DESIGN IMPACTS OF COOL ROOF COATING, VENTILATION AND THERMAL INERTIA ON COMMERCIAL LOW-RISE BUILDING ENERGY DEMAND AND SUMMER COMFORT

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ABSTRACT

Few studies focus on commercial low-rise buildings which are often characterized by low-cost constructions materials and weak energy performances. For these large volumes, the heat transfers with the roof and the ground are prevalent. In this article, we show how the analysis of heat transfers through both the roof and the ground can achieve their thermal performance. The roof design and its opening systems is a key factor of the thermal and lighting performance. Roof openings (skylight) and radiative properties of roof coating (cool roof) have a direct impact on solar gains, thermal losses and natural ventilation potential. The overall building thermal behavior depends both on the combination of these design parameters (solar reflectance, opening size, etc.) and weather conditions. Yet, the inertia of these lightweight structures is mainly given by the slab on the ground; and the performance of the roof design cannot be separated from the type of soil and slab which determine the dynamic behavior of these buildings.
A simple and typical case study is presented and modeled and, an extensive parametric study (840 annual simulations) is performed to point out these key parameters impacts on building energy demand and comfort. The mixed use of efficient roof techniques (skylights and cool roof) combined with a high inertia of the building can be an adequate passive cooling solution in summer, with a 99.8% drop of 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, passive cooling, simulations

1 INTRODUCTION

With a growth of 1% per year, the world population estimated at 8.2 billion in 2030 will rise energy demand up to 87% (2006-2030) especially for non-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 global annual primary energy consumption in 2010 (*Chiffres clés de l'énergie édition 2012*) is allocated for building sector (71 MTep). 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 up, and is 15% higher than in 2001. Commercial buildings' energy consumption associated to heating and air-conditioning accounts for 57% of total expenses (Balaras et al., 2000; Chwieduk, 2003).

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 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, outer surface of roof coated by high solar reflectance material will reflects more solar radiation, while the absorbed heat is emitted to the sky due to the high thermal emittance. Cool roof technologies on a commercial building can reduce the peak temperatures of roof surfaces about 33°C to 42°C in summer (Akbari et al., 2005; Xu et al., 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. (Bozonnet et al., 2011) conducted a study for moderate climate in France that shows a result of 10°C roof surface mean temperature decrease, in summertime, due to cool roof technology.

Natural and night ventilation can help to mitigate overheating by removing out the warm indoor air. A study conducted by (Wang et al., 2009) indicated that the night ventilation is quite effective especially in northern hemisphere to be a passive-cooling way. The night ventilation can reduce the average indoor temperature from 1.5°C up to 4°C (Blondeau et al., 1997; Geros et al., 1999; Kubota et al., 2009; Shaviv et al., 2001) according to the location, envelopes and building usage scenarios.

As for the roof, the large surface of slab on ground and the ground characteristics are key-parameters in the energy balance and performance of roof techniques for commercial low-rise building. Most studies focus on typical houses, but even in those studies the role of ground floor is not negligible; thus a study conducted by (Labs K et al., 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 building. 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 metal construction). The study of a test cell (small building) by (Aste et al., 2009) showed a 10% difference in the heating loads between high and low thermal inertia envelopes. Ground properties and thermal inertia (including shelving) of low-rise buildings can contribute to the dynamic of passive cooling techniques, and we focus on these combinations 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 very simple case study of low-rise commercial building. The building energy demand and 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 cubic-shape one-floor commercial building (*Figure 1*) located in temperate climate (Marseille, France). The base of the building is a square of 36 m sides. The building 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.

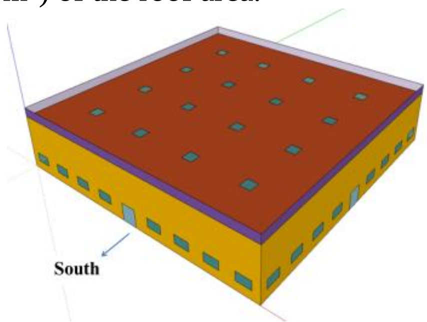


Figure 1. Geometry of the studied commercial building

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. Besides, thermal inertia of the commercial shelves is considered with 10% of the building volume (787.9 m^3). It consists of 40% cardboard, 30% liquids/oils, 10% metals and 20% plastics. The building is equipped with a heating system and no cooling system is installed. To ensure the 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, within the interval 0.1-0.9. The high thermal emissivity (0.9) is considered constant.

