Cost-Based Control of Supply Air Temperature: Field Evaluation of Cost-Responsive Supply Air Temperature Reset in a Large Office Building

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Acknowledgements

Key Contributors

- Shuyang Li, Baihong Jin, Ming Ting, Fred Bauman – *CBE*
- Hwakong Cheng – *Taylor Engineering*
- Gwelen Paliaga – *TRC*

Funding

- California Energy Commission PIER Program
- Center for the Built Environment

Overview

Objective

- Develop and test a control strategy that identifies the optimal supply air temperature for an air handling unit

Approach

- No new hardware
- Minimize complexity so it can be implemented within building automation system software & hardware
- Test in a randomized (daily) repeated crossover trial

Sutardja Dai Hall, UC Berkeley

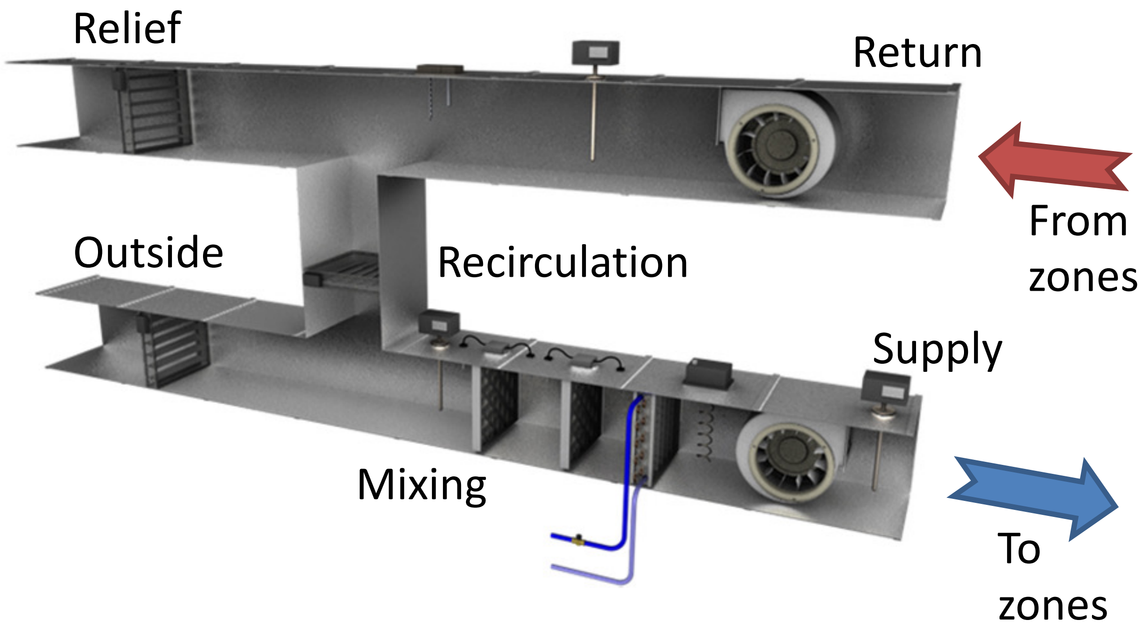
Background: Supply air temperature setpoint (SAT)

Comfort constraint

- SAT should be low enough to cool the most demanding zone

Energy impact

- Lower SAT increases cooling and reheat, but decreases fan energy.
- Other considerations:
  - Zone minimum airflows
  - Economizer status,
  - etc.



Air handling unit schematic

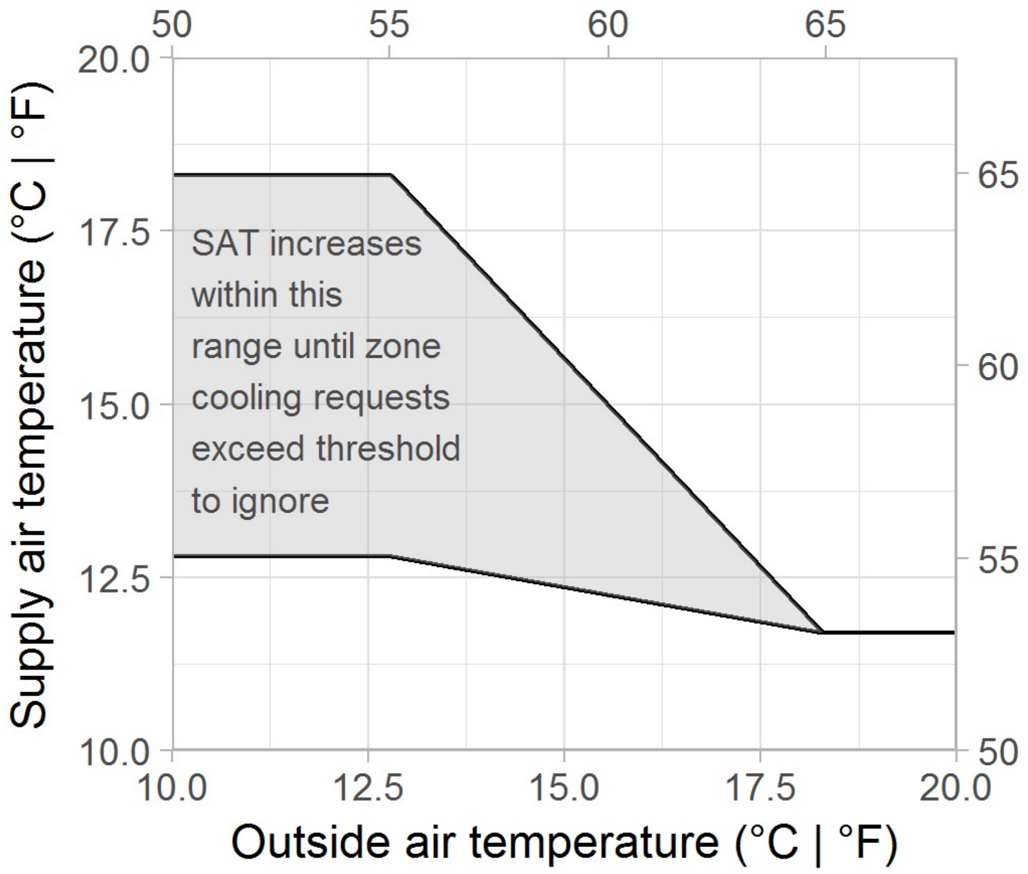
The most efficient SAT varies depending on zone conditions and the relative cost of fan, cooling and heating energy.

A brief history of best practice for SAT setpoint controls

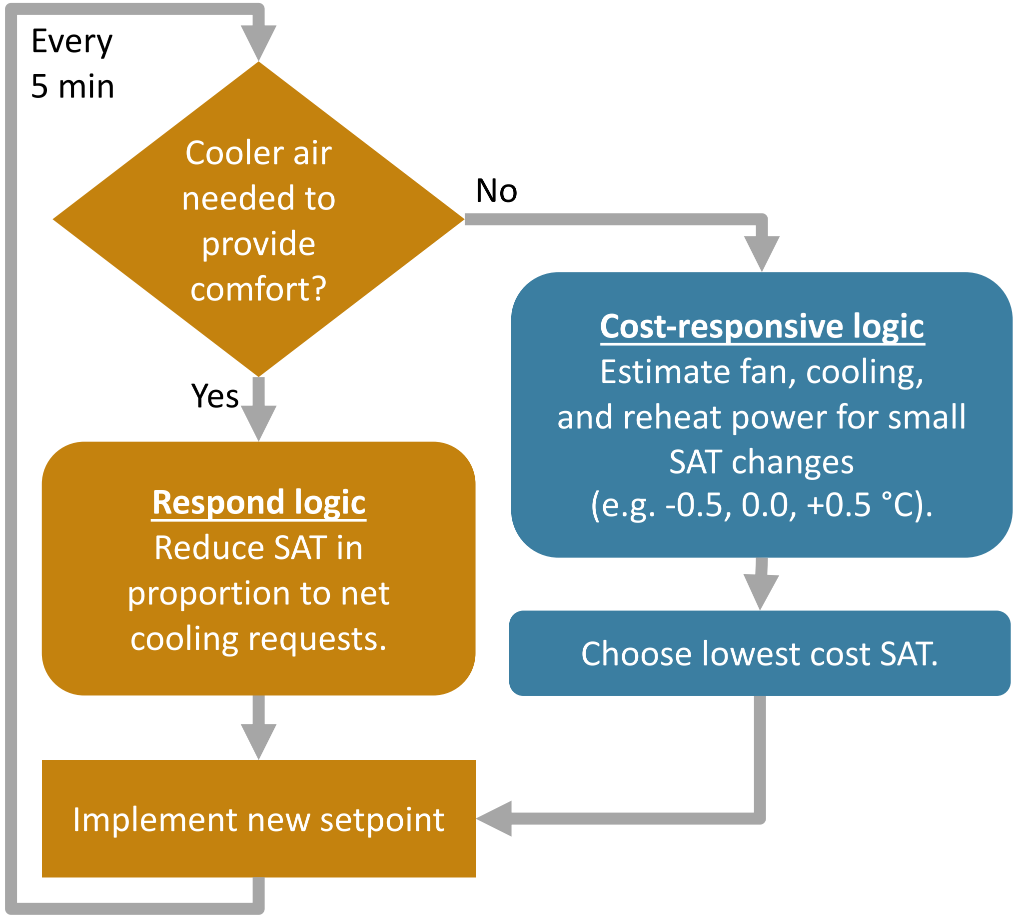
Constant (manually adjusted)	Based on outside air temperature	Warmest to satisfy most demanding zone	Warmest with outside air temperature based limits
		Advent of DDC systems	Current best practice
SAT is 58 °F (14°C), modified seasonally or as needed	↑ **SAT** when **OAT** ↓	↑ **SAT** until one zone at max airflow	↑ **SAT** until one zone at max airflow - within limits that vary based on **OAT**

Current best practice vs. cost-responsive controls

Current best practice
(similar to current ASHRAE G36)



