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Energy savings from temperature setpoints and deadband: Quantifying the influence of building and system properties on savings

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HIGHLIGHTS

- We provide a systematic approach to quantify the impact of factors on energy usage.
- We study setpoints, deadbands, building size, construction, occupancy, and climate.
- We derive the HVAC optimal control parameters with respect to dynamic factors.
- We present quantification of optimal setpoints and deadbands energy usages.
- Daily optimal setpoints based on outside temperature improves energy efficiency.

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ABSTRACT

This paper provides a systematic approach for quantifying the influence of building size, construction category, climate, occupancy schedule, setpoint, and deadband on HVAC energy consumption in office buildings. Simulating the DOE reference office buildings of three sizes and three construction categories in all United States climate zones, using the EnergyPlus, we conducted several N-way ANOVA analyses to study the interrelationships between setpoints, deadbands and several building related and environment related factors. In summary, daily optimal deadband selection of 0, 1, 2, 4, 5, and 6 K would result in an average energy savings of −70.0%, −34.9%, −13.7%, 9.6%, 16.4%, and 21.2%, respectively, compared to baseline deadline of 3 K. Selecting the daily optimal setpoint in the range of 22.5 ± 1 °C, 22.5 ± 2 °C, and 22.5 ± 3 °C would result in an average savings of 7.5%, 12.7%, and 16.4%, respectively, compared to the baseline setpoint of 22.5 °C. Additionally, we found that when the outdoor temperature is within −20 to 30 °C, the optimal setpoint depends on the building size. We also observed a range of outdoor temperatures (e.g., 9–14 °C for small buildings and 8–11 °C for medium buildings) where the setpoint selection would only slightly influence the energy consumption. However, the choice of setpoints becomes very influential (up to 30% of energy savings) where the outdoor temperatures are slightly outside the mentioned ranges on either direction. The potential savings from selecting daily optimal setpoints in the range of 22.5 ± 3 °C in different climates and for small, medium and large office buildings, would lead to 10.09–37.03%, 11.43–21.01%, and 6.78–11.34% savings, respectively, depending on the climate.

1. Introduction

Commercial buildings account for about 18.9% of the energy consumption and 19.6% of the total greenhouse gas emissions in the United States [1,2]. There are several techniques that can help building stakeholders to reduce energy consumption in buildings and consequently reduce the associated greenhouse gas emissions. Among some of these techniques are advanced system operations and maintenance [3], standard and deep retrofits, and techniques that would control and manage the demand, including smart grid applications [3–5]. However, these approaches focus on the physical systems with fixed requirements. Building systems are operated to meet occupants needs which could be unique and may

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change over time. Learning the dynamic needs of occupants, in terms of services from building systems, can potentially lead to improved energy efficiency. Only a few research efforts has focused on the quantification of potential energy savings from integration of occupant needs into the control logic of building systems [6,7]. In this paper, we specifically focus on quantifying potential energy savings in Heating, Ventilation, and Air Conditioning (HVAC) systems through set point (i.e., the target temperature that HVAC system tries to maintain) and deadband (i.e., the range around the setpoint at which the system is not required to respond) adjustments as these systems account for the largest share of the energy usage and gas emissions (43% of the commercial building energy consumption) [1].

HVAC systems in buildings are primarily responsible for providing satisfactory thermal conditions and indoor air quality for building occupants. The common practice of defining operational settings for HVAC systems is to use fixed setpoints, which assume occupants have static comfort requirements. However, it is proven that humans perceive comfort in a range of environmental thermal conditions [8]. In addition, many dynamic environment related variables (e.g., weather [8]) and human related variables (e.g., acclimation [9]) effect thermal comfort and therefore, the individuals' thermal comfort ranges change over time [10–13]. Given the range of comfortable conditions for an occupant, we can potentially control a service system to provide thermal conditions in that range while minimizing the overall energy consumption [6,7]. However, there are several other factors, such as building type and size, insulation and construction materials, HVAC system operation efficiency, climate, and occupant behavior, which also influence overall building energy consumption. The amount of energy savings related to comfort-aware HVAC setpoints with respect to different factors could be used as heuristics for building stakeholders to decide on the strategy for comfort-aware and energy-efficient HVAC operations.

