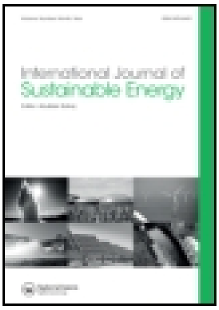


International Journal of Sustainable Energy
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gsol20

Synergic effects of thermal mass and natural ventilation on the thermal behaviour of traditional massive buildings

A. Gagliano[a], F. Nocera[a], F. Patania[a], A. Moschella[b], M. Detommaso[a] & G. Evola[a]
[a] Department of Industrial Engineering, University of Catania, Catania, Italy
[b] Department of Civil Engineering and Architecture, University of Catania, Catania, Italy
Published online: 29 Apr 2014.

International Journal of Sustainable Energy, 2014
http://dx.doi.org/10.1080/14786451.2014.910517

Synergic effects of thermal mass and natural ventilation on the thermal behaviour of traditional massive buildings

A. Gagliano[a], F. Nocera[a], F. Patania[a], A. Moschella[b], M. Detommaso[a] and G. Evola[a]*

[a]*Department of Industrial Engineering, University of Catania, Catania, Italy;* [b]*Department of Civil Engineering and Architecture, University of Catania, Catania, Italy*

(*Received 20 February 2014; accepted 26 March 2014*)

The energy policies about energy efficiency in buildings currently focus on new buildings and on existing buildings in case of energy retrofit. However, historic and heritage buildings, that are the trademark of numerous European cities, should also deserve attention; nevertheless, their energy efficiency is nowadays not deeply investigated. In this context, this study evaluates the thermal performance of a traditional massive building situated in a Mediterranean city. Dynamic numerical simulations were carried out on a yearly basis through the software DesignBuilder, both in free-running conditions and in the presence of an air-conditioning (AC) system. The results highlight that the massive envelope of traditional residential buildings helps in maintaining small fluctuations of the indoor temperature, thus limiting the need for AC in the mid-season and in summer. This feature is highly emphasised by exploiting natural ventilation at night, which allows reducing the building energy demand for cooling by about 30%.The research also indicates that, for Mediterranean climate, the increase in thermal insulation does not always induce positive effects on the thermal performance in summer, and that it might even produce an increase in the heat loads due to the transmission through the envelope.

Keywords: natural ventilation; thermal mass; traditional buildings; dynamic simulations

Nomenclature

A	amplitude of a cyclic temperature fluctuation (°C)
C_{a}	thermal capacity of air ($\mathrm{J\,K^{-1}}$)
c_{p}	specific heat ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
DF	decrement factor (-)
g	glass g-value (-)
h_{0i}	overall surface heat transfer coefficient ($\mathrm{W\,m^{-2}\,K^{-1}}$)
I	solar irradiance ($\mathrm{W\,m^{-2}}$)
m	surface density ($\mathrm{kg\,m^{-2}}$)
$\mathrm{m_{inf}}$	airflow rate for infiltration or natural ventilation ($\mathrm{kg\,s^{-1}}$)
$\mathrm{PE_C}$	specific primary energy needs for cooling ($\mathrm{kWh\,m^{-2}}$)
PE_H	specific primary energy needs for heating ($\mathrm{kWh\,m^{-2}}$)
Q_{sys}	thermal load of plant (W)
Q_{i}	convective internal loads (W)

*Corresponding author. Email: gevola@unict.it

s_i	wall thickness (m)
S	surface area of a building component (m^2)
T_a	indoor temperature (°C)
T_{ai}	indoor temperature in adjacent zones (°C)
T_{si}	inner surface temperature (°C)
T_{so}	outer surface temperature (°C)
T_o	outdoor air temperature (°C)
TL	time lag (h)
U	thermal transmittance ($W\,m^{-2}\,K^{-1}$)

Greek letters

$\Phi_{int,occ}$	occupancy heat gains (W)
$\Phi_{int,eq}$	equipment heat gains (W)
$\Phi_{int,ill}$	lighting heat gains (W)
ε	thermal emissivity (-)
ρ	density ($kg\,m^{-3}$)
τ	time (h)

1. Introduction

Among existing buildings, traditional buildings represent a particular case, due to their uniqueness and the need to be protected. The term 'traditional building' covers a broad range of buildings, not just those referred to as 'historic' or 'heritage'. As a general rule, traditional buildings are designed with the aim of protecting inhabitants against the adverse external environment: thus, their features and the thermal properties of their envelope are conceived according to the site-specific weather conditions.

Several studies discuss the thermal performance of heritage or traditional buildings throughout the world (Labaki and Kowaltowski 1998; Singh, Mahapatra, and Atreya 2010; Jiaping et al. 2011; Martins and Carlos 2014). However, there are not many studies that refer to traditional buildings located in either Italy (Cardinale et al. 2013; Gagliano et al. 2014) or adjacent Mediterranean countries (Martìn, Mazarrón, and Cañas, 2010; Oikonomou and Bougiatioti 2011). In Italy, traditional buildings are commonly built using load-bearing massive masonry walls with pitched roofs and windows with timber frames: this type of envelope, characterised by high thermal mass, introduces a good thermal inertia but, given its poor thermal insulation, it also shows high thermal losses.

Therefore, the authors believe that it is fundamental to identify practical solutions for an energy-efficient renovation of the historic and traditional building stock, as suggested by Troi (2011). The methodologies of intervention should allow retaining the historic character of the traditional building and minimising the visual impact of the changes. In this framework, this study evaluates the possibility of getting both energy savings and improved thermal comfort through moderate interventions of refurbishment on Mediterranean traditional building envelopes. In particular, this paper refers to a traditional residential building situated in Catania (Southern Italy).

The investigation is based on the results of dynamic simulations: building dynamic energy analysis is by now a well-established tool to effectively assess energy performance of buildings under real climatic conditions (Corgnati, Fabrizio, and Filippi 2008; Gagliano et al. 2012; Olofsson and Mahlia 2012; Pisello, Goretti, and Cotana 2012). The results are discussed not only in terms of energy needs, but also by looking at the possibility of assuring indoor thermal comfort without the use of AC systems (Peeters et al. 2009), both during the heating and cooling periods.

This study was developed in different steps. The first step assesses the thermal behaviour of the building in its current configuration, see Section 4. The second step evaluates the thermal performance of the building after the proposed retrofit interventions (RIs) on the envelope, see Section 5. Finally, the potential contribution of night-time ventilation is investigated and described in Section 6, so as to understand how the air change rate, building envelope and climatic parameters affect the effectiveness of this strategy: about this issue, see also Shaviv, Yeizoro, and Capeluto (2001) as well as Pfafferott, Herkel, and Jaschke (2003).

2. Hints about thermal inertia and night ventilation

As highlighted in the previous section, traditional buildings in Italy are characterised by high thermal mass. Thus, it may be useful to recall the main effects of thermal mass on the thermal performance of buildings.

First of all, the cooling loads in summer are closely correlated to the building thermal mass, as this helps to attenuate the outdoor temperature peak and to keep the internal conditions within the comfort range by absorbing the excess heat (Geros et al. 2005). In fact, it is well established that structures with high heat capacity contribute to the reduction and the time delay of the peak cooling load (Asan and Sancaktar 1998; Evola and Marletta 2013).