Cost-responsive



Cost-responsive strategy: Estimating cost at current SAT

Airflow estimate

- Sum zone airflows

Fan power estimate

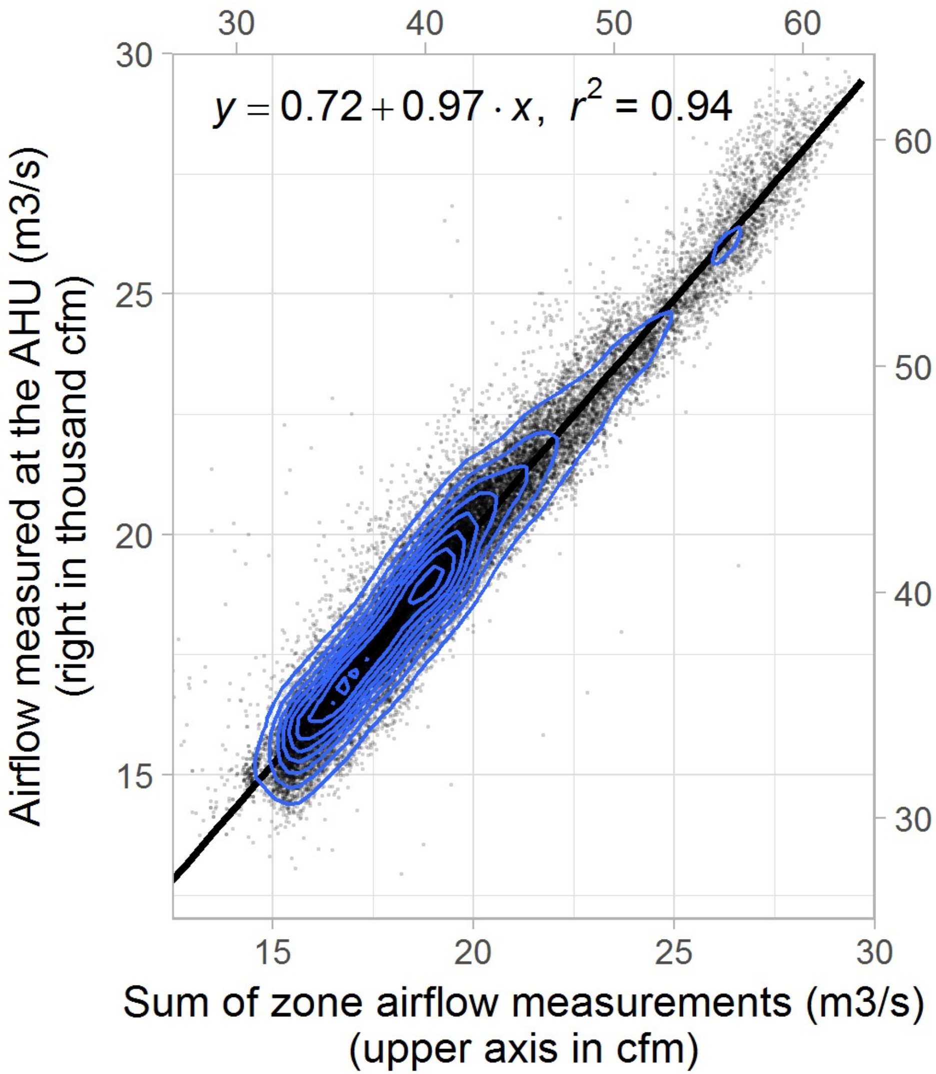
- Use VFD output and motor rating

Coil 'power' estimates

- Use sensible heat balance
- Cooling: mixing to supply air temperature difference.
- Reheat: supply to discharge air temperature difference.
- Adjust temperature difference using long term average delta T whenever the valve is closed for ≥5 min. Accounts for sensor error, fan/duct heat gain, passing valves, etc.

Cost per unit energy

- Use common metric to compare fan, reheat, and cooling energy
- Use actual utility rates, carbon, etc.



Cost-responsive strategy: Estimating change in cost at new SAT

Airflow

- For each VAV box in cooling mode, estimate new airflow at candidate SAT.
- Sum to reach total at AHU

Fan

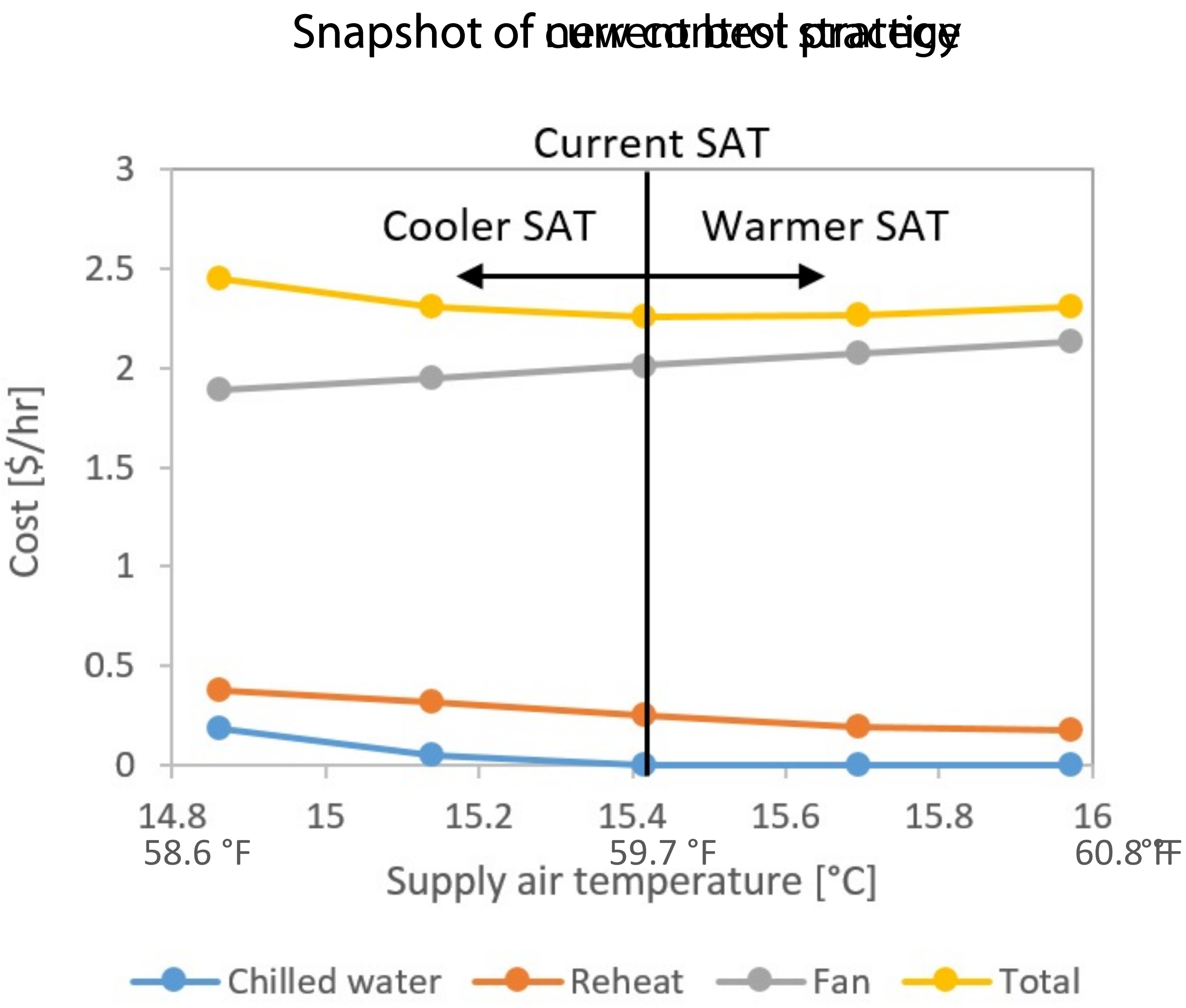
- Use total airflow estimate and fan affinity law to predict fan power at candidate SAT

Cooling

- Use new airflow estimate and re-calculate cooling estimate at candidate SAT.

Reheat

- For each reheat box with an open reheat valve, re-calculate reheat estimate at candidate SAT.
- Sum to reach total reheat



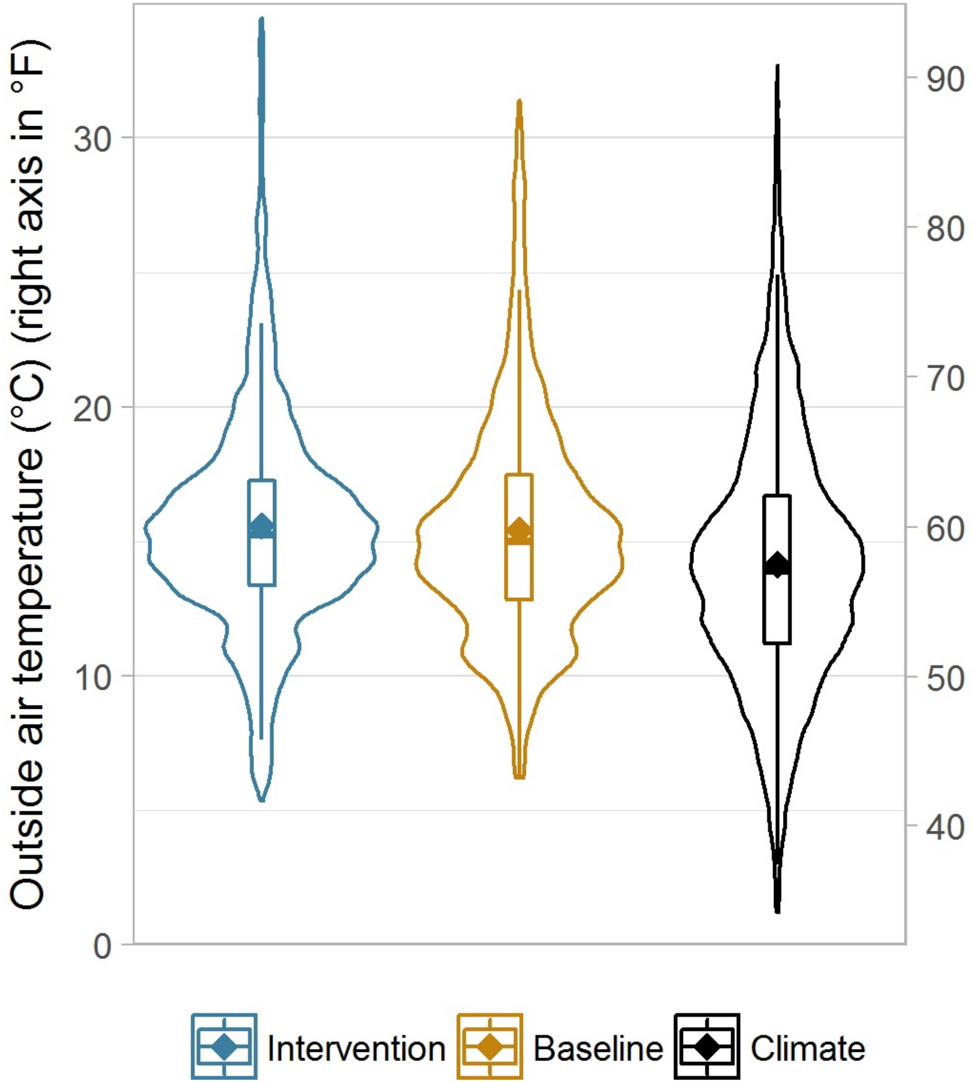
Case study in Sutardja Dai Hall

- Variable air volume system with hot water reheat
- 141,000 ft^2
- Offices, an auditorium, and cleanrooms
- Completed 2010
- Implemented directly over bacnet

Sutardja Dai Hall. Source: Hathaway Dinwiddie

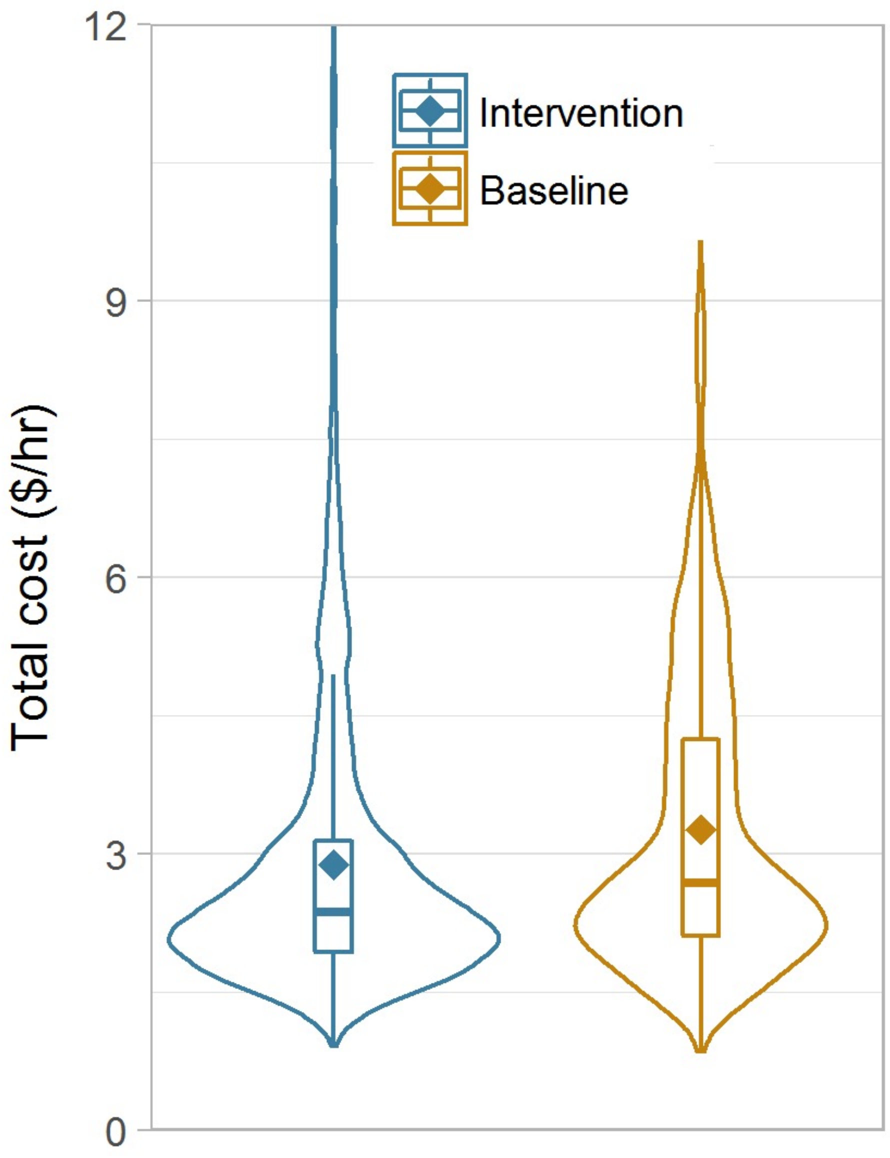
Method: Randomized crossover trial

- Randomly select control strategy every day at midnight between Sept 2016 and Feb 2017
- **Current best practice controls: 'Baseline' (77 days)**
- **Cost-responsive controls: 'Intervention' (68 days)**
- Minimizes the effect changes in weather, occupant behavior, operation of building and systems, etc., have on results

