

# Project 2.3 – HVAC controls and diagnostics

## BP4 Final deliverable: D2.3.2

<p><b>Description of the BP4 Final deliverable</b> HVAC controls deployment case studies</p>
<p><b>Type of deliverable:</b> Case study</p>
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<p><b>Major findings/Result:</b></p> <p>In 2014-2015 United Technologies Research Center (UTRC), in collaboration with Consortium for Building Energy Innovation (CBEI) at Pennsylvania State University and Radius Systems, demonstrated cost effective scalable commissioning of an advanced building HVAC control system at two medium scale commercial building sites. These pre-commercial demonstration efforts were successful in showing low-touch installation and commissioning and consistent energy performance benefits of the advanced controls. The installation and commissioning process was automated so that the application can be deployed with market available skill sets. At the first building site the control system was tested in August-September 2014 (cooling season) and it maintained comfort in the building zones while achieving energy consumption reductions of 12-17%. At the second building site the controls were tested in March 2015 (heating season) and achieved improved thermal comfort as well as reducing energy consumption by 7%. The estimated ROI based on the measured performance satisfies less 3 years simple payback period. This demonstration gathered key feedback and lessons-learned on the installation and operation of a HVAC controls system that will help guide future functionality and maturation.</p>

# HVAC Controls Deployment Case Studies:

## UTRC Campus, High Performance Building Testbed, East Hartford CT and West Chester University, Swope School of Music Building, West Chester PA

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### **Abstract**

In 2014-15 United Technologies Research Center (UTRC), in collaboration with Consortium for Building Energy Innovation (CBEI) at Pennsylvania State University and Radius Systems, demonstrated cost effective scalable commissioning of an advanced building HVAC control system at two building sites. The first demonstration site is a 40,000 sq-ft office building at UTRC Campus in East Hartford Connecticut. The second demonstration site is a 88,000 sq-ft academic building at West Chester University, Pennsylvania. These pre-commercial demonstration efforts were successful in showing low-touch installation and commissioning and consistent energy performance benefits of the advanced controls. The installation and commissioning time of advanced controls technology at each of the two sites required less than one hour (excluding BAS override and data mapping tasks). The process was automated so that the application can be deployed with market available skill sets. At the first building site the control system was tested in August-September 2014 (cooling season) and it maintained comfort in the building zones while achieving energy consumption reductions of 12-17%. At the second building site the controls were tested in March 2015 (heating season) and achieved improved thermal comfort as well as reducing energy consumption by 7%. Finally, this demonstration gathered key feedback and lessons-learned on the installation and operation of a HVAC controls system that will help guide future functionality and maturation.

## **I. Introduction**

**T**HIS case study details the pre-commercial demonstration of building Heating Ventilation and Air-Conditioning (HVAC) system controls undertaken by United Technologies Research Center in collaboration with the Consortium for Building Energy Innovation at Pennsylvania State University, and Radius Systems a building automation system installer. The objective of this demonstration was to evaluate the installation process and benefits of UTC's pre-commercial building HVAC controls capability as overlays on the building automation system in order to assess the technical maturity and market potential of this technology. This capability was demonstrated at two building sites in North America consisting of HVAC systems composed by Air Handling Units (AHUs) and Variable Air Volume (VAV) terminal distribution units served by chiller plant and hot water boilers. The two demonstrations were focused on enhancing the operation of the HVAC air-side equipment (AHUs and VAVs).

The first demonstration site is a 40,000 sq-ft office building at the UTRC Campus in East Hartford Connecticut (Figure 1). The existing WebCTRL building automation system (BAS), from UTC's Automated Logic Corporation, enables the automated operation of the building HVAC. The advanced control scheme was commissioned and executed online on one AHU and the associated 19 VAVs with reheat serving half of the building square footage, i.e. the core area laboratories and conference rooms. The second demonstration site is a 88,000 sq-ft academic building, rated LEED Silver, the Swope School of Music Building and Performing Arts Center at West Chester University, Pennsylvania (Figure 2). The building HVAC includes seven AHUs, five Fan-Coil Units (FCUs) and two air conditioning units. The

building includes a central chilled water and heating hot water equipment feeding built-up air handling units throughout the facility. Terminal equipment includes VAV boxes with reheat and perimeter fin-tube radiation. The building automation system is ALC WebCTRL. The advanced controls demonstrated at this facility has been commissioned and executed online on one AHU and its 51 VAV units that provide conditioned air to approximately 40% of the building square footage.



