**Title**

# INFLUENCE OF SUPPLY AIR TEMPERATURE ON UNDERFLOOR AIR DISTRIBUTION (UFAD) SYSTEM ENERGY PERFORMANCE



**Authors**
Webster, Tom
Lee, Kwang Ho
Bauman, Fred
et al.

**Publication Date**
2012-08-11

Peer reviewed

# INFLUENCE OF SUPPLY AIR TEMPERATURE ON UNDERFLOOR AIR DISTRIBUTION (UFAD) SYSTEM ENERGY PERFORMANCE

Tom Webster[1]*, Kwang Ho Lee[1], Fred Bauman[1], Stefano Schiavon[1,] Tyler Hoyt[1], Jingjuan Feng[1], and Allan Daly[2]

[1]Center for the Built Environment (CBE), University of California at Berkeley, Berkeley, CA

[2]Taylor Engineering, Alameda, CA

## ABSTRACT

Underfloor air distribution (UFAD) systems have received attention in recent years due to a number of potential advantages over conventional overhead (OH) systems. These potential advantages include increased layout flexibility, improved indoor air quality and thermal comfort, and energy savings. In particular, energy performance advantages have been difficult to evaluate analytically due to the lack of simulation tools that accurately model the complex heat transfer processes of stratification in the room and "thermal decay" (supply air temperature gain) in the underfloor plenum. Furthermore, the impact of key design and operating parameters cannot be easily determined without such tools. Fortunately, EnergyPlus v3.1 and beyond now contain validated calculation modules suitable to model these UFAD systems (U.S. DOE 2010).

Elevated supply air temperature is one of the distinguishing features of UFAD systems as compared to conventional overhead (OH) systems. In this paper EnergyPlus v3.1 simulations have been used to take a detailed look at the impact of variations in the air handling unit (AHU) supply air temperature (SAT) on the performance of one UFAD system commonly used in U.S. office buildings. The results indicate that raising design AHU SAT produces net savings in HVAC electricity consumption, even though cooling energy reductions trade off against fan energy increases; but the magnitude is climate dependent. However, heating energy (gas consumption) increases with increasing SAT, which tends to counterbalance decreases in electricity consumption. The paper includes a discussion of these somewhat counterintuitive findings.

## INTRODUCTION

Underfloor air distribution (UFAD) is an innovative method of providing space conditioning to offices and other commercial buildings. Under cooling operation, properly controlled UFAD systems produce temperature stratification. UFAD systems supply cool air to the room from an underfloor plenum through vents, known as floor diffusers, located in a raised floor. In the most common application, cool air is forced upwards through supply diffusers by the pressure difference between the pressurized plenum and the space. In some cases, the airflow is fan-driven.

Previous research describes the UFAD modeling algorithms installed in EnergyPlus (Webster et al. 2008, Bauman et al. 2007a that make this study possible.

The potential energy savings of UFAD compared to conventional overhead systems are predominantly associated with two factors:

1. *Fan energy reductions*. Fan discharge pressures for UFAD systems can be lower than for OH due to reduced ductwork and thus reduced pressure drops in the supply distribution system. Differences in required airflow rate will also influence fan energy use. UFAD airflow rates are dependent on a variety of factors and design conditions. The amount of airflow required to satisfy the room cooling load will tend to decrease with lower SAT because of increasing heat transfer from the room to the underfloor supply plenum (thereby, reducing room cooling load). However, common practice is to use higher air handler SATs (typically 3-4°C (5-7°F) greater than OH) which tends to increase airflow by increasing the diffuser discharge temperatures. The increased diffuser temperature results from the dual effects of higher SAT and temperature gain (known as thermal decay, see below) in the supply plenum. The combined effect of all these factors produces UFAD cooling airflow rates that can be lower or higher than OH systems (Bauman et al. 2007b). For the

particular system type used for this study, perimeter fan coil unit (FCU) energy also adds to the air handling energy consumption.

2. *Cooling savings*. With the higher SATs commonly used for UFAD systems, there are increased opportunities for 'free cooling' savings from airside economizers in suitable climates.

Dynamic hourly models that can respond to changing operating conditions are required so that the impact on annual energy use of all the above factors can be accurately determined.