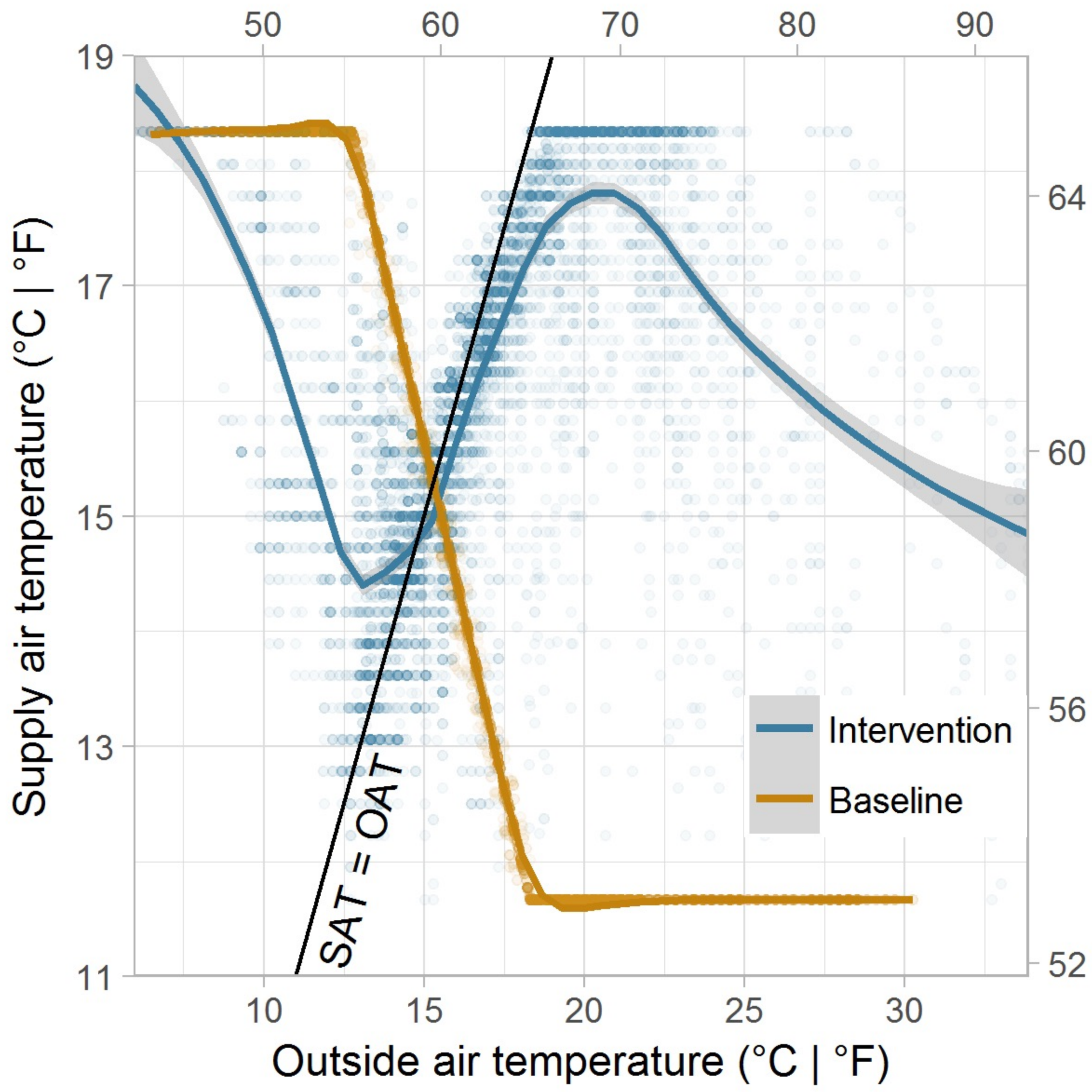


Results: Overall

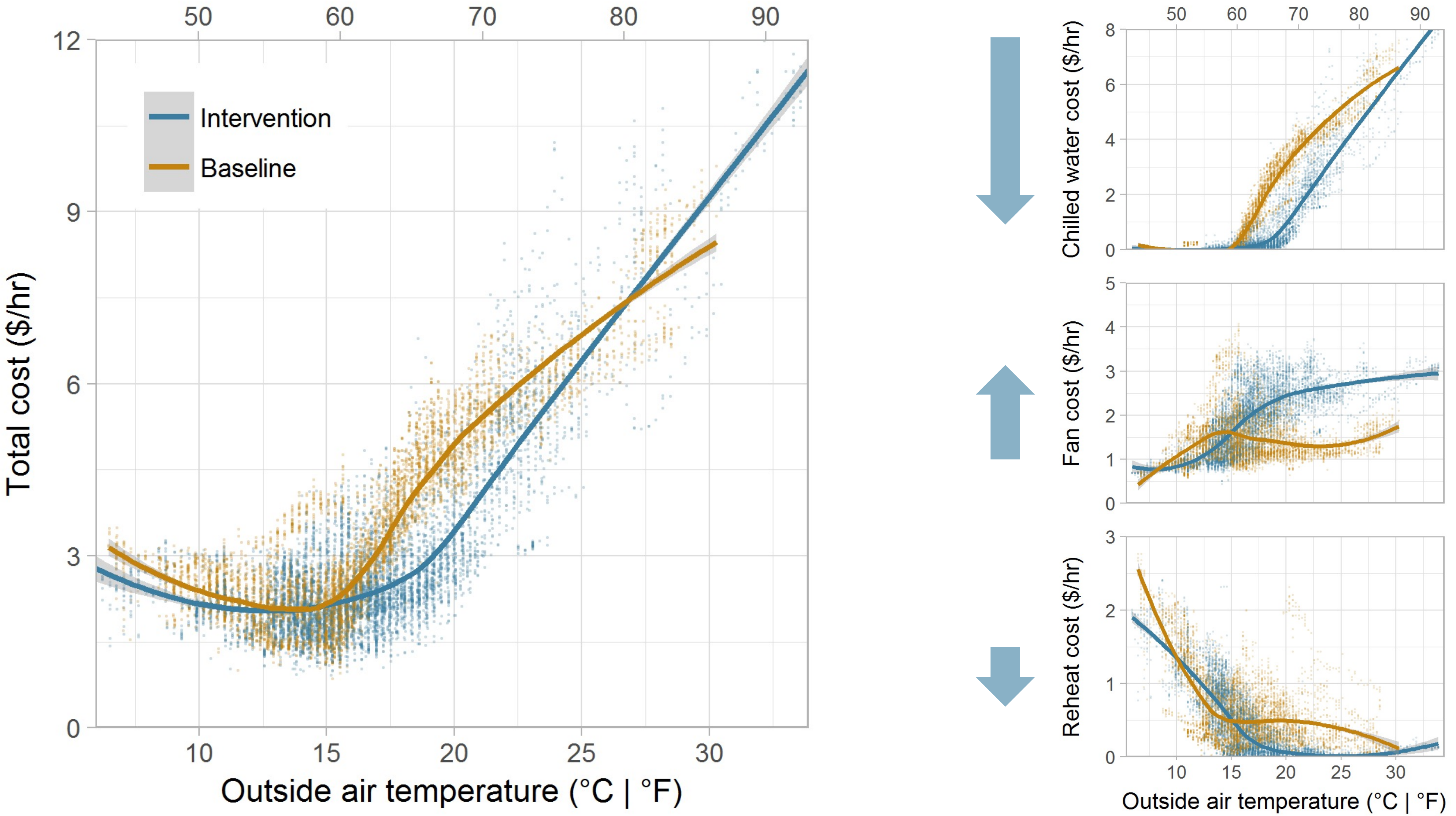
- 17% total HVAC savings during randomized control trial (6 months)
- Savings occur at all outside air temperatures
- Savings highest between 16 °C (60 °F) to 24 °C (75 °F) outside air temperature
- **29% total HVAC savings** when normalized to typical office hours (8am-6pm) in a typical meteorological year