Natural ventilation is provided by opening some skylights and windows. This ventilation is carried out on summer during night 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 TRNSYS building model (Type 56) and the CONTAM airflow model under the TRNSYS 17 simulation environment. As illustrated in *Figure 2*, 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.

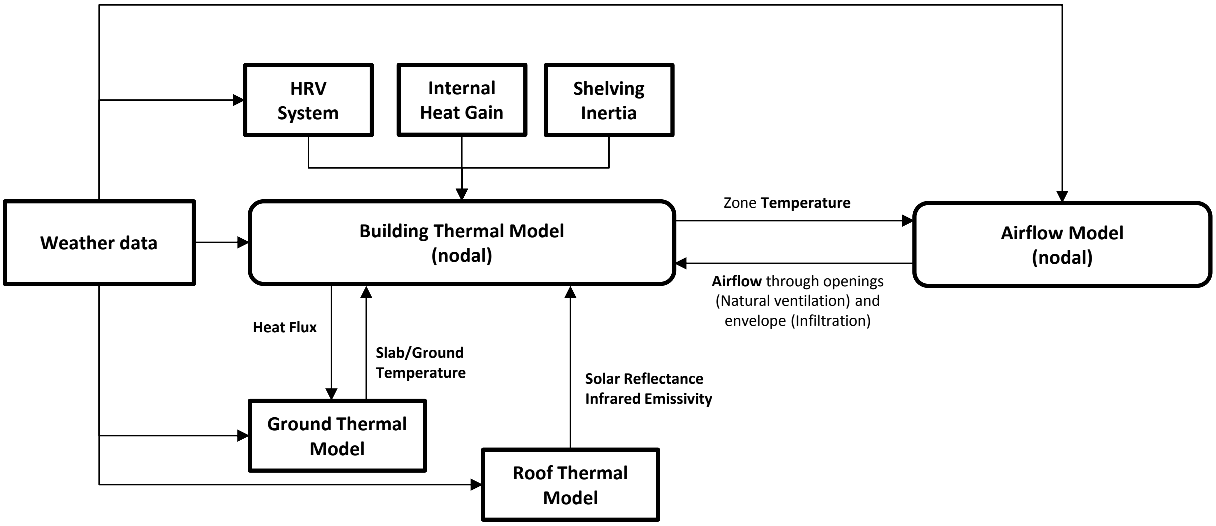


Figure 2. Schematic representation of the building energy simulation coupling process

Two modeling levels have been used to calculate heat transfer through the ground: the so-called one-dimensional (1D) and adiabatic models. Note that those models account for heat transfer only, no moisture transfer is considered here.

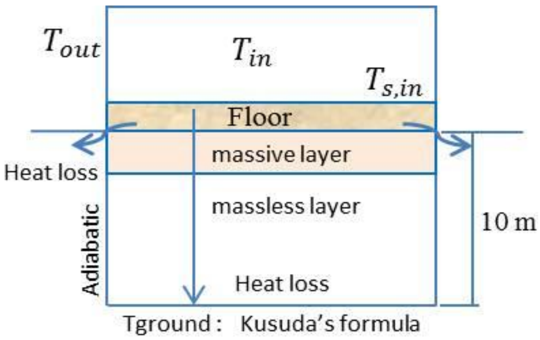


Figure 3. One-dimensional model of ground heat transfer

The 1D model, illustrated in *Figure 3*, splits the ground below the concrete slab into two layers of the same soil materials. The first layer, modeled as a massive layer, accounts for thermal inertia and is defined as a wall in TRNSYS building model. The second layer is modeled as a resistance layer, with no thermal inertia, and is referred as massless layer. A shown by (Adjali et al., 2000), the temperature of the ground at 10 m can be considered independent of the building behavior so that the total thickness above the building has been set to 10 m. The required temperature in the model at this depth is calculated by the model of Kusuda (Eckert and Drake Jr, 1987; Kusuda and Bean, 1984):

$$T(z,t) = T_m - T_a\, e^{-z\times\sqrt{\frac{\pi}{365\alpha}}} \times \cos\left(\frac{2\pi}{365}\left(t - t_p - \frac{z}{2}\sqrt{\frac{365}{\pi\alpha}}\right)\right) \tag{1}$$

