

Drivers for the heterogeneous response of commercial buildings to temperature setpoint adjustments

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ABSTRACT

Commercial buildings offer significant potential to reduce cooling load by raising zone temperature setpoints. This is useful for demand response, avoiding blackouts during heat waves, and during normal operations to reduce costs, water usage, and emissions. In previous work experimenting with commercial buildings on the Stanford campus, it was found that building energy systems responded differently to temperature setpoint adjustments with load reductions ranging from 4 to 29 percent. This work investigates the drivers for response heterogeneity by analyzing equipment-level behavior in three of those buildings. We leverage distributed sensor data throughout the buildings to develop diagnostics for the behavior of Air Handling Units and Variable Air Volume systems. We find that the main driver for load reduction was changes in chilled water valve positions, which differs from previous experiments reported in literature. Since one possible explanation is that the HVAC equipment in this testbed implement the most recent ASHRAE standards of supply air temperature reset through logic called Trim-and-Respond, this finding suggests that new building control sequences could alter conclusions from previous DR field experiments. We also find that the interaction of ventilation and cooling requirements can impact operational energy efficiency, sometimes causing over-cooling of certain zones. In the absence of ventilation constraints, more efficient buildings are more dependable flexibility resources. This will not always be true, such as when dominant zones cause over-cooling, yet drive large load reductions observed from setpoint changes.

Introduction

Motivation and context

The US Department of Energy estimates that the buildings sector is responsible for 40% of US energy related carbon emissions and accounts for 74% of US electricity use, 35% of which comes from commercial buildings (DOE 2015). Optimizing building efficiency and utilizing buildings for Demand Response (DR) pose significant opportunities for global decarbonization and aiding the resiliency of the electric grid as it undergoes a massive transition. While new buildings are typically more energy-efficient, decarbonizing the existing commercial building stock is important because buildings are long-term investments: the median year of construction for US commercial buildings is 1982 (EIA 2021) and their lifetime is sixty-eighty years (DOE 2015). Existing buildings can have different consumption patterns than what they were initially designed for, so operational measurement tools and testing procedures are needed to better understand the energy patterns of buildings and their response to controlled perturbations.

DR services are critical as variable renewable energy penetration increases on the grid. The thermal mass of buildings is one of the most underutilized sources of DR potential (Arteconi 2012). Commercial buildings can provide several types of DR by altering the operation of their HVAC systems, which often account for more than 30 percent of their electric load (Yin et al. 2016; Motegi et al. 2007). Simulations as well as field experiments indicate significant potential for building flexibility, but that this potential varies depending on the building construction materials, design, operations, occupancy, thermal requirements, and weather conditions (Motegi et al. 2007; Hoyt, Arens, and Zhang 2015; Yin et al. 2016). To enable mass deployment of DR technologies in buildings, both an improved understanding of the full cyber-physical response of buildings and standardization of flexibility measures are needed, ultimately to build trust and reliable communication between building managers and grid operators (Kathirgamanathan et al. 2020; MacDonald, Vrettos, and Callaway 2021).

Previous work: empirical response of commercial buildings to daily cooling setpoint adjustments

In previous work (de Chalendar et al. 2022), we conducted experiments in six large office and laboratory buildings representing a total floor space of 56,000 m² in California's climate zone 4. Building-level chilled water and electricity loads, zone-level temperatures, and external weather conditions were measured continuously during the testing period. A two-degree Fahrenheit increase of the top of the zone-level temperature boundaries, or “deadbands”, resulted in a 12-29% reduction in daily building-level cooling loads on average for the four office buildings and 4-5% for the two laboratory buildings. The impact on electric loads, excluding for cooling water, but including for ventilation, was much smaller, less than 2%. Zone-level temperature impacts were measurable but within the target temperature deadbands.

There were two important empirical findings from analyzing the experiment data that were collected. First, while the impacts from the temperature setpoint adjustments were significant in all buildings, the buildings did not all respond identically to the setpoint changes nor to outside weather conditions. Second, a building's response to a set of given temperature setpoints, weather conditions and occupancy levels is uncertain, but regularly tested building HVAC systems can still be expected to provide a reliable DR resource in future energy systems, because that uncertainty can now be quantified.

These experiments confirmed the potential for energy management strategies based on zone-level temperature setpoint adjustments to significantly impact building-level energy loads. They also motivated this study, that explores the drivers for response heterogeneity by analyzing equipment-level behavior. Better understanding these drivers is critical to improving the response of tested buildings but will also be critical to build confidence in extrapolations of experimental results to untested buildings. In this study, we analyze additional equipment-level data from three of the six buildings considered in de Chalendar et al. (2022). The buildings are served by HVAC systems that rely on Air Handling Units (AHUs) and Variable Air Volume (VAV) systems, like 30% of US commercial floor space (EIA 2021). Some buildings also rely on Fan Coil Units (FCUs) but are not analyzed here.

Review of related work

HVAC flexibility: simulations, experiments and field demonstrations

To provide DR, the energy consumption of buildings must become flexible. Controllable building loads can offer services to the electric grid at different time scales while providing financial benefits for the buildings. Various HVAC flexibility strategies exist, including pre-cooling, switching off specified non-critical units, chilled water temperature changes, ventilation fan speed changes, as discussed e.g. in (Motegi et al. 2007). In this work we focus on strategies that rely on zone-level temperature setpoint adjustments which are a promising solution, because they are scalable, less invasive to lower-level equipment controls and easily interpretable. For cooling, it has been shown that these strategies can result in load reductions with moderate to low impacts to occupant comfort levels (Aghniaey and Lawrence 2018).

