Title

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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.

Highlights

- Using standard medium office building prototypes, we model the energy impact of the thermostat setpoint range
- We examine the results in seven climate zones
- The minimum airflow volume of Variable Air Volume boxes is a key parameter impacting energy consumption and occupant comfort
- Results are compared to previous empirical and simulated data.

Keywords

Thermal comfort, Thermostats, Variable Air Volume (VAV) systems, EnergyPlus simulations

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 2K (4°F), even though there is little scientific evidence supporting such a range.

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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 4–6K (7–10°F) [1, 2, 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 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, 21, 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 [6]. 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 2.1.

Table 2.1 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

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), and occupancy at 18.6 m^2/person (200 ft^2/person). Ribbon windows span the length of the façade, with a window-to-wall ratio of 33%.

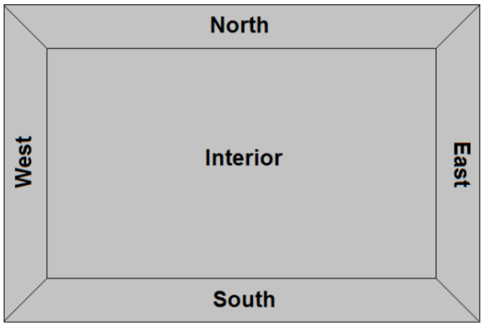


Figure 2.1 Plan view of the reference model

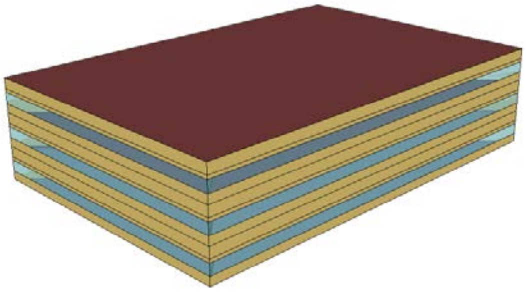


Figure 2.2 Isometric view of the reference model

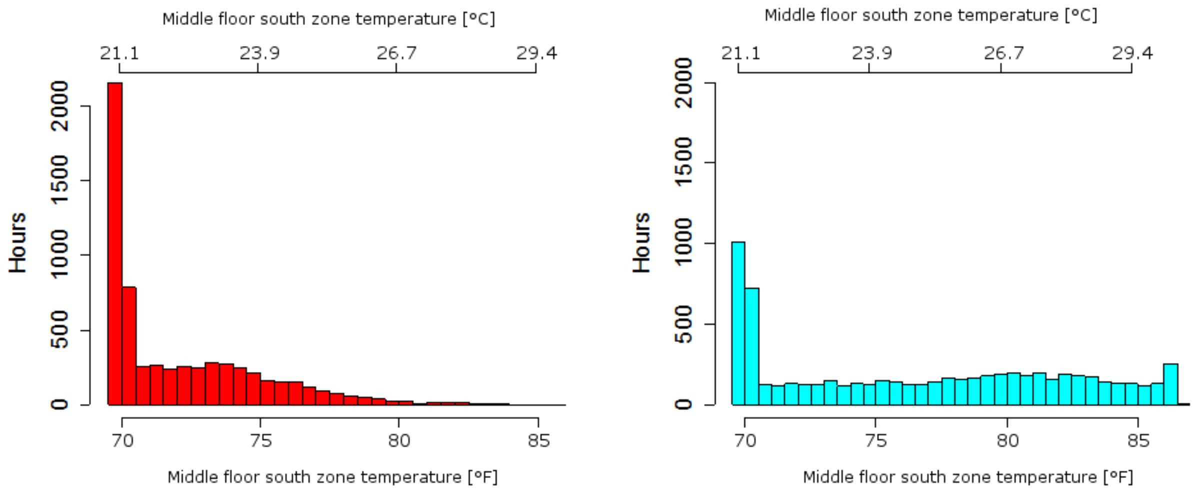
The simulations consider increasing the cooling setpoint and decreasing the heating setpoint independently. In other words, the heating setpoint is fixed at the nominal value of 21.1°C (70°F) while the cooling setpoint is varied in the range of 22.2–26.7°C (72–80°F). Similarly, the cooling setpoint is fixed at 22.2°C (72°F) while the heating setpoint is varied in the range of 17.8–21.1°C (64–70°F). Note that the heating setpoint can affect the behavior of the cooling system and vice versa.

To carry out the parametric simulations, the software *JEPlus* was used [36]. This software allows the user to parameterize fields in an *EnergyPlus* model and specify a discrete set of values for these fields. Upon execution, the set of values will supply the parameterized fields in the model, and the simulations are automated [37]. In our case, the heating and cooling setpoints during occupied hours are parameterized in the reference models for each climate. Summary results were collected and hourly results stored for detailed zone temperature analysis. A total of 1,638 simulations were carried out comprising 7 climates, 6 model types, and 39 distinct setpoint combinations (including 29 cooling setpoints, 11 heating setpoints, and 1 baseline combination).

A smaller set of simulations were carried out to examine whether independent heating and cooling savings calculated in the large parametric are additive. 7 distinct temperature setpoint ranges were considered in this analysis: 20.6–23.3°C (69–74°F), 20.0–24.4°C (68–76°F), 19.4–25.6°C (67–78°F), 18.9–26.7°C (66–80°F), 18.3–27.8°C (65–82°F), 17.8–28.9°C (64–84°F), and 17.2–30.0°C (63–86°F). As in the main analysis, these simulations are carried out for 7 climates and 6 model types, totaling 294 simulations.