In winter, the energy conveyed by solar radiation and internal gains (radiant component) is stored by the envelope, and then slowly released into the indoor environment at a later time, when it can contribute more efficiently to reduce heating loads.

In addition, the thermal inertia of the envelope has also positive effects in terms of indoor thermal comfort in free-running buildings. Indeed, the higher is the thermal inertia of a building the slower is the rate at which its indoor temperature rises and drops.

In order to describe the thermal response of a building envelope to outer forcing conditions as well as to measure its storage capability, the *time lag* and the *decrement factor* can be adopted; their definition is schematically depicted in Figure 1. As concerns the time lag (TL), it is defined as the time required for a temperature wave to be transferred from the outer surface of the wall to its inner surface (Ozel and Pihtili 2007). In formulae, TL is measured by the difference between the instants of time when the maximum outer and inner surface temperatures occur:

$$\mathrm{TL} = \tau_{T_{\mathrm{so,max}}} - \tau_{T_{\mathrm{si,max}}}. \quad (1)$$

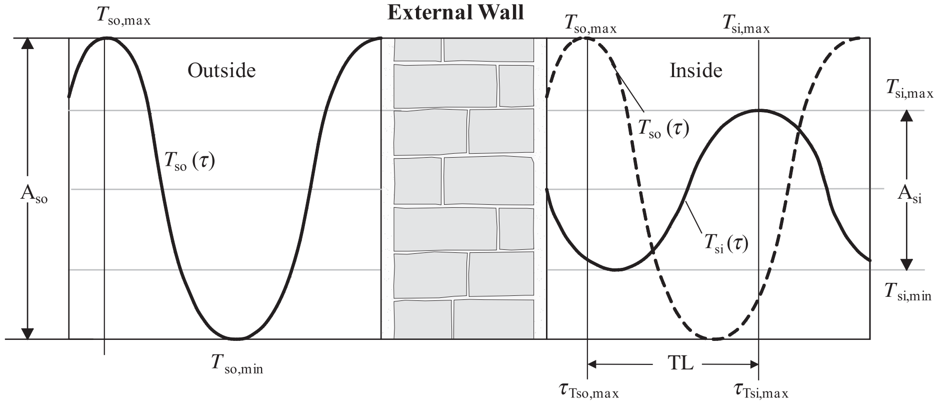


Figure 1. Thermal wave and thermal inertia factors.

On the other hand, the decrement factor (DF) is defined as the ratio of the amplitude of the inner surface temperature fluctuation to that of the outer surface temperature fluctuation (Ozel and Pihtili, 2007), see Equation (2):

$$\mathrm{DF} = \frac{A_{\mathrm{si}}}{A_{\mathrm{so}}} = \frac{T_{\mathrm{si,max}} - T_{\mathrm{si,min}}}{T_{\mathrm{so,max}} - T_{\mathrm{so,min}}}. \tag{2}$$

The energy savings associated with the inertial effects are more evident in climates where the diurnal variation of the external temperature is above 10 K and ranges from a few percentages to more than 80% (Gratia and De Herde 2004; Aste, Angelotti, and Buzzetti 2009).

Furthermore, in summer a well-known strategy for discharging the structural mass in massive buildings, thus further improving their thermal performance, consists in space ventilation at night. In this sense, natural night-time ventilation contributes to the decrease in the cooling load of AC systems, improvement in indoor air quality and also to thermal comfort.

The symbiotic action of building thermal inertia and nocturnal ventilation allows creating an optimum level of comfort and minimum energy consumption.

3. Methodology

The influence of the thermal mass on the thermal performance of buildings can be evaluated only through dynamic thermal simulations. Nowadays, many software tools are available for building dynamic simulations: in this paper, DesignBuilder (2012) has been used.

Building thermal simulation usually requires that the building is divided into thermal zones, differenced in relation to activity and occupancy schedules, shading systems, energy plants, set-point and set-back temperatures for winter and summer as well as air infiltration rate.

The calculation method used by the software is based on a heat-balance model in which the air in each thermal zone is considered well mixed and with uniform temperature. The heat-balance equations are used to calculate:

- surface-by-surface conductive, convective and radiant heat balance for each room surface (surface-heat-balance module)
- convective heat balance for the room air (air-mass-balance module).

The surface-heat-balance module simulates the heat balance on the inner and the outer surfaces and takes into account the boundary conditions as well as conduction, convection, radiation and mass transfer (water vapour) effects.

On the other hand, the air-mass-balance module deals with various mass streams, such as ventilation air, exhaust air and infiltration; it also accounts for the thermal mass of zone air and evaluates direct convective heat gains.

The air-heat balance is given by:

$$C_a \cdot \frac{\mathrm{d}T_a}{\mathrm{d}\tau} = \sum_{i=1}^{n} \dot{Q}_i + \sum_{i=1}^{N_s} h_i \cdot A_i \cdot (T_{\mathrm{si}} - T_{\mathrm{a}}) + \sum_{i=1}^{N_z} \dot{m}_i \cdot c_{\mathrm{p}} \cdot (T_{\mathrm{ai}} - T_{\mathrm{a}}) + \dot{m}_{\mathrm{inf}} \cdot c_{\mathrm{p}} \cdot (T_{\mathrm{o}} - T_{\mathrm{a}}) + \dot{Q}_{\mathrm{sys}}, \tag{3}$$

where

$$\sum_{i=1}^{n} \dot{Q}_i = \text{sum of the convective internal loads}, \tag{4}$$

$$\sum_{i=1}^{N_s} h_i \cdot A_i \cdot (T_{\text{si}} - T_{\text{a}}) = \text{convective heat transfer from the zone surfaces,} \quad (5)$$

$$\sum_{i=1}^{N_z} \dot{m}_i \cdot c_{\text{p}} \cdot (T_{\text{ai}} - T_{\text{a}}) = \text{heat transfer due to interzone air mixing,} \quad (6)$$

$$\dot{m}_{\text{inf}} \cdot c_{\text{p}} \cdot (T_{\text{o}} - T_{\text{a}}) = \text{heat transfer due to infiltration or natural ventilation,} \quad (7)$$

$$C_{\text{a}} \cdot \frac{\text{d}T_{\text{a}}}{\text{d}\tau} = \text{energy stored in the zone air.} \quad (8)$$

The term Q_{sys} is the thermal power that must be provided by the AC system in order to get the energy balance. This calculation model is adopted by the DesignBuilder software; more details are provided in the reference documentation provided by the US Department of Energy (2011).

As concerns the evaluation of the air flow rate introduced through natural ventilation, this is a challenging task due to the complexity of the physical phenomena involved. The driving forces for natural ventilation are the pressure and temperature differences between the indoors and outdoors. Two different ventilation patterns can be identified: single-sided and cross ventilation. Single-sided ventilation is characterised by openings located on a single façade; cross ventilation is characterised by the presence of openings on opposite sides of the building, and it can provide ventilation rates larger than those obtained by single-sided ventilation (Awbi 1996; Evola and Popov 2006).

In DesignBuilder, it is possible to exploit a CFD tool (computational fluid dynamics) to study in detail the pressure and velocity distribution both inside and outside the building. However, in this paper a simpler approach was followed, based on the definition of a pre-defined schedule for the ventilation rate, that is to say, by imposing specific constant values during appropriate time intervals.