**Figure 1. High Performance Building Testbed at United Technologies Research Center located in East Hartford, Connecticut**

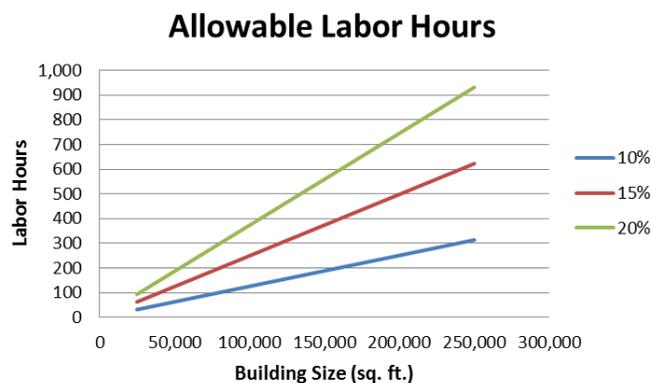
Advanced solutions such as Model Predictive Control (MPC) have been shown to offer HVAC energy savings of 10-50%. Previous demonstrations by UTRC of building controls have achieved building-level energy reductions of >17% in a commercial medium sized building [3] and >20% HVAC energy reduction in a navy barracks [4, 5]. These solutions involve the complexity of developing and calibrating building models and are not adaptive to building use or environmental changes. In addition, commissioning of an MPC approach for building HVAC control poses the challenge of formulating a building-specific centralized optimization problem in the context of a heterogeneous building systems landscape. These challenges result in a high initial cost that is a function of the time required for installation and commissioning, as well as high level of expertise required (typically not available in the field).



**Figure 2. Swope School of Music Building and Performing Arts Center at West Chester University located in West Chester, Pennsylvania.**

The market requirements for medium and small commercial buildings are as follows: a) less than 3 years simple payback return on investment; b) can be deployed with existing industry workforce skillset;

c) can be offered as overlay on existing BAS or data management platform [1,2] with standard HVAC instrumentation. Figure 3 establishes expected available labor hours for customer engagement, site preparation and application installation and commissioning as a function of potential energy savings and building size in order to achieve a 3 year simple payback. The graph has been generated based on the 2003 CBECS data, considering all non-mall small and medium scale commercial buildings with less than 200,000 sq. ft., amounting to an average energy consumption of 96 kBTU/sq. ft./year, and energy cost of \$1.69/sq. ft. It is assumed that the HVAC energy consumption amounts to 40% of the total building energy, an HVAC contractor labor rate of \$82/hour, and the application cost is \$0.1/sq.ft. Figure 3 indicates that for small and medium sized commercial buildings the number of available labor hours to be used for activities such as customer engagement, site preparation and application installation and commissioning reduces significantly with the building size.



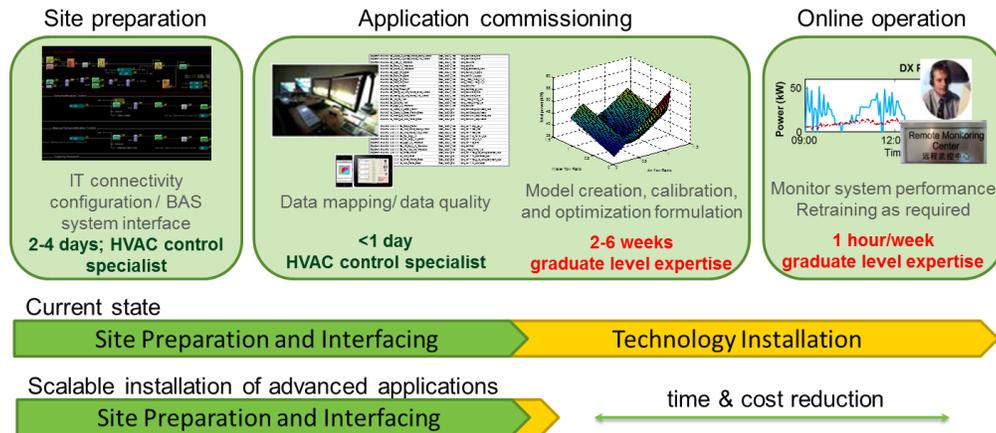
**Figure 3. Allowable labor hours for application deployment as a function of potential energy savings and building size**

