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An automated optimization method for calibrating building energy simulation models with measured data: Orientation and a case study

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HIGHLIGHTS

- A complete and inclusive optimization automated calibration flow is developed.
- Sensitivity analysis is applied to determine the target tuned parameters.
- PSO is adopted and compiled to perform the optimization procedure.
- Sub-metered energy use are simultaneously calibrated through a weighted function.
- A case study in Shanghai based on sub-metered energy data is presented.

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ABSTRACT

Due to the discrepancy between simulated energy consumption and measured data, it is essential to calibrate building energy models to improve its fidelity in evaluating the performance of retrofitting. Currently, most calibration methods are conducted manually to minimize this discrepancy, heavily relying on the knowledge and experience of analysts to discover a reasonable set of parameters. Because of the myriad independent and interdependent variables involved, the reliability of the entire simulation is largely undermined. In the presented paper, we propose a complete and fluent optimization automated calibration flow by introducing the mathematical optimization method (Particle Swarm Optimization is adopted) into the building energy model calibration process, thus leveraging the advantages of the efficiency and flexibility of the automated computer procedure. This approach is also characterized by its inclusivity, for it is compatible with other advanced manual methods and able to largely assist the experts in improving the efficiency of tuning relative input parameters. Moreover, a case in Shanghai is presented to verify the validity of the proposed method. After calibration, the simulation model demonstrates a satisfactory predicting accuracy. The calculated electricity consumption from the HVAC, lighting and equipment matches the actual monitored data with 11.6%, 7.3% and 7.2% CV (RMSE), respectively, and the total electricity consumption is within 6.1%.

1. Introduction

1.1. Original significance

Energy problems have become increasingly hot topics in the world, and the relationship between the demand and supply of energy use has also been of great concern. Buildings contribute significantly to the total energy use on the global scale and are responsible for 40% of energy consumption and one-third of Greenhouse Gas (GHG) emissions [1–4]. Therefore, buildings are important in the overall strategy of energy conservation and emissions reduction; energy goals will be achievable if we focus more on the retrofitting of buildings. At the same time, various reports and researches indicate that some adverse factors, such as defective building design without sufficient consideration of energy conservation, the degeneration and faults of the HVAC system, and changes in manipulation strategies, all result in the unsatisfactory energy efficiency of building operation. To ensure the practical

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contribution of buildings, it is critical to introduce several retrofit programs in existing buildings immediately. Mills et al. [5,6] believed the United States will achieve 16% median energy savings if the operation of existing buildings is improved. If these retrofit methods associated with building envelopes, mechanical equipment, and lighting systems are applied in commercial buildings in the USA, the reduction in money conversed from the potential energy savings will reach 30 billion in approximately 2030. In China, building energy efficient retrofitting is also significant. In the north of China, the floor area of inefficient existing residential buildings is 4.16 billion m^2, accounting for 76.33% of the total northern residential building [7]. To address this issue, the Chinese government released the "Green Building Action Plan" [8], aiming at retrofitting 570 million m^2 of existing buildings by 2015. Meanwhile, subsidies of approximately \$7.0/m^2–\$8.6/m^2 are provided to facilitate implementation of this plan [9].

1.2. Building energy model calibration

Before initiating the building retrofit program, it is necessary to evaluate the cost-efficiency of various proposed energy saving measures. The main approaches usually applied to evaluate the building energy consumption are measurement and simulation [10]. Due to its convenience and efficiency, the latter, building energy simulation (BES), is always recommended by the researchers [11–13]. However, although this technique has been developed mature gradually for many years, one problem still exists. That is the discrepancy between the calculated results in the energy simulation and the monitored data in actual buildings [14]. This deviation mostly results from the differences between the initial design and practical operation [15], such as using default/standard values for parameters [16], which are difficult to be described in the building energy model. In most situations, it is essential to calibrate the model to at least roughly match the given actual building, thus increasing its fidelity in the energy evaluation. Only if the energy model is properly calibrated, could it be applied reliably to implement such studies as evaluating the potential energy saving from various energy conservation measures (ECMs), or predicting the future energy consumption.