3 Results

In model type 3, High-Existing-VAVFixed, changes to the cooling setpoints resulted in a distinct lack of energy savings compared to the other model types. In this model type no changes are made to the VAV system as the setpoint is increased, preserving the design minimum and maximum flow rates according to the baseline setpoint range. The savings are thus constrained by the high rate of consumption occurring while the VAV units operate at minimum volume. The cooling delivered by the minimum air volume will prevent the zone temperature from reaching the cooling setpoint.



High VAV Minimum Volume (30%)

Low VAV Minimum Volume (10%)

Figure 3.1 Middle floor south zone air temperature histograms for high (L) and low (R) VAV minimum setpoints

Figure 3.1 shows the behavior of this model type in Chicago for a very large thermostat setpoint range of 21.1–30°C (70–86°F). The left histogram represents the zone temperature distribution during occupied hours for a middle-floor south-facing zone with a 30% minimum flow rate. The first two bins show that more than half of annual occupied hours are spent at the heating set point of 21.1°C (70°F), indicating that this condition is often caused by unnecessary cooling. Conversely, in the low VAV minimum case, the zone temperature varies freely according to the internal load and climate conditions. The cooling delivered in the high VAV minimum case prevents the zone temperature from staying inside the widened setpoint range, thus requiring constant reheat and not saving energy as a result.

In Figure 3.2, the HVAC energy savings in the Chicago climate for three model types and eleven setpoint combinations for the annual simulations are shown. Each group has Cooling Setpoint (CSP), Heating Setpoint (HSP), and Baseline simulation results. In the HSP simulations, the CSP is held constant, and vice versa. The chart shows two phenomena: (1) as the CSP increases, there may be a tradeoff between terminal heating and central heating. This tradeoff is desirable when more heating is accomplished by the central coil in this case, because the central heating coil's hot water is supplied cheaply by a gas-fired boiler, whereas the terminal heating coils are electric. (2) Raising the CSP in the High-Existing-VAVFixed case has little or no effect on the energy consumption. As described above, there are little or no cooling energy savings, because the zones do not reach the cooling setpoint due to high flowrates and oversized VAV boxes. Other model types may exhibit some overcooling, but still exhibit energy savings as the setpoint range is widened.

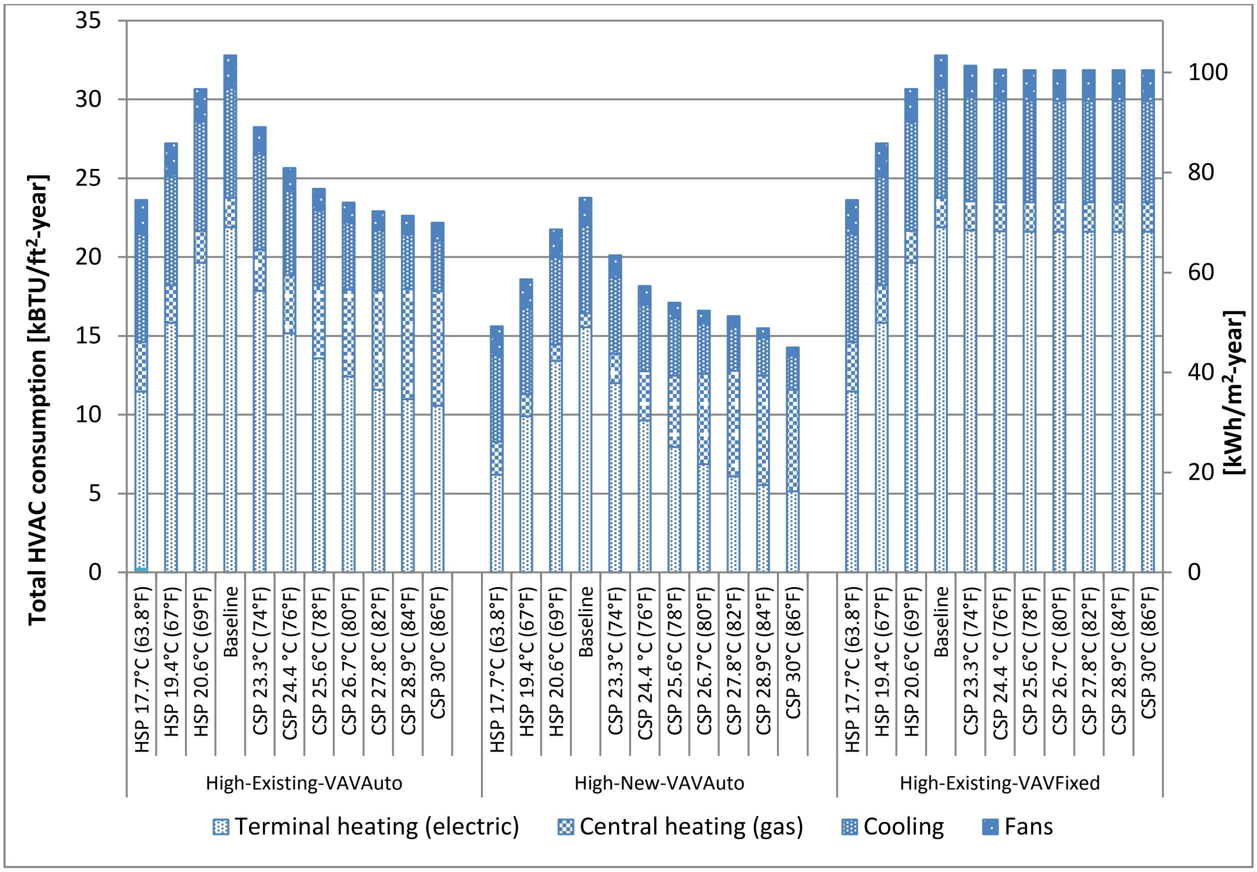


Figure 3.2 Total HVAC energy savings for three model types in the Chicago climate, compared to baseline energy consumption with setpoint range 21.1-22.2°C (70-72°F).

