The Consortium for Building Energy Innovation

CBEI is focused on generating impact in the small and medium-sized commercial buildings (SMSCB) retrofit market. CBEI is comprised of 14 organizations including major research universities, global industrial firms, and national laboratories from across the United States who collaborate to develop and demonstrate solutions for 50% energy reduction in existing buildings by 2030. The CBEI *FINDINGS* series highlights important and actionable technical, application, operation and policy research results that will accelerate energy efficiency retrofits when applied by various market participants. CBEI views these FINDINGS as a portal for stakeholders to access resources and/or expertise to implement change.

Building Innovative Retrofit Strategies

Commercial buildings account for almost 20% of the total U.S. energy consumption. A significant portion of the pre-1950 medium-sized building stock consists of ducted constant volume heating systems. Subsequent to their initial construction, often air conditioning was added either to the central or decentralized systems and adapted into the ductwork to maintain employee comfort and attract tenants as buildings were repurposed. Philadelphia Business & Technology Center (PBTC) is one of a number of such buildings in Philadelphia. Originally constructed in the 1930's, it is a sprawling six story building approximately 272,000 ft^2 with a building envelope that consists of face brick with 12" concrete block and a central steam boiler. During the repurposing of the building the steam system now heats duct mounted coils served by constant volume unitary air conditioning units.

Another CBEI research project which focused on HVAC system design and equipment selection of small to medium-sized commercial buildings determined that one of the most impactful HVAC measures to economically improve energy efficiency is to change from constant air volume (CAV) flow to variable air volume (VAV) flow[1].

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 of these 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.

Research Finding:

Working with real buildings as testbeds generally provides findings beyond those to be tested. The PBTC testbed is no exception. Three key findings were made:

Value of fixing air flow and set points

The first step was to improve airflow to the spaces including fixing duct leaks to the return plenum. This accounted for about 38% improvement.

Value of right sizing

Right sizing equipment is no surprise. In this case, a 20%-point reduction was achieved.

Value of low cost VAV system

The low cost VAV system further reduced the energy consumption by an additional 20%-points when assessing 50% occupancy versus full occupancy.

VAV Retrofit Efficacy

This site exhibited largely stable occupancy during operating hours at about 50% of the occupied spaces. Measured savings for the VAV system operating with the same occupancy level exhibited measureable fan power savings. Greater variation in occupancy patterns would result in greater retrofit energy savings.

[1] This testbed opportunity was triggered by "end of life" compressor failures in both of the CAV units on the fourth floor.

PBTC Testbed

The 4th floor on the west wing of the PBTC building (Figure 1), was selected to test a Low Cost VAV retrofit concept. This space has an approximate floor area of 10,000 square feet. As shown in Figure 2, the floor area is divided in two sections, each with a two-stage vertical packaged direct expansion (DX) air conditioning (AC) unit and a steam coil in a dedicated mechanical room. Two separate steam coils are used for heating of the perimeter areas. The steam heating coils are driven by a boiler for the whole building and are turned off during April 15–October 15. Air from the AC unit is delivered to the conditioned spaces through ducts and returns in the plenum through an opening in the internal wall to the mechanical room. Outdoor air enters the mechanical room through an opening in the external wall and is mixed with return air in the room before entering the unit.

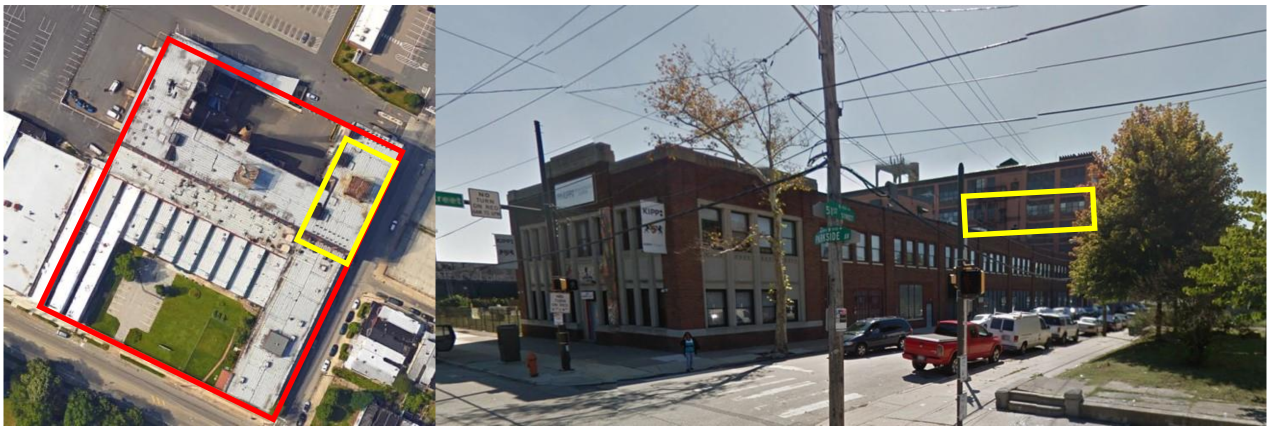

Figure 1. Satellite View: PBTC (red) 4th Floor Test space (yellow) Elevation: 4th Floor Test space (yellow)

PBTC Modeling and Right Sizing

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.

