AIR-CONDITIONING ENERGY REDUCTION THROUGH A BUILDING SHAPE OPTIMIZATION

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ABSTRACT

The air-conditioning energy consumption, for cooling or heating, has currently a growing trend. The purpose of this work is to develop a method suitable to design optimal three-dimensional building forms to reduce air-conditioning needs in a chosen location by using weather data. The method exploits in particular both diffuse and direct solar radiation; not independently but rather in relation with the external temperature. For this reason this method could be applied in any climatic region. In fact the warmer the region is the more negative the contribution of the solar radiation is in terms of building energy balance. Hence in this case the problem tends to be equivalent to the one of the annual solar irradiation minimization. On the contrary, in the case of cold regions, the problem tends to be equivalent to the one of the annual solar irradiation maximization. The final aim is to guide designers to reduce energy consumptions in buildings, since the first stages of the design process of future buildings.
To achieve that aim, an algebraic cumulative sky is introduced for the computation of the annual useful incident solar irradiation on the building envelope. The methodology consists in using weather data to define in which case the solar irradiation on the envelope gives a positive or negative contribution depending on the external temperature in order to maintain internal comfort of the occupants. The contribution is further associated to the data of the solar irradiation for each hour of a typical year. The algebraic cumulative sky constructed on that basis has the advantage to present particular zones where the solar radiation is useful all year long. Finally we use an hybrid evolutionary algorithm (CMA-ES/HDE algorithm) already applied to maximize solar energy utilization to explore the optimal building forms maximizing the annual useful solar irradiation on the envelope.

Keywords: building form optimization, algebraic cumulative sky, air-conditioning energy reduction

INTRODUCTION

The electricity consumption due to the air-conditioning (AC) in summer is a relevant problem in various warm and temperate climate regions. E.g. the annual electricity peak power in Italy is reached in summer for the first time in recent years and is increasing in intensity, probably due to an increasing diffusion of AC for the summer cooling of buildings [1]. A relevant source of internal gains is solar radiation. This radiation can enter buildings directly through windows or it can heat the building shell to a higher temperature than the ambient, increasing the heat transfer through the building envelope.

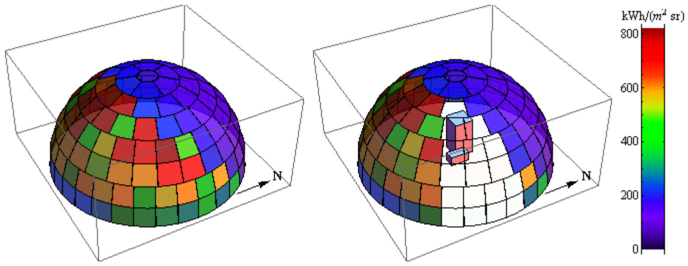

Figure 1: Schema of the cumulative sky, simulated for Basel.

Optimizing the global form of the building envelope is an approach that could be useful to reduce solar irradiation. The optimization of the building form has been studied to maximize the solar energy utilization in cold climatic regions [3, 2] by using a new hybrid evolutionary algorithm (CMA-ES/HDE algorithm) developed in [4].
In this paper, we generalize this method for all climatic regions, by taking into consideration the 'algebraic' solar energy irradiation, i.e. considering solar gains positive or negative respectively in cold or warm hours of the year. The method is applied to two families of possible building forms.

METHOD

The methodology consists in using weather data and RADIANCE [5] in order to build the virtual scene representing the annual solar energy source of algebraic radiation on the building, i.e. considering in which case the solar irradiation on the envelope gives a positive or negative contribution depending on the external temperature. The contribution is further associated to the data of the solar irradiation for each hour of a typical year. The algebraic cumulative sky constructed on that basis has the advantage to present particular zones where the solar radiation is useful all year long.
Finally we use an hybrid evolutionary algorithm (CMA-ES/HDE algorithm) to explore the optimal building forms minimizing the annual air-conditioning energy consumption.