The average cooling savings as the cooling setpoint is increased is shown in Figure 3.3. This shows the problematic nature of the High-Existing-VAVFixed model type.

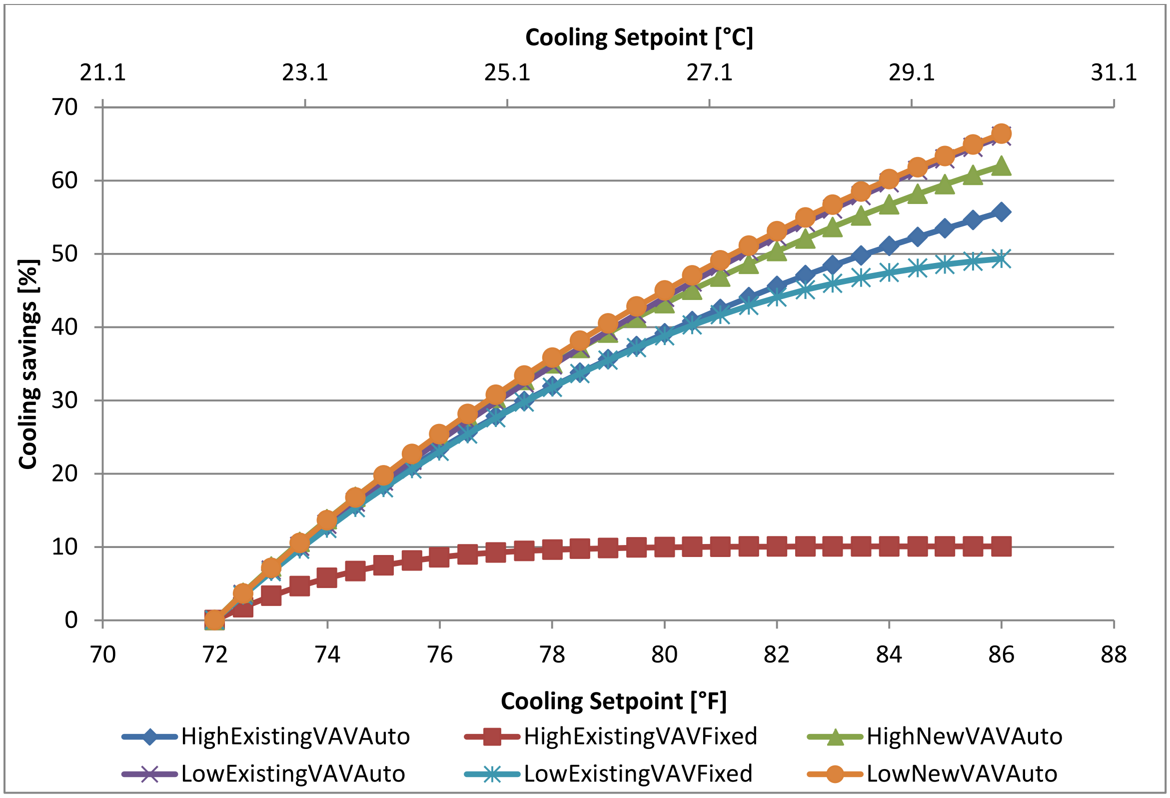


Figure 3.3 Average cooling HVAC energy savings from increased cooling setpoint relative to consumption with cooling setpoint of 22.2°C (72°F). Averages include seven climates. By increasing the cooling setpoint to 25°C (77°F), an average cooling savings of 29% is achieved.

The effect of energy savings being constrained by high VAV minimums is not present in simulations in which the heating setpoint is decreased while the cooling setpoint is held constant. The proportions of terminal heating savings are shown in Figure 3.4, and are comparable for all model types. Note that the heating consumption is markedly less sensitive to the VAV sizing. The results of the VAVAuto and corresponding VAVFixed model types were virtually identical, so the VAVFixed types were omitted from the chart for readability. Because heating energy consumption is not sensitive to the VAV minimum setpoint, changes to the heating setpoint for purposes of energy savings may be implemented without major changes to VAV operation. However, implementing lower VAV minimum volume setpoints may save heating energy without modifying heating setpoints [1].

