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A model calibration framework for simultaneous multi-level building energy simulation

Zheng Yang [a,1], Burcin Becerik-Gerber [b,*]

[a] Astani Department of Civil and Environmental Engineering, University of Southern California, 3620 S. Vermont Avenue, Kaprielian Hall 217, Los Angeles, CA 90089-2531, United States

[b] Astani Department of Civil and Environmental Engineering, University of Southern California, 3620 S. Vermont Avenue, Kaprielian Hall 224C, Los Angeles, CA 90089-2531, United States

HIGHLIGHTS

- Introduce a framework for multiple levels of building energy simulation calibration.
- Improve the performance reliability of a calibrated model for different ECMs.
- Achieve high simulation accuracies at building level, ECM level and zone level.
- Create a classification schema to classify input parameters for calibration.
- Use evidence and statistical learning to build energy model and reduce discrepancy.

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ABSTRACT

Energy simulation, the virtual representation and reproduction of energy processes for an entire building or a specific space, could assist building professionals with identifying relatively optimal energy conservation measures (ECMs). A review of current work revealed that methods for achieving simultaneous high accuracies in different levels of simulations, such as building level and zone level, have not been systematically explored, especially when there are several zones and multiple HVAC units in a building. Therefore, the objective of this paper is to introduce and validate a novel framework that can calibrate a model with high accuracies at multiple levels. In order to evaluate the performance of the calibration framework, we simulated HVAC-related energy consumption at the building level, at the ECM level and at the zone level. The simulation results were compared with the measured HVAC-related energy consumption. Our findings showed that MBE and CV (RMSE) were below 8.5% and 13.5%, respectively, for all three levels of energy simulation, demonstrating that the proposed framework could accurately simulate the building energy process at multiple levels. In addition, in order to estimate the potential energy efficiency improvements when different ECMs are implemented, the model has to be robust to the changes resulting from the building being operated under different control strategies. Mixed energy ground truths from two ECMs were used to calibrate the energy model. The results demonstrated that the model performed consistently well for both ECMs. Specific contributions of the study presented in this paper are the introduction of a novel calibration framework for multi-level simulation calibration, and improvements to the robustness of the calibrated model for different ECMs.

1. Introduction

Buildings account for one-third of the total global energy consumption [1]. In the commercial building sector, more than 80% of building energy consumption occurs during the operation phase [2] to maintain indoor environments and provide building-based services. By analyzing the differences between actual energy consumed and energy required to satisfy building operation demands, it is found that up to 30% of thermal energy and 13% of electrical energy could be saved if energy conservation measures (ECMs) were to be adopted in office buildings [3]. Simulation, the virtual representation and reproduction of building energy process, is widely used for integrating heat and mass transfer, environmental data, and load-HVAC interactions, as well as generating periodical

* Corresponding author. Tel.: +1 (213) 740 4383.
E-mail addresses: zhengyan@usc.edu (Z. Yang), becerik@usc.edu (B. Becerik-Gerber).
[1] Tel.: +1 (323) 868 1913.

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energy performance estimates for building systems, such as HVAC (heating, cooling and air conditioning) systems [4–6]. Compared to field experiment, simulation has several advantages: (1) simulation allows analysts to evaluate the system performances when field experiments are infeasible; (2) simulation facilitates the investigation of various ECMs before being implemented; (3) simulation is less expensive and less time consuming; (4) simulation can be reversed after implemented; (5) simulation could control factors that cannot be controlled in a field experiment (e.g., weather conditions); (6) simulation is non-intrusive for a building and its occupants; (7) simulation outputs different performance indicators, which are hard to be metered in field experiments; and (8) simulation makes it easier for analysts to interpret results.

Despite its advantages, expected energy savings from relatively optimal ECMs reported in simulations do not usually match those measured in actual buildings due to the discrepancies between actual buildings and their virtual representations. Empirical studies have revealed noticeable differences between simulation results and actual measurements [7,8]. Simulated results sometimes deviate significantly from the measured ones [9]. Only if a simulation model can generate outcomes that closely match the measured energy performance of a building, it has potential to be reliable and representative in its ability to accurately estimate energy savings from different ECMs. The accuracy of a simulation model largely depends on how well the outputs are compatible with available measured data, which in turn depends on how accurate the inputs could empirically reproduce the properties of a building the model simulates [10].

