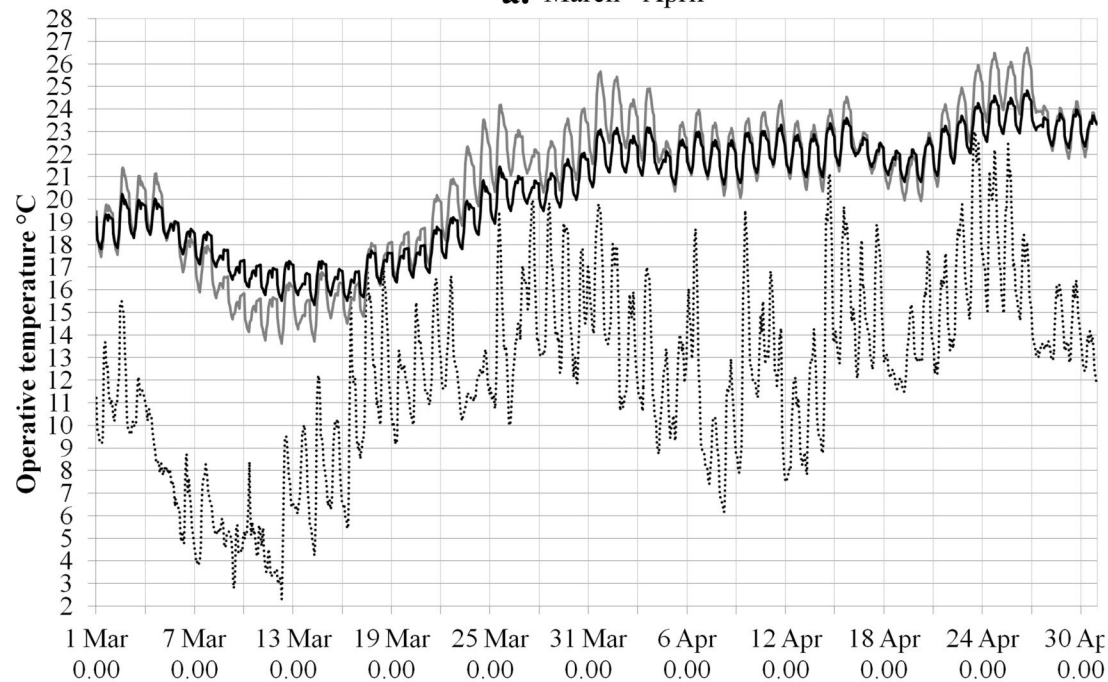
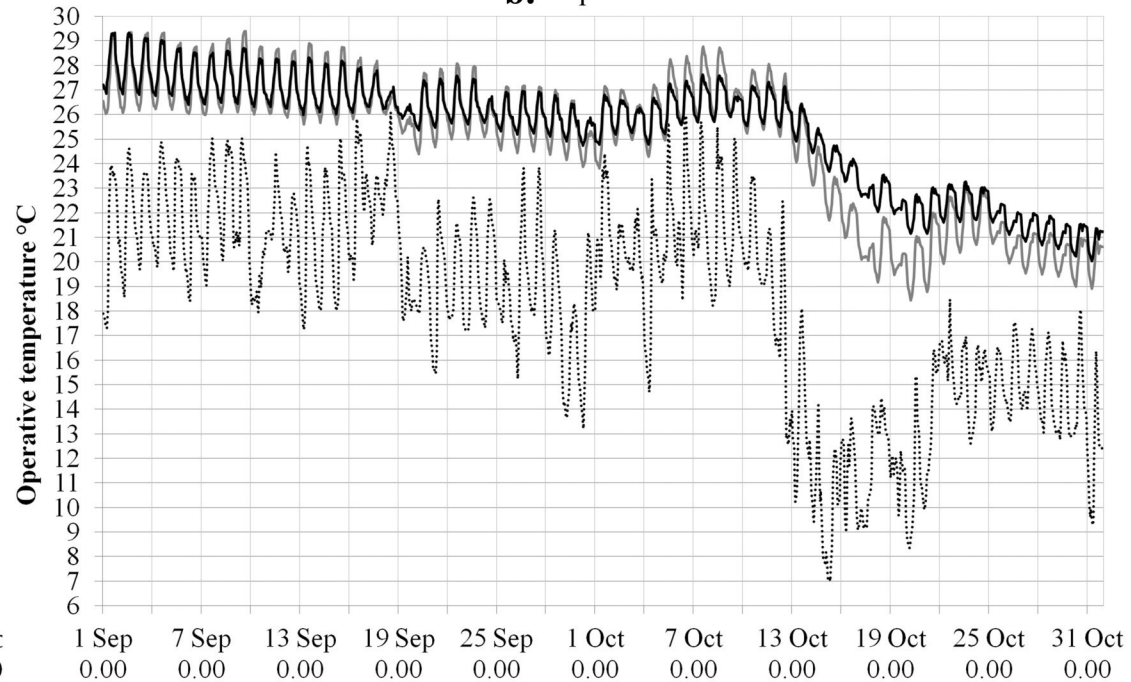
— Opened windows and 'as built' ground floor
 — Closed windows and 'as built' ground floor
 - - - Opened windows and adiabatic ground floor
 - - - Closed windows and adiabatic ground floor

