LOW-RISE COMMERCIAL BUILDINGS OPTIMIZATION – ENERGY PERFORMANCE AND PASSIVE COOLING POTENTIAL IN FRANCE

ABSTRACT

Large indoor volumes and lightweight materials characterize low-rise commercial buildings. Thermal and visual comfort is a commercial issue usually solved with air conditioning and artificial lightings. This could be considered in the building envelope design itself, throughout a passive building design. These envelopes are characterized by high thermal interactions of ground floor and roof surface to environment. In order to optimize energy performance and passive thermal strategies, several parameters have been selected: thermal insulation of various walls, natural ventilation, roof radiative characteristics, windows and skylights surfaces.

The proposed optimization process has been developed considering both mitigation objectives of energy consumption and summer thermal discomfort. Moreover, we consider here all French climates, with passive cooling only for summer, and climate change effects. Using NSGA-II optimization algorithm, this study points out that optimal solutions depend greatly on climate characteristics.

For stakeholders, the optimal design can be chosen given the Pareto front results, and compromises are mapped for France considering both objectives and construction costs. This methodology and the numerical results can be helpful for design guidelines of new commercial building or refurbishments as the proposed study is based on a typical low-rise building for commercial.

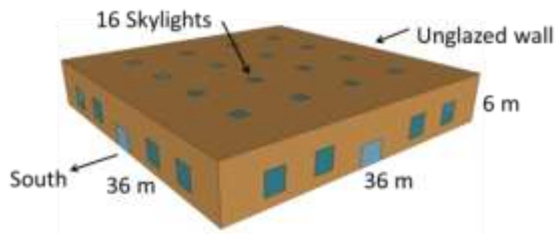
INTRODUCTION

Commercial building context

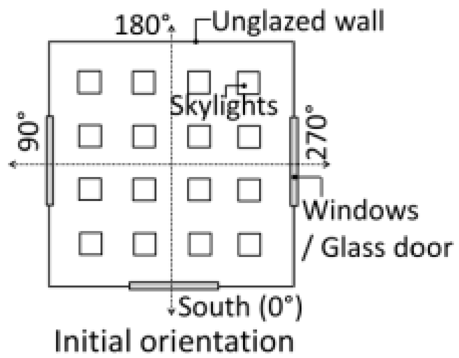
Commercial buildings account for 7% of the total world energy consumption (Pérez-Lombard et al. 2008) and this energy use is mostly due to heating and cooling systems with more than 60% of the consumption (Carvalho et al. 2010). Therefore, considering thermal performance through the design of new commercial buildings, as well as the improvement of existing ones, presents a significant potential for energy savings and environmental impacts. Indeed, there is a wide variety of optimization parameters for building thermal design or retrofitting. Air-conditioning and heating systems have also to be optimized in the design process, depending on the building envelope performance. However, passive cooling solutions are often a good and possible alternative that avoids installation and operating costs as well as environmental impacts. However, the effectiveness of free heating/cooling strategies depends on the climate conditions, building thermal characteristics, occupancy pattern, ventilation mode, internal heat gain intensity, etc. A suitable building configuration for one geographical location is not necessarily well suited to another location.

Definition of a generic low-rise commercial building structure and operation

In this study, we consider a generic commercial building morphology for which the building envelope parameters varies for the optimization study. This is a steel structure with a square floor surface of 36 m sides and a ceiling height of 6m (Figure 1).



a – Building sketch



b – Building top view

Figure 1 geometry of the studied low-rise commercial building.

The thermal inertia of the building envelope is mainly due to a 160mm concrete slab. Commercial shelve

(30% of the floor area) is also modelled as internal walls composed of cardboard, liquids, metals and plastics. The building air permeability level is equivalent to 2cm^2/m^2 which is representative of a common steel construction building (Persily 1998). An occupation density of 11.6 m^2/person is considered here (Deru et al. 2011). The occupancy period is 07:00 AM - 10:00 PM every day except on Sundays (empty building). A heating system is set to maintain the indoor temperature to a minimum of 19 °C when the building is occupied and 5 °C otherwise. No cooling system is present in this prototypical building. A heat recovery ventilation (HRV) system provides 0.5 air changes per hour (ACH) when the occupants are present. Artificial lighting is turned off if natural daylighting exceeds 300 lux (NF EN 12464-1 2011; Rea 1993). To improve building summer comfort, natural ventilation is provided during nights from 23:00 pm to 06:00 am by opening ad-hoc vents in the lower part of the building and the skylights located on the roof. The nighttime ventilation is considered here for warm periods determined by the control diagram Figure 2.