The building energy model calibration involves tuning miscellaneous input parameters to minimize the aforesaid discrepancy. This process is usually conducted based on various available monitored data of energy behavior [17,18]. If the virtual monitoring system is well-established in the target building and can record hourly energy consumption, open-closed state data on time scales [19–21] and the operational data in different zones or systems on spatial scales [22], it will greatly facilitate the analysts and increase the efficiency and accuracy of the calibrated model. Coakley et al. [23] summarized the hierarchy of some source information in his research, as presented in Fig. 1. Apparently, the smaller time and spatial scale the monitored data are divided into, the more accurate and difficult it is to achieve the synthetic calibration [19]. However, at present most buildings are not equipped with the monitoring system, and the monthly end-use of energy consumption comes available in a better situation.

So the question comes: What constitutes a qualified building energy model? Its accuracy is currently confirmed by the fact that outputs generated by the model should closely match the measured utility data, which also conversely relies on how accurate the inputs could represent the properties of the given actual building [22]. To address the errors between the model simulation results and the measured data, Error (*ERR*) (calculated by Eqs. (1) and (2)) and Coefficient of Variation of Root Mean Square Error (*CV(RMSE)*) (calculated by Eqs. (3)–(5)) are specified by three relative guidelines: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guideline 14 [24], International Performance Measurement and Verification Protocol (IPMVP) [25], and Measurement and Verification of Federal Energy Projects (FEMP) [26], as presented in Table 1. Some researchers [17,27] validate and recommend *Mean Bias Error* (*MBE*) and *CV (RMSE)* for the tolerance evaluation of model calibration.

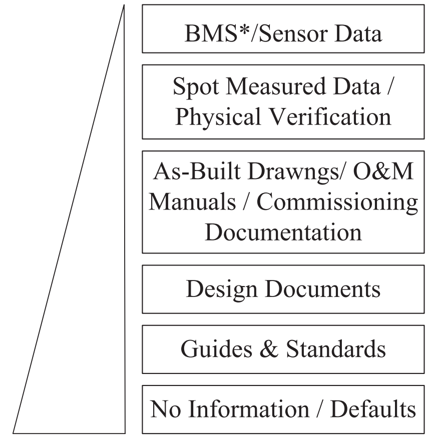

Fig. 1. The hierarchy of various source information [23] (*BMS: Building Management System).

Apart from the authoritative criteria for error evaluation, there is no uniform calibration method [28–30]. Nevertheless, for the procedure of calibrating model, some experts have made their own clear descriptions [24,28,31–34], of which the most detailed and prevailing is from ASHRAE-14: (1) Make a calibrated simulation plan, (2) Collect data, (3) Input data and run the model, (4) Calibrate the simulation model, (5) Tune the error, (6) Calculate the energy, (7) Build a baseline model and post-retrofit model, (8) Summarize and report.

$$ERR_{month}\ (\%) = \left[\frac{(M-S)_{month}}{M_{month}}\right] \times 100\% \tag{1}$$

$$ERR_{year}\ (\%) = \sum_{month}\left[\frac{ERR_{month}}{N_{month}}\right] \tag{2}$$

$$RMSE_{month} = \left[\frac{\sum_{month}(M-S)^2_{month}}{N_{month}}\right]^{1/2} \tag{3}$$

$$CV(RMSE_{month})(\%) = \left[\frac{RSME_{month}}{A_{month}}\right] \times 100\% \tag{4}$$

$$A_{month} = \frac{\sum_{month} M_{month}}{N_{month}} \tag{5}$$

where M is the measured electricity (kW h), S is the simulated electricity (kW h), N_{month} is the number of annual utility bills, and A_{month} is the averaged measured electricity (kW h).

The specific calibration method of establishing the energy model, namely how the process of adjusting the inputs in the models is conducted, is absolutely the focus of the current research. Experts and scholars have explored some significant achievements

Table 1
Acceptable range of monthly data calibration [24–26].

Index	ASHRAE 14	IPMVP	FEMP
ERR_{month}	±5%	±20%	±15%
ERR_{years}	–	–	±10%
$CV\ (RMSE_{month})$	15%	5%	10%