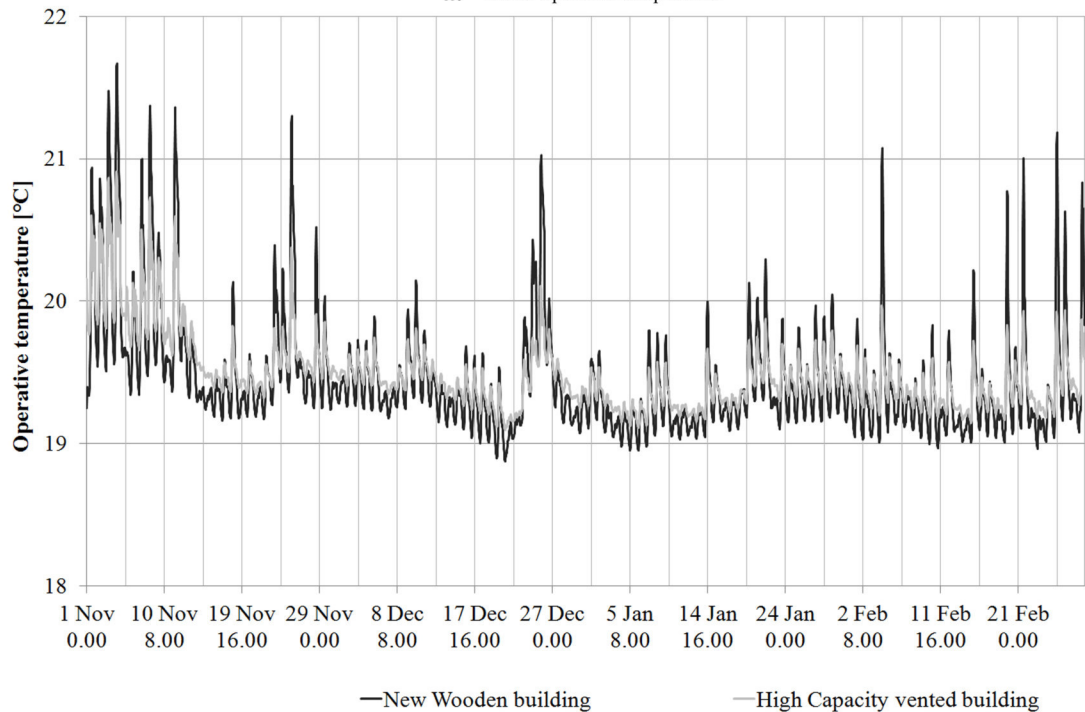
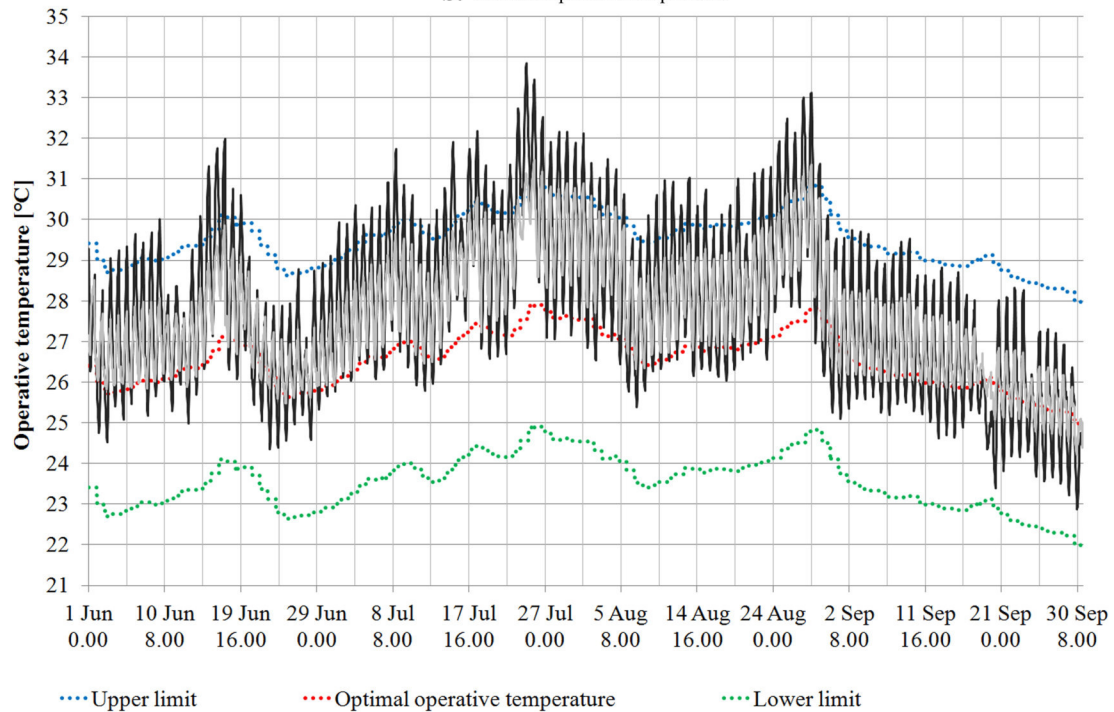








