Building and Environment 132 (2018) 83–95

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Optimized design of low-rise commercial buildings under various climates – Energy performance and passive cooling strategies

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ARTICLE INFO

Keywords:
Low-rise commercial building
Building energy performance
Passive cooling strategies
Building envelope design optimization
Natural ventilation
Cool roof

ABSTRACT

The design of low-rise commercial building envelopes is mainly driven by functional large volumes, and low-cost and lightweight materials that often present weak thermal performances. Thermal and visual comfort is a key parameter for these buildings' purpose, but poor envelope designs have significant consequences on the high-energy demand for HVAC and artificial lighting systems. Considering the resources outside the building envelope for both cooling and heating seasons, this study aims to optimize the building design under various climates. Energy for ventilation, heating and lighting, and summer thermal discomfort are mitigated considering natural resources such as solar energy, low sky temperatures, ground inertia, and ambient air. For this specific building typology, main thermal fluxes are transmitted through large surfaces of soil (to the ground) and roof (to the environment). In the study, we found that summer thermal discomfort can be minimized, and near zero for some climates, without active cooling system. This objective is balanced by the energy demand objective; a multi-objective optimization using the NSGA-II algorithm gave optimal solutions according to local climate and global warming effects. This methodology and numerical results presented here can be helpful to design new commercial buildings and improve energy efficiency of existing ones. Most adapted set of design parameters for passive cooling solutions such as cool roofs and night natural ventilation are mapped for various climate, including climate change effects.

1. Introduction

The commercial sector presents a significant potential for energy saving and reduction of environmental impacts. Commercial buildings are actually responsible for 7% of the total world energy consumption [1]. This energy use is mostly due to heating and cooling systems with more than 60% of building consumption [2,3]. Commercial buildings represent more than 20 billion square meters in 2010 and there surface should increase fast in the future [4]. This surface would increase together with the population growth and higher living standards, and could be up to 80 billion square meters in 2050 [4]. The thermal performance improvement of commercial buildings, through their refurbishment or better designs of new constructions, can be promising in worldwide energy policies. Many studies focus on better design of air-conditioned building, but developing alternative cooling strategies without air-conditioning is a challenge for balancing increase of energy demand [4]. Actually, most buildings are still not air-conditioned either due to low standards of living or like in French climates where adequate design can be enough.

In order to minimize energy consumption of these buildings, we focus in this paper on heating, cooling, lighting and ventilation systems that ensure thermal and visual comfort. In this context, there are a wide variety of optimization parameters and strategies to tend toward low or near-zero energy buildings. For example, increasing roof albedo can significantly improve overall building performance except in some building typologies or for high insulation levels [5]. Unlike many published studies, we focus here on simultaneously optimal set of parameters for construction and ventilation control. Indeed, main progresses for NZEB should be obtained from a good combination of those key parameters [6]. A review of building thermal performance studies highlights various groups of key parameters such as building morphology and envelope's performance [7–10], building orientation, construction material [8,11,12], HVAC system operation and design [11,13,14]. Besides, the effect of climate change presents a significant impact on building energy consumption especially on heating and cooling system depending on climatic condition and building characteristics [4,15–19]. In order to predict the future climate, the HadCM3 is the most widely used model because of its high resolution

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https://doi.org/10.1016/j.buildenv.2018.01.029
Received 25 August 2017; Received in revised form 5 January 2018; Accepted 17 January 2018

[15–19]. Optimization process through all these parameter groups, even active systems, has to consider passive cooling or heating techniques, environmental resources and waste energy recovery. It has been demonstrated that passive cooling techniques such as cool roofs are highly dependent on building operation and occupant behavior [20].

In this paper, we considered the optimization of building envelope together with the control strategy for natural ventilation by taking into account the impact of climate change. However, some constraint parameters are fixed: occupancy patterns, ventilation modes, internal heat gains. Then, the real effectiveness of passive techniques is highly unpredictable, especially for free heating or cooling strategies, depending both on the climate and building environment, and on the latter building complex interrelationships of intrinsic parameters. The potential of cooling techniques for large flat roof, such as green or cool roofs, can be limited depending on the climate zone as demonstrated by several studies [21–23]. A suitable building design for one geographical location is not necessarily well suited to another location.

