ABSTRACT
In this paper the effect of different roofs on cooling energy need has been evaluated through dynamic simulation of the energy need and of the cooling load of a building model. For the analysis purposes a base module of 100 m$^2$ of floor and a large number of cases (about 900) have been considered changing the characteristics of the roof, (thermal capacity, insulation layer thickness and position, absorptivity of external surface), the insulation position in the other walls and the size and the orientation of the glazings for Rome climatic conditions, in accordance with a factorial plan.

INTRODUCTION
Considering the last 10 years a consistent number of studies has been conducted in order to analyze the influence of thermal mass of building’s components on thermal performance of buildings. Some of them have been focused on external walls’ mass [Gregory et al., 2008, Kossecka et al., 2002], or internal walls mass [Gregory et al., 2008], a few on roof’s mass.

Gregory et al. (2008) studied, by simulation, the effect of thermal mass on thermal performance of residential modules. They considered a simple model and they changed the wall construction systems, entity of windows (with or without), window orientation and addition of an internal wall. The analysis shows that increasing window area requires thermal mass to be increased proportionally; when the wall mass is on the indoor side of the wall the energy need and temperature oscillation is lower than in other cases. Their work emphasizes the role of thermal mass to reduce energy need in residential buildings but actually the simulation has been carried on a module and not on a real building.

Another study about the influence of the position in the wall of thermal insulation (and of the effect of thermal mass) on heating and cooling loads has been conducted by Kossecka et al. (2002). The building considered for the study was a ranch house model exposed to different US climatic conditions. The conclusion was that the best performance occurs when massive material layers are located at the inner side and when they are exposed directly to the interior space.

Aste et al. (2009) have compared six walls with the same thermal resistance but with different thermal capacity and mass. For the comparison a test cell was simulated with an adiabatic envelope with just an exterior wall oriented towards south. The virtual test cell was simulated under the climatic conditions of Milan (Italy) and the heating and cooling energy need was calculated. From the comparison of the different cases evident difference in energy need was found out. On the contrary, the simulation of a sample building on which a parametric study was carried out, shows that the influence of the thermal inertia of different wall systems having the same thermal resistance in building thermal energy demand may be either negligible or relevant depending on the design and the operational parameters (ventilation rates, shading devices, intermittent operation of the system).

About roofs behaviour Sami A. Al-Sanea (2002) has performed a numerical analysis of six roofs under steady periodic climatic conditions during two average days (one which is the average of all days in July and the other which is the average of all days in January). The roofs analyzed differ from each other for presence or not of insulation and the position of insulation (indoor or outdoor). Comparing the cases with insulation indoor or outdoor it is shown that both roofs give the similar amount of mean cooling load, but the trend of temperature inside the roof thickness is very different: when insulation layer is inside, temperature values are very high for almost the whole width, while when insulation layer is outside the temperature drops immediately. Without insulation there are large heat flux oscillations, while the insulation layer leads to much smaller fluctuations and mean values of flux particularly low. An added effect of insulation is that the peak and the minimum load occurs later compared to non insulated roof: the insulation added to the same structure (not depending from the position) introduces a time lag. From the comparison of the same roof with insulation indoor or outdoor, no significant difference are marked in terms of heat transfer loads per square meter, on the other hand the
thermal resistance leads to the major differences in heat transfer loads.

In this work the effect of different roofs thermal properties on cooling energy need has been evaluated through dynamic simulation and with the help of statistical analysis. In particular a new approach is proposed to establish the relative importance of the thermal properties of roof and envelope in determining the cooling energy need over a wide range of configurations. In this way it has been possible to compare the influence of the different variables in predicting cooling energy need entity.

**SIMULATION CASES AND ASSUMPTIONS**

The aim of the work is to understand the role of thermal capacity in the thermal behaviour of a roof coupled with a simple building. For the analysis purposes a base module of 100 m² of square floor and 3 m of internal height has been considered. The floor has been simulated as adiabatic, and the four vertical walls are exposed to the outside facing the four cardinal points. The geometric configuration is such that the roof surface represents the 31% of the total envelope, but it is the 45% of the dispersing envelope, the other 55% being the vertical walls.

