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Building shape optimisation to reduce air-conditioning needs using constrained evolutionary algorithms

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Abstract

The purpose of this paper is to analyse the optimal three-dimensional form of buildings that minimise energy consumption due to solar irradiation. We use an evolutionary algorithm (hybrid CMA-ES/HDE algorithm) already applied to maximise solar energy utilisation (Kämpf and Robinson, 2010), which uses a cumulative sky model approach for the computation of incident irradiation on the building envelope.

Various families of possible building forms are investigated with this methodology to find the optimal building form, in two locations with radically different climatic conditions, showing the features that a building should posses in order to optimise its energy performance with respect to the solar irradiation.

Keywords: Building form optimisation; Constrained evolutionary algorithms; Point of maximum algebraic/cumulated solar irradiation; Hybrid CMA-ES/HDE algorithm

1. Introduction

In building facing particularly hot climatic conditions, the greatest 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 one, increasing the heat transfer through the building envelope. As a result, 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 (Terna s.p.a).

Solar gain can be reduced by adequate shading from the sun, light coloured roofing, spectrally selective (heat-reflective) paints and coatings and various types of insulation for the rest of the envelope. However, these solutions reduce in general interior daylighting, increasing energy consumption due to artificial lighting.

Another approach is to optimise the global form of the building envelope to reduce energy consumption due to solar irradiation. The problem of building's form optimisation has been investigated in many publications with an analytical approach based on variational methods (Caruso et al., 2013), and with a numerical approach by using multicriteria optimisation (Marks, 1997; Farmani

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Nomenclature

$\vec{\gimel}$, $\gimel$	the radiance distribution in the cumulative sky
$\dot{\gimel}$	the normalised radiance distribution in the cumulative sky
$\vec{\gimel}_i$	the radiance on the ith Tregenza patch
I	the total solar irradiation on a surface
r	the ratio of the direct solar radiation contribute to the total radiation
$\hat{n}(\sigma, \psi)$	the normal vector of a given surface
σ, Σ	the tilt angle of a given surface, i.e. the angle between the surface and the vertical
ψ	the orientation of a given surface (zero to the South and positive to the West)
θ	the zenith angle defining the position in the cumulative sky of a radiant source
ϕ	the azimuth angle defining the position in the cumulative sky of a radiant source (zero to the South and positive to the West)
φ	the day angle
θ	the solar zenith angle
δ	the declination
L	the latitude
ω	the hour angle
$\mathbb{R}$	the set of real numbers
$\mathbb{R}^+$	the set of positive real numbers
$\mathcal{B}$	a Banach space
$\mathcal{D}$	a space of distributions
λ	the wavelength
$H_{0\lambda}$	the extraterrestrial spectral irradiance at the mean solar distance
D	the correction factor for the earth–sun distance
$T_{r\lambda}$	the transmittance function for Rayleigh scattering
$T_{a\lambda}$	the transmittance function for aerosol extinction
$T_{0\lambda}$	the transmittance function for ozone absorption
$T_{w\lambda}$	the transmittance function for water vapour absorption
$T_{u\lambda}$	the transmittance function for absorption by the uniformly mixed gases (oxygen and carbon dioxide)
$a_{0,\lambda}$	the ozone absorption coefficients
$a_{w,\lambda}$	the water vapour and mixed gas absorption coefficients
$a_{u,\lambda}$	the mixed gas absorption coefficients
W_0	the single scattering albedo of the aerosol
F_a	the forward to total scattering ratio of the aerosol
T_e	the external temperature
T_c	the internal comfort temperature

Superscripts

$^{(v)}$	refers to the visible spectrum

Subscripts

$_d$	refers to the direct solar radiation
$_s$	refers to the diffuse solar radiation

et al., 2002), genetic algorithms (Farmani et al., 2002; Rivard et al., 2006; Tuhus-Dubrow and Krarti, 2010; Kampf and Robinson, 2009, 2010; Kampf et al., 2010), discrete polyoptimisation (Jedrzejuk and Marks, 2002) and hierarchical geometry relations (Yi and Malkawi, 2009). In particular Kämpf and Robinson developed a method based on genetic algorithms to find the 3-dimensional form that maximises solar energy utilisation (Kampf and Robinson, 2009, 2010; Kampf et al., 2010).

In this paper, we use a numerical method and, in particular, an hybrid evolutionary algorithm developed in Kampf and Robinson (2009) and applied to optimise building geometric form for solar radiation utilisation (Kampf et al., 2010; Kampf and Robinson, 2010). We discuss the validity of the method used and exhibit optimal individuals of some parametrisation of the building's shape and associated results. Moreover a new algebraic cumulative sky is introduced in order to estimate the energy consumption due to solar gains. We conclude by extrapolating the shape that a building form should follow in order to optimise its energy consumption by a suitable solar exposure.

2. Methodology

The methodology consists in using weather data and RADIANCE (Larson and Shakespeare, 1998) 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 minimising the annual air-conditioning energy consumption.

2.1. Solar potential determination

The backward ray tracing program RADIANCE is used, in order to measure the solar potential of