The remainder of this case study describes the installation and commissioning process for the controls capability (Section II), the performance of the controls capability during on-line operation and the resulting impacts in energy consumption and comfort (Section III). Conclusions are provided in Section IV.

## II. Overview of Building Controls Installation and Commissioning Process

The high initial cost and complexity involved in installing advanced controls has held back the widespread deployment and energy savings particularly in small- and medium-sized buildings. This case-study addresses the technology challenges underlying high commissioning cost. The cost of commissioning advanced control technology as an overlay on top of existing BAS systems is driven by (a) the time required to develop interfacing requirements with the BAS system and (b) level of expertise required for application commissioning. This project demonstrates a reduced time to commission and reduced need for advanced engineering skills through automated installation and execution of an advanced control overlay. Moreover the project demonstrates a framework for automated composition of the optimal control problem to support a high level of scalability to heterogeneous HVAC system types and installations.

The steps undertaken to implement building controls are summarized in Figure 4. Each step, along with key lessons-learned, is discussed below.



**Figure 4. UTC's building controls deployment process.**

### A. Site Preparation

The first step involves surveying the building HVAC system, establishing connectivity to the WebCTRL server, implementing control overrides in the WebCTRL Eikon control logic, and installing any additional meters for measurement and verification purposes.

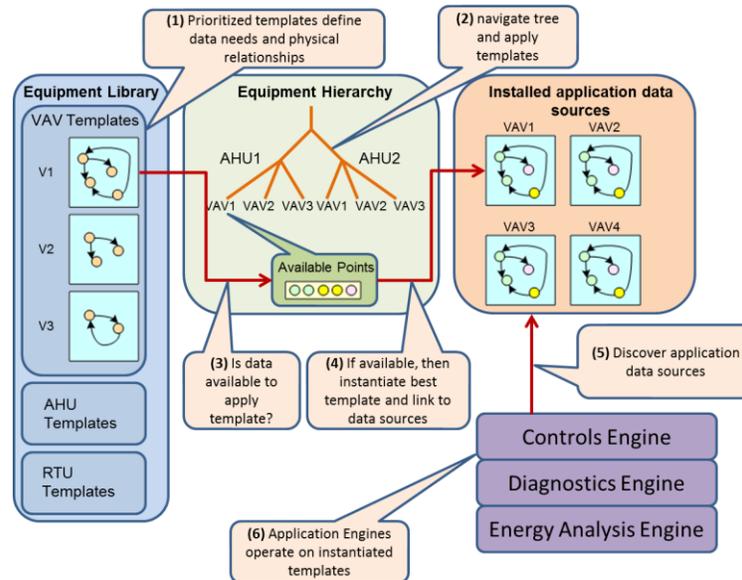
During the building survey the topology of the HVAC system was documented, including the number of sensors and equipment. Overrides of key control variables (i.e. equipment control set-points) were implemented in WebCTRL by Radius Systems to allow coupling between the supervisory control and the local control loops. Internet connectivity was established between UTC and the Swope building in Pennsylvania to allow remote implementation of the advanced controls application and monitoring its on-line performance. Additional instrumentation, such as AHU BTU meters, were installed to support measurement and verification and evaluate energy performance but are not needed for HVAC controls application.

The site preparation and customer engagement is estimated to a time period of one week.

*Key Lessons Learned:* Automation of HVAC topology discovery and override implementation within WebCTRL (or other BAS platform) will greatly reduce the labor involved in installing the controls application.