4. Case study

4.1. *Description of the building in its current configuration*

The case study concerns a historic residential building situated in the historic centre of Catania (lat. 37°47′, long. 15°05′, Southern Italy). The building was built in the late eighteenth century; it consists of four floors above ground and its fabric is realised with constructive technologies and materials typical of Sicilian traditional architecture. The opaque vertical closures are characterised by walls made of lava stone roughly squared, with variable thickness between 80 cm and 60 cm. The horizontal load-bearing structures are mainly constituted by pavilion vaults with the directrix made of brick and the ‘skin’ with pumice and gypsum mortar, which ave a mean thickness of 42 cm (see Figure 2). The remaining part of the horizontal load-bearing structures is composed of floors with iron beams and hollow flat tiles with the filling of pumice and gypsum mortar (the overall thickness is about 30 cm).

Windows and doors are realised with a 5-cm chestnut wood frame and a single 3-mm glazing. The main geometric and thermophysical data of the building components are reported in Tables 1–3. Here, the surface density m is calculated through Equation (9), where ρ_j and s_j are the density and the thickness of each layer, respectively.

$$m = \sum_{j=1}^{n} \rho_j \cdot s_j. \quad (9)$$

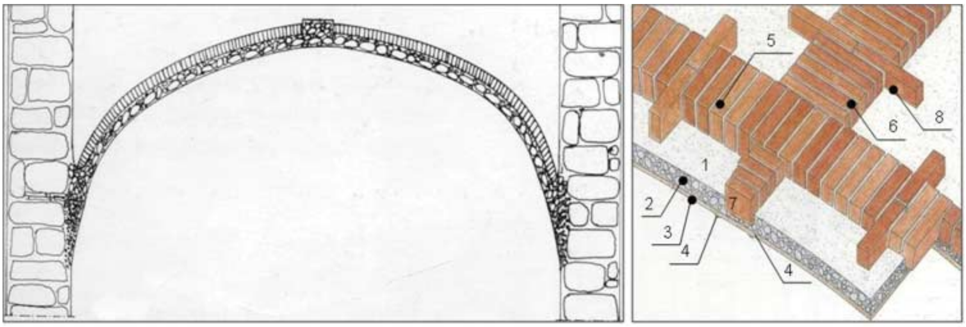


Figure 2. Left: cross section of the pavilion vault; right: stratigraphy. *Source*: Sapienza (2004).

Table 1. Geometric data of the building and characteristic parameters.

Heated gross volume	Envelope surface area	Net floor area	Opaque surface	Glazed surface
3930.0 m^3	1169.1 m^2	459.9 m^2	1075.5 m^2	93.5 m^2

Table 2. Thermal transmittance and surface density of the opaque components.

Building components	m ($kg\,m^{-2}$)	U ($W\,m^{-2}\,K^{-1}$)	U_{RI} ($W\,m^{-2}\,K^{-1}$)	$\Delta U = U - U_{RI}$ ($W\,m^{-2}\,K^{-1}$)
External masonry in roughly squared lava stone (80 cm)	1813	1.39	0.83	0.56
External masonry in roughly squared lava stone (60 cm)	1373	1.67	0.92	0.75
Floor in iron beams and hollow flat tiles with pumice and gypsum mortar (versus outdoors)	417	1.56	0.57	0.99
Floor in iron beams and hollow flat tiles with pumice and gypsum mortar (versus attic)	240	1.48	0.53	0.95
Vault in pumice and gypsum	658	1.28	0.58	0.70
Pitched roof in tiles	80	6.25	–	–
Basic horizontal closure	2730	0.40	–	–

Table 3. Main thermophysical properties of the windows.

		Value	
Property	Unit	Before	After
Emissivity of the glazed surface	–	0.84	0.1
Glass g-value	–	0.85	0.50
Thermal transmittance of the glazing	$W\,m^{-2}\,K^{-1}$	5.88	2.0
Thermal transmittance of the frame	$W\,m^{-2}\,K^{-1}$	3.50	3.50
Overall thermal transmittance of the windows	$W\,m^{-2}\,K^{-1}$	4.55	2.70

From Tables 2 and 3, one can observe that the thermal transmittance U of both the opaque components and the windows is higher than the standard values required by national regulations for new buildings in mild climate area, that are about 0.46 and 3.00 $W\,m^{-2}\,K^{-1}$ respectively, for exterior walls and windows. Therefore, such high U-values could suggest a very low energy performance of the building envelope, at least in winter.

On the other hand, the traditional masonries have enormous mass capacity, since their surface density m is about 1800 kg m^{-2}, that is to say far higher than for modern construction technologies (e.g. hollow bricks and concrete walls), whose surface density ranges between 200 kg m^{-2} and 350 kg m^{-2}.

4.2. *Description of the proposed intervention on the envelope*

The technologies for energy refurbishment of buildings situated in historic city centres should be designed considering both the construction and the specific historical–cultural instances of the buildings.

In this context, some specific interventions on the sample building are proposed in the following. They essentially consist in:

- replacement of the glazed component (while keeping the same frame as in the actual configuration);
- application of thermal insulation on the roof slab and façade facing the internal courtyards. On the contrary, the main façade is not disturbed by any intervention, with the aim of not interfering with the historical, cultural and architectural attractiveness of this traditional building.

More precisely, the proposed solution is based on the installation of a 4-cm panel of glass wool ($\lambda = 0.035$ W m^{-1} K^{-1}) on the outer side of the horizontal roof as well as on the addition of a 3-cm thick thermal plaster on the outer side of the external masonries. The thermal plaster has a low thermal conductivity ($\lambda = 0.056$ W m^{-1} K^{-1}) and is composed by hydraulic binders and fine polystyrene pearls.

The intervention on the external windows consists in the replacement of the current glazing with a double glazing (s = 3 mm) separated by an air gap (s = 12 mm) compatible with the existing frame. The glasses have the further following characteristics: low-emissive coating on the inner glazing ($\varepsilon = 0.1$) and selective coating on the outer glazing, which allow getting a solar gain factor $g = 0.5$. The values of the thermophysical properties and the thermal transmittance of the envelope components after the RIs are reported in Tables 2 and 3. Table 2 also presents the comparison between the current state of the building (U) and the thermal transmittance of the opaque components after retrofit (U_{RI}).

It can be observed that, in spite of the solutions proposed for the building refurbishment, the thermal transmittance of the building components is still higher than the values imposed by current Italian regulations (0.46 and 3.00 W m^{-2} K^{-1} respectively, for exterior walls and windows). Indeed, the specificity of the traditional building envelope makes it difficult to install a thicker layer of thermal insulation; however, an excessive thermal insulation may have negative effects in the cooling period, when it might act as a barrier against the transfer of the heat stored by the envelope to the colder outdoor environment. The results of the simulations will help to understand the appropriateness of this choice.

4.3. *The model of the building for simulations*

As previously stated, the study was carried out with the code DesignBuilder. In the model realised on this tool, the residential units were considered as occupied zones equipped with AC systems. On the other hand, the well of the staircase, the attic and the ground floor were considered as semi-external non-conditioned zones. The boundary walls with adjacent buildings due north and south do not undergo any heat exchange (adiabatic walls).