1.1 Algebraic solar potential determination

The backward ray tracing program RADIANCE is used, in order to measure the solar potential of hypothetical buildings. As done by Kämpf and al. [2], a virtual scene is defined by a sky, buildings and a ground. In order to compute the irradiation on buildings over an average year, a cumulative sky is produced for the location [6]. In this study, we have taken two locations to be Basel in Switzerland (47°N,7°E) and Dubai (25°N,55°E) and the corresponding meteorological data from the Meteonorm software [7]. The sky is composed of 145 Tregenza patches with corresponding cumulative radiance ($Whm^{-2}sr^{-1}$), as shown in Fig. 1.

The RADIANCE software is then used to determine the irradiation on surfaces that composes the virtual scene. To realize this, each surface is fitted with virtual watt-meters in order to compute their irradiation. The total irradiation is computed by multiplying the point irradiation (in Whm^{-2}) by the corresponding surface area (in m^2) and summing over all the points.
Solar irradiation is clearly counter-productive only in *warm* conditions, and, not in *cold* conditions. In order to estimate the effect due to solar radiation in a year, an 'algebraic' cumulative sky is reproduced, i.e. an algebraic sum in which solar radiation, at a defined

hour of the year, is taken positive if the atmospheric conditions are *cold* and negative if it is *warm*.
The definition of *warm* and *cold* are here introduced ad hoc for our purpose, as a relation between the monthly average external temperature T_e and the corresponding internal comfort temperature T_c. These two quantities are in fact linked by the following equation [8]:

$$T_c = 13.5 + 0.54 \cdot T_e \quad (1)$$

The software Meteonorm provides the values at each hour of the year, as an average of experimental data, of the external temperature and solar irradiance, and then the sign of the corresponding sky radiance is evaluated for each hour of the year, as shown in Fig. 2. In particular, the following definitions are introduced:

- there are *warm* conditions, in which the sky radiance contribution are accounted for negatively if $T_e > T_c$;
- there are *cool* conditions, in which the sky radiance contribution are accounted for positively if $T_e < T_c$.

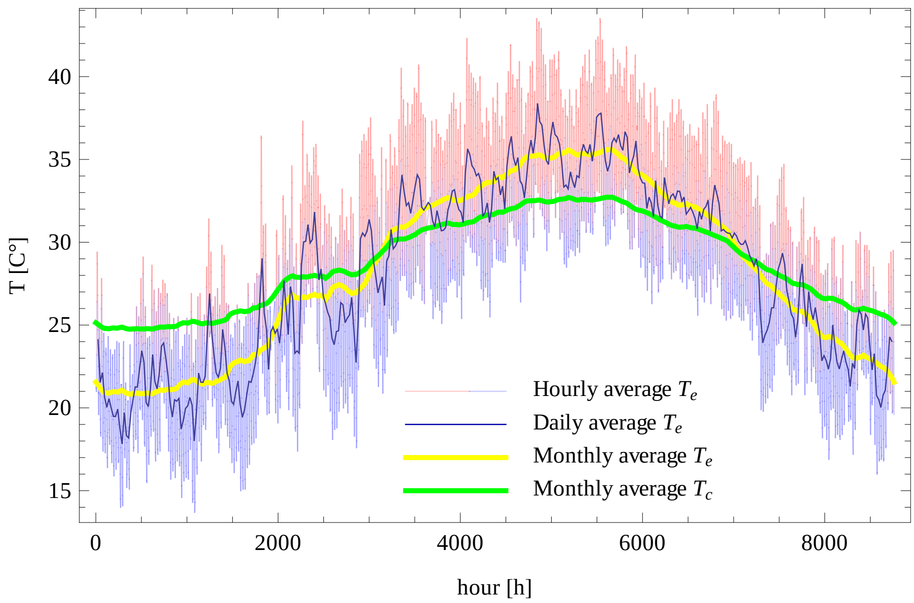

Figure 2: Comparison between the external temperature T_e and the internal comfort temperature T_c, in Dubai.

Finally the 'algebraic' cumulative sky is calculated by summing all positive and negative sky radiance contributions for all hours of the typical year.