The analysis has been conducted in a parametric way considering different combinations of the variables values, as in table 1. The components changed during the analysis are the following:

- roof: three cases of insulation thickness (5 cm, 10 cm, 15 cm); three position of insulation layers (indoor, intermediate, outdoor), fig. 1; three cases of areal mass corresponding to different non insulating layers (wooden slab, clay slab, concrete slab) whose thickness was determined to give the same thermal resistance (table 2); an additional case was the one with an equivalent resistive single layer roof without thermal capacity (reference case indicated as ML); three solar absorption coefficients on the outside surface (α =0.2/0.4/0.6), the inside solar absorption coefficient being constant and equal to 0.3;
- external walls and floor: two position of insulation layer (indoor and outdoor), the same massive structure composed of 0.2 m of clay block and one thickness of insulation layer (5 cm); a solar absorption coefficient on the outside and inside of 0.3, except for the floor with inside solar absorption coefficient of 0.6;
- windows: three different window sizes (without windows, 12% of the floor surface; 23% of the floor); the 100% of the window area collocated on the same façade and two orientations are considered (south and east); the glazing system is a low-e double glass filled with argon with thermal transmittance, $U_d$ of 1.1 Wm⁻²K⁻² and with a SHGC of 0.6; the frame transmittance is 1.2 Wm⁻²K⁻².

All the 900 cases considered have been simulated under Italian climatic conditions, in particular for the city of Rome (Latitude N 42° 54' 39''; Longitude E 12° 28' 54'').

The energy need has been calculated by means of TRNSYS and its multizone building simulation subroutine, Type 56. The simulation hypotheses are the following:

- direct and diffuse solar radiation on internal surfaces are distributed by absorptance weighted area ratios;
- for the long wave radiation internal exchanges, view factor equal to the area fraction and black surfaces are considered;
- fixed value convection coefficients are calculated from the standard EN ISO 6946:2007
- hourly climatic data were calculated from the Italian Standard UNI 10349:1994 for Rome by using the TRNSYS subroutine Type 54 Weather Data Generator;

**Table 1 Parameters**

<table>
<thead>
<tr>
<th>Parameters of the rest of the envelope</th>
<th>Position of the insulation</th>
<th>Percentage ratio $A_{s}/A_{t}$</th>
<th>Orientation of the window</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>External insulation</td>
<td>0%</td>
<td>East</td>
</tr>
<tr>
<td></td>
<td>Internal insulation</td>
<td>11.66%</td>
<td>South</td>
</tr>
<tr>
<td></td>
<td></td>
<td>23.34%</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Roof parameters</th>
<th>Insulation</th>
<th>Position of the massive layer</th>
<th>Materials considered</th>
<th>External solar absorptance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>1 External insulation (IM)</td>
<td>1 Wooden slab</td>
<td>1 α = 0.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2 Intermediate insulation (MIM)</td>
<td>2 Clay slab</td>
<td>2 α = 0.4</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3 Internal insulation (MI)</td>
<td>3 Concrete slab</td>
<td>3 α = 0.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
<td>4 Single equivalent resistive layer</td>
<td>without thermal capacity</td>
</tr>
</tbody>
</table>

**Figure 1** Configurations simulated for roof insulation, IM: external insulation (I); massive layer internal (M); MIM: massive layer, intermediate insulation, massive layer; ML: external massive layer, internal insulation layer; ML: massless roof.
Table 2

<table>
<thead>
<tr>
<th>Characteristics of the massive roof slabs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness [m]</td>
</tr>
<tr>
<td>Thermal conductivity [W/(m K)]</td>
</tr>
<tr>
<td>Thermal resistance [m²K/W]</td>
</tr>
<tr>
<td>Areal mass [kg/m²]</td>
</tr>
<tr>
<td>Thermal capacity [kJ/(m² K)]</td>
</tr>
</tbody>
</table>

Influence of the insulation thickness

The increment of the insulation layer thickness leads to an increase of the seasonal cooling energy need in all cases except in the unrealistic case of building without windows, as shown in figures 4a and 4b. The same figures allow to compare the three roofs analyzed. The roof thermal capacity influences the entity of cooling energy need just when collocated inside (both in the cases of external and intermediate insulation): in these cases, in fact, the concrete roof gives the lower energy need.

If the roof is internally insulated all the performance are similar with slightly lower cooling needs with the wooden slab.

External or intermediate insulation is always preferable to the internal one.

All these behaviours are much more evident when external vertical walls are insulated on indoor surface and with the larger values of window area.

