Applied Energy 185 (2017) 82–94

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Analysis of uncertainty indices used for building envelope calibration

Germán Ramos Ruiz [*,1], Carlos Fernández Bandera [1]

School of Architecture, University of Navarra, Spain

HIGHLIGHTS

- Calibration methodology using Multi-Objective Genetic Algorithm (NSGA-II).
- Multi-zone building calibration.
- Calibration methodology that enables use of non-continuous time periods.
- Analysis of the best objective functions to calibrate buildings.
- The methodology captures the heat dynamic of the building.

ARTICLE INFO

Article history:
Received 28 May 2016
Received in revised form 15 October 2016
Accepted 19 October 2016

Keywords:
Multi-zone calibration
Energy simulation
Uncertainty analysis
Multi-objective optimisation
Genetic algorithm (NSGA-II)

ABSTRACT

Nowadays there is a growing concern about climate change and the global warming effect produced by the concentration of greenhouse gases (GHG). At the Paris climate conference (COP21), 195 countries adopted a global climate agreement, limiting global warming to well below 2 °C. Buildings are large producers of GHG and therefore international standards such as ISO 50001 focus on improving their energy performance, including energy efficiency, use and consumption. To achieve this goal it is important to have a detailed knowledge of the thermal behaviour of buildings. The International Performance Measurement and Verification Protocol (IPMVP), proposes a calibrated simulation model (Option D) to gather this knowledge and to determine the savings associated with Energy Conservation Measures (ECMs).

This paper improves the calibration methodology proposed by Ramos et al. (2016) [1], solving the limitations regarding the number of thermal zones and the use of free-floating time periods. Through a real case-study that guides the process, the paper explains how to achieve a calibrated Building Energy Simulation (BES) model using an optimisation process based on a meta-heuristic strategy (genetic algorithm - NSGA-II). Different uncertainty indices such as: CV(RMSE) and Goodness of Fit (GOF) are used as objective function to obtain the calibrated model. These indices, frequently used to measure the accuracy of models, are combined to provide a double possibility to find the best solution, as they are an objective function and a model accuracy measure.

1. Introduction

Currently there is growing concern about energy. The population growth rate and the necessity of energy for well-being makes energy demand a question of great interest. Climate change and the global warming effect produced by the concentration of greenhouse gases (GHG) put the spotlight on research papers referring to improvement of energy production and reduction of energy demand. On the other hand renewable energy penetration requires control and optimisation of energy.

Buildings have a key influence in global energy consumption [2] and therefore in the production of GHG. For that reason there are many studies on the energy optimisation of new and existing buildings. If these studies could be supported by a calibrated energy model, their energy saving quantification would improve greatly. ASHRAE [3] defines calibration as: “*the process of comparing the output or results of a measurement or model with that of some standard, determining the deviation and relevant uncertainty and adjusting the measuring device or model accordingly*”. As can be seen the definition emphasises the measurement of the uncertainty to determine the level of fitness of the model.

On the other hand, the process of obtaining a calibrated Building Energy Simulation (BES) model is not an easy task, among many other reasons we can highlight some arguments of three of

---

* Corresponding author.
E-mail address: gramrui@unav.es (G. Ramos Ruiz).

[1] These authors contributed equally to this work.

http://dx.doi.org/10.1016/j.apenergy.2016.10.054

the most important documents related to energy measurement: ASHRAE Guidelines 14-2002 [3], M&V Guidelines [4] and IPMVP [5], such as the skill experience of personnel with both the software and calibration process, the effort required for data acquisition, the accuracy of sensors used, the difficulties of simulating special parts of the building (atriums, double skin façades, complex HVAC systems, etc.) and the investment cost of different equipment. However, the use of calibrated BES models offers many benefits [6] such as the identification and quantification of the savings of different Energy Conservation Measures (ECM); the study of the building behaviour for on-going commissioning and retro-commissioning [7]; the analysis of the resulting improvement due to different HVAC strategies or building configurations because testing them in a simulation environment is not so intrusive for the building or its occupants [8]; the Fault Detection and Diagnosis if the simulation works together with the building automation system (FDD software) and the measurement of the energy stored in the building for demand response strategies.

The calibration methodology is the search for the parameters that characterise the envelope of the building. The methodology consists of a careful survey of the building characteristics in order to create a model as similar as possible to the real construction. A short-term monitoring campaign is then carried out and temperature data are used to calibrate the model. The calibration models are a reliable portrayal of the building envelope and can then be used to assess the energy demand of the building quantitatively instead of qualitatively (non-calibrated BES models).