Results: Detail

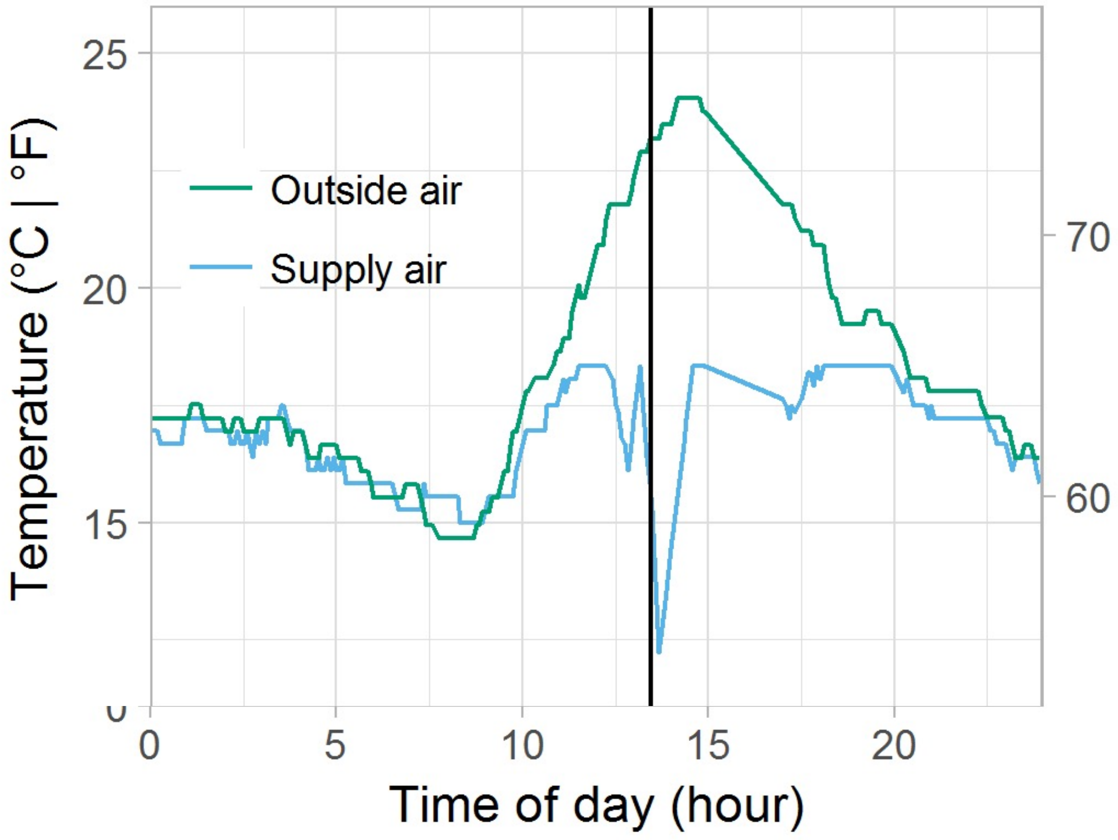


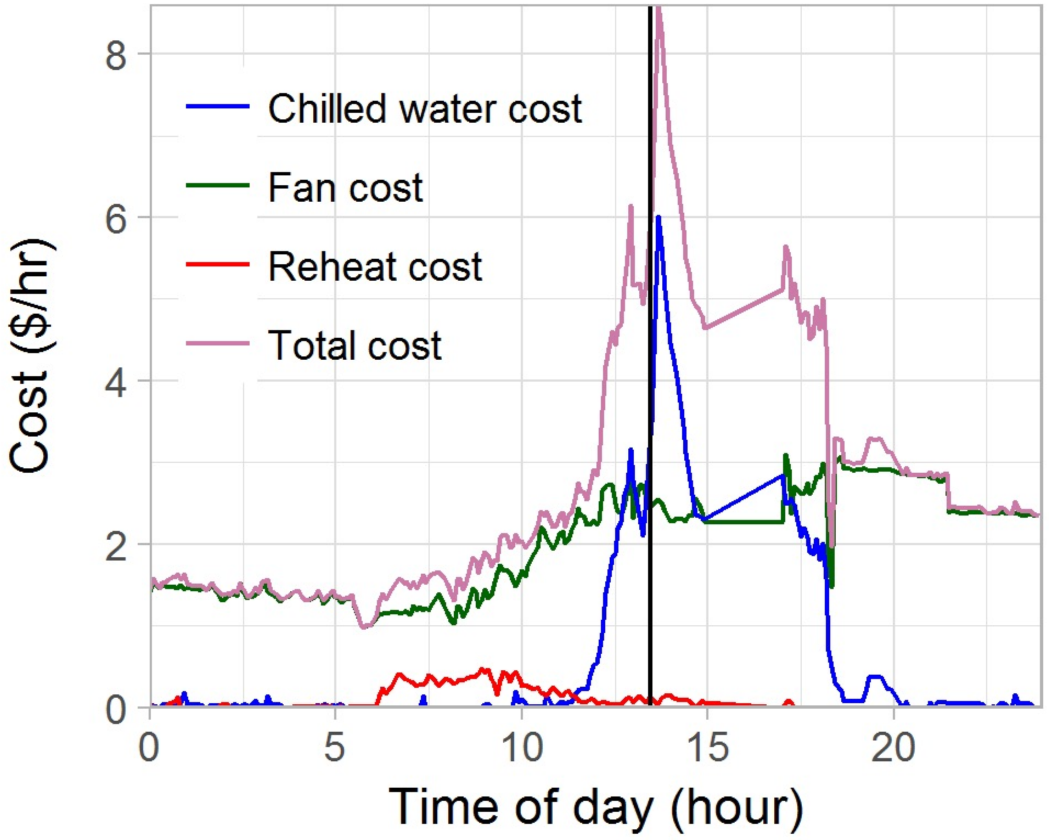
Results: Detail



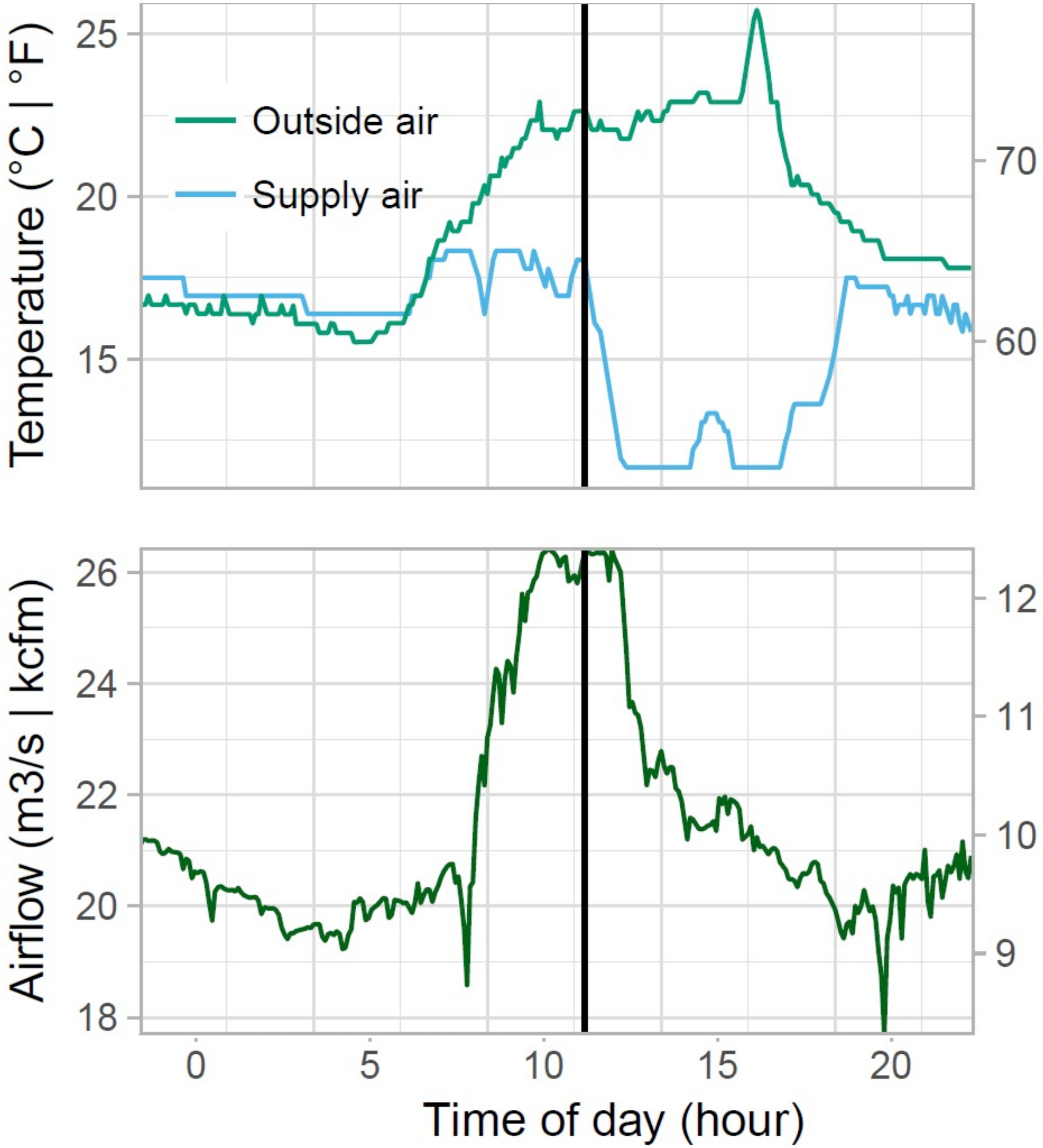
Response to unusual events – communications failure

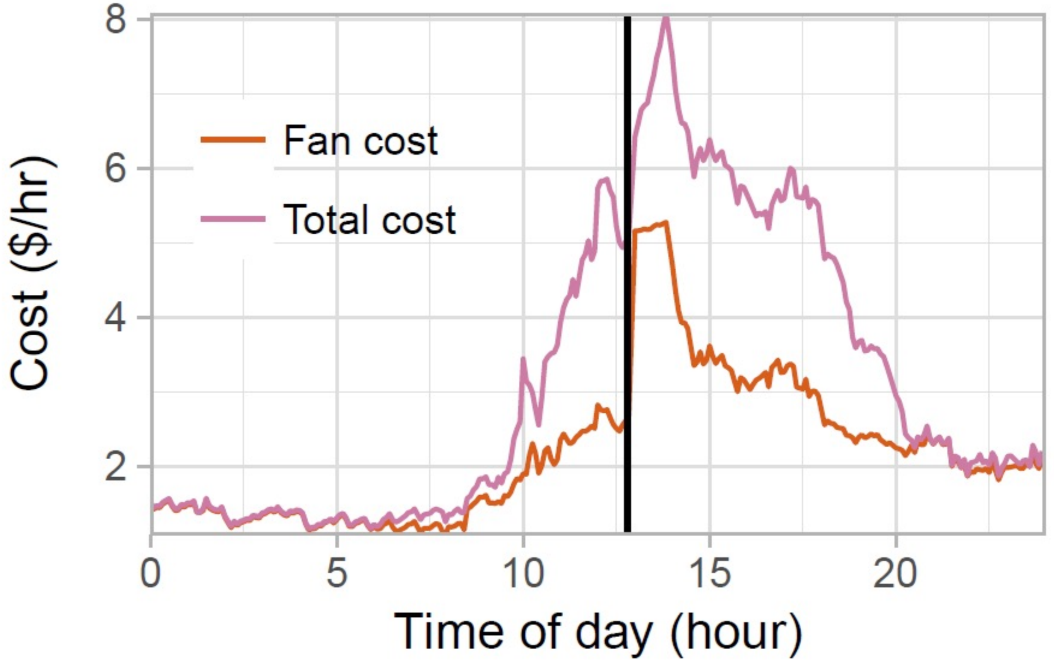
Reverts to fixed 14 °C (58 °F) setpoint if communications fail





Response to unusual events – one fan maintenance shut down





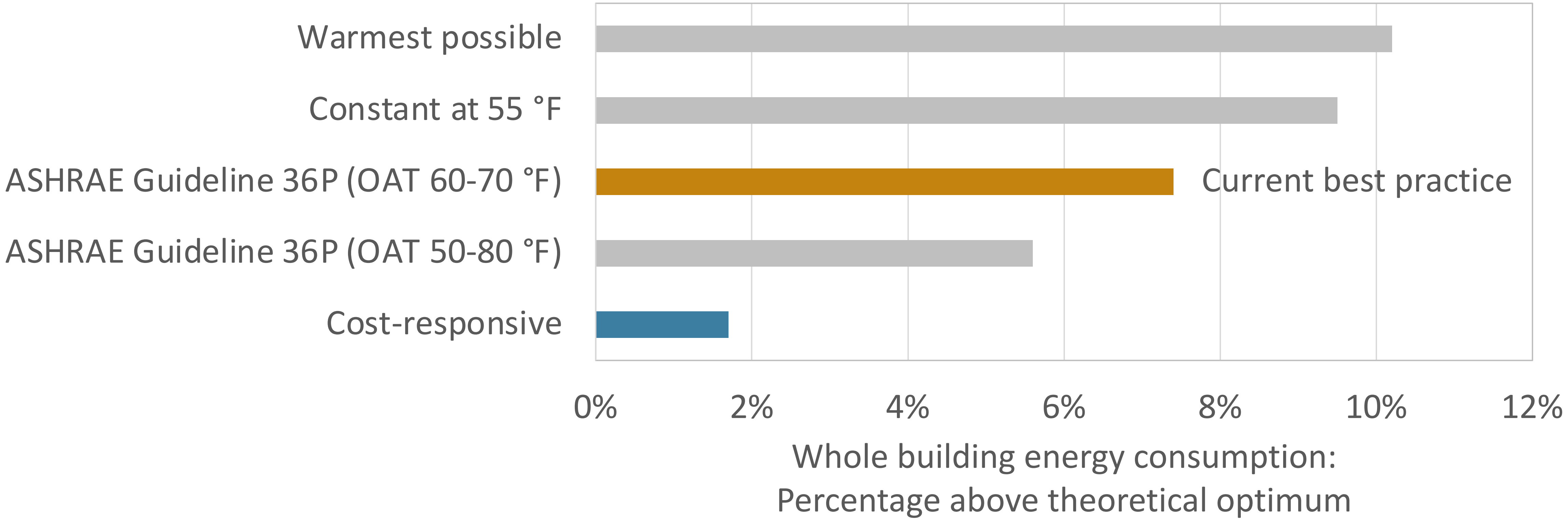
Results: Limitations of generalizing savings to other buildings