In general, energy model calibration is an over-parameterized and context-related process. The model calibration is commonly defined as an inverse approximation because of the need for tuning necessary inputs to reconcile the outputs by a simulation program, as closely as possible to the measured energy data. It is over-parameterized because of the large number of independent and interdependent input parameters to be specified, which represent the complex correlations and dynamic interactions among envelope thermal conditions, HVAC responses, exterior impacts (e.g., solar radiation) and interior impacts (e.g., light related heat gains). They cannot always be determined by available evidence in calibration. Two sources are recognized to be generally responsible for discrepancies in building energy simulation. One is the uncertainty in input parameters and the other one is the simplification of building and building systems, assumptions of thermal processes, and algorithmic differences used in simulation programs [11,12]. Since the second source of error depends on the simulation program chosen, this paper focuses on the first source of error: reducing the discrepancies in outputs caused by the uncertainty of input parameters. Quality of the calibration is limited by the determination of input parameter values, which represent the building as abstraction in a simulation. Therefore, simulation is a context-related process.

Current calibration methods focus on single-level simulation accuracy. Single level of calibration considers the accuracy for one scale of output in an energy simulation, such as building level gas consumption or zone level electricity consumption. Since there are a large number of input parameters but few output variables (depending on the required resolution and the length of simulation), it is usually relatively easy to approximate high accuracy for a single level of simulation. However, simultaneous accuracy for multiple levels of simulation is crucial. For example, building level accuracy could provide an insight about overall energy performance of a building and building systems; ECM level accuracy could represent the direct energy consequences of applying a certain type of energy conservation measure, and is important for guiding further research and practice towards more energy-efficient controls; zone level accuracy could decompose energy consumption by a zone that is the control unit for heat balance and load calculations, and closely relates to occupant comfort and building system functionality. Although different levels of energy consumptions are interconnected and they reflect the approximation of simulation results to the measured energy performance, accurate simulation of single level does not necessarily mean accurate simulations for other levels, especially when there are several zones and multiple HVAC units in a building [13,14]. It becomes more difficult to achieve high accuracies for multiple levels of simulations simultaneously as the complexity increases due to the complicated and dynamic correlations and interactions among envelope thermal conditions, HVAC responses, exterior impacts and interior impacts. In sum, the research towards studying energy-efficient measures in a building influences more than one level of energy performance and might require other levels of energy simulation for analysis and exploration [15]. Therefore, a multi-level calibration framework is necessary to achieve multiple calibration objectives simultaneously.

This paper introduces and validates a multi-level energy model calibration framework for simultaneously calibrating energy model at multiple levels. To estimate potential energy savings when different ECMs are evaluated, the model has to be robust to the changes resulting from the building being operated differently. This paper uses ground truth energy data from implementations of two ECMs to calibrate the model and demonstrates the model has consistent performance for either ECM. The framework creates a classification schema for parameters (definitions and categorizations of parameters are introduced in Section 3) and integrates the statistical learning based calibration and analytic calibration. It comprises five steps: (1) **initial energy modeling** using available evidence, (2) **sensitivity analysis** to rank the influence of parameters, (3) **parameter estimation** for determining the values of estimable parameters, (4) **discrepancy analysis** to analyze the sources of discrepancies, and (5) multi-objective **discrepancy minimization**. The framework is evaluated using a case study. Simulated HVAC-related energy consumption is compared with the measured HVAC-related energy consumption to validate the proposed calibration framework. The rest of the paper is organized as follows: Section 2 briefly describes the motivation for the proposed calibration framework and discusses the traditional calibration approaches and their disadvantages; Section 3 outlines the objectives and methodology of the paper. Section 4 describes how the case study model is calibrated using the proposed framework, and Section 5 analyzes the case study results and discusses the limitations. Finally, Section 6 concludes the paper.

2. Building energy model calibration

Building simulation could be error-prone because of the complex correlations and dynamic changes in envelope thermal conditions, exterior impacts (e.g., solar radiation) and interior impacts (e.g., light related heat gain), as well as because of the large number of independent and interdependent input parameters, which cannot be all obtained empirically [11]. The time and effort required to collect data and determine input parameters make energy model calibration a challenge for large-scale applications [16].

Considering the fact that ECMs are specifically designed for appointed buildings, each building has to be modeled and calibrated individually. Using typical/standard values for input parameters or estimating energy performance based on similar building data does not provide accurate energy model calibration for another specific building [17]. A review of current calibration works has revealed that there is no generally adopted