### B. Application commissioning – data mapping

Data-mapping was undertaken to determine the correspondence of the required sensor and control inputs for the controls capability and the associated data point addresses within the WebCTRL building automation system. The data requirements are generated automatically based on the HVAC system configuration and the specified data needs of the advanced control application to be implemented on top of the building automation system. The process is described in Figure 5.



**Figure 5. UTC's process for installation and execution of building systems applications**

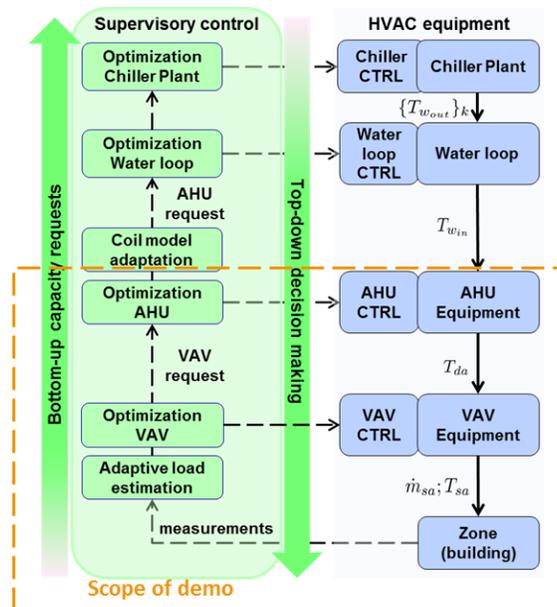
Similarly to the HVAC system configuration specification step, the data mapping can be mediated by an easy-to-use HMI front end. Currently this step must be manually completed by the application HVAC controls engineer by adding in the corresponding data point addresses from the BAS system. The execution for the data mapping step is estimated to a time period of one day.

*Key Lessons Learned:* Future automation of data-mapping will further reduce the labor involved in installing the controls application.

### C. Application commissioning – optimization problem formulation

This step consists of the automated composition of the optimization-based control problem based on a library of equipment specific modeling and optimization software, the building HVAC architecture, and the operational constraints that characterize the building HVAC system. Similarly to the data mapping step, the definition and hierarchical decomposition of the optimization problem is driven by the building specific equipment hierarchy. Relative to the centralized model predictive control approach to problem formulation, this hierarchical decentralized approach provides increased scalability as it enables automatic installation and composition of the advanced control problem with only slight trade-offs in energy benefits. The HVAC system architecture specification drives the specification of the optimization problem as described in Figure 6. This hierarchical decentralized architecture of the control scheme allows for automated composition of the optimization problem as well as scalable execution of the model calibration and optimization modules.

The execution of each automated model estimation routine and optimization module is orchestrated by a distributed control system communication infrastructure. At both demonstration sites the application commissioning amounted to automated calibration of building zones and equipment models based on readily available data associated to typical building operation. The highly automated application commissioning step scales linearly with the system size and required less than one hour to be completed at both demonstration sites.



**Figure 6. Optimization-based control hierarchical architecture mirrors the hierarchical topology of the HVAC system**

*Key Lessons Learned:* The application can operate in a robust manner based on the models calibrated using typical baseline operation data.

#### D. Online operation

Models are recalibrated periodically based on recalibration triggered by statistical comparisons of load and operation patterns. It is expected that model accuracy will increase if functional test data characterizing the building operation in range of operating conditions is available for model calibration.

### III. Performance of On-line Supervisory Controls Application

The performance of the controls capability, i.e. its ability to reduce energy consumption associated with the operation of the building HVAC system while maintaining or improving the thermal comfort specified for the building zones was evaluated at the two demonstration sites.