- Climate (Berkeley, cool summer Mediterranean climate, ASHRAE 3C)
- Size of the HVAC system relative to the actual building loads
- Relative cost of fan, cooling and reheat energy.
- Zone minimum airflows
- … and many other factors

Mild Berkeley weather

Results: Parametric energy modeling

- Varied loads, zone airflow minimums, HVAC sizing, chiller efficiency, etc.
- Identified the theoretical optimum using a brute force approach
- Compared a range of different SAT reset strategies



Results: Parametric energy simulation (detail)

Strategy	Basecase	High Load Variability	Low Load Variability	Low Load Magnitude	Medium Load Magnitude	High VAV Minimums	Low Fan Power	Low Fan, High Chiller Power	Autosized Zones
Warmest	13.7%	7.7%	15.0%	14.6%	15.4%	3.3%	8.1%	5.4%	12.6%
Fixed 55	3.2%	8.8%	2.3%	37.9%	10.6%	24.6%	6.9%	5.6%	3.1%
G36 (60-70)	7.9%	3.1%	11.6%	9.2%	5.1%	8.0%	7.5%	5.5%	5.9%
G36 (50-80)	4.8%	1.7%	11.1%	6.0%	2.3%	7.6%	5.7%	3.3%	3.1%
Cost-Based	1.4%	0.2%	1.1%	1.3%	0.1%	1.6%	4.5%	3.1%	1.4%
Optimum	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Practicality

- Both approaches have the same no. of building specific user inputs (4):
  - Current best practice: upper and lower limits for SAT at high and low OAT.
  - Cost-responsive: electricity & hot water prices, chiller plant efficiency, fan motor horse power.
- More complex to program… but hopefully can be implemented once, as standard 'block'
- Sequences of operations (4 pages) available to share now.

Sutardja Dai Hall. Source: Hathaway Dinwiddie

Open questions and further developments

Open questions

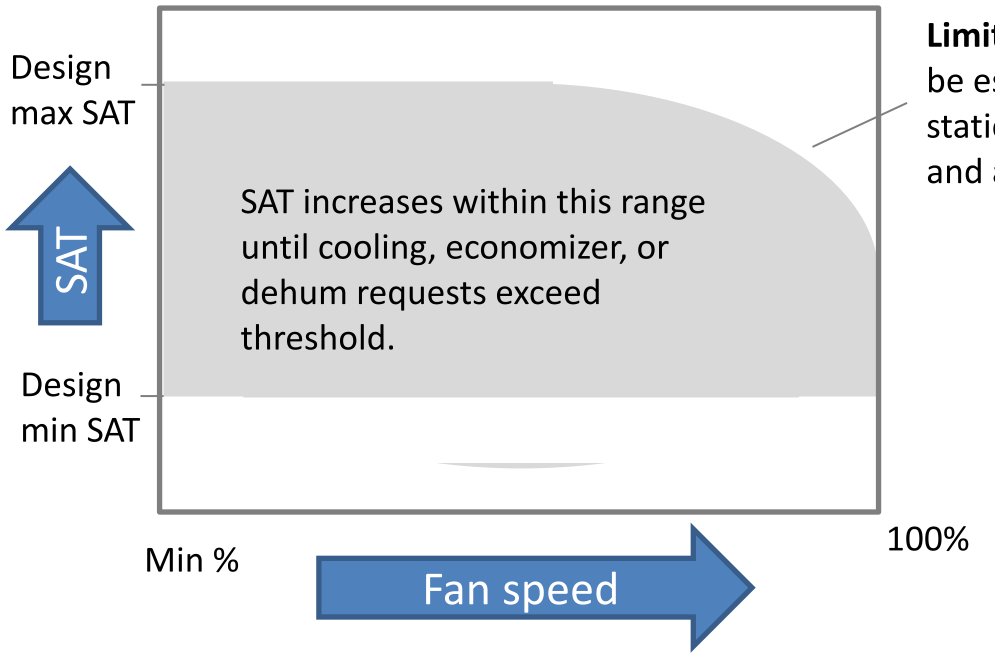
- Test performance in other buildings
- Identify issues implementing in native building automation system hardware & software
- Identify issues with control stability and overall complexity
- Develop and test in more humid climates.

Sutardja Dai Hall

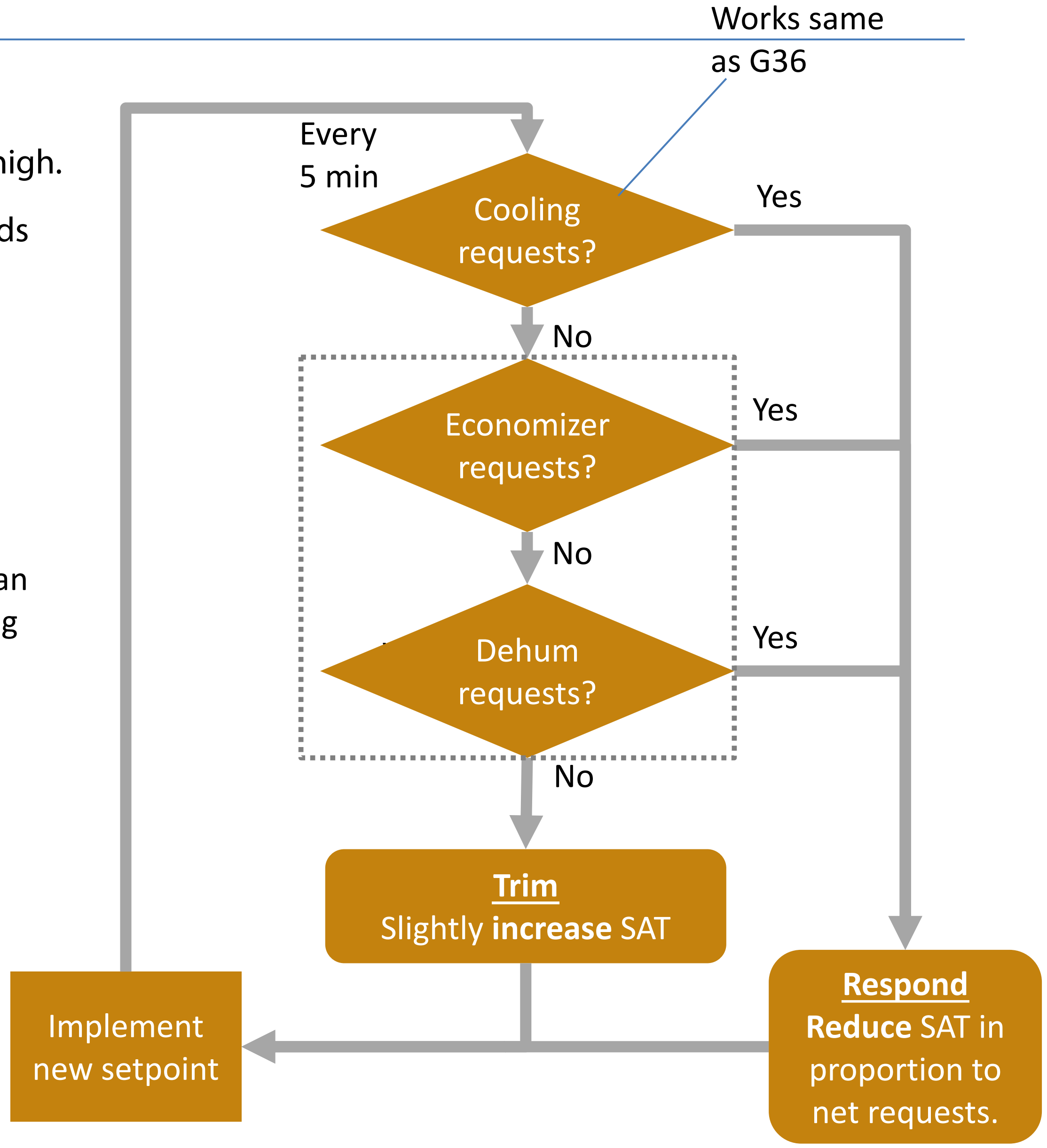
Working on improved version

Economizer aware SAT reset with fan speed limits

- Where comfort is not a constraint, prioritize economizer unless fan power is high.
- Can also partially optimize for climates with substantial dehumidification loads
- Much less programming required (no new controller constraints)
- No DATs required, no *new* zone level data/network constraints
- Easily adapted to variety of relief design configurations



Limit curve line can be estimated using static calculations and assumptions



Questions?

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Journal paper (incl. English language sequences of operation in supplemental material):

Raftery, P., Li, S., Jin, B., Ting, M., Paliaga, G., & Cheng, H. (2018). Evaluation of a cost-responsive supply air temperature reset strategy in an office building. *Energy and Buildings*. http://escholarship.org/uc/item/1fk2m3v6

Time-Averaged Ventilation (TAV) Controls for Variable Air Volume Systems

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CBE
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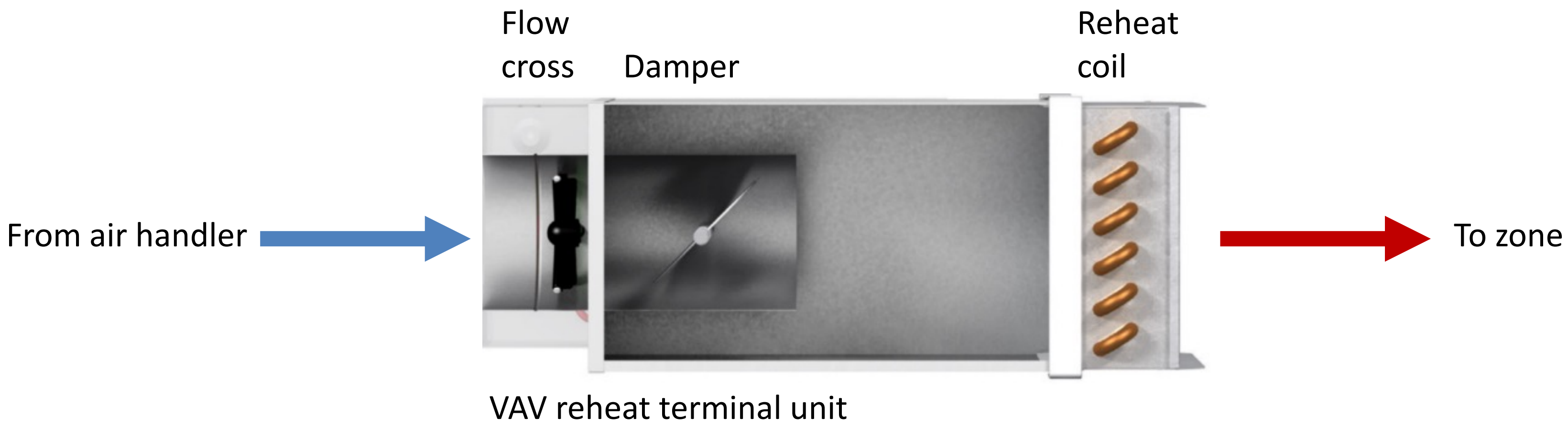
TRC

