Enhancing Building Operations through Automated Diagnostics: Field Test Results

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ABSTRACT

The Whole Building Diagnostician (WBD) is a modular diagnostic software system that provides detection and diagnosis of problems with the operation of heating, ventilation, and air-conditioning (HVAC) systems and major energy end-uses. It has been extensively field tested and demonstrated in buildings over the past several years. WBD found problems with many air-handling units at all sites. The problems ranged from a simple set point deviation to improper implementation of controls. The results from these demonstrations, along with the feedback from building operators and managers on the use of diagnostic tools, are presented in the paper. Experience from field tests indicates that providing diagnostic tools to building operators can increase their awareness of equipment faults, but it will not by itself solve the problems of inefficient operations. Changes in operation and maintenance practices and behavior are needed. We discuss how these new technologies might be delivered and used more effectively to better manage facilities, improving their condition and increasing their energy efficiency.

INTRODUCTION

According to the Annual Energy Outlook 2003 (EIA 2003), in 2001, 17.4 quadrillion Btu (1 quad = 10^{15} Btu) of primary energy was consumed by commercial buildings in the United States at a cost of about 127 billion dollars (in 2001 dollars). Many regional studies in the past have shown that a significant fraction, as much as 30%, of energy consumption by commercial buildings is wasted (Ardehali et al. 2003; Ardehali and Smith 2002; Claridge et al. 2000, 1996, and 1994;). Much of this waste can be tracked to operation and maintenance problems. Most problems are related to bad and un-calibrated sensors, improper operation practices (such as schedules), and improperly implemented controls. Many of these problems can be detected and diagnosed by use of automated diagnostic tools such as the WBD. The WBD is a modular diagnostic software system that provides detection and diagnosis of common problems associated with the operation of HVAC systems and major energy end-uses. It has two diagnostic modules: the Outdoor-Air Economizer (OAE) diagnostician and the Whole Building Energy (WBE) module. It was developed at Pacific Northwest National Laboratory for the U.S Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (http://www.buildings.pnl.gov:2080/wbd/) with collaborators from the Honeywell Technology Center and the University of Colorado.

The WBD has been extensively field tested in private and public buildings over the past several years. In 2000, as part of the California Energy Commission's Public Interest Energy Research Program, (http://www.energy.ca.gov/pier/index.html), the OAE diagnostic module has been demonstrated at several buildings in the State of California. The OAE found problems with many air-handling units at all sites. The problems ranged from a scheduling error to improper implementation of controls.

The results from these demonstrations, along with the feedback from building operators and managers on the use of diagnostic tools, are presented in this paper. The next section provides background information on why and how automated diagnostic technologies can be used to enhance building operations and maintenance. It is followed by a section that provides a brief description of the diagnostic approach used by the OAE diagnostician. The results from field tests and conclusions are presented as well.

BACKGROUND

Evidence of extensive performance problems in buildings shows that an efficient commercial building stock will not result from solely designing efficient buildings and installing efficient equipment in them. Operational problems associated with degraded equipment, failed sensors, improper installation, poor maintenance, and improperly implemented controls plague most commercial buildings (Ardehali et al. 2003; Ardehali and Smith 2002; Claridge et al. 2000, 1996, and 1994;). Today, most problems with building systems are detected as a result of occupant complaints or alarms provided by building automation systems (BAS). Building operators often respond by checking space temperatures or adjusting thermostat settings or other set points. Unfortunately, the root cause of an operational problem is often not diagnosed, so problems reoccur, and the operator responds again by making an adjustment. When the operator diagnoses problems more carefully by inspecting equipment, controls, or control algorithms, the process is time consuming and often based on rudimentary or incorrect physical reasoning and rules-of-thumb built on personal experience. Often a properly operating automatic control is overridden or turned off, when it appears to be the cause of a problem. Moreover, some "silent" problems (such as simultaneous heating and cooling) do not manifest themselves in conditions that directly affect occupants in obvious ways and, as a result, they go undetected in many cases. These undetected problems may affect energy costs and indoor air quality.