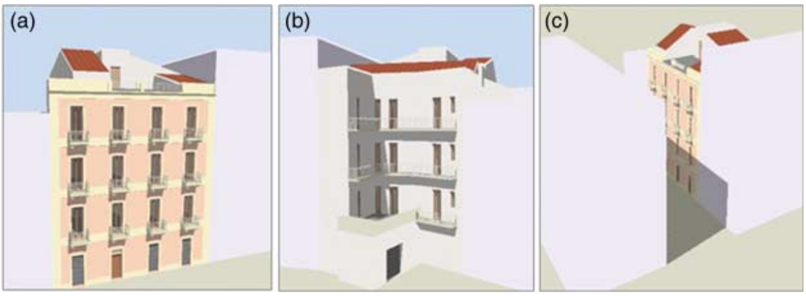


Figure 3. The simulated building on DesignBuilder. (a) westward view; (b) eastward view; (c) side view.

The calculation model includes also the neighbouring (nearby) buildings, so as to take into consideration the shading effect. Figure 3 depicts the three-dimensional model of the building façades.

The building is equipped with an AC system that supplies both heating and cooling, with an average coefficient of performance COP = 3.5. As concerns internal gains, the occupancy rate is 0.04 people m^{-2}; electric equipment and lighting were also considered, with an appropriate time profile and the maximum overall density power ranging from 10 to 12 W m^{-2} between 17:00 and 21:00 hours.

For the infiltration of outdoor air, a constant air change rate of 0.5 h^{-1} was considered. In order to investigate the effects of night-time natural ventilation, in some simulations an additional air flow rate from the outdoors is introduced between 24:00 and 06:00 hours, with a constant air change rate ranging from $n = 1\,h^{-1}$ to $n = 3\,h^{-1}$.

The calculation of the overall building energy performance was carried out in two different periods: the heating period from 1 December to 31 March and cooling period from 1 June to 30 September. The meteorological data used for the simulations have been extracted by the Energy Plus database for the city of Catania.

During the heating period, the AC system operates for about 8 h per day, with a set-point temperature of 20.0°C. Whereas during the cooling period, the AC system operates for 6 h per day, with a set-point temperature of 24.0°C.

5. Results: the building in its current configuration

5.1. *Energy needs*

The first results of the simulations for the current building are shown in Figures 4 and 5, which highlight the different contributions to the energy balance – transmission through the envelope, outdoor air infiltration, internal gains, solar gains – together with the total seasonal energy needs both during the heating and cooling periods.

The convention used for the contributions to the energy balance is as follows:

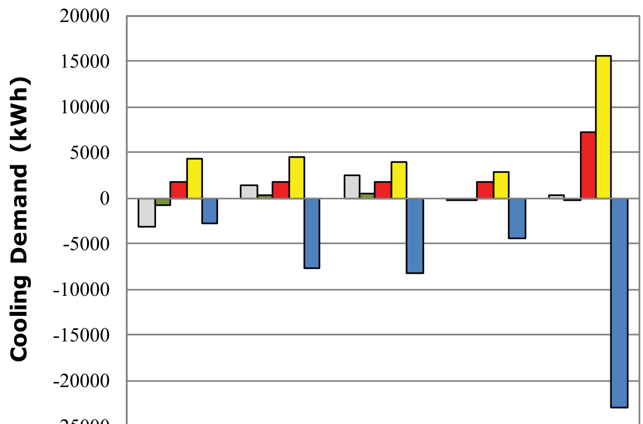
- the negative sign indicates the heat losses;
- the positive sign indicates the heat gains.

On the other hand, the convention used for the overall energy needs for heating and cooling is:

- the negative sign indicates that energy has to be extracted from the building;
- the positive sign indicates that energy has to be provided to the building.

	Dec	Jan	Feb	Mar	Total
Thermal energy for transmission	-7720	-10955	-9817	-8593	-37085
External infiltration	-3143	-3844	-3294	-3038	-13319
Internal gains	1891	1894	1708	1888	7381
Solar gains	1059	1248	1565	2483	6354
Energy for Heating	7915	11666	9868	7297	36747

Figure 4. Seasonal energy demand for heating (1 December–31 March).



	Jun	Jul	Aug	Sep	Total
Thermal energy for transmission	-3186	1367	2529	-292	417
External Infiltration	-684	310	481	-299	-192
Internal gains	1785	1833	1835	1777	7230
Solar gains	4319	4490	3953	2905	15667
Sensible cooling	-2829	-7601	-8234	-4337	-23000

Figure 5. Seasonal energy demand for cooling (1 June–30 September).

In summer, the sensible cooling load represents the sum of the energy needs necessary to balance the heat loads of the building due to transmission, external infiltration, solar and internal gains.

According to the results, the overall value of the energy demand for heating in winter is 36,747 kWh (see Figure 4). The specific energy demand, calculated as the ratio of the energy demand for heating to the net floor area, corresponds to $PE_H = 79.90\,\text{kWh}\,\text{m}^{-2}$.

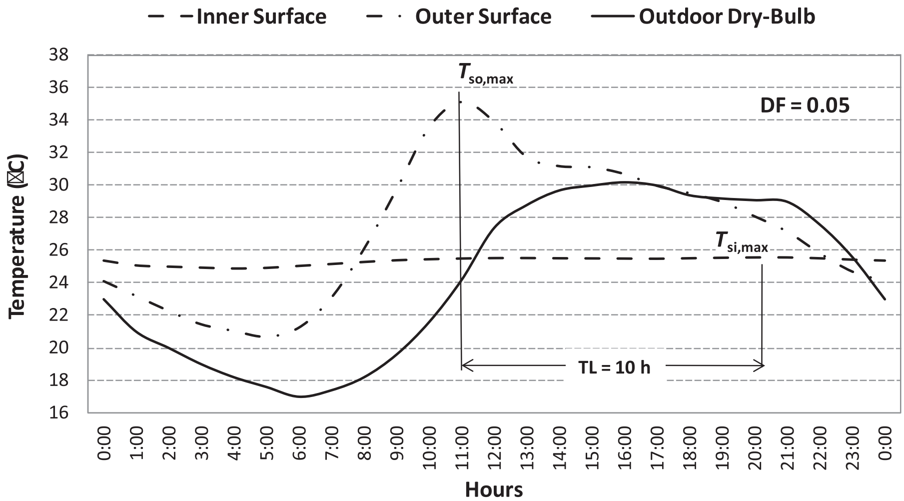


Figure 6. Temperature variations for a representative day in summer (15 July, east-facing wall).

As concerns the sensible energy demand for cooling, the overall value is 23,000 kWh (see Figure 5): the specific energy demand for cooling is $PE_C = 50\,kWh\,m^{-2}$. The latent load, related to people and infiltration, is not significant and does not change with the envelope solution, thus in the following it will not be considered. It is interesting to point out that the heating energy needs are higher than the cooling energy needs.

5.2. *Free-running performance*

Buildings with very high thermal inertia provide the interesting perspective of behaving as almost passive buildings. In this context, it is meaningful to investigate the thermal behaviour of the building under free-running conditions, i.e. without any AC system. In this way, it is possible to examine the potentiality of the high thermal inertia of the building for keeping thermal comfort conditions in the indoor environment.

In Figure 6 one can observe, for a representative day in summer, the simulated daily profile of the outdoor temperature T_o, the inner (T_{si}) and outer surface temperature (T_{so}) for an east-facing outer wall. The daily variation of T_{so} is strictly related to the convective and radiant heat fluxes on the external wall, which is hit by solar radiation. Such heat fluxes determine a peak of T_{so} at 11:00 hours, in accordance with the maximum daily value of solar radiation that strikes the façade (around 800 W m^{-2}).

