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Development and calibration of an online energy model for campus buildings

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ABSTRACT

Previous studies show that building HVAC systems can consume greater than 20% more electrical energy than was the design intent largely because of equipment performance degradation, equipment failures, or detrimental interactions among subsystems. A key barrier is the lack of sufficient and detailed information to isolate abnormal changes in load conditions or anomalous equipment operations. One of the solutions is to develop model-based diagnostic methods. Hence, developing a calibrated energy performance model becomes a key component. In this paper, an integrated energy model for campus buildings was developed based on a Reduced-Order Model (ROM), which includes building envelope model, and HVAC primary and secondary system models. The integrated model was validated against real-time measured data within the ±15% error in terms of the load differences.

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1. Introduction

In commercial buildings, building HVAC system consumes nearly 40%, and lighting and plug loads are responsible for about 35% of total building energy consumption [1]. Because of equipment performance degradation (e.g., filter or heat exchanger fouling), equipment failures, or detrimental interactions among subsystems, HVAC systems can consume greater than 20% more electrical energy than was the design intent [2]. In order to save HVAC energy consumption, a few studies were carried out to conduct fault detection and diagnostics, without effective results because of lack of detailed and sufficient information from available sensor data to isolate abnormal changes in different load conditions [3–7]. One of the solutions is to develop first principles model-based diagnostic methods because a reliable model can provide rich simulated data sets as the reference for both fault free and faulty scenarios. Hence, developing a calibrated energy performance model becomes a key component.

Model-based methods include physical models of the Heating Ventilation and Air Conditioning & Refrigeration (HVAC&R) equipment and control processes. Faults are detected as the difference between measurements and corresponding model outputs exceeds a threshold. With measured physical parameters, model based energy diagnostics approaches [8,9] have been developed for different HVAC systems and components. Detection and diagnosis of simultaneous faults have been demonstrated for selected fault groups of packaged rooftop air conditioning systems [10]. Energy diagnostics with system-level energy tracking and load monitoring has been explored to isolate major energy end use problems [11].

Calibrated energy models have received more and more attentions for better building operations in the last two decades [12–14]. Particularly, Reddy (2006) reported a detailed literature review on calibration of building energy simulation programs, which pointed out the time consuming nature of this process [15]. The proposed methodology is from an ASHRAE research project 1051-RP, which included sensitivity analysis (pre-selected parameters for the perturbation), identifiability analysis, numerical optimization, and uncertainty analysis. The purpose of this study is to provide a calibrated building energy performance model as a reference point for model based performance monitoring, HVAC operation sensitivity study, and energy diagnostics.

In this study, we focus on the energy performance models used for supervisory optimal controls and HVAC Fault Detection and Diagnostics (FDD), which requires flexible access to states of the models. Building models incorporated within whole building simulation programs such EnergyPlus, TRNSYS, and ESP-r are not explicit [16] and would require significant computational effort when integrated with control and diagnostics algorithms for an online implementation in buildings.

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Nomenclature

List of Symbols

m_{air_zone} air mass for the given zone [kg];
C_{pa} specific heat capacity of dry air [J/kg·K];
C_{pv} specific heat capacity of water vapor [J/kg·K];
T_{AMB} ambient air temperature [°C]
T_{zone} zone air temperature [°C]
T_{SUP} supply air temperature [°C]
T_e suction saturation temperature[°C]
T_c discharge saturation temperature [°C]
T_{isurf} inside surface temperature [°C]
T_{osurf} outside surface temperature [°C]
T_{amb_rated} ambient temperature at rated condition [°C]
T_{case_rated} display case temperature at rated condition [°C]
T_{wr_c} calculated return water temperature [°C]
T_{ws_c} calculated supply water temperature [°C]
$\dot{m}_{w\_c}$ calculated water flow rate [kg/s]
$\dot{m}_{sup}$ supply air mass flow rate [kg/s]
$\dot{m}_{inf}$ infiltration mass flow rate [kg/s]
$\dot{m}_v$ internal water vapor generation rate [kg/s]
$\dot{Q}_{int}$ convective internal loads [W]
$\dot{Q}_{surfo}$ outside surface absorbed solar radiation [W]
$\dot{Q}_{surfi}$ inside surface absorbed solar radiation [W]
$\dot{Q}_{int}$ internal load [W]
$\sum_{i}^{N_{surface}} Q_{structure\_i}$ sum of the convective heat transfer between the zone air and zone's internal surface temperature [°C]
α relax function parameter
h_o outside surface heat transfer coefficient [W/m2·K]
h_i inside surface heat transfer coefficient [W/m^2·K]
A wall or window surface area [m^2]
k thermal conductivity of surface [W/m·K]
ρ density of the surface material [kg/m^3]
U overall heat transfer coefficient [W/m^2·K]