This research is supported by our last work [1] which explains the methodology of calibrating buildings using genetic algorithms, but in this case it is focused on solving two main shortcomings: firstly the use of one thermal zone in the analysis and secondly the necessity of the objective function to have a continuous free-oscillation period of building operation. The second condition is not always possible because for a building to have a long free-oscillation period special circumstances are necessary. In addition, the period used should be as long as possible to capture the heat dynamic of the building in order to give the algorithm sufficient stimulus to find a proper solution for the envelope parameters. University buildings can deal easily with these limitations because of the holiday season, but for other buildings such as hospitals, shopping malls, hotels, residential homes and many others used in an intensive way these periods are rarely available. In this research, we are proposing several measures that greatly improve the methodology allowing these problems to be tackled.

As described further on, we have implemented a new methodology that allows us to take advantage of all the intermittent free-oscillation periods. Furthermore, these periods can be different for each thermal zone because their sum will produce the same effect as that of one long period only. The script developed in our first work to reproduce the thermal history of the whole building now takes on a more important role because it enables us to maintain an individual thermal history for each thermal zone. Hence, for a whole building envelope calibration, we can count on the contribution of each thermal zone, although its free oscillation periods occur at different times. There is no limit to the number of thermal zones or to the number of small periods considered for each. The more information we have, the better quality calibration we get. The objective function will take advantage of the contribution from all the intermittent free-oscillation periods and will use them with the same effectiveness as if it were a single and continuous period for the whole building. This improvement in the methodology gives the process great flexibility and opens up the methodology for other buildings whose calibration process was difficult before due to their intensive use and their lack of long free-oscillation periods (hospitals, hotels, shopping malls, etc.). As an improvement, the new calibration methodology can be carried out in a specific area of the building, thus being of assistance in multi-property buildings.

Furthermore, we make a detailed analysis of the different objective functions based on uncertainty analysis, to check which one is the best option to obtain a calibrated model.

The paper is structured as follows. Section 2 briefly summarise the state-of-the-art of calibration strategies. Section 3 describes the calibration methodology highlighting the improvements regarding the use of several thermal zones and non-continuous free-floating time periods for calibration. In particular, Section 3.2.1 explains the special objective function used in this calibration approach, the fact that it is based on different uncertainty indices. Section 4 describes a detailed study of the different results obtained by the genetic algorithm (NSGA-II) guided by these uncertainty indices to assess which of them is the best choice to calibrate the BES model. Section 5 analyses the different models proposed by each optimisation of the genetic algorithm. And finally Sections 6 and 7 show the conclusions and the future work of this study.

2. A brief state-of-the-art

There are different approaches to performing a calibration. Clarke et al. [9] first classified it in four groups based on: "(i) *manual, iterative, pragmatic intervention*, (ii) *a suite of informative graphical comparative displays*, (iii) *the use of special tests and analysis procedures to isolate and compare individual energy flows*, (iv) *a technique for automatically adjusting user selected input parameters to reduce the discrepancy between measured and predicted data*". In general, as Coakley et al. [10] say, all the approaches can be defined as manual or automated. The tools and techniques of each one are different; the manual approach depends largely on the Modeller's experience and expertise [11], and automated approach uses the mathematical and statistical properties of the model to achieve the calibrated BES model.

An automated calibration technique is ultimately about how to optimise a BES model, but focusing the problem on a special objective: adjusting several parameters of the model to fit the simulated values with the measured ones. For these reason it is interesting to analyse both papers focusing in how calibrate BES models [8,12–16] and papers related to optimising some aspects [17–24]. The techniques described in both groups are quite different and the use of genetic algorithms is limited to the ones related with optimisation problems.

3. Methodology

In general this methodology was described more in depth in our last paper [1], but now we solve the two important limitations described before: the number of thermal zones analysed and the necessity of continuous periods of time to develop the calibration.

One of the key aspects of this methodology is the use of data from temperature sensors to obtain a model with a high degree of accuracy. Saltelli et al. [25] describe these models as data-driven. Because the goal is to capture the heat dynamic of the real building, temperature sensors are adequate tools, and are cheaper than energy meters. The frequency selected is a ten-minute time-step due to the high accuracy that we are attempting to reach. This procedure allows us to dependably represent the thermal behaviour of the building. Other authors use simulated vs. measured temperatures as a calibration target but with a different approach [26,27].

Another key aspect of this methodology is that it focuses on calibrating the building envelope. The reason is that the energy demand of the building is closely related to the energy gained/lost