1.2 Optimization

The form of the building is described by relevant variables, called 'alleles'. The optimization consists to find the combination of these parameters that minimizes solar irradiation on the envelope. For a few different discrete variables it may be possible to exhaustively test all possibilities, but when the parameter space to explore becomes large to very large, it is desirable to use optimization algorithms.
With these algorithms, we should be able to find the global minimum (or minima) of a function f that depends on n independent decision variables. Put formally, the algorithm

searches for the supremum (the set of variables that maximizes the function) as in Eq. (2).

$$sup\{f(\vec{x})|\vec{x} \in M\sigma\mathbb{R}^n\} \tag{2}$$

with:

$n \in \mathbb{N}$	dimension of the problem
$f : M \longrightarrow \mathbb{R}$	objective function
$M = \{\vec{x} \in \mathbb{R}^n \| g_j(\vec{x}) \geq 0$	feasible region
$\forall j \in \{1, ..., m\}\}, M \neq \emptyset$	
$m \in \mathbb{N}$	number of constraints

The set of inequality restrictions $g_j : \mathbb{R}^n \longrightarrow \mathbb{R}, \forall j \in \{1, ..., m\}$ includes a special case of constraints due to the domain boundaries $\vec{L} \leq \vec{x} \leq \vec{H}$, with $\vec{L}, \vec{H} \in \mathbb{R}^n$. $\vec{L}$ is named the lower bound and $\vec{H}$ the upper bound of the domain.
In our case, the parameter space is defined by a geometrical characterization of the buildings and the measure to improve is the received useful irradiation. For this, RADIANCE is used as a black-box together with the 'algebraic' cumulative sky introduced before.

RESULTS

The method is applied to two families of possible building forms. The first one is the family of general three-dimensional surfaces parameterized as Taylor series and the second one is a family of buildings designed as union of cuboids.

1.3 The first parametrization of the building's shape: Taylor series

This first case is based on the idea that consists to use a two dimensional (2D) Taylor series to describe the geometry of the roof. We seek to minimize the algebraic solar irradiation on the envelope throughout a year, on both the roof and the vertical facades. For this application, the two-dimensional Taylor series is expressed as follows:

$$h(x, y) = \sum_{k=0}^{N-1} \sum_{l=0}^{M-1} A_{kl} \cdot \left(\frac{x - L_x/2}{L_x}\right)^k \left(\frac{y - L_y/2}{L_y}\right)^l . \tag{3}$$

where $h : \mathbb{R}^2 \longrightarrow \mathbb{R}$ gives the height as a function of the position (x, y) in the plane, $x \in [o, L_x]$, $y \in [o, L_y]$, L_x and L_y delimit the domain of interest in x and y and A_{kl} are the coefficients of the series, that are used here as parameters in the optimization process. The domain boundaries were chosen to be $L_x = 20\ m$, $L_y = 30\ m$ and $N = M = 5$. The coefficients are limited between a lower and an upper limit as follows:

$$A_{kl} \in [-200, 200]. \tag{4}$$

A minimum cut value was chosen in the height of the surface at 0 m, so that when the surface goes below the ground (placed at 0 m), it is not taken into account in the irradiation calculation.
Further constraints dictate that the volume under the surface must be less than 1000 m^3. The simulations were made for Basel and Dubai, for which results are presented in Fig. 3.

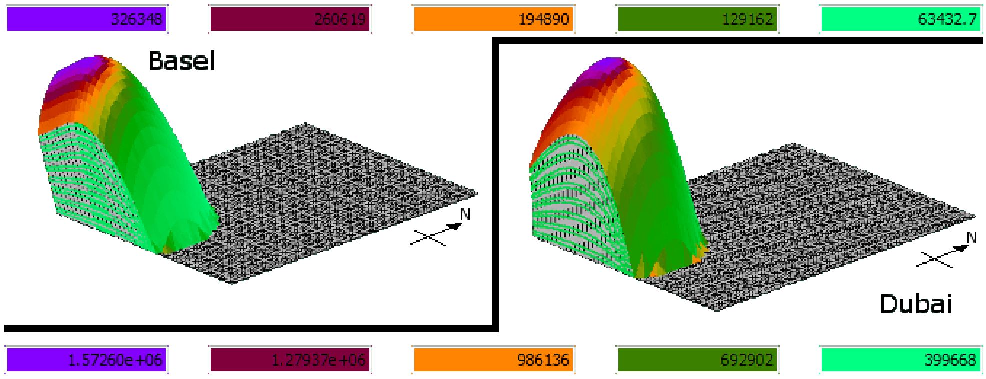

Figure 3: Optimal forms of the first parametrization, with $V_{min} = 1200\ m^3$*, in 3D view, with irradiance in Wh, respectively for Basel and Dubai.*

