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Modeling of HVAC operational faults in building performance simulation

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HIGHLIGHTS

- Discuss significance of capturing operational faults in existing buildings.
- Develop a novel feature in EnergyPlus to model operational faults of HVAC systems.
- Compare three approaches to faults modeling using EnergyPlus.
- A case study demonstrates the use of the fault-modeling feature.
- Future developments of new faults are discussed.

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ABSTRACT

Operational faults are common in the heating, ventilating, and air conditioning (HVAC) systems of existing buildings, leading to a decrease in energy efficiency and occupant comfort. Various fault detection and diagnostic methods have been developed to identify and analyze HVAC operational faults at the component or subsystem level. However, current methods lack a holistic approach to predicting the overall impacts of faults at the building level—an approach that adequately addresses the coupling between various operational components, the synchronized effect between simultaneous faults, and the dynamic nature of fault severity. This study introduces the novel development of a fault-modeling feature in EnergyPlus which fills in the knowledge gap left by previous studies. This paper presents the design and implementation of the new feature in EnergyPlus and discusses in detail the fault-modeling challenges faced. The new fault-modeling feature enables EnergyPlus to quantify the impacts of faults on building energy use and occupant comfort, thus supporting the decision making of timely fault corrections. Including actual building operational faults in energy models also improves the accuracy of the baseline model, which is critical in the measurement and verification of retrofit or commissioning projects. As an example, EnergyPlus version 8.6 was used to investigate the impacts of a number of typical operational faults in an office building across several U.S. climate zones. The results demonstrate that the faults have significant impacts on building energy performance as well as on occupant thermal comfort. Finally, the paper introduces future development plans for EnergyPlus fault-modeling capability.

1. Introduction

The building sector has become the largest consumer of primary energy in the world, exceeding both industry and transportation sectors. According to the United States Department of Energy (U.S. DOE) and the European Parliament and Council, buildings (both commercial and residential) account for about 40% of the total primary energy consumption in the United States and Europe [1,2]. This not only leads to enormous consumption of fossil fuel resources, but also produces severe environmental impacts such as ozone layer depletion and global warming.

Heating, ventilating, and air conditioning (HVAC) system operations in buildings represent a significant potential for reducing energy use in buildings by improving energy efficiency, indoor air quality, and comfort levels. However, most buildings, especially those embedded with complex building energy systems, have various degrees and types of operational problems. It is reported that the number of maintenance requests for building energy systems have increased exponentially throughout the past decades, indicating an increase in building operational faults [3]. Typical operational faults may come from improper installation, equipment degradation, sensor offset or failures, or control logic problems. They can be grouped into several categories, including: (1) control fault, (2) sensor offset, (3) equipment performance degradation, (4) fouling fault, (5) stuck fault, and (6) others [4,5]. Fig. 1 depicts a

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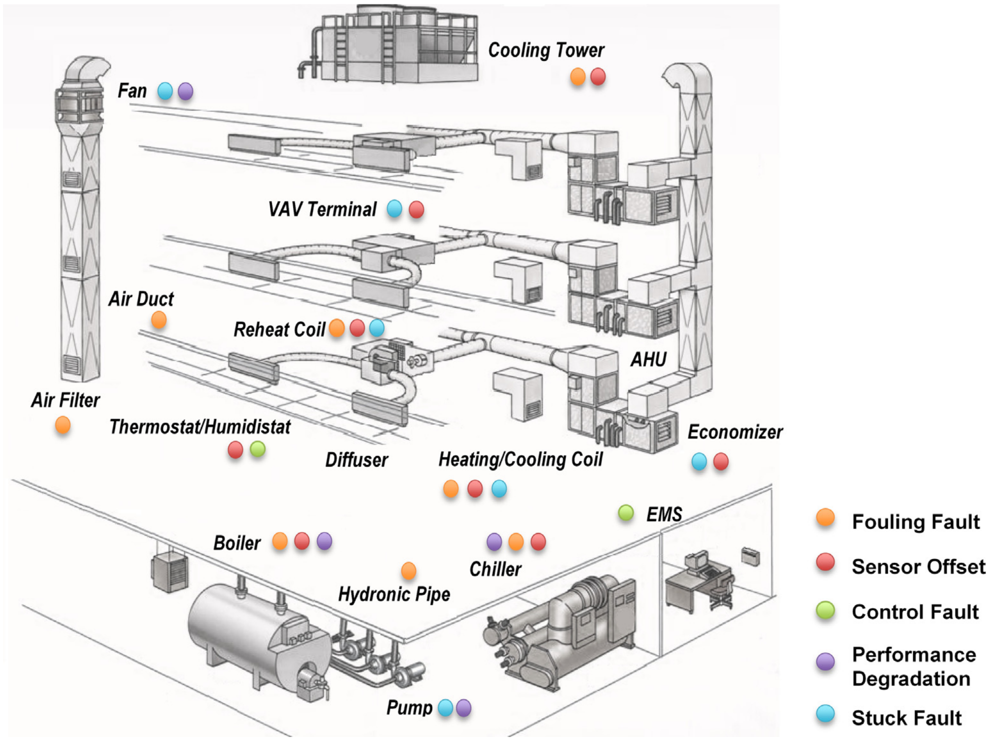