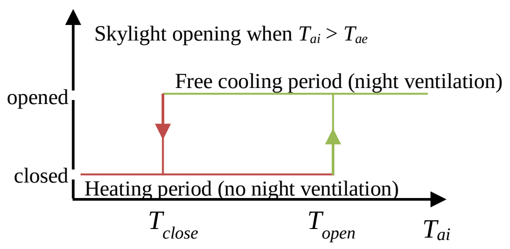


Figure 2 heating and free cooling periods determined by T_{close} and T_{open} parameters for night natural ventilation

During free cooling season (mainly summertime) skylights are controlled considering ambient and indoor air temperature (T_{ae} and T_{ai}). The choice of the parameters T_{close} and T_{open} for this passive cooling technique have also an impact on the heating energy demand.
We have then defined default envelope parameters, which will be modified in the following optimization study:

- The terrace-flat roof has 31.36 m^2 of skylights (2.42% of the roof surface area), see Figure 1a and b.
- All vertical walls are glazed with a 30m^2 surface, except the northern one.
- Vertical exterior walls are well insulated and have a total thickness of 30.5cm (1.3cm of gypsum, 14cm of glass wool, 15cm of rock wool and an outer steel cladding of 2mm).
- The roof is also well-insulated (24 cm rock wool). The 160mm concrete slab is non-insulated; the ground is sand.

Properties of envelope layers and windows are presented in Table 1 and Table 2.

Table 1 wall characteristics: thickness e, thermal conductivity λ, density ρ and specific heat c_p

MATERIAL	e mm	λ W/(mK)	ρ kg/m^3	c_p J/(kgK)
Vertical walls				
Sheet steel	2	50	7 800	419
Stone wool	150	0.042	50	920
Glass wool	140	0.038	50	840
Plaster	13	0.25	825	801
Roof				
Sheet steel	2	50	7 800	419
Glass wool	240	0.038	50	840
Plaster	13	0.25	825	801
Slab				
Concrete	160	2	2 450	1 000

Table 2 double-glazing window properties: glazing surface area A_w, window U-value U_w, solar factor F_w, light factor F_L

WINDOWS	A_w m^2	U_w W/(m^{2}K)	F_w	F_L
Glass doors	6	2.89	0.789	0.747
Windows	24	2.89	0.789	0.747
Skylights	31.36	2.95	0.777	0.817

Optimal design objectives in French climate context

The main objective here is to determine design rules through the optimization of this generic low-rise commercial building. The building model includes coupled airflow and thermal simulation with a 3D description for the ground inertia. The design parameters listed Table 3 are optimized using a genetic algorithm, NSGA-II (Deb et al. 2002).

Table 3. optimization parameters and their impact on heating, cooling, lighting and ventilation systems.

OPTIMIZATION PARAMETERS	HEATING	COOLING	LIGHTING	VENTILATION	VALUES	UNIT
Building orientation	×	×	×		0 – 360	°
Solar reflectivity of roof	×	×			0,1 – 0,9	-
Skylights surface area	×	×	×	×	2,5 – 15	%
Roof thermal insulation	×	×			0,1 – 50	cm
Ground thermal insulation	×	×			0,1 – 50	cm
Vertical wall insulation	×	×			0,1 – 50	cm
T_{open}	×	×		×	15 – 26	°C
T_{close}	×	×		×	19 – 26	°C

