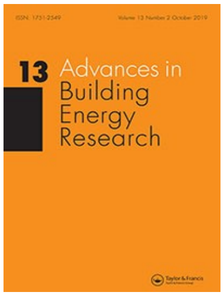


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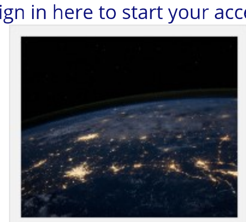

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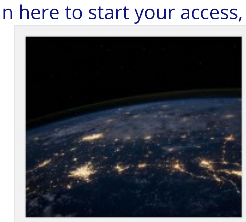



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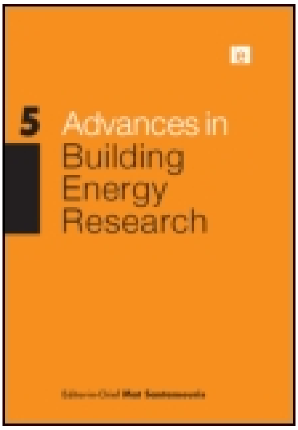


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# Cool roof and ventilation efficiency as passive cooling strategies for commercial low-rise buildings - ground thermal inertia impact

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# Cool roof and ventilation efficiency as passive cooling strategies for commercial low-rise buildings – ground thermal inertia impact

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Commercial low-rise buildings are often characterized by weak energy performances, and heat transfers through roof and ground are prevalent. The roof design and its opening system is a key factor of the thermal performance. Skylights and radiative properties of roof coating have a direct impact on solar gains, thermal losses and natural ventilation potential. The overall performance depends on the combination of these design parameters (solar reflectance and opening size), on the weather conditions and on the inertia given by the slab on the ground. The roof design performance depends on the ground which determines the dynamic behavior of these buildings. A generic case study is modeled and an extensive parametric study (about 840 annual simulations) is performed to point out these key parameters' impacts on energy demand and comfort. The combination of efficient roof techniques (skylights and cool roof) along with a high thermal inertia of the building can be an adequate passive cooling solution in summer, with a 99.8% drop in degree-hours above the discomfort temperature in summer. Nevertheless, we show that these passive strategies could not be totally efficient without taking care of the ground thermal inertia which account up to 58.6%.

**Keywords:** commercial building; thermal inertia; ventilation; cool roof; thermal building simulation



## 1. Introduction

With a growth of 1% per year, the world population estimated at 8.2 billion in 2030 will raise energy demand up to 87% (2006–2030) especially for non-Organisation for Economic Co-operation and Development (OECD) countries (IAE, 2008). The main part of energy use is dedicated to supply the building energy needs in urban areas. In France, 43.87% of the energy consumption in 2010 (Chiffres clés de l'énergie édition, 2012) is allocated for the building sector (71 Mtoe). A total of 20.9% of this energy is required by the tertiary and commercial sector (Rabai, 2012). The part dedicated to the tertiary sector has continuously increased, and is 15% higher than in 2001.

The present study aims at defining design key factors to improve the energy performance of commercial low-rise buildings by seeking to reduce the heating energy demand while providing thermal comfort in summer without a cooling system. The combination of cool roof to limit the solar heat gains through the roof and ventilation to reject the heat stored by the building is investigated here as passive cooling techniques to meet thermal comfort requirements in summer.

The main principle of cool roof is to reduce radiative heat gain by modifying its solar reflectance and thermal emittance. With this technique, roofs coated by high solar reflectance material

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will reflect more solar radiation, while the absorbed heat is emitted to the sky due to high thermal emittance. There is a direct effect on the building cooling load reductions which can vary between 10% and 40% and, as underlined by Santamouris (in press), many studies have demonstrated the effect of cool roofs on urban heat island mitigation, especially for an albedo above 0.7. At the European level, as well as the Cool Roof Rating Council (CRRC) in the USA, a European Cool Roof Council (ECRC) was set up after several experiments that confirmed the interest of cool roof technology (Synnefa & Santamouris, 2012). The experimental and numerical results highlighted that cool roof technology reduces indoor temperature by 1.2–2°C, saves 10–40% of air conditioning energy and decreases heat island effect by 1–2°C depending on building characteristics and climatic conditions. Bozonnet, Doya, and Allard (2011) conducted a study for moderate climate in France which shows a result of 10°C roof surface mean temperature decrease, in summertime, due to cool roof technology. For Mediterranean climate regions, the cool roof application was found to be the most effective solution compared with increased insulation and other different cooling technologies such as windows improvement for a specific building study (Kolokotsa, Diakaki, Papantoniou, & Vlissidis, 2012; Romeo & Zinzi, 2013). In commercial buildings, using these techniques, the roof peak temperatures can decrease up to 42°C in summer (Akbari, Levinson, & Rainer, 2005; Xu, Sathaye, Akbari, Garg, & Tetali, 2012). In these studies, cooling energy demand was reduced up to 20 Wh/m$^2$/day (52% of total energy requirement) and $CO_2$ emission decreased from 11 to 12 kg $CO_2$/m$^2$ of flat roof area.

Depending on the ambient temperature, natural and night ventilation can help to mitigate building overheating. A study conducted by Wang, Yi, and Gao (2009) indicated that night ventilation is an effective passive cooling technique, especially in the northern hemisphere. Night ventilation can reduce the average indoor temperature from 1.5°C to 4°C (Blondeau, Spérandio, & Allard, 1997; Geros, Santamouris, Tsangrasoulis, & Guarracino, 1999; Kubota, Chyee, & Ahmad, 2009; Shaviv, Yezioro, & Capeluto, 2001) according to the location, envelopes and building operation.

As for the roof, the large surface of the slab on the ground and the soil characteristics are key parameters in the energy balance and for the overall performance including the roof techniques for commercial low-rise buildings. Most studies focus on typical houses, but even in those studies the ground floor effect is not negligible; thus a study conducted by Labs, Shen, Huang, Parker, and Carmody (1988) on heat loss through a non-insulated floor showed that 10% of the energy losses are attributed to the floor for poorly insulated and up to 30% to 50% for well-insulated walls/roof buildings. Moreover, the ground is a key factor considering its thermal inertia potential for low-rise buildings which are often built with low inertia materials (mainly metallic construction). The study of a test cell (small building) by Aste, Angelotti, and Buzzetti (2009) showed a 10% difference in the heating loads between high and low thermal inertia envelopes. So the thermal performance will depend both on the thermal inertia (including shelving) and on the passive cooling techniques. Particular attention has to be paid to their combination as it has to be handled properly to reduce building energy consumption.

In this paper, we will demonstrate the effect of cooling strategies (cool roof and natural ventilation) on a typical case study of low-rise commercial buildings. The building energy demand and adaptive thermal comfort model is detailed in the following parts and takes into account all the main parameters with coupled heat and airflow transfers. Parametric analyses are performed to highlight the single and combined impacts of the cool roof, natural ventilation and ground/shelving thermal inertia.

## 2. Case study description and passive cooling strategies

### 2.1. Description of the typical commercial building

The study is carried out on a cube-shaped one-floor commercial building located in Mediterranean climate (Marseille, France, Figure 1).