1.4 The second parametrization of the building's shape: Cubotron (squared forms)

The second parametrization introduced is closer to the common and widespread constructions, with squared form. In particular, the form is defined by a three floor building, each 3 m high, with a fixed total floor area , and vertical walls. Each floor has a squared form, in particular we use 2 parameters to define with continuity the form of the floor (obtaining rectangular, 'L' or 'Z' shapes), without changing the total area of the floor. In this case the alleles define the form of each floor, how to distribute the gross floor area and the position, rotation and deformation (by homothetic transformation) of each floor. The simulations were made for Basel and Dubai, for which results are presented in Fig. 4.

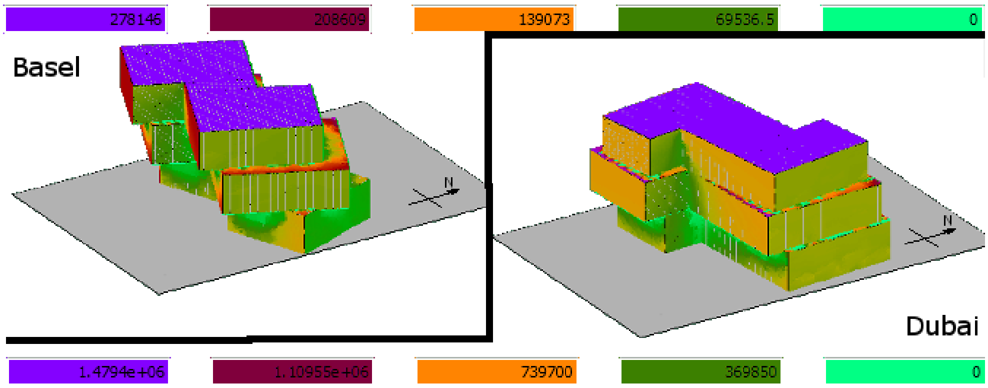

Figure 4: Optimal forms of the second parametrization, with $V = 1200\ m^3$*, in 3D view, with irradiance in Wh, respectively for Basel and Dubai.*

DISCUSSION

The optimization method is applied to two families of possible building forms. The first one is the family of general three-dimensional surfaces parameterized as Taylor series and the second one is a family of buildings designed as union of cuboids. In both cases we find coherent results in which the optimal forms have more extended portion of the envelope exposed to directions in the sky close to the solar path in the cooler hours of an annual average day. Vice versa the optimal forms tend to have compact sections orthogonal to

directions in the sky close to the solar path in the hottest hours of an annual average day. The final results are shown in Table. 1, where, in particular, it is interesting to note that the optimal forms are inclined to a direction close to the direction of the minimum algebraic solar radiation in the sky, i.e. the direction in respect to which a flat plane should be oriented to minimize the algebraic annual solar radiation.
The method here introduced is applicable to specific architectural projects, to find the optimal solution among a parametric family of potential building forms, previously chosen by the designer. Moreover it could be generalized to study optimized urban settlements to reduce the air-conditioning needs at urban level. Indeed, a building in an urban context cannot see the whole sky, other buildings are shading portions of it, then not intuitive solutions could be found due to the complexity of this scenario.

	BASEL			DUBAI		
Parametrization	V (m^3)	Σ $(60.23°)$	Φ_{sol} $(Wh/year)$	V (m^3)	Σ $(73.65°)$	Φ_{sol} $(Wh/year)$
Taylor $V_{min} = 1200m^3$	1204.58	70.44°	$0.57 \cdot 10^8$	1203.56	82.11°	$2.97 \cdot 10^8$
Cubotron	1200	–	$0.65 \cdot 10^8$	1200	–	$3.33 \cdot 10^8$

Table 1: Results of optimal forms of Taylor and Cubotron parametrization to reduce energy consumption, in Dubai and Basel, where V, Σ and Φ_{sol} are the volume of, the tilt angle of and the algebraic annual solar irradiation on the optimal forms respectively. The angles in brackets are the zenith angles of the direction of minimum algebraic solar radiation in the sky for the location considered.

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