On the other hand, despite the effect of the outer forcing conditions, the inner surface temperature oscillates only between 24.9°C and 25.6°C. From Figure 6, it is also possible to determine the values of the time lag and the decrement factor; they are respectively TL = 10 h (as the peak inner surface temperature occurs around 21:00 hours) and DF = 0.05. These values testify a good thermal inertia of the envelope and introduce the possibility of exploiting the combined effect of the thermal mass and natural ventilation at night for reducing the energy needs for space cooling.

On the other hand, Figure 7 outlines the results of the simulations in terms of indoor air and mean radiant temperatures for two representative days of the heating (15 January) and cooling periods (15 July); the curves refer to a room facing east.

From Figure 7, one can observe that, both in winter and summer, the variation of the indoor temperature throughout the day is quite limited. A slight increase in the indoor temperature can

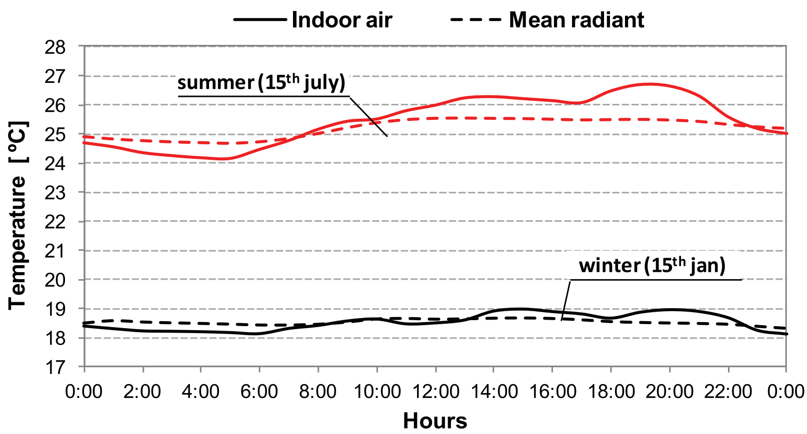


Figure 7. Results of the simulations in free-running mode for a typical day in winter (15 January) and summer (15 July).

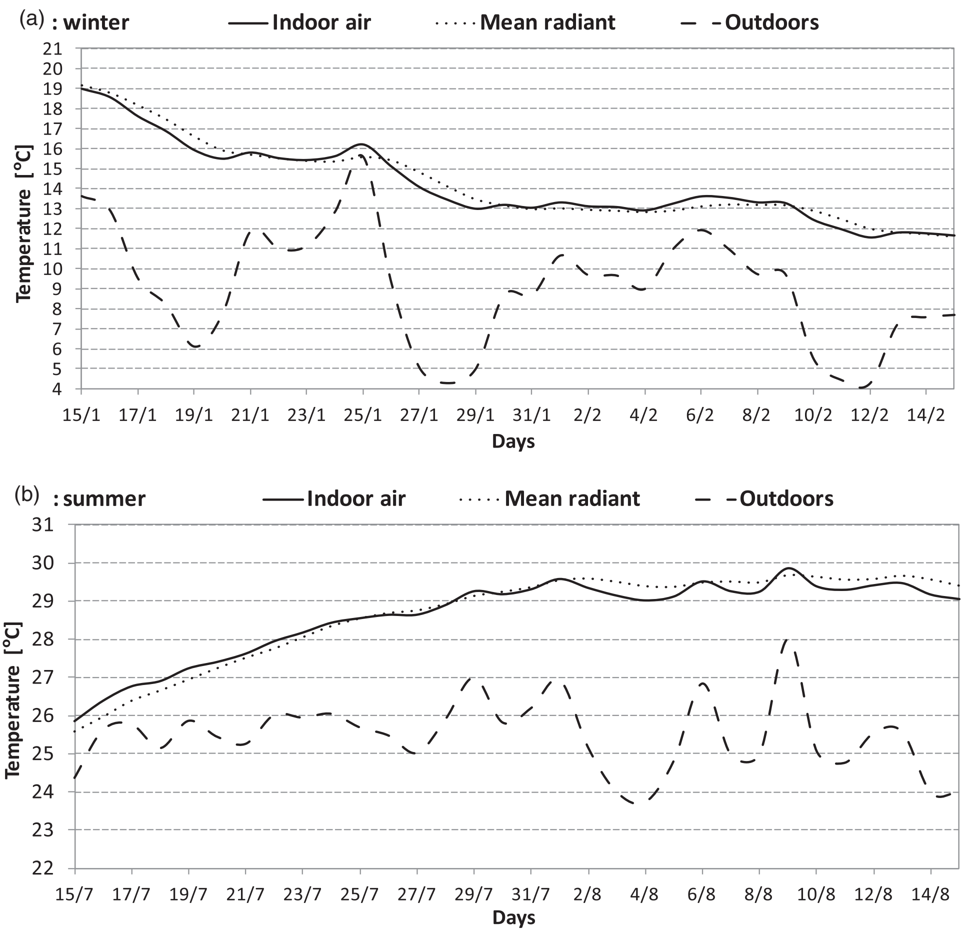


Figure 8. Results of the simulation in free-running mode over a month in (a) winter and (b) summer.

be observed in the late afternoon, especially in summer (around 0.5°C), and is related to the convective component of the internal loads, which reach their peak in this period of the day.

However, it is to remark that the indoor air temperature in winter that oscillates between 18°C and 19°C in this room might produce a slight sensation of cold to the occupants. On the other hand, in summer the indoor air temperature is kept around more comfortable values, i.e. between 24.5°C and 26.5°C.

In addition, Figure 8 reports the results of the simulation over a month period, both in winter and summer. In this figure, one average temperature value per day is reported; the initial temperature at the beginning of the simulation, i.e. in the first day of the season, was set at 20°C and at 24°C respectively, in winter and summer.

It can be observed that, over a long period, the absence of an AC system in winter would lead to a slow but constant indoor temperature reduction. Indeed, after less than two weeks the indoor temperature stabilises around 13°C, and then it lowers again to 11.5°C, thus it remains just slightly higher than the outdoor temperature (see Figure 8(a)). On the other hand, in the hot season the temperature inside the building is always higher than the external mean air temperature and stabilises above 29°C after about two weeks (see Figure 8(b)). In both cases, the evolution of the average indoor temperature is significantly influenced by the occurrence of severe outdoor conditions, whose effects cannot be easily recovered.

This result further confirms that thermal inertia operates as a screen to the fluctuation of the external forcing conditions, at least for a period of 24 h. This also suggests that faults or short periods of maintenance of the AC system might be balanced by the thermal inertia of the building.

However, a very uncomfortable sensation of cold is expected at length in winter as well as a considerable sensation of hot should be perceived in summer. This disappointing result in summer can be partially justified by the lack of a correct exploitation of nocturnal free cooling.

In conclusion, it is possible to state that, in its current configuration, the building cannot guarantee the thermal comfort of the occupants if the heating and cooling systems are not activated.

6. Expected results after refurbishment

6.1. *Energy needs*

The calculation of the building energy demand after the interventions for renovation proposed in Section 4.2 was carried out under the same assumptions as in the first series of simulations, in terms of occupancy, artificial lighting and electric equipment (see Section 4.3).The results, i.e. the energy needs for space heating and cooling, are reported in Figures 9 and 10.