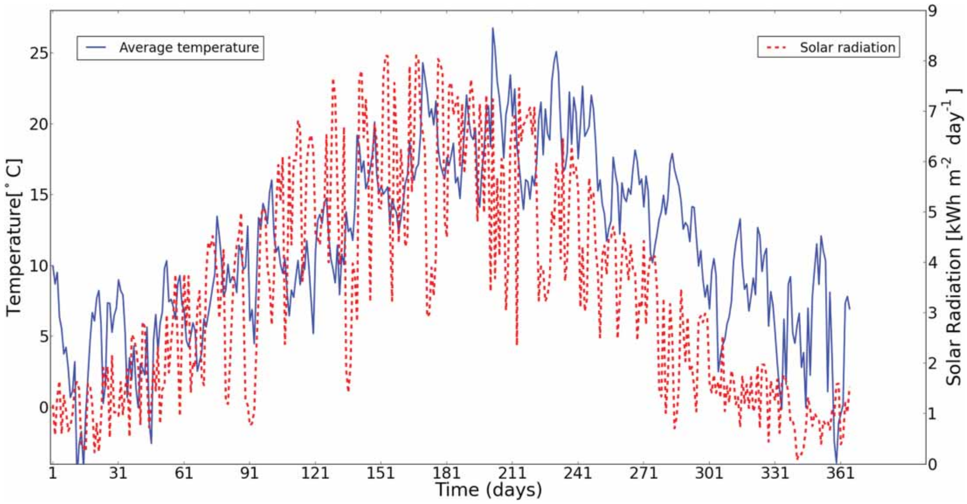


Figure 1. Climate of Marseille.



The building surface is a square of 36 m sides (Figure 2), its height is 6 m and its steel structure with a large flat roof surface is covered by 16 skylights, i.e. 2.4% (31.36 $m^2$) of the roof area.

The vertical walls (except the northern one) include 30 $m^2$ of windows. The vertical exterior walls are well insulated and have a total thickness of 30.5 cm (1.3 cm of gypsum, 14 cm of glass wool, 15 cm of rock wool and an outer steel cladding of 2 mm). The ground thermal inertia of the building is mainly due to the concrete slab (160 mm thick with no thermal insulation) which directly lies on sand. It is assumed that the commercial shelves occupy 10% of the building volume (787.9 $m^3$). It consists of cardboard (40%), liquids/oils (30%), metals (10%) and plastics (20%). A heating system is installed but no cooling system. To ensure fresh air renewal, a heat recovery ventilation (HRV) system provides 0.75 air changes per hour (ACH) during daytime. The occupancy period of this building is 07:00 am–10:00 pm every day except on Sunday.

### 2.2. Cooling strategies: cool roof and natural ventilation

A roof surface albedo of 0.3 is given for this reference building. For the parametric study, the cool roof strategy is studied through the modification of the roof coating albedo from 0.1 to 0.9. The high thermal emissivity (0.9) is considered constant.

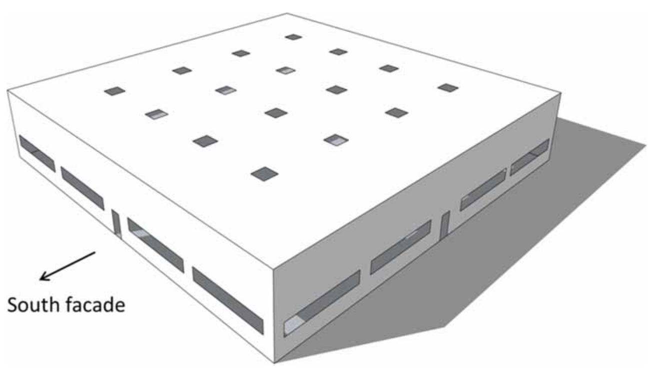


Figure 2. Geometry of the studied commercial building.

Natural ventilation is provided by opening some skylights and windows. This ventilation is carried out in summer during nights from 08:00 pm to 06:00 am only when the indoor air temperature is 2°C higher than the ambient temperature. Mechanical ventilation remains in operation during the summer and can be adjusted based on requirements.

## 3. Building models

The simulation of the commercial low-rise building has been performed using the coupling between the transient system simulation tool (TRNSYS) building model (Type 56) and the muntizone airflow and contaminant transport analysis software (CONTAM) airflow model under the TRNSYS 17 simulation environment. As illustrated in Figure 3, the building is modeled as a unique zone (nodal approach) that interacts with the following main elements: the *Airflow Model* used to calculate the airflow rates through the openings and the envelope, the *Roof Thermal Model* to account for the cool roof radiative properties and the *Ground Thermal Model* to evaluate the heat transfer through the ground.

Two modeling levels have been used to calculate the heat transfer through the ground: the so-called one-dimensional model (1D) and the adiabatic one. Note that those models account for heat transfer only; no moisture transfer is considered here. These two models represent, respectively, a non-insulated ground slab and a high insulated ground slab.

The 1D model, illustrated in Figure 4, splits the ground below the concrete slab into two layers of the same soil. The first layer, modeled as a massive layer, accounts for thermal inertia and is defined as a wall in the TRNSYS building model. The second layer is modeled as a resistance layer, with no thermal inertia, and is referred to as the massless layer. As shown by Adjali, Davies, Rees, and Littler (2000), the temperature of the ground at a depth of 10 m can be considered independent of the building behavior. Consequently, the total thickness above the building has been set up to 10 m. The temperature at the lower boundary ($T_{\text{ground}}$) is calculated by the following relationship (Eckert & Drake, 1987; Kusuda & Bean, 1984):

$$T_{\text{ground}}(z,t) = T_{\text{m}} - T_{\text{a}} e^{-z \times \sqrt{\frac{\pi}{365\alpha}}} \times \cos\left(\frac{2\pi}{365}\left(t - t_{\text{p}} - \frac{z}{2}\sqrt{\frac{365}{\pi\alpha}}\right)\right), \tag{1}$$

where $T_{\text{m}}$ (°C) is the mean annual ground temperature; $T_{\text{a}}$ (°C) the annual temperature amplitude at the ground surface ($z = 0$ m); $z$ (m) the subsurface depth of soil; $t$ the time of the

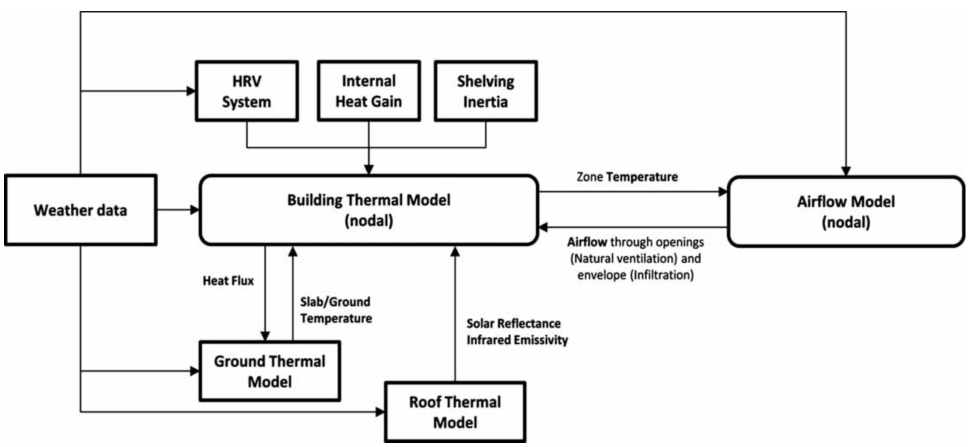


Figure 3. Schematic representation of the building energy simulation coupling process.

