CONSORTIUM for BUILDING ENERGY INNOVATION

Case Study

CBEI Retrofit Demonstration Testbed:

Novel CAV to VAV AHU Retrofit

Background

Philadelphia Business and Technology Center, 5070 Parkside Avenue, Philadelphia, PA, 19131

Former manufacturing facility retrofitted to office space and commercial use

Constructed in the 1930's

Six floors

272,000 square feet

10,000 ft^2 Testbed
(4th floor offices in west wing)

Masonry construction

Existing HVAC system is ducted constant volume AHU's, Natural gas fired steam boilers

Philadelphia Business and Technology Center

The question, addressed by this project, is how to cost effectively save space conditioning energy and dollars in buildings with ducted constant air supply systems, particularly since many older central city buildings are 50% or less occupied. The problem for these older systems is how to design a low cost VAV system. CBEI researchers worked with a local HVAC contractor to test a unique approach to this problem and determine the energy performance of a potential low cost option.

The existing HVAC system on the 4th floor, which had reached its "end-of-life", was a constant air volume system with central air handler (self-contained vertical DX unit). The space was approximately 50% occupied during the test which wastes energy by conditioning the unoccupied spaces. The key retrofit idea is to implement occupancy sensor controlled air flow dampers, so that when a zone is unoccupied, the supply air damper will be in a minimum position. The supply fan will be controlled by duct static pressure.

Research Project

Project Goal

Energy reductions related to HVAC optimization achieved by HVAC system sizing and configuration modification, including use of zone level dampers controlled by occupancy sensors for variable occupancy optimization.

Project Participants

Building owner: Philadelphia Business & Technology Center (PBTC)
Mechanical Contractor: ECSI (Environmental Construction Services, Inc. / Element Mechanical)
M&V/BAS Contractor: Radius Systems, Inc.
CBEI Investigators:
PSU – Mark Stutman, Ben Cohen, Scott Wagner
Exergy Partners Corp. – Rich Sweetser
CMU –Vivien Loftness, Azizan Aziz, Erica Cochran, Jihyun Park, numerous grad students…
UTRC – Teijun Wu
Purdue – Travis Horton, grad students
Covestra – (former Bayer Material Sciences) – Mughda Mokashi, Amy Wiley, Walt Clevenstine

Rationale for Selecting EEMs/ Initial Proposal to Owner

Environmental Construction Services Inc. (ECSI) prepared and submitted a proposal to the owner of the PBTC to replace two end-of-life AHU's. ECSI proposed to replace the existing HVAC system with variable air volume units without installing VAV boxes in the existing ductwork. The existing branch supply air ducts were retrofitted with two-position zone dampers in each office space, effectively converting the constant air volume distribution system into a simplistic VAV system. The following energy efficiency measures were carried out as part of this retrofit proposal:

- Replace existing vertical packaged AHU's with smaller (15 to 12 tons) units
- Select AHU's with economizers and add necessary ductwork for outside air intake
- Use variable speed fan motors and add variable frequency drives to the AHU's
- Install duct static pressure sensors to control supply fan VFD's
- Add occupancy sensors to each office to control lighting and associated zone damper
- Seal rigid ducts from inside to reduce leakage into the return plenum and maximize static pressure control
- Control AHU's with new building automation system

10,000 ft^2 Testbed

The concept was to replace the old AC units (SEER 8.3) with high-efficiency units (SEER 15) with a variable speed fan, install a two-position on/off actuator on the existing balancing dampers in the supply duct to diffusers for each room, and install an occupancy sensor in each room to control both the lights and the dampers. In the mechanical room, the plan was to replace the two vertical packaged AC units and use variable frequency control for the supply fans so that when the dampers in some zones were 'closed', the fan speed would be decreased to maintain the duct static pressure. In this way fan power would be reduced. For the purpose of properly sizing the HVAC units, a building envelope model with a simple zone model assuming fully occupied spaces was constructed. Based on this model, a full year hour by hour building load analysis was performed and the peak cooling and heating load was used to size the HVAC units.