Operational problems lead to inefficiencies (increased energy costs), a loss in cooling and heating capacity (comfort), discomfort (loss of productivity and loss of tenants), and increased wear of components (decreasing reliability). These performance problems are not inherent with efficiency technologies themselves, but instead result from errors in installation and operation of complex building heating/cooling systems and their controls. It is also significant that these systems are becoming increasingly more sophisticated to obtain ever higher levels of energy efficiency, adding to the complexity and subtlety of problems that reduce the net efficiency acquired. Such problems are more common in existing than new buildings because they arise over time from operational changes and lack of maintenance (Ardehali et al. 2003; Ardehali and Smith 2002; Potter et al. 2002; Claridge et al. 2000, 1996, and 1994; Lunneberg 1999; also check the commissioning resources at http://www.peci.org). They often cause problems with comfort control and indoor-air quality, which affect occupant health and productivity (Daisey and Angell 1998).

Assuring efficient performance by commissioning of new buildings followed by regularly-scheduled preventative maintenance is clearly insufficient to address this issue. Manually commissioning buildings is valuable in terms of both finding problems and developing the techniques for doing so, but it is expensive. With only 1 to 2% of total construction costs devoted to commissioning and with the few experts available to provide such services in high demand, commissioning is not performed adequately for most commercial buildings. Commissioning is also difficult to sell in a low-bid construction environment, where variations in the effort allocated to commissioning can be the difference between winning and losing bids and where building owners (rightfully) feel they should not have to pay extra to get buildings to work properly. Further, commissioning is often short-changed because it largely occurs at the end of the construction process, when time-to-occupancy is critical and cost overruns drive last minute budget cuts in remaining items.

Effective, on-going maintenance of building systems as usually performed is notably ineffective, being almost exclusively complaint-driven and "quick fix" oriented. This is especially true for problems affecting air quality and efficiency because they are "silent killers" that go unnoticed until complete system failure occurs.

Automated commissioning and diagnostic technologies for building systems and equipment promise to help remedy these problems and improve building operation by automatically and continuously detecting performance problems and maintenance requirements and bringing them to the attention of building operators and engineers. In addition, early diagnosis of equipment problems using remote monitoring techniques can reduce the costs associated with repairs by improving scheduling and reducing on-site labor time. Furthermore, as performance contracting for services becomes more prevalent, the need for tools to ensure performance will increase.

By embedding the expertise required to detect and diagnose operational problems in software tools that leverage existing sensors and control systems, detection and diagnosis can be conducted automatically and comprehensively without the ongoing cost of expensive human expertise. Furthermore, these tools can remain as a legacy in buildings after they are constructed, protecting building systems against slow mechanical degradation, as well as faults inadvertently introduced by operators seeking to resolve complaints without finding root causes.

Automation and visual presentation of information are key elements of automated fault detection and diagnostic systems (AFDD). Because the building industry is cost sensitive and lacks sufficient numbers of well-trained building operators and engineers, fully automated tools can help alleviate the problem. Visual display of the information developed by AFDD tools is the key link between the building system and building operators in fully automated systems. Clear information presentation helps the building operator avoid the need to scan, sort, and interpret raw data, thus freeing time for correcting the problems identified by the AFDD system, performing maintenance, and otherwise improving equipment performance and efficiency.

Currently, most building owners are not aware of the power of automated commissioning and diagnostic technologies to provide them more cost effective, comfortable, and productive buildings. The technology is in its infancy and not yet well known in practice. Because of the high first cost associated with the development of such systems and some difficulties in establishing streamlined, cost-effective, delivery mechanisms for these tools, the industry has not yet embraced the technology. Finally, energy service companies who may eventually offer commissioning and diagnostic services have been slow to expand their business practices beyond their current focus on lighting and equipment retrofits. Despite this current state of affairs, these difficulties will eventually be overcome so that automated diagnostic technology offers promise of a future with improved facility operation, better indoor environments, and enhanced and higher-quality offerings by service companies.

