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Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings

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ABSTRACT

The thermostat setpoint range (deadband) in office buildings impacts both occupant thermal comfort and energy consumption. Zones operating within the deadband require no heating or cooling, and the terminal unit airflow volume rate may be reduced to its design minimum. Wider deadbands allow energy savings as well as lower total airflows through the terminal. The extent of such savings has not been systematically quantified. Reference models representing standard HVAC and building design practice were used to simulate the impact of thermostat setpoint ranges on annual HVAC energy consumption. Heating and cooling setpoints were varied parametrically in seven ASHRAE climate zones and in six distinct medium-sized office buildings, each representing either a new building design or a building controls retrofit. The minimum airflow volume rates through the VAV terminal units were also varied to represent both standard and best practices. The simulations are compared to empirical data from monitored buildings. Without reducing satisfaction levels, by increasing the cooling setpoint of 22.2 °C (72 °F) to 25 °C (77 °F), an average of 29% of cooling energy and 27% total HVAC energy savings are achieved. Reducing the heating setpoint of 21.1 °C (70 °F) to 20 °C (68 °F) saves an average of 34% of terminal heating energy. Further widened temperature bands achieved with fans or personal controls can result in HVAC savings in the range of 32%–73% depending on the climate. It is demonstrated that in order to fully realize energy savings from widening thermostat temperature setpoints, today's typical VAV minimum volume flow rates should be reduced.

1. Introduction

Typical office buildings equipped with overhead Variable Air Volume (VAV) systems consume large amounts of energy maintaining their occupied spaces within temperature ranges that their designers and operators consider acceptable. These thermostat setpoint ranges are often narrow, around 2 K (4 °F), even though there is little scientific evidence supporting such a range. Examination of the extensive ASHRAE RP-884 field study database has shown that indoor environments controlled to narrow temperature ranges do not result in higher occupant satisfaction than environments with wider ranges, such as 4–6 K (7–10 °F) [1–3,7,34]. Wider temperature control ranges might therefore be implemented in some climates without a reduction in the occupants' thermal comfort. We aim to demonstrate, through a parametric simulation in several climates, the magnitude of energy savings from raising cooling setpoints and lowering heating setpoints.

It is possible to possible to maintain equal levels of comfort well beyond the ranges observed in the RP-884 field study database. Personal comfort systems (PCS) can be provided to increase convective cooling of the occupant (ceiling and desk fans), radiant heating (foot warmers), and conductive heating or cooling (heated and cooled seats and workstation surfaces). Such PCS systems can be extremely energy efficient while providing high levels of thermal comfort and satisfaction in a wide range of ambient conditions [15,19,25,33,35,38].

The primary benefit of widening the thermostat setpoint range is to lessen energy consumption by the building's HVAC system. This occurs as a result of zones spending more hours within the wider range without need for cooling or activating terminal heating coils. The throttling range of the VAV air flow volume is a key factor dictating how much time is spent inside the thermostat setpoint range. If a terminal unit cannot reduce its volume low enough during periods of low internal heat loads, it delivers excessive cool air from the central system and pushes the zone temperature down, often to the heating setpoint. This behavior restricts the

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potential for energy savings from widening thermostat setpoints. The minimum volume setpoint is often specified by HVAC designers according to longstanding rules of thumb. These concern the diffuser's ability to mix cold supply air with room air, the terminal unit's ability to accurately control itself, or for the system to meet minimum ventilation requirements. Such rules have recently been challenged and largely disproven [1,12,20–22,31].

Changing thermostat setpoints, rescheduling VAV terminal minimum flow rates, and providing personal control systems are the key measures in realizing both occupant comfort and energy savings. Each of them can be implemented in existing buildings without any upgrade to their HVAC hardware. This widespread retrofit potential has huge societal energy saving potential.

In this paper, a portion of the simulations are dedicated to demonstrating the potential in existing building retrofits, using an established reference model representing buildings constructed after 1980. In these simulations the HVAC sizing and design are fixed independently of the changes in operation. We also simulate the case for new construction using an established new-building reference model, whose HVAC equipment is resized according to the load requirements of widened temperature setpoint ranges. Further simulations demonstrate the relationships between the temperature setpoint range and VAV minimum flow setpoint fractions.

