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Urban layout optimization framework to maximize direct solar irradiation

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A B S T R A C T

The need to save energy at the urban level leads to study how numerical simulations and optimization methods can help the architects to design buildings and districts with the best possible energetic performances, regarding daylight, warming or cooling, and photovoltaic capabilities.

This work presents a study of solar potential maximization over a district and its relation with urban shape. For this purpose, two geometrical models are proposed. The first one is derived from the literature and describes a grid of buildings in open area; the second one studies moderately dense urban configurations with a pre-existent urban-context. A clear sky model is considered to compute direct solar radiation and an evolutionary algorithm is used to optimize the shape and the distribution of buildings inside a fixed area.

Results show some clues on the optimal distribution of buildings considering the total direct solar irradiation to be captured by an urban district for various densities and compare the solar potential at different latitudes between 40° and 60°N.

1. Introduction

For several decades, optimization has been applied to computational mechanics and has shown its capability to improve existing solutions (size or shape optimization), or to provide new ones (topology optimization) with high performance (life duration, rupture criteria, buckling, natural frequencies...) and low cost. In the field of urban and architectural design, the main motivation has emerged with the urbanization of a world with limited resources: to improve the environmental performances of the buildings in order to save energy by all possible ways while ensuring a high level of comfort (Beckers, 2011).

Solar radiation has a significant role in the design of energy efficient cities for it relies on strong geometric features. Its maximization for heating and daylight purposes is therefore heavily influenced by building shape and urban organization. A classical approach to consider the access to sunlight in urban context uses solar right envelopes. Those envelopes, originally developed in the 1970s (Knowles, 1981), consist in 3D boundaries for the maximum height of buildings in a given area ensuring sunlight over existing buildings for a given period of the year. Later, complementary notions were introduced: the solar collection envelope corresponding to the volume shadowed by pre-existent building on the buildable area (Capeluto & Shaviv, 2001; Capeluto, 2012) and the iso-solar surfaces ensuring a certain amount of irradiation over a period of interest (Morello & Ratti, 2009). The latter adds an energetic component to solar envelopes by computing dynamic solar irradiation instead of few instant shadow casting. To design the solar envelope, it is mandatory to know the shape and the position of the surrounding buildings. Therefore, in the case of a high-density district design, composed of close buildings which are frequently projecting shadows one to another, the construction of solar envelopes cannot usually be performed.

The optimization of the features of the buildings is being used from about twenty years, with a strong development in the last decade as confirmed by recent literature reviews (Evins, 2013; Machairas, Tsangrassoulis, & Axarli, 2014; Nguyen, Reiter, & Rigo, 2014; Stevanović, 2013). Most of building shape optimization studies on energetic criteria, with or without urban component, rely on the use of simulation software tools to compute the energy consumption of the building like CitySim (Kämpf & Robinson, 2011; Vermeulen, Kämpf, & Beckers, 2013), EnergyPlus (Yi & Malkawi, 2009) or DOE-2 (Caldas, 2008). In those cases, optimization is related to the overall building consumption for heating, cooling or daylighting, and thus includes heat transfer through the

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Nomenclature

A	area (m^2)	V	volume (m^3)
G_{sc}	solar constant (W/m^2)	x_G, y_G	footprint centroid coordinates of a building
h_{floor}	height of a floor (m)	δ, γ	scaling factors
$I_{b\alpha}$	direct irradiance on a surface with an angle of incidence α (W/m^2)	θ	rotation angle (radians)
J	direct irradiation cumulated on the district (W h)	μ	number of parents (optimization parameter)
k	number of floors	λ	number of offsprings (optimization parameter)
m	optic mass number	τ	atmospheric transmittance
		ψ	solar zenith angle

envelope and air renewing, which depend on additional parameters such as materials and systems. Few works are however studying urban shape optimization with solar irradiation criteria (Kämpf & Robinson, 2010; Kämpf, Montavon, Bunyesc, Bolliger, & Robinson, 2010).