Parametric simulations have been performed to evaluate the necessary thickness of the massive layer in a previous study (Lapisa et al., 2013). Results show that this building model using a 30 cm massive layer gives comparable results regarding the heat transfers through the ground than a more complicated, and heavy computation time, three-dimensional ground model (McDowell et al., 2009; Zhou et al., 2002).

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

4 PASSIVE COOLING POTENTIAL OF COOL ROOF AND NATURAL VENTILATION

All the studies are based on the previously defined reference building: low roof solar reflectance (0.3), mechanical ventilation operating only during the occupancy period and skylights closed (no natural ventilation). In the following parts, the criteria for indoor overheating (based on operative temperature) during summertime and occupancy hours are:

- The **degree-hours** (DH) above the adaptive summer comfort temperature defined by the standard EN-ISO-1525. 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-1525).

4.1 Impact of cool roof

Temperature evolutions are compared, see *Figure 4*, for three days in summer (1-3 August) using both ground heat transfer models and 2 roof solar reflectance values (0.3 for standard roof and 0.9 for cool roof): ambient temperature ($T_{outside}$), roof surface temperature ($T_{s\text{-}roof}$) and indoor operative temperature (T_{op}).

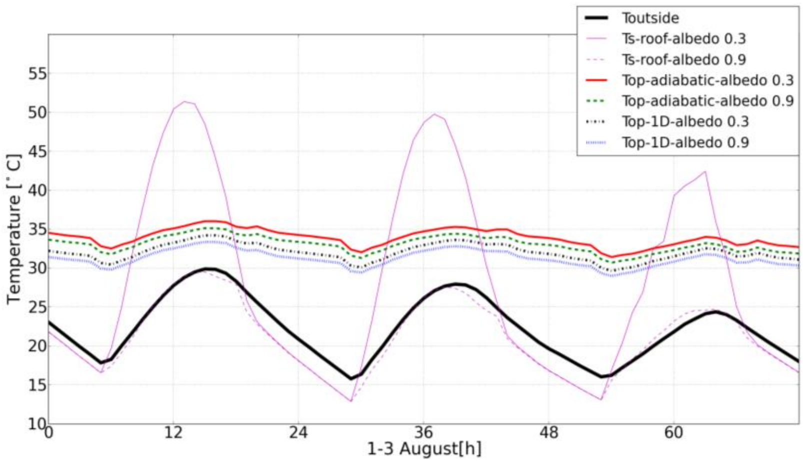


Figure 4. Ambient, operative and roof surface temperature in summer

The temperature peaks occur on the interval 12.00 AM-03.00 PM. With cool coating the solar absorption decreases and the roof external surface temperature drastically drops of 22°C, but the operative temperature drop is here only 1°C. This mainly comes 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 results difference between both 1D and adiabatic models, is more significant on the operative temperature with a difference of 2.5°C (*Figure 4*) for all albedo values. This inertia effect and heat transfers to/from the ground are facilitated by the lack of insulation below the slab on ground which mitigates the indoor air overheating.

Figure 5 presents the cool roof effects on previously defined summer comfort criteria (DH and discomfort ratio) evaluated with or without ground thermal inertia (two ground models), and with or without shelving.