Both energy performance and thermal comfort are assessed here in the optimization process of passive

strategies. The proposed strategies, see Table 3, include building geometry (orientation and surface of skylights), thermal insulation (ground, roof and vertical walls), and passive cooling (cool roofs and natural night ventilation). Cool roofs are interesting for passive cooling southern areas (Synnefa et al. 2007) and also for moderate climates and well insulated buildings (Bozonnet et al. 2011). Cool roofs and natural ventilation are also combining well for passive cooling (Lapisa et al. 2013a).
However, the design parameters can have contradictory effects on the objectives, and the proposed compromise can vary depending on the climate. In a first approach, climate variations are proposed for all French locations, which represent a large variety of climates and design optimal solutions. Moreover, taking into account the climate change, optimal solutions are certainly modified and we propose to take into account this climate change effect.

SIMULATION

French weather climates and climate change

24 cities are selected to cover the variety of the climatic conditions in France. The standard weather data are representative of the current conditions based on Meteonorm© weather data. The climate change weather data has been determined for 2080 using a morphing method developed by University of Southampton (Belcher et al. 2005; Jentsch et al. 2013). This climate change simulation is a rough first approach to study the necessary modifications and consequences with a high-emission IPCC scenario. Figure 3 presents the annual average value distribution of ambient temperatures for France under current climate, Figure 3a, and future climate, Figure 3b.

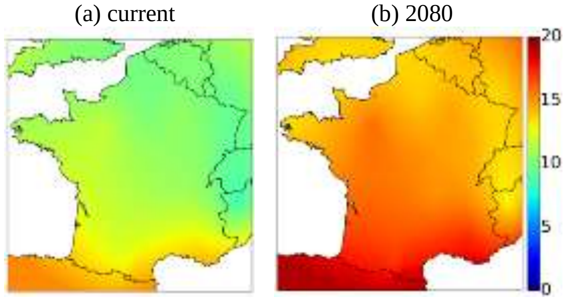


Figure 3 annual mean values of ambient temperatures (°C) for current (a) and future climate (b).

The average ambient temperature increases by about 3.9°C globally, but the annual variations of all climatic parameters (solar irradiation, rainfall, etc.) is taken into account for an hourly time step. This would change the possible use and the potential of the proposed passive strategies for the building. All these parameters should be adapted in the design stage considering the location but also the climate change effects concerning sustainability or building energy's policy.

Building thermal simulation model

The transient coupled simulation of the building has been performed using both the TRNSYS© thermal model (Type 56) and the CONTAM© airflow model (Type 97), see Figure 4.

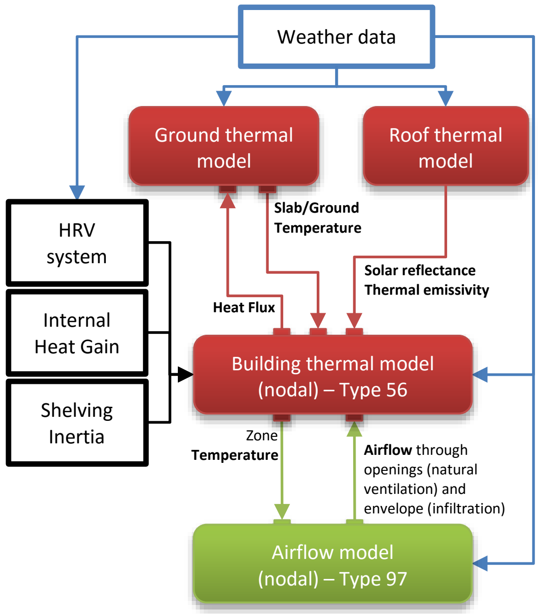


Figure 4 coupled models

The large volume of the generic building described Figure 1 is modeled as a monozone building. Specific models interact following the diagram Figure 4 in a nodal approach:

- Airflow rates through openings and the envelope are calculated by the *Airflow Model*. Infiltration and natural ventilation airflow rates are due to wind and stack effects. Wind pressure coefficients on the building envelope are determined from the Swami and Chandra correlations (Swami & Chandra 1988).
- Roof radiative properties vary in the *Roof Thermal Model*.
- Tridimensional ground heat transfers are evaluated in the *Ground Thermal Model*. Due to the strong inertia of the ground, a whole first year initialization is performed as described in previous papers (Lapisa et al. 2013b; Lapisa et al. 2013), which include also the model description.