a. March - April**b.** September - October

a. Winter operative temperature**b.** Summer operative temperature

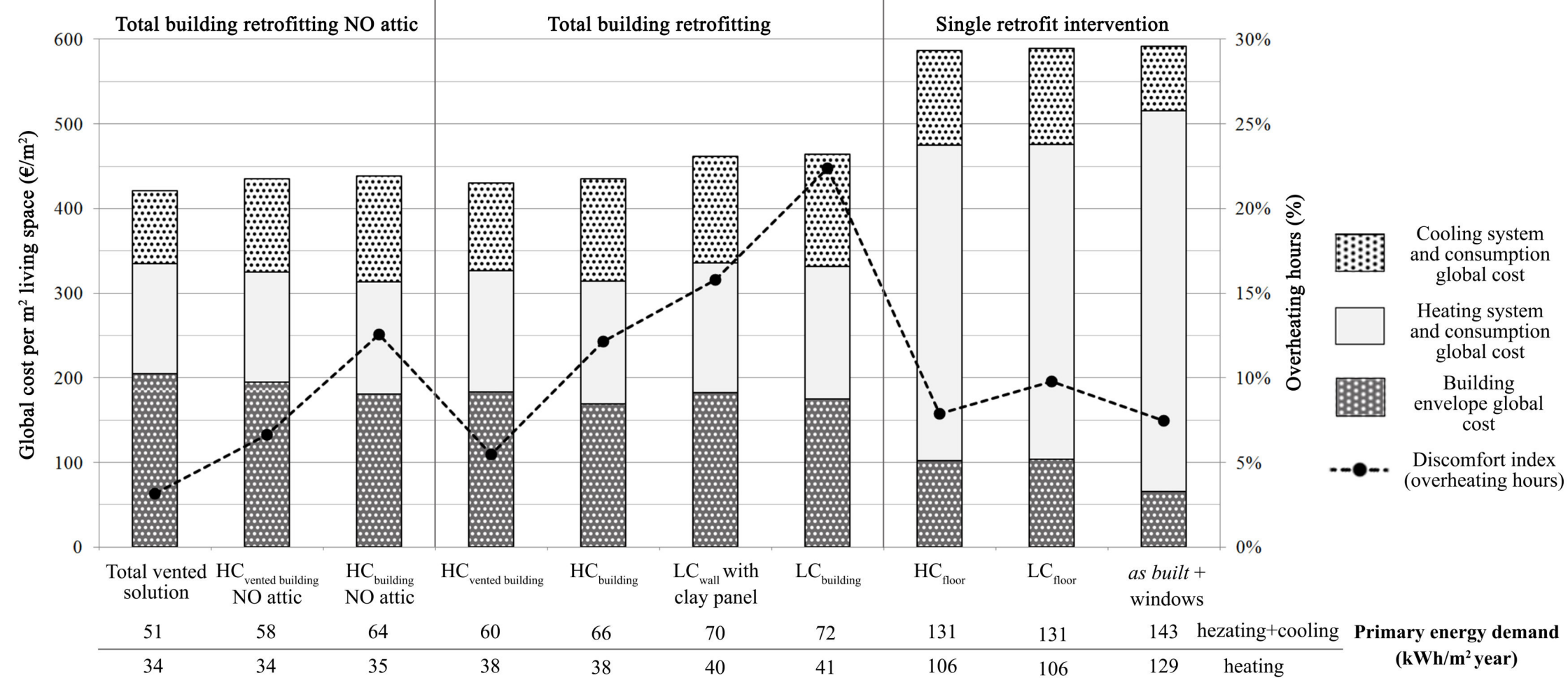


Table 1. Thermal characteristics of each studied envelope.