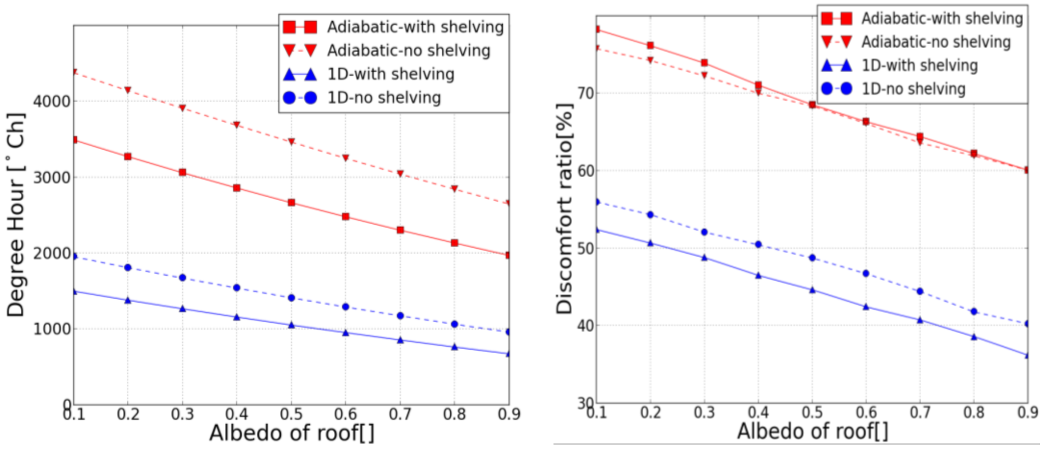


Figure 5. Effect of the roof albedo on a) DH [°Ch] and b) Discomfort ratio

DH decreases vary from 46.8% for the ground coupled building and 35.6% for the adiabatic one for an albedo variation from 0.1 to 0.9. The ground inertia participates in reducing the degree hours from 3060°Ch to 1265°Ch (58.6%) for the reference building (0.3 of albedo) and from 1970°Ch to 673°Ch (65.8%) for the building with cool roof. On the other side, the shelving also absorbs a notable portion of the heat from the indoor air and reduces the DH value of about 24.2% compared to the empty building. For this type of well-insulated roof building, the cool roof effect is lower than ground inertia impact.
Figure 5.b presents the discomfort ratio versus albedo. The albedo effect follows the same global trend as for the DH; except for the shelving only effect which does not have a significant impact on the discomfort ratio. This is due to the too small shelving inertia and it highlights the importance of the design and the minimum inertia needed for summer thermal comfort.

4.2 Impact of ventilation

4.2.1 Impact of natural ventilation

Figure 6 shows the impact of opening the skylights on the natural ventilation flow rate and the degree hours (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 the 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.

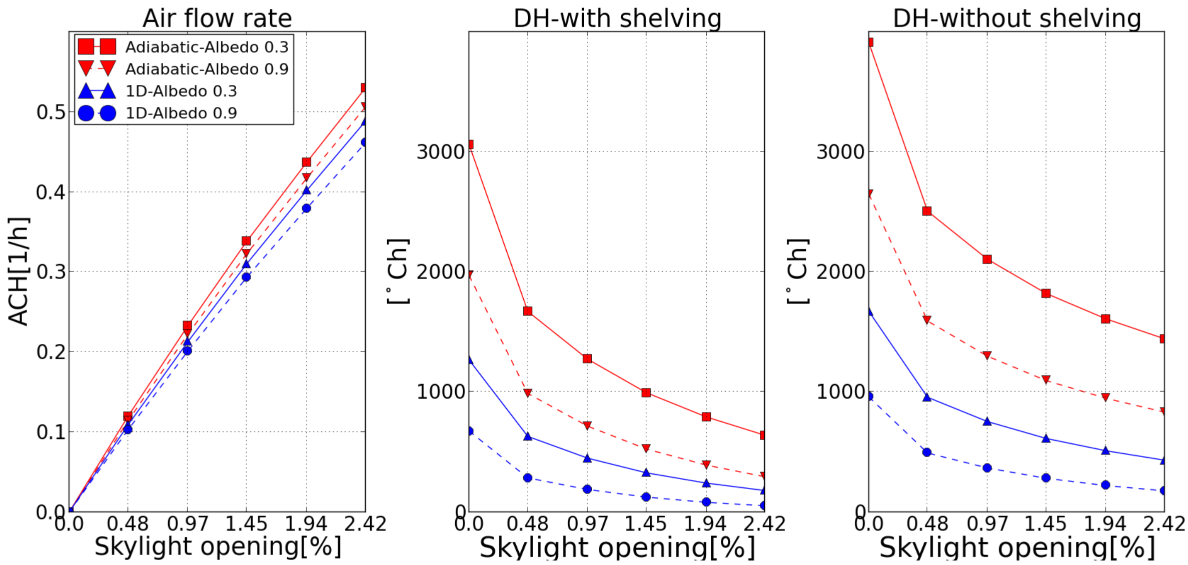


Figure 6. Skylight ratio effect on (a) natural ventilation rate (ACH), and (b) DH with shelving and (c) without