WHOLE-BUILDING DIAGNOSTICIAN

Developed by the Department of Energy's (DOE) Pacific Northwest National Laboratory (PNNL),[1] initially in collaboration with the Honeywell Technology Center and the University of Colorado, the WBD is a production-prototype software package with two modules providing automated diagnostics for buildings based on data collected through BASs. The two diagnostic modules are deployed within the WBD's user interface and data and process management infrastructure, as shown in Figure 1.

The WBD's Outdoor-Air Economizer module (OAE) diagnoses whether each monitored air handler in a building is supplying adequate outdoor air for the occupants it is designed to serve, by time-of-day and day-of-week. It also determines whether the economizer is providing free cooling with outdoor air when appropriate, and is not wasting energy by supplying excess outdoor air. Few, if any, sensors other than those used to control most economizers are required, making the OAE practical in near-term markets because of its potential low cost (Figure 2).

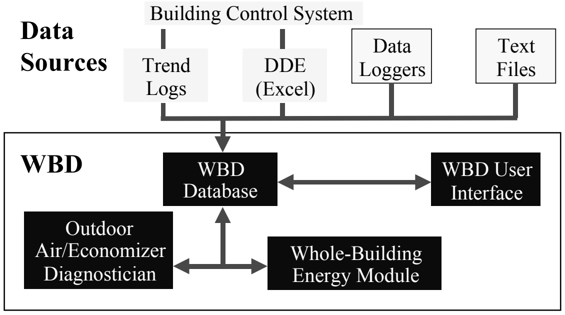

Figure 1. Schematic Diagram of the WBD Software

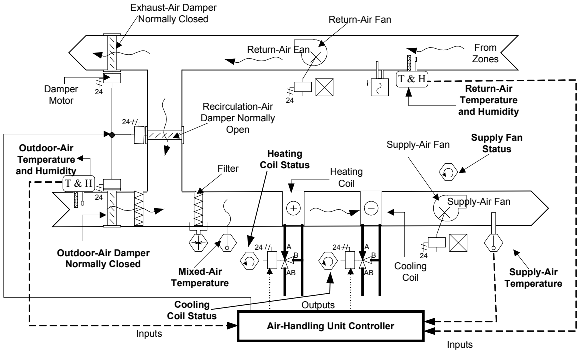

Figure 2. Schematic of an Air-Handling Unit Showing Typical Sensors

The WBD also contains a Whole-Building Energy (WBE) module that monitors whole-building or subsystem (end-use) energy performance. For details on WBE refer to Katipamula et al. (2003b).

Both modules provide information to users in simple, graphical displays that indicate the presence or absence of problems at a glance. They also provide cost estimates of detected energy waste to provide feedback to users on the relative importance of the problems detected.

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[1] Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RL01830.

OAE DIAGNOSTIC APPROACH

This section provides a brief overview of the OAE module. The OAE diagnostician continuously monitors the performance of air handlers and can detect basic operation problems or faults with outside-air control and economizer operation. The current version detects about 25 different basic operation problems and over 100 variations of them [for details refer to Brambley et al. (1998) or Katipamula et al. (1999)]. It uses color coding to alert the building operator when problems occur and then provides assistance in identifying the causes of problems and advice for correcting them. It, however, does not detect problems with the water-side or the refrigerant-side of the air handler; it only detects problems on the air side, i.e., economizer operation and ventilation.