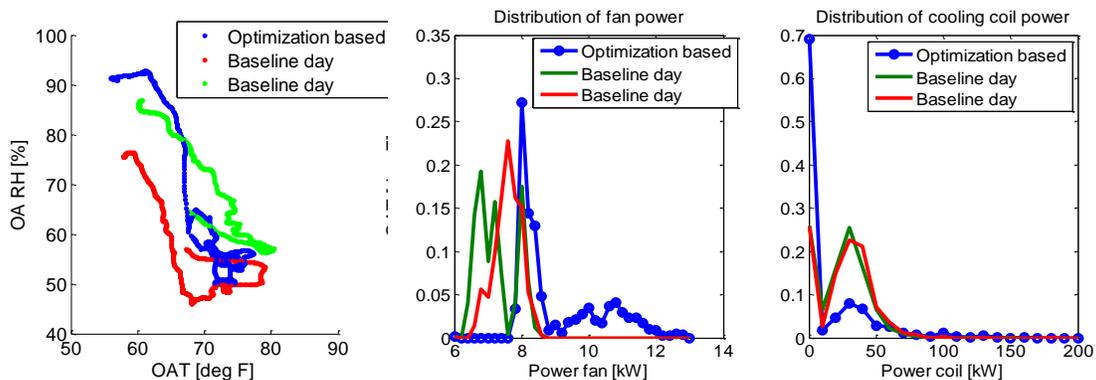
#### A. UTRC High Performance Testbed Building in East Hartford Connecticut

At the first demonstration site the advanced control scheme has been commissioned and executed online on one AHU and its 19 VAVs with reheat coils serving the building internal area consisting of laboratories, conference rooms and office space. The demonstration site floor map is presented in Figure 7. The building HVAC operation schedule is on during the Monday-Friday work week and it is off during Saturday-Sunday. The advanced supervisory control application was executed for nine 24-hour week days and five additional afternoons through the months of August and September with no tuning or re-calibration. The control algorithm maintained the zone temperatures within the bounds specified by the building occupants and the building operations manager.



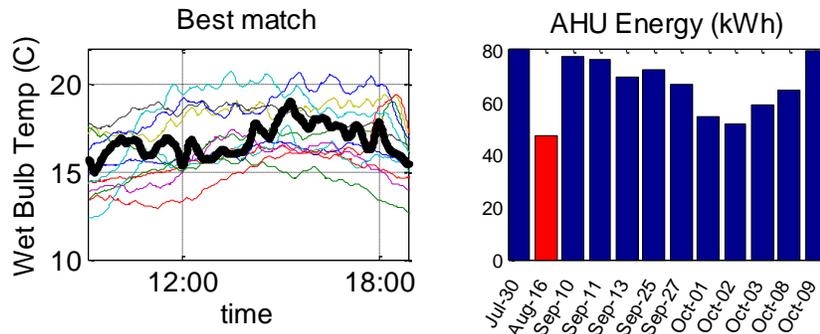
**Figure 7. Demonstration site floor map.**

Figure 8.a presents plots of data that indicate similar load profiles for two days of baseline operation and one day of advanced supervisory control operation. Figures 8.b and 8.c contrast the power consumption patterns corresponding to the baseline supervisory controller and optimization-based supervisory controller. The results indicate reduced usage of chilled water energy and increased consumption of fan power.



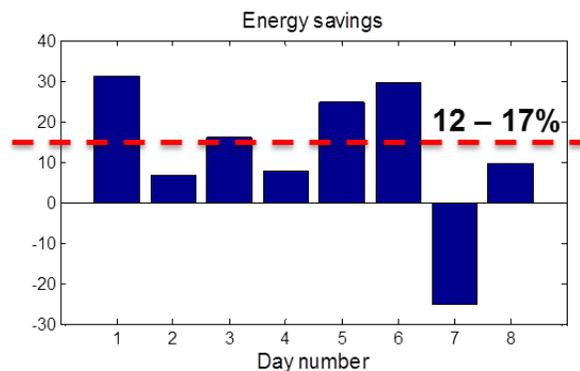
**Figure 8. Power consumption comparisons at AHU level using 1 min sampled data: (a) (a) load indicators outside air temperature (OAT) and relative humidity (OAH); (b) Fan power consumption distribution (fan power meter); (c) Cooling coil power consumption distribution (BTU meter)**

The baseline supervisory control uses a state of the art trim-and-respond for the adaptive continuous selection of the AHU discharge air temperature set point based on heating and cooling requests from the building zones. Quantitative evaluation for each day of advanced supervisory control execution included the following steps: a) use outside air wet bulb temperature to identify a set of days with similar load; b) quantify the energy consumption for each similar day using the energy meter data; c) calculate average energy consumption for all identified similar days; d) calculate energy benefit relative to the average energy consumption of the similar days set. The analysis result for the day of August 16 is presented in Figure 9.