Differences in energy and demand performance between conventional overhead and UFAD systems were previously reported using the new UFAD capabilities of EnergyPlus (Linden et al. 2009). The present study examines one issue illuminated in that work; the tradeoff between cooling and fan energy use for UFAD systems in relation to changes in AHU supply temperature.

## METHODS

This study uses a comparative, parametric approach where all building and system elements are the same and only the design AHU supply air setpoint is changed.

### Description of EnergyPlus modeling

EnergyPlus is a building energy simulation program developed and supported by the U.S. Department of Energy (DOE). Based on a combination of two predecessor programs, DOE-2 and BLAST, it has greater capabilities than either one. The following key features make EnergyPlus an ideal candidate for simulating UFAD systems.

- *Room air stratification* – In UFAD systems stratification is a key feature that affects performance and thus must be modeled to accurately simulate these systems. Detailed heat balance calculations use a two-layer model of the room that is a simplified representation of the temperature stratification produced by UFAD systems under cooling operation. A semi-empirical algorithm predicts the distribution of heat gains between the lower and upper layers of the room and augments the heat balance calculations for each.

- *Simultaneous simulation of zone, system and plant*. EnergyPlus performs the system and plant simulation, and the air and surface heat balances (including radiant exchange) simultaneously. This is essential for realistic energy modeling of non-mixed systems like UFAD.

### UFAD building model characteristics

This and other studies is based on a whole-building prototype created for EnergyPlus v 3.1[1] and run with California weather files for climate zone 12 (CZ12RV2.epw), herein referred to as Sacramento, and climate zone 3 (CZ03RV.epw) referred to as San Francisco. A summary of the prototype building characteristics follows.

*Building geometry*. The prototype is a three-story rectangular medium-sized office building with an aspect ratio of 1.5. Each 1,852 $m^2$ (20,000 $ft^2$) floor plate consists of four perimeter zones, an interior zone and a service core[2], representing approximately 40, 45 and 15 percent of the floor area, respectively. "Ribbon" windows with a 38% window-to-wall ratio (WWR) are used; other ratios can be simulated by changing the height of the window. Window properties and wall thermal characteristics adhere to ASHRAE 90.1-2004 performance rating specifications contained in 90.1 Appendix G. However, since real windows rarely match properties listed in the standard, the prototype contains specifications for real glazing systems with properties that are as close as possible to, but no worse than, the values listed in the standard. Key features of the building design can be found in Appendix A of Linden et al. (2009).

*Supply plenum modeling*. The prototype supports modeling of supply plenum effects by including supply plenum thermal zones below each room zone. Room zones receive cool supply air through these plenums. EnergyPlus performs a full heat balance on the underfloor plenum accounting for heat gain into the plenum from both the room above and return plenum from the floor below. This arrangement ensures accurate modeling of thermal decay (temperature increase in supply air as it passes through the plenum resulting from heat transfer to the plenum). The total floor-to-floor height and the occupied zone floor-to ceiling height (13 ft and 9 ft,

[1] For this study, a special development version of EnergyPlus v3.1 was used that incorporated a number of enhancements primarily to UFAD objects.

[2] The service core was not modeled in this project; no loads or schedules were applied. Occupancy, lighting, and equipment intensities need to be adjusted appropriately when comparing to other work where service cores are not included.

respectively) are equivalent to buildings with a conventional overhead VAV system but with return plenum height adjustments made to accommodate the supply plenums. For the bottom floor, ground temperature schedules were derived from the EnergyPlus slab simulator utility. For the supply plenum, airflow dependent convective heat transfer coefficients derived from work done by Bauman et al. (2007a) are used.

*Internal Loads and Schedules.* Table 1 lists internal loads assumed (based on total floor plate area). These values are similar to those found in the literature (NREL 2008) for other simulation studies.

*Table 1. Internal load characteristics*

| | |
|---|---|
| Overhead lighting, W/m$^2$ (W/ft$^2$) | 10.8 (1.0) |
| People sensible, W/m$^2$ (W/ft$^2$) | 4.0 (0.37) |
| Peak occupancy, m$^2$/person (ft$^2$/person) | 18.6 (201) |
| Equipment W/m$^2$ (W/ft$^2$) | 8.1 (0.75) |
| Total, W/m$^2$ (W/ft$^2$) | 22.9 (2.1) |

Schedules for people, internal loads, and outside air ventilation are 8am to 5pm weekdays, and 8am to 12pm on weekends. The HVAC system operates from 7am to 10pm, and thermostat occupied setpoint schedules operate from 6am to 7pm. The HVAC system is off at night. Thermostats are set at 21.1°C/15.6°C (70°F/60°F) heating, 23.9°C/29.4°C (75°F/85°F) cooling for occupied/unoccupied hours.