Fig. 1. Potential HVAC operational faults in a typical VAV system in a central plant.

number of common potential faults in a typical variable air volume (VAV) system with a central plant.

HVAC operational faults may lead to a considerable discrepancy between actual HVAC operation performance and design expectations [6–9]. It is estimated that poorly maintained and improperly controlled HVAC equipment is responsible for 15–30% of energy consumption in commercial buildings [5]. A series of questionnaire surveys and interviews conducted by Au-Yong, et al., show the significant influence of poor HVAC operation on occupant comfort, and a number of maintenance factors are identified that are significantly correlated with the occupants' satisfaction [10].

Modeling and simulating HVAC operational faults can lead to greater understanding by quantifying the impact of the faults on building energy use and occupant comfort. Modeling and simulation allows for an estimation of the severity of common faults and, thus, supports decision making about timely fault corrections—which can then enable efficient system operation, improve indoor thermal comfort, reduce equipment downtime, and prolong equipment service life [11–13]. It can also support commissioning efforts by providing estimates for potential energy/cost savings that could be achieved by fixing the faults during retro-commissioning. Quantified information on the impacts and priorities of various coexisting operational faults can be provided to the commissioners or the building management system, resulting in more reasonable and reliable commissioning decisions, especially when budget and staff resources are limited [13]. Moreover, modeling operational faults is critical to achieving more reliable energy model calibrations when most energy models for existing buildings assume ideal conditions without any operational problems. This ability to estimate the severity of common faults is expected to improve the accuracy and transparency of the calibrated model, therefore increasing the analysis accuracy of different retrofit measures [14,15].

A variety of fault detection and diagnosis (FDD) tools have been developed with various approaches, focusing on identifying and analyzing the HVAC operational problems. Cheung and Braun developed the fault models for a variety of typical building energy system equipment with three modeling techniques: empirical modeling, semi-empirical modeling, and physical modeling [4,16]. Radhakrishnana, et al. investigated the various constraints of HVAC scheduling and proposed a novel, token-based distributed control/scheduling approach that can account for varying indoor environment and occupant conditions [17]. Zhao, et al. proposed a pattern recognition-based method to detect and diagnose faults in chiller operations, using a one-class classification algorithm [18]. Li, et al. also investigated the chiller operational problems, but with a two-stage, data-driven approach based on the linear discriminant analysis [19]. Cai, et al. developed a novel method to analyze the faults of the ground-source heat pump. Cai's model achieves multi-source information fusion-based fault diagnosis by deriving Bayesian networks based on sensor data [20]. Han, et al. proposed an automated fault detection and diagnosis strategy for vapor-compression refrigeration systems, combining the principle component analysis feature extraction technology and the multiclass support vector machine classification algorithm [21]. The operational faults of several other major HVAC components have also been investigated, such as air handle unit (AHU) [22–24], heat exchanger [25], and fan coil unit [26].

Compared with the extensive investigations conducted on the design efficiencies and control strategies of HVAC systems, however, research on the impacts of HVAC operational faults is still insufficient. Most fault-related research focuses on the component or subsystem performance rather than the whole-building performance and therefore cannot predict the overall impacts of the faults at the building level. The synchronized effect between simultaneous faults occurring in multiple components cannot be effectively addressed by existing approaches. Moreover, the current fault analysis methods are usually designed for specific HVAC systems employed in particular case buildings. This leads to significant challenges in applying the approaches to buildings with different system types or configurations.