**Figure 9. Power consumption comparisons at AHU level using 1 min sampled data. Left: similar wet bulb outside air temperature load profiles; Right: energy consumption measured at AHU level**

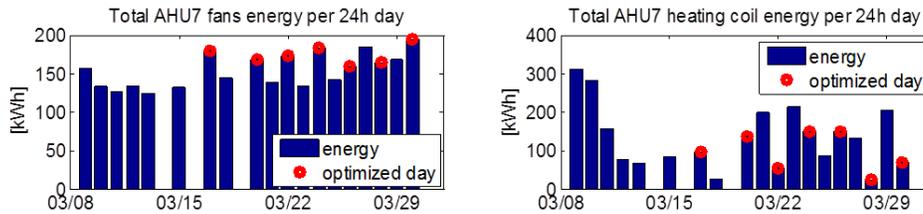
The results summarizing the total energy consumption reduction for the eight sample days of advanced supervisory control execution are presented in Figure 10. The average daily energy savings vary between 32% and 8%. Excessive energy consumption was observed during day seven of the experimental set. More detailed analysis revealed that simultaneous heating and cooling has occurred during that particular day due to simultaneous activation of the enable switches of the two AHU heating and cooling controllers. The average energy savings are estimated at 17% (excluding the day when simultaneous heating and cooling was observed).



**Figure 10. Power consumption reduction at AHU level for each of the 8 test days**

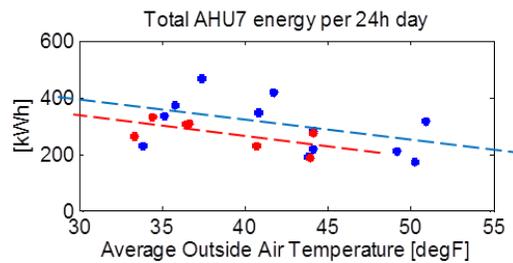
**Key Lessons Learned:** In order to avoid simultaneous activation of heating and cooling at the AHU level when coupling a supervisory control scheme with the local control loops implemented by the building automation system, the local control enable switches should be available for implementing the decisions of the supervisory advanced control system.





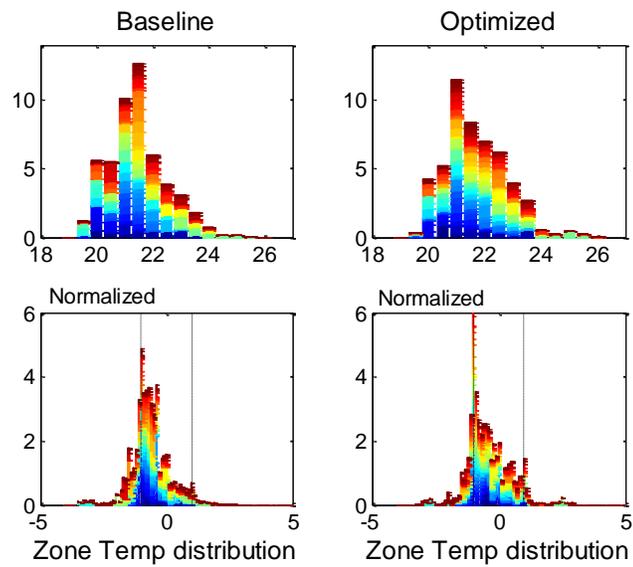
**Figure 12. Energy performance measurements during the testing period. Left: total fan energy consumption during the 24 hour day; Right: total energy consumption at the AHU heating coil measured by the BTU meter**

Figure 13 presents the total measured daily energy consumption relative to the outside air temperature daily average (red – optimized days; blue – baseline days). The energy measurement result indicates that energy consumption was reduced during the days where optimized controls were executed by an average of 7%. This is a notable improvement given that the baseline control used dead band control to minimize energy consumption at the expense of the comfort in some zones.