As illustrated by the other two graphs, *Figure 6.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 the increase of the skylight opening, dropping up to 79.2% for the maximal opening value. In this case, the shelving is also important as the night cooling participates to the indoor temperature reduction during daytime. Combined effects of ground and shelving thermal inertia are obviously as important as the natural ventilation, giving very good results with high inertia and skylight opening.

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, the permanent mechanical ventilation (*Figure 7*) brings a reduction of DH from 1265°Ch to 221°Ch (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 mean nighttime natural ventilation with all the skylights opened (about 0.5 ACH). The combination of mechanical and natural ventilation during the night can avoid thermal discomfort during occupancy by reducing the DH by 97.6% as illustrated by *Figure 7*.

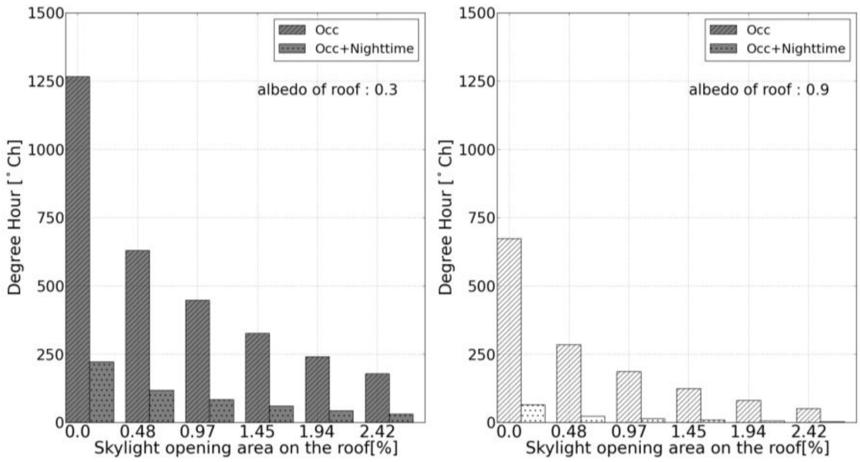


Figure 7. Degree Hours above adaptive temperature (DH) for mechanical and natural ventilation scenarios

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 degree-hours (DH above adaptive comfort temperature following 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 8* varying both parameters skylight opening and roof albedo. The two graphs have the same tendencies and both passive-cooling strategies have a similar and significant effect.