On the shorter time scales, significant effort has been devoted to studying inefficiencies associated with providing the DR service (MacDonald, Vrettos, and Callaway 2021). A series of experiments conducted with this goal on the University of Michigan and North Carolina State University campuses share many similar features with the ones that generated the data for this study (Keskar et al. 2020a; Keskar et al. 2020b). As in many prior field studies, the main target for these experiments is providing electrical flexibility from changes in fan power consumption. In contrast, our work reports on: 1) experiments to provide flexibility on a daily rather than hourly timescale; 2) separately considers flexibility from both the chilled water and electrical loads (excluding for cooling water); 3) benefits from even wider sensing capabilities (e.g. sensors are available in every zone, rather than in a subset); and 4) considers AHUs with more recent control logic (discussed in Background). One common conclusion with these works is that analyses of zone- and equipment-level behavior can help explain the overall response of a building to controlled perturbations, and ultimately inform improved DR strategies.

Several studies highlight discrepancies between experimental and simulation-based DR models (Yin et al. 2016, MacDonald, Vrettos, and Callaway 2021). Baseline modeling, control accuracy, the transient response of building thermal mass, and inefficiencies in real-world buildings are often cited as possible causes for discrepancies. These studies motivate further work and a deeper analysis of the drivers for the heterogeneous response of commercial buildings to temperature setpoint adjustments. Using experiments to build data-driven flexibility models of buildings captures real-world complexities of HVAC systems that simulations may not consider. Examples drawn from prior experimental works as well as ours include: 1) communication issues and bandwidth limitations in networked control systems; local, 2) user-determined, non-controllable static temperature setpoint offsets; and 3) sensitive zones excluded from the experiments, that often have especially high cooling needs and/or importance factors. When excluded zones request cooling, all zones served by the AHU may be impacted, which can cause inefficiencies through increased reheat energy (Hoyt, Arens, and Zhang 2015).

Impact of zone-level minimum air flow setpoints

The competition between ventilation and cooling requirements can limit controllability of building energy consumption. Higher than required air flows can cause over-cooling and wasted fan, cooling, and reheat energy (Taylor and Stein 2004). This can arise when dominant zones drive AHU behavior while several other zones operate near the minimum air flow.

The main standards for VAV terminal units are documented in ASHRAE Standard 62.1, ASHRAE Standard 90.1, and in California Title 24 (ASHRAE 2019b, ASHRAE 2019a, CEC 2019). Practitioners often use rules of thumb for selecting minimum setpoints, e.g. 30% of the maximum cooling air flow. Since 2013, ASHRAE 90.1 states that it should be no larger than 20%. A simulation study showed that lowering minimum air flow setpoints from 30% to 10% of the air flow capacity reduced cooling, fan, and reheating energy by 29%, 27%, and 34%, respectively (Hoyt, Arens, and Zhang 2015). While some studies report that VAVs can operate successfully at only 10% of their air flow capacity, others report that VAVs cannot perform satisfactorily at reduced air flow rates. Solutions include “time-averaged ventilation” (Kaam, Raftery, Cheng, and Paliaga 2017) and demand-controlled ventilation (Zhang, Li, Lau, and Liu 2014.).

Background

Buildings, HVAC equipment and control sequences

The buildings studied in this paper are described in Table 1. Each building’s HVAC systems are comprised of multi-zone VAV/AHU systems equipped with the industry standard of rule-based control sequences (Figure 1).

Table 1. Building information: conference building, office building, and library located on the Stanford University campus, in California's climate zone 4.

Building	CONF-1	OFF-2	LIB-3
Area (kft2)	145	28	170
# Of AHUs	5	2	13
# Of VAVs	136	33	143
# Of FCUs	0	50	0
Total Zones	136	83	143

AHUs are where chilled water is used to cool a mixture of outside air and return air from the building zones. As shown in Figure 1A, the AHU economizer damper controls the fraction of air that is recirculated. The supply fan maintains the air pressure to a specified setpoint to distribute the conditioned air. The air flows through the ducts to the VAV systems where dampers control the amount of air to the zones. Optional reheat coils can be used to increase the air temperature.

Various sensors throughout the system allow feedback from the VAV units to the AHUs, weighted by zone importance factors, also called “multipliers”. The VAV units are designed to

minimize energy consumption while maintaining zone air temperature within specified temperature boundaries, and zone ventilation at or above the minimum air flow setpoint. As illustrated in Figure 1B, if the zone temperature goes above the cooling setpoint, the VAV unit generates a positive cooling demand signal, and the damper opens to allow more air flow. To maintain the duct pressure setpoint, the fan increases its speed. Therefore, the first response to satisfy cooling requirements is from the fan. If the damper reaches 90 percent open and the air flow is below its maximum setpoint, the VAV requests more air pressure from the AHU. If the damper opens such that the VAV reaches its maximum air flow setpoint, the VAV requests a lower supply air temperature from the AHU. If the zone is within the temperature deadband (Figure 1B green), the air flow will be at the minimum setpoint. If the temperature is below the heating setpoint, a cooling-only VAV will generate a heating request as shown but stay at the minimum air flow. A VAV with reheat will use heating coils by opening its reheat valve.