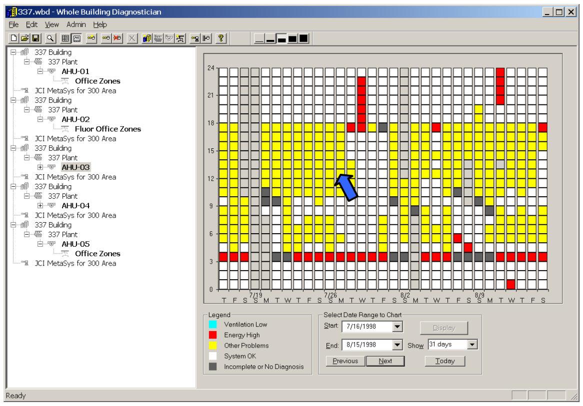
The OAE uses rules derived from engineering models and understanding of proper and improper air-handler performance to detect and diagnose operating conditions. The rules are implemented in a decision tree structure in the software. The OAE diagnostician uses periodically measured conditions (temperature or enthalpy) of the various air-flow streams, measured outdoor conditions, and status information (e.g., fan on/off status) to navigate the decision tree and reach conclusions regarding the operating state of the air handler. At each point in the tree, a rule is evaluated based on the data, and the result determines which branch the diagnosis follows. A conclusion is reached regarding the operational state of the air handler when the end of a branch is reached. Measurement uncertainty is assigned to each data point, and uncertainty is propagated through all calculations.

Each problem state known by the OAE module has an associated list of possible failures that could have caused the state; these are identified as possible causes. Thus, at each metered time period, a list of possible causes is generated.

The WBD user interface is used to display the results from the OAE diagnostician; it uses color coding to alert the building operator when problems occur (Figure 3). The building operator can get additional assistance to identify the causes of the problems detected and in correcting them by clicking on the non-white cells. On the left pane of the window in Figure 3 is a directory tree showing the various systems implemented in this particular WBD system. The tree can be used to navigate among the diagnostic results for various systems. In this case, we are looking at results for air handler 03 (AHU-03), which is highlighted in the tree. In the right pane is a color map, which shows the OAE Diagnostic results for this air handler. Each cell in the map represents an hour. The color of the cell indicates the type of operational state. White cells identify OK states, for which no problems were detected. Other colors represent problem states. Clicking on any shaded cell brings up the specific detailed diagnostic results for that hour.

Figure 4 and Figure 5 show pop-up windows providing a description of a problem and more detailed explanation of the problem, energy impacts of the problem, potential causes, and suggested actions to correct each cause. The second window (Figure 5), labeled “Details,” is revealed by "clicking" on the "Details" button in the first window (Figure 4). In this case, the problem investigated is a sensor problem. The current version of this diagnostician cannot, by itself, isolate the specific sensor that has failed out of the three sensors, but instead it suggests manual inspection and testing of the sensors and their wiring to identify the specific problem.

From this simple example, it should be evident that the OAE Diagnostician can alert building operators to problems in air handlers and assist operators in identifying specific causes that they can investigate further or correct. Without this assistance many of these problems go undetected and uncorrected, as our field results show. In the next section, we describe a few more examples of problems found in field tests.



Start: 7/16/1998

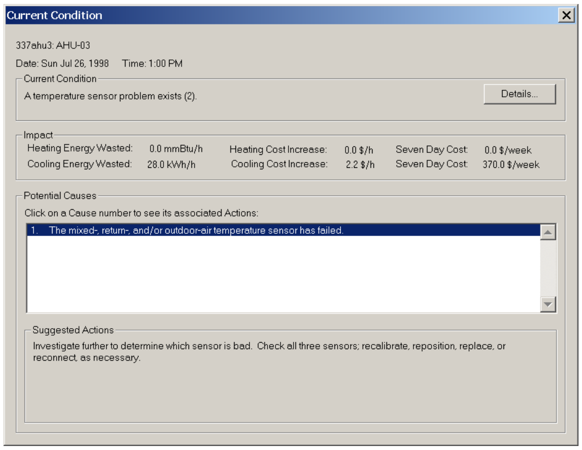
End: 8/15/1998

Show 31 days

Figure 3. Diagnostic Results Showing Proper and Faulty Operation for an Air Handler. The arrow identifies the cell for which more detailed results are given in Figures 4 and 5.