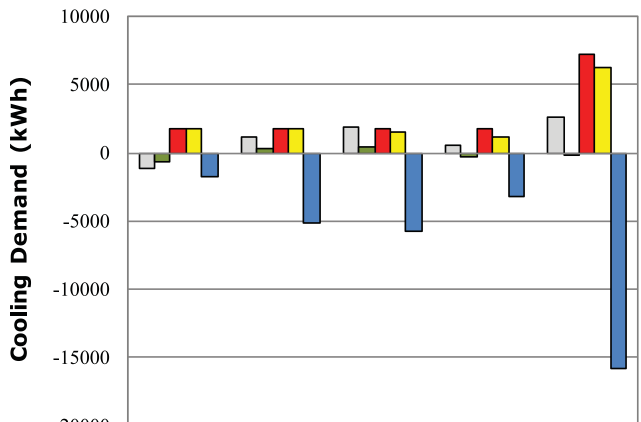
The annual energy demand for heating is now 25,372 kWh (see Figure 9), calculated by making a balance between the thermal energy exchanged through the building envelope and the internal and solar gains. The specific energy demand, i.e. the ratio of the heating energy demand to the net floor area, is $PE_H = 55.16\,kWh\,m^{-2}$. The energy savings achieved through the proposed solutions in the heating period amount to 11,375 kWh, which corresponds to about 30% of reduction. This result is mainly due to the reduction in the transmission heat losses.

On the other hand, the overall sensible energy demand for cooling is now 15,760 kWh (see Figure 10).

It is very important to underline that in summer the contribution of the heat transfer through the opaque envelope changes from 417 kWh (see Figure 5) to 2583 kWh (see Figure 10). This happens because the increased thermal insulation of the envelope contrasts the heat discharge from the envelope to the outdoor environment at night (when T_o is lower than T_i); therefore this kind of intervention seems to produce negative effects in summer.

	Dec	Jan	Feb	Mar	Total
Thermal energy for transmission	-3633	-6685	-6375	-5301	-21993
External infiltration	-3192	-3844	-3294	-3038	-13368
Internal gains	1891	1894	1708	1888	7381
Solar gains	424	500	626	997	2547
Energy for heating	4475	8109	7332	5456	25372

Figure 9. Seasonal energy demand for heating after renovation (1 December–31 March).



	Jun	Jul	Aug	Sep	Total
Thermal energy for transmission	-1089	1208	1897	568	2583
External infiltration	-670	310	481	-300	-179
Internal gains	1787	1833	1835	1777	7231
Solar gains	1736	1801	1585	1165	6287
Sensible cooling	-1723	-5099	-5749	-3189	-15760

Figure 10. Seasonal energy demand for cooling after renovation (1 June–30 September).

The specific energy demand for cooling is now $PE_c = 34.26\,\text{kWh m}^{-2}$. The reduction in the total cooling demand corresponds to 7240 kWh, which means a reduction of around 31% if compared to the existing building, despite the negative effect of the envelope insulation previously discussed.

In fact, the decrease in the energy demand is mainly associated with the use of reflective coatings on the glazing, which reduces the solar gain factor from 0.85 to 0.50. As a consequence, the solar gains are cut from 15,667 kWh to 6287 kWh.

6.2. *Free-running performance*

As previously discussed, it is also interesting to investigate the thermal behaviour of the building for free-running conditions, in order to evaluate its potentiality to maintain indoor comfort conditions in its new configuration.

To this aim, Figure 11 shows the results of the simulations with the application of the retrofit solutions for two representative days in winter (15 January) and summer (15 July); the curves refer to the same east-facing room considered in Figure 7. It can be observed that in both seasons the indoor temperature is more comfortable than that observed in Figure 7. The improvement in the thermal comfort conditions is evident: in winter the indoor air temperature now oscillates between 19.8°C and 20.7°C, whereas in summer it does not exceed 26°C in the late afternoon

It is also interesting to underline that, after the installation of the insulation layer, the decrement factor of the walls would be DF = 0.03, whereas the time lag would remain as high as that for the original envelope (TL = 10 h).

Moreover, Figure 12 shows the results of the simulation carried out over a longer period (one month) both in winter and summer. According to these results, in winter the average indoor temperature is higher than that calculated for the current building, shown in Figure 8(a). Actually, the indoor air temperature stabilises around 15°C after two weeks without any heating system and remains higher than 13°C even after a month (see Figure 12(a)); however, this is obviously not sufficient to provide thermal comfort.

In addition, during the cooling period the average thermal performance of the building has improved, since the maximum value of the indoor temperature is now generally lower than that in the current building (see Figures 8(b) and 12(b)), even if at length the two situations converge more or less towards the same temperature level. Anyway, even after the interventions the building cannot guarantee a long-term thermal comfort to the occupants in summer, if no cooling system is activated.

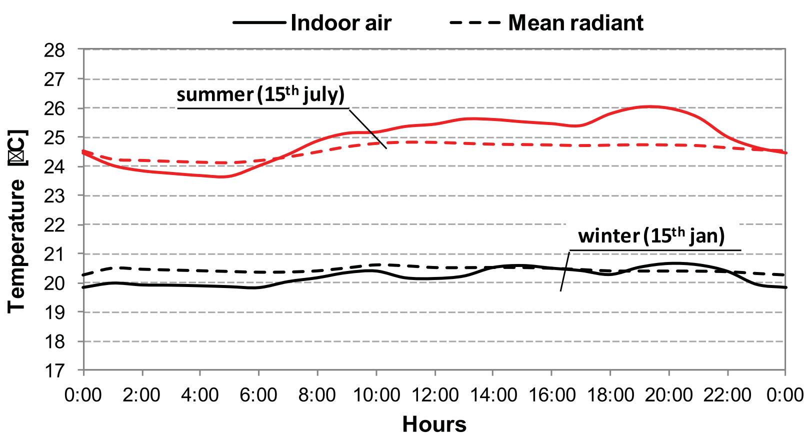


Figure 11. Results of the simulations in free-running mode after refurbishment for a typical day in winter (15 January) and summer (15 July).