Figure 2 Test Floor Configuration

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.

Low Cost VAV Retrofit

M&V System Description: Sensors and an energy management system[2] (EMS) were installed to enable pre- and post-retrofit monitoring of system operation. 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.

Retrofit System Description: When a zone is unoccupied, the overhead lights will shut off and the supply air dampers serving the zone are in a minimum air flow position. The dampers close to a minimum position to always allow for required fresh air to be provided to the fourth floor space. The supply fan is controlled by duct static pressure that is affected by the open/close state of all the terminal dampers. Energy consumption can therefore be saved with the new AC units and more accurate occupancy-based zone control.

An annual DOE EnergyPlus simulation was performed for the integrated system with the old low efficiency AC units and the new high-efficiency AC units separately based on the performance data available. Simulation with different design cooling capacities of the AC units indicated that a 12-ton unit is sufficient for each section of the area to maintain the indoor air conditions with an approximate oversizing factor of 20%. This led to a 20% reduction of the design capacity of the 15-ton pre-retrofit units. Excessive oversizing of the pre-retrofit unit was also observed by the continuous operation of the units at low stage even at low return air temperatures of about 66°F on average during operation.

To estimate the annual energy consumption of the actual pre-retrofit operation with the 15-ton units, return air temperature setpoints of 64/68°F were assumed for the first and second stage cooling based on observation of measured data. To understand the impact of the temperature setpoint alone, system operation was also simulated with return air temperature setpoints of 75/79°F for the first and second stage cooling. In the system post-retrofit, with a variable speed fan and terminal air flow control, the AC units were simulated to maintain thermal comfort in the occupied zones only. Since nearly half of the floor area is not currently occupied, this results in a reduction of supply air flowrate by about 43%. Based on simulation outputs, annual energy consumption of three potential retrofit design and operation options were compared against the pre-retrofit baseline. As summarized in Figure 3, with full occupancy of all the spaces, by adjusting the indoor air temperature setpoint for cooling from the pre-retrofit 64/68°F to 75/79°F (option 1), annual electric energy can be reduced by 38%; using the new high-efficiency AC units (Option 2), annual HVAC electric energy will decrease by 58%. If only the occupied spaces are conditioned (Option 3), not only can cooling electric energy be reduced by 78%, but heating load will also be saved by 51% compared to the pre-retrofit system versus the space being fully occupied.

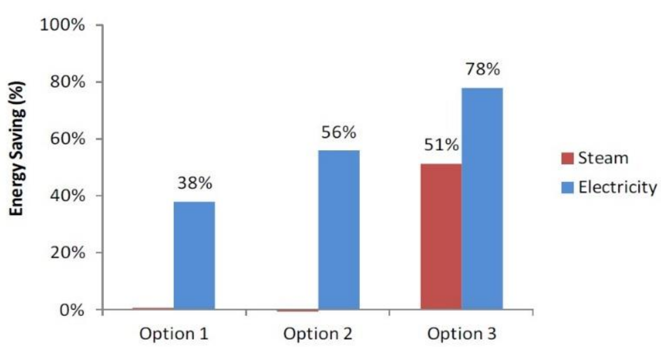

Figure 3 Setpoint Optimization, Right Sizing and VAV System Improvement vs 100% Full Occupancy

[2] A controller capable of serving both as a data collection system and EMS

Lessons Learned

CBEI researchers continue to gain experience deploying various measurement and verification systems. At PBTC it was decided to use an advanced BAS system as an M&V overlay for data acquisition and communication. This involved using a controls company for installation, which led to delays and unexpected M&V data lapses. As a result, CBEI researchers continue to recommend improvements in education and training in this emerging field.

Air balancing and supply remains a significant energy opportunity. In this case, duct repair and sealing the air delivery system allowed significant increase in return air temperatures leading to 38% reduction in energy use.

Right sizing equipment continues to be a significant means of improving system operation and saving energy (in this case about 20%-point reduction).

Moving from constant volume air systems to occupancy-based variable air volume systems can save significant energy, particularly in buildings with variable occupancy. (in this case about 20%-point reduction).

The key question, with respect to older building retrofits, remains the conversion cost from constant air volume to variable air volume.

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.

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CBEI is a research and demonstration center that works in close partnership with DOE's Building Technologies Office.

Moving Forward

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.

A commercial grade costing exercise should be undertaken to determine if retrofitting supply diffuser balancing dampers controlled by occupancy sensors can be economically matched with variable frequency drive (VFD) supply fans and duct static pressure sensor retrofits.

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