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A quick auto-calibration approach based on normative energy models

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ABSTRACT

When modeling the energy performance of existing buildings, model calibration always serves as an essential and necessary step to ensure the accuracy and applicability of building models. Model calibration for detailed energy models, which is also known as calibrated simulation (CS), refers to the process of tuning model's input parameters to narrow down the mismatch between the simulation result and the real-monitored data of building energy consumptions. Two major problems of current CS are: (1) a successful calibration requires HVAC domain knowledge of modelers. (2) Traditional building calibration process is labor-intensive and time-consuming. To solve these problems, a normative energy modeling based quick auto-calibration approach is proposed in this study. This approach is able to reduce the modeling time and simplify the calibration procedures. Firstly, this paper demonstrates the working principles and the credibility of Normative Energy Modeling (NEM). Then, the methodology of the proposed quick auto-calibration approach is elaborated. The energy performance model of a large hotel located in Shanghai, China with NEM is used as a case study to investigate the effectiveness of the proposed quick auto-calibration approach. The simulation result of the case study suggests that the proposed approach can significantly simplify the procedures of model calibrations while still achieve a good accuracy specified by ASHRAE Guideline 14 [1]. Besides, the results further confirm that such method requires much less time and computational power for modeling, compared with other counterparts (e.g., "Autotune" calibration [2]). With the advantage of speed and accuracy, the auto-calibration proposed in this paper is promising to be applied in both engineering and research field.

1. Introduction

About 13% of all the energy produced in the United States is used to heat, cool and ventilate buildings to satisfy the requirement of occupants for thermal comfort and indoor air quality (IAQ) [3] With energy saving raising widespread concerns more than ever in history, how to unravel the complexity and mystery of the building Heating, Ventilation and Air-Conditioning (HVAC) system and thus reduce building energy consumption has gradually become an urgent issue to be tackled. Benefiting from the emergence of computational modeling technology, engineers, scientists, and other stock holders now have a great opportunity to look deeper into this problem. Building energy simulation (BES), which is also known as building energy modeling (BEM), is a powerful analytic tool to model future innovation and technological progress in the architecture, engineering, and construction (AEC) industry. By assuming dynamic and time-continuous boundary conditions of building energy models, BES software can provide modelers with numerical solutions of a realistic model which tends to be incredibly complicated in the real world [4]. Due to its powerfulness in predicting the future behavior of buildings, BES has earned a solid reputation and is widely applied in building design and commissioning at present [5].

Past a few decades have witnessed a prosperity in the development of various BES software tools which provide practitioners with some key building performance indicators such as building loads, energy usage and demand, and the energy bills [6]. Some of the most widely-applied calculation engines include DOE-2 and EnergyPlus developed by the U.S. Department of Energy, TRNSYS developed by the University of Wisconsin-Madison, and ESP-r developed by the University of Strathclyde. Based on these engines, many interfaces which provide a more user-friendly platform for entering inputs and viewing outputs were further created, e.g., eQUEST, DesignBuilder, and OpenStudio. After a long period of further improvement and enhancement, many of these popular BES programs around the world are gradually reaching maturity and have made significant contributions to the study of building energy conservation measure (ECM). Pan et al. [7] applied calibrated

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Nomenclature

Variables, parameters and indices

RMA	Reduced Major Axis
MBE	Mean bias error
CV(RMSE)	Coefficient of variation of root-mean-square error
SRC	Standardized regression coefficient
R^2	Goodness of fit
R_j	Sensitivity index
I	Modeled energy consumption
v	Value of energy model parameter
s	Standard deviation
b_j	Regression coefficient of the jth variable
b_0	Intercept
x	The number of unimportant parameters
K	The number of all energy model parameters