*HVAC Systems and Plant.* Table 2 shows details of system and plant inputs. At the zone level, the UFAD system consists of swirl diffusers in interior zones and linear bar grille diffusers in the perimeter zones served by a variable speed series fan coil unit. The FCU shuts off when zone temperatures are in the heating-cooling dead band, but airflow of 6% of design volume is assumed to leak through the FCU when it is off. Consistent with currently available products, when the FCU is on, it starts at a minimum speed, which provides airflow of 12%. A conventional VAV reheat system serves the service core although no loads are assigned to this zone during this study.

The zones are served by a single variable speed central station air-handling unit including an economizer, chilled water cooling coil, and supply fan. The fan is a high efficiency airfoil where part-load operation is represented by a simulated static pressure reset strategy. Design static pressure requirements reflect an open plenum design where minimal ductwork is used. All simulations used the same design static pressure, which is assumed about 25% lower than OH primarily due to the elimination of distribution ductwork. (See Table 2.) The model simulates supply plenums in series, meaning that air is first delivered to the interior zone plenum and then to the perimeter zones. No central heating coil at the AHU is included to maintain comfort in interior zones, since it is not common practice in California climate types to do so. However, there are some comfort ramifications as discussed below.

*Table 2. Summary of HVAC system configuration*

| HVAC | |
|---|---|
| AHU supply temp | 13.9, 15.6, 17.2°C (57, 60, 63°F) |
| AHU fan design static press | 775 Pa (3.1 iwc) |
| AHU fan design efficiency | 63% |
| AHU part load shutoff[1] | 125 Pa (0.5 iwc) |
| Relief fan design static | 150 Pa (0.6 iwc) |
| Relief fan design efficiency | 37% |
| Outside air rate | 0.76 l/(s m$^2$) (0.15 cfm/ft$^2$) |
| System cycles at night | No |
| Zone Min airflow, % max | Opt[2] |
| Interior zone reheat | No |
| FCU design static pressure | 125 Pa (0.5 iwc) |
| FCU design efficiency | 15% |
| Plant | |
| Chiller (screw) design COP | 5.26 |
| Boiler design efficiency | 80% |

[1]Designates low shutoff pressure associated with static pressure reset
[2]Opt = Optimized for 0.76 l/(s m$^2$) (0.15 cfm/sf) (CA Title-24)

The central plant consists of dual central screw chillers with variable speed pumps and cooling tower using chilled water reset based on outside air temperature. Two gas fired, forced draft hot water boilers provide heating to all heating coils. The boiler simulation includes a special boiler curve that more accurately simulates turndown at low part load conditions. Hot water supply temperature is reset based on outside air temperature.

## Sizing issues

For each parametric run, system components are re-sized. However, during this and other studies conducted by the authors it became obvious that the autosizing procedures used in EnergyPlus are not always appropriate or are not even available for UFAD system components (e.g., determining the number of diffusers). In EnergyPlus, the user should explicitly specify the VAV box cooling design supply air temperature (SAT) for the sizing of each VAV box. With that information, EnergyPlus sizes each VAV box based on the peak cooling load determined from the design day calculation. In contrast to a conventional OH system, the actual diffuser discharge air temperature in a UFAD system is significantly different from the central air handler SAT due to the heat gain of the conditioned air in the underfloor plenum. The user needs to take this into account and specify the correct VAV box design SAT under each condition. Several methods to more accurately size system components were developed. For example, to support the use of low minimum ventilation rates, a special routine allows simulation of minimum ventilation airflows that UFAD systems can provide (as opposed to higher minimums used in OH VAV to prevent dumping during cooling and short-circuiting in heating). Design day runs were made first to determine zone design air volumes. Then these results plus minimum ventilation requirements were used to specify the minimum fraction for each zone, since the current EnergyPlus version only allows the user to specify the minimum fraction of each VAV box, not the minimum airflow. This technique ensures that all simulations have consistent ventilation rates. A calculation of the design number of UFAD diffusers was the focus of another method where design day results plus diffuser design volumes determines the number of diffusers used in the annual simulation. This ensures accurate simulation of stratification. In addition to determining the zone design airflow volumes, other HVAC components such as chillers and boilers were also sized based on the design day run results instead of relying on the EnergyPlus autosizing function.