Optimization algorithm

Optimal solutions are determined with the eights design parameters presented Table 3 to minimize both the building primary energy consumption for heating and lighting (*EP* kWh/(m².yr)) and the degree hours number of summer thermal discomfort (*DH* °Ch). The discomfort criteria *DH* is evaluated with the standard adaptive comfort model (NF EN 15251 2007).
The multiobjective genetic algorithm method is based on the NSGA-II algorithm (Deb et al. 2002). NSGA-

II algorithm has been widely used for building design (Magnier and Haghighat 2010), renovation of the existing building (Chantrelle and al. 2011), optimization of energy consumption in nearly zero-energy buildings (Carlucci et al. 2015). The following optimization algorithm parameters are chosen (Nassif et al. 2005; Gosselin et al. 2009):

- Initial population: 200
- Generations: 10
- Crossover coefficient: 0.9
- Mutation coefficient: 0.04.

The computation time with these parameters is about 28h for these 2000 simulations (for a 2 years' period per simulation) with an eight processor desktop PC; we use here parallel computing. A preliminary convergence evaluation highlights an acceptable accuracy of the results with these parameters comparable to other studies (Wright et al. 2002).

Selection of an optimal solution for each climate location

The optimal solutions are computed for each building location as represented for one example Figure 5.

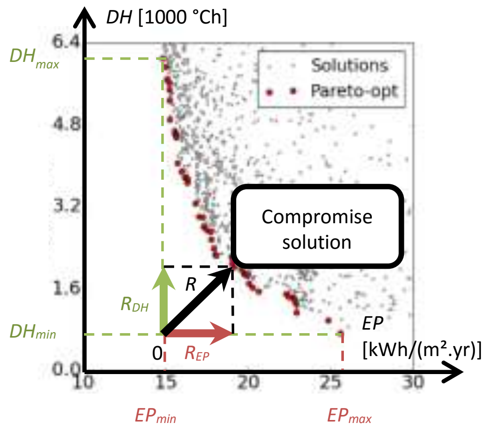


Figure 5 Pareto optimal solutions and compromise solution R

Considering these solutions, the choice of a solution varies between the most energy efficient solution (EP_{min}) and the minimum of summer thermal discomfort hours (DH_{min}). In a first approach, we consider the compromise between both objectives as the minimum value of the dimensionless distance $R = \sqrt{R_{EP}^2 + R_{DH}^2}$. R_{EP} and R_{DH} are defined as the dimensionless variations of both objectives from 0 to 1 (minimum and maximum values).

Then, the construction cost is used as a supplementary criteria to seek the best trade-off solution around the minimum value of R. The final compromise R_C is determined for the minimum value of the construction cost C_R (€) of the solution determined for each parameter including both material and labor costs. Table 4 includes some cost values.

Table 4 construction cost for the passive solutions.

PARAMETERS	PRICE (€/UNIT)	UNIT	NOTE
Skylights - Single glazing, square 1.4×1.4m², electric motor, rain and wind sensor			
	1 184	1.96m²	
Ground floor - Thermal insulation - Extruded polystyrene			
	13.48	3cm	
	23.66	10cm	
Roof and vertical walls			
Not insulated	25	Fixed	Galvanized steel façade
Steel facade with thermal insulation	52,25 66.52	3cm 12cm	Rockwool volcanic rock plus – E 220

As the parameter variations are continuous, the cost is automatically assessed with interpolated values from the cost database. This cost selection criteria is particularly around low insulation values or when the considered objectives are little sensitive to these parameters.

DISCUSSION

Energy demand and summer discomfort for compromise solutions in France

From the results of optimization process for the 24th locations in France, and the choice of a compromise solution, the energy demand *EP* [kWh/(m²yr)] and the summer thermal discomfort *DH* [°Ch] have been mapped for France Figure 6.

