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Development of a new multi-stage building energy model calibration methodology and validation in a public library

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ABSTRACT

Calibration of a Building Energy Model (BEM) is necessary to reduce the discrepancies between the simulation results and real data. This research work proposes a novel ground-breaking calibration methodology that divides the entire building into different sub-models and calibrates them separately to obtain an accurate model. To validate this new procedure, a public library Heating, Ventilation and Air Conditioning (HVAC) system with a Ground-Source Heat Pump (GSHP) and a Radiant Floor (RF) was simulated and calibrated using TRNSYS and GenOpt. The results demonstrated that this new multi-stage procedure met the ASHRAE standards and achieved better results than those obtained with a global calibration. The Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) of the hourly temperature data were reduced below −3.74% and 6.03% respectively, involving an improvement of approximately 50% over typical global calibration methods.

1. Introduction

Buildings, both residential and commercial, are responsible for approximately 40% of the total energy consumption in developed Western countries exceeding other major sectors in recent years, such as industrial and transportation [1,2]. In Spain this percentage is reduced by half due to the milder weather conditions. However, this energy consumption is undeniably an important source of greenhouse gas (GHG) emissions, mainly carbon dioxide (CO_2). For this reason, building energy efficiency is currently a key factor for energy policies at every level, regional, national and international [1,3], especially to accomplish the 2020 targets for the European Union in terms of climate change and energy sustainability. Over the past decades, Heating, Ventilation and Air Conditioning (HVAC) systems have been used increasingly, consuming almost half of the energy of the buildings that they reside in [1,4]. Therefore, addressing this part of the system will be the most effective to reduce energy consumption.

The performance of a building HVAC system depends on multiple parameters that affect its efficiency, and the relationship between them is complex. To reduce the energy consumption of a building HVAC system or evaluate the energy savings corresponding with retrofits of existing buildings [5], it is very important to first investigate the influence of the modifiable and relevant variables from the Building Energy Model (BEM) [6]. In this context, dynamic simulation becomes a really useful tool, enabling assessment of system performance, evaluation of energy efficiency, calculation of energy consumption and implementation of improvements to optimize the model [7]. Simulation is clearly the most complete practice to analyse the influence of each parameter on the building performance. There are several Building Energy Performance Simulation (BEPS) tools available, such as TRNSYS [8], DOE-2, EnergyPlus [9] and ESP-r, among others. In particular, TRNSYS has been

Abbreviations: GHG, greenhouse Gas; CO_2, carbon dioxide; HVAC, heating ventilation and air conditioning; BEM, building energy model; BEPS, Building Energy Performance Simulation; ECM, Energy Conservation Measure; GSHP, Ground-source Heat Pump; RF, radiant floor; ASHRAE, American Society of Heating Refrigerating and Air-Conditioning Engineers; MBE, Mean Bias Error; CV(RMSE), Coefficient of Variation of the Root Mean Square Error; GHE, Geothermal Heat Exchanger; PSO, Particle Swarm Optimization; GPSPSOCCHJ, Generalized Pattern Search Particle Swarm Optimization with Constriction Coefficient Hooke-Jeeves; EER, Energy Efficiency Ratio; COP, Coefficient of Performance; TRT, Thermal Response Test; IPMVP, International Performance Measurement and Verification Protocol; BWM, Box Whisker Mean.

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Nomenclature

δ	Inside diameter [m]
d_x	Pipe spacing [m]
d_r	Pipe thickness [m]
d_i	Layer thickness [m]
θ_i	Temperature of the zone i [°C]
U_i	Overall heat transfer coefficient for wall i [W/m^2 °C]
h_i	Convection heat transfer coefficient for wall i [W/m^2 °C]
R_i	Pipe spacing [m]
R_x	Resistance of the equivalent star network [m^2 °C/W]
q_i	Heat flux [W/m^2]
m	Mass flow [kg/h]
C	Thermal capacity [J/m^3 °C]
λ	Conductivity [W/m°C]
k	Heat coefficient function [J/m^3 °C]
M_i	Measured data
S_i	Simulated data
N_p	Number of values during the intervals

successfully used in the literature, having been proven to yield reliable results by many authors [7,10–14]. In addition, TRNSYS offers some advantages over its competitors, such as the incorporation of unconventional cogeneration systems that could fit the building energy demands.