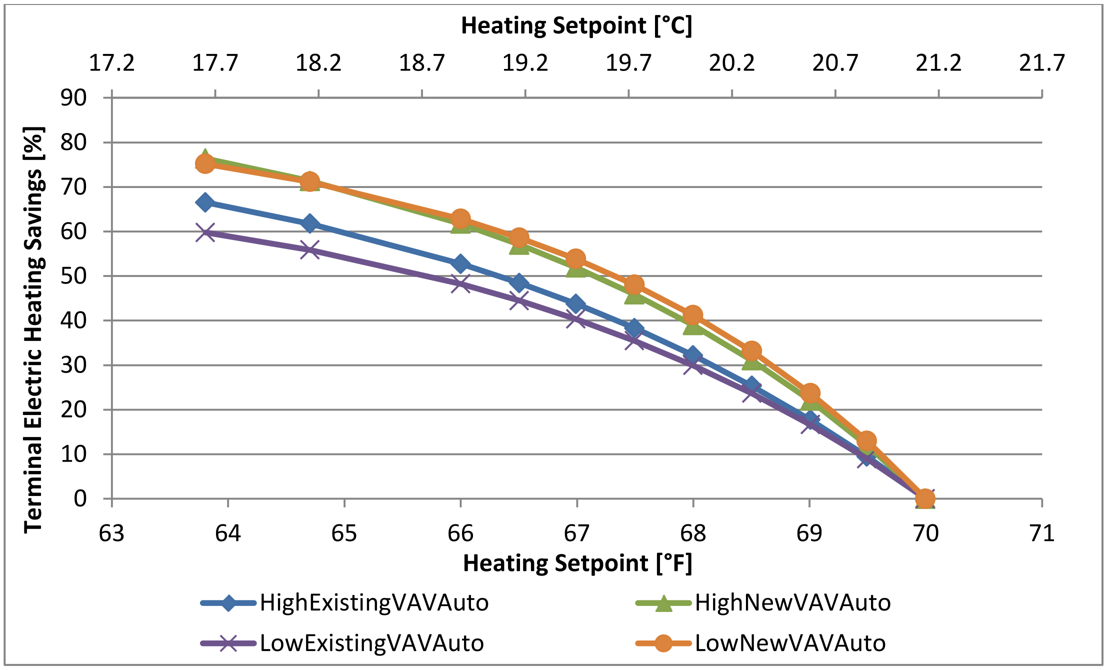


Figure 3.4 Average terminal heating HVAC energy savings from decreased heating setpoints relative to consumption with heating setpoint of 21.1°C (70°F). Averages include seven climates. Reducing the heating setpoint of 21.1°C (70°F) to 20°C (68°F) saves an average of 34% of terminal heating energy.

In the subsequent analysis and aggregates, we will omit the High-Existing-VAVFixed model type since it exhibits the problematic behavior illustrated above. For each setpoint, 35 simulation results in 7 climates and 5 model types were averaged to create the summaries for heating and cooling energy savings in Table 3.1 and Table 3.2.

Table 3.1 Total HVAC energy savings summary averaged over 7 climates and 5 model types when varying cooling setpoints.

	HVAC Savings [kWh/m^2-year ($kBTU/ft^2$-year)]			**HVAC Savings [%]**		
Cooling Setpoint [°C (°F)]	**Mean**	**Maximum**	**Minimum**	**Mean**	**Maximum**	**Minimum**
22.2 (72)	Baseline					
23.3 (74)	8.8 (2.8)	16.4 (5.2)	0.8 (0.25)	13	26	1
24.4 (76)	15.6 (4.9)	27.8 (8.8)	1.4 (0.45)	23	45	1
25.6 (78)	20.7 (6.6)	36.3 (11.5)	2.3 (0.73)	31	58	2
26.7 (80)	24.7 (7.8)	42.8 (13.6)	3.1 (0.98)	37	66	3
27.8 (82)	27.8 (8.8)	47.8 (15.1)	3.7 (1.2)	42	70	4
28.9 (84)	30.3	51.7 (16.4)	4.0 (1.3)	46	73	4

	(9.6)					
30.0 (86)	32.7 (10.4)	57.0 (18.1)	4.2 (1.3)	50	77	4

The maximum HVAC cooling savings as a result of increasing the cooling setpoint occurred in the hot Miami climate, while the minimum occurred in the cold Duluth climate. The magnitude of the temperature difference between the indoor environmental control conditions and the outside air conditions is high during Miami's summer. The largest heating savings occurred in San Francisco, and the smallest in Miami.

Table 3.2 Total HVAC energy savings summary averaged over 7 climates and 5 model types when varying heating setpoints.

	HVAC Savings [kWh/m^2-year (kBTU/ft^2-year)]			**HVAC Savings [%]**		
Heating Setpoint [°C (°F)]	**Mean**	**Maximum**	**Minimum**	**Mean**	**Maximum**	**Minimum**
21.1 (70.0)	Baseline					
20.6 (69.0)	3.5 (1.1)	8.1 (2.6)	0.13 (0.04)	5	15	0.2
20.0 (68.0)	6.5 (2.1)	15.3 (4.9)	0.22 (0.07)	10	29	0.4
19.4 (67.0)	8.9 (2.8)	21.2 (6.7)	0.25 (0.08)	13	40	0.4
18.9 (66.0)	10.9 (3.4)	25.8 (8.2)	0.25 (0.08)	16	48	0.5
18.2 (64.7)	12.8 (4.1)	30.3 (9.6)	0.28 (0.09)	19	57	0.5
17.7 (63.8)	13.9 (4.4)	32.5 (10.3)	0.28 (0.09)	21	61	0.5

Figure 3.5 summarizes the average HVAC energy savings over five model types for this study. On the right hand side of the chart, the heating setpoint is held fixed at 21.1°C (70°F) while the x-axis represents the cooling setpoint. On the left hand side of the chart, the cooling setpoint is fixed at 22.2°C (72°F), while the x-axis represents the heating setpoint.