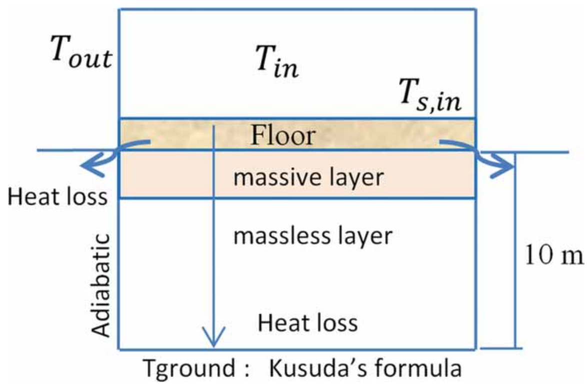


Figure 4. 1D model of ground heat transfer.



year (in days); $t_p$ the phase constant of the day of minimum surface temperature and $\alpha$ (m²/day) the thermal diffusivity of the soil.

A parametric study has been performed (Lapisa, Bozonnet, Abadie, Salagnac, & Perrin, 2013) to evaluate the smallest thickness of the massive layer needed to ensure a good representation of the ground thermal inertia. The proposed model with a thickness of 30 cm of massive layer gives proper results regarding the heat transfer through the ground and compared with a reference ground model, three-dimensional and more precise but with a greater computing time (McDowell, Thornton, & Duffy, 2009; Zhou, Rees, & Thomas, 2002).

A simplified model (adiabatic) is also used in order to characterize the effect of the ground thermal inertia on the building energy demand and comfort. For this model, there is no heat transfer below the concrete slab so that no ground thermal inertia is taken into account.

For both models, the cold bridges between the slab and outside are calculated according to the standards (EN ISO 13370, 2007)

## 4. Passive cooling potential of cool roof and natural ventilation

The parametric study is based on the previously defined reference building: low roof solar reflectance (0.3), operation of mechanical ventilation during the occupancy period only and closed skylights (no natural ventilation). In the following parts, the criteria for indoor overheating (based on operative temperature) during summer and occupancy hours are:

- The degree-hours (DH) above the adaptive summer comfort temperature defined by the standard EN-ISO-15251. DH (°C h) drops are proportional to cooling energy gains required for a mechanically cooled building.
- The discomfort ratio based on the occupancy hour's ratio above summer comfort temperature (EN-ISO-15251).

### 4.1. Impact of cool roof

The temperature evolutions are compared (Figure 5), for three days in summer (1–3 August) using both ground heat transfer models and two roof solar reflectance values (0.3 for standard roof and 0.9 for cool roof): ambient temperature ($T_{ambient}$), roof surface temperature ($T_{s\text{-}roof}$) and indoor operative temperature ($T_{op}$).

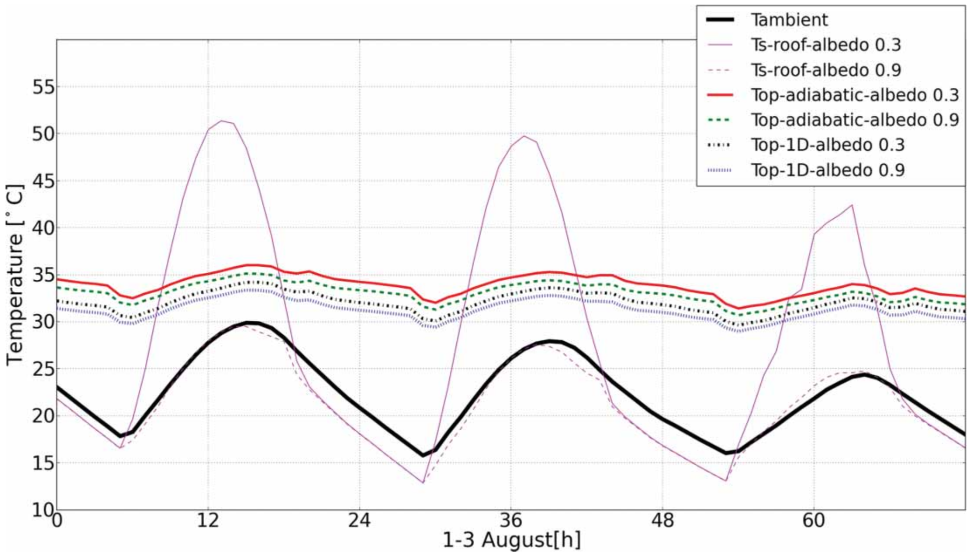


Figure 5. Ambient, operative and roof surface temperatures in summer.

The temperature peaks occur in the 12:00 am–03:00 pm interval. In the presence of a cool roof coating, the solar absorption decreases and the roof external surface temperature drastically drops by 22°C whereas the operative temperature is reduced by only 1°C. This comes mainly from the highly insulated roof that lessens the effect of very high temperatures at the external side. However, the ground thermal inertia impact, assessed from the differences between the 1D and adiabatic models, is more significant on the operative temperature with a difference of about 2.5°C (Figure 5) for all albedo values. This inertia effect and the heat transfers to/from the ground are facilitated by the lack of insulation below the slab which mitigates the indoor air overheating.

Figure 6 presents the cool roof effects evaluated with the previously defined summer comfort criteria (DH and discomfort ratio) for the building with or without ground thermal inertia (two ground models) and with or without shelving.

DH reductions of 46.8% for the ground-coupled building and 35.6% for the adiabatic one are observed for an albedo variation from 0.1 to 0.9 (Figure 6(a)). The ground thermal inertia participates in reducing the DH from 3060°C h to 1265°C h (58.6%) for the reference building (albedo of 0.3) and from 1970°C h to 673°C h (65.8%) for the building with the cool roof. On the other hand, shelving also absorbs a significant portion of the heat from the indoor air and reduces the DH value by about 24.2% compared with an empty building. For this type of well-insulated building, the ground inertia impact is really important, i.e. the ground insulation can reverse the benefits from an increased albedo.

Figure 6(b) presents the discomfort ratio versus albedo. A trend similar to the DH results is observed here with the exception of the shelving effect which does not have a significant impact on the discomfort ratio. This is due to the too small shelving thermal inertia; this result highlights the importance of the design and the minimal thermal inertia needed for summer thermal comfort.