The objectives of this paper are (1) to develop an optimization tool using the NSGA-II algorithm [24] in order to evaluate the best configurations of low-rise building according to the climatic conditions and (2) to evaluate passive strategies' effectiveness regarding both energy performance and thermal comfort. In a first stage, we describe a generic low-rise commercial building together with the passive cooling strategies for this building typology. Then, we processed optimal solutions for different climates in term of energy consumption and summer comfort. We assessed sensitivities of key design parameters through the analysis of these commercial building optimal solutions. However, climate change can impact the performance of passive building design [25–27]. Then, climate change for the case of France is accounted for evaluating future optimal designs. The methodology and results of this study can be very useful for the architectures to design a passive building with similar characters in the future.

2. Description of the generic low-rise commercial building

The generic low-rise commercial building defined for this study is made of steel structure with a square floor surface of 36 m sides (Fig. 1). This simple building typology is common especially for commercial and industrial use due to various economic and practical advantages [28,29].

The building height is 6 m. 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 thermal inertia of the building envelope is mainly due to the concrete slab (160 mm) which directly lies on sand. The terrace-flat roof has a thickness of 25.5 cm (24 cm rock wool, 2 mm outer steel cladding and 13 mm plasterboard) and is fitted with 31.36 m^2 of skylights (2.42% of the roof surface area). Vertical wall windows have a total surface of 30 m^2; only the northern wall has no windows. Sizes and thermal properties of wall layers are detailed in Tables 1 and 2.

The commercial shelves stand on 30% of the floor surface area. These elements consist of cardboard (40%), liquids/oils (30%) metals (10%) and plastics (20%). The building air permeability level is equivalent to 2 cm^2/m^2 which is representative of a common steel construction building [30].

Table 1
Structure of the building envelope.

Wall	Material	Thickness (mm)	Thermal conductivity ($W.m^{-1}.K^{-1}$)	Density ($kg.m^{-3}$)	Specific heat ($J.kg^{-1}.K^{-1}$)
Vertical walls	Sheet steel	2	50	7800	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	7800	419
	Glass wool	240	0.038	50	840
	Plaster	13	0.25	825	801
Slab	Concrete	160	2	2450	1000

Table 2
Windows properties.

Windows	Type	A_w (m^2)	U_w ($W.m^{-2}.K^{-1}$)	F_w (−)	F_L (−)
Glass doors	Double glazing	6	2.89	0.789	0.747
Windows	Double glazing	24	2.89	0.789	0.747
Skylights	Double glazing	31.36	2.95	0.777	0.817

A_w: glazing surface area, U_w: heat transfer coefficient of the window, F_w: solar factor, F_L: light factor.

An occupation density of 11.6 m^2 per person is considered here [31]. The occupancy period is 07:00 a.m.–10:00 p.m. 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. In this study, there is no active cooling system and we aim to optimize passive cooling solutions. A heat recovery ventilation (HRV) system provides 0.5 air changes per hour (ACH) during occupancy hours. Artificial lighting is turned off when natural daylighting exceeds 300 lux by using the daylight factor [32,33]. To improve building summer comfort, natural ventilation operates during nights from 23:00 p.m. to 06:00 a.m. by opening ad-hoc vents in the lower part of the building and skylights located on the roof.

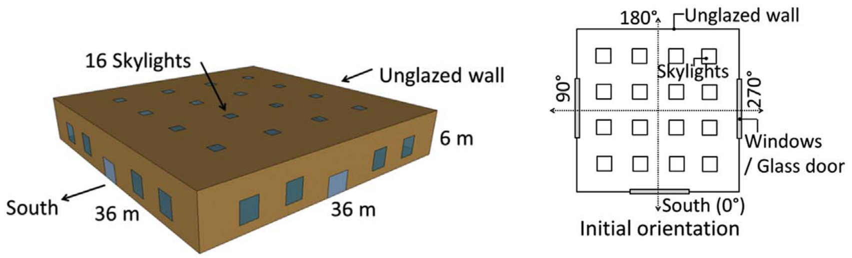
3. Methodology

3.1. Passive strategies for low energy consumption and summer comfort

In order to improve the building thermal performance, some techniques of passive solutions were considered here (Table 3). They can be characterized according to various building aspects: geometry (orientation, surface of skylights), thermal insulation (ground, roof and vertical walls), and passive cooling techniques (reflective coating of roof surface, natural night ventilation).

3.1.1. Strategy of natural night ventilation

In the present study, the natural night ventilation (NNV) through



a. Three-dimensional view

b. Building orientation

Fig. 1. Geometry of the studied low-rise commercial building.