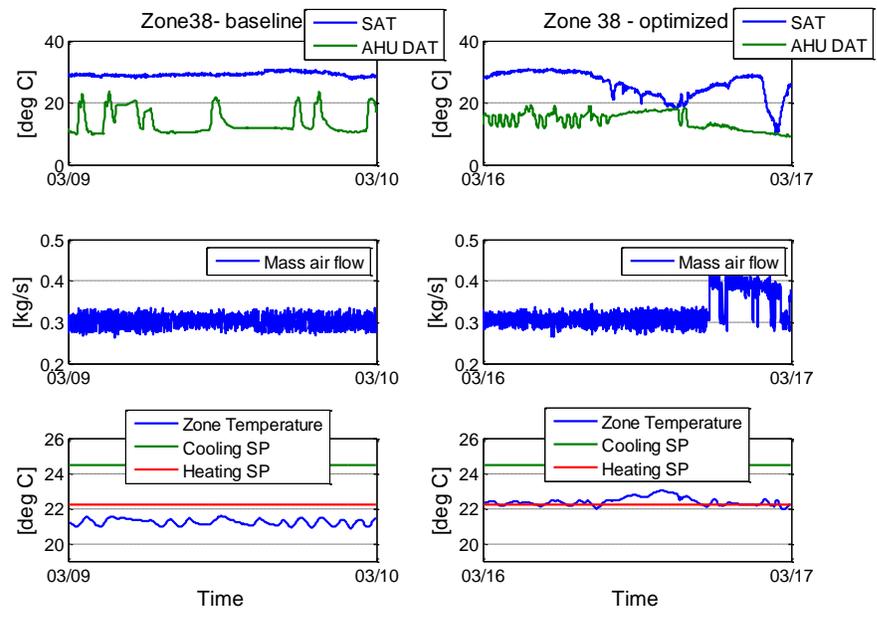


**Figure 13. Energy performance relative to average load defined by the outside air temperature**

The advanced control algorithm maintains the zone temperatures within the bounds specified by the building occupants and the building operations manager. Figure 14 presents a comparison of the temperature distribution in the 51 thermal zones during an optimized versus a baseline operation day. The top two histograms indicate that in both days the building zone temperatures are distributed towards the lower value; this is typical for an energy efficient operation in the heating season. The bottom two histograms present the normalized temperature data relative to the specified temperature set points in each zone. Specifically the temperature measurements in each zone, sampled with a rate of one sample per minute have been normalized such that the comfort zone temperatures are mapped inside the [-1, 1] interval. The resulting histograms of the normalized zone temperatures indicate less excursion of the zone temperature below the heating set-point. Figure 15 shows a comparison of the comfort provided by each control scheme for a typical building zone. The data shows that in the optimized operation case the zone temperature has fewer excursions outside the defined comfort band. A higher AHU discharge air temperature is also observed resulting in reduced need and use of local reheat capacity at the VAV and zone level.



**Figure 14. Temperature distribution in the building zones: baseline vs. optimized operations comparison** Top two quadrants present actual temperature measurement distribution; Bottom two quadrants present the distribution of the normalized temperature values relative to the comfort band.



**Figure 15. Operation comparison for a building zone indicates performance improvement**

*Key Lessons Learned:* In addition to energy savings, improvements in zone thermal comfort can be achieved by advanced building HVAC controls. The comfort metric it is believed to have a direct impact on occupant productivity and health that, while harder to measure, is likely commensurate or larger in value than the energy cost savings.

## IV. Conclusions

This section includes in Table 1 a summary of the cost-benefit evaluation of the implementation of building HVAC controls at the two demonstration sites. One must note that energy consumption reduction at each demonstration site was measured relative to the existing baseline that in both cases corresponds to a state of the art energy efficient operation. At both building sites the advanced supervisory control application has been commissioned in less than 1 hour, without building specific manual tuning. Reduced energy consumption has been observed at both demonstration sites while the thermal comfort in the building zones has been maintained or improved.