The cool roof decreases the solar heat gains in all seasons and so the operative temperature in summertime for a passive cooling solution. For a mechanically cooled building, this would decrease the cooling energy demand. On the contrary, this technique can penalize the winter

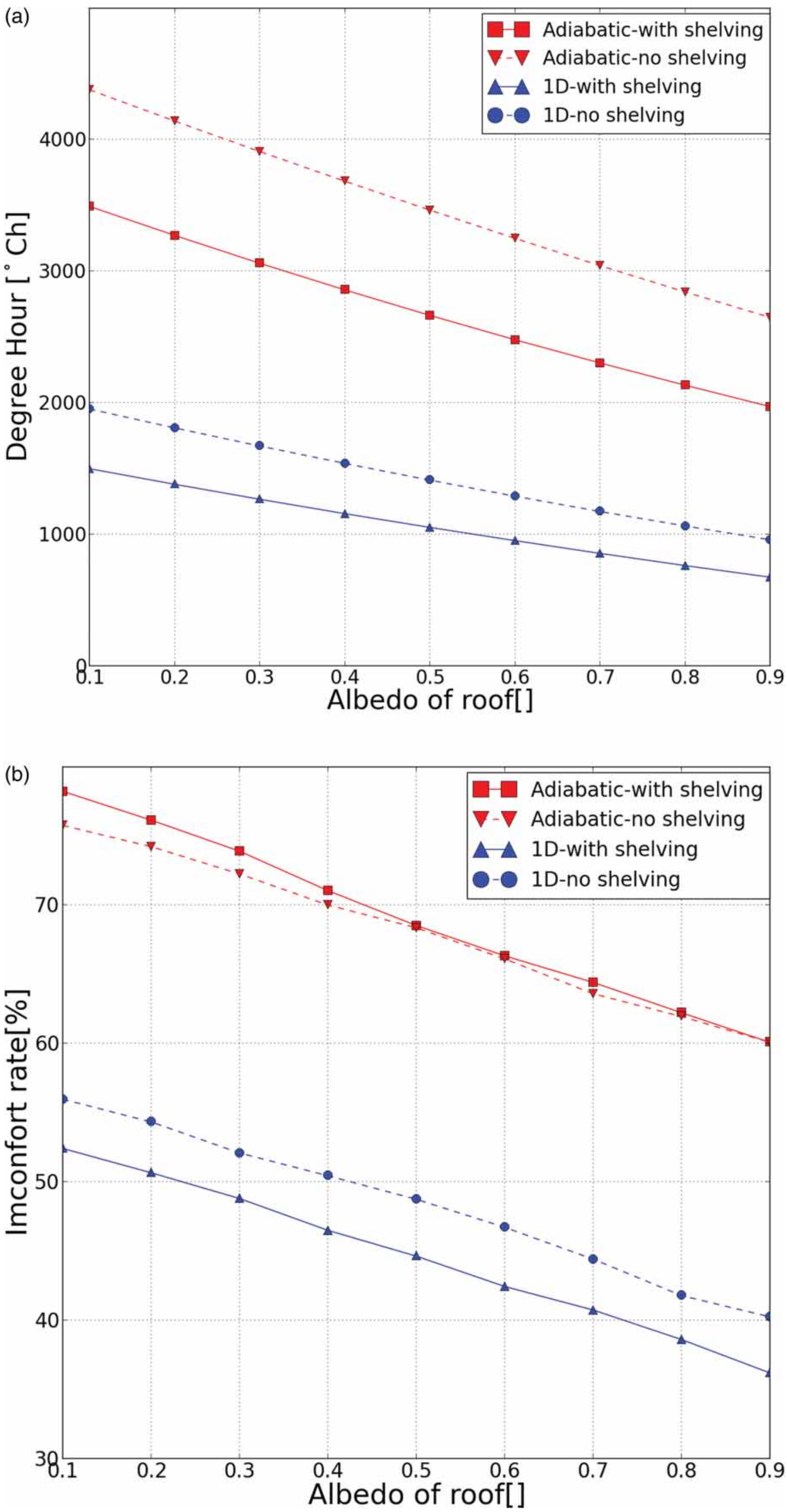


Figure 6. Effect of the roof albedo on (a) DH (°C h) and (b) discomfort ratio.

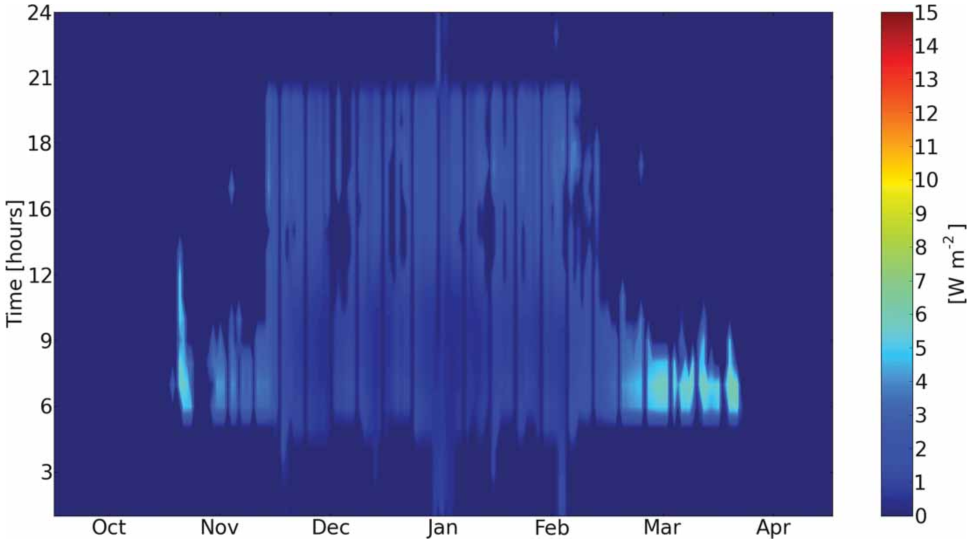


Figure 7. Heating load penalty due to the cool roof technique (W/m$^2$).

energy performance by decreasing the solar heat gains from the roof. Although the study focuses on passive cooling performances, in Figures 7 and 8 the overall effect on energy demand for winter and summer is analyzed in order to compare both heating demand penalty and cooling benefits.

Figure 7 presents the additional heating load needed during computation for each hour of the days, and especially for the occupancy period (06:00 am–10:00 pm). Note that this representation that gives a global view of the variability according to the hour of the day and for the whole year has been previously proposed by Foldbjerg and Asmussen (2013).

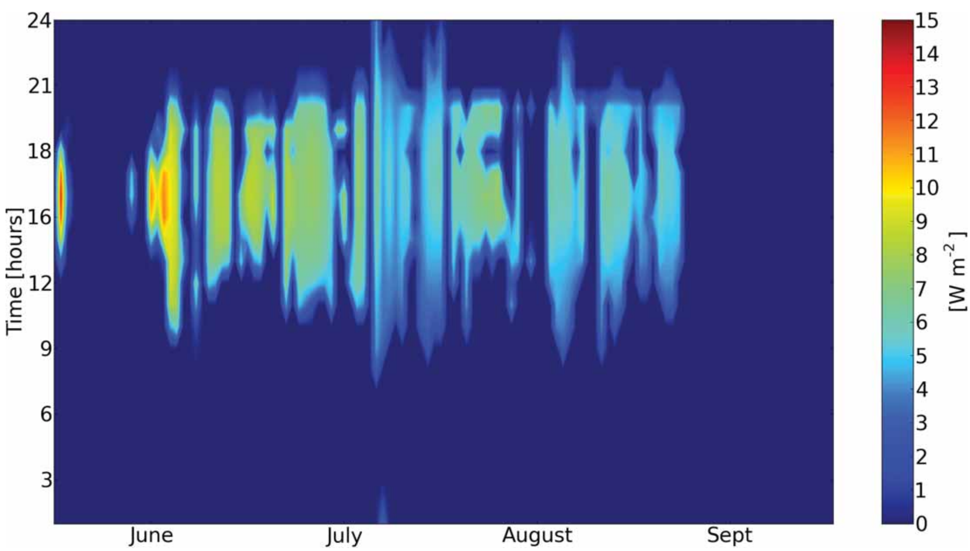


Figure 8. Cooling load saving due to cool roof technique (Wh/m$^2$ years).