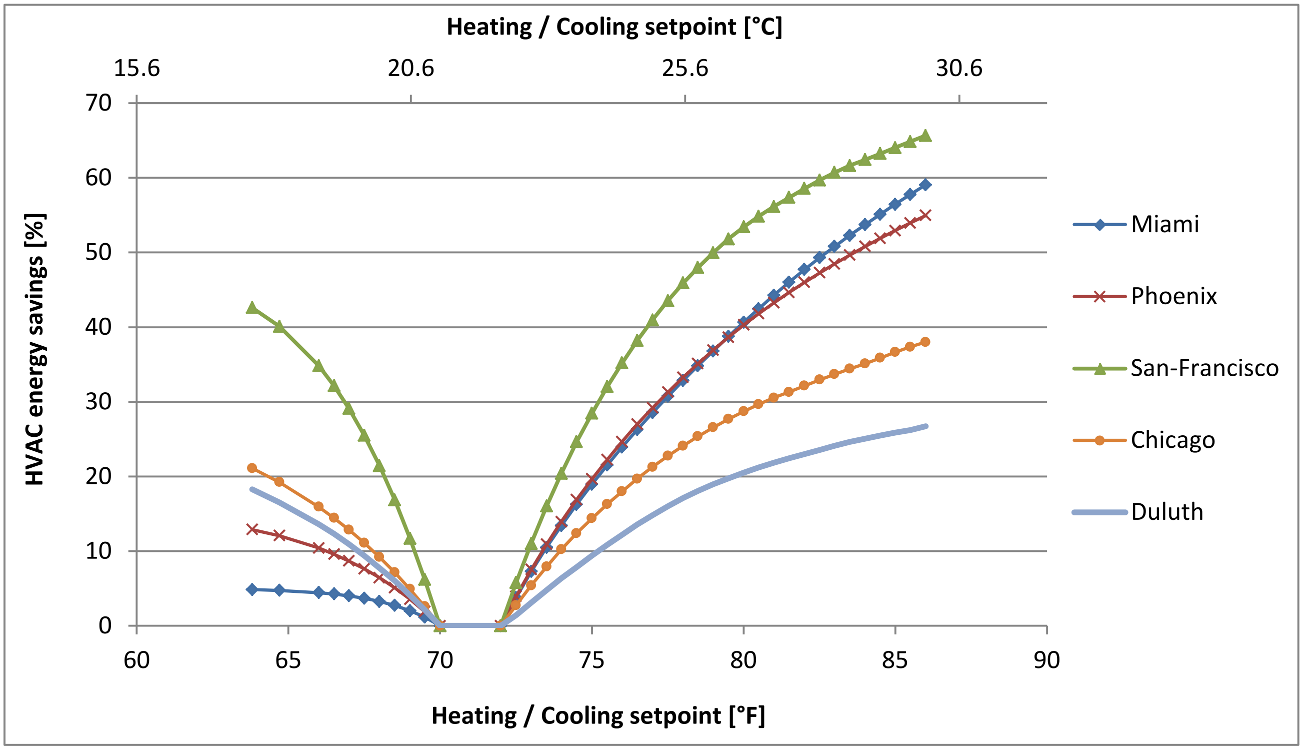


Figure 3.5 Summary of average HVAC energy savings over the five model types (excluding High-Existing-VAVFixed), compared to baseline.

Since most of the savings from lowering the heating setpoint are heating energy savings, and most of the energy savings from raising the cooling setpoint are cooling energy savings, the total savings of modifying both setpoints can usually be estimated by simply adding the savings respectively. To examine this, we carried out a set of simulations in which both setpoints were modified, and then compared the results to the baseline case. Figure 3.6 shows the energy simulation results averaged over the five model types when compared to the baseline calculated in the parametric part of the study.

Note that in all climates except San Francisco, the HVAC savings reported in Figure 3.5 from raising the cooling setpoint can be added to the HVAC savings from lowering the setpoint to produce an upper bound estimate and approximate the cumulative effect of simultaneously widening the setpoints. In the case of San Francisco where reheat is a substantial fraction of the total HVAC energy consumption, the cooling setpoint strongly influences the reheat energy use. Because of this, adding the independent heating and cooling energy savings overestimates the total savings greatly. This overestimate also occurs in the other climates to a lesser degree, but the method still produces valid first-order estimates.