HOURLY ENERGY NEED ANALYSIS

Analysing the thermal load profiles for a day in July (fig. 5) it is possible to notice the sinusoidal trend of the load when no solar gains enter inside the building through transparent envelope components. In this case the increasing of insulation thickness leads to a decrement in the load amplitude and in a minor way to a shift of maximum and minimum values. When solar radiation enters into the building the heat flux is no more sinusoidal and the decrement due to insulation thickness is not so evident as in the previous case (figure 5d, 5e, 5f). Comparing the hourly energy need when the massless roof is considered with hourly energy need when the wooden, clay and concrete roofs are simulated, it can be seen that the roof thermal mass influences the amplitude of the oscillation and the shift of the maximum and the minimum of the oscillation. Considering the cases with windows, for roof with the same thermal transmittance, the increment of the thermal mass influences the decrement but it does not influence the time shift of peaks.

STATISTICAL ANALYSIS

A statistical analysis of the monthly cooling needs collected has been performed. The inferential statistical technique employed is a multivariate linear regression with a confidence level of 95%. In the models developed, the added variables have been selected through the stepwise algorithm among:

a. the variables related to the envelope, except the roof:
   - the internal heat capacity of the vertical walls and the floor \( A_{env} C_{env} \) [kJ/K]
   - the glazings area \( A_{gl} \) [m²]
   - the equivalent window cooling degree days CDD, determined in accordance with
Gasparella et al. (2011), where the sol-air temperature for glazings is defined by Eq. (1) [K d]
\[
\theta_{\text{sol-air,gl}} = \theta_{c} + \frac{g_{l}}{U_{gl}} + R_{se} \cdot h_{r,sky} \cdot (\theta_{sky} - \theta_{c})
\] (1)

b. and the roof characteristics:
- the stationary thermal transmittance $U_{\text{roof}}$ [W/(m² K)]
- the internal heat capacity $C_{\text{roof}}$, estimated by means of the detailed method proposed by the EN ISO 13786:2007 [kJ/(m² K)]
- the periodic thermal transmittance $Y_{se,\text{roof}}$ according to EN ISO 13786 [W/(m² K)]
- the equivalent roof cooling degree days $CDD_{\text{roof}}$, defined as in Eq. (2) [K d].

\[
CDD_{\text{roof}} = \sum(26 - \theta_{\text{sol-air,roof}})
\] (2)

Where:
\[
\theta_{\text{sol-air,roof}} = \theta_{c} + \frac{I_{a} + h_{r,sky}(\theta_{sky} - \theta_{c})}{h_{se}}
\] (3)

and 26°C is the cooling temperature of setpoint. For each solar absorptance, a different $\theta_{\text{sol-air,roof}}$ has been evaluated and so a different monthly $CDD_{\text{roof}}$ value.

In addition to the single variables described above, some composite quantities in terms of products between simple variables have been considered as significant in predicting the cooling need and they have been included in the analysis:
- the interactions between the $CDD_{\text{roof}}$ with the stationary thermal transmittance;
- the product between the $CDD_{\text{roof}}$ with the periodic thermal transmittance;
- the product between the $CDD_{gl}$ and the glazings area.

The developed model has been reported in Table 3. Standardized coefficients, are obtained multiplying the un-standardized coefficients by the ratio between the standard deviation of the independent variable selected and the one of the dependent variable. Analyzing the standard coefficients, it is possible to compare the influence of the different variables in predicting cooling energy need entity.

The parameter with the largest influence is the product of the glazings area and the equivalent window cooling degree days, $A_{gl} \cdot CDD_{gl}$. Second in order of importance there is the equivalent roof cooling degree days $CDD_{\text{roof}}$ which are about the 30% of the previous one, that means the external solar absorptivity of the roof is less important than the windows radiative properties in determining the cooling needs but it is the most relevant among the roof parameters. The amount of the glazings surfaces and other thermal properties of the building envelope.
as roof thermal transmittance and roof capacity are less relevant.

The internal heat capacity of the vertical walls and the floor, $C_{env}$, and the internal heat capacity of the roof, $C_{roof}$, have a comparable behavior, even if the first one is more influent. The roof thermal transmittance is also significant, both if considered as a single factor and if taken into account in interaction with the equivalent cooling degree days for the roof. On the contrary the roof periodic thermal transmittance, both alone and with the CDD$_{roof}$, has a negligible contribution.

