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Sensitivity analysis of urban morphology factors regarding solar energy potential of buildings in a Brazilian tropical context

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ABSTRACT

Today, 75% of global energy consumption occurs in cities. On the topic of climate change, adapting urban settlements to face this growing demand is a priority issue, especially for fast-growing cities in developing countries such as Brazil. Planning the urban morphology of the built environment is a key issue in shifting to a climate adapted urban environment. This paper addresses an important threefold energy challenge of tropical cities: the major potential of harnessing solar energy as renewable resource for local electricity production and the energy-saving paradox of reducing the undesirable solar heat gains in buildings while providing satisfactory levels of daylight. It aims at measuring the effect size of urban form factors regarding these energy goals. This study applies the Design Of Experiments (DOE) approach. A DOE analysis is a statistical technique that provides a set measure of how design parameters are correlated and the effective contribution of each one to a given response of interest. This study proposes a fractional factorial DOE method coupled to a Simplified Radiosity Algorithm (SRA) aiming to evaluate the irradiation availability on building envelopes while taking a large representative sample of contrasted urban block geometries into account. The buildings' envelope solar irradiation availability assesses a set of energy-related morphological parameters. Results indicate a significant impact of the aspect ratio, the distance between buildings and the surface equivalent albedo. Establishing high values of street aspect ratio may cut solar irradiation on roofs by 130 kW h/m^2 year, while increasing the plot ratio may only yield 26 kW h/m^2 year. The results also point out important first order interaction effects between certain variables.

1. Introduction

Urban population has grown exponentially over the past decades in many cities around the globe. Cities currently concentrate more than half of the world population (PopulationReferenceBureau, 2009). In Brazil, more than two-thirds of the population is urban-based, and this figure is expected to increase in the years to come. In most Brazilian cities, this galloping urbanization process has not yet met effective urban development control, and this unchecked process has progressively led to an explosion of the energy demand. In the coming decades, sustainable urban planning should face two major challenges: promoting adaptation measures to mitigate local climate change effects as well as moving towards a new energy paradigm (Van Hove et al., 2015). Changing the energy model of cities can only succeed in a long-term perspective with considerable efforts to integrate some crucial spatial development policies. Many scientific studies have already discussed and pointed out urban morphology as being a key issue in determining overall energy consumption in cities (Owens, 1986; Droege, 2007; Batty, 2008; Williams et al., 2000; Breheny, 1992; Ratti et al., 2003; Steemers, 2003) as well as its potential for producing energy locally (Grosso, 1998; Serralde et al., 2015; Martins et al., 2014a,b). The particular shape and dimensions of the built environment together with the analysis of its physical structures at different scales defines urban morphology. Among many different urban scales: the neighbourhood and block have been presented as the two most

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relevant scales to analyse local building energy impact (Wong et al., 2011; Robinson et al., 2009; Bonhomme, 2013). At this scale, urban morphology directly affects both outdoor and indoor climates and has a direct bearing on embodied and operational energy use (Adolphe, 2001).

In cities, buildings account for a large part of the energy demand. In Brazil, this fraction is 47% (Ministério de Minas e Energia, 2010). Though many efforts have been made recently to promote energy efficiency in the built environment, they are mostly applied to individual building units (Ministério de Minas e Energia, 2010). However, a few studies have recently attempted to quantify the effect of urban density and layouts on the energy consumption of buildings (Martins et al., 2013; Boyeur et al., 2011) and on the potential to produce renewable energy, such as solar energy (Compagnon, 2004; Kampf et al., 2010; Takebayashi et al., 2015; Li et al., 2015) in developed and emerging countries (Wittkopf et al., 2012). Nevertheless, an extensive and unbiased approach that would quantify the relative effect size of multiple urban form variables on solar energy potential in tropical climate is still not readily available.

In tropical regions, the sun offers great potential for integrating renewable energy in several forms: indoor daylight, and solar thermal and electrical energy (Reddy and Harinarayana, 2015; Ho et al., 2014), for instance. However, in these sunny regions, the solar heat gains through the building's envelope can also produce extremely undesirable indoor thermal comfort conditions, which may consequently increase electricity demand for space cooling (Michels et al., 2008a,b).

