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Residential building design optimisation using sensitivity analysis and genetic algorithm

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ABSTRACT

The objective of this paper is to combine sensitivity analysis and simulation-based optimisation in order to optimise the thermal and energy performance of residential buildings in the Argentine Littoral region. An actual house was selected as case study. This is a typical, local, single-family house having some rooms conditioned only by natural ventilation, and other rooms with natural ventilation supplemented by mechanical air-conditioning (hybrid ventilation). Hence, the total degree-hours at the naturally ventilated living room and the total energy consumption by air-conditioning at the bedrooms were chosen as objective functions to be minimised. The global objective function characterising the thermal and energy performance of the house was defined as the weighted sum of these objective functions. This objective function was computed using the EnergyPlus building performance simulation programme. Then, we performed a sensitivity analysis using the Morris screening method to rank the influence of the design variables on the objective function. This showed that the type of external walls, the windows infiltration rate and the solar azimuth were the most influential design variables on the given objective function for the considered house, and also that the azimuth either had a highly nonlinear effect on the objective function or was highly correlated to the others variables, deserving in any case a finer discretisation.

Finally, we solved an optimisation problem using genetic algorithms in order to find the optimal set of design variables for the considered house. The results highlighted the efficiency and the effectiveness of the proposed methodology to redesign a typical house in the Argentine Littoral region, improving hugely its thermal and energy performance.

1. Introduction

Nowadays, buildings are the largest energy consumers in Argentina [1]: considering the total energy (mainly electricity and gas), 26% is consumed by residential buildings and 8% is consumed by public and commercial buildings. Furthermore, the supply, transport and distribution of electricity in Argentina is facing a critical situation (the current level of operational reserve under extreme meteorological conditions is less than 5% of the whole available power, the availability of the imported gas and diesel is uncertain in the medium term), leading the central government to declare the national electricity sector in state of emergency on December 2015 [2]. This urges to reduce the energy consumption in buildings, mainly in the residential ones.

In this work, we focus on residential buildings located in the Argentine Littoral region (from now on referred to as "Littoral"). This 0.5-million km^2 area is located in northeastern Argentina, southeastern South America, see Fig. 1. Its climate is Cfa according to the Köppen-Geiger classification [3]. In a finer classification [4], Littoral is divided into three bioclimatic zones (those ones separated by red dashed lines in Fig. 1: very hot in the north (I), hot in the centre (II), and warm temperate in the south (III). Further, each zone is divided into two subzones *a* and *b*, those ones separated by a green dashed line in Fig. 1, regarding the daily temperature range be greater or lesser than 14 °C. Temperatures throughout Littoral are already not only high to very high during summer, but also they will be 2–4.5 °C higher by 2100 according to the 2014 report of the Intergovernmental Panel on Climate Change (IPCC) [5]. Although we have no information to quantify the concomitant increase of cooling demand in Littoral, we refer to studies in the USA pointing

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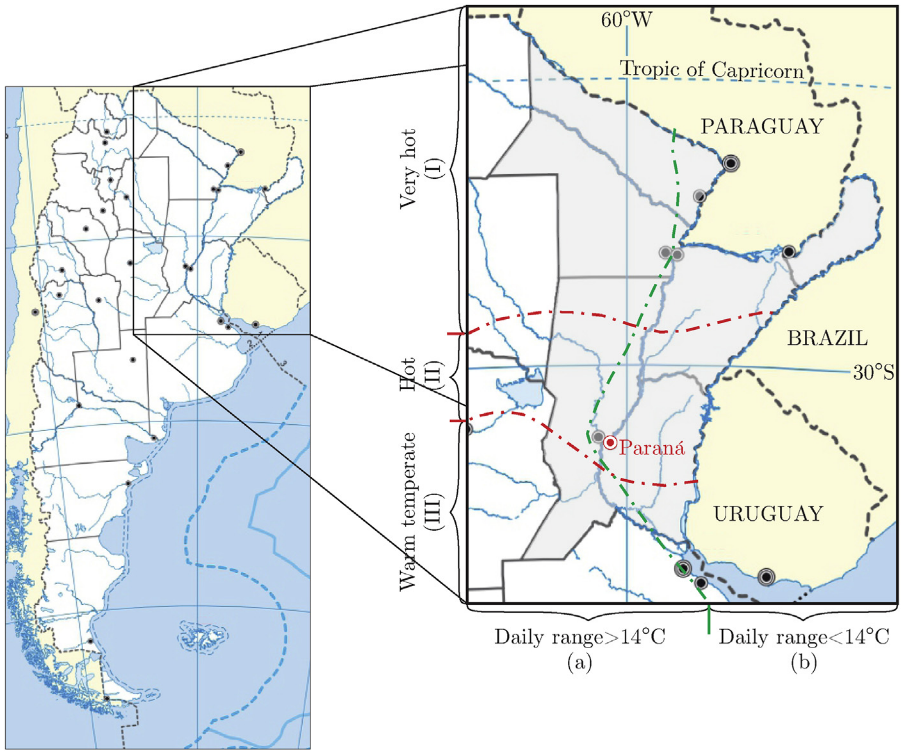