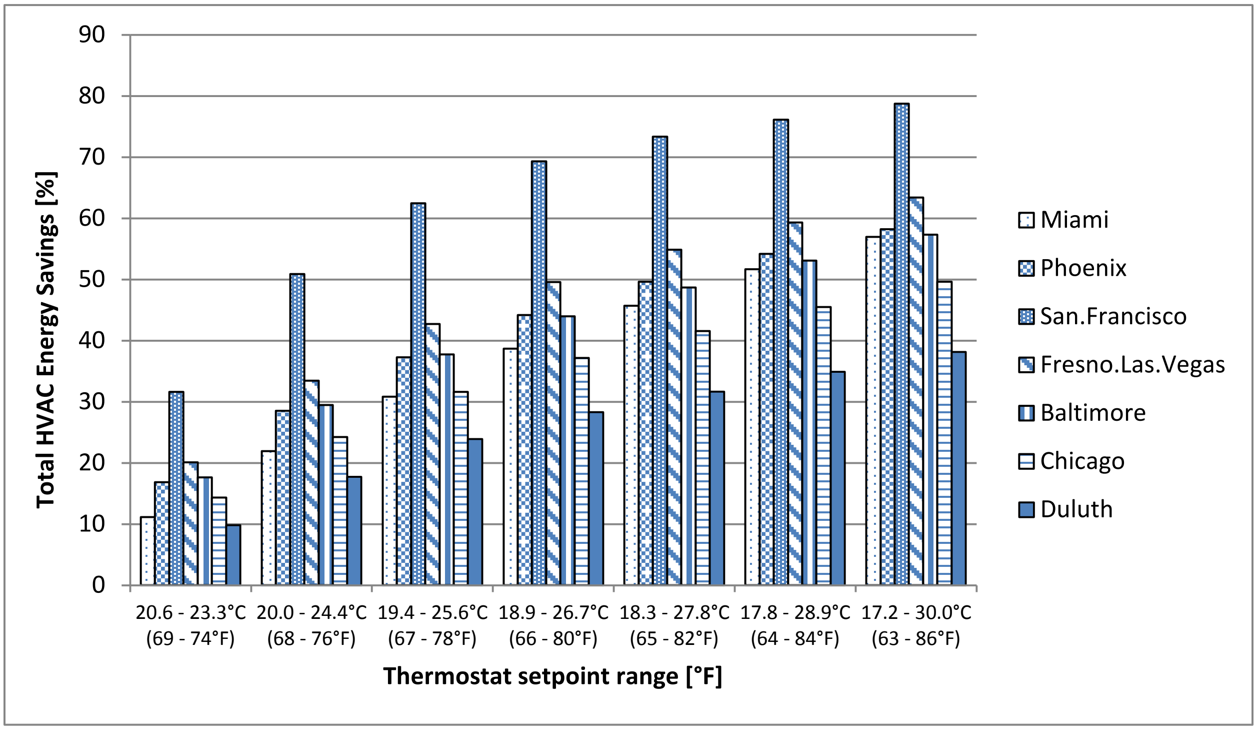


Figure 3.6 HVAC Energy savings for seven widened setpoint ranges in seven climates averaged over the five model types (excluding High-Existing-VAVFixed), compared to baseline. A range of 18.3–27.8°C (65–82°F) saves 32%–73%.

The baselines listed in Table 3.3 can be used to make HVAC energy savings estimates according to a baseline thermostat setpoint range not used in this study. While our baseline range is 21.1–22.2°C (70–72°F), a different baseline and subsequent estimates for energy savings resulting from widened thermostat setpoint ranges can be estimated. First, calculate an adjusted baseline by starting with the original baseline and adjusting it according to the energy savings found in Table 3.1 and Table 3.2. Second, calculate the energy consumption of the case with a widened thermostat setpoint range with the same tables. The energy savings relative to the adjusted baseline can then be computed.

Table 3.3 also contains a summary of the effect of High and Low VAV minimum fractions on HVAC energy consumption. Low VAV minimums help avoid overcooling, afford greater controllability of zone air temperatures, and reduce fan, heating, and cooling energy [1]. The change from high to low VAV minimums results in an average of 31% HVAC energy savings over seven climates and the three high/low pairs of model types.

Table 3.3 Baseline HVAC consumption, thermostat setpoint range 21.1-22.2°C (70-72°F) (* Total HVAC energy consumption [kWh/m^2-year (kBTU/ft^2-year)]. VAV Min High: VAV terminals have 30% minimums. VAV Min Low: VAV terminals have 10% minimums). Over the three pairs of model types, average HVAC energy savings from reducing the VAV minimum is 31%.

	Existing VAVAuto			**Existing VAVFixed**			**New VAVAuto**		
Climate	**VAV Min High ***	**VAV Min Low ***	**VAV Change HVAC Savings [%]**	**VAV Min High ***	**VAV Min Low ***	**VAV Change HVAC Savings [%]**	**VAV Min High ***	**VAV Min Low ***	**VAV Change HVAC Savings [%]**
Baltimore	66.2 (21.0)	48.9 (15.5)	26	92.7 (29.4)	58.4 (18.5)	37	48.9 (15.5)	36.3 (11.5)	26
Chicago	78.5 (24.9)	60.9 (19.3)	22	100.6 (31.9)	72.6 (23)	28	55.2 (17.5)	41.3 (13.1)	25
Duluth	106.3 (33.7)	84.2 (26.7)	21	124 (39.3)	99.1 (31.4)	20	77.6 (24.6)	59.0 (18.7)	24
Fresno	53.6 (17.0)	40.1 (12.7)	25	77.6 (24.6)	44.8 (14.2)	42	32.8 (10.4)	25.6 (8.1)	23
Miami	67.2 (21.3)	58.4 (18.5)	13	85.2 (27.0)	60.3 (19.1)	29	66.9 (21.2)	42.0 (13.3)	37
Phoenix	65 (20.6)	54.6 (17.3)	16	85.8 (27.2)	56.8 (18)	34	73.5 (23.3)	40.4 (12.8)	45
San Francisco	28.5 (9.02)	15.8 (5.01)	44	53.9 (17.1)	19.1 (6.06)	65	24.5 (7.77)	12.5 (3.95)	49
Average	66.5 (21.1)	51.8 (16.4)	24	88.5 (28.1)	58.7 (18.6)	36	54.2 (17.2)	36.7 (11.6)	32

4 Discussion

4.1 Empirical Corroboration

The high terminal airflow rates and overcooling in these simulations are corroborated by recent empirical data collected at a seven-building office campus in Sunnyvale California during the ASHRAE-1515 study. A field study of the energy impact and indoor environmental effects of the MVSF was carried out in several buildings, in which periods of low and high MVSF settings were examined. The study shows that lowering the MVSF from 30% to a setting around 10% that delivered the minimum required ventilation, saved 15–38% of cooling and fan energy, and an average of 12% of heating energy [1].

We compare this with a representative south-facing perimeter zone in the Chicago climate with a VAV reheat terminal and a thermostat setpoint range of 21.1–22.2°C (70°F–72°F). During the High MVSF period, the VAV terminal has a maximum of 0.94 m^3/s (2,000 cfm) and a minimum flow rate of 0.28 m^3/s (600 cfm) or 30%. During the low MVSF period, the minimum flow rate was changed to 0.18 m^3/s (385 cfm) or 19%. These periods are compared respectively to the high and low MVSF simulations. In a middle floor south zone of the simulation model, the maximum flow rate is 1.01 m^3/s (2130 cfm), the minimum flow rate is 0.30 m^3/s (639 cfm) (30%) in the high minimum case, and 0.10 m^3/s (213 cfm) (10%) in the low minimum case. All simulated data represents annual hourly data. Empirical data collected at the ASHRAE RP-1515 site is in fifteen-minute intervals, collected in several month-long periods from November 2010 to August 2012. The thermostat setpoint range in this zone is also 21.1–22.2°C (70–72°F).