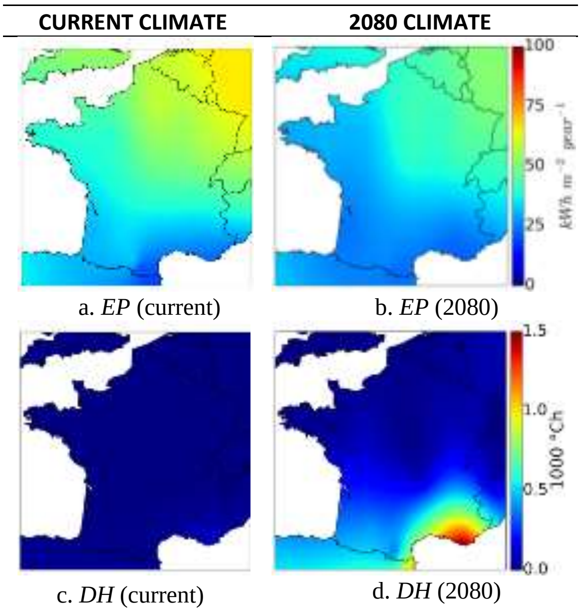


Figure 6 (a,b) energy demand (EP) and (c,d) number of degree hour (DH) of thermal discomfort for France for optimized solutions.

Under the current climate (Figure 6a and c), the energy demand of optimal buildings varies from 18.9kWh/(m²yr) in Nice (south east) to 65.7kWh/(m²yr) in Metz (north east). During summertime under current climate, all the configurations can

ensure a good thermal comfort, with a low maximum discomfort level in Marseille (Mediterranean climate) of about 117°Ch without air-conditioning. Considering 2080 climate assessment, the optimization results (Figure 6b) give better energy performances; *EP* varies from 21.2 to 50.9kWh/(m²yr). However, the summer discomfort becomes non negligible in south areas and increases up to 1662°Ch in Marseille.
All these key performance indicators depend on the optimized building envelopes and cooling strategies found with the parameters mapped in the following sections.

Skylight surface ratio on commercial roofs and cooling strategy through natural ventilation

Skylights can have a positive effect on both energy performance and summer comfort as they transmit solar radiation during heating season, limit artificial lighting use, and allow natural ventilation during summertime for free cooling. However, for well-insulated buildings and few solar radiations during winter, these skylights represent significant heat losses since their *U*-value is low. The optimum surface ratio varies from 2.5 to 7.5% in France and current climate, Figure 7a.

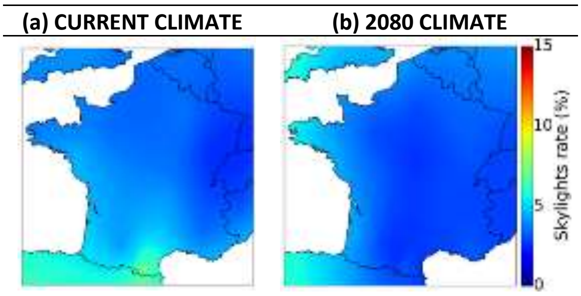


Figure 7 optimal solution for building orientation and skylight surface area.

Optimal surface ratio is lower than 4% in the northern areas, Figure 7a. In the southern regions, natural lighting covers a large part of lighting needs with an optimal value up to 7.5% of the roof surface. Still, for 2080 climate, the potential gain from night cooling is counterbalanced by the increase of daytime solar gains. The optimal ratio decreases down to around 4%, while this ratio is quite constant in northern regions.
The night ventilation is controlled by skylight opening through the given temperature limits T_{close} and T_{open} defined Figure 2. The free cooling efficiency is indeed not only linked to the opening ratio and stack effect, but also to the control strategy. Optimal values vary between 18 and 26°C for opening and closing limits mapped Figure 8. As indoor temperature set point during occupancy periods is 19°C, the opening limit T_{close} [°C] for indoor air temperature is found around this value except for some cities (Figure 8a and b). The same trend can be found for the summer thermal comfort which is often around 26°C with similar values for closing limits, see Figure 8c and d. When indoor air temperatures are higher than T_{open} night natural ventilation is allowed. For 2080 climate, the global warming decreases the T_{open} limit in most locations, which means that natural ventilation for free cooling is triggered earlier and more often as the summer thermal discomfort becomes important. In some locations, the skylight opening has a very balanced effect on the natural ventilation potential and the heating energy performance, which results in very narrow intervals between opening and closing limits.