Schematic of a pressure independent VAV box

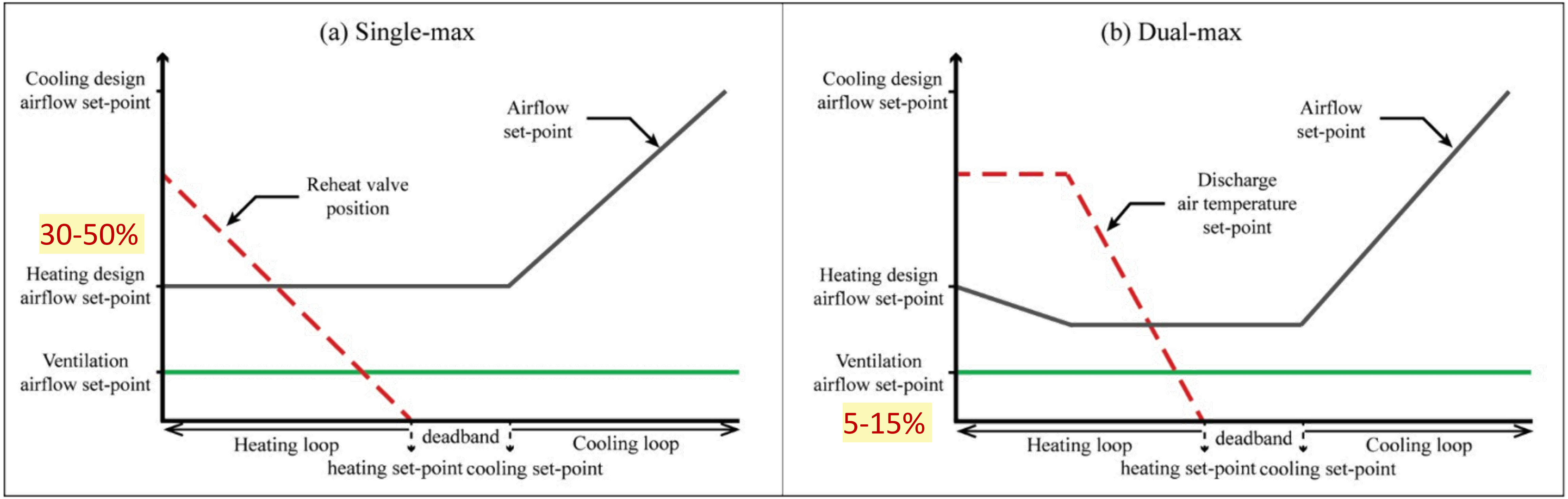
A VAV box controls airflow and heat supplied to a zone to maintain comfortable conditions and provide ventilation



- The flow cross measures airflow at the inlet
- The damper controls airflow to a setpoint
- The maximum setpoint is the design maximum cooling airflow

What is the minimum setpoint?

Variable air volume (VAV) controls logic

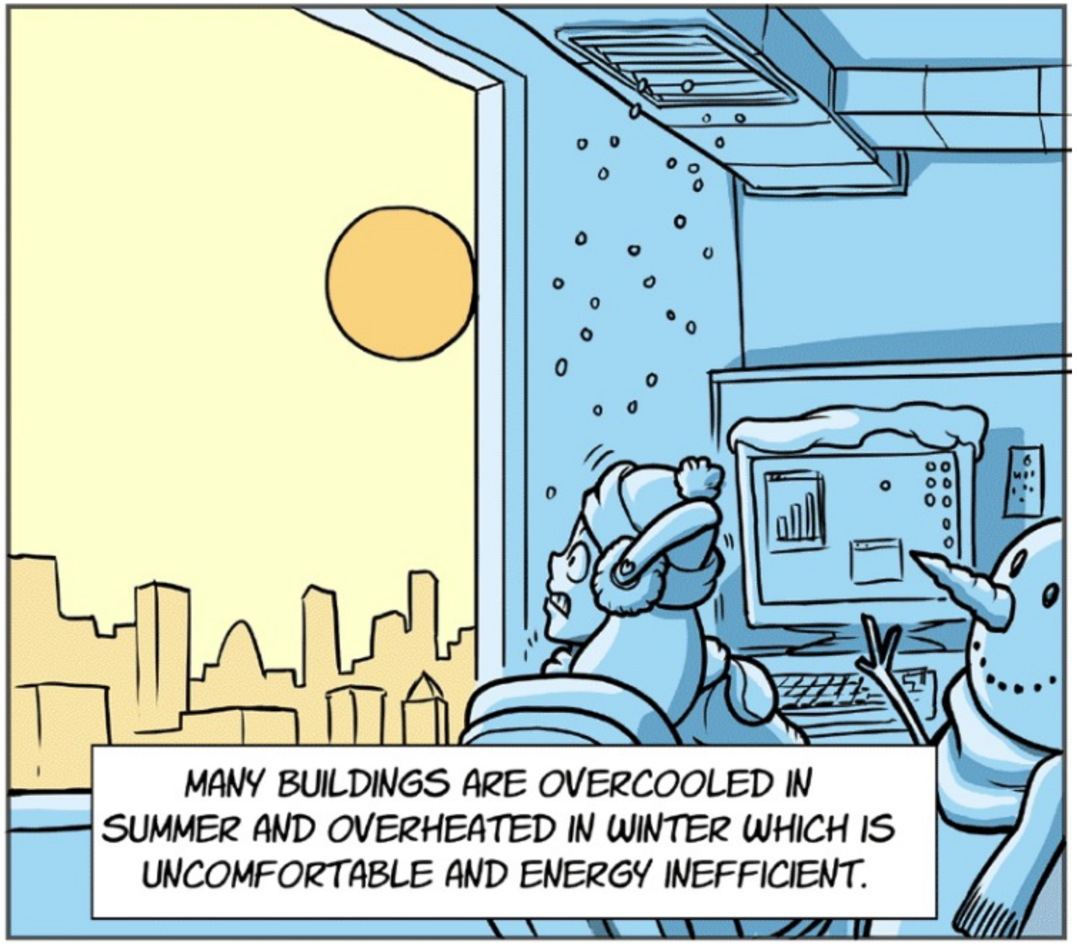


Historical: Single Maximum

Dual Maximum
(Low Minimum)
Required by code

Background

- Zones spend majority of their time at their minimum airflow set-points
- Minimum airflow set-points are typically higher than ventilation requirements
- Current practice causes overcooling and wastes energy
- However, there are perceived (and sometimes real) issues when operating at low airflow



Source: tandfonline.com

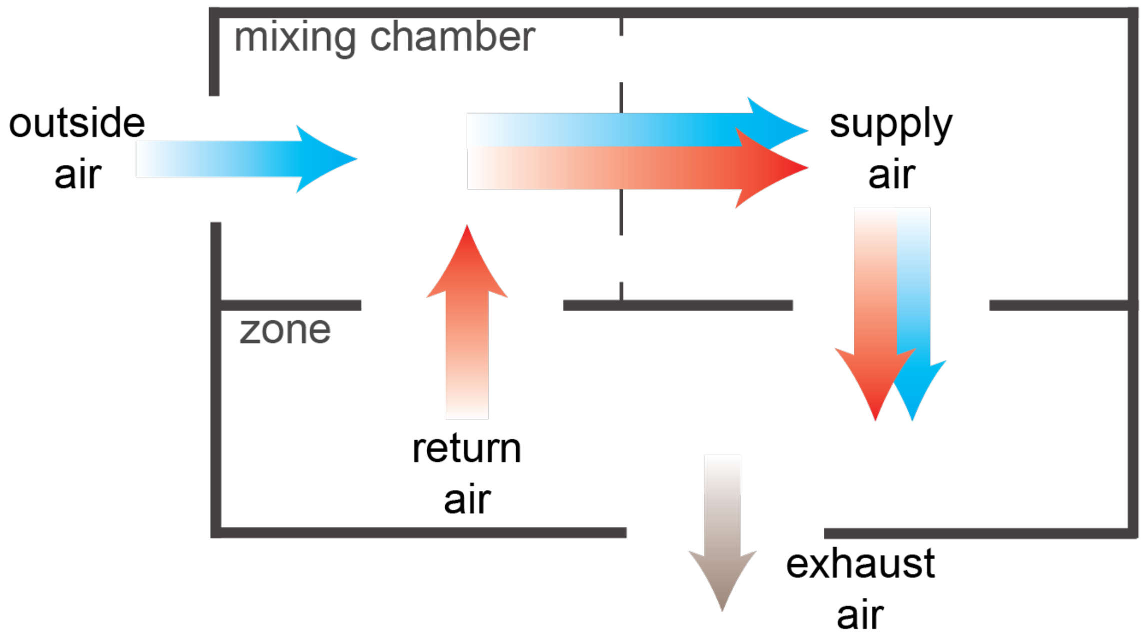
What happens ventilation when you reduce minimum setpoints?

Total amount of outside air entering the building remains the same

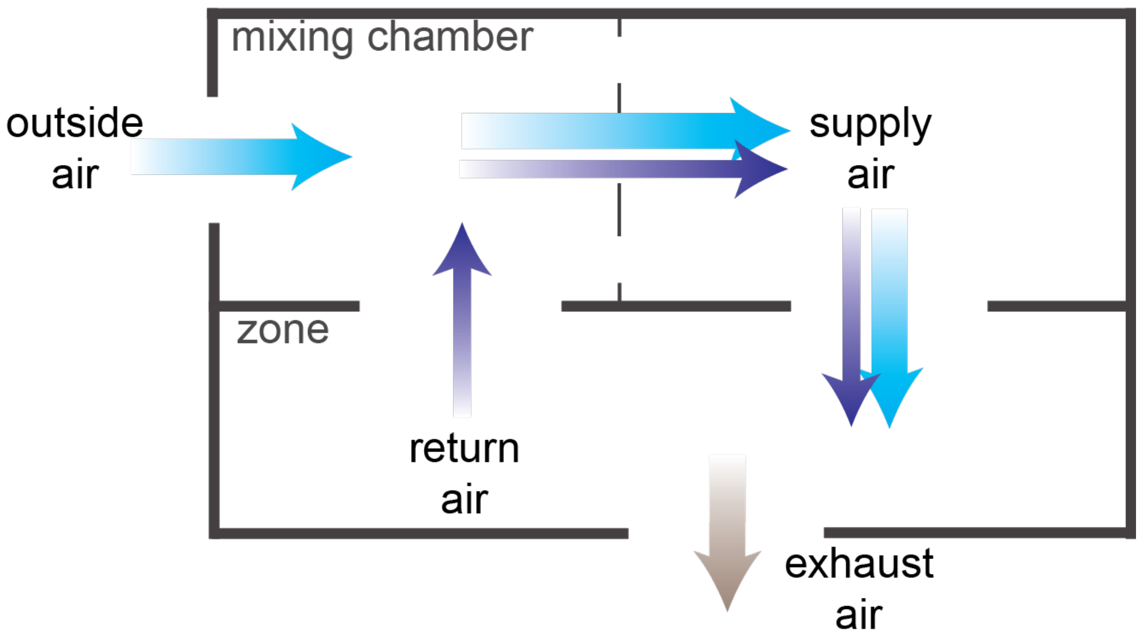
Correct minimums reduce the total amount of mixed air circulating in the building