4th Floor Testbed

Sensors and an energy management system2 (EMS) were installed to enable pre- and post-retrofit monitoring of system operation to be measured. In addition, valuable baseline operating data was obtained for verification of the integrated system model for more accurate evaluation of retrofit options. The AHU instrumentation included power, temperatures (outdoor air, return air, supply air, condenser entering and leaving air), outdoor air flow, return air flow, and return air CO_2. Space condition monitoring included temperature, relative humidity, and CO_2. Plenum temperatures, outdoor air temperature, steam valve position, and solar irradiance were also measured.

Testbed Interior Layout

Figure 1 – 4th Floor West Floor Plan, AHU Location and Duct Layout

HVAC Retrofit

Existing System Description

The 4th floor was served by two constant volume 15 ton packaged AC units (self-contained vertical DX type) housed in two mechanical rooms at opposite ends of the space (Figure 1). The units supplied conditioned air to all spaces whether the space was occupied or not. The compressors in these units had both failed, necessitating their replacement. Internal steam coils fed from the building's boiler supplied heat. The space above the drop ceiling serves as a common return air plenum for both AHUs. Air was supplied to 24 individual offices through ducts, and returned to the mechanical rooms through a plenum bounded by the drop ceiling and the underside of the concrete 5th floor. Each AHU served two duct branches, one serving the outside (east) perimeter offices, the other the interior offices. Outside make-up air was drawn through fixed louvers in the wall. The old AHUs were unconventionally controlled by the facility manager, who typically powered them on during occupied hours and off at night and on weekends. Thermostatic control was not employed which resulted in over conditioning of several spaces. Sometimes an AHU was turned off during normally occupied hours to compensate for over conditioning, which deprived the spaces of fresh air.

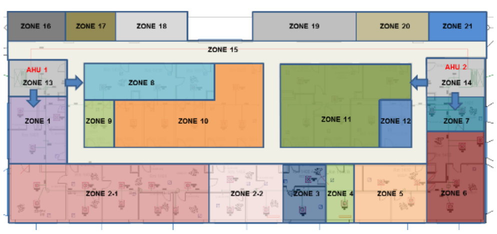
New System Description

Investigators from UTRC and Purdue modeled the cooling load of the space and concluded that 12 tons of cooling capacity was adequate for the space, and that replacing the AHUs with same-sized 15 ton ACs was not necessary. Two 12-ton Carrier split system AC's (model number: 50XCR14) replaced the existing AHU's in the mechanical rooms. Remote condensing units (model number: 09XC14), were set on the roof adjacent to the office space. This change from a packaged unit to a split system left space and exterior wall access to accommodate the addition of an economizer damper. Typically, the air side economizer can result in ~5-10% cooling energy savings in transitional seasons when the outdoor air temperature is lower than the indoor cooling setpoint and the building needs cooling. The economizer also allowed the controlled introduction of outdoor air into the space. Variable speed motors and VFD's were selected for the supply fans of each air handler, two-position on/off actuators were installed on the existing balancing dampers in the supply duct to diffusers for each room, and occupancy sensors were installed in each room to control both the lights and the dampers to emulate a variable air volume system.

HVAC Retrofit

Ductwork Changes - Two-position dampers were installed in each office supply duct, to be controlled by newly installed occupancy sensors which would also control the zone lighting. The dampers were set with a minimum position to allow 10% of full supply air to enter the zone at all times. A static pressure sensor was installed in the main supply trunk for each AHU to gauge supply air demand. The ducts were later internally sealed by a subcontractor to ECSI. Two steam coils were installed in the supply ducts (two branches) of each air handler to replace the steam coils that were internal to the previous AHU's. These coils supply boiler steam via uninsulated pipes in the return air plenum, which add additional heat to the return air when hot. Unfortunately, control of the boilers, which serve the entire building, is beyond the scope of this retrofit.

