Field Results from Application of the Outdoor-Air/Economizer Diagnostician for Commissioning and O&M

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Synopsis

This paper presents results of field testing an automated diagnostician for outdoor-air-supply and economizer systems that can be used for commissioning purposes. The fundamental capabilities of the tool are described and key results of its application on six air handlers in a large hotel building are discussed. Ancillary issues pertinent to the development and application of such tools are also presented.

About the Authors

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Introduction

Automated diagnostics for building systems and equipment have been explored for a number of years (Haves et al. 1996; Lee et al. 1997; Li et al. 1997; Peitsman and Soethout 1997; Stylianou 1997; Rossi and Braun 1997). Most research in this field has focused on developing methodologies for automatically detecting and diagnosing operation problems, thus the often-used title fault detection and diagnostics (FDD). Approximately three years ago, the U.S. Department of Energy undertook development of a diagnostic system at Pacific Northwest National Laboratory (PNNL) with Honeywell Technology Center and the University of Colorado Joint Center of Energy Management (JCEM) participating in the development effort (Brambley et al. 1998; Katipamula and Brambley 1999). The resulting system, known as the Whole-Building Diagnostician (WBD) has been undergoing field testing since about a year into the development process and continues today, first on a limited basis at PNNL and more recently at a number of commercial sites with collaborating building owners and operators.

Early in field testing, the research team found upon installation of the WBD that it detected existing problems in every building where it was installed (and this has continued through the present time). Although the WBD had been designed as an "operation assistant," it also performed like a tool used for commissioning or diagnostics during start-up. This paper presents some of the experiences from field testing of the Outdoor-Air Economizer (OAE) module of the WBD, shows how the diagnoses might be extended, estimates potential energy impacts of the problems found, and documents a set of other observations valuable for users as well as developers of automated diagnostic tools for building systems.

Whole-Building Diagnostician (WBD) System

The Whole-Building Diagnostician (WBD) is a modular diagnostic software system designed to provide detection and diagnosis of common problems associated with operating heating, ventilating, and air-conditioning (HVAC) systems and equipment in buildings. The WBD has two modules (see Figure 1): one that tracks overall building energy use and the other that monitors the performance of the air-handling units and detects problems with outside-air control. The WBD is a development of the commercial buildings research program of the U.S. Department of Energy's Office of Building Technology, State and Community Programs.

The WBD currently consists of four primary modules: the two diagnostic modules, the user interface, and a database that stores measured data as well as diagnostic results. These are connected by an infrastructure providing data transfer, data management, and process control. Raw data (e.g., sensor measurements) may be obtained from a data logger or building automation system (BAS), from another database, or from some other analytic software tool in

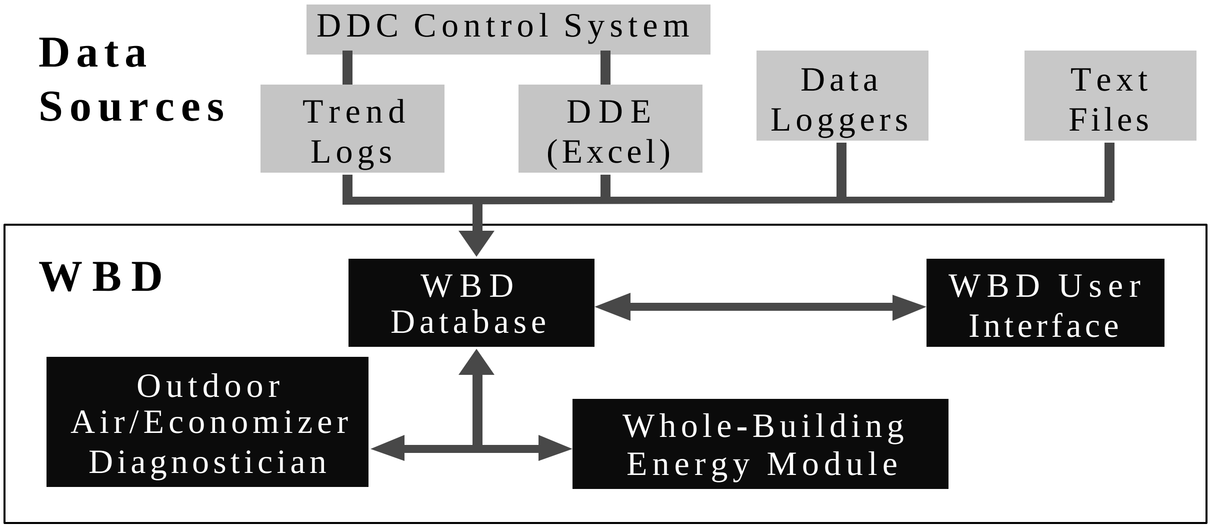

Figure 1. Schematic diagram of the WBD software system. Boxes represent major components; lines represent flows of data and control.

batch or online modes. The system also requires one-time entry of setup data that customizes the WBD modules to each specific building and HVAC system. The system is written in the C++ language and uses a SQL database.

