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Modelling energy efficiency performance of residential building stocks based on Bayesian statistical inference

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ABSTRACT

This paper provides a model based on Integrated Nested Laplace Approximation to predict the energy performance of existing residential building stocks. The energy demand and the discomfort hours for heating and cooling were taken as response variables and five parameters were considered as potentially significant to assess the building energy performance: urban block pattern, street height-width ratio, building class through the building shape factor, year of construction and solar orientation of the main façade. A total of 240 dynamic energy simulations were run varying these parameters, by using the EnergyPlus software with the Design Builder interface, which allowed the response variables to be determined for a set of sample buildings. Simulation results revealed the most and least significant parameters in the energy performance of the buildings. The model developed is a useful decision-making tool in assisting local authorities during energy refurbishment interventions at the urban scale.

1. Introduction

Knowing the dynamics of a current real system allows values to be predicted considering the effect of certain variables. This can be studied within the framework of inference by using systems of differential equations which enable the values to be forecast taking into account the influence of a set of particular variables. Particularly, this work uses Bayesian inference, which delivers an integrated approach to perform inference, prediction and decision. Modern Bayesian models use simulation methods to generate drawings from the posterior distribution. Markov Chain Monte Carlo (MCMC) combined with the Stochastic Partial Differential Equation (SPDE) approach were the motivation for the Integrated Nested Laplace Approximation (INLA) package for the R software (R Development Core Team, 2011). The library was initiated by Rue and Martino (2007) and subsequently improved through contributions by Rue and Martino (2009). The use of INLA in computational time allows the user to work with relatively complex models in an efficient way. The INLA package for the R software was employed to conduct this study.

The aim of this work is to develop a model to forecast the passive energy efficiency performance of the existing residential building stock, according to a set of specific parameters. Some examples of precursor methods aimed at conducting energy assessment of building stocks were found in the literature (Farahbakhsh et al., 1998; Huang and Berkeley, 2000; Shorrock and Dunster, 1997). More recently, some authors have based their studies on these previous ones in order to improve them (Johnston et al., 2005; Boardman, 2007; Natarajan and Levermore, 2007) and others have developed new more complex models that enhance the energy efficiency assessment process (Gouveia et al., 2012; McKenna et al., 2013). In the context of building energy efficiency, many aspects can be assessed, but generally those related to energy use are the most common. For example, Cheng and Steemers (2011) estimated the energy consumption and CO_2 emissions of English building stocks considering the size of buildings, internal and external temperatures, thermal characteristics of the envelope and gas boiler efficiency, as input parameters. Their model also allowed them to determine the influence of different energy efficiency measures on dwellings to assist energy policies at local and national levels. Florio and Teissier (2015) proposed a model to estimate the energy performance certificate (EPC) of the French housing stock based on the building typology and conducted a statistical analysis of the French EPC database. Other items have been assessed by Mauro et al. (2015), who predicted the energy demand (ED) and the discomfort hours (DH) taking into account

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the building geometry, orientation and physical characteristics of the envelope. At the same time, they analysed the influence of different energy efficiency measures.

Taking into account this framework, this study provides a model based on INLA, aimed at predicting the energy demand and discomfort hours (considered as response variables) for the heating and cooling, respectively, of the existing residential building stock, considering five parameters that affect the energy efficiency (considered as covariates), namely: year of construction, building shape, solar orientation of the main façade, street height-width ratio and urban block pattern. The data set for this study was obtained by modelling the energy performance of sample buildings of an urban district located in Castellón de la Plana (Spain) by using EnergyPlus software (U.S. DOE, 2015).

The work is structured as follows. Section 2 draws the methodological approach of the study based on INLA, broken down into three different stages. Section 3 presents the selection of the response variables and covariates used to conduct the study. Section 4 provides the data set, describes the response variables and covariates, and then presents the configuration of the simulations run. Section 5 deals with the INLA modelling process and provides the configuration of the battery of prediction models and a comparison among them in order to finally choose the most accurate ones. This section also addresses a statistical analysis to outline the significance of the covariates in the models. The paper ends with a final Section 6 offering the conclusions.