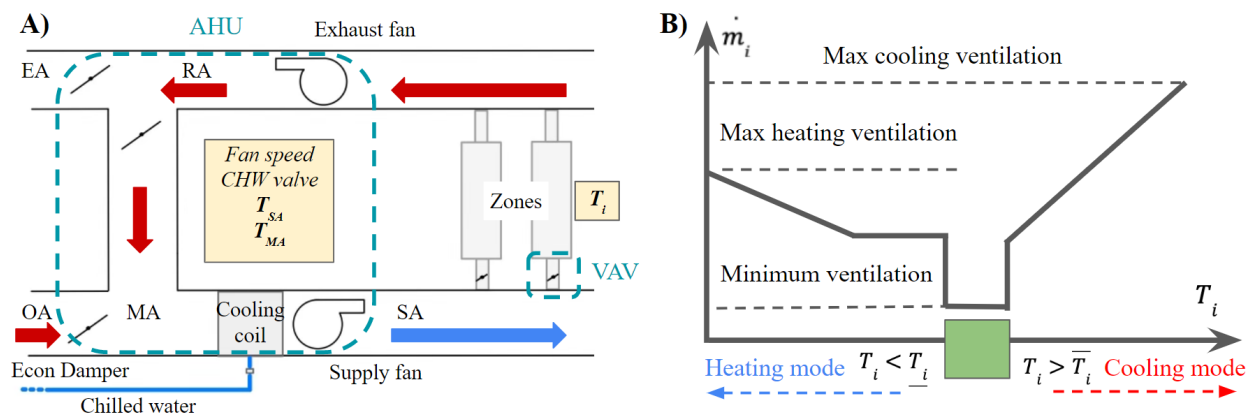


Figure 1. Multi-zone Air Handler Unit/Variable Air Volume systems (AHU/VAV). A) Schematic. OA: Outside Air, MA: Mixed Air, SA: Supply Air, RA: Return Air, EA: Exhaust Air. B) Deadband control logic for the VAV systems, adapted from ASHRAE Guideline 36-2021. The VAV has heating demand when its zone temperature T_i is below its heating setpoint $\bar{T}_i$, and cooling demand when T_i is above its cooling setpoint $\bar{T}_i$. AHU control logic uses Trim-and-Respond as described in ASHRAE Guideline 36-2021.

The AHUs in these buildings implement the most recent ASHRAE Guideline 36-2021 recommendation of Trim-and-Respond supply air temperature and pressure reset capabilities (ASHRAE 2021). If the number of cooling requests is above the Ignore-Request (IR) threshold, the AHU will incrementally lower the supply air temperature (SAT) setpoint. The chilled water valve will open to meet the setpoint. Once the cooling requests are satisfied, it will incrementally raise the SAT setpoint back towards its maximum value until there are more cooling requests. The chilled water valve will close to increase the SAT. Pressure requests are handled similarly. These building control sequences are increasingly widespread, to maximize energy efficiency while meeting ASHRAE 90.1 and Title 24 (ASHRAE 2021). We note that this does not seem to be the case for many previously reported field experiments, whether on hourly or daily timescales (Motegi et al. 2007, Keskar et al. 2020, MacDonald 2020). Details on Trim-and-Respond logic and examples can be found in (Taylor 2015).

Motivating case study

One building that was not discussed in de Chalendar et al. (2022) serves as a motivating case study for this paper, shown in Figure 2. This building was not responsive to temperature setpoint changes and illustrates the competition between ventilation and cooling requirements of zones. As seen in Figure 2A, zone temperatures were 4-6 degrees colder than their cooling setpoints on average before July 7th. Most zone temperatures remained towards their heating rather than their cooling setpoint, a signal of inefficient operation. Figure 2B shows several zones used their reheat valves. This behavior was driven by an electrical room, the “dominant zone”. This zone is served by 4 VAVs with a high importance factor in the controls logic that were constantly requesting cooling (shown in orange). Most other zones operated at minimum ventilation but were over-cooled. The AHU SAT was very frequently set by the control logic to the maximum of 65F. On July 7th (the vertical blue dashed line), the AHU's SAT was manually set to 70F. The dominant zone was also included in the experiments, to neutralize its cooling requests. Zone temperatures increased over the next two days, although the median zone temperature remained colder than required, indicating some over-cooling remains. This case study illustrates how the competition between cooling and ventilation needs in AHU/VAV systems can lead to high inefficiency and low flexibility. This building would have a very minimal ability to participate in demand response through temperature setpoint adjustments. Lower minimum air flow setpoints using dynamic calculations (ASHRAE 2021) in the over-cooled zones would result in less cooling load. A local cooling capacity upgrade might also be needed for the dominant zone. Due to the changes in HVAC settings and issues during the testing period, this building is excluded from analyses in the remainder of the paper.

