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Linking measurements and models in commercial buildings: A case study for model calibration and demand response strategy evaluation

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ABSTRACT

This paper describes a step-by-step procedure for using measured end-use energy data from a campus building to calibrate a simulation model developed in EnergyPlus. This process included identification of key input parameters for reducing uncertainties in the model. Building thermal zones were modeled to match the actual heating ventilation and air conditioning (HVAC) zoning for each individual variable air-volume (VAV) zone. We evaluated most key building and HVAC system components, including space loads (actual occupancy number, lighting and plug loads), HVAC air-side components (VAV terminals, supply and return fans) and water-side components (chillers, pumps, and cooling towers). Comparison of the pre- and post-calibration model shows that the calibration process greatly improves the model's accuracy for each end use. We propose an automated model calibration procedure that links the model to a real-time data monitoring system, allowing the model to be updated any time. The approach enables the automated data feed from simple measuring and actuation profile (sMAP) into the EnergyPlus model to create realistic schedules of space loads (occupancy, lighting and plug), performance curves of fans, chillers and cooling towers. We also field-tested demand response (DR) control strategies to evaluate the model's performance in predicting dynamic response effects. Finally, this paper describes application of the calibrated model to analyze control systems and DR strategies with the goal of reducing peak demand.

1. Introduction

1.1. Background

The engineering, controls, and buildings energy research community is developing a number of building energy optimization and advanced control concepts to reduce energy use and enable demand-response (DR) capabilities in buildings. To accurately model the effect of optimal control strategies, a detailed simulation model is needed that produces highly accurate results for each of the building's mechanical system components. The objective of this study is to demonstrate a new approach to develop and automating calibration of a model that can be used to evaluate the effect of various DR control strategies on peak demand reduction. The calibrated simulation model can be implemented in building energy management systems (BEMs) to assist building operators in predicting the effects of various control strategies.

For modelers, an advantage of a building simulation physical model is that it enables them to evaluate various design strategies, energy conversation measures (ECMs), and building system operational modes and to choose an optimal operational scheme for achieving a given target, such as reducing demand or maximizing energy efficiency. Calibration of such a model is critical; the model must closely approximate the actual building being studied to ensure that costly mistakes are avoided. A number of studies demonstrate that simulation models provide valuable support for conceptual and integrated system design, enabling designers to evaluate new architectural concepts and the impacts of different types of building façades; daylighting, solar shading, passive cooling, and integrated control strategies; and other design elements. However, when building energy simulation moves from the design phase to the operational phase, there are many uncertainties in models' ability to accurately reflect actual building performance, especially on a large scale. As reported in a study of Energy Performance of Leadership in Energy Efficiency and Design (LEED) for New Construction Buildings [1], discrepancies between simulated and measured energy use intensity show an acceptably close match between simulated and measured values for only a small number of buildings.

Empirical validation methods have traditionally been used to evaluate the accuracy of models for simulating the energy intensity of existing buildings, to identify model uncertainties, and to

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calibrate input variables by comparing them to measured values. Empirical validation has been demonstrated in many field studies [2–8]. Among the milestones in model calibration was the development of a systematic method using a "base load analysis approach" [9], which uses a combination of monthly utility billing data and sub-metered data to calibrate a building energy performance model. A case study of this approach showed that it reliably and accurately simulated monthly and annual building energy requirements. Other key studies [10,11] proposed a general methodology for calibrating detailed building energy simulation programs based on performance data and applied this methodology to three case-study office buildings. In that study, building system loads were characterized as "weather dependent" (HVAC system loads) and "weather independent" (e.g., lighting and plug loads). Pan et al. [2] calibrated a simulation model in a high-rise commercial building using a step-by-step method based on the approach proposed in American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) Guideline 14-2002. In 1994, Norford et al. presented a common-sense procedure for calibrating a DOE-2 computer model of a commercial building [12], identifying the major building loads, including lighting and equipment. New et al. [13] introduced an "Autotune" methodology for calibrating building energy models by using a suite of machine-learning algorithms, parameter sensitivity analysis and sensor data. Finally, O'Neill and Eisenhower [8] proposed a systematic, automated way to calibrate a building energy model. Their optimization-based approach leveraged the analysis of parametric uncertainty with parametric simulations minimizing the error between the simulated and measured data.

Table 1 compares different types of model calibration methods in terms of their applications, advantages, and disadvantages.