In this paper, we introduce a systematic approach for quantifying the effects of a number of factors on overall building energy consumption. We specifically focus on the HVAC control parameters (i.e., set points and deadband) and study how occupancy, building, and outdoor environment influence savings from optimal selection of these control parameters. We explore the optimal annual setpoints in each climate, along with quantification of their potential energy savings. In addition to the annual setpoints, we study daily optimal setpoints, as well as their relationship with outdoor temperature in different climates. In comparison with the optimal setpoints, optimal deadbands and their relationships to other factors are also studied in this paper. For our investigations, we used Department of Energy (DOE) reference commercial building models [14], which are EnergyPlus software simulation files. These models represent 70% of the commercial buildings stock in the United States. In this study, we focus on office buildings and use small, medium, and large size office buildings in three different construction categories (e.g., built after 2004, built after 1980–before 2004, and built before 1980) in all climate zones of the United States.

The paper is structured as follows. Section 2 provides a review of recent studies on the influence of temperature setpoints on building energy consumption. In Section 3, we introduce a systematic approach for identifying the influential factors on setpoint-energy consumption and we quantify the savings from annual and daily setpoint selection strategies. In Section 4, the DOE energy simulation models and simulation procedures are discussed. We present the results of our methodology in Section 5. Section 6 provides a discussion on the generalization of the results and limitations and future steps of the study. Finally, Section 7 summarizes the results and concludes the paper.

2. Literature review

HVAC system controllers often work with a negative feedback single temperature control loop [15,16]. A controller adjusts several internal variables to provide air with different flow rates, temperatures and humidity to keep the difference between thermostat readings and a setpoint in a certain range. The range around the setpoint at which no action is required from a system is called the deadband. HVAC systems, similar to any other mechanical system, require to have a non-negative deadband (any value greater or equal to 0) around the target setpoint to maintain stability. When the thermostat reading lies within the deadband range, the system only provides minimum airflow to maintain acceptable air quality (ASHRAE Standard 62.1 (Ventilation for Acceptable Indoor Air Quality) [17]). The temperature at which the system begins heating is called the heating setpoint (associated with the higher value on the deadband) and the temperature at which cooling starts is called the cooling setpoint (associated with the lower value on the deadband). Previous research efforts have tried to quantify the influence of setpoints by extending the deadband [18,19]. HVAC systems operate based on a single input/single output control logic (i.e., univariate control as opposed to bivariate control of both heating and cooling setpoints) [16]. Therefore, adjusting solely the setpoint fits to this operation logic.

A study on the influence of widening the deadband on energy consumption of medium-sized office DOE reference buildings built between 1980 and 2004 and built after 2004 was conducted by the authors in [19]. They carried out the study for 7 different cities (climate zones): Miami, Phoenix, Fresno, San Francisco, Baltimore, Chicago, and Duluth. The baseline setpoint range was 21.1 °C (heating setpoint) and 22.2 °C (cooling setpoint). The heating setpoint was extended to 17.7 °C and the cooling setpoint was extended to 30 °C. The results showed that through increasing the cooling setpoint of 22.2 °C to 25 °C, an average of 29% of the cooling energy and 27% of the total HVAC energy savings could be achieved. Their findings also pointed that an 18.3–27.8 °C temperature range could save 32% to 73% of the total HVAC energy consumption, depending on the climate. The authors also argued that the savings can be achieved through occupant involvement in control of HVAC systems [19]. The same authors in their previous studies [18] found that extending the setpoint range from 21.1–23.9 °C to 20.6–25 °C reduces between 13% and 28% HVAC energy consumption on different types of medium-sized office buildings. In another study on the large office DOE reference buildings [20], the authors showed that extending the temperature setpoints range from 21.6–22.8 °C to 20.6–23.9 °C reduced the energy consumption by 9–20% depending on the climate and time of the year. However, the influence of heating and cooling setpoints extension on actual setpoints and deadband remains unclear. In addition extending the difference between cooling and heating setpoints would always lead to energy savings. Accordingly, it is unaddressed which cooling and heating setpoints are optimal for a certain climate. Furthermore, the impact of outdoor weather on energy consumption at different setpoints were not explored in these studies.

The authors in [21] evaluated the effects of temperature setpoints and deadband on the HVAC system energy consumption and occupant thermal comfort in two cities (i.e., Copenhagen and Madrid). The setpoints ranged from 19 °C to 33 °C and the deadbands were ±1 K and ±2 K at 21 °C. The case study building was a one story, single family house with an area of 66.2 m^2 and a conditioned volume of 213 m^3. The results showed that the deadband had a significant influence on the thermal comfort as it required the occupants to adapt to a wider range of thermal environment. They also found that temperature setpoints had higher impacts