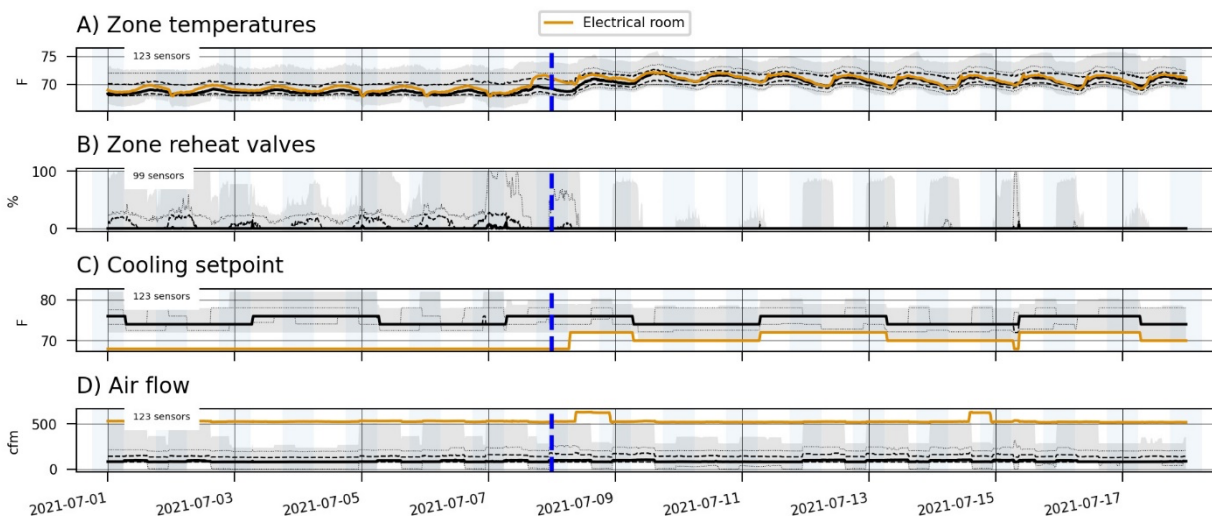


Figure 2. In each plot, the hourly median is in full black, while the 25th and 75th percentiles are dashed lines, and 5th to the 95th percentile is shaded in gray. The vertical blue line represents the date the dominant zone was included, and AHU maximum SAT was increased from 65F to 70F.

Methodology

Cooling load per AHU

Cooling load data are only available for the entire building. The measurement uses the flow rate of water through the building and the difference in temperature between the chilled water supply and return loops. To disaggregate cooling load to the AHU level, we calculate cooling load at AHU j , Q_j , using the flow rate of air in the zones and the air temperature difference across the AHU,

$$Q_j = \dot{m}_j c_{air} (T_{MAT} - T_{SAT}), \quad (1)$$

where c_{air} is the heat capacity of air, T_{MAT} is the temperature of the air before entering the AHU and T_{SAT} is the temperature of the air leaving the AHU. The air flow rate $\dot{m}_j$ through AHU j is not measured, but instead calculated as the sum of the measured zone-level air flow rates

$$\dot{m}_j = \sum_{i=1}^{N_j} \dot{m}_i \quad (2)$$

where N_j is the number of zones served by AHU j . The mass flow rate of air in zone i is

$$\dot{m}_i = \rho \dot{V}_i \quad (3)$$

where ρ is the density of air and $\dot{V}_i$ is the zone-level volumetric air flow rate. Figure 3 shows the accuracy of this method compared to each building's total cooling load calculated using the water system measurements. OFF-2 has fan coil units which are not included in this calculation.

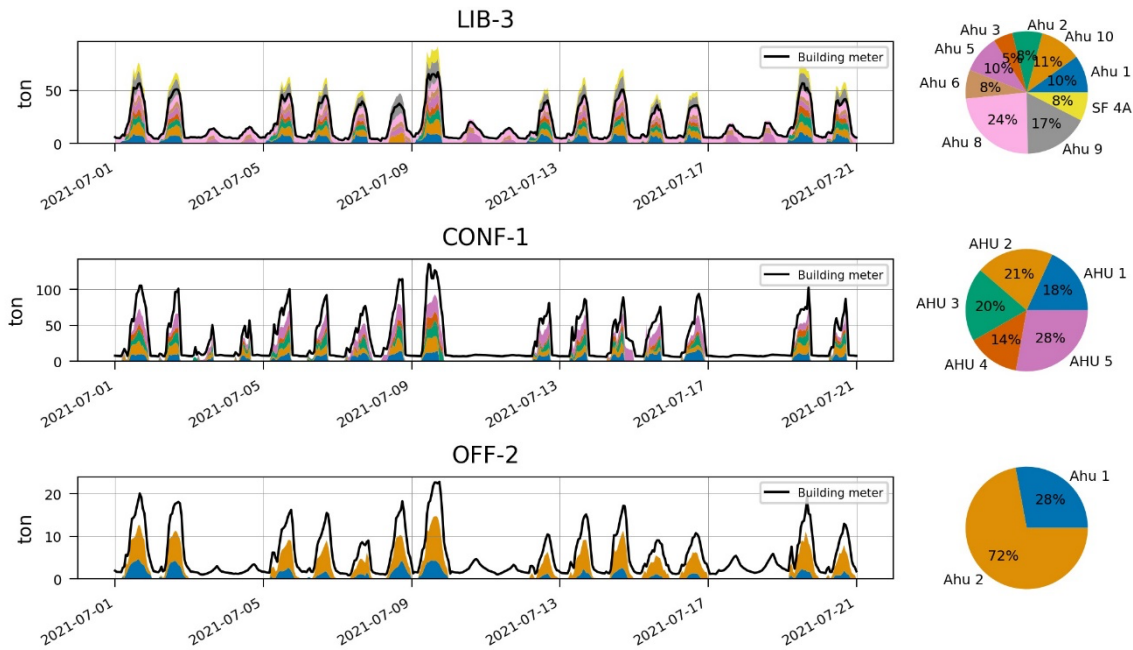


Figure 3. Decomposing the load of a building (black line) into the load of the different AHUs using Equation 1. The pie charts correspond to the weight of each of the AHUs relative to total AHU load.

The AHU load calculated using Equation 1 and illustrated in Figure 3 is used to estimate the flexibility of each AHU, discussed next.