### Sensitivity of energy performance

In comparison studies, it is important to understand how representative the results are for other design and operating conditions. In the Linden study, the impact of building design parameters on the comparison of HVAC system energy use was assessed by a set of sensitivity runs. Figure 1 shows (from Linden et al. 2009) there is little impact on HVAC system performance *differences* (e.g., in this case the difference between OH and UFAD) due to window-to-wall ratio and internal load levels. These figures show results for Sacramento only, but are representative of results in other California climates.

## RESULTS AND DISCUSSION

### Cooling tradeoff analysis

In this study, the SAT leaving the air handler was fixed throughout annual operation but was varied parametrically from 13.9°C (57°F)[3], representative of OH system setpoints, to 17.2°C (63°F), a commonly employed setpoint for UFAD systems. All other parameters were unchanged. Figure 2 shows HVAC site energy consumption results in terms of the energy use intensity (EUI) for the three cases in two California climate zones and Figure 3 shows the gas/electric breakdown.

As shown in Figure 2, and contrary to expectations of the researchers, best design SAT performance appears to be climate dependent; 15.6°C (60°F) in Sacramento but 17.2°C (63°F) for San Francisco. From Figure 3 it is clear that there is a net electric savings as SAT is increased but more so for San Francisco than Sacramento; savings for both appear to level off as SAT is increased. It is also clear that this is due to a tradeoff between fan energy and cooling energy; increased SAT tends to lower cooling energy due to more economizer hours but fan energy is increased due to the higher cooling airflows required.

As Table 3 shows, the net tradeoff (sum of cooling, fan, and auxiliary energy) varies with climate. In warm climates like Sacramento, cooling and fan energy changes tend to offset each other as SAT is increased so there is little difference between SAT 15.6°C (60°F) and 17.2°C (63°F). In a mild, “good economizer” climate like San Francisco there are noticeable savings at SAT 17.2°C (63°F). However, as shown by Figure 3, heating energy increases with increasing SAT. This increase counterbalances the net electric savings producing the counterintuitive results shown yielding, for example, an optimum SAT for Sacramento of 15.6°C (60°F).

### Heating energy analysis

The following describes how the heating system operation leads to higher heating energy use as SAT increases. Two major processes are occurring concurrently to produce the breakdowns shown in Figure 3:

---

[3] A SAT of 13.9°C (57°F) was used in an attempt to provide some consideration for the impact of OH system duct heat gain on airflow requirements. To keep consistent economizer performance, the same value was used for the UFAD base case.

- Zone heating loads decrease as SAT increases. This is due to increased concrete slab and raised floor surface temperatures caused by higher temperatures of the air passing through the underfloor plenum at higher SATs. However, as shown, this effect is relatively small.
- As shown in Figure 3, the reheat portion of the FCU heating energy increases as SAT increases (i.e., reheat is calculated from the FCU supply volume and the temperature difference between the room and supply air temperature entering the FCU). This occurs primarily because the minimum volume of the FCU (i.e.,12% of maximum design volume) is greater due to the larger size FCUs required to accommodate the higher cooling airflows at higher SATs.

  The reheat increases despite the fact that the temperature entering the FCU is higher as SAT is increased; the higher minimum volume dominates this tradeoff. The entering temperature is higher with increased SAT even though the thermal decay actually decreases; the temperature rise through the plenum is less as airflow increases with higher SAT, but not enough to lower the FCU entering temperature.

**Comfort considerations**

One method to assess relative comfort is to compare zone operative temperatures (average of zone dry bulb and mean radiant temperature) during occupied hours for different simulations. For UFAD, the temperature in the lower occupied region of the zone is used for the dry bulb component. Operative temperature is a necessary but not sufficient metric to measure occupant comfort completely since other parameters such as clothing level, metabolic rate, air velocity and humidity are not included. It also does not account for other factors such as any benefit assigned for occupant personal control, which may be applicable to UFAD systems in particular. However, for this study, it at least provides an indicator when applied to the zone where problems are most likely to arise; interior zones when operating near heating conditions (recall that interior zones have no terminal heating equipment).