Zone Model



New BAS Control - Radius Systems installed an Automated Logic BAS along with M&V sensors to control and monitor the new HVAC system. The following sensors were included to each AHU:

- Wireless zone temperature and RH% sensors in each office
- CO2 sensors in half of the offices
- Wireless temperature sensors throughout? the return plenum
- Outside temperature and RH%
- AHU supply/return/mixed air temperatures
- Return air CO2
- AHU power (indoor unit only, condensers un-metered)
- Duct static pressure
- Supply fan VFD signal and motor speed

Cooling system change-out and improved thermostatic control

Impact - Two existing 15-ton package units were each replaced by a 12-ton split-system. Energy savings should come from downsizing of tonnage, more efficient compressors and more efficient supply fan system (i.e., more efficient fan and fan motor) and improved thermostatic control of units. Energy Savings during occupied hours: 8am to 5pm M-F.

i. Useable pre-retrofit data for AHU-1 was not available. Since the pre-retrofit AHUs were identical and running at constant volume, Aug 2013 pre-retrofit energy use data for AHU-2 was projected into July 2015 post-retrofit period for both AHU-1 and AHU-2.
ii. For Aug 2013, AHU-2 ran full-out at an average of 16.49 kW during occupied hours, except when unit was manually turned off.

Cooling system change-out and improved thermostatic control performance

iii. July 2015 post-retrofit data captures the hours the unit was manually shut off during Aug 2013. The August 2013 pre-retrofit baseline data also captures periods when either new AHU-1 or new AHU-2 were shut-off for extended periods of time (which would have also happen had the old units still be installed) in 2015. Incorporating these changes into the baseline creates an Adjusted Baseline Energy Use for July 2015.

iv. In order to estimate total energy use of the new split system, sub-metered data was adjusted by adding 2 kW of power consumption associated with the remote condenser units (which could not be submetered separately).

v. Figure 2 show pre- and post-retrofit energy use profile for AHU-2.

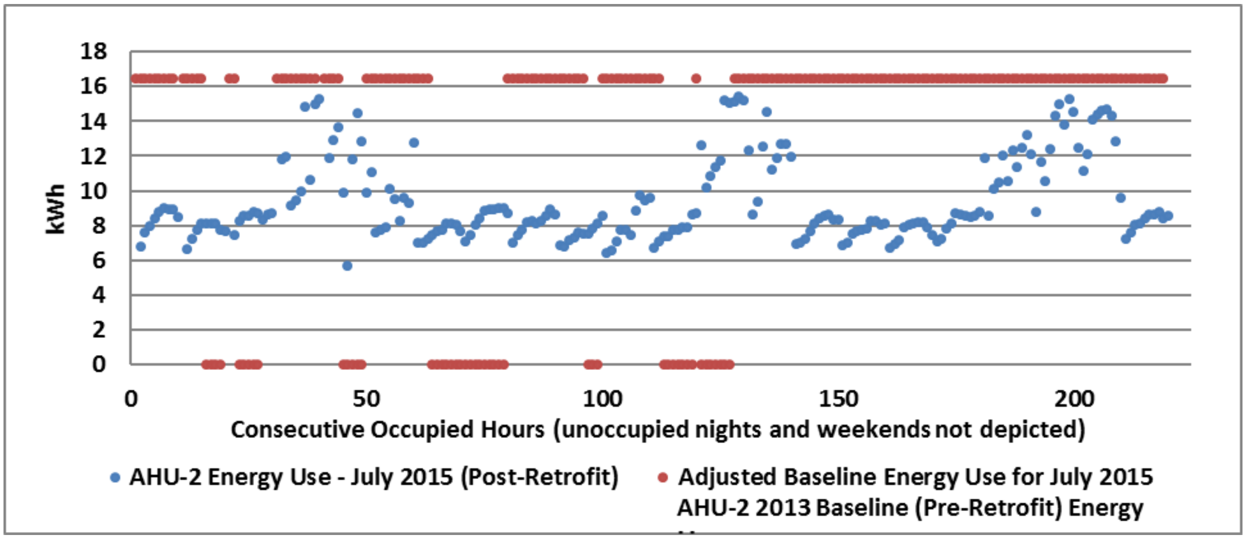


Figure 2 - Cooling Energy Use Pre- and Post-Retrofit AHU-2.