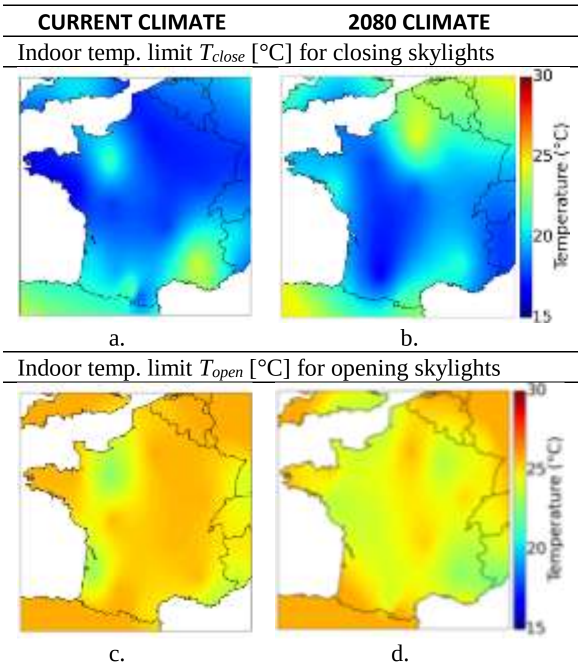


Figure 8 indoor air temperatures limits for skylights opening control for natural ventilation.

Cool roof strategy

Cool roofs are a complimentary passive cooling strategy which relies mainly on roof radiative properties. The thermal emissivity remains high and constant; only the albedo varies. The optimal albedo values are mapped for France Figure 9.

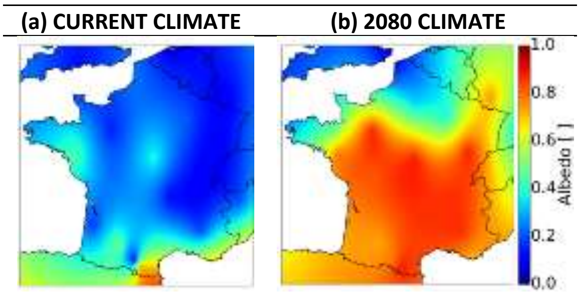


Figure 9 optimal albedo values for current (a) and 2080 (b) climate.

For the current climate conditions in France, Figure 9a, most of the found optimal solutions for this building typology are found to require a low albedo value. Winter heating penalty are yet not compensated in southern areas where moderate or high albedo values are found. For the 2080 climate, Figure 9b, cool roof solutions are widely selected due to the prevalence of summer thermal discomfort effect compared to the winter heating penalties.

Thermal insulation

On one hand, passive cooling with natural ventilation and cool roofs cannot be totally efficient without a good thermal inertia (Lapisa, Bozonnet, M. O. Abadie, et al. 2013). Moreover, radiative cooling effects of roofs are highly dependent on the night heat transmission through the roof layers. On the other hand, highly insulated walls are usually recommended for passive building solution in moderate and cold climates to limit heating energy demand. For the studied building typology, the thermal mass is mainly given by the slab on the ground, and the slab insulation can limit the building inertia. Then, there is a strong link between this parameter and the benefits of thermal inertia for both summertime and heating season. Optimal thermal insulation thicknesses vary strongly between considered regions and from current to future climate conditions as mapped Figure 10.