Although the heating period starts at the beginning of October until 21 May for the present geographical region (43.3° latitude), the heating system is actually operating at the beginning of November. During the months of November and March, the required additional heating energy is higher than for the rest of the winter. During these periods, the sun is still high in the sky and the potential heat gain from solar irradiation is higher on a horizontal roof. The high reflectivity of the cool roof lessens this heat gain. Between December and February, the solar angle is small and the sky is not always clear so that the solar heat gains are lower for both the cool roof and the reference one. We can conclude that the penalty on heating demand due to the cool roof is noticeable during mid-season but very low during winter. Because of the thermal inertia of the building (including the ground slab), the period of additional energy supply spans after daytime even though there is no more solar radiation. This shifting time clearly depends on the characteristics of the building envelope, the shelving and the soil. The annual heating energy penalty due to the cool roof coating is only 2.39 kWh/$m^2$ year (11%).

The positive impact of the cool roof during summer is studied here as cooling load savings (Figure 8), considering an air-conditioning system.

The solar gain decreases and induces significant cooling energy savings during the 09:00 am–21:00 pm period, especially when solar irradiation is high (June to August). The annual cooling energy saving amounts to about 3.49 kWh/$m^2$ year (33.8%). A benefit of 1.1 kWh/$m^2$ year (3.4%) is obtained on annual energy balance, integrating energy savings and losses for both seasons. This balance of sensible energy needs does not take into account the efficiency differences of cooling and heating systems.

Heating and cooling needs vary according to the solar irradiation, especially during the summer period as outlined in Figure 9.

During winter (Figure 9(a)), the relative difference due to the cool roof is very low and the heating power variation with solar irradiation is not as noticeable as for the typical summer day (Figure 9(b)). The cooling demand increases in a similar way as the solar irradiation with a time shift of several hours due to the inertia which performs in a same way for both reference roof and cool roof.

## 4.2. Impact of ventilation

### 4.2.1. *Impact of natural ventilation*

Figure 10 shows the impact of opening the skylights on the natural ventilation flow rate and the DH above adaptive temperature. The flow rate increases almost linearly with the skylight opening area. Among the different calculations, the flow rate only slightly differs at the highest opening area showing that wind is the predominant parameter and not ambient to indoor temperature difference. The adiabatic case (red curves) with higher indoor temperatures (see previous section) presents the highest flow rate which demonstrates that the temperature gradient acts with the wind-driven ventilation in the present configuration.

As illustrated by the other two graphs (Figure 10(b) and (c)), using natural ventilation during night to decrease DH is very efficient even at very low airflow. DH values (for occupancy period) sharply decrease with an increase in skylight opening, dropping down to 79.2% for the maximal opening value. In this case, the shelving is also important as the night cooling participates in the indoor temperature reduction during daytime. Then, the ground and the shelving thermal inertias are important factors which have to be taken into account in the assessment of the efficiency of the natural ventilation as a passive cooling technique.

### 4.2.2. *Impact of mechanical ventilation scenario*

Two mechanical ventilation scenarios have been defined: ventilation during the occupation period (*occ*) and permanent (*occ* + *Nighttime*). Without natural ventilation, permanent mechanical

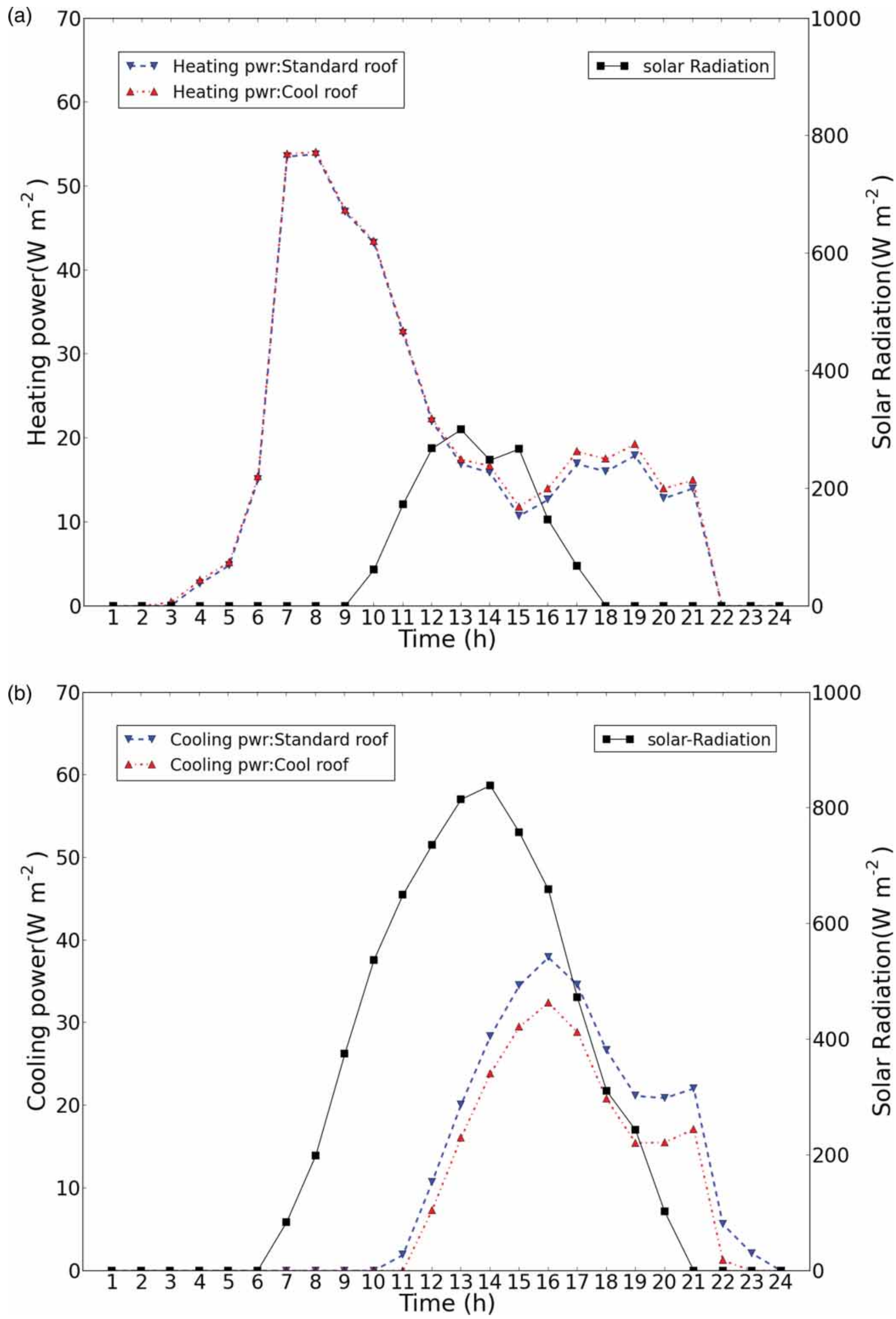


Figure 9. Heating and cooling loads and solar irradiation; (a) heating demand on 31 December and (b) cooling demand on 30 July.