A key question is whether large-scale simulations have low predictive value in existing buildings. The answer is no, but intense calibration is needed to sufficiently reduce model uncertainties in order to achieve high predictive value in large-scale, highly complex simulations. For simulating building energy in these situations, a good solution is to break the model calibration problem down into smaller, sub-level systems and manageable segments. Calibrating each smaller segment of the building improves the model's overall predictive value. Typically, a building's energy usage is composed of lighting, plug, and HVAC system loads. Lighting and plug loads are assumed to be weather-independent variables even though lighting power consumption is influenced by daylighting. This portion of load can be measured by sub-metering on each floor of a building. HVAC power usage is driven by a number of factors, including weather, internal loads (occupant, light, and plug), HVAC equipment specifications, and system configurations and control schemes. As more and more building information becomes available, a critical problem is enabling the simple and efficient transmission of building energy data to the simulation model.

Another challenge for building simulation models is to predict buildings' behavior under dynamic conditions such as DR events or to evaluate the effects of energy-saving strategies such as peak-demand reduction. Several past studies have looked at modeling these types of dynamic control strategies. Rabl et al. [14] studied the application of DR simulation models in commercial buildings, developing a data-driven based dynamic model to simulate the effect of different thermostat control strategies for reducing peak demand. Morris et al. [15] investigated two optimal dynamic building control strategies in a representative room in a large office building; experiments showed as much as 40% reduction in peak cooling load from this approach.

Several studies have demonstrated building control strategies for reducing peak load that are applicable to our objective of using the calibrated simulation model to model peak-load reduction approaches. Keeney et al. [16] developed a building control strategy and tested it in a large office building, finding that pre-cooling could limit peak cooling loads to 75% of cooling capacity. Xu et al. [17] demonstrated the potential for reducing peak electrical demand in moderate-size commercial buildings by modifying HVAC system control. Field tests of this approach showed that chiller power was reduced by 80–100% (1–2.3 watts per square foot [W/ft^2]) during the peak period without thermal comfort complaints from occupants. Xu et al. [18] conducted a series of field tests in two commercial buildings in Northern California to investigate the effects of various pre-cooling and demand-shed strategies. These tests showed the potential to reduce cooling load 25–50% during peak hours and demonstrated the importance of discharge strategies to avoid rebounds. Braun [19] presented an overview of research related to the use of building thermal mass for shifting and reducing peak cooling loads in commercial buildings and provided specific results obtained through simulations, laboratory tests, and field studies.

Peak-load reduction strategy modeling studies include Yin et al. [3]; this study developed and calibrated simulation models of 11 commercial buildings for evaluating the effect of different thermostat control strategies. There have been a number of other simulations, laboratory and field tests, and pilot studies on DR in buildings [20,21].

1.2. Methodology

A framework and methodology are created to develop and calibrate a component-based model to meet the requirement of predictive value of the demand response potential estimation. To calibrate the model's foundation, we modeled the building geometry and internal thermal zones to match the actual HVAC zoning for each individual variable air-volume (VAV) zone. Following an evidence-based methodology, the model was developed from (1) as-built architectural, mechanical design, and control drawings; (2) actual building operation and behavior (occupancy, lighting and plug loads, HVAC system operations); and (3) detailed mechanical equipment specifications and actual operational performance (part-load operational curves of chiller, pump and fan, etc.). We propose an automated calibration procedure that links the model to the building's real-time data monitoring system so that the model can be updated with measured data at any time, especially when there is any change in building system operations or when energy-efficiency measures are implemented. The following building system components are validated: (1) CO_2 concentration-based occupant behavior; (2) submetered lighting and plug loads; (3) sensor based HVAC system components' performance curves.

1.3. Objective

In this study, our main goal is to develop and calibrate the building model by linking measurements and each model component. Besides the component-based model development and automated model calibration, another objective of this study is to use the model to optimize various DR control strategies for achieving the goal of 30% peak demand reduction in the building.

This paper adds to the body of research on model calibration and application to dynamic building scenarios such as DR events by developing an EnergyPlus [22] model for a campus office building and calibrating it with actual measured data from the building's energy management system. We used the calibrated model to evaluate the effect of different DR control strategies for peak-load reduction. Various DR strategies were proposed that addressed HVAC, lighting, and plug loads and were simulated using the calibrated model.