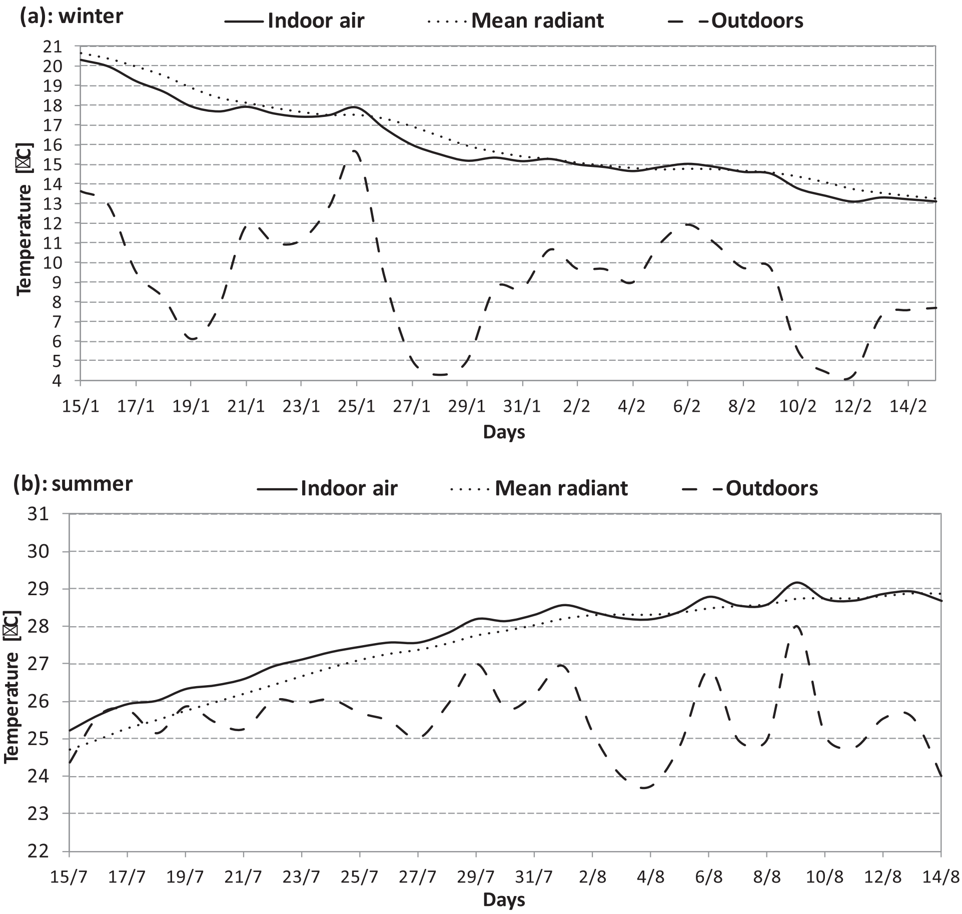


Figure 12. Results of the simulation in free-running mode after refurbishment over a month in (a) winter and (b) summer.

7. Effectiveness of night ventilation as a passive cooling strategy

7.1. *Effect on the energy needs*

It is well known that the synergic effect of thermal inertia and natural ventilation at night helps to reduce the energy needs for space cooling.

In this study, this possibility is investigated by introducing, in the sample building after retrofit, an additional air flow rate from the outdoors between midnight and 6:00 hours, with a constant air change rate ranging from $n = 1\,\mathrm{h}^{-1}$ to $n = 3\,\mathrm{h}^{-1}$. The latter value corresponds to what may be obtained by opening the 33% of the fenestration surface; higher ventilation rates would not be easily accomplished. This ventilation rate adds up to the amount of fresh air that is constantly introduced for hygienic purposes ($n = 0.5\,h^{-1}$).

Now, Figure 13 shows the comparison between the sensible building energy demand for cooling with and without the presence of night-time ventilation, before and after the RIs. It can be observed that the exploitation of a small ventilation rate during night-time ($n = 1\,\mathrm{h}^{-1}$) is already sufficient to provide a non-negligible reduction in the building energy demand for cooling after refurbishment, which lowers from 15,760 kWh (no additional night-time ventilation) to 13,581 kWh, i.e. by 13.8%. Furthermore, higher ventilation rates would introduce even greater improvements: with

$n = 3\,h^{-1}$, the cooling demand would be 10,809 kWh, and the reduction would amount to 31.4% with respect to the solution without night-time ventilation.

However, it is to remind that a too high ventilation rate may induce the building overcooling, especially in the warmest months, i.e. in June and September. Furthermore, an unexpected countereffect might consist in a slight increase in the heat transfer through the envelope, due to the higher energy difference between indoors and outdoors.

These results indicate that for traditional massive buildings night ventilation is a crucial tool to reduce the building energy demand for cooling. Indeed, they are far more encouraging than the results obtained in Section 6.1, where the night-time ventilation was not considered yet.

7.2. *Effect on thermal comfort*

The thermal behaviour of the building under long-term free-running conditions was also investigated in order to evaluate the role of night ventilation for keeping thermal comfort in the indoor environment.

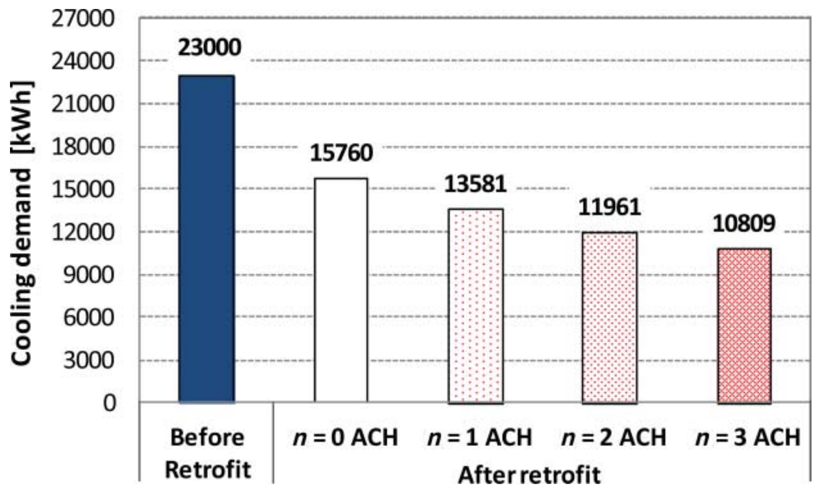


Figure 13. Total building energy demand for cooling with and without night-time ventilation.

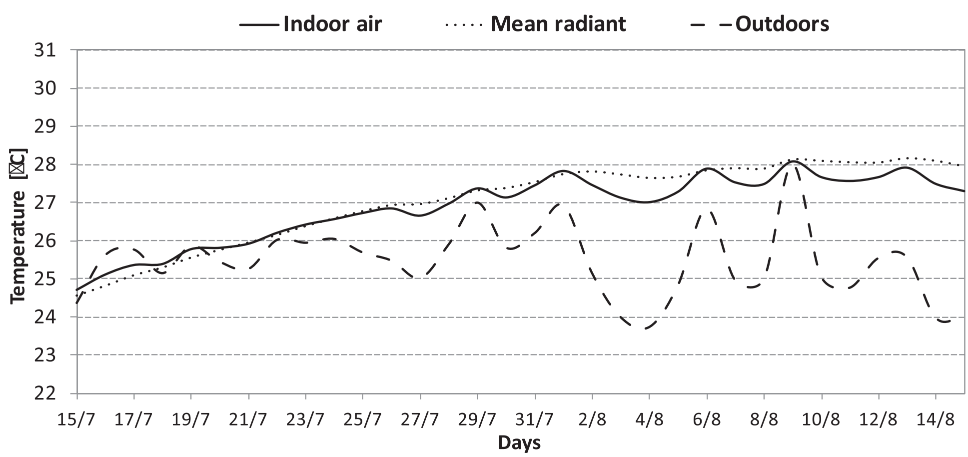


Figure 14. Monthly simulation in free-running mode after refurbishment and with natural ventilation at night ($n = 2\,h^{-1}$). The results refer to summer.

Figure 14, which refers to the case with $n = 2\,h^{-1}$, outlines the results of the simulations carried out over a whole month. Here, one can observe that, on average, the building now keeps its internal temperature below 28°C even after one month without any intervention of the AC system. This means that night natural ventilation leads to a reduction in the indoor peak temperature of about 1.5°C, in comparison with the previous cases (see Figures 8 and 12).