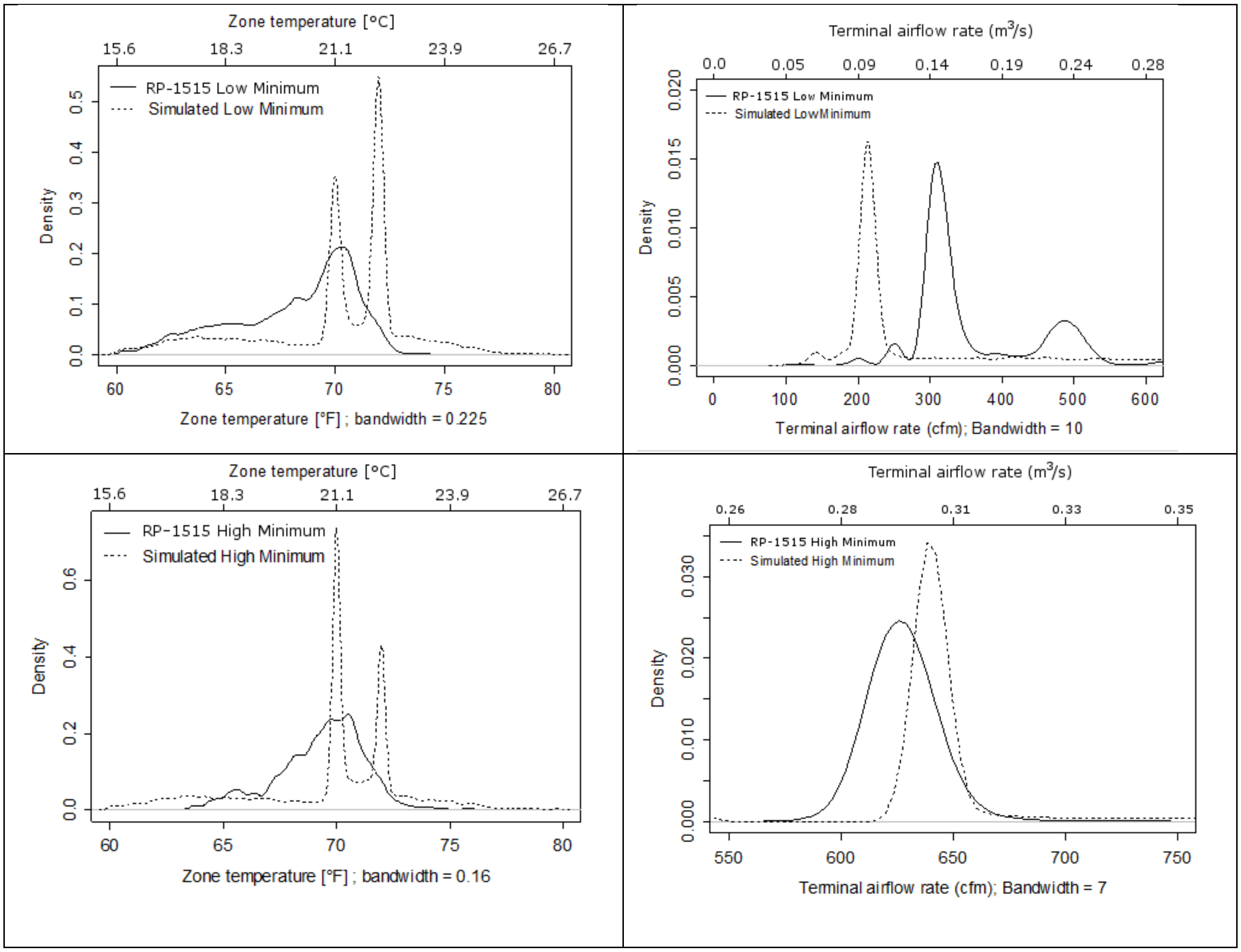


Figure 4.1 Hourly simulated data compared with fifteen-minute empirical data collected during a field study concerning the energy and comfort implications of lowered VAV minimum volume setpoints.

In both simulated and empirical data for a high minimum flow mode, the zone airflow remained at or very close to the minimum setpoint. This suggests that the minimum flow is often exceeding that needed for cooling the space, and often continues to cool the space to the heating setpoint, which in turn activates the terminal reheat coils. In the simulated high minimum case, the zone spends almost 70% of hours at the heating setpoint, which suggests that overcooling occurs in the simulation with great frequency. The low minimum simulated case shows much less time being spent at the heating setpoint due to overcooling, and modulates the flow rate to meet the load as necessary.

In the zone from the RP-1515 study, the zone temperature remains close to the heating setpoint of 21.1°C (70°F) for the majority of the observed periods in both the high and low minimum cases. In the high minimum case, this occurs despite the fact that the terminal airflow rate is always at its minimum. This suggests that all cooling in this zone is accomplished by the minimum airflow rate, and effectively overcooling the space when the cooling load is not large and the terminal heating coil is not active. In the low minimum case, a similar phenomenon occurs to a lesser extent. There is some raised airflow in the range of 0.24 m^3/s (500 cfm) which is the zone requiring a higher airflow rate to meet a larger cooling load.