Outdoor-Air Economizer Diagnostician

This paper focuses on the OAE diagnostician. This module monitors the performance of the air-handling units and detects problems with outside-air control. The current version detects about 25 different basic operation problems and over 100 variations of them. The system 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.

Diagnostic Approach

The OAE Diagnostician uses a logic tree to determine the operational "state" of outdoor-air ventilation and economizer systems at each point in time for which measured data are available. The tool uses rules derived from engineering models and understanding of proper and improper air-handler performance to diagnose operating conditions. The rules are implemented in a decision tree structure in the software. The 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 AHU. 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 AHU when the end of a branch is reached. Tolerances are assigned to each data point, and uncertainty is propagated through all calculations. The tolerances can be adjusted by the user through a sensitivity control in the software.

Many of the states correspond to normal operation and are dubbed "OK states." For example, one "OK state" is described as "ventilation and economizer OK; the economizer is correctly operating (fully open), and ventilation is more than adequate." For this case, the system is apparently operating correctly with the outdoor-air damper fully open to benefit to the maximum extent possible from cool outdoor-air used for free cooling. Ventilation rates for the occupants are also being met by the current outdoor-air ventilation rate. Other states correspond to something operationally wrong with the system and are referred to as "problem states." An example "problem state" might be described as "economizer should not be off; cooling energy is being wasted because the economizer is not operating; it should be fully open to utilize cool outside air; ventilation is adequate." As with the previous "OK state," conditions are such that the outside-air damper should be fully open to benefit from free cooling; however, in this case the economizer is incorrectly off, yet the outdoor-air ventilation is still adequate to meet occupant needs. Thus, the building is experiencing an energy penalty from not using the economizer. Other states (both OK and problem) may be tagged as incomplete diagnoses, if critical data are missing or results are too uncertain to reasonably reach a conclusion.

Each OAE "problem state" has an associated list of possible failures that could have caused the state; these are identified as possible causes. In the example above, a stuck outdoor-air damper, an economizer controller failure, or perhaps a misconfigured setup of the OAE module could cause the "economizer should not be off" problem to be detected. Thus, for each time period, a list of possible causes like this is generated.

An overview of the logic tree used to identify operational states and to build the lists of possible failures is given by Katipamula et al. (1999).

Data Requirements

The OAE Diagnostician uses two primary types of data—measured and setup. The measured data include information on mixed-air, return-air, and outdoor-air temperatures (and enthalpies for enthalpy-controlled economizers), supply fan on/off status, and heating/cooling on/off status. These data are ordinarily available from BASs at semi-regular intervals (typically hourly, half-hourly, etc.). Alternatively, measured data can be collected using custom metering and data collection systems, or the diagnostician could be used to process an existing database containing the required data (as shown in Figure 1). The setup data, which must be provided by the user (building operator or installer), include information describing the type of economizer, its control strategies and set points, and building occupancy (and hence, ventilation) schedules.

Basic OAE Functionality

The OAE user interface uses a color-coding scheme (shown as gray shading in this paper) to alert the building operator when problems occur. It then provides assistance in identifying the causes of the problems detected and in correcting them. Figure 2, for example, shows a representative OAE Diagnostician window. On the left pane of the window 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 12 (Ah-12), 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