Correct minimums increase the proportion of outside air in supply air

High minimums case



Correct minimums case

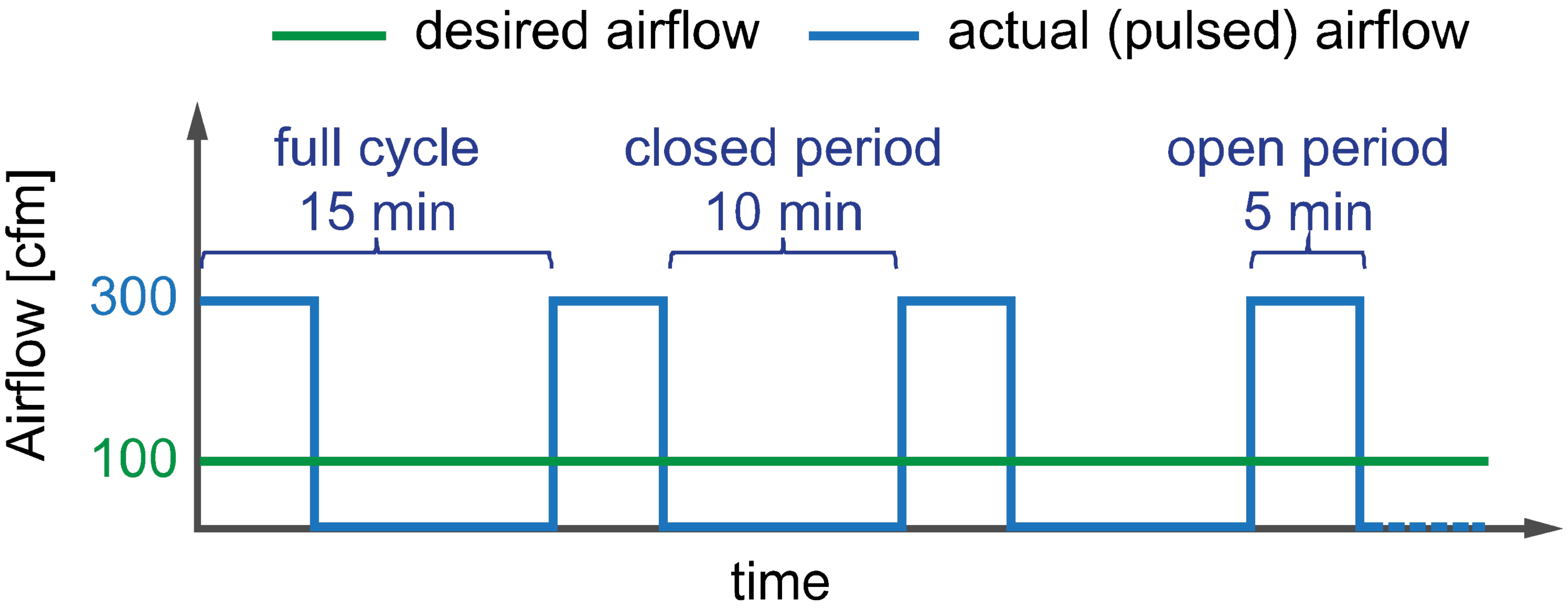


Implementing correct minimums

- Required by code in new buildings.
- Existing buildings typically still have high minimums - Hui Zhang will present the energy and comfort results from correcting these in several large office buildings.
- In some existing buildings, VAV box and controller characteristics may prevent using the ventilation minimum as the setpoint, for example:
    - Many existing buildings lack discharge air temperature sensors (required for dual maximum logic)
    - Many existing buildings do not have programmable controllers, and don’t support dual maximum logic.
- Time-averaged ventilation is an option to implement correct minimums in boxes with limited turndown capability

Time-averaged ventilation principle

TAV controls the average airflow of a zone
to the minimum ventilation rate required by code



Field study in Sutardja Dai Hall

Building site

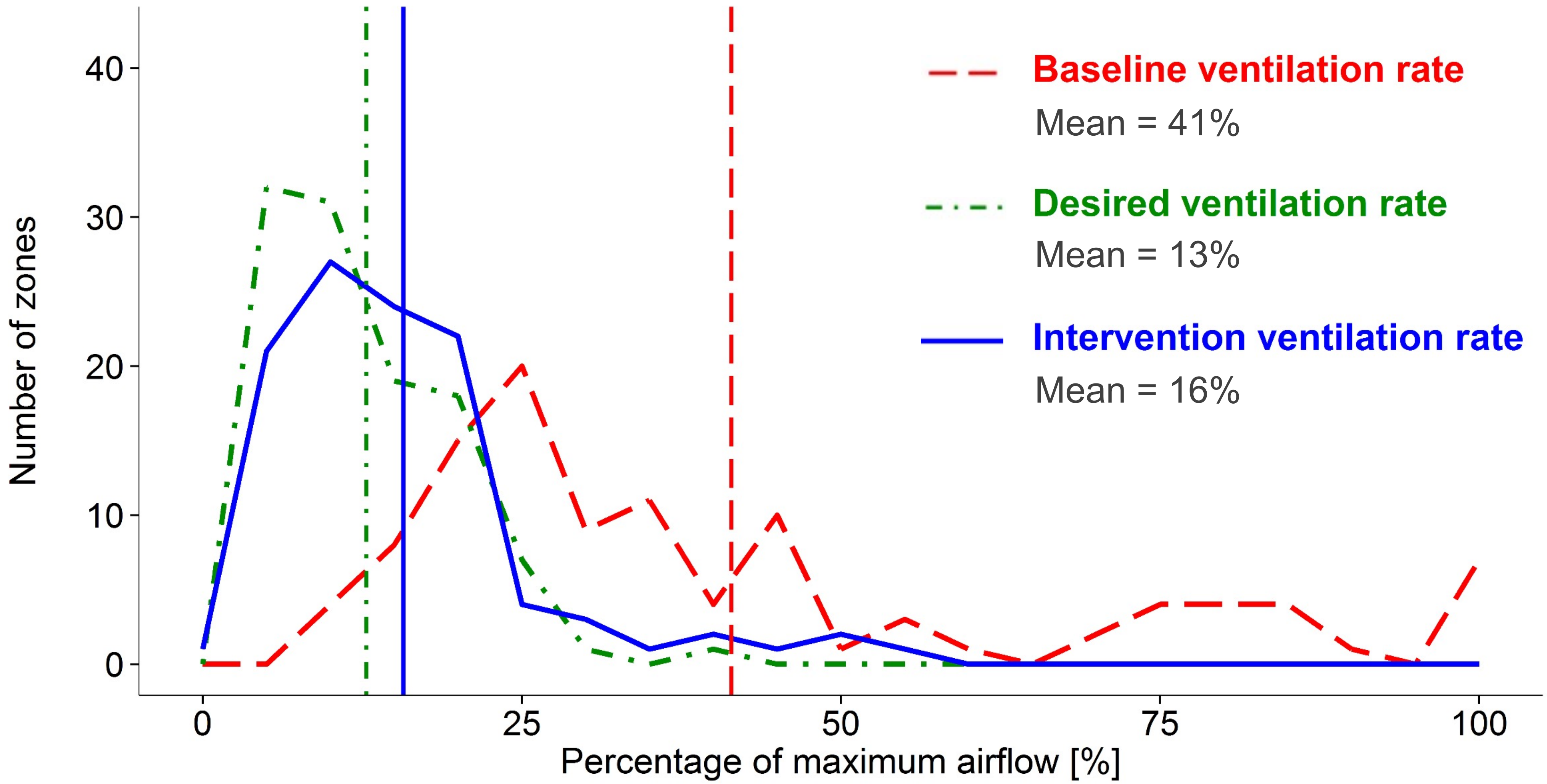
- All-air VAV system
- Single-max controls
- TAV implemented in 109 zones out of 138

Schedule

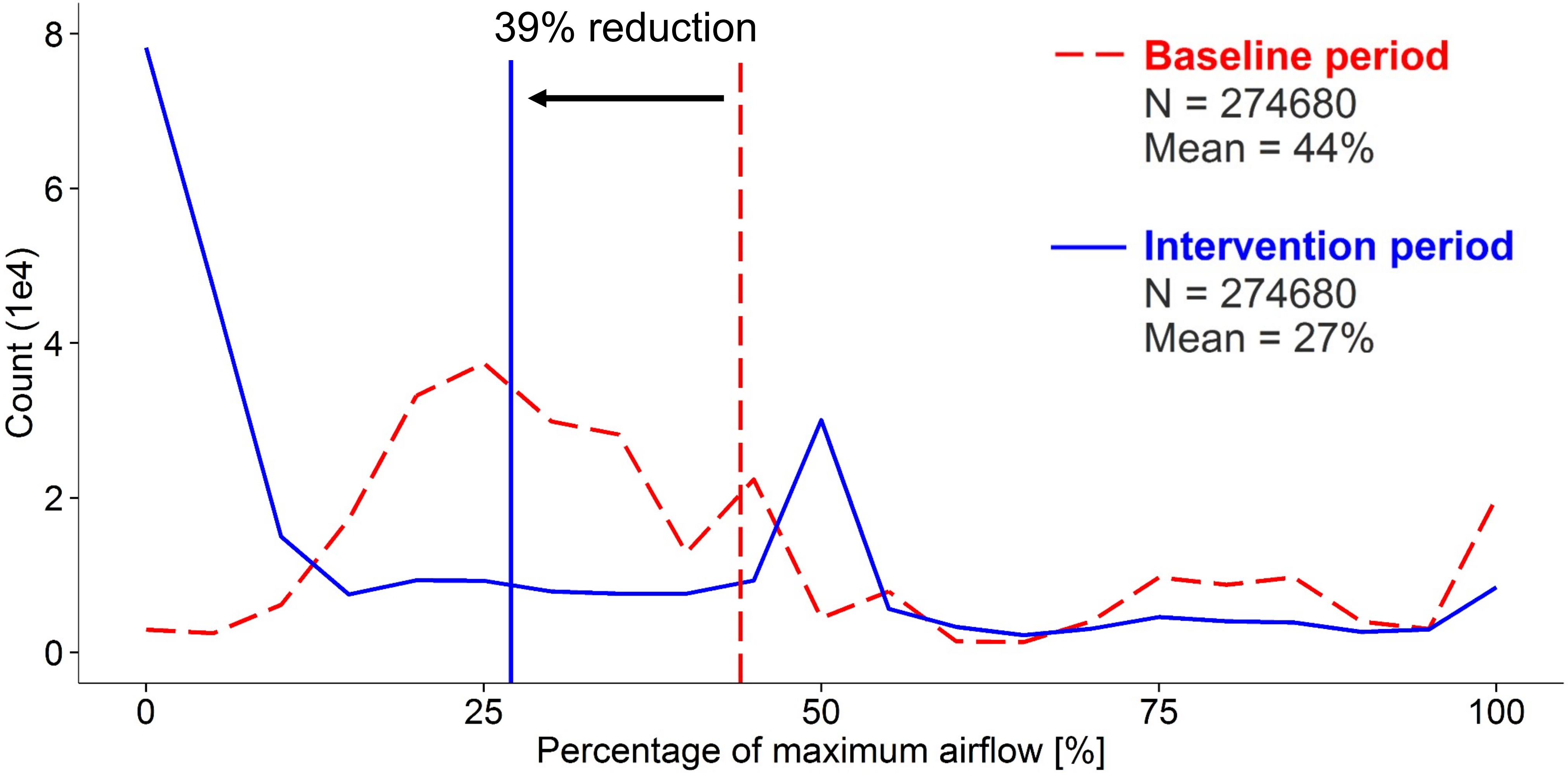
- April 2016
- Baseline period: 10 weekdays
- Intervention period: 10 weekdays
- Similar outside air temperature between baseline and intervention periods