Estimating the impacts of the +2F temperature setpoint adjustment

To study the impact of daily setpoint changes at the AHU level, we use a similar linear regression framework as developed in (de Chalendar et al. 2022). Ordinary Least Squares estimates are computed for the parameters of linear models relating the log-transformed response variable y to two predictors: the outside air temperature T measured at a local weather station and a binary variable I_{SP} that represents whether the setpoint was high or low,

$$\log y = \alpha T + \beta I_{SP} + \delta + \epsilon. \quad (4)$$

Here ϵ is an error term. Weekend data are excluded in this study. Equation 4 is used for each response variable of interest y : chilled water valve position, fan speed, zone air flow, building and AHU cooling load. The main assumption underlying Equation 4 is that the impact of the setpoint change is a fixed percentage, independent of outside air temperatures. While this assumption is unlikely to hold for extreme temperatures, we expect it to be reasonable for the mild outside air temperatures experienced during our experiments (mean daily temperatures between 60 and 76 F). Similarly, Equation 4 assumes that +1F in outside air temperature has a fixed percentage effect, independent of setpoint change. We interpret $e^{\hat{\beta}} - 1$ as the percent change of the variable y from the temperature setpoint change. In this paper we define the flexibility of an AHU as the percent change in cooling load from the setpoint change. Figure 4 shows this method applied to an AHU in the second office building, OFF-2, for each variable presented in the results sections. The variables are all measured data from the experiments, except for AHU flexibility (leftmost plot in Figure 4) which uses Equation 1.

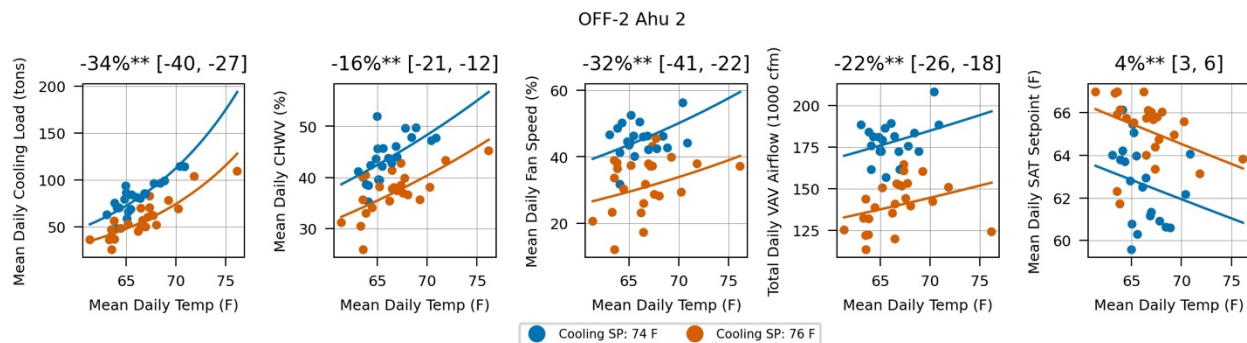


Figure 4. Each plot is the daily average of a variable versus the daily average outside air temperature. The title is the percent change of the y-axis variable from the setpoint increase, with significance and confidence intervals.

Zone-level efficiency metrics

To understand AHU behavior, examining zone behavior is required. One goal of VAV systems is to maintain its zone temperature within the temperature boundaries. An efficient VAV

will keep its zone temperature near its cooling setpoint to minimize energy usage. The average deviance of zone temperatures from the setpoint for zones supplied by AHU j , D_j^c , is defined as

$$D_j^c = \frac{\sum_{i=1}^{N_j} (\bar{T}_l - T_i)}{N_j} \quad (5)$$

where the cooling setpoint $\bar{T}_l$ is the scheduled setpoint that day, N_j is the number of zones on AHU j , and the zone temperatures are the T_i 's. Summary statistics representing AHU j 's zone temperatures state relative to their scheduled cooling setpoint throughout the experimentation period are calculated. These include average of D_j^c throughout the experiments, as well as a measure of the time spent near the setpoint: the number of hours the zone temperatures are within ± 1 F of the setpoint, divided by the total number of hours of the experiments. A large positive Cooling Setpoint Deviance D_j^c can be an indicator of over-cooling and inefficiency.

The other goal of a VAV system is to maintain air flow at or above a minimum setpoint. If the air flow varies significantly each day, the zones are likely operating efficiently. If the air flow stays close to its minimum value, there is potential the zones are limited by their ventilation requirements. To represent the amount of change, the standard deviation is calculated for each zone's air flow, not including times when the building is scheduled to be off. Then, each zone's air flow standard deviation is normalized by its average air flow. For each AHU, the normalized standard deviations for the zones supplied by the AHU are averaged together to get an estimate of air flow change at the AHU-level, σ_m . A high value represents variability in air flow. A low value can provide evidence of ventilation requirements. The other possibility for low air flow change is low cooling needs. This can happen if the zones are often unoccupied, the zones can maintain temperatures at the minimum air flow setpoint, the zones are not near an electric room or other heat source, or the zones are located on the north, east, or a shaded part of the building.