2. Methods

The whole-building energy and simulations were carried out with *EnergyPlus* version 7.2, software well suited for modeling VAV systems [39]. Reference models created by the U.S. Department of Energy (DOE) [8] are used to represent realistic engineering practices and to simplify the assumptions made in the simulation study. By using these reference models, targeting medium-sized office buildings, and varying control setpoints parametrically we aim to achieve a high level of generality without creating a large number of energy models. In this study we target three domains of analysis using the Medium Office DOE reference model: (1) new construction in which each of the simulated zone heating and cooling setpoints is designed with appropriately sized HVAC equipment, (2) existing buildings constructed in or after 1980 in which only the zone setpoints are altered, and (3) existing buildings as in (2) in which the zone setpoints and maximum VAV terminal flowrates are altered as part of a low-cost controls retrofit. The base case setpoint range is 21.1–22.2 °C (70–72 °F). This base case was chosen to represent the most restrictive setpoint range that is commonly used in practice, rather than the most common practice. By starting with a restrictive case and widening the setpoint range parametrically, savings relative to wider setpoint ranges can be estimated. The simulations and analysis were carried out for 7 cities, each representative of an ASHRAE climate zone. The cities and respective climate zones are Miami (1A), Phoenix (2B), Fresno (3B), San Francisco (3C), Baltimore (4A), Chicago (5A), and Duluth (7). The DOE reference buildings are tailored specifically for each of these climates. For example, the economizer settings differ in each climate, and the Miami climate model does not have an economizer. The Miami climate model is the only model with a central cooling coil. Other possible differences between models in each climate include insulation thickness, window U-factors and solar heat-gain coefficients, and economic models.

Upon execution of each simulation, EnergyPlus performs a detailed load calculation in order to size central and terminal equipment (e.g. the nominal capacity of central heating coils and nominal airflow capacity of VAV terminal units) as well as to fix control variables (such as the maximum VAV terminal flow rate) that determine how the equipment is operated during the simulation. This process is known as autosizing. In Case (1) above, all equipment is autosized, representing a building that is designed according to specific heating and cooling setpoints. In order to represent Case (2), we fixed the sizing results yielded from the base case where the setpoint range is 21.1–22.2 °C (70–72 °F), and altered only the heating and cooling setpoints in the remaining simulations. In Case (3), the sizing results from the nominal case are held fixed, with the exception of VAV terminal maximum air flow rates, which are autosized. This assumption represents the ability to reduce maximum airflow settings in VAV terminals without any hardware modifications.

Recent research has discovered that the VAV minimum volume setpoint (MVS) is a highly significant factor in determining a VAV system's overall energy consumption [9,29,30] and the savings of thermostat setpoint adjustments [1]. A rule of thumb in engineering practice is to specify the MVS as a fraction of the VAV unit's maximum flow capacity. The DOE medium office reference models use 30% for the MVS Fraction (MVSF). This reflects average engineering practices [32], while values as high as 50% are common [1,9]. Flow rates at this level provide a significant amount of cooling, in effect continuing to cool the zone well below the cooling setpoint and often below the heating setpoint despite high outside air temperatures. The phenomenon known as overcooling is caused, with significant energy and health impacts [1,23].

Restricting the MVSF restricts the energy savings that can be realized by increasing the cooling setpoint and/or decreasing the heating setpoint, because less time is spent in the region between the setpoints (the deadband) where air is supplied at the minimum volume. Thus we repeated the simulations representing the three Cases above, changing only the VAV MVSs to 10%. Earlier research has shown that VAV MVSs can be reduced to approximately 10% (or less), and still provide adequate mixing and fresh air [1]. Ideally the volume minimum at a given time is not driven by MVS but directly calculated from outside air requirements using ASHRAE Standard 62.1-2010 procedures [5]. In simulating these cases at 10%, we aim to demonstrate two things: the energy savings potential of reducing the VAV MVS, and the impact of the VAV MVS on energy savings when implementing a wider thermostat setpoint range. The final list of model and simulation types is shown in Table 1.

The post-1980 and new construction DOE reference building models adhere to ASHRAE Standards 90.1-1989 and 90.1-2004 respectively [8], and are identical with few exceptions. Depending on the climate, these exceptions include fan and DX coil efficiency, lighting loads, envelope insulation thickness, glazing U-values, and/or infiltration rates. The properties and diagrams below are common to both vintages and all climates.

The HVAC system is VAV with terminal electric reheat coils. There are three floors with one packaged air handling unit per floor, each containing a direct expansion (DX) coil, a gas heating coil, and a variable volume supply fan. The building model is a typical 5-zone floor plate, with a large interior zone and perimeter zones with depth 4.57 m (15 ft). Equipment loads peak at 10.8 W/m^2 (1 W/ft^2),

Table 1
Model type summary.

Model type	VAV MVS fraction	Vintage	VAV capacity sizing
High-New-VAVAuto (1)	High (30%)	New construction	Yes
High-Existing-VAVAuto (2)	High (30%)	Post-1980 construction	Yes
High-Existing-VAVFixed (3)	High (30%)	Post-1980 construction	No
Low-New-VAVAuto (4)	Low (10%)	New construction	Yes
Low-Existing-VAVAuto (5)	Low (10%)	Post-1980 construction	Yes
Low-Existing-VAVFixed (6)	Low (10%)	Post-1980 construction	No