RESULTS FROM FIELD TESTS

This section provides a summary of results from field demonstration of the WBD/OAE. The WBD's OAE module has been field tested at several large office and laboratory buildings, mostly in the Western States (Washington, Colorado, and California). Table 1 and Table 2 provide a summary of some key AHU parameters, problems, and cost impacts associated with the problems. A more detailed table of results is provided in Appendix A (Table 3). For more detailed descriptions of the sites and field tests, refer to Katipamula et al. (1997), Pratt et al. (2003), and Katipamula et al. (2003a).



337ahu3: AHU-03

Date: Sun Jul 26, 1998 Time: 1:00 PM

A temperature sensor problem exists (2).

Heating Energy Wasted: 0.0 mmBtu/h Heating Cost Increase: 0.0 $/h Seven Day Cost: 0.0 $/week

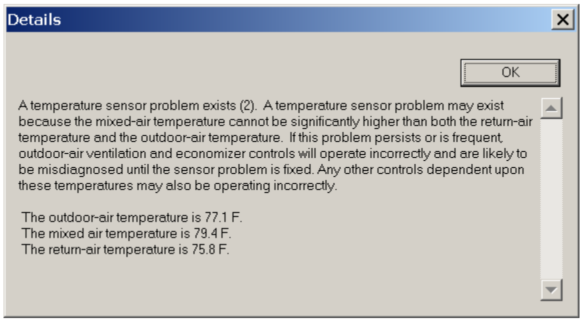
Cooling Energy Wasted: 28.0 kWh/h Cooling Cost Increase: 2.2 $/h Seven Day Cost: 370.0 $/week

Click on a Cause number to see its associated Actions:

1. The mixed-, return-, and/or outdoor-air temperature sensor has failed.

Investigate further to determine which sensor is bad. Check all three sensors; recalibrate, reposition, replace, or reconnect, as necessary.

Figure 4. Window Showing a Description of the Diagnosis, the Impacts of the Problem Found, Potential Causes of the Problem, and Suggested Corrective Actions.



A temperature sensor problem exists (2). A temperature sensor problem may exist because the mixed-air temperature cannot be significantly higher than both the return-air temperature and the outdoor-air temperature. If this problem persists or is frequent, outdoor-air ventilation and economizer controls will operate incorrectly and are likely to be misdiagnosed until the sensor problem is fixed. Any other controls dependent upon these temperatures may also be operating incorrectly.

The outdoor-air temperature is 77.1 F.
The mixed air temperature is 79.4 F.
The return-air temperature is 75.8 F.

Figure 5. "Details" Window Showing a Detailed Description of the Temperature Sensor Problem Identified in Figure 4.

The OAE diagnostician found problems with almost all AHUs monitored. The problems ranged across faulty sensors, mis-positioned sensors, stuck dampers, unscheduled operations, excess ventilation, and inadequate ventilation. At one site, the OAE was installed immediately after the building was occupied and yet the OAE found several problems that should have been detected during commissioning. It is likely that some of the AHUs may have multiple simultaneous faults. The OAE diagnostician highlights a single predominant fault, in cases where an AHU has multiple simultaneous faults. Unless the first fault is corrected and new data then processed, the other faults may not manifest depending on the prevailing indoor and outdoor conditions and whether the first fault masks other faults (e.g., a faulty temperature sensor will make all diagnoses based on its measurements meaningless).