Energy Savings of Equipment Change-out

Energy Savings of Equipment Change-out

a. Savings for the month were found to be about 34% (999 kWh) and 26% (693 kWh) for AHU-1 and AHU-2, respectively. At $0.10/kWh, cost savings were approximately $100 and $69.
b. Savings for the cooling season were assumed to be 4x the monthly savings.
c. Due to equipment scheduling issues during the post-retrofit period in July 2015, cooling energy savings for unoccupied hours were not calculated.

Table 1 shows kWh energy savings from the equipment change-out during occupied hours:

Table 1 - Air Handler Unit Change-Out and Improved Thermostatic Control
Cooling Energy Savings - Occupied Hours

	AHU-1 Energy Use (kWh):	AHU-2 Energy Use (kWh):
Adjusted Baseline Energy Use:	2902	2704
New Unit July 2015:	1903	2011
kWh Savings:	999	693
% Savings:	34%	26%
$ Savings for Month (@ $0.10/kWh):	$100	$69
$ Savings for Cooling Season (@ $0.10/kWh):	$400	$277

Energy Savings of Custom VAV System, Duct Sealing, & Duct Static Pressure Set-Point Reset

Energy Savings of the Custom VAV system, duct sealing and duct static pressure set-point reset

To assess the impact of custom VAV system and associated duct sealing and duct static pressure set-point reset, the baseline to measure energy savings was defined as January 2013 (January was selected since there is no cooling system energy use). This was done to remove the potential impact of the equipment change-out of the new cooling system (i.e., compressors and condenser fan energy use). Energy savings are generated by the custom VAV system, duct sealing and duct static pressure set-point reset.

d. Energy savings were assessed for the occupied hours of 8am to 5pm M-F.
e. During occupied hours, both AHUs ran continuously for Jan 2013 and Jan 2016.
f. For Jan 2013, fan kW draw was assumed to be a constant 2 kW.
g. Figures 3 and 4 show energy use (average hourly kW) for both AHU-1 and AHU-2 at each hour of occupancy for January 2013 and January 2016:

Continued - Energy Savings of Custom VAV System, Duct Sealing, & Duct Static Pressure Set-Point Reset

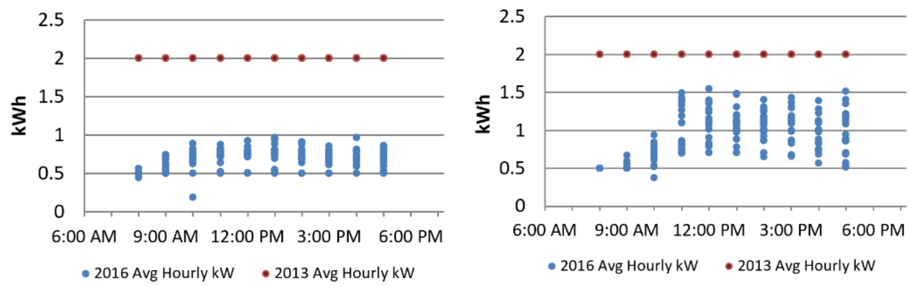


Figure 3 - Fan Energy Use AHU-1 (left) and AHU2 (right)

Table 2 shows kWh energy savings from the custom VAV system, duct sealing and duct static pressure set-point reset during occupied hours:

Table 2 - Custom VAV System, Duct Sealing and Duct Static Pressure Set-Point Reset Fan Energy Savings - Occupied Hours		
	AHU-1 Energy Use (kWh):	**AHU-2 Energy Use (kWh):**
kWh Consumption Jan 2013:	376	376
kWh Consumption Jan 2016:	129	167
kWh Savings:	247	209
% Savings:	66%	56%
Monthly $ Savings (@ $0.10/kWh):	$25	$21
Annual $ Savings (@ $0.10/kWh):	$296	$251