Figure 4 shows operative temperature histograms for each SAT in each of the two climates. The curves show cumulative results on the right hand axis. If we assume that heating conditions occur at operative temperatures below about 21°C (equal to the heating dry bulb set point), lower SATs appear to affect comfort very little in San Francisco. However, in Sacramento they have more of an effect; 24% below 21°C for SAT =13.9°C (57°F), and 13% for SAT= 15.6°C (60°F), the optimum energy operating point. With this knowledge, designers can make a judgment about whether to install a central heating coil in the AHU to mitigate low interior zone temperatures or possibly rely on occupants controlling their diffuser to manage their comfort instead. Other work by the authors indicates that these coils can have a significant energy impact. In San Francisco, it appears that there is little risk of overcooling interior zone occupants, which confirms common practice in this area.

**Further studies**

Further studies may reveal variations on these results due to factors not studied such as the following:

- other system types and configurations (e.g., alternative plenum distribution strategies),
- improved performance from more or alternative diffusers types,
- different control strategies (e.g., SAT reset strategies; wider thermostat deadbands that allow credit for personal control),
- methods for, and impact of, improved ventilation effectiveness,
- operation in other more severe climates and in larger buildings.

The authors anticipate conducting studies such as these in the future.

## CONCLUSION

The purpose of this study was to determine the impact of changes in AHU supply air temperature on UFAD system energy performance and to better understand how cooling, heating and fan energy "tradeoff" as SAT is increased.

Although limited to two California climate zones, the results indicate that there are net decreases in HVAC electricity (cooling, fans, and auxiliaries) consumption as SAT (using fixed setpoints) is increased, but the magnitude is climate dependent. In general, diminishing returns occur as SAT is increased since fan energy increases tend to balance cooling energy decreases (due to more economizer hours available at higher SATs). However, heating energy increases as SAT is increased. This results in varying optimum design SATs depending on climate.

The results also indicate that there may be interior zone comfort consequences to operating these systems without a central AHU heating coil, again depending on climate. The optimum operating SAT is likely to be affected for those cases (e.g., cold climates) where a heating coil is required. It appears that designers need to consider this energy vs. comfort tradeoff carefully in cool and cold climates.

## ACKNOWLEDGMENTS

This work was supported by the California Energy Commission (CEC) Public Interest Energy Research (PIER) Buildings Program under Contract 500-08-044 and the Center for the Built Environment (CBE) at the University of California, Berkeley.

## REFERENCES

Bauman, F., T. Webster, et al. 2007a. “Energy Performance of UFAD Systems” – Final Report to CEC PIER Program. CEC Contract No. 500-01-035. Center for the Built Environment, University of California, Berkeley, CA. http://www.cbe.berkeley.edu/research/briefs-ufadmodel.htm.

Bauman, F., T. Webster, and C. Benedek. 2007b. “Cooling Airflow Design Calculations for UFAD.” *ASHRAE Journal*, Vol. 49, No. 10, October, pp. 36-44.

Linden, P., J. Yu, T. Webster, F. Bauman, K.H. Lee, S. Schiavon, and A. Daly. 2009. “Simulation of Energy Performance of Underfloor Air Distribution (UFAD) System.” Final Report to CEC Building Energy Research Grant (BERG) Program, June.

NREL. 2008. “DOE Commercial Building Benchmark Models.” Conference Paper NREL/CP-550-43291, National Renewable Energy Laboratory, July

U.S. DOE. 2010. “Input-output Reference.” EnergyPlus Manual, US Department of Energy, April

Webster, T., F. Bauman, F. Buhl, and A. Daly. 2008. “Modeling of Underfloor Air Distribution (UFAD) Systems.” SimBuild 2008, University of California, Berkeley, CA, July 30 – August 1.