	STANDARD [39] / SUGGESTED [22] limits	SCHEME 0	SCHEME 1 and 2		SCHEME 3
		As built Ground floor (G₀)	High Capacity Ground floor (HC_{ground})	Low Capacity Ground floor (LC_{ground})	New Wooden building Ground floor (NW_{ground})
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 ² K)	0.34	1.44	0.3	0.3	0.30
Periodic thermal transmittance Y_{ie} (W/m ² K)	< 0.20	0.19	0.01	0.01	0.01
Internal areal heat capacity kI (kJ/m ² K)	Suggested ≥ 50	62	62	41	30
		As built Roof (R₀)	High Capacity Roof (HC_{roof})	Low Capacity Roof (LC_{roof})	New Wooden building Roof (NW_{roof})
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 Y_{ie} (W/m ² K)	< 0.20	0.90	0.03	0.03	0.02
Internal areal heat capacity kI (kJ/m ² K)	Suggested ≥ 50	75	66	20	17
		As built Wall (W₀)	High Capacity Wall (HC_{wall})	Low Capacity Wall (LC_{wall})	New Wooden building Wall (NW_{wall})
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 Y_{ie} (W/m ² K)	< 0.12	0.18 ^a (0.42) ^b	0.01	0.01	0.03
Internal areal heat capacity kI (kJ/m ² K)	Suggested ≥ 50	66 ^a (58) ^b	63	16 (30) ^c	26

^a, ^b correspond to the as built wall at the ground floor, ^b correspond to the as built wall at the first floor

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

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

^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
<i>as built</i>	WWR 7% $U \approx 5 \text{ W/m}^2\text{K}$	G_0	R_0	W_0
SCHEME 0	WWR 9% $U \approx 2 \text{ W/m}^2\text{K}$	G_0	R_0	W_0
SCHEME 1	WWR 9% $U \approx 2 \text{ W/m}^2\text{K}$	a. High (HC_{ground})	High (HC_{roof})	W_0
		b. Low (LC_{ground})	Low (LC_{roof})	W_0
SCHEME 2	WWR 9% $U \approx 2 \text{ W/m}^2\text{K}$	a. High (HC_{ground})	High (HC_{roof})	High (HC_{wall})
		b. High (HC_{ground})	High (HC_{roof})	Vented ($HC_{\text{vented wall}}$)
		c. Low (LC_{ground})	Low (LC_{roof})	Low (LC_{wall})
SCHEME 3	WWR 9% $U \approx 2 \text{ W/m}^2\text{K}$	Wood	Wood	Wood
SCHEME 4	WWR 9% $U \approx 2 \text{ W/m}^2\text{K}$	Low (LC_{ground})	Low (LC_{roof})	High (Massive inner finish)
SCHEME 5	WWR 9% $U \approx 2 \text{ W/m}^2\text{K}$	High (HC_{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_{floor} and LC_{floor}: 22.43		
Roof	HC_{roof}: 39.33	HC_{vented roof}: 53.76	LC_{roof}: 42.22
Wall	HC_{wall}: 53.12	HC_{vented wall}: 67.26	LC_{wall}: 48.78 LC_{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
	<i>as built</i>	0	128	378	83
SCHEME 0	<i>as built</i> + 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	Intermittent heating energy consumption (6:00-10:00, 12:00-16:00, 18:00-22:00)	Continuous cooling energy consumption
	(kW _p /m ² year)	(kW _p /m ² year)	(kW _p /m ² year)
<i>"as built"</i>	138.62	102.88	14.18
SCHEME 0 <i>"as built"</i> + windows	128.71	95.95	14.57
SCHEME 1	HC _{floor}	105.93	25.15
	LC _{floor}	105.47	25.77
SCHEME 2	HC _{building}	38.31	27.86
	HC _{vented building}	37.67	22.19
	LC _{building}	41.22	30.69
SCHEME 3	NW _{building}	40.79	24.89
SCHEME 4	Inner massive finish	40.33	28.18
SCHEME 5	Totally vented solution	33.69	17.30