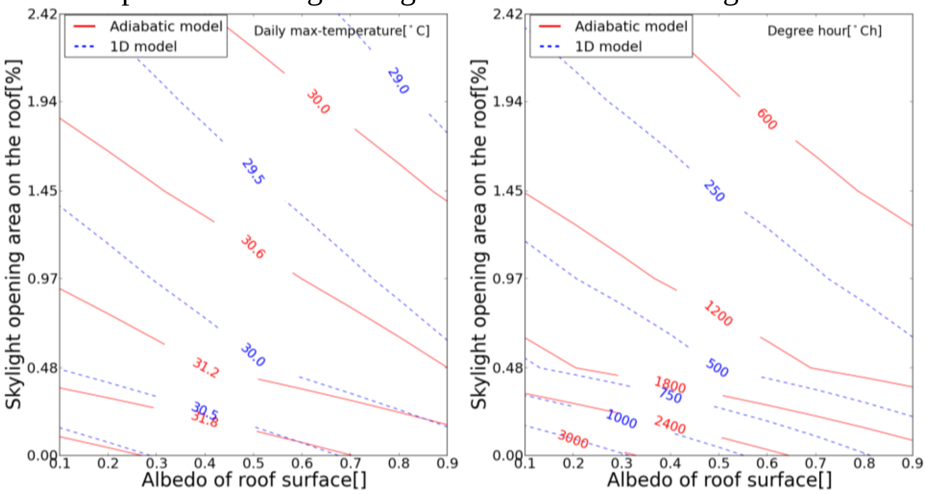
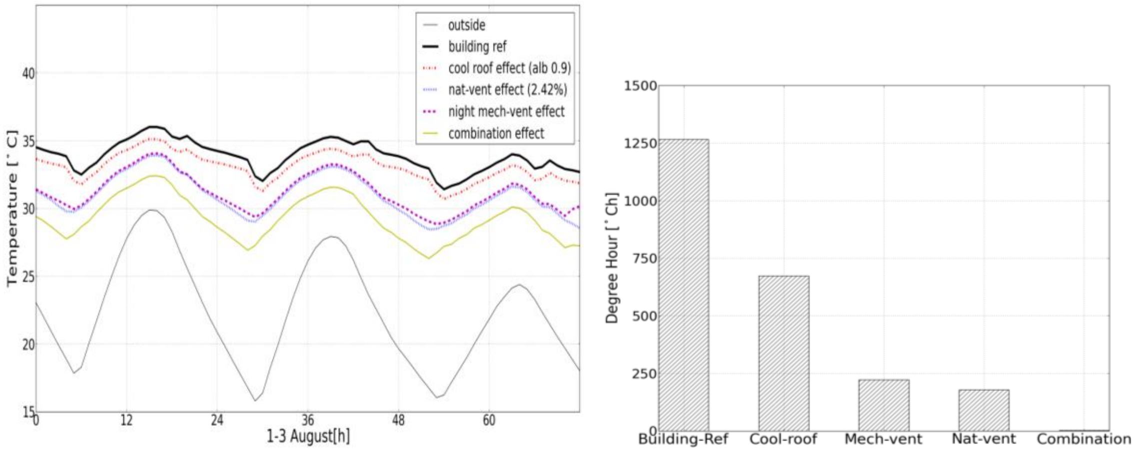


Figure 8. Skylight ratio of roof and roof albedo effects on both:
a) Average of daily max operative temperature [°C], b) DH above comfort temperature [°Ch]

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 on maximum temperature, *Figure 8.a*, and around 1000°Ch gains on DH, *Figure 8.b*, whatever is the albedo. The gains of cool roof decrease with the increase of skylight opening ratio, mainly considering the degree hours. Yet the relative gains are always important and these two figures can be helpful in building design phase to help defining balanced requirements for roof albedo and skylights' ratio.

4.3.2 Effectiveness comparison of all natural cooling strategies

In order to compare all previous cooling strategies, we analyzed, see *Figure 9*, 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 gains in cooling effect when compared to cool roof alone. For the considered three days, see *Figure 9.a*, the operative temperature drops from around 1°C with cool roof, and up to 3°C with night natural ventilation. With additional nighttime mechanical ventilation, the operative temperature drops only slightly below the natural ventilation case. Here, ventilation effectiveness is highly dependent on the air flow 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 9.a*). DH [°Ch] 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 9.b*). For well-insulated roof building, the most effective passive 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 offer more effective passive cooling gains and replaces mechanical ventilation needs.



a. b.

Figure 9. a. Effects of cooling strategies on operative temperature,
b. Effects of cooling strategies on DH above adaptive discomfort temperature

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 of summer discomfort with a 86% drop of degree hours (DH) above discomfort temperatures. The cool roof technique alone is also valuable with a 46.8% drop of DH of discomfort. The use of mechanical ventilation at night performed not better than natural ventilation with a 82% drop of 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 of DH up to 99.8%. These tendencies of DH 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 of DH compared to an adiabatic floor model. This mean 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 a 24.2% DH drop compared to a building without shelving.

These parametric results and the methodology used have given first results which could be used in commercial building design phase, but it has to be extended. The ongoing work and the outlooks on this topic is now to assess the optimal ratio of skylights in order to provide the best passive cooling effects and checked 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.

6 ACKNOWLEDGEMENTS

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