While not relying on optimization tools, other approaches like parametric study (Beckers & Beckers, 2008; Hachem, Fazio, & Athienitis, 2013; Muhaisen, 2006) or real case modeling (Compagnon, 2004; Montavon, 2010), are extensively investigating urban fabrics in relation with solar radiation. A natural continuation of these works is to investigate this field using optimization algorithms to evaluate if it is possible to draw further methods and guidelines for the planners, by working on higher complexity case studies.

The present study exposes a geometric framework for the optimization of the shape of buildings with equality constraints (imposed constant volume), and inequality constraints (each building should remain within the limit of its parcel). The objective function is the total irradiation on the district during the winter solstice in mid latitudes, considering a clear-sky model.

The paper is organized as follows: the physical and geometrical models are described in the next two sections; the optimization problems are then stated and we show how an evolutionary algorithm with specific crossover, mutation and repair operators is adapted to building design. Results are finally presented to illustrate the optimization in the field of urban design.

2. Physical model

The basis of an optimization strategy is to have a reliable and fast model to simulate the system behavior. In this study, a clear sky model is used to give, for a small computation time, an approximation of the solar direct irradiation received by the buildings façades and roofs. The sun path is first computed for the chosen location and time period (Beckers & Beckers, 2012). The power of the direct solar radiation under clear sky conditions is then determined with a model from (Liu & Jordan, 1960) as adapted by (Campbell & Norman, 1998). This model computes the direct radiation as a function of the solar zenithal angle ψ. The direct irradiance $I_{b\alpha}$ on a surface due to solar radiation with an incident angle α is obtained through the expression:

$$I_{b\alpha} = \tau^m \cdot G_{sc} \cdot \cos(\alpha) \tag{1}$$

where τ is the atmospheric transmittance (here, $\tau = 0.7$), G_{sc} the extra-atmospheric solar irradiance ($G_{sc} = 1367$ W/m), and m is the sea-level optic mass, approximated by:

$$m = \frac{1}{\cos(\psi)} \tag{2}$$

This model (Campbell & Norman, 1998) does not depend on meteorological data and thus does not take into account climatic specificities. Diffuse radiation computation is not included in this work to emphasize the geometrical features of the solar paths.

The overall direct solar irradiation received on the district is given by the expression:

$$J = \int_{T_1}^{T_2} \int_{X \in S} I_{b\alpha} Vis(X,t) dX dt \tag{3}$$

where $[T_1, T_2]$ is the time interval considered, S is the total surface where irradiance is calculated, $I_{b\alpha}$ is the irradiance on surface S, and $Vis(X, t)$ is the sun visibility function equal to 1 if the sun is visible from the x point at time t and 0 otherwise.

As only straight edges are considered, limits between shadowed and lighted surfaces are polygonal lines and can be exactly determined without meshing techniques, by projections and intersections (Atherton, Weiler, & Greenberg, 1978). The integral that determines the total irradiance is thus exact at a given time step. A sensitivity analysis on the time step was carried out by evaluating the irradiation on 20 random urban configurations drawn with the parameters of the following studies, for the winter solstice and the equinox at 50°N latitude. For each case, a time step of half an hour gives differences lower than 0.5% on the overall energy received compared with 5 min time step and is thus selected.

The objective function consists in maximizing the overall direct irradiation on the district on the worst day of the heating period in terms of clear sky direct radiation, which corresponds to December 21th in Europe. We do not consider the integration over the year or the heating period, but focus on a one-day sun path. Furthermore, the winter solstice direct irradiance can be considered as representative of winter months because few variations of the sun paths are occurring around the solstices.

The summer solar radiation which plays an important role in thermal comfort and energy consumption through air conditioning is not considered in this work. After having optimized the urban configuration, façades design (window shape, static or mobile solar protections) could be added to the optimization parameters at building level in the future.

3. Geometrical model and design variables

Although very accurate geometrical representations of buildings are used by architects, in the early stages of district design, urban planners consider volumes with low level of details to define the general layout of streets and built areas, and draw ground planes. In this scope, a general urban parameterization with associated constraints is introduced for the allotment of a given volume over buildings in parcels. Two geometrical cases are then defined to validate the optimization methodology and describe urban optimal forms.

3.1. General description

We consider an urban scene constituted of buildings, each associated to a convex polygon representing a parcel. While buildings are associated with a set of parameters that transform their