Results

AHU-level flexibility confirms building-level results

The linear regression coefficient method and zone-level efficiency metrics are applied to each AHU in the three buildings explored in this paper. Results are presented in Table 2, sorted by flexibility. The first finding is that the flexibility of the AHUs confirms the heterogeneity in building-level flexibility (de Chalendar et al. 2022), summarized in Table 3. OFF-2, the building with the largest overall flexibility of -29%, has two highly flexible AHUs with only slight over-cooling and no apparent ventilation constraints. The AHU with the larger cooling reduction serves zones on the north side, while the AHU with the smaller cooling reduction serves zones on the south, like findings in CONF-1. The building flexibility of CONF-1 is slightly lower than OFF-2, at -20%. This can be explained by the large flexibility of four AHUs, and low flexibility of only one. Over-cooling appears to be occurring in zones on AHU 2 and 5, which both have the two smallest percent changes in air flow. These AHUs illustrate over-cooling due to ventilation requirements. LIB-3 has the lowest building-level flexibility of these three buildings. The high flexibility of AHU 5 is muted by low flexibility in the others. Specifically, low flexibility in

AHUs 1, 2 and 6 are caused by ventilation limitations leading to over-cooling. AHU 8 has 0% changes from the setpoint change because it serves excluded zones: 1 VAV and four constant air volume (CAV) systems. These do not vary their air flow, creating over-cooling.

Table 2. Results sorted by flexibility with confidence intervals. The first six columns use the linear regression coefficient method to calculate the percent change of the variable from the setpoint adjustment. ** significant at 5% level, * significant at 10% level, NS p-value > 10%. The last three columns are the zone-level efficiency metrics. D_j^c is the Cooling Setpoint Deviance, % near $\bar{T}$ is the time near the cooling setpoint, and σ_m is the normalized air flow standard deviation.

Unit	Flexibility	CHWV	Fan speed	VAV air flow	SAT SP	T_i	D_j^c	% near $\bar{T}$	σ_m
LIB-3 AHU 5	-40%** [-48, -30]	-23%** [-29, -17]	-9%** [-12, -6]	-11%** [-14, -7]	4%** [3, 5]	1%** [1, 1]	1.84	17.2	0.24
OFF-2 AHU 1	-39%** [-52, -24]	-15%** [-26, -2]	-2%* [-5, 0]	-7%** [-10, -3]	4%** [0, 8]	1%** [0, 1]	1.86	18.22	0.19
CONF-1 AHU 4	-36%** [-46, -25]	-29%** [-39, -18]	-4%** [-7, -0]	-9%** [-16, -1]	6%** [4, 9]	1%** [1, 2]	1.26	26.02	0.54
CONF-1 AHU 3	-35%** [-43, -25]	-43%** [-50, -34]	-12%** [-15, -9]	-14%** [-18, -9]	10%** [8, 12]	2%** [2, 2]	1.34	28.11	0.50
OFF-2 AHU 2	-34%** [-40, -27]	-16%** [-20, -12]	-32%** [-41, -22]	-22%** [-26, -18]	4%** [3, 6]	1%** [1, 1]	2.43	12.95	0.30
CONF-1 AHU 5	-29%** [-44, -10]	-34%** [-48, -14]	4%NS [-3, 12]	1%NS [-3, 4]	9%** [4, 14]	2%** [1, 2]	2.99	8.85	0.32
CONF-1 AHU 2	-23%** [-32, -14]	-24%** [-35, -11]	-5%** [-8, -2]	-4%** [-6, -2]	5%** [3, 6]	2%** [1, 2]	1.93	23.62	0.46
LIB-3 AHU 1	-18%* [-35, 3]	-11%** [-16, -5]	4%** [1, 8]	7%** [2, 12]	4%** [3, 6]	1%** [1, 2]	3.00	15.36	0.29
LIB-3 AHU 10	-18%** [-25, -11]	-7%** [-13, -2]	-4%** [-7, -1]	-8%** [-12, -4]	1%** [1, 2]	1%** [0, 1]	2.09	20.06	0.39
LIB-3 AHU 6	-14%** [-22, -4]	-4%NS [-8, 1]	-4%** [-5, -2]	-7%** [-8, -5]	-0%NS [-0, 0]	0%NS [-0, 0]	4.02	5.68	0.19
LIB-3 AHU 2	-12%* [-23, 0]	-5%NS [-13, 2]	-6%** [-9, -2]	-10%** [-13, -6]	1%NS [-0, 3]	0%** [0, 1]	1.55	20.71	0.31
LIB-3 AHU 9	-9%NS [-21, 5]	-7%NS [-17, 5]	-2%NS [-4, 1]	-3%NS [-7, 2]	2%NS [-0, 5]	1%* [-0, 1]	1.47	35.64	0.33
CONF-1 AHU 1	-8%NS [-22, 10]	6%NS [-4, 17]	-3%NS [-7, 1]	-9%** [-14, -3]	0%NS [-2, 3]	1%** [0, 1]	0.96	47.43	0.54
LIB-3 AHU 8	-0%NS [-10, 11]	-0%NS [-8, 8]	-0%NS [-2, 2]	-0%NS [-2, 2]	0%NS [-2, 3]	0%NS [-0, 0]	3.55	3.89	0.07

Table 3. Building-level flexibility (de Chalendar et al. 2022) for comparison with Table 2 AHU-level flexibility.

Building	CONF-1	OFF-2	LIB-3
Flexibility	-20%	-29%	-13%

Chilled water usage is the main driver of highly flexible units

High flexibility is correlated with a large impact on chilled water valve position. This is illustrated in Figure 5 and Figure 6A. Six out of seven AHUs with high flexibility have a significantly higher chilled water valve impact compared to fan speed. These units make up the top half of Table 2. The other highly flexible unit is OFF-2 AHU 2 where the cooling load impact is mainly due to fan speed decrease. Although the zones served by this AHU are mostly interior zones surrounded by FCUs, being on the south side of the building may lead to high cooling needs supported by both chilled air and high air flow rates.