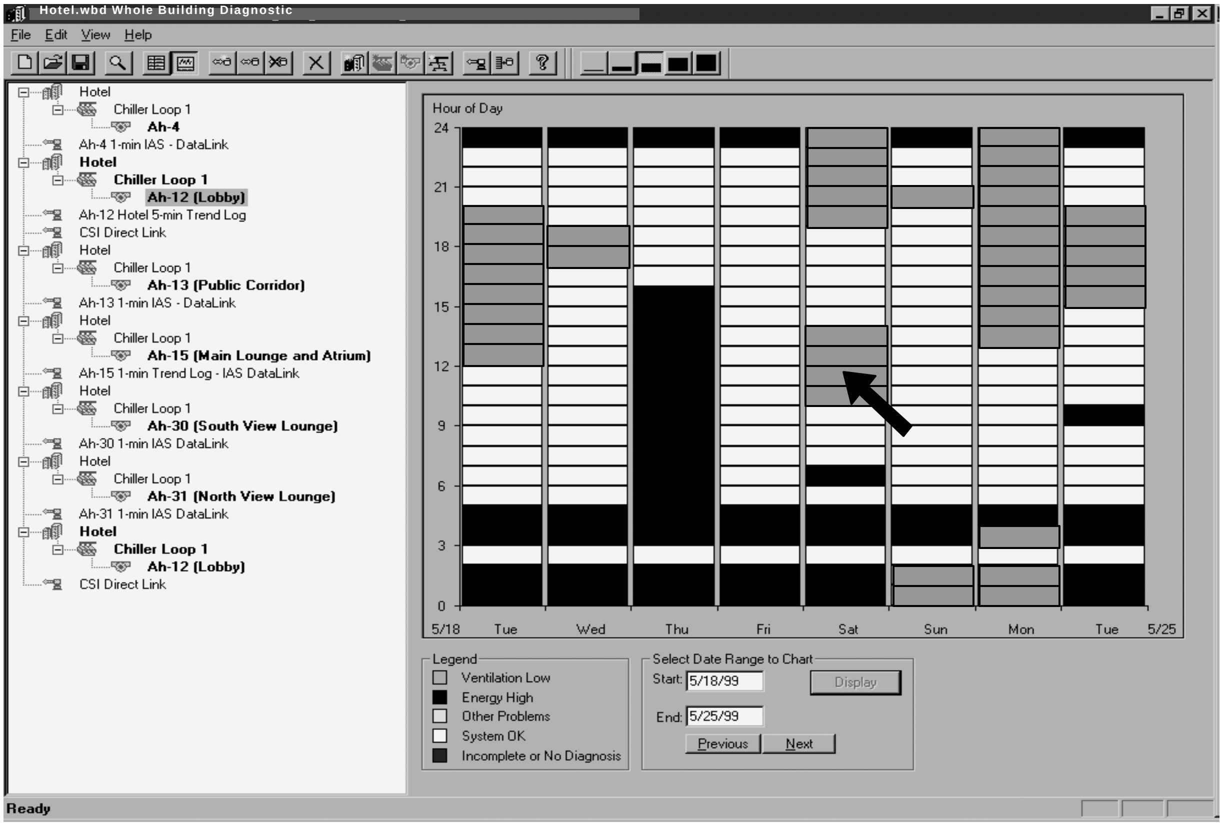

Figure 2. Diagnostic results showing proper and faulty operation for an air handler with a faulty outdoor-air sensor. The arrow identifies the cell for which more detailed results are given in Figures 4 and 5.

represents an hour. The color (gray shade) of the cell indicates the type of state. White cells identify "OK states," for which no problems were detected. Other colors (shades of gray) represent problem states.

"Clicking" the computer mouse on any shaded cell brings up the specific detailed diagnostic results for that hour. Figures 4 and 5 show pop-up windows providing a description of a problem, a more detailed explanation of the problem, energy impacts of the problem, potential causes, and suggested actions to correct each cause. The second window (Figure 4) labeled “Details” is revealed by "clicking" on the "Details" button in the first window (Figure 3). 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, 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 them 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.