Sutardja Dai Hall (SDH)
Source: Hathaway Dinwiddie

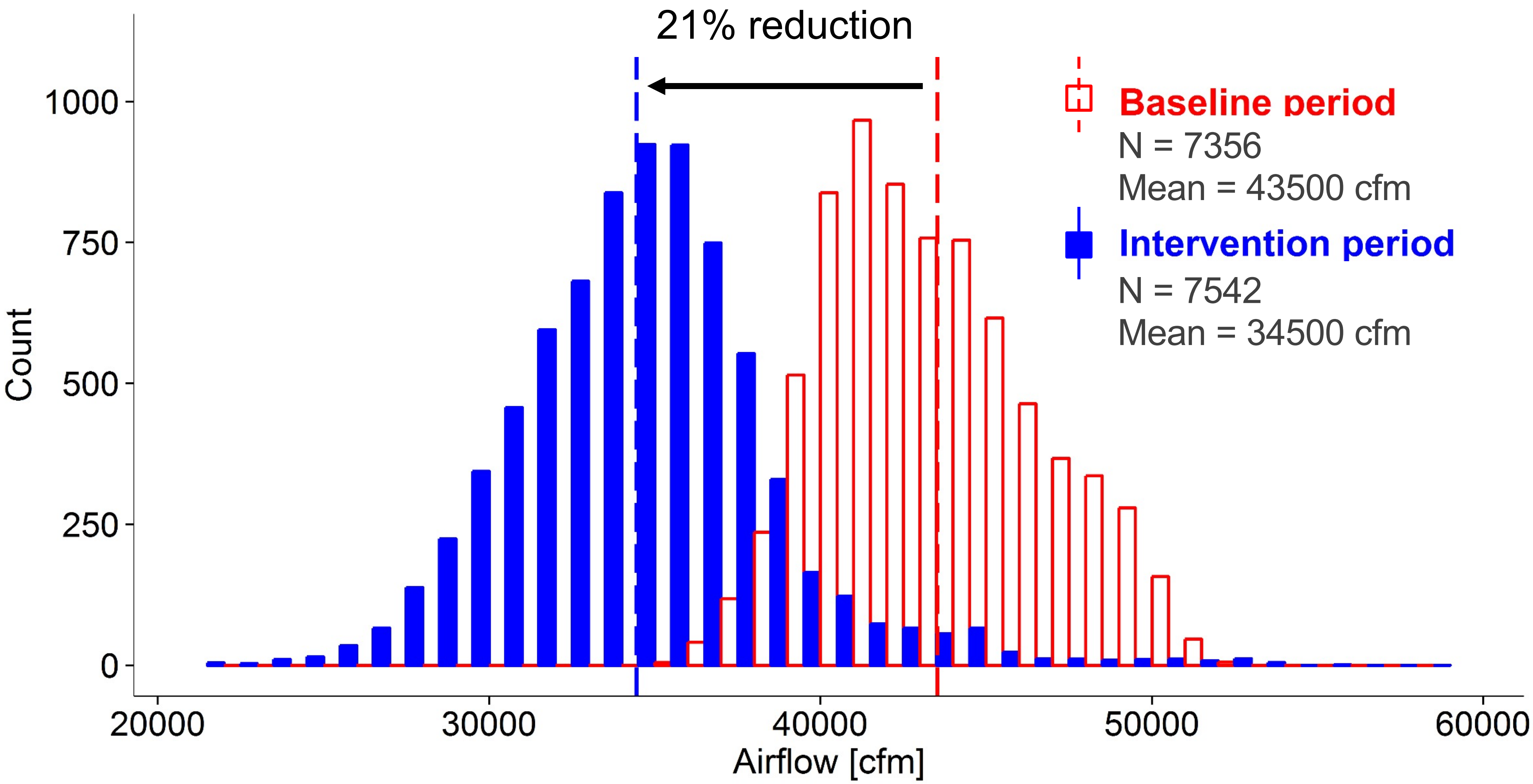
Results: Airflow at the zones



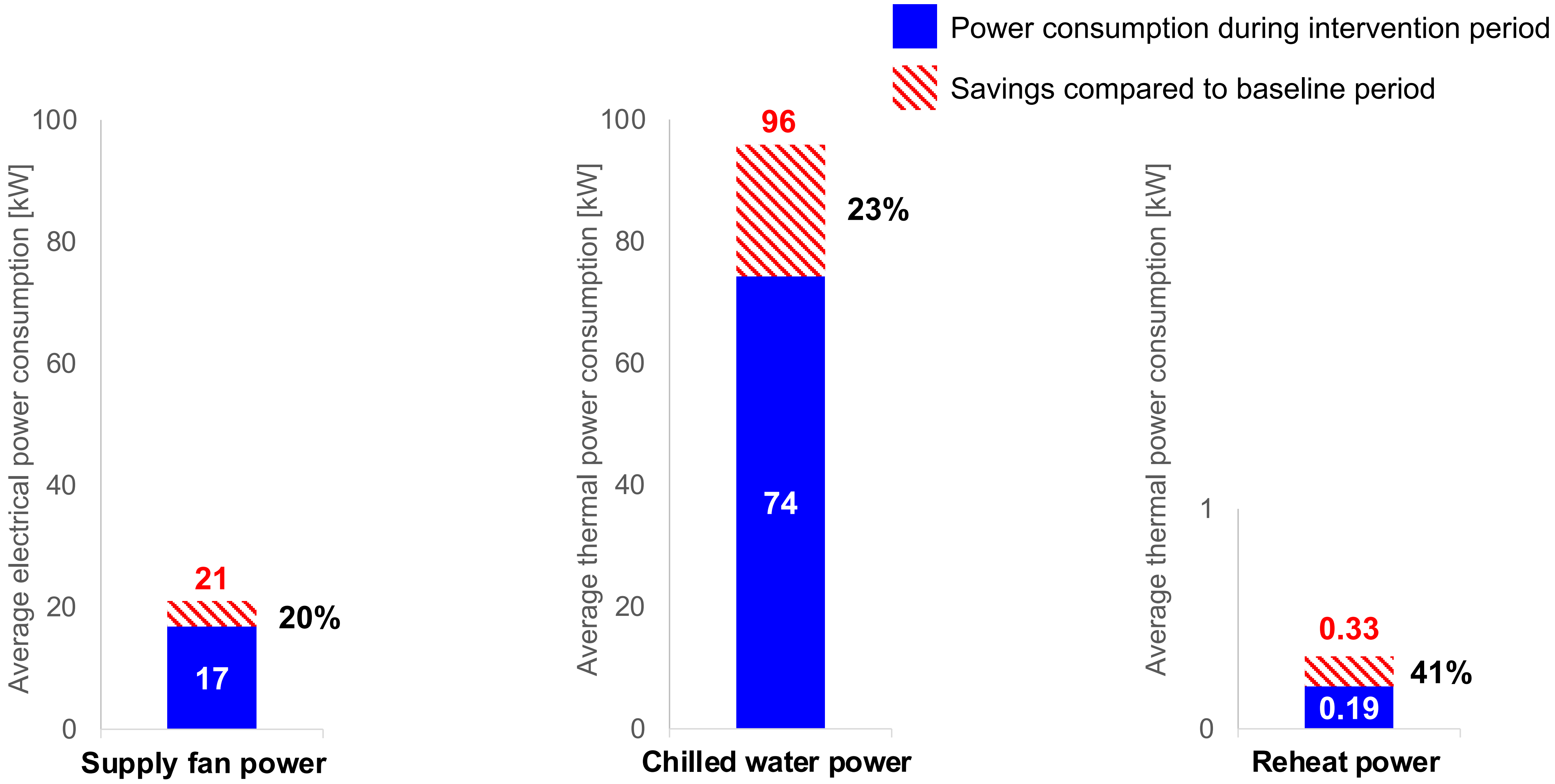
Results: Airflow at the zones (continued)



Results: Airflow at the air handler



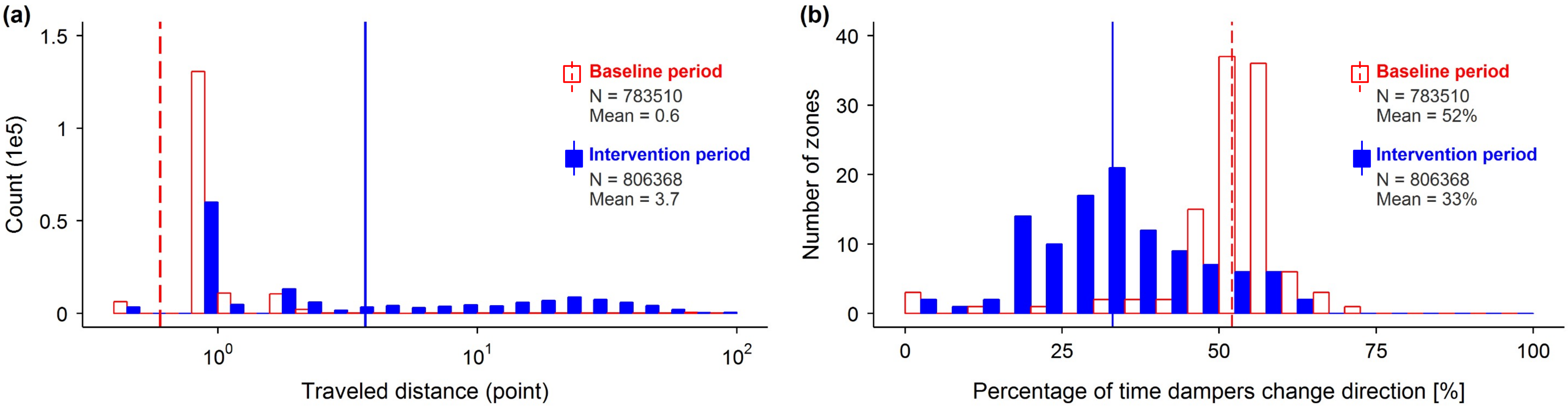
Results: Energy savings



What about damper wear?

(a) Distance traveled by the dampers increased with TAV

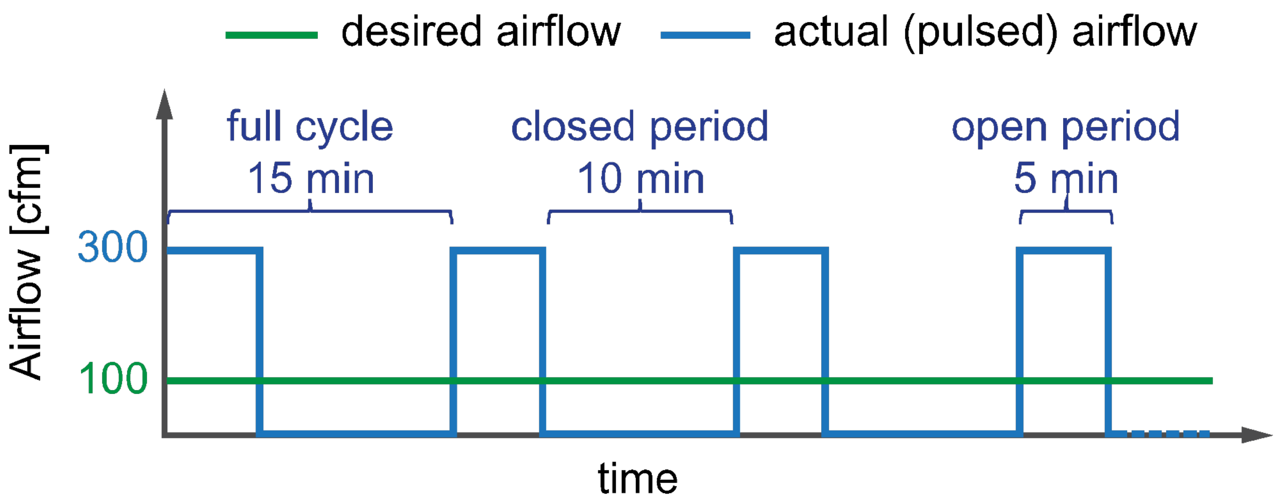
(b) Number of dampers direction changes reduced with TAV



Takeaways

- VAV boxes minimums should be based on ventilation requirements to reduce energy use and improve comfort.
- VAV boxes should use dual maximum control logic where possible.
- Where the VAV box or controller have limited turndown capability, use TAV to control average airflow to the ventilation rate required by code.

Principle of operation



- ASHRAE Guideline 36 adopted TAV (Best in Class Sequences of Operation)
- Correcting minimums has shown great potential for airflow and energy savings

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Journal paper

Kaam, S., P. Raftery, H. Cheng, and G. Paliaga. (2017). Time-averaged ventilation for optimized control of variable-air-volume systems. *Energy and Buildings*.
https://escholarship.org/uc/item/5jq443p4

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