ventilation (Figure 11) brings a reduction in DH from 1265°C h to 221°C h (6 times smaller). Mechanical ventilation during night is actually effective enough in reducing temperatures for the next day. Note that the mechanical ventilation rate (0.75 ACH) is on the same order of the

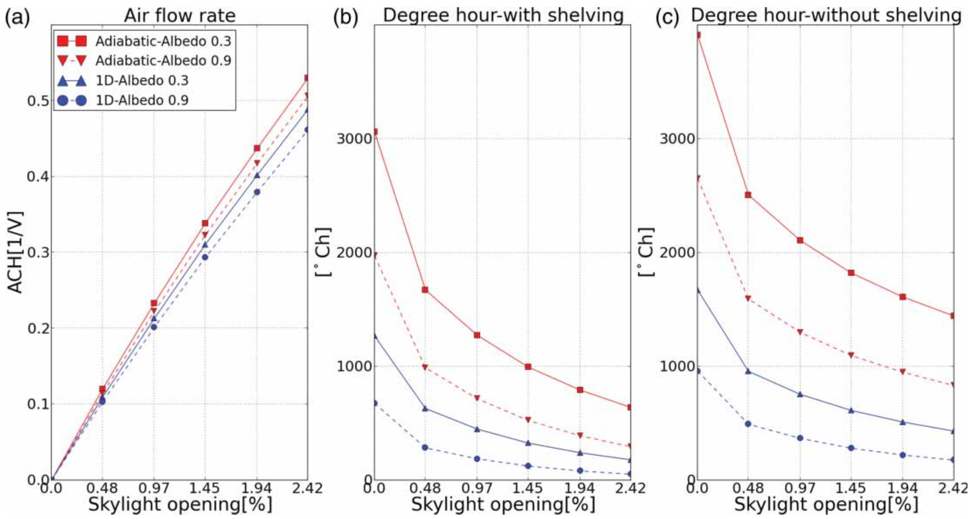


Figure 10. Skylight ratio effect on (a) natural ventilation rate (ACH), (b) DH with shelving and (c) without.

mean night-time natural ventilation with all the skylights opened (about 0.5 ACH). The combination of mechanical ventilation and natural ventilation during the night can avoid thermal discomfort during occupancy by reducing the DH by 97.6% as illustrated in Figure 11.

### 4.3. Passive cooling strategies

Following this study of passive cooling strategies alone (i.e. cool roof and natural ventilation), the present section aims at evaluating their combined effect along with the thermal inertia brought by the ground and the shelving. Here, the indoor overheating during summertime and occupancy hours is highlighted by the average of maximum daily temperatures and the DH (DH above adaptive comfort temperature following the EN-ISO-15251).

#### 4.3.1. *Cool roof and natural ventilation coupled effects*

The potential of the coupling of both cool roof and natural ventilation is analyzed (Figure 12), varying both parameters of skylight opening and roof albedo. The two graphs have the same tendencies and both passive cooling strategies have a similar and significant effect.

From no skylights to 0.5% of skylight ratio of roof surface, the natural ventilation effect is the most efficient with almost 1°C gain in maximum temperature (Figure 12(a)) and around 1000°C h gains in DH (Figure 12(b)), whatever the albedo. The gains in cool roof decrease with an increase in skylight opening ratio, mainly considering the DH. Yet the relative gains are always important and these two figures can be helpful in building design phase to help define balanced requirements for roof albedo and skylight ratio.

#### 4.3.2. *Effectiveness comparison of all natural cooling strategies*

In order to compare all previous cooling strategies, we analyzed (Figure 13) the absolute temperatures and the DH mitigation for cool roof (albedo 0.9), night natural ventilation and night mechanical ventilation (with ref. building characteristics). In this case study, considering the Mediterranean weather of Marseille, ventilation alone (natural or/and mechanical) provides more

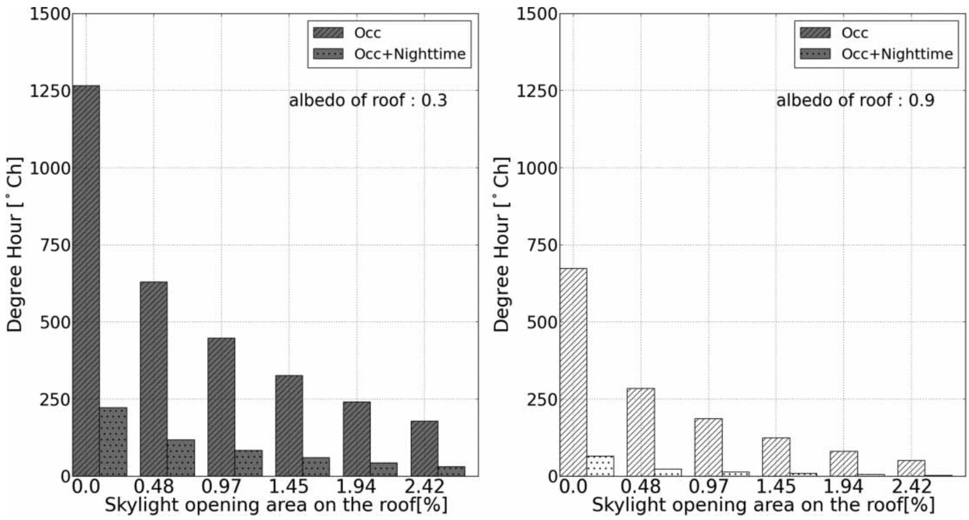


Figure 11. DH above adaptive temperature (DH) for mechanical and natural ventilation scenarios.

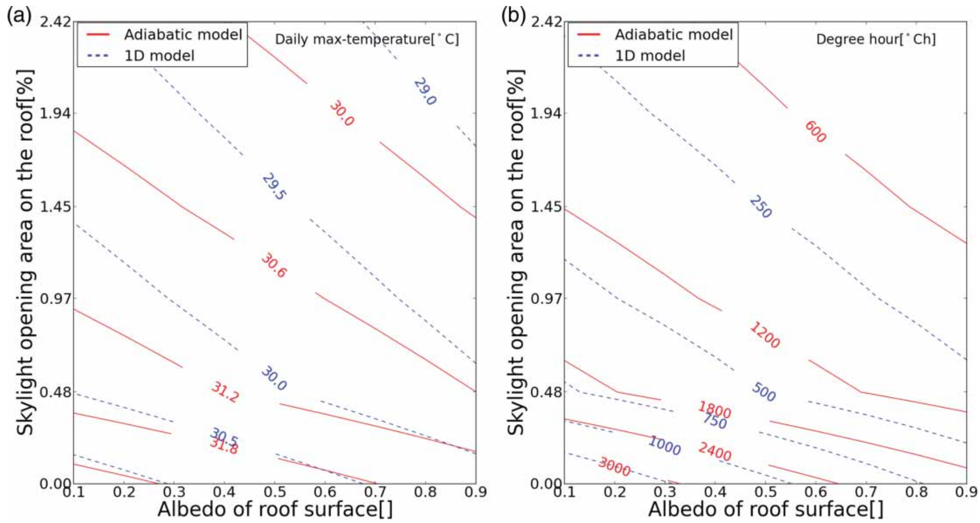


Figure 12. Skylight ratio of roof and roof albedo effects on both: (a) average of daily max operative temperature (°C) and (b) DH above comfort temperature (°C h).

