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Characterization of a building's operation using automation data: A review and case study

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ABSTRACT

This paper presents a critical review of the automated on-going commissioning (AOGC) methods for air-handling units (AHU) and variable air volume terminal (VAV) units in commercial buildings. The common faults studied in the literature were identified. The diagnostic approaches taken and the characteristics of the fault-symptom datasets utilized were categorized. It was found that the diagnostics methods were vastly fragmented, and most of them employed pure-statistical approaches. Only a few studies attempted to assimilate the automation data within the underlying physical processes. In addition, a large fraction of the reviewed literature has been devoted to physical faults in AHUs. Only a few studies were conducted to diagnose faults-related with controls programming and faults at the zone level. Upon the literature survey findings, an inverse greybox modelling-based AOGC approach was put forward. Its strengths and weaknesses were demonstrated through a case study conducted using the archived building automation system (BAS) data of an office building in Ottawa, Canada. The results of this case study indicate that inverse greybox modelling-based AOGC is a promising method to diagnose both physical and controls programming related faults at AHUs and VAVs.

Contents

1. Introduction

A survey in 2004 identified that more than 50% of the buildings in the United States with building automation systems (BAS) do not operate per their design intent [1]. Improper operating conditions in building equipment and components are estimated to waste 30–50% of the energy use in commercial buildings [2–7]. Given that indoor climate control in commercial buildings in North America accounts for more than 15% of the secondary energy use, over 10% of the CO_2 emissions and a major driver for new energy

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infrastructure, early diagnoses of these improper operating conditions represent great potential to reduce commercial buildings' environmental and economic impact and to provide comfortable, healthy, and productive indoor environments [8,9].

During the service life of a building, some of the sensors and actuators inevitably fail; and parts of the building envelope lose its ability to resist heat, air, and moisture transfer. At least as important as these physical system and component failures, inappropriate operating setpoints and equipment schedules can result in energy waste and/or chronic discomfort conditions. Traditionally, these improper operating conditions (i.e., faults) remain invisible to the facility managers until the occupants begin to complain or a labour-intensive *retro-commissioning* is undertaken.

Automated on-going or continuous commissioning (AOGC) is a process to characterize the operation of a building through a network of sensors [10], and resolve operational problems, improve comfort, and optimize energy use [11]. The operational data from connected sensors and actuators in modern automation and control networks in commercial buildings represent great potential to employ AOGC methods. Particularly, the research conducted during IEA EBC Annexes [12–14] and ASHRAE RPs [15,16] advanced the state-of-the-art AOGC in buildings. Despite this research potential, AOGC has been seldom employed in commercial buildings [17]. As recently highlighted at the Experts Research Forum on Intelligent Buildings [18], we need scalable AOGC methods that can be used in different types of buildings without manual tuning and any extra configurations.

This paper first presents a critical review of the state-of-the-art AOGC methods in commercial buildings. The scope of the review entails studies on fault detection and diagnostics, prognostics, virtual sensing, remote auditing, and continuous health monitoring efforts on air handling units (AHU) and variable air volume (VAV) terminal units in the last 20 years. The common faults studied in the literature were identified. The diagnostic approaches taken and the characteristics of the fault-symptom datasets utilized were categorized. By looking at the distribution of the studies across these categories, research needs were identified. Subsequently, upon the literature survey findings, an inverse greybox modelling-based AOGC approach was put forward. Its advantages and limitations were demonstrated through a case study conducted using the archived BAS data of an office building in Ottawa, Canada.

Our focus in this paper is on the research conducted to diagnose and triage faults in AHU and VAV terminal units. This is due to their common usage in the North American commercial building stock, and due to the fact that the controls infrastructure deployment and programming for these pieces of equipment are custom and manual – and thus prone to human-error. Despite the large number of papers from the literature, fault diagnoses research for the mass-manufactured plant level equipment is outside the scope of this study.