Energy savings for the month were found to be about 66% (249 kWh) and 56% (209 kWh) for AHU-1 and AHU-2 respectively. At $0.10/kWh, monthly cost savings were approximately $25 and $21 with annual cost savings were of $296 and $251 for AHU-1 and AHU-2, respectively.

a. During the same baseline period the fans typically began operation about 5am and turned off about 7pm.
b. The AHU fans' power draw was estimated to be 2 kW when the AHU operated. Total energy use for the one-month pre-retrofit period was 112 kWh for each AHU.
c. Post-retrofit scheduling during unoccupied hours was not as tight as in the pre-retrofit period, but total fan energy was reduced slightly by the variable speed control. Energy use for AHU-1 was 65 kWh for the month, while AHU-2 used 47 kWh over the one-month post-retrofit period.

Table 3 shows kWh energy savings from the custom VAV system, duct sealing and duct static pressure set-point reset during un-occupied hours:

Table 3 - Custom VAV System, Duct Sealing and Duct Static Pressure Set-Point Reset Fan Energy Savings - Unoccupied Hours		
	AHU-1 Energy Use (kWh):	**AHU-2 Energy Use (kWh):**
Existing Unit Aug 2013:	112	112
New Unit Jan 2016:	65	47
kWh Savings:	47	65
% Savings:	42%	58%
Monthly Savings:	$5	$7
Annual $ Savings (@ $0.10/kWh):	$56	$78

Overall Performance Improvement

Total energy savings from all measures during unoccupied hours

Savings for the month were found to be about 42% (47 kWh) and 58% (65 kWh) for AHU-1 and AHU-2, respectively. At $0.10/kWh, monthly cost savings were on the order of $5 and $7 for AHU-1 and AHU-2 with annual cost savings of $56 and $78 for AHU-1 and AHU-2, respectively.

Total energy savings from all measures

Efficient cooling equipment savings are assumed to be 4x the July savings as a proxy for energy savings for the whole cooling season and fan energy savings for both occupied and unoccupied periods were extrapolated to 12 months. Table 4 shows total annual energy savings from all measures combined. Total annual energy and cost savings were found to be 43% ($753) and 36% ($606) for AHU-1 and AHU-2, respectively.

Table 4 - Air Handler Unit Energy Efficiency Measure Assessment Total Annual Savings - All Measures Combined		
	AHU-1 Energy Use (kWh):	**AHU-2 Energy Use (kWh):**
Pre-Retrofit 2013	17468	16672
Post-Retrofit 2016	9940	10612
kWh Savings:	7528	6060
% Savings:	43%	36%
Annual $ Savings (@ $0.10/kWh):	**$753**	**$606**

IAQ and Comfort

The Center for Building Performance and Diagnostics (CBPD) at Carnegie Mellon University conducted pre- and post-retrofit Post Occupancy Evaluation (POE) for the Philadelphia Business and Technology Center (PBTC) from May 7th to 15th (swing season) 2013, and again on September 15 (cooling season), 2015. The purpose of the study was to compare the indoor environmental quality (IEQ) of the 4th floor of the building before and after a retrofit of HVAC system. The set of measures for the IEQ assessment, described in detail in the full report, include: as-built records of the technical attributes of building systems; spot measurements using the National Environmental Assessment Toolkit (NEAT) instrument cart and 24-hour continuous measurements using GrayWolf unit for the thermal, air quality, acoustic, and visual conditions in the workplace; and short-term user satisfaction questionnaires in the sampled workstations. A summary of the team's findings for occupant thermal comfort is:

Summary Pre- & Post-Retrofit IEQ Assessment Results

- The new centralized control system operates for occupants in thermal comfort range.
- People are still using a personal fans and heaters in some cases.
- Post-retrofit CO2 levels across the space averaged >100 ppm lower than pre-retrofit levels
- User satisfaction results show that more occupants are satisfied with their post-retrofit air quality.
- Two specific dissatisfaction workstations are located at the end of duct runs, along the outside wall, suggesting that additional balancing may be appropriate.