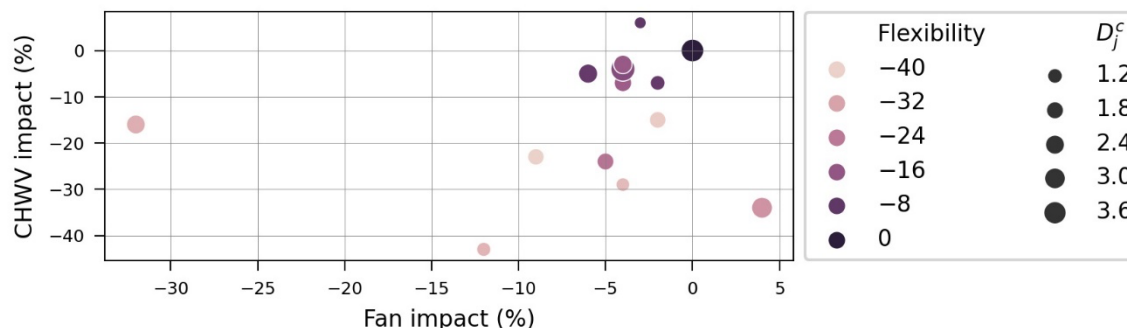


Figure 5. Each AHU's percent change in CHWV position is plotted against its percent change in fan speed. Highly flexible units are light and inflexible units are dark. Over-cooled units (high D_j^c) are large dots and units near the cooling setpoint (low D_j^c) are small dots.

Low flexibility is correlated with a small impact on chilled water valve position. This is shown by the seven AHUs on the bottom half of Table 2 and in Figure 5. LIB-3 AHUs 1 and 6 are ventilation constrained with over-cooling, explaining their low chilled water valve response and flexibility. For LIB-3 AHU 2, the small chilled water valve response could be from ventilation constraints since the air flow standard deviation is only mid-range relative to the other buildings. However, this variation is the highest among LIB-3 AHUs and the air flow lowers by 10% on high setpoint days. More research needs to be done to conclude why the chilled water valve is not responding. Similarly, LIB-3 AHU 10 has -18% flexibility, with high air flow variation and zone temperatures closely following the setpoint.

As discussed in (de Chalendar et al. 2022), these experiments had minimal impacts on electric loads, yet significant impacts on cooling loads. This can be explained by the large changes in chilled water valve positions, and consequently chilled water usage, as compared to smaller impacts on the fan speed shown in Figure 6. Reasons for this are the daily time scale, the

SAT reset capabilities, and ventilation constraints. Ventilation constraints refer to zones being at their limits of air flow rates. Increasing the cooling setpoint will not impact the electric or cooling load if many zones are at their minimum air flow setpoints, especially if zones are over-cooled. Since half of the AHUs studied have an over-cooling median greater than 2 degrees, there may not be notable electric load impacts. If several zones greater than or equal to the Ignore Request threshold are at their maximum air flow setpoint, decreasing the cooling setpoint will not have any impact. Increasing the cooling setpoint above their zone temperatures will relieve the cooling request, so the chilled water valve will close. This will lower the cooling load. Ventilation constrained zones mainly have an impact on cooling load as opposed to electrical load. Additionally, zones first attempt to meet their temperature requirements by varying their damper positions. Fan speed is likely to vary throughout the day to balance thermal load, and not change so much between days. Since SAT reset is used as a second step to satisfy cooling, daily setpoint changes result in more chilled water valve position variation between days.

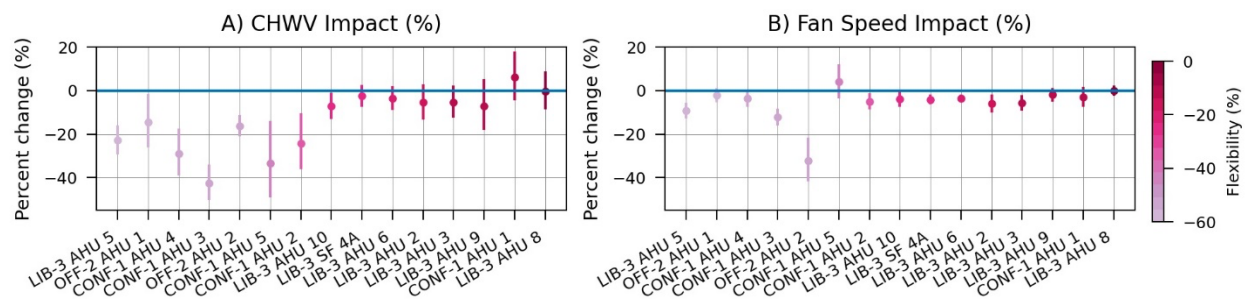


Figure 6. The points represent the A) CHWV and B) fan speed percent change in response to setpoint adjustments using the regression coefficient method. The whiskers capture the 2.5th and 97.5th percentiles. Highly flexible units are light, inflexible units are dark.

Ventilation constraints complicate flexibility

Ventilation constraints are apparent when VAVs have limited air flow variation σ_m and/or a small percent change in air flow from the daily temperature setpoint change. AHUs serving zones with ventilation constraints often have low flexibility, illustrated in Figure 7. The values in Figure 7 are reported in Table 2. Units with active ventilation constraints are dark dots and/or towards the left of the x-axis. They have lower flexibility than AHUs with large percent changes in air flow and/or high σ_m . Ventilation constraints are often accompanied by over-cooling.