2. Literature review

Identifying improper operating conditions from existing sensor networks in BASs has been vastly studied. In general, the process is executed in three consecutive stages: (1) detect, (2) isolate, and (3) triage the improper operating conditions. The first-stage deals with detecting whether or not there is an anomaly in a building's operation. The second-stage deals with isolating the sensor, actuator, equipment or controls programming issues causing the detected anomaly in operation. The faults can be grouped as hard-faults – issues in sensors, actuators, equipment – or soft-faults – issues in controls programming [19]. Hard-faults often require component replacement and manual-labour, whereas most soft-faults can be automatically corrected without human intervention (e.g., [20,21]). The process of detecting and isolating faults in tandem is defined as fault diagnosis. The third-stage deals with proposing an importance ranking of the diagnosed faults in terms of their urgency for health, productivity, comfort, and energy use [22].

Table 1 lists the AHU and VAV faults studied in the literature in the past 20 years. The vast majority of the previous research efforts have been dedicated to diagnosing physical faults in the AHUs. Only a small fraction of the studies focus on faults in the VAV terminal units and soft-faults in the VAV-AHU systems. In reality, an AHU serves many VAV thermal zones; and thus, in modern buildings, more than 90% of the sensors and actuators are distributed to individual zones [20,23,24]. This situation represents great potential for us to optimize energy use and comfort by providing indoor climates tailored for each zone's occupancy and comfort preferences [20]. However, distributed sensing also represents a major challenge; as more sensors and actuators mean a larger number of components and equipment that can fail, and need to be diagnosed and maintained. A fault-free AHU with near-optimal control sequences will keep wasting energy and/or cause discomfort, if the sensors and actuators are faulty and/or setpoints and schedules are inappropriate in the thermal zones.

Faults listed in Table 1 affect comfort and energy performance differently [22]. For example, if an AHU cooling coil valve stuck open, aside from its detrimental impact on the energy performance, it will likely cause discomfort in many thermal zones served by that AHU. On the other hand, if an AHU supply fan is scheduled to operate beyond the operating hours of a building, it will waste energy but will not affect comfort. Faults that affect comfort are inherently more visible to the operators and facility managers. And, faults that affect the comfort of many occupants are more visible than those that affect only a few occupants. In case of a malfunctioning AHU cooling coil, many complaint calls can be expected – leading into work-order requests. In case of a broken VAV terminal unit damper, the complaint calls will be fewer, and operators will likely try to mitigate this issue by a permanent override [93]. Similarly, inappropriate zone temperature and airflow setpoint choices may waste energy without causing discomfort – at least not severely enough to lead into complaint calls [94]. An example of such an inappropriate setpoint choice can be the excessive airflow from a VAV unit, while there is a perimeter heater providing an alternative means of maintaining the temperature setpoints. In addition, arguably, providing on-going commissioning services to occupied spaces (VAVs) is a bigger challenge than mechanical rooms (where AHUs are located) due to tenants' privacy concerns and interruptions to their activities. These factors underline why AOGC efforts should primarily focus on zone level systems/components and AHU components that do not affect comfort, but affect energy performance. Table 2 categorizes faults in terms of their impact on energy use, comfort, spatial impact scale, type (hard or soft faults), and their visibility to the facility managers and operators.

Fault detection methods used in the reviewed literature mostly employ residual-based approaches. The residuals are the differences between the real and the expected operating conditions. For example, for cases in which the objective is not to isolate an energy intensive fault but to merely detect it, the difference between the expected and the real energy performance of a building can be adequate [95–97]. However, it is worth noting that our focus is on studies to detect and isolate faults in tandem. The residuals can be determined through expert-rules, physical models, or data-driven models trained with the normal (i.e., non-faulty) operation data. Salsbury and Diamond [98] was one of the early studies to introduce this categorization. A fundamental challenge is to classify residuals pertaining to faulty operation correctly – which leads to too many false positives or false negatives (i.e., undetected faults) in fault detection [42]. After all, how much discrepancy between