Fig. 1. Map of the Argentine Littoral Region (in light grey), showing the bioclimatic zones (I, II or III, a or b) and the location of the studied house (Paraná). (For interpretation of reference to color in this figure legend, the reader is referred to the web version of this article.)

out that the electricity demand for residential cooling will increase by roughly 5–20% per 1 °C warming [6]. Combined with the current state of emergency in the Argentine electricity sector, these estimates make the improvement of building energy efficiency even more urgent in Littoral.

For the architectural design of an energetically efficient building, the thermal and energy performance of a large series of alternative designs of such building must be analysed in seek of a sufficiently good or even optimal solution. Building performance simulation (BPS) makes affordable the study of a large number of alternative designs, allowing the designer to achieve specific objectives such as reducing environmental impact and energy consumption or improving the indoor thermal comfort [7]. The most popular software for BPS, EnergyPlus [8], is used in this work.

Since a time ago, researchers had been making significant efforts to automate the search of more efficient designs. A pioneer in this area is Wright [9], who applied the direct search method to optimise HVAC systems. Since that time, different objectives, design variables, and optimisation algorithms have been considered: Fesanghary et al. [10] used a harmony search algorithm to minimise the life cycle cost and carbon dioxide equivalent emissions of residential buildings; Bichiou and Krarti [11] optimised the building envelope and the HVAC design and operation using three different methods (genetic algorithm, particle swarm algorithm and sequential search), comparing them in terms of robustness and effectiveness; Ihm and Krarti [12] applied a sequential search method to optimise the design of residential buildings in Tunisia; Nguyen and Reiter [13] used a particle swarm optimisation and hybrid algorithms to optimise passive designs and strategies for low-cost housing. Recent reviews of the optimisation methods applied to building energy performance are given by Evins [14], Nguyen et al. [15], and Machairas et al. [16]. From these reviews, it is concluded that genetic algorithms (GA) are the widest used methods in building design optimisation, the reasons being that they do not "get stuck" in local optima, they have low sensitivity to discontinuities in the objective function, and they are well-suited for parallel computing. Considering these advantages, we choose GA as the current optimisation method.

Some authors used the sensitivity analysis (or "design of experiment" method) as an alternative to mathematical optimisation to improve the building performance [17–19]. Primarily, sensitivity analysis gives a ranking of the influence of the design variables on the objective. In this work, we decided to use this method not to improve the building performance but to determine the relevant design variables. Subsequently, we kept only such variables for the optimisation problem, making it cheaper to solve. Up to our knowledge, the only previous work combining sensitivity analysis and optimisation for building energy performance was performed by Evins et al. [20]. In their study, the objective was computed on the base of building regulations, which is a crucial difference with the current approach where the energy performance of the building is computed using EnergyPlus (the objective being defined by such performance). Further, we used the Morris screening method [21] for sensitivity analysis, which is considerably cheaper than the factorial method used by Evins et al. [20] from the computational point of view.

In summary, this paper presents a methodology for the optimisation of thermal and energy performance of a house, combining: (1) EnergyPlus to evaluate such performance; (2) sensitivity analysis to keep as design variables only the relevant ones; and (3) genetic algorithms as optimisation solver. Finally, we show that the application of such methodology for the design of a typical house in Littoral makes affordable a huge improvement of the thermal and energy performance of this house.

2. Case study

Let us take as case study a typical residential building in Littoral, particularly at Paraná, a city located in the centre of Littoral, with latitude 31.78S, longitude 60.48W and altitude 78 m. We have