4.2 Comparison to other simulation studies

A simulation study of energy-saving measures in large office buildings carried out by Pacific Northwest National Labs examined the energy impact of a widened thermostat setpoint range [11]. In a similar fashion, this study used the DOE large office baseline models, which are similar to the medium office building models used in this study. A baseline setpoint range of 21.6–22.8°C (71–73°F) was used. Widening this baseline range by 1.1K (2°F) on each side, a simulation using a setpoint range of 20.6–23.9°C (69–75°F) was carried out. The resulting energy savings are reported to be in the range of 12–20%, except for the cold Fairbanks Alaska climate, where 9% was saved. Notably, the large bulk of the total energy savings are heating energy savings. Small cooling energy savings (~0–4%) are reported for all climates and both vintages of the large office model. As we discovered in our study, this apparent lack of efficacy of raised cooling setpoints for saving energy is in fact caused by the phenomenon of overcooling. The large office model terminal units are simulated with an extremely high VAV minimum flow fraction of 50%, which will cause a great deal of overcooling and excess reheat.

A similar simulation study was done by the authors with a smaller scope [12]. This study used a custom medium office model very similar to the DOE medium office benchmark model. The model was designed to represent good practice in modern HVAC design. The results of the parametric study are comparable to the results of this study. The baseline thermostat setpoint range was larger, which requires a different interpretation of the results.

A comparison of the results of this study, the PNNL study, and the previous study are shown in Table 4.1. We only present one adjusted thermostat setpoint range from each study, since the PNNL study only tested one adjusted setpoint range.

Table 4.1 A comparison summary of this work with a PNNL study of energy efficient building retrofits, and a previous simulation study.

Building Model Type	Vintages	VAV Minimum Volume Setpoint Fraction [%]	Baseline Thermostat Setpoint Range	Adjusted Thermostat Setpoint Range	HVAC Energy Savings [%]
DOE Large Office	Pre-1980 and Post-1980	50%	21.7–22.8°C (71–73°F)	20.6–23.9°C (69–75°F)	9–20%
DOE Medium Office	Pre-1980 and Post-1980	10%	21.1–22.2°C (70–72°F)	20.6–23.3°C (69–74°F)	7.5–20%
Custom Medium Office	Post-1980	30%	21.1–23.9°C (71–75°F)	20.6–25.0°C (69–77°F)	13–28%

4.3. Thermal comfort at wide range of ambient air temperature and reduced minimum flowrate

There are many field studies supporting the feasibility of the thermostat and VAV setpoint retrofits described in this paper. The ASHRAE 1515 study found that lowering the VAV minimum volume setpoints reduced complaints by 50% [1]. Laboratory and field studies have shown high acceptability at temperatures above typical cooling setpoints and below typical heating setpoints. The high acceptability can be achieved by means of general adaptability [17], operable windows [6], elevated air movement [14, 25], personal controls, or other strategies. Examples of personal controls shown to be effective include heated and cool chairs [24, 26], personal heaters [28], or personal fans [33]. Naturally ventilated buildings are found to be preferable despite operating at higher and lower indoor temperatures than a conventional HVAC building [27].

Adaptive models with wider than typical comfort zones are included in both the ASHRAE Standard-55 [4] and EN-15251 [10] thermal comfort standards. ASHRAE Standard 55 also includes a model for elevated airspeed enabling elevated temperatures with the use of ceiling fans or other sources of air movement.

Even without any additional provisions for comfort outlined above, the PMV/PPD model of thermal comfort [4, 10, 18] allows a thermostat setpoint width of about 3K (5.4°F) with a PMV range of -0.5–0.5 PMV [13]. This thermostat setpoint range is much wider than typical practice. The PMV range is defined as comfortable by ASHRAE Standard 55 [4] and Class-II compliant by EN-15251 [10].

4.4. Accounting for energy consumed by use of PCS

Where personal comfort systems are used to enable wider ranges of indoor ambient temperatures, it is important that they be intrinsically energy efficient. 1500 W heaters in each workstation could not save heating energy. The energy use of efficient PCS (under 25 W/occupant over time) is 20 to 50 times less than the per-occupant energy use of central heating and cooling systems. It is sufficiently low that it can almost be ignored in the analysis [24, 28].

5 Conclusions

In a large parametric simulation study of seven climates and six model types, we examined the benefit of widening thermostat heating and cooling setpoints to save energy in a typical medium office building.

If implemented correctly, a widened thermostat setpoint range results in significant energy savings. Hot climates will see more benefit from increased cooling setpoints, whereas cold climates see more benefit from decreased heating setpoints. Temperate climates such as San Francisco may see great benefit from a widened thermostat setpoint range. 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. A wide thermostat setpoint range such as 18.3–27.8°C (65–82°F) can save 32%–73% of HVAC energy consumption depending on the climate, and can be achieved on comfort grounds with personal controls. The benefit is cumulative, and small incremental changes to the setpoints result in proportional savings. In practice, the type of heating or cooling system will have a large impact on actual energy savings resulting from this method.

It should be noted that the energy use of efficient PCS is almost vanishingly small compared to the energy use of central systems, so it pays to use PCS to maintain comfort while expanding the range of ambient space temperatures.

When VAV boxes have adequate throttling range as a result of appropriately low minimum volume setpoints, the zone temperature will often remain within the heating and cooling setpoints, resulting in less heating and cooling required by the zone. However if the minimum volume setpoints are high, the cooling delivered by this volume will often unnecessarily cool the zone, even to the heating setpoint. This causes the costly phenomenon of overcooling and must be avoided. A field study conducted on a large corporate campus provided empirical evidence of the problem, which can be remedied by a simple change to the VAV box minimum volume setpoint.

Reducing VAV minimum flow fractions can have a large impact on HVAC energy consumption, saving an average of 31%. A large empirical study corroborates this, where cooling and fan energy savings from lowered VAV minimums ranged from 15-38%, and heating savings averaged 12%.

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7 References

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