Table 1. Details of Field Test Sites

Location	Building Type	Number of AHU	Type of AHU	Typical Schedule (military time)
Richland	Office/Lab	6	VAV	0 to 24
Richland	Office	3	CAV	6 to 18
Denver	Office	3	VAV	0 to 24
San Francisco	Hotel	6	CAV	6 to 23
Sacramento	Office	4	VAV	7 to 19
Sacramento	Office	6	CAV	6 to 18
San Diego	Office	4	VAV	8 to 18

VAV: Variable Air-Volume Systems
CAV: Constant Air-Volume Systems

In most cases, the problems identified by the OAE were visually verified and confirmed by the building operator, but the problems were seldom corrected. As shown in Table 2, the annual cost impacts estimated by the OAE, ranged from $130 to $16,000. For AHUs with temperature sensor problems, the OAE cannot estimate the cost impact because estimating impacts relies on measured values of temperature as inputs. With the exception of a few cost estimates, all of them were estimated by the cost module in the OAE diagnostician. The OAE diagnostician uses the cost of energy, efficiency of equipment and expected performance to estimate the impact of improper operations. In cases, where heating is provided as reheat in the zones, the OAE does not estimate heating impacts; therefore, some of the estimates provided in Table 2 values are low by the corresponding impact on heating.

CONCLUSIONS

The WBD OAE module was shown to successfully identify a number of major problems with the air-handling units at all demonstration sites. Observations by users at demonstration sites provided mixed results. Although more knowledgeable and experienced users of the WBD were comfortable with the design of the module's user interface and diagnostics, inexperienced users found them difficult to interpret when several problems appeared on the screen simultaneously. This may have implications for interface design changes in the future. For example, a simpler user interface that produces an action item list or list of problems based on OAE results for a block of time may be preferable for users overwhelmed by the detailed hourly results.

Table 2. Summary of Problems and Cost Impacts

Problem	Number of AHUs	Air Flow Rate# (CFM)	Annual Cost Impact ($)
Temperature sensor	4	< 20,000	*
	3	> 40,000	*
Supply air controller	1	< 20,000	2,000
Scheduling	1	< 20,000	130
	1	> 40,000	700
Not fully economizing	2	< 20,000	115 to 250
	8	> 40,000	190 to 16,000
Excess ventilation	1	< 20,000	250
	8	> 40,000	300 to 12,000
Inadequate ventilation	1	< 20,000	*
	1	> 40,000	*
Stuck damper	2	< 20,000	0 to 4,000
Mis-calibrated sensor	1	> 40,000	*

 # cost impacts estimated using bounding value shown.
*** cannot be estimated.**

Although collection of data from air handlers was smooth at sites with BASs that supported the Microsoft DDE protocol, fully automated data collection was a challenge at many sites. In some cases, alternative automated procedures (non-DDE) or semi-automated procedures (using trends logs) were necessary to access to the sensor data. Even at sites where the data collection was fully automated, there were large gaps in the data collected mainly caused by manual shutdown of the data acquisition module on the operator's workstation. This may point to the need to protect this module from inadvertent shutdown or closing by an unauthorized user.

The demonstration reinforced the rather obvious notion that diagnostic tools produce savings only when the identified problems are fixed. Merely identifying operational problems and their impacts is not sufficient by itself; building staff must fix them. If building staff are not able to use their control systems to correct problems, are too busy with other duties, or lack resources to obtain help from control contractors, savings will not be realized. A delivery mechanism is needed that helps ensure that building staff take action when alerted to problems with significant impacts.

The time and cost of diagnostic-tool installation are significant to implementing diagnostic technologies. Sites with larger air handlers (10,000 cfm or larger air flow rates) have greater savings per problem fixed, while installation costs do not vary with air-handler size (i.e., savings are greater relative to costs). Software setup costs per air handler also go down as the number of air handlers at a site increase, provided the units use similar operating control strategies and are part of the same underlying control system.

Overall, the WBD's OAE diagnostician was successfully applied at several demonstration sites. It identified problems with significant energy and cost penalties that would provide significant savings if fixed. Getting building staff to correct these problems, however, was difficult. This points to a need to develop a mechanism for delivering the OAE or providing its results to users in a way that better encourages them to correct the problems found or selectively identifying users predisposed to correcting problems reported by the tool.