Greek letters

ε	User-defined parameter to identify important parameter
δ	Relative deviation

Abbreviations

AEC	Architecture, engineering and constriction
ASHRAE	American Society of Heating, Ventilation and Air-conditioning
BAS	Building automation system
BEM	Building energy modeling
BES	Building energy simulation
CAV	Constant air volume
CS	Calibrated simulation
COP	Coefficient of performance
DHW	Domestic hot water
DOAS	Dedicated outdoor air system
ECM	Energy conservation measure
EPBD	Energy Performance in Buildings Directive
FCU	Fan coil unit system
HVAC	Heating, Ventilation and Air-Conditioning
IAQ	Indoor air quality
IPMVP	International Performance Measurement and Verification Protocol
NEM	Normative energy modeling
OA	Outdoor air
SW	Southwest
SHGC	Solar heat gain coefficient
SRF	Shading reduction factor
TMY	Typical meteorological year
VAV	Variable air volume system
N	North
S	South
E	East
W	West
H	Horizon
NE	Northeast
NW	Northwest
SE	Southeast
SW	Southwest

building energy simulation with DOE-2 on a high-rise commercial building in Shanghai, China to evaluate its energy saving potential. Cho et al. [8] researched the energy saving performance of enthalpy recovery ventilator on a residential building by TRNSYS. Pang et al. [9] evaluated the energy saving performance of a new solar ventilated window on a building in Shanghai city with EnergyPlus as simulation tool. Song et al. [10] analyzed the performance of several energy saving measures on a university library with eQUEST as the simulation tool.

Thanks to the rapid progress of BES technology, model calibration has been applied to optimize the operation and cut the energy consumption of existing buildings nowadays. Model calibration, which is also known as calibrated simulation (CS), refers to the process of tuning model's input parameters to narrow down the mismatch between the simulation result and the real-monitored data. CS is usually necessary for the simulation of existing buildings due to the fact that most existing buildings do not operate as well or as efficiently as they could and should [4]. This fact results in a considerable discrepancy between the simulated and the measured energy consumptions [11,12]. Therefore, the model calibration serves as an essential and necessary step to ensure the accuracy and applicability of building models, in particular, used in the operation stage [13] (e.g., model-based controls, model-based diagnostics, etc.).

CS of existing buildings has long been considered to be compute-intensive and time-consuming because of the high nonlinearity, multi-parameters characteristics, and the inherent complexity of the building system [4]. This is especially true for traditional CS which tunes the parameters of the building energy model on a trial-and-error basis. For this reason, an increased number of studies have been proposed for a more efficient method for building model calibration. Clarke et al. [14] came up with a calibration method which emphasized the empirical data from building automation system and applied this procedure with the ESP-r program. O'Neill and Eisenhower [15] presented a systematic way for building energy model calibration using a parametric uncertainty analysis. Chaudhary et al. [2] conducted two case studies through using an "Autotune" approach to tune input parameters in EnergyPlus models. These methods all require mass computational power since it tends to take a lot of iterations to reach the convergence of the numerical solutions of the energy model. For example, in the case study presented by Chaudhary et al. [2], the whole calibration process lasted for 6.7 h, which is obviously too long to be put into large-scale use in practice.

In building energy simulation, sensitivity analysis is typically adopted to identify the importance of various input parameters and rank them by their influences on the simulation results. By conducting such an sensitivity analysis of these parameters, those input parameters that have a large impact on model outcomes can be selected and prioritized in the following calibration [16]. This identification can help modelers or auto-calibration programs to tune the model parameters in a more efficient way by avoid tuning parameters which hardly influence the simulation result.

With the advantages of simplicity, transparency, robustness, and reproducibility, normative energy modeling (NEM) technology offers an alternative solution to this problem (i.e. present calibration approaches require much computational power and time.) [17]. NEM is a building energy simulation approach which uses a set of standardized building energy equations to calculate the building energy consumption without dynamic simulation (i.e., the simulation based on iterative computation, e.g., the heat balance model of EnergyPlus). These equations are mostly based on international energy calculation standards such as ISO 13790 [18] and EN 15232 [19], which demonstrate a set of simplified procedures to simulate building heating and cooling load, and energy consumption. These standards are made by Energy Performance in Buildings Directive (EPBD) to quickly calculate building energy consumption and evaluate the building energy performance. There are some software tools based on NEM technology, such as EPSCT which is developed by High Performance Building Group, Georgia Institute of Technology [17]. A comparative study between NEM and dynamic simulation is conducted with EPSCT and EnergyPlus. The study result proves that NEM could finish a round of calculation within 1 s