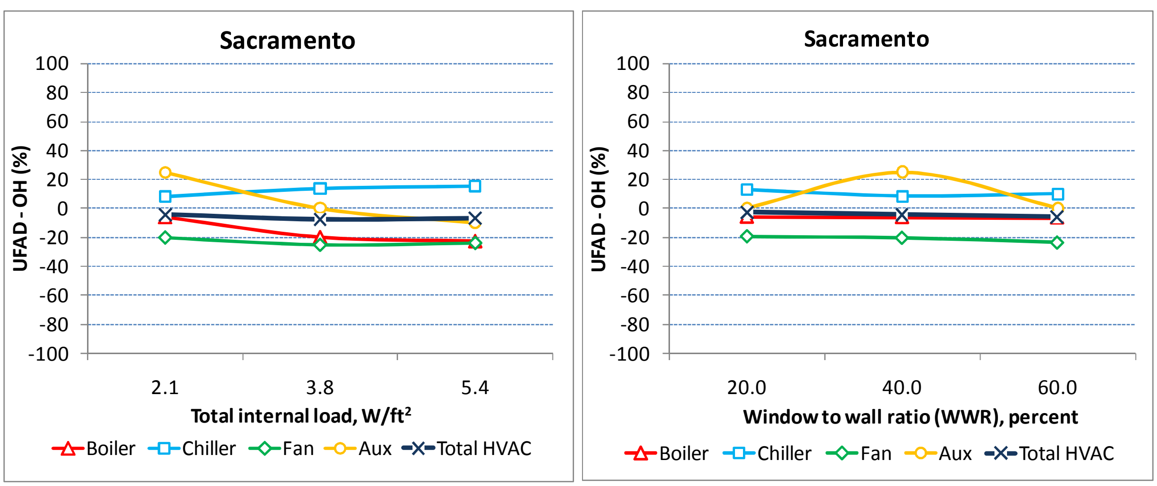



*Figure 1. Example of sensitivity analysis for internal load and window-to-wall ratio for overhead to UFAD comparison (from Linden et al.)*

