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Why is the reliability of building simulation limited as a tool for evaluating energy conservation measures?

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HIGHLIGHTS

- The reliability of ECM performance assessment using energy simulation is limited.
- Using assumed occupancy data in ECM assessment reduces reliability of the results.
- Cross-ECM estimation of building energy consumption is statistically inaccurate.
- Current assessments of ECMs should be interpreted and used with caution.

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ABSTRACT

Buildings account for approximately 32% of the total energy consumption globally and up to 40% in the developed countries, which makes buildings a prime target for energy conservation. Various energy conservation measures (ECMs) have been proposed to improve the energy efficiency in buildings, and these ECMs are usually designed and assessed using calibrated building energy models. However, there is empirical evidence that reveals noticeable discrepancies between simulated performances of ECMs reported in building energy models and their actual performances measured in buildings. This paper examines two possible causes of such discrepancies. Specifically, this paper tests the following two hypotheses: (1) using assumed occupancy data as opposed to actual occupancy data in building energy simulation reduces the reliability of estimated performance of demand-driven ECMs; and (2) using an energy model built for one ECM to cross estimate energy consumption of another ECM is statistically inaccurate. An educational building was used as a test bed. The results proved both hypotheses true, showing that estimations were more accurate and consistent for models calibrated using actual occupancy compared with those using assumed occupancy, and that cross-ECM estimation resulted in statistical inaccuracy. The findings indicated that current building energy modeling methods have limited reliability in ECM performance assessment, and need to be improved to better support the design and implementation of ECMs in buildings.

1. Background

Buildings account for approximately 32% of the total energy consumption globally and up to 40% of the total energy consumption in the developed countries [1]. The fact that buildings are widely reported to be inefficient in terms of system operations [2,3] makes them a primary target for energy conservation. Considering the fact that existing buildings are generally in operation for 30–50 years and will account for 70% of the total building stock by 2050 [4], it is imperatively important to reduce energy consumption in existing buildings, for which various energy conservation measures (ECMs) have been proposed. For example, demand-response controls for lighting [5] and heating, ventilation, and air conditioning (HVAC) [6,7] are increasingly finding their way into building automation systems (BAS) and have reportedly achieved significant potential for energy savings. A more drastic approach for improving building energy efficiency is through energy retrofits, which usually involve the upgrade of building envelopes [8], building systems [9], and implementation of latest energy-efficient technologies [10].

Investigation of the feasibility and cost effectiveness of ECMs before their actual implementation is critical, especially that some of the ECMs might involve major retrofits or system changes and

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hence cannot be reversed once implemented, exerting long-term impacts on the energy performance of a building [11]. For ECMs that are tested or implemented by BAS and are hence reversible, their implementation may cause additional equipment depreciation and thermal discomfort to occupants, therefore, energy simulation could still be used as an inexpensive and non-intrusive alternative for ECM performance assessment. It has become the mainstream to employ building energy simulation models, believed to accurately reflect the physical characteristics and internal dynamics of the buildings, to quantify expected energy savings from the ECMs [12] and justify their applications [11]. First, ECMs are virtually implemented by appropriately modifying building energy models, and the simulations are performed to examine the expected energy performance of buildings given these new changes. Repeated simulations can be performed to investigate potential opportunities for energy efficiencies [13], identify optimal strategies for building design [14] and daily building operations [15], and select among competing energy retrofit plans [16].

The reliability of reported performance of ECMs largely depends on the accuracy of the simulation model in representing the properties of the building it simulates [17], which in turn depends on how well the model is calibrated against available audit data [18]. The need for calibrating building energy simulation models in order to ensure reliable simulation results was first recognized in the 1970s [19], and since then it has been recognized as a fundamental factor in substantiating how well the models represent the characteristics of real buildings [20].