gains in cooling effect when compared with cool roof alone. For the considered three days (Figure 13(a)), the operative temperature drops from around 1°C with cool roof and up to 3°C with night natural ventilation. With additional night-time mechanical ventilation, the operative temperature drops only slightly below the natural ventilation case. Here, ventilation effectiveness is highly dependent on the airflow rate and outside air temperature. The last cooling strategy by combining natural–mechanical ventilation and cool roof allows a temperature drop above 5°C (Figure 13(a)). The DH (°C h) of discomfort drops by 46.8% due to cool roofs, by 82.5% due to night mechanical ventilation, by 86% due to night natural ventilation and by 99.8% due to the combination of the passive solutions (Figure 13(b)). For well-insulated roof buildings, the most effective passive

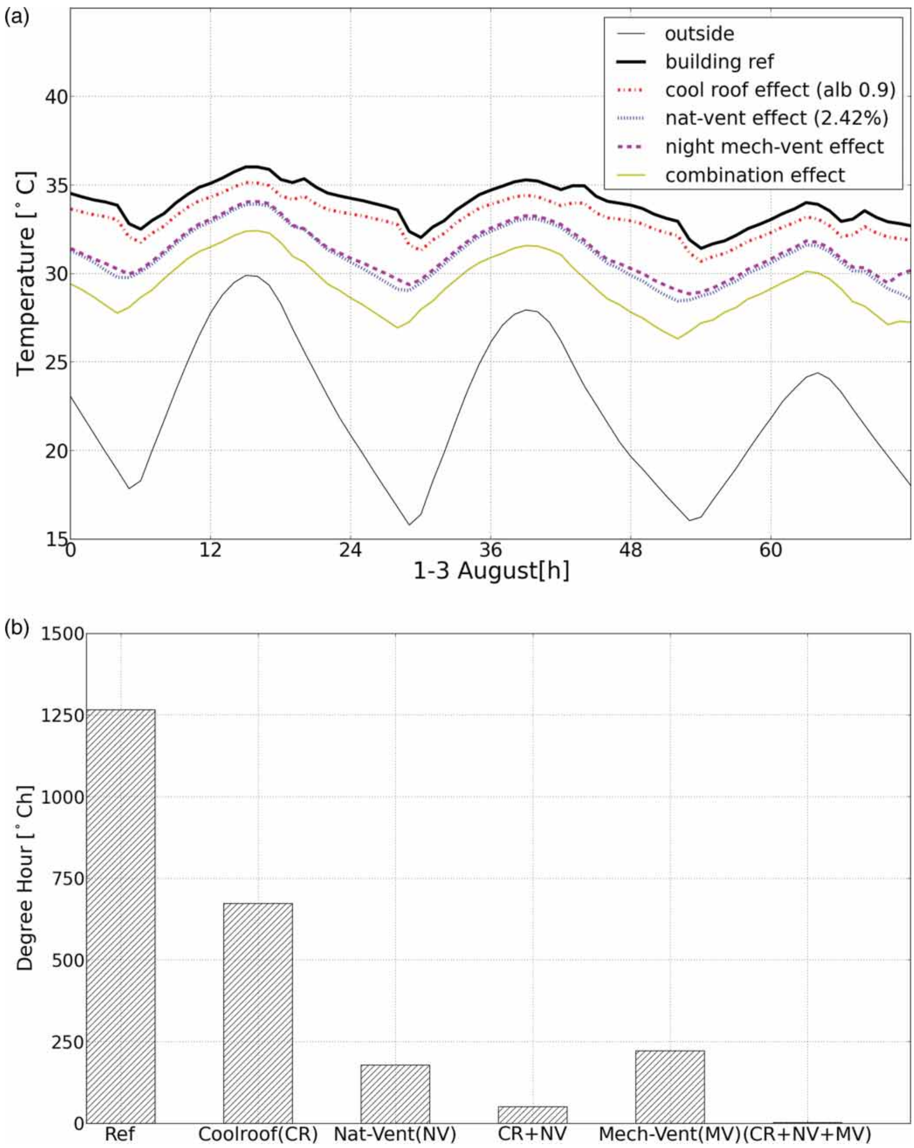


Figure 13. (a) Effects of cooling strategies on operative temperature and (b) effects of cooling strategies on DH above adaptive discomfort temperature.

cooling potential could be improved by increasing the air flow rate through ventilation. Natural ventilation is preferred here because it does not require any energy. Enlarging the surface area of skylights offers more effective passive cooling gains and replaces mechanical ventilation needs.

#### 4.3.3. *Discomfort temperature profile based on adaptive thermal comfort*

The comfort level varies depending on the climate and occupants' adaptability to temperature changes. The adaptive approach which is based on the findings of field surveys is a good

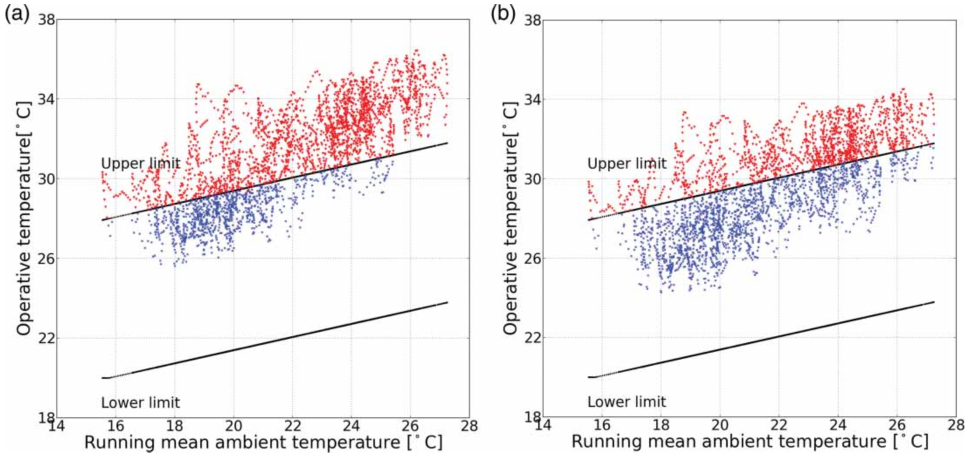


Figure 14. Operative temperature on running mean ambient temperature; (a) ground heat transfer model without inertia (adiabatic floor) and (b) with inertia.



alternative to determine the thermal comfort at different locations. Several studies were performed to propose a general approach of adaptive comfort, for different regions (Karyono, 2000; Nicol & Humphreys, 2002). In this paper, the European NF EN 15251 standard on calculating the adaptive comfort is used as a reference.

4.3.3.1. *Effect of thermal ground inertia*. Figure 14 shows the indoor operative temperature profile according to the running mean outside temperature for the summer period and for category III buildings (EN 15251) with two ground heat transfer models: adiabatic floor without thermal inertia (Figure 14(a)) and uninsulated floor with inertia (Figure 14(b)). The ground thermal inertia effect lowers the operative temperature mainly under the free-floating condition, i.e. in the absence of any cooling system.