8. Conclusions

The research presented in this paper investigates, by means of dynamic simulations, the thermal performance of a traditional residential massive building located in Southern Italy.

The discussion of the results casts light on the specificity of 'massive' historic buildings, which may achieve good energy performance without necessarily having to meet the values of thermal insulation imposed by current Italian regulations. The results also highlight some possible techniques suitable for improving the thermal performance of most traditional buildings, without adversely affecting their fabric and character.

Such observations have very important consequences, since for historic buildings it is often difficult to introduce a high thickness of thermal insulation. The research also indicates that, in Mediterranean climate, only increasing thermal insulation does not lead to a considerable reduction in the energy needs in summer, and in some cases it might even produce drawbacks in more moderate periods. In this season, it is far more important to take appropriate measures to attenuate the solar gains, either through high-reflective glazing or by means of movable or fixed blinds.

Another crucial aspect of the research is that natural ventilation at night is fundamental for the improvement in the thermal performance of 'massive' buildings in summer. The research highlights that it is possible to reduce the overall energy demand for cooling by up to 30%, if an appropriate ventilation strategy is introduced. Without the exploitation of this strategy, more disappointing results have to be expected.

Acknowledgements

We gratefully acknowledge funding from the Italian Ministry of Education, University and Research through PRIN 2009 project 'Metodologie innovative per la riqualificazione energetica ed il recupero prestazionale del patrimonio edilizio esistente strutturato in geocluster' (code 2008S22MJC_005).

References

Asan, H., and Y. S. Sancaktar. 1998. "Effects of Wall's Thermophysical Properties on Time Lag and Decrement Factor." *Energy and Buildings* 28 (2): 159–166.

Aste, N., A. Angelotti, and M. Buzzetti, 2009. "The Influence of the External Walls Thermal Inertia on the Energy Performance of Well Insulated Buildings." *Energy and Buildings* 41 (11): 1181–1187.

Awbi, H. B. 1996. "Air Movement in Naturally-Ventilated Buildings." *Renewable Energy* 8 (1–4): 241–247.

Cardinale, T., D. Colapietro, N. Cardinale, and F. Fatiguso. 2013. "Evaluation of the Efficacy of Traditional Recovery Interventions in Historical Buildings. A New Selection Methodology." *Energy Procedia* 40: 515–524. http://dx.doi.org/10.1016/j.egypro.2013.08.059

Corgnati, S. P., E. Fabrizio, and M. Filippi. 2008. "The Impact of Indoor Thermal Conditions, System Controls and Building Types on the Building Energy Demand." *Energy and Buildings* 40 (4): 627–636.

DesignBuilder. 2012. "Energy Simulation Software." Version 3. http://designbuilder.co.uk

Evola, G., and L. Marletta. 2013. "A Dynamic Parameter to Describe the Thermal Response of Buildings to Radiant Heat Gains." *Energy and Buildings* 65: 448–457. http://dx.doi.org/10.1016/j.enbuild.2013.06.026

Evola, G., and V. Popov. 2006. "Computational Analysis of Wind Driven Natural Ventilation in Buildings." *Energy and Buildings* 38 (5): 491–501.

Gagliano, A., F. Patania, F. Nocera, A. Ferlito, and A. Galesi. 2012. "Thermal Performance of Ventilated Roofs During Summer Period." *Energy and Buildings* 49: 611–618. http://dx.doi.org/10.1016/j.enbuild.2012.03.007

Gagliano, A., F. Patania, F. Nocera, and C. Signorello. 2014. "Assessment of the Dynamic Thermal Performance of a Massive Building." *Energy and Buildings* 72: 361–370. http://dx.doi.org/10.1016/j.enbuild.2013.12.060

Geros, V., M. Santamouris, S. Karatasou, A. Tsangrassoulis, and N. Papanikolau. 2005. "On the Cooling Potential of Night Ventilation Techniques in the Urban Environment." *Energy and Buildings* 37 (3): 243–257.

Gratia, E., and A. De Herde. 2004. "Guidelines for Improving Natural Daytime Ventilation in an Office Building with a Double-Skin Façade." *Building and Environment* 39 (2): 1157–1170.

Jiaping, L., W. Lijuan, Y. Yasuko, and L. Yanfeng. 2011. "The Thermal Mechanism of Warm in Winter and Cool in Summer in China Traditional Vernacular Dwellings." *Building and Environment* 46 (8): 1709–1715.

Labaki, L. C., and D. C. Kowaltowski. 1998. "Bioclimatic and Vernacular Design in Urban Settlements of Brazil." *Building and Environment* 33 (1): 63–77.

Martín, S., F. R. Mazarrón, and I. Cañas. 2010. "Study of Thermal Environment Inside Rural Houses of Navapalos (Spain): The Advantages of Reuse Buildings of High Thermal Inertia." *Construction and Building Materials* 24 (5): 666–676.

Martins, A. M. T., and J. S. Carlos. 2014. "The Retrofitting of the Bernardas' Convent in Lisbon." *Energy and Buildings* 68 (Part A): 396–402.

Oikonomou, A., and F. Bougiatioti. 2011. "Architectural Structure and Environmental Performance of the Traditional Buildings in Florina, NW Greece." *Building and Environment* 46 (3): 669–689.

Olofsson, T., and T. M. I. Mahlia. 2012. "Modeling and Simulation of the Energy Use in an Occupied Residential Building in Cold Climate." *Applied Energy* 91 (1): 432–438.

Ozel, M., and K. Pihtili. 2007. "Optimum Location and Distribution of Insulation Layers on Building Walls with Various Orientations." *Building and Environment* 42 (8): 3051–3059.

Peeters, L., R. de Dear, J. Hensen, and W. D'haeseleer. 2009. "Thermal Comfort in Residential Buildings: Comfort Values and Scales for Building Energy Simulation." *Applied Energy* 86 (5): 772–780.

Pfafferott, J., S. Herkel, and M. Jäschke. 2003. "Design of Passive Cooling by Night Ventilation: Evaluation of a Parametric Model and Building Simulation with Measurements." *Energy and Buildings* 35 (11): 1129–1143.

Pisello, A. L., M. Goretti, and F. Cotana. 2012. "A Method for Assessing Buildings' Energy Efficiency by Dynamic Simulation and Experimental Activity." *Applied Energy* 97: 419–429. http://dx.doi.org/10.1016/j.apenergy.2011.12.094

Sapienza, V. 2004. *Residenze in villa a Catania – tra ottocento e novecento* [Residences in the villa in Catania between nineteenth and twentieth century]. Enna: Il Lunario.

Shaviv, E., A. Yeizoro, and I. G. Capeluto. 2001. "Thermal Mass and Night Ventilation as Passive Cooling Design Strategy." *Renewable Energy* 24 (3–4): 445–452.

Singh, M. K., S. Mahapatra, and S. K. Atreya. 2010. "Thermal Performance Study and Evaluation of Comfort Temperatures in Vernacular Buildings of North-East India." *Building and Environment* 45 (2): 320–329.

Troi, A. (2011). "Historic Buildings and City Centers: The Potential Impact of Conservation Compatible Energy Refurbishment on Climate Protection and Living Conditions." Paper presented at the Conference on Energy Management in Cultural Heritage, Dubrovnik (Croatia), April 6–8.

US Department of Energy. 2011. "EnergyPlus." Version 7.0. http://apps1.eere.energy.gov/buildings/energyplus