FUTURE WORK

Diagnosing the cause of a fault with limited sensors is difficult because of lack of physical redundancy. In addition, proper selection of sensitivity settings for both the OAE and WBE modules is critical in balancing fault detection sensitivity against the rate of false alarms. Additional laboratory and field tests are required to establish more definitive guidelines for users, but even then, the selection of sensitivity settings will depend on the preferences of the users. Like setting the volume level on a radio, the user must 'listen" to the results and adjust the "volume" (sensitivity) based on what is "heard."

Three topics that the authors see as productive for additional research and development on the OAE in the future are:

- Develop analytical techniques to improve isolation of the causes of faults without additional sensors

- Study the impact of sensitivity settings further

- Develop better guidance for operators for selecting sensitivity settings.

ACKNOWLEDGEMENTS

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APPENDIX A

Table 3. More Detailed Summary of Field Test Results

Site/Location	AHU-#	AHU-Type	Air Flow Rate (CFM)	Typical AHU Schedule	Type of Economizer	Minimum O/A[2] Damper Position (fraction)	Problem Detected	Problem Confirmed	Problem Corrected	Annual Energy Cost Impact ($)
Laboratory, Richland, WA	AHU-6	VAV	16,000	24 X 7	High-Limit Dry-Bulb	0.1 (0.1[3])	Scheduling problem	Yes	Yes	$110
	AHU-7	VAV	16,000	24 X 7	High-Limit Dry-Bulb	0.1 (0.1)	Not fully economizing periodically	Yes	No	$250
	AHU-8	VAV	16,000	24 X 7	High-Limit Dry-Bulb	0.1 (0.1)	Temperature sensor problem	Yes	No	NA
	AHU-9	VAV	15,000	24 X 7	High-Limit Dry-Bulb	0.15 (0.1)	Not fully economizing	Yes	No	$115
	AHU-10	VAV	6,500	24 X 7	High-Limit Dry-Bulb	0.1 (0.15)				
	AHU-11	VAV	4,000	24 X 7	High-Limit Dry-Bulb	0.1 (0.15)	Excess ventilation periodically	Yes	No	$250
Office, Richland, WA	AHU-1	CAV	26,400	06:00 to 16:00	High-Limit Dry-Bulb	0 (0.1)	Excess ventilation during heating and not fully economizing during cooling	Yes	No	$190[4]
	AHU-2	CAV	27,500	06:00 to 16:00	High-Limit Dry-Bulb	0 (0.1)	Scheduling problem	Yes	No	$700[3]

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[2] Outdoor-Air

[3] Corresponding outdoor-air fraction is shown in parenthesis.

[4] Does not include heating energy cost impacts.

Site/Location	AHU-#	AHU-Type	Air Flow Rate (CFM)	Typical AHU Schedule	Type of Economizer	Minimum O/A[2] Damper Position (fraction)	Problem Detected	Problem Confirmed	Problem Corrected	Annual Energy Cost Impact ($)
	AHU-3	CAV	37,000	04:00 to18:00	High-Limit Dry-Bulb	0.15 (0.15)	Excess outdoor-air	Yes	No	$300[3]
Office I, Denver, CO	AHU-1	VAV	18,000	24 X 7	NA	0.11 (0.20)	Excess outdoor-air when not economizing, outdoor- and mixed-air temperature sensor problem	Yes	Yes	$800[5]
	AHU-2	VAV	18,800	24 X 7	NA	0.13 (0.20)	Excess outdoor-air when not economizing, outdoor- and mixed-air temperature sensor problem	Yes	Yes	$1,800[4]
	AHU-1	VAV	18,600	24 X 7	NA	0.10 (0.20)	Excess outdoor-air when not economizing, outdoor- and mixed-air temperature sensor problem	Yes	Yes	NA
Hotel, San Francisco, CA	AHU-4	CAV	16,000	06:00 to 23:00	Differential Dry-Bulb	0.1	Inadequate ventilation – o/a damper stuck fully closed	Yes	No	NA
	AHU-12	CAV	16,000	24 X 7	Differential Dry-Bulb	0.1	Return-air and mixed-air signals swapped	Yes	Yes	NA
	AHU-13	CAV	10,000	06:00 to 18:00	Differential Dry-Bulb	0.1	Supply-air controller	Yes	No	$2,000
	AHU-15	CAV	10,000	08:00 to 2300	Differential Dry-Bulb	0.1	O/A damper stuck open	Yes	No	$4,000
	AHU-30	CAV	16,000	06:00 to 23:00	Differential Dry-Bulb	0.1	Temperature sensor	Yes	No	NA

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[5] Estimated outside OAE diagnostician.