Even though urban densification is generally associated with potential energy savings, a high-density and high-rise built morphology can be dangerously subject to the so-called "surface paradox" (Arantes et al., 2014). When buildings share party walls and have a reduced surface-to-volume ratio, the result should be reduced direct solar heat gains/losses through their envelopes. But, paradoxically, enhancing city compactness can also lead to increased obstructions to daylight, natural ventilation and renewable energy potential. Solar energy potential in urban areas remains highly dependent on the urban morphology (buildings that cast shadows, inappropriate surface orientation, etc.) (Zomer et al., 2013). Since the urban densification process has great impact on the solar irradiation balance on building surfaces, it is important to characterize the magnitude of this impact according to the main morphological and climatic parameters.

This paper aims to identify the most relevant urban morphological factors for improving solar potential for energy production and energy saving by computing the solar radiation budget (solar direct, diffuse and infrared radiation), as well as the daylight level over building facades, in cities under a tropical climate in Brazil.

2. Method

The research study follows a systematic set of procedures:

1. Firstly, a set of known energy-related urban morphological parameters is identified within the specific literature. A statistical hypothesis is established, which consists of assuming that all variables considered in this study are relevant to the response-variables under investigation: solar energy potential, daylight potential and thermal radiation emission from building surfaces.
2. Through a Design of Experiments (DOE) methodology, all urban morphological parameters are brought together on a simplified urban block base model, composing a set of diverse and contrasted urban scenarios. For this purpose, a fractional factorial design methodology is applied, which allows statistically representative and non-redundant scenarios to be elaborated. The urban scenarios are then assessed regarding the solar irradiation and daylight availability on their surfaces using a Simplified Radiosity Algorithm (SRA), with an application for the tropical context of the city of Maceió, located in the northeast of Brazil.
3. The results obtained are assessed through a statistical hypothesis test, which identifies the effect size of each variable on the response of interest.

To conduct the research procedure described above, we coupled two computer programs: Citysim (Robinson, 2011) for the dynamic simulations of the solar irradiation availability of urban models, and modeFRONTIER® (Esteco, 2013) for the DOE analysis.

As an application of the proposed research, the climate context of Maceió was considered. This city is located at 9.45°S and 35.42°W, and is 7 m above sea level.

Like many Brazilian cities, Maceió has experienced rapid, intensive urbanization during recent decades, frequently without any effective control, particularly regarding environmental and infrastructural concerns. This kind of urbanization process has been gradually modifying the local urban climate, which has had major adverse effects on thermal comfort conditions (outdoors and indoors) as well as on building energy demand.

Regarding local climatic particularities, the variations in radiant energy are extremely slight, both annually and seasonally, demonstrating a vast natural potential to engage new solar energy strategies (Fig. 1). Nevertheless, we must also bear in mind that, in tropical regions, we also have constantly high air temperature and high levels of relative air humidity, all year long (Fig. 1). Then, enhanced radiation incidence on buildings may constitute an important and undesirable heating source, undermining comfort conditions and so encouraging an increase in energy consumption. Thus, revising current urban building control parameters, notably regarding morphology, might play decisive role in adequately addressing this controversial issue.

3. Design Of Experiments (DOE)

The urban built form comprises a large spectrum of factors (or urban design variables) that can play crucial roles in modifying urban climate as well as the potential energy demand and supply in cities. It is imperative to understand the relative influence of these design variables on the response of interest so as to better support decision-making processes and enable actions in urban planning to be prioritized, especially in top-down design phases. To understand the impact of design variables, many researchers have applied parametric studies (Wong et al., 2011; Miller, 2013). However, this may involve the analysis of several individual cases (Rodrigues and Iemma, 2009). In addition, it remains difficult to minimize the subjectivity of the process. Performing dynamic computer simulation of numerous, and often unplanned, cases can be extremely time consuming and involve excessive computational effort.

An efficient alternative to carrying out this kind of study is to apply a statistical sensitivity analysis. Sensitivity analysis can be defined as the study of how changes in the output of a model can be assigned (qualitatively or quantitatively) to different bases of input variation. It can provide valuable information regarding the structure of the model, and its reliance on the input variables (Saltelli et al., 2000).

One common method for performing sensitivity analysis is to apply a Design of Experiments (DOE). The original use of DOE was as a method to obtain the most relevant qualitative information from a database of experiments by performing the smallest