Figure 1 shows the overview of an integrated reduced-order energy performance modeling approach, derived from building physics. The development of a BIM based database and information extraction workflow are described in another paper [17]. The whole building energy model was developed in MATLAB environment based on a reduced-order building envelope model, and HVAC primary and secondary system models [18]. The internal heat gains/losses were estimated from real-time measurements using an Extended Kalman Filter based estimator [19]. The model integration between HVAC systems and building zones is modeled through a ping-pong coupling approach.

Table 1
Individual modules in the building envelop model.

Component	Module	Validation/Verification
Air Heat Balance	(1)	√
Wall Heat Transfer	(2)	√
Window Heat Transfer	(3)	√
Internal Load Estimation	(4)	√
Transmitted Solar Radiation	(5)	√
Infiltration	(6)	N/A*
Ground Heat Transfer	(7)	N/A*

*N/A No data available for validation/verification at the time of this study, but validated by other studies (Gowri et al., 2009).

2. Whole Building Model Development

2.1. Building envelope model

A thermal network model was adopted in this study. This modeling framework has been widely used to represent the heat transfer and dynamic thermal process through building envelope and the subsequent effects on indoor air temperature [20]. One major assumption used by this approach is that the zonal air is well mixed, with only one temperature node and one humidity node. Figure 1 shows a typical energy flow in buildings for reduced-order model (ROM), which is a low order and lumped model compared with those in EnergyPlus etc. Table 1 lists out all the modules that have been developed and validated with measured data, except for the infiltration and ground heat transfer modules. The following paragraphs describe in detail how indoor air and wall heat transfer equations were developed as examples. Figure 2

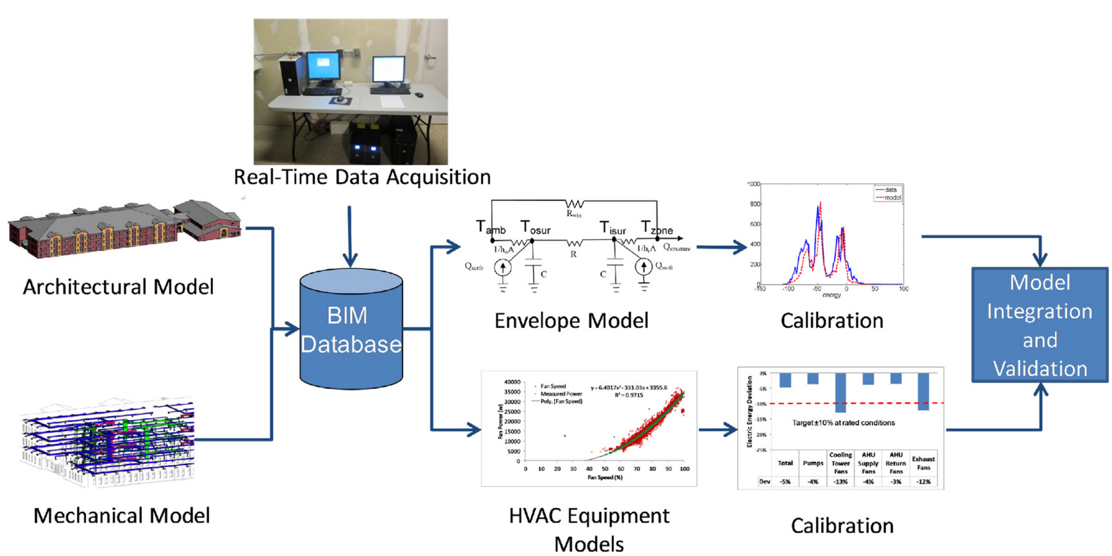

Figure 1. Overview of integrated reduced-order energy performance modeling approach.