The cost associated with the time required to deploy the advanced controls application, including customer engagement and site preparation (1 week), data mapping (1 day), and application installation and commissioning (1 hour), and assuming the HVAC contractor labor rate of \$82/hour, is estimated at approximately \$4000.

At the first demonstration building the energy consumption during the cooling season measured at AHU level during the cooling season is 2.8M kBTU cooling and 25,000 kWh fan energy consumption. Assuming an average chiller COP of 3, a cost of electricity per kWh of \$0.126 [6], and 15% energy consumption reduction observed during the cooling season, then 50% of the installation cost can be recovered in less than one year of operation.

At the second demonstration site the energy consumption during the heating season measured at the AHU level is 0.9M kBTU heating and 22000 kWh fan energy consumption. Based on the 7% energy consumption reduction during heating season operation, assuming the gas boiler efficiency of 0.87, and \$0.0483 cost of gas per kWh, 50% of the installation cost can be recovered after approximately three years of operation.

**Table 1: Performance summary for demonstration at two building sites**

Performance Metric/ Project Goals	On	Off	Additional Information
> 15% HVAC energy consumption reduction	✓		<ul style="list-style-type: none"> <li>- Relative to baseline.</li> <li>- First Building observed energy consumption reduction of average 17%, up to 40%</li> <li>- Second Building baseline was more energy efficient, but did not meet comfort bands. Energy consumption reduction of average 7% while improving comfort.</li> </ul>
Packaged solution requires no additional commissioning	✓		<ul style="list-style-type: none"> <li>- Approximately &lt; 1hour for additional commissioning (excluding overrides and data-mapping)</li> </ul>
< 3 years simple payback	✓		<ul style="list-style-type: none"> <li>- Achieved based on energy consumption reduction in both buildings.</li> <li>- Simple Pay Back: cost/savings</li> <li>- Time to install: 1 week (customer engagement/preparation) + 1 day (data mapping) +1 hour (commissioning) = 49 hours; labor cost = \$4000</li> <li>- First Building: summer months only, SPB = 0.8 years (assume ½ of cost)</li> <li>- Second Building: winter months only, SPB= 3.2 years (assume ½ of cost)</li> </ul>
Comfort	✓		<ul style="list-style-type: none"> <li>- Improved comfort while achieving energy savings</li> </ul>

The two building HVAC supervisory control demonstration case studies showed that advanced energy efficient controls can be installed and commissioned in medium scale commercial buildings in a reduced time with market available skill set. At both demonstration sites the advanced controls helped establish and sustain significant improvements in HVAC energy consumption as well as improved thermal comfort. These demonstration studies gathered key feedback and lessons-learned on the

installation and operation of a HVAC supervisory controls system that will help guide future functionality and maturation towards further enhancing the cost effectiveness and applicability in the small and medium size commercial building sector.

## **V. Acknowledgments**

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## **VI. References**

1. VOLTRON™: An Intelligent Agent Platform for the Smart Grid, [http://gridoptics.pnnl.gov/docs/VOLTRON\\_An\\_Intelligent\\_Agent\\_Platform\\_Flier.pdf](http://gridoptics.pnnl.gov/docs/VOLTRON_An_Intelligent_Agent_Platform_Flier.pdf)
2. Haack, J. et al., VOLTRON™: An agent platform for integrating electric vehicles and Smart Grid, IEEE International Conference on Connected Vehicles and Expo (ICCVE), 2013.
3. Li Pengfei, Vrabie D., Li D., Bengea S., O'Neil Z., Mijanovic S., "Simulation and Experimental Demonstration of Model Predictive Control in a Building HVAC System", Science and Technology for the Built Environment, 2015. - accepted
4. ESTCP Program EW2011-42, "Energy Performance Monitoring and Optimization", Final Report, December, 2013.
5. Bengea, S., Kelman, A., Borrelli, F., Taylor, R., and Narayanan, S., 2014, "Implementation of model predictive control for an HVAC system in mid-size commercial building", Journal of HVAC & R Research, Volume 20, Issue 1, pp. 121-135, 2014.
6. [https://www.cl-p.com/ESuppliers/Average\\_Bill/](https://www.cl-p.com/ESuppliers/Average_Bill/)