**Table 3**

Regressive model elaborated. The depended variable “cooling energy need” is considered in [kWh]

<table>
<thead>
<tr>
<th>Variables</th>
<th>Unstd. Coefficients</th>
<th>Std Coeff.</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{gl}$</td>
<td>17.428</td>
<td>8.815</td>
<td>0.048</td>
</tr>
<tr>
<td>$CDD_{gl}$</td>
<td>0.023</td>
<td>0.000</td>
<td>1.002</td>
</tr>
<tr>
<td>$C_{roof}$</td>
<td>2.729</td>
<td>0.091</td>
<td>0.364</td>
</tr>
<tr>
<td>$A_{gl}$</td>
<td>-13.938</td>
<td>0.405</td>
<td>-0.259</td>
</tr>
<tr>
<td>$A_{env}$</td>
<td>-0.014</td>
<td>0.001</td>
<td>-0.090</td>
</tr>
<tr>
<td>$C_{env}$</td>
<td>-1.465</td>
<td>0.078</td>
<td>-0.064</td>
</tr>
<tr>
<td>$U_{roof}$</td>
<td>-288.89</td>
<td>21.441</td>
<td>-0.062</td>
</tr>
<tr>
<td>$U_{roof} \cdot CDD_{roof}$</td>
<td>1.783</td>
<td>0.278</td>
<td>0.082</td>
</tr>
<tr>
<td>$Y_{ic,roof}$</td>
<td>54.169</td>
<td>14.194</td>
<td>0.019</td>
</tr>
<tr>
<td>$CDD_{gl}$</td>
<td>-0.009</td>
<td>0.003</td>
<td>-0.020</td>
</tr>
<tr>
<td>$Y_{ic,roof} \cdot CDD_{roof}$</td>
<td>0.513</td>
<td>0.220</td>
<td>0.023</td>
</tr>
</tbody>
</table>

In conclusion, the summer heat balance is highly dependent on the properties of the transparent surfaces; the roof characteristics seem to be of relevant importance only as regards the solar radiation absorbed on the outer surface (absorptivity).

In figure 3 it is possible to see that the model has good capacity in describing the data distribution. In fact the value of the adjusted coefficient of determination, $R^2_{adj}$, is quite high and equal to 86%.

In order to understand more precisely the influence of the roof in determining the cooling need, the cases without solar gains have been analyzed alone. As shown in table 4 this second model has a lower coefficient of determination but it is still relevant for discussing the different properties of the roof:

- the equivalent cooling degree days for the roof are confirmed as the main parameter, and so the external solar absorptivity of the roof is significant in cooling need determination;
- the roof stationary thermal transmittance is present both in interaction with the CDD, and as a single factor;
- the periodic thermal transmittance is still negligible with respect of the other parameters;
- the heat capacity terms have been excluded from the model, probably because of the lack of solar radiation entering into the zone.

**Table 4**

Regressive model for the cases without windows. The depended variable “cooling energy need” is considered in [kWh]

<table>
<thead>
<tr>
<th>Variables</th>
<th>Unstd. Coefficients</th>
<th>Std Coeff.</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Constant)</td>
<td>42.818</td>
<td>9.773</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$CDD_{roof}$</td>
<td>1.166</td>
<td>0.089</td>
<td>0.565</td>
</tr>
<tr>
<td>$U_{roof} \cdot CDD_{roof}$</td>
<td>1.427</td>
<td>0.268</td>
<td>0.254</td>
</tr>
<tr>
<td>$U_{roof}$</td>
<td>-109.49</td>
<td>29.419</td>
<td>-0.088</td>
</tr>
<tr>
<td>$Y_{ic,roof}$</td>
<td>29.512</td>
<td>11.256</td>
<td>0.036</td>
</tr>
</tbody>
</table>