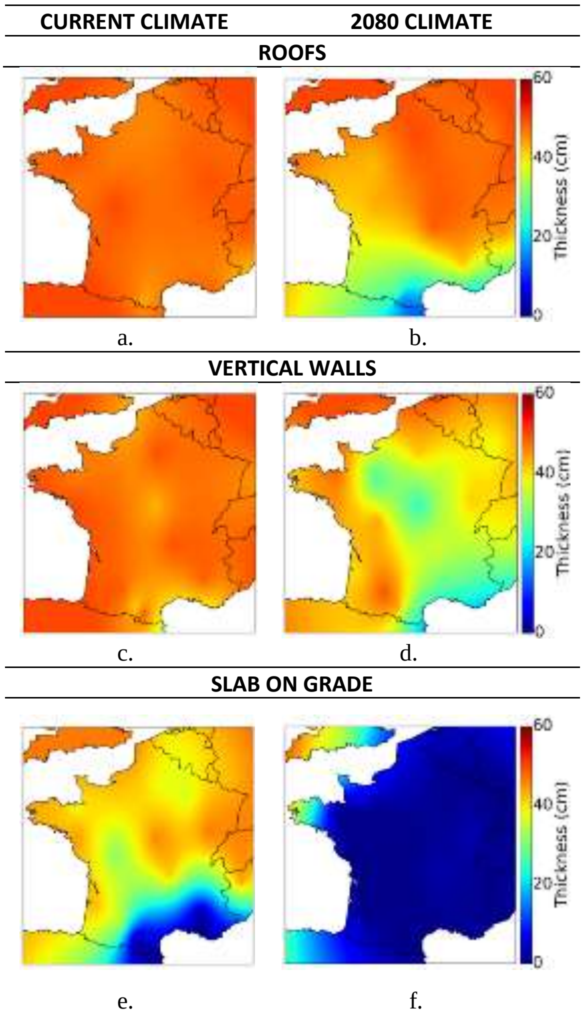


Figure 10 optimized thermal insulation thickness for walls.

Optimal values are high (from about 45 to 50cm) for roof and vertical walls, Figure 10a and c, except for southern area walls with lower values (30 to 40cm). The interest of slab inertia is mainly found for passive cooling effects in summer and the slab optimal insulation thickness varies from 0 to 47.5cm (Figure 10e). Roofs have also a good potential for passive cooling with a high thermal emissivity and nighttime radiation toward the sky in summer. This passive cooling effect is found to be efficient in optimal solutions for 2080 climate, Figure 10b. The insulation thickness decrease from about 50 to 25cm in the northern areas. Optimal wall insulation decreases and slab insulation is almost not necessary with these new climatic conditions, see Figure 10d and f.

CONCLUSION

This optimization study of commercial buildings in France represent the various climates of France and gives the possible strategies for passive cooling solutions and energy performance for heating and lightning. About 1344h computing time has been required for the 24th locations and both current and future climate. The proposed future climate predictions and simulation results are questionable, in particular the high-emission scenario and the rough approach of global warming simulation. Still, these simulations highlight the optimal parameter evolutions due to global warming. Further work should include other emission scenario and more accurate global warming model.

In a first approach, the choice of best compromises among 48 Pareto front solutions has demonstrated that the considered passive cooling solutions can be really efficient for all French locations without any need for an air-conditioning system. However, increased climatic loads could compromise these solutions for some southern areas. Indeed, summer thermal discomfort *DH* increases by an average of 265°Ch for France and a maximum of 1544°Ch for the city of Marseille, i.e. 13 times more than the current climate's optimal solution. In a further analysis, the method to determine a compromise solution should be adapted either with a maximum value of acceptable summer discomfort to keep the passive solution, or with the implementation of an air-conditioning system. Further studies on passive cooling solutions could also give better summer performances.

The obtained optimal parameters mapped in this paper can be useful for design stages of this commercial building typology. However, these parameters values have to be carefully considered as the optimized values are obtained for a specific building operation and are dependent one from each other. E.g., increased roof albedo values are obtained together with a strong slab inertia effect, i.e. low or no slab insulation, and decreased roof insulation.

For passive building strategies this study highlights the complex balance between highly insulated envelope benefits for northern climates, and lower insulation required for southern climates with the potential strong benefits of natural ventilation and cool roofs.

In this first approach, we have also considered the natural ventilation control together with the building envelope design itself. This integrated approach should be extended to other key parameters of the building operation either for passive strategies or for heating and cooling systems.

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