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Optimal topology of urban buildings for maximization of annual solar irradiation availability using a genetic algorithm

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HIGHLIGHTS

- A mathematical model is proposed to optimize annual solar irradiation availability.
- Maximization of incident solar irradiation on roofs and facades of buildings.
- Dynamic interaction of buildings is simulated aiming to evaluate shadowing zones.
- Search for optimal topological solutions for urban grid based on genetic algorithm.
- Solutions are compared with the conventional configurations for urban grid.

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ABSTRACT

An approach based on the optimal placement of buildings that favors the use of solar energy is proposed. By maximizing the area of exposure to incident solar irradiation on roofs and facades of buildings, improvements on the energy performance of the urban matrix are reached, contributing decisively to reduce dependence on other less environmentally friendly energy options. A mathematical model is proposed to optimize the annual solar irradiation availability where the placement of the buildings in urban environment favors the use of solar energy resource. Improvements on the solar energy potential of the urban grid are reached by maximizing the exposure of incident solar irradiation on roofs and facades of buildings. The proposed model considers predominant, the amount of direct solar radiation, omitting the components of the solar irradiation diffused and reflected. The dynamic interaction of buildings on exposure to sunlight is simulated aiming to evaluate the shadowing zones. The incident solar irradiation simulation and the dynamic shading model were integrated in an optimization approach implemented numerically. The search for optimal topological solutions for urban grid is based on a Genetic Algorithm. The objective is to generate optimal scenarios for the placement of buildings into the urban grid in the pre-design phase, which enhances the use of solar irradiation.

1. Introduction

The autonomy offered by the reinforced concrete construction system releases walls of their structural function allowing the design of spaces, volumes and facades with a much larger size. Thus, conditions were reached that led to many of the problems of the cities of the twentieth century, namely the demographic explosion, constructive solutions for height, the limitations in physical space and its increasing value per square meter. The urban grid has been refined, grew in height and the space between buildings became cramped. Then, it follows the concern of some architects with the use of natural light in buildings and its functionality. It is with this background that during the second half of the last century appeared the first studies of the morphology of the buildings. These began to be analyzed to improve the creative process in the conceptual phase of design [1,2].

With the oil crisis in the seventies and increasing comfort conditions of houses, particularly in cities, there arose the need to rethink urban planning, making it more sustainable. Solving this problem can have several approaches, notably: (i) Reduction of energy consumption, (ii) Bioclimatic architecture, (iii) Replacement of primary energy sources by renewable energy from endogenous resources. If on the first item, it may be the result of policy implementation of voluntary or forced sustainability rules, the latter depends on how the man thinks the implementation and construction of housing. The third item relates statement paradigm

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replacing the current energy matrix, based mainly on use of fossil fuels by renewable energy sources, especially solar energy available throughout the earth's crust.

Lund et al. [3] explored energy systems design to increase the use of renewable energy (RE) such as photovoltaic and wind power in cities. They propose that smart energy system design could help mainstreaming renewable electricity as part of the cities' carbon reduction strategies. The approach was based on simulating the cities' hour-by-hour energy demand and supply patterns both temporally and spatiotemporally. In this way, it is possible to determine the energy system response to RE power and the contribution of renewable energy in the different cases. Leduc and Van Kann [4] proposed a sustainable urban energy planning approach, based on the thermodynamic principle – Urban Harvest Approach. This approach integrates multi-functionality, interaction between urban functions, and harvesting of local renewable and residual resources. The method addresses: (i) land-use inventory; (ii) energy demand inventory; (iii) local renewable/residual energy potential analysis; (iv) clusters of spatial functions exploration; (v) energetic linkages analysis; (vi) network patterns exploration. They showed that spatial planning based on urban energy harvesting is a useful method to translate generic goals to local spatial interventions.

Battaglini et al. [5] describe a SuperSmart Grid approach, which combines what is often understand as two exclusive alternatives: wide area power generation and decentralized power generation. They propose that by combining these complementary measures, it is possible to address the crucial issue of RE generation, the fluctuating supply, in a comprehensive and technological procedure. The concept of nominal urban areas was introduced by Ivezic et al. [6]. Nominal urban area is modeled for representation of real urban area with two basic characteristics, peak load density and number of buildings per predefined area. According to urbanistic characteristics of cities, a network of nominal urban areas was created to decide on preferable energy supply system. A photovoltaic (PV) system can be differently designed, depending on the goal that the investor wishes to achieve. In Cucchiella et al. [7] three different design principles were simultaneously considered: environmental maximization, economic maximization and self-sufficiency of the system during first year. The economic results are strongly influenced by the annual average insolation value encouraging the most exposed areas to sun. For a proper PV sizing, the data on energy consumption and the loss of efficiency of the generator are very relevant. Although the target of reduced emissions remains unchanged, each design principle has consequences on sizes of the RE system. However, the same environmental results are obtained using all three design principles. So, only the investment required is different, depending on the maximization principle used.