Despite the precision of these simulations tools, there are always discrepancies between simulation results and real data. For this reason, a calibration methodology is needed. Calibration processes aim to approximate the thermal model results to the real ones as closely as possible [15,16]. Calibration of the BEM is necessary to improve the accuracy of the energy model results and for the successful determination of meaningful Energy Conservation Measures (ECM) [5,15,17]. However, there too many interacting variables in a BEM, and sometimes it is very difficult to determine the real values of all of them. Thus, calibration of a simulation is one of the toughest works required to validate a result. To obtain an adjusted calibration, it is essential to gather all the operating data and estimate the missing information. Some authors divided the calibration processes into different adjustments levels [2]. In the first level, information about the building description and the HVAC systems is collected and simulated. In the second level, the simulation results are compared with measured consumptions and monitoring data from different equipment.

Reddy et al. [18] proposed a classification of the most common calibration procedures: manual and iterative calibration methods, graphical and statistical methods and automated calibration methods. Although graphical approaches or manual techniques are acceptable tools to verify and calibrate a model [2], computational techniques allow for the inclusion of more detailed data corresponding to the geometric construction and building performance. Furthermore, these calibration processes or a combination of some of them come to different solutions that accomplish standard specifications. Neural networks, genetic algorithms and screening tools are different methods based on simulations and/or statistical techniques, which, in some cases, require less information from the building to carry out the thermal model [19]. However, because they do not compile all of the data from the building, it is difficult to reflect the changes when an ECM or a variation of some parameter is implemented in the BEM. Normally, these actions are directed towards a reduction in the operation costs of the building and an improvement of indoor conditions. Therefore, the task is challenging because building zone temperatures or energy consumption from the building HVAC system depend on too many parameters.

However, it is not worthwhile to calibrate every parameter of the simulation due to the costs in terms of time and computing resources. Therefore, in a general calibration process, a sensitivity analysis can anticipate the influence of each variable on the global energy consumption. This can be very useful, especially when there are many parameters that affect the behaviour of the system. Some authors have successfully conducted sensitivity analyses to detect the main factors affecting the building energy model performance [20–22]. Casasso et al. [23] carried out a sensitivity analysis of a geothermal heat pump while investigating the most important parameters within the borefield performance: the length of the borehole, the characteristics of the heat carrier fluid, the conductivity of the grout and the thermal conductivity of the soil.

Therefore, achieving an appropriate calibration methodology for building energetic simulations with accurate results is one of the most important problems to be solved, and many authors are contributing in this field of research [2,17,24,25]. Heo et al. [5] proposed a methodology based on a Bayesian calibration of normative energy models and evaluated retrofitting actions. Royapoor et al. [16] studied the accuracy of a calibrated building model and identified several ECMs during the process. Raftery et al. [15] developed a methodology for calibrating an entire BEM using hourly energy consumption data. Thus, the greatest challenge is to create a BEM that behaves like the real building. Once this model has been achieved, it will be possible to implement ECMs, energy savings, and retrofitting actions without the need to implement them physically simply by simulating different scenarios that will help in the final decision making.

A first approach of a calibrated simulation methodology was studied in a previous article [26]. In that work, a public library HVAC system simulation was calibrated. The heating and cooling system of the building consisted of a Ground-Source Heat Pump (GSHP) combined with a Radiant Floor (RF). The building was simulated using TRNSYS and calibrated using GenOpt. However, in that first approach, all of the simulations were performed with a large timestep, 30 min, and the calibration was conducted globally, taking into account the entire building with its HVAC system and yearly data. The achieved results met the monthly criteria of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards. However, they required a better adjustment to meet the hourly criteria of the ASHRAE standards. ASHRAE Guideline 14 [27] states that an entire building can be considered calibrated when the computer model has a Mean Bias Error (MBE) of 5% and a Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) of 15% relative to monthly calibration data. If the data sampling period is hourly, these requirements shall be 10% and 30%, respectively.

Therefore, in an attempt to improve the BEM, a novel groundbreaking calibration procedure is proposed in this work. The global simulation model was divided into clearly differentiated stages. Each sub-model was calibrated according to output temperatures, delivery energy or power consumptions, varying the most influential parameters during different periods of the year. These periods were carefully selected according to the operation modes and external effects. The calibration was carried out using a simulation timestep of 5 min. This shorter timestep was used specifically to reflect the transitional behaviour of the impulsion and borefield systems, avoiding unrealistic fluctuations of temperatures. To accomplish this methodology, experimental data from intermediate variables were needed. This methodology was experimentally applied and validated in the simulation of the same previous HVAC system with a GSHP that feeds a public library equipped with a radiant floor energy distribution system. Furthermore, this procedure allowed for investigation of the influence of the most important variables in each sub-model.