**CONCLUSION**

This study is focused on the effect of roof thermal characteristics on cooling energy need and on cooling thermal loads of a simple model of building. The roof characteristics investigated are in particular: the thermal resistance, the thermal capacity, the mass position with respect to the insulation layer, the external solar absorptance. Looking to the thermal resistance it has been shown that cooling energy need increases when insulation thickness increases, but this phenomenon doesn’t happen if solar gains through windows are not present (which is the simulated case without windows). As far as the thermal load is concerned the variation of roof thermal resistance leads to a decrement of peak and minimum load, but produces very little effect on time lag of the peaks. When there are windows admitting solar radiation entering, the insulation (that means the thermal resistance) does not produce any effect on time lag nor on decrement of loads.
From the comparison of different roof slabs (wooden, clay and concrete) it has been shown that the increment of the thermal capacity of the roof, for the same thermal resistance, has more evident effect on the hourly thermal loads for that cases in which the thermal resistance is lowest. Thus in Mediterranean climatic conditions it seems preferable to have roof with low thermal resistance and high thermal capacity in order to have lower cooling loads. Concerning the position of the mass (and consequently of the thermal capacity) with respect to the insulation layer, results are not the same for the three kinds of roof. For wooden and clay roofs the mass best position to minimize cooling load and also cooling needs is the inside one that means the IM configuration. But for the concrete roof the best configuration is the MIM, with the mass half on the outside and half on the inside face of the insulation layer. This behavior has been already highlighted in Kontoleon et al. (2007) and in Kontoleon et al. (2008) for a wall with similar heat capacity as the concrete roof of this study.

Considering the effect of the mass on the peaks time lag it has been shown that the roof mass produces negligible time lag when windows are present. On the contrary, for the case without windows the entity of the roof mass determines the time lag of the thermal load peaks. This time lag is however evident for consistent increasing in thermal capacity, that means increasing of 100 kJ m$^{-2}$ K$^{-1}$ (as it happens changing from the case without mass to the wooden roof, or changing from the wooden roof to the concrete one).

About the influence of roof solar absorptance on outside surface, the study lets emerge that for high values of this parameter the differences in cooling energy need, due to the presence of the thermal mass are more evident: that means that the thermal mass plays a more important role in energy need determination when the solar absorptance is higher.

The statistical analysis has shown in particular that the most significant parameters in predicting cooling energy need entity are the properties of the windows associated with their entity, but also the solar absorptance of roof, which is also related to the quantity of solar irradiation entering inside the building. Moreover the stationary thermal transmittance of roof seems to have the same importance as its thermal capacity. The periodic thermal transmittance is not found to be a significant parameter in predicting the cooling energy need.

If the results, from one hand, confirm some of the initial expectations, from the other hand they represent the final outcome of an original approach application. This methodology enables to check the credibility of the conclusions in a very wide range of configurations, discriminating the sensitivity of the cooling needs to different variables. This approach has put in evidence the relative contribution of single factors to the global performance (cooling needs), cutting out some unexpected variables (the thermal mass for instance) and establishing an order of importance between the really significant variables. In particular the methodology has highlighted the slight importance of the envelope thermal mass not only for extremely high insulated buildings, but also for buildings with the minimum insulation prescribed by the Standards. This consideration is, especially for European context, of particular interest because many countries’ legislations have imposed limitations on thermal mass or on properties depending from thermal mass. As put in evidence from this work thermal insulation and roof solar absorptance influence the cooling need much more than periodic transmittance.

**NOMENCLATURE**

- $A$ area [m$^2$]
- $C$ heat capacity [J/(m$^2$ K)]
- $CDD$ cooling degree days [K d]
- $h$ surface heat transfer coefficient [W/(m$^2$ K)]
- $I$ global irradiance [W/m$^2$]
- $Q$ cooling energy need [kWh]
- $R$ thermal resistance [m$^2$ K/W]
- $U$ thermal transmittance [W/(m$^2$ K)]
- $Y$ periodic thermal transmittance [W/(m$^2$ K)]

**Greek**

- $\alpha$ solar absorptance [-]
- $\theta$ temperature [°C]

**Subscripts**

- $c$ cooling
- $e$ external
- $env$ referred to the envelop (roof excluded)
- $f$ floor
- $g$ g-factor
- $gl$ referred to the glazings
- $i$ internal
- $r$ radiative
- $roof$ referred to the roof
- $s$ surface
- $sol-air$ solar-air
- $sky$ referred to the sky dome

**REFERENCES**


N. Aste, A. Angelotti, M. Buzzetti, The influence of the external walls thermal inertia on the energy


Figure 4 Annual cooling energy need in kWh for different roofs in the case without windows (a, b); windows area 23% (c, d); walls external insulated (a, c), walls internal insulated (b, d), windows orientation towards south (a, b, c, d); absorptance 0.6 (a, b, c, d)
Figure 5 Hourly heat flux towards outside on 13th July; for the case without window (a, b, c) and with window area of 11% (d, e, f). Internal insulated walls and absorptivity of 0.6; insulation layer thickness of 5 cm (a, d); 10 cm (b, e) and 15 cm (c, f)