Energy and Buildings 108 (2015) 236–243

Contents lists available at ScienceDirect

Energy and Buildings

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

Calibrating historic building energy models to hourly indoor air and surface temperatures: Methodology and case study

Francesca Roberti [a,b,*], Ulrich Filippi Oberegger [a], Andrea Gasparella [b]

[a] European Academy of Bolzano/Bozen, Institute for Renewable Energy, Via G. Di Vittorio 16, I-39100 Bolzano/Bozen, Italy
[b] Free University of Bolzano/Bozen, Faculty of Science and Technology, Piazza Università 5, I-39100 Bolzano/Bozen, Italy

ARTICLE INFO

Article history:
Received 11 June 2015
Received in revised form 8 September 2015
Accepted 9 September 2015
Available online 10 September 2015

Keywords:
Historic building
Case study
Simulation
Monitoring
Calibration
Sensitivity analysis
Particle swarm optimization
EnergyPlus

ABSTRACT

Uncalibrated building energy models, as well as models calibrated only on a single performance indicator such as energy consumption or indoor temperature, can be significantly unreliable regarding model parameters and other performance indicators. The risk of obtaining a calibrated model whose parameters are far from the actual values is particularly high in historic buildings because of the increased uncertainty about the building construction. In this paper, we propose a calibration methodology aimed at reducing this risk and apply it on a medieval building. The building was modeled in EnergyPlus based on an energy audit. A sensitivity analysis was performed to identify significant parameters affecting the errors between simulated and monitored indoor air temperatures. The model was calibrated on the hourly indoor air temperatures in summer by minimizing the root mean square error averaged over the building using a particle swarm optimization algorithm. A second calibration was performed by varying the parameters of a representative room. By comparing the results from these two calibrations, we obtained indications about the accuracy of the model parameters. Finally, the model was validated on hourly indoor air and surface temperatures in winter where temperature root mean square errors ranged from 0.4 to 0.8 K.

1. Introduction

1.1. The context

Historic buildings represent the cultural identity of our countries, characterizing many cities and giving continuity with the past. Energy retrofitting is an effective strategy to preserve this heritage, reducing operation costs and improving comfort. Because each historic building is unique, designers have to develop specific retrofit solutions compatible with conservation, taking into account renovation costs. Energy simulation models can help in comparing alternative retrofit interventions, but they might lead to wrong conclusions if not carefully calibrated. The challenge is to build a model that not only fits monitoring data but also represents the real building, allowing evaluation of alternative retrofits in a reliable fashion. This is particularly important when dealing with historic buildings, as choosing an inappropriate retrofit action could cause degradation of valuable parts of the building or represent a significant waste of money. The aim of this work is to present a methodology that tackles this challenge by performing semi-automatic calibration as the first step in the design of a historic building retrofit. We applied this methodology on a vacant medieval building in northern Italy, calibrating the model with respect to monitored indoor air temperatures. Main issues related to model complexity and uncertainty about the input data were considered and addressed. First, we performed a sensitivity analysis on an initial model, deciding on parameters, parameter ranges, and design of experiment. Second, we calibrated the model, choosing model outputs to be compared with measured data and goodness-of-fit indicators. Third, we selected the model with the best goodness-of-fit. Finally, we validated the model analyzing the errors using a different period of the year from the calibration. Furthermore, we calculated the errors of the surface temperatures, a monitored parameter not involved in the calibration. Particular attention was paid to the envelope properties. They may be related specifically to the uncertainty in building geometry, wall composition (for example, stone, wood, and mortar) and thickness, and glass properties of the windows. In historic buildings, envelope properties often vary considerably from place to place. Components can be damaged, partially destroyed or dirty. Therefore, historic building energy models have usually either important limitations or high complexity, requiring numerous measurements for calibration.

* Corresponding author. Tel.: +39 0471055644; fax: +39 0471055699.
E-mail address: francesca.roberti@eurac.edu (F. Roberti).