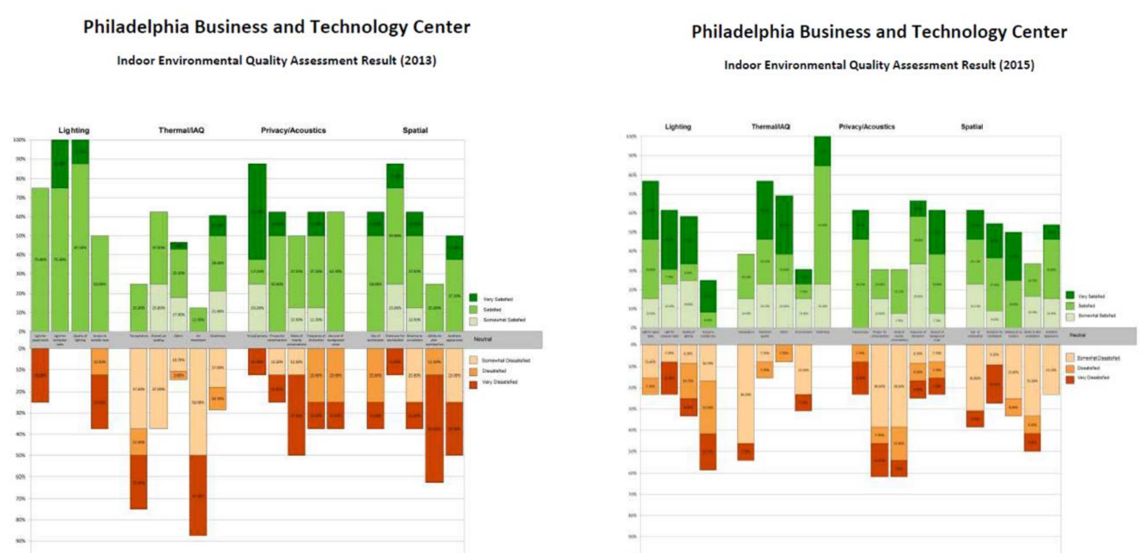


Figure 4 - IEQ Assessment Results

Conclusions

The CAV to VAV AHU retrofit resulted in substantial cooling season and fan energy savings, and some improvement in occupant thermal comfort. Gaps in the available, validated pre- and post-retrofit M&V data, the manual mode of control for the old AHUs, and the common return plenum above the drop ceiling all presented complications when analyzing the performance and energy savings from this retrofit. Nominal cooling season energy savings of ~30% was observed during occupied hours.

Cooling season energy savings of ~30%

The combination of occupancy controlled supply air dampers, duct sealing, and lower static pressure set-points for the fans resulted in nominal 61% fan energy savings during occupied hours, and ~50% fan energy savings during unoccupied hours. Analysis showed that overall annual AHU electric energy savings of ~40% was observed for all measures combined.

While specific IEQ issues remain in the space, in general, dissatisfaction levels are lower in the Post Retrofit survey.

Overall annual AHU electric energy savings of ~40%

Traditional VAV systems are load control-based (generally zonal thermostat control), this low cost retrofit VAV system was occupancy control-based (occupancy sensor control). This approach was taken to reduce installation costs and fundamentally changed the operating sequence from matching air flow to load to matching air flow to occupancy. This testbed exhibited a 50% occupancy that was largely fixed from day to day. Therefore, the diffuser dampers were largely always open in the occupied spaces and closed in the unoccupied spaces. This low cost VAV approach would show more energy reduction if the occupancy were more variable.

The data suggests that there is advantage in reducing airflow in unoccupied rooms. However, given the occupancy-based control scheme and stable space occupancy during operating hours, manually closing dampers in unleased spaces and manually adjusting variable speed fans would achieve similar results at a substantially reduced capital cost. However, this building does not employ an operator who could directly perform the requisite manual adjustments.

A test protocol has been developed to alternate VAV and CAV testing on a weekly basis to add to the space conditioning body of knowledge during winter, shoulder and summer seasons.

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Disclaimer
This material is based upon work supported by the Consortium for Building Energy Innovation, sponsored by the U.S. Department of Energy under Award Number DE-EE0004261.