Calibration of building energy models is typically done by iteratively adjusting model parameters, based on the available audit data, until estimated energy consumption matches actual measurements [21–24] within tolerances dictated by certain criteria [25–27]. Uncertainty and sensitivity analyses are usually performed to identify the parameters that are the most impactful on key indicators predicted by the model of building energy performance, and these parameters are given higher weights in the calibration process. The audit data are usually composed of various sources, which are not necessarily coherent. The sources can be prioritized as follows in a descending order of reliability: sensor data, spot measurements, as-built drawings, design documents, and building standards [28]. The accuracy of calibrated models relies on various factors, such as the quantity of audit data and the complexity of building dynamics. More importantly, as a mostly trial-and-error process, the energy model calibration largely relies on the expert knowledge, past experience, statistical expertise, and engineering judgment [29]. The above calibration process is challenged by many researchers due to its ad-hoc and subjective nature, and recent efforts have focused on establishing formal and systematic calibration methodologies. As a result, a number of approaches, such as Bayesian calibration [12], reproducible calibration [10], evidence-based calibration [18,30], multi-stage calibration [31], and simultaneous multi-level calibration [32], have been proposed.

Despite the proposition of these new calibration approaches, there is accruing evidence showing significant discrepancies between estimated and actual energy savings [17,33,34]. Recent efforts have focused on improving the reliability of building energy models for ECM assessments. For instance, Heo et al. generated normative models based on Bayesian calibration to account for the quantitative interventions of ECMs and provided probabilistic predictions for energy implications of different ECMs [11]; Parker et al. divided the calibration process into stages to comply with different ECMs [35]; Judkoff et al. investigated the uncertainties and variability of energy consequences of different ECMs resulting from different simulation programs [36]; Reddy et al. used a group of models instead of a single model to estimate the effects of ECMs within range [29]; Coakley et al. proposed to update evidence in calibration to improve the representation of each parameter in order to increase the robustness of the model to different ECMs [28]. While these efforts have contributed to the reliability of energy simulation in ECM assessment, the improvements are generally limited and sometimes ECM-specific. Further efforts to reduce the discrepancy between estimated and actual energy savings of various ECMs are difficult, before the fundamental question of what have caused such discrepancy, in what way and to what extent, is clearly answered. Various factors may be responsible for the discrepancy, such as weather variations, faults in building control systems, occupant behaviors, and occupancy schedules. This paper aims to investigate two possible causes of the discrepancy, including the use of actual occupancy data in energy modeling and the changes to building functionalities due to implementation of ECMs, and examine the overall reliability of building simulation as a tool for ECM assessment.

2. Research motivation and hypothesis

2.1. Challenges and motivations

The performance of ECMs in simulation lays the basis of their design and implementation, and a variety of building energy simulation approaches have been proposed in the literature [37]. However, because of the discrepancies between actual buildings and their virtual representations, the optimality and expected energy savings of the ECMs as reported in simulations are not always met in practice. In fact, there is empirical evidence that reveals noticeable discrepancies between simulated and measured performances of ECMs [33,34]. From a theoretical point of view, there are two challenges that may prevent the simulated performances of the HVAC ECMs from being accurate.

First, occupancy is one of the most important influences on the thermal behavior of buildings [38]. It is a critical factor that determines the total and peak loads of HVAC systems and related energy consumption. Most building energy models built in prior research relied on assumed or simulated building occupancy, which inevitably deviates from the actual occupancy. Such simplification overlooks the impact of occupancy on building energy usage and, more importantly, cannot reflect the energy implications from interplays between occupancy patterns and the changes to building functionalities introduced by the ECMs. For instance, when estimating energy savings from an increase of indoor temperature set points in a warm climate, estimations from the simulation may be an underestimation, as occupants may react to the increased indoor temperatures by reducing the duration of their presence and hence their usage of the cooling service. Such implicit impacts of occupancy on building energy usage, not observable when assumed occupancy is used, highlight the need for using actual occupancy in assessing the effectiveness of HVAC ECMs. In fact, building occupancy detection itself is an area that has seen active research in the past decade. Different technologies have been proposed for occupancy detection, such as videos [39], CO_2 sensors [40], PIR sensors [41], Internet activity monitoring [42], or a combination of different technologies [43]. Despite the exploration of these solutions, large-scale occupancy detection has remained a challenging task, and has rarely been deployed at a building scale for evaluating ECMs.

Second, current modeling approaches calibrate models using the data collected when buildings are operated under a specific physical condition and operational strategy. The calibrated models are then used to estimate the energy consumption under various ECMs, assuming the buildings would have the same energy-consumption behaviors. However, buildings can be sensitive to physical conditions and operational strategies, and might behave differently