Site/Location	AHU-#	AHU-Type	Air Flow Rate (CFM)	Typical AHU Schedule	Type of Economizer	Minimum O/A[2] Damper Position (fraction)	Problem Detected	Problem Confirmed	Problem Corrected	Annual Energy Cost Impact ($)
	AHU-31	CAV	16,000	06:00 to 23:00	Differential Dry-Bulb	0.1	Temperature sensor	Yes	No	NA
Alameda County Buildings, CA	HHOJ AHU-S1	VAV	90,500	06:00 to 18:00	Differential Dry-Bulb	0.2 (0.2)	Not fully economizing	No	No	$1,700[6]
	HHOJ AHU-S2	VAV	98,750	05:00 to 18:00	Differential Dry-Bulb	0.2 (0.2)	Not fully economizing	No	No	$270[5]
	OPMC AHU-S1	VAV	103,750	07:00 to 19:00	Differential Dry-Bulb	0.2 (0.2)	Not fully economizing	No	No	15,750
	OPMC AHU-S2	VAV	87,160	07:00 to 19:00	Differential Dry-Bulb	0.2 (0.2)	Not fully economizing	No	No	10,000
Office, San Diego, CA	AHU-1	VAV	80,000	08:00 to18:00	Differential Enthalpy	0 (0.2)	Mis-calibrated temperature sensor and higher minimum o/a when not economizing	Yes	Partially	$12,000
	AHU-2	VAV	144,000	07:00 to 20:00	Differential Enthalpy	0 (0.2)	Temperature sensor	Yes	No	NA
	AHU-3	VAV	144,000	07:00 to 20:00	Differential Enthalpy	0 (0.2)	Temperature sensor	Yes	No	NA
	AHU-4	VAV	126,000	07:00 to 19:00	Differential Enthalpy		Temperature sensor	Yes	No	NA
Office, Sacramento, CA	AHU-1	CAV	100,000	06:00 to 18:00	High-Limit Dry-Bulb	0.1 (0.1)	o/a damper problem – not economizing fully	Yes	No	$5000[5]
	AHU-2	CAV	100,000	06:00 to 18:00	Differential Dry-Bulb	0.1 (0.1)	o/a damper problem – not economizing fully in cooling mode and too much o/a in heating mode	No	No	$3,200[5]
	AHU-3	CAV	40,000	06:00 to 18:00	Differential Dry-Bulb	0.1 (0.1)	o/a damper problem – not economizing fully in cooling mode and too much o/a in heating mode	No	No	$650[5]
	AHU-4	CAV	40,000	06:00 to 18:00	Differential Dry-Bulb	0.1 (0.1)	Inadequate ventilation and not fully economizing	No	No	$500[5]

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[6] Savings estimated only for a partial year.

Site/Location	AHU-#	AHU-Type	Air Flow Rate (CFM)	Typical AHU Schedule	Type of Economizer	Minimum O/A[2] Damper Position (fraction)	Problem Detected	Problem Confirmed	Problem Corrected	Annual Energy Cost Impact ($)
	AHU-5	CAV	50,000	06:00 to 18:00	Differential Dry-Bulb	0.1 (0.1)	Too much o/a during heating mode and not economizing during cooling mode	No	No	$3,450[5]
	AHU-6	CAV	50,000	06:00 to 18:00	Differential Dry-Bulb	0.1 (0.1)	Too much o/a during heating mode	No	No	$3,200[5]