The ground thermal inertia has a tremendous effect on the reduction of the thermal discomfort. Figure 15 presents the numbers of degree Celsius above the upper limit of the comfort zone in the same way as for the heating and cooling energy (Figures 7 and 8). Discomfort clearly happens when the solar heat gain is high, i.e. between 09:00 am and 08:00 pm. In the summer period, 69.6% of the indoor temperature is above the comfort limit for buildings with adiabatic ground slab. When compared with the first ground model, involvement of the ground thermal inertia

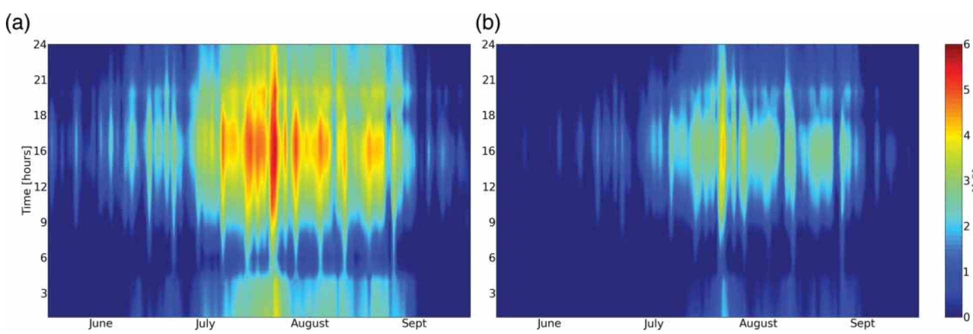


Figure 15. Discomfort temperature profile based on adaptive comfort for two ground models; (a) adiabatic floor model without inertia and (b) ground with thermal inertia model.

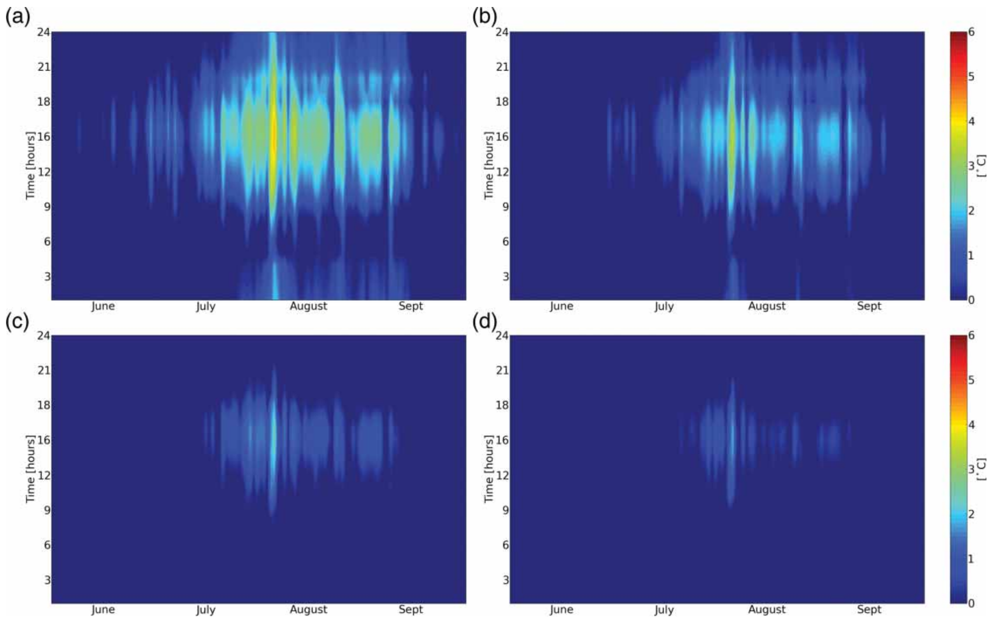


Figure 16. Hourly evolution for the summer period of the thermal discomfort (temperature difference) based on adaptive comfort; (a) reference building, (b) effect of cool roof, (c) effect of natural ventilation and (d) combined effect of cool roof and natural ventilation.

significantly reduces the level of discomfort temperature (remaining 42.7%). Note that a thermal discomfort peak is observed at the end of July when solar irradiation is the highest.

4.3.3.2. *Effect of passive cooling technique: cool roof and natural ventilation*. Figure 16 highlights the mitigation of the thermal discomfort obtained by the passive cooling techniques of the present analysis: cool roof coating and night natural ventilation. In order to evaluate correctly this impact and as observed in the previous section (Figure 15), the thermal inertia effect of the ground floor has been modeled.

For each time-step, the thermal discomfort due to overheating is characterized by the positive values of temperature difference between the operative temperature and the adaptive comfort temperature. For the Mediterranean climate, the night-time natural ventilation appears to have a greater impact compared with the cool roof technique. This result originates from a higher effect of the ambient temperature difference between day and night, i.e. the ventilation potential, compared with the reduction in the solar heat gain at the roof obtained with the cool coating. The natural ventilation is carried out during the night (after occupancy time), but the heat dissipation through the skylights has a greater effect on the temperature reduction only at the beginning of the next day. By combining the two techniques, the minimization of the solar heat gain during daytime and the heat dissipation during night-time induces a comfortable indoor temperature almost all the time in the summer, except for a few hours at the end of July. The combination of both techniques tremendously reduces the thermal discomfort.

## 5. Conclusions

The typical commercial building analyzed here, located in a Mediterranean climate and well insulated, has demonstrated the interest of passive cooling strategies such as natural ventilation ensured by skylights (2.4% of roof surface) which alone contributes to a strong reduction in summer discomfort with an 86% drop in DH above the comfort upper limit.

The cool roof technique alone is also valuable with a 46.8% drop in the discomfort assessed by the DH. For this studied case, we can compare the 11% heating energy penalty caused by the loss of free solar heat gain in winter considering an air-conditioning system for the summer. Then, the energy saving due to the cool roof accounts for 33.8% of the cooling energy demand which represents a higher sensible energy demand than the heating demand.

The use of mechanical ventilation at night performed not better than natural ventilation with an 82% drop in DH. But these well-known techniques can operate in a very efficient way when combined together: night natural and mechanical ventilation together with cool roof give a huge drop in DH up to 99.8%. These DH tendencies can be used also to design mechanically cooled buildings, as the energy consumption varies in the same way, even if a good design could give in this case a satisfactory solution.

Moreover, we have demonstrated that these solutions could be not totally effective without the contribution of the ground thermal inertia. Indeed, it contributes up to a 58.6% drop in DH compared with an adiabatic floor model. This means that for large-volume low-rise buildings, the ground floor is a key factor to be considered and its insulation from the ground could be counterproductive. The shelving inertia participates also in the passive cooling process, and it was assessed to result in a 24.2% DH drop compared with the same building without shelving.

These parametric results and the methodology presented here have given the first results which could be used in the commercial building design phase, but it has to be extended. The ongoing work and the outlooks on this topic are now to assess the optimal ratio of skylights in order to provide the best passive cooling effects and check against additional heat losses in winter. Moreover, the model has to be refined in order to take into account thermal stratification within the building and to study comfort zones. The ground thermal inertia has definitely a great impact on the low-rise building thermal behavior and additional works need to be engaged to account for the building shape, the soil thermal properties and the connection between the building slab and the ground.

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