http://dx.doi.org/10.1016/j.enbuild.2015.09.010

1.2. Review of previous work

In recent years, many authors have demonstrated the importance of calibrating building simulation models, in particular to predict the effects of energy conservation measures. Calibration techniques include iterative revisions of an initial model, driven by identified discrepancies, which are corrected based on evidence and expert's knowledge [1]. Calibration methodologies have been formalized in the following five steps: (a) preparing a preliminary simulation input file; (b) identifying the most influential model parameters; (c) coarse search using Monte Carlo simulation; (d) guided search; and (e) using a small number of plausible calibrated models to determine the prediction uncertainty [2]. Bayesian approaches have been suggested to quantify uncertainties associated with model parameters and retrofit interventions [3]. Raftery et al. [1] calibrated a detailed EnergyPlus model of a new office building consisting of over 100 thermal zones. The authors gradually reduced the coefficient of variation of the root mean square error between predicted and actual energy consumption based on a source hierarchy of information ordered by decreasing presumed accuracy. Sources higher in the hierarchy have a priority over sources lower down, with logged measurements at the top and standards and guidelines at the bottom. Following this methodology, uncertainties are not investigated. In contrast, Heo et al. [3] quantified the uncertainty in the retrofit decision-making process by applying Bayesian calibration to an office building model. Bayesian calibration requires assigning prior Probability Density Functions (PDFs) to model parameters and computing posterior PDFs from results. The computational effort required to quantify uncertainty is balanced by using quasi-steady-state models instead of transient models, especially when the objective is to evaluate macro-level retrofit measures based on monetary savings. All papers underline the risk of working with a calibrated model whose parameters or outputs do not correspond to reality. Recommendations to reduce this risk are: (a) using hourly measured data as the target function for the calibration; (b) tightening the acceptance criteria; (c) reducing the amplitude of the parameter space through visual inspection and walk-through audits; (d) calibrating against more than one outcome variable; (e) combining more acceptance criteria to a single goodness-of-fit indicator; and (f) using a small number of calibrated models rather than one single model to obtain robust predictions of the energy and demand reductions.

Only a few papers focus on historic building calibration. Pernetti et al. [4] calibrated the model of a 19th century manufacturing facility in Italy with respect to indoor air and surface temperatures using a fully factorial combination of the weather data, air change rate and envelope properties. For each factor, two to four levels were selected according to measurements and standards, for a total of 24 simulations. After the first calibration, a sensitivity analysis was performed to identify parameters for further model improvement. Results demonstrated the indoor temperature mitigation effect by the thermal mass and the importance of reliable weather data. Cardinale et al. [5] performed an energy and comfort assessment of two vernacular building districts at world heritage sites in southern Italy through in-situ and lab measurement and dynamic simulation. The model parameters were set according to measurements. No explicit calibration was used. As a means of validation, measured and simulated indoor air temperatures were compared. Ascione et al. [6] manually calibrated an EnergyPlus model of a historic building in southern Italy to monthly energy bills.

As opposed to manual calibration, we found only a couple of studies concerned with semi-automatic calibration of historic (or old) buildings. Caucheteux et al. [7] calibrated a transient energy model of a 16th century manor house in western France considering the daily gas consumption monitored during two weeks in December. The authors performed a sensitivity analysis to identify seven influential model parameters and applied a solver to determine the values for the identified parameters that minimize the coefficient of variation of the root mean square error. O'Neill and Eisenhower [8] performed a sensitivity analysis on a transient energy model of an office building dating back to 1901 and refined the influential model parameters by applying an optimization algorithm to an approximation model.

2. Method

The focus of our work consisted in the calibration of a XIII century building model in EnergyPlus 7.2, performing two optimizations with the Particle Swarm Optimization algorithm (PSO) [9] on data monitored in summer. In the first calibration, building properties were varied uniformly for all zones. In the second calibration, we kept the parameters from the first calibration except for a single reference room. The differences between the two optimizations gave indications about the trustworthiness of the optimized parameters. As further control, we validated the model on the air temperature in winter and on the monitored temperatures of three internal surfaces of the exterior wall. Summarizing the whole methodology, we performed six steps: (1) energy diagnosis of the building; (2) creation of an initial model (IM) using the measurement results from the energy diagnosis as inputs; (3) definition of the most influencing parameters along with uncertainty ranges through a sensitivity analysis based on the elementary effects method; (4) model calibration using as target averaged indoor air temperatures monitored in summer weighted on the rooms' volumes; (5) model validation comparing simulated and monitored indoor air temperatures in winter; (6) model validation comparing simulated and monitored inside surface temperatures of the exterior wall in summer.

This general calibration methodology helps define envelope parameters of a historic building simulation model. Steps 1 and 2 are crucial as starting point for a fairly accurate initial model. Step 3 is useful to understand the most influencing parameters on the calibration and is foundational to the calibration, Step 4. Steps 5 and 6 are validation steps that complete the calibration process. Step 5 is necessary to check the model parameters during a period not included in the calibration, during which the model could behave differently than the actual building because of different climate conditions. Step 6 gives indications about the accuracy of the external wall material properties, which have a high impact on the calibration errors (see the results from the sensitivity analysis).

3. Case study

The *Waaghaus* (weigh house) is located in the historic center of Bolzano in northern Italy (Fig. 1). Constructed in the 13th century in Romanesque style, it was rebuilt in the 17th and 18th century. Until 1780 it was the official seat of the city scales. The building has three floors, an attic and a basement, for a total volume of 2000 m^3. Except for the roof, the envelope is made of stone. The lightweight roof is composed by timber beams and badly damaged mineral wool insulation. All original windows were replaced by coupled windows during the 1950s/60s. The building has been vacant since the 1990s. After a thorough structural and energy renovation, it is going to be transformed into a museum of photography.

3.1. Energy audit

3.1.1. Thermal conductance

We measured the thermal conductance of the external walls at a representative spot on the north side of the building with a