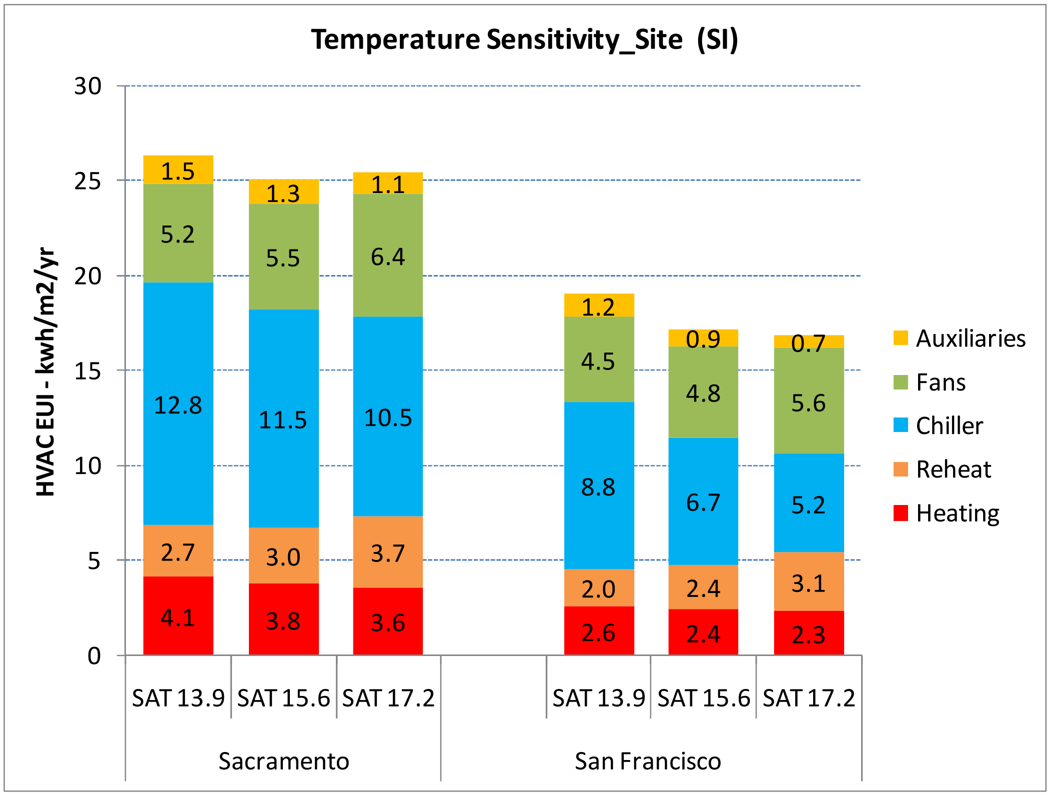



*Figure 2. Impact of AHU supply air temperature in two climates*

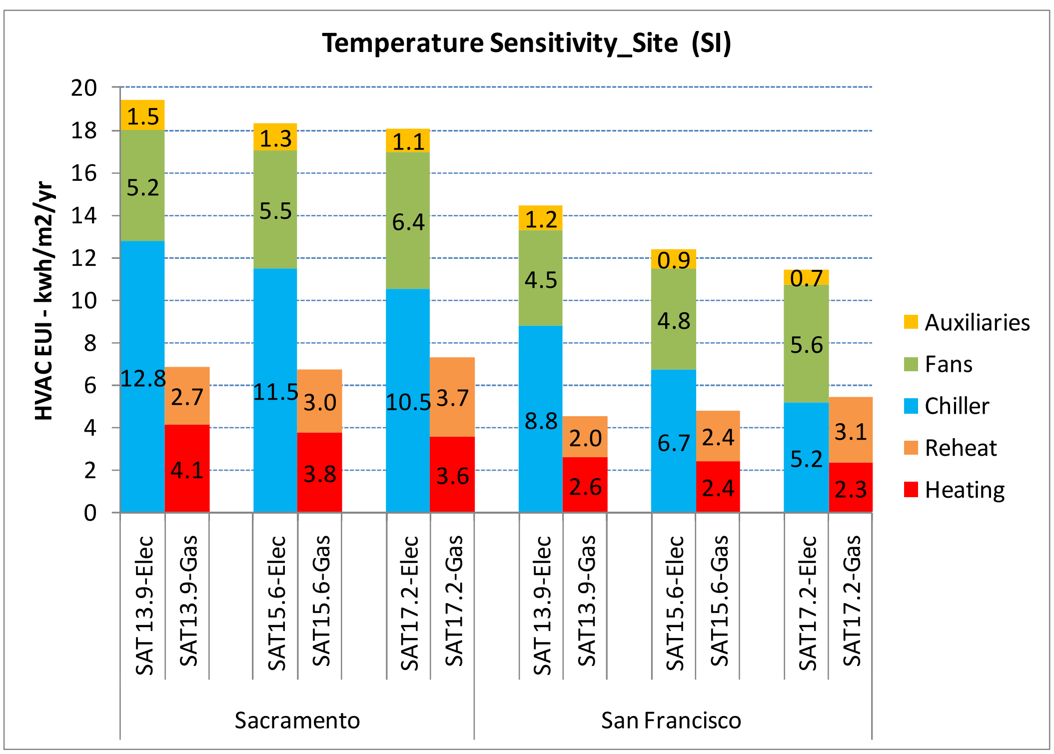
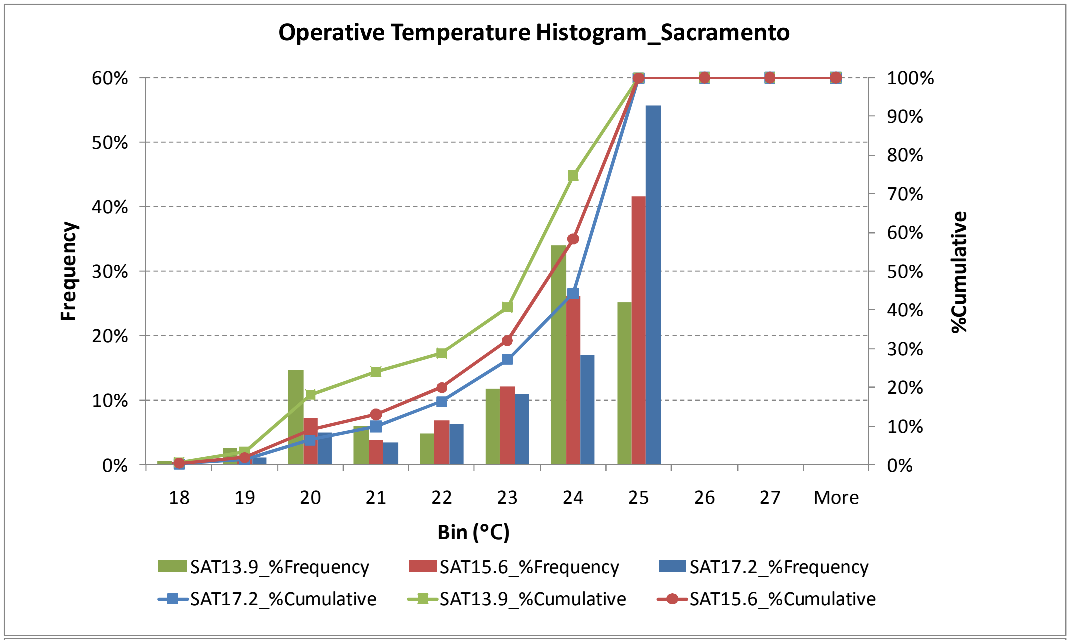