An interesting study has been driven by Mattinen et al. [8] based on the visualization of the energy and emission results employing geographical information system (GIS) techniques. They concluded that the annual energy usage is explained by the age of the building in general. Single family houses have higher gas emission intensities than apartment buildings. The information on residential buildings can be useful for regional planning and related decision-making, especially when designing the regional energy systems, accounting for both production and consumption. Various aspects, such as the availability of renewable energy sources and the necessary infrastructures can be taken into account using this approach.

With the goal of contributing to the optimization of this resource, some authors have proposed models aiming to improve the use of solar energy. Caldas and Norford [9] and Caldas et al. [10], used a Genetic Algorithm (GA) to optimize the construction budgets by minimizing costs with HVAC, lighting and building itself. Hensen [11] developed an application in Java environment using a GA as a mechanism for evaluating the performance of project design coupled with creative functionality. Oliveira Panão et al. [12] presented thermal performance indicators for urban construction related to the placement of buildings on the north-south alignments. Robinson [13] considers a GA to manage energy consumption for application to urban environment. In Pisello et al. [14], a method for evaluating the energy performance of a building from an inter-building perspective was proposed and described. This method was also applied to real American urban block morphology of twenty single-family residential buildings. This research was aimed at examining the potential for an Inter-Building Effect that may impact on energy use modeling predictions when the level of analysis is expanded from a single building to the network of buildings that surrounds a modeled building. The results demonstrate that buildings can mutually impact the energy dynamics of other buildings and that this effect varies by climatologically context and by season.

Chesné et al. [15] propose a method to assess both: (i) The capacity of the resources (sun, sky and outside air) to cover the building needs; (ii) The ability of the building to exploit the available energy resources. The method developed is mainly based on energy simulation. The basic data is a comparison of the behavior of a building with and without a given environmental resource. Gustafsson [16] deals with how to optimize retrofit measures, i.e. how to act in order to minimize the Life-Cycle Cost (LCC) of a building. Insulation measures are used but also other retrofits are dealt with such as changing the heating system. It is shown that the heating system has a vital influence on the optimal amount of extra insulation which is to be applied. Déqué et al. [17] presents the techniques used to describe, with a variable degree of refinement, the thermal phenomena in building envelopes. Together with physical models, involving a large number of equations and parameters which must be entered to describe the building, the 'grey box' set of models provides an efficient solution for processing energy consumption studies. Wright et al. [18] investigate the application of a multi-objective genetic algorithm (MOGA) search method in the identification of the optimum pay-off characteristic between the energy cost of a building and the occupant thermal discomfort. Kalogirou [19] presented an approach based on artificial neural-networks and genetic algorithms, to optimize a solar energy system in order to maximize its economic benefits. The system is modeled considering the climatic conditions of Cyprus, included in a typical meteorological year. An artificial neural-network is trained using a small number of results generated by TRNSYS computer program. The objective is to learn the correlation of collector area and storage-tank size on the auxiliary energy required by the system from which the life-cycle savings can be estimated. After for maximizing life-cycle savings, a genetic algorithm is employed to estimate the optimum size of these two design variables. Robinson et al. [20] describe the development and application of a new tool to support designers to optimize the sustainability of urban neighborhoods (SUNtool). This essay introduces (i) the software architecture, (ii) the integrated solver and related innovations in the modeling of radiation exchange, reduced thermal modeling, stochastic modeling of occupant presence and behavior, and urban plant modeling, (iii) interface design and innovations in building attribution, and (iv) results analysis methods.

The problem of optimal placement of buildings on urban grid environment using GAs or other evolutionary techniques has been investigated by some authors [21–24]. Xiyu et al. [21] developed a design model based on co-evolution where area and solar constraints of housing design problems are considered. Znouda et al. [22] developed a genetic algorithm in order to provide a method for obtaining a set of optimal architectural configurations adapted to the Mediterranean climatic conditions. Kämpf and Robinson