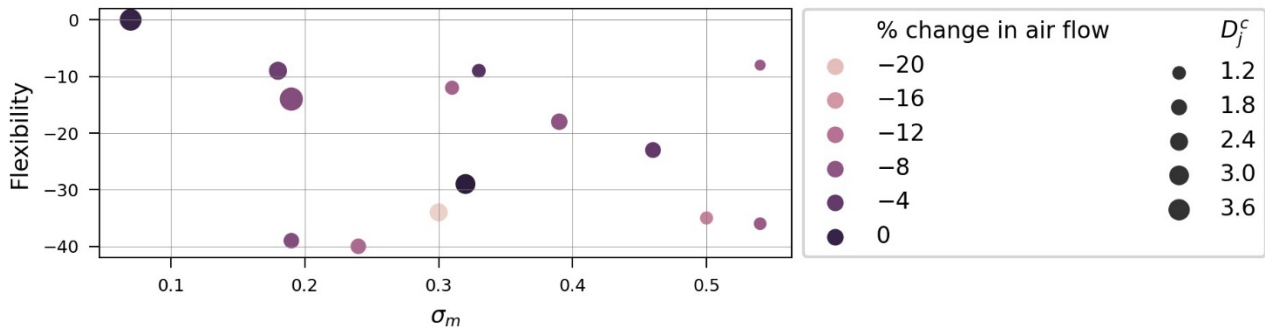


Figure 7. Each AHU's flexibility is plotted against its normalized air flow standard deviation, σ_m . Dots are colored by the percent change in air flow from the setpoint change. Dots are sized by the magnitude of over-cooling, D_j^c .

One example of ventilation constraints causing over-cooling and low flexibility is LIB-3 AHU 6. It exhibits extreme over-cooling with zones being on average 4-5 degrees colder than the setpoint. It is recommended to raise the maximum AHU SAT SP from 65 to 70 like other AHUs. On the other hand, ventilation constraints sometimes allow high flexibility due to dominant zones, discussed in the next section.

The absence of ventilation constraints usually leads to high flexibility as shown by Figure 7 and CONF-1 AHUs 2, 3, and 4, and OFF-2 AHUs 1 and 2 in Table 2. CONF-1 AHUs 3 and 4 both serve zones located on the north side of the building, with their main source of flexibility attributed to the change in chilled water usage. They both have slight over-cooling of 1.7 degrees on average. This is not related to ventilation constraints since their respective zone air flow rates have large standard deviations, allowing high levels of flexibility.

Low flexibility not associated with ventilation constraints remains unclear in CONF-1 AHU 1 and LIB-3 AHUs 2 and 9. Their impacts on cooling load in response to 2 F temperature setpoint adjustments are found to be insignificant with wide confidence intervals, demonstrating unreliable flexibility. CONF-1 AHU 1 has an insignificant positive chilled water valve percent change. This signals that there may be controlling zones minimizing the impact of setpoint changes or some other reason leading to the lack of controllability. Additionally, the maximum SAT of LIB-3 AHU 9 could be raised from 65 to 70.

Dominant zones can complicate flexibility

Dominant zones are VAVs which drive AHU behavior. They often have a multiplier of two or three, meaning they have a higher weight in determining AHU behavior compared to other zones with a multiplier of one. The Ignore Request (IR) threshold of AHUs is typically set as three (Taylor 2015). For a zone with a multiplier of three, any request it has will provoke an AHU response. The AHU will follow Trim-and-Respond logic to decrease SAT, supplying colder air to all zones even if they are at minimum ventilation. Dominant zones have high cooling demands. Whether this results in increased or decreased flexibility depends on the zone's temperature and if it is excluded from experiments. CONF-1 AHU 5 has dominant zones with wide variability in occupancy which often go above design levels, creating high loads that vary.

LIB-3 AHU 5 had dominant zones that caused over-cooling through ventilation constraints. It frequently requests cooling and is at its maximum air flow, yet the damper position is only 40 percent open. The air flow setpoints can be raised. In both AHUs, when these dominant zones are requesting cooling on low setpoint days, and their zone temperature is below the new cooling setpoint on high setpoint days, there will be a large reduction in cooling load. However, if the dominant zone is excluded from experiments, like in LIB-3 AHU 1, raising the cooling setpoint will have no impact on relieving the cooling request.

Conclusions

The goal of this paper was to understand the relationship between efficiency and flexibility of air handler units in commercial buildings. Metrics were created to quantify efficiency and flexibility using data from setpoint adjustment experiments and examined with building equipment behavior. The heterogeneous response in building level flexibility is well explained by computing estimates for the flexibility contributed by each of the AHUs. The chilled water valve position response to setpoint change is found to be the main driver of load reduction. Reasons being the daily time scale of the experiments, SAT reset capabilities, and ventilation constraints. The AHUs with the smallest cooling reduction have small chilled water valve impacts, active ventilation constraints, and over-cooling. However, ventilation constraints do not limit flexibility if there are dominant zones included in the experiment.

Future work includes conducting similar analyses for the other buildings experimented in de Chalendar et al. (2022) with FCUs and estimating zone level impact through energy balance calculations. Further investigation into fan speed and chilled water valve increases is also required. Lastly, we have designed experiments for the summer of 2022 to evaluate the impact of remedying these dominant zones on AHU cooling flexibility.

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