*Figure 3. Gas/electric breakdown for variation in AHU supply temperature in two climates*

*Table 3. HVAC electric and gas breakdown (difference from result for SAT = 13.9°C)*

| kWH/m2-yr | Sacramento | | | San Francisco | | |
|---|---|---|---|---|---|---|
| **SAT** | **13.9°C** | **15.6°C** | **17.2°C** | **13.9°C** | **15.6°C** | **17.2°C** |
| HVAC Gas EUI | 6.9 | 6.7 (-0.1) | 7.3 (+0.5) | 4.6 | 4.8 (+0.2) | 5.4 (+0.8) |
| HVAC Elec EUI | 19.4 | 18.3 (-1.1) | 18.1 (-1.3) | 14.5 | 12.4 (-2.1) | 11.4 (-3.0) |
| Total | 26.3 | 25.0 (-1.3) | 25.4(-0.9) | 19.0 | 17.2 (-1.8) | 16.9 (-2.2) |
| Change, % | -- | -4.9% | -3.4% | -- | -9.5% | -11.1% |



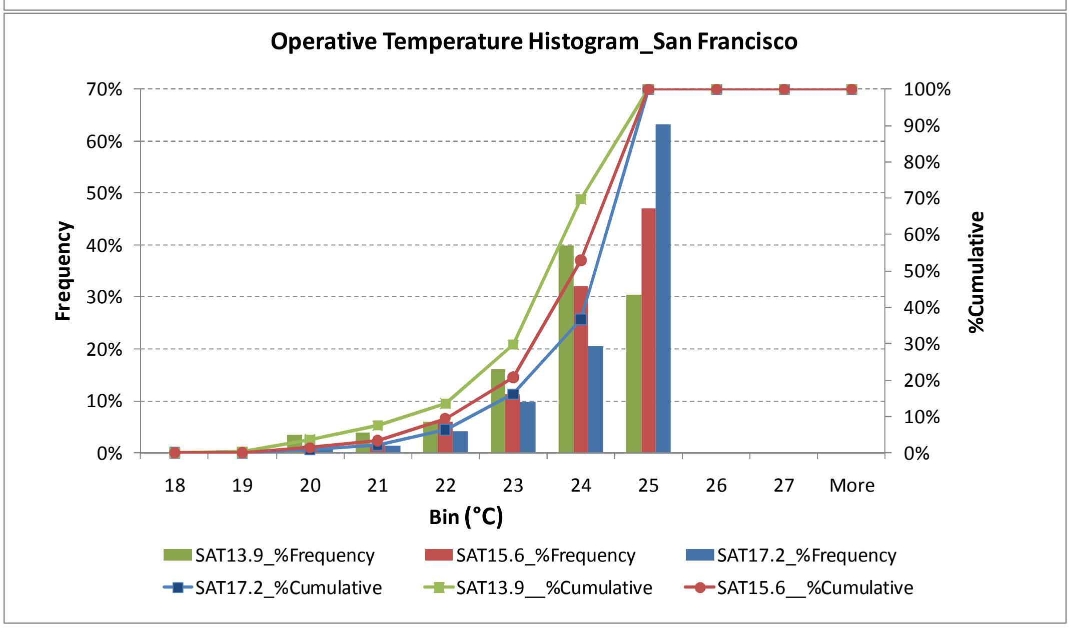




*Figure 4: Comfort histograms*