2. Methodology

With the aim of obtaining the prediction models (based on INLA) for characterising the energy demand and discomfort hours for the heating and cooling of an existing residential building stock, the stages showed in Fig. 1 were applied:

- Stage I: Response variables and covariates selection. Based on a literature review, the response variables and the covariates that characterise the energy performance of an existing building stock needed to be selected.
- Stage II: Data set. After analysing the advantages and disadvantages of different software applications available for simulating the energy efficiency of buildings and building stocks (Machairas et al., 2014), DesignBuilder Software (2014) was chosen to obtain the values of the response variables against a combination of the selected covariates. After this, a descriptive analysis of the data results was conducted.
- Stage III: Modelling the data set with R-INLA in order to obtain the functions for prediction of the response variables. Firstly, the models that include all the possible combinations of response variables and covariates were obtained. Then, the correlation coefficients and the root mean square error (RMSE) were calculated, which allowed the models to be compared. Subsequently, the significance of the covariates was explored in order to identify the most and least significant ones. Finally, the four models with the best fit for determining the response variables were selected, according to the correlation coefficients and RMSE.

3. Selection of response variables and covariates

The selection of the response variables and covariates that mainly characterise the passive energy efficiency of an existing residential building stock was based on the literature review. As Table 1 reports, four response variables are the key variables considered to assess the energy performance of the residential building stock:

- Energy demand for heating (ED_h) and energy demand for cooling (ED_c). Both variables measure the amount of energy that the thermal installations of the building have to provide in order to ensure inner comfort conditions according to the building use and climatic zone (CTE, 2013), for heating and cooling, respectively. Both are measured in $kWh/m^2 \cdot year$.
- Discomfort heating hours (DH_h) and discomfort cooling hours (DH_c). Both variables measure the time when the combination of the zone humidity ratio and the operative temperature is not

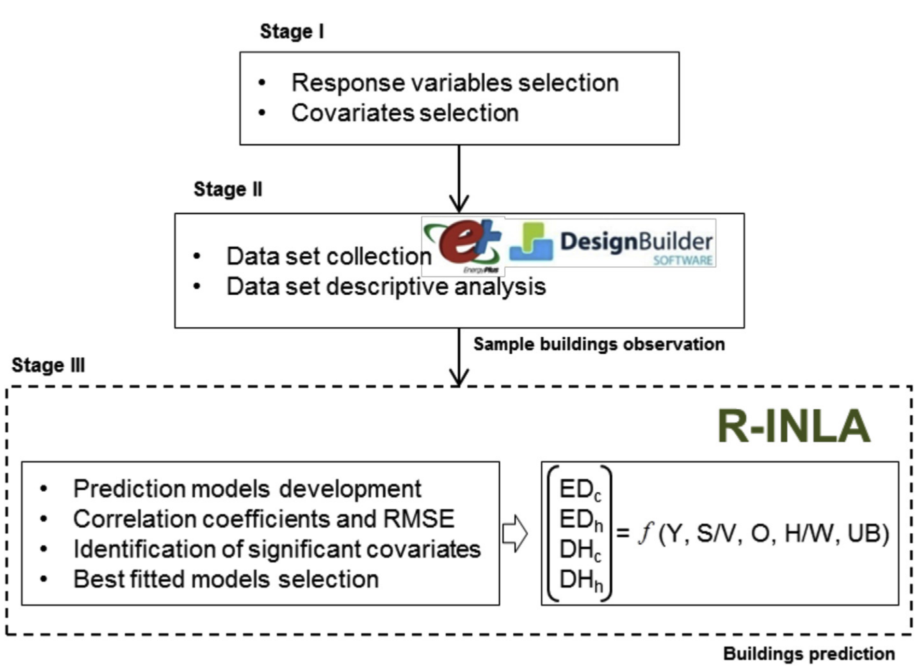

Fig. 1. Methodological approach.