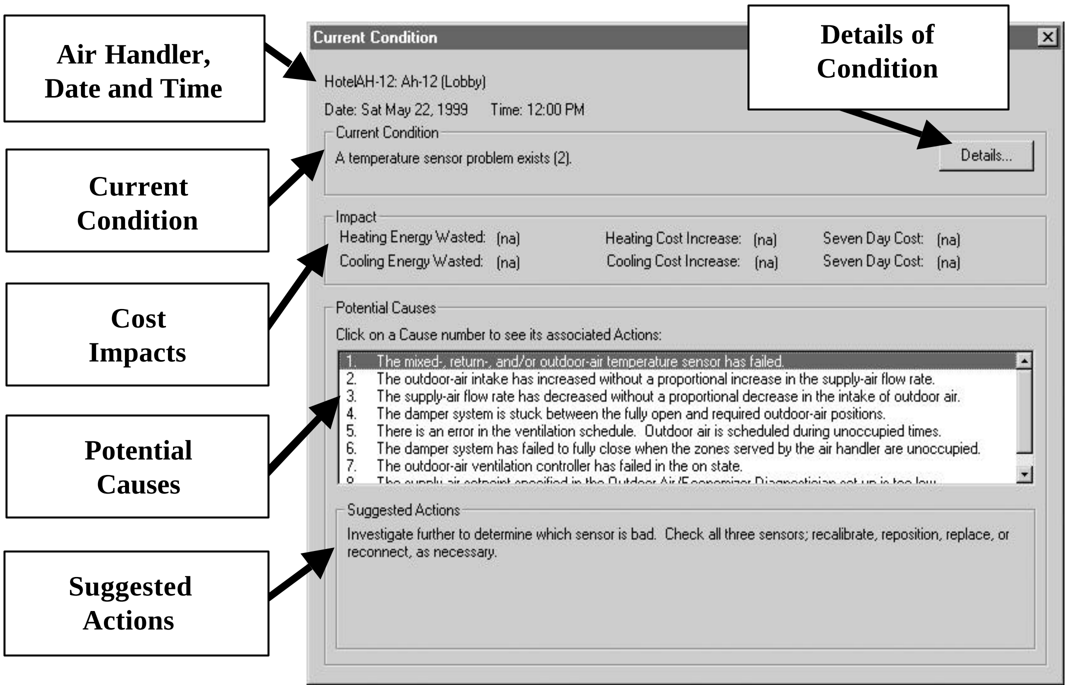

Figure 3. Window showing a description of the diagnosis, the impacts of the problem found, potential causes of the problem, and suggested corrective actions.

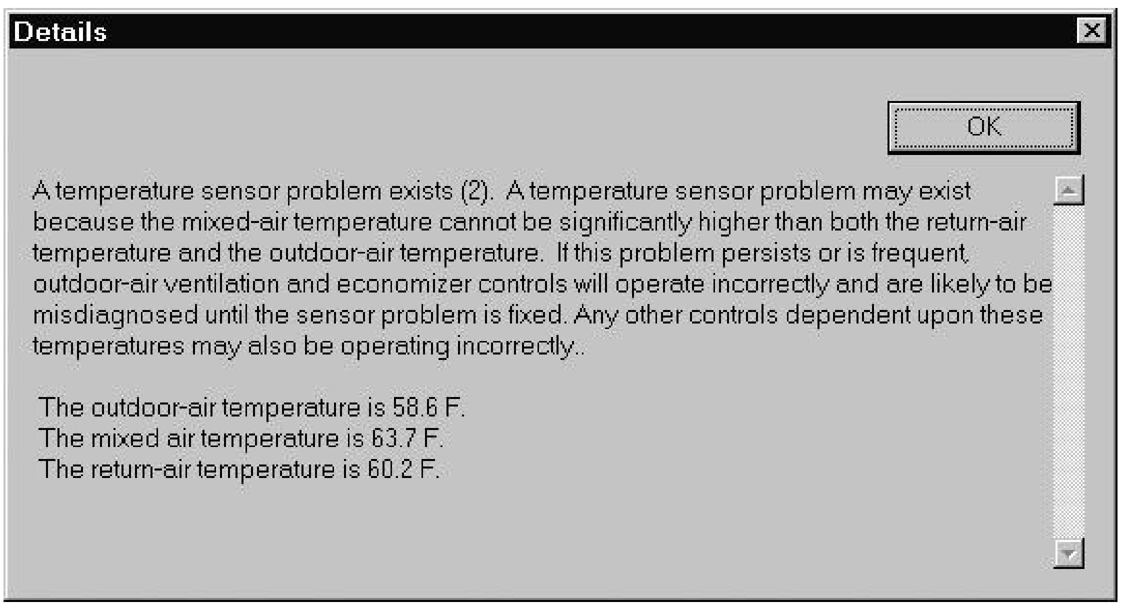

Figure 4. "Details" window showing a detailed description of the temperature sensor problem identified in Figure 3.

More Diagnostic Results

The results shown in this paper are for air handlers in a large hotel in San Francisco. Out of approximately 40 air handlers in the hotel, the PNNL research team connected the OAE diagnostician to six. These six were selected because of the spaces they served and their use of economizing, not because of any suspicion regarding problems with their performance. As shown in the previous section, air handler 12 was initially found by the diagnostician to have a faulty sensor.

Air handler 15, which serves the hotel's main lounge and atrium, had a much different problem. Its results for a week in November are shown in Figure 5. From 6 a.m. until 10 p.m., this air handler was using excessive amounts of energy. The diagnostician explained (Figure 6) the problem as "Mechanical cooling should be off, but instead it is on," identified five potential causes of this problem, and suggested corrective actions for each possible cause. The operators were left to use their experience to uncover the specific cause or to rely on the research team to analyze the situation further (presented in the next section).

Diving Deeper into Diagnosis

The OAE Diagnostician, like all tools, has limitations. In this case, the ability of the diagnostician to isolate the cause of the observed conditions is limited by two factors: 1) the specific set of sensors used by the diagnostician, and 2) the knowledge embedded in the tool.

The first constraint was imposed by the development team in order to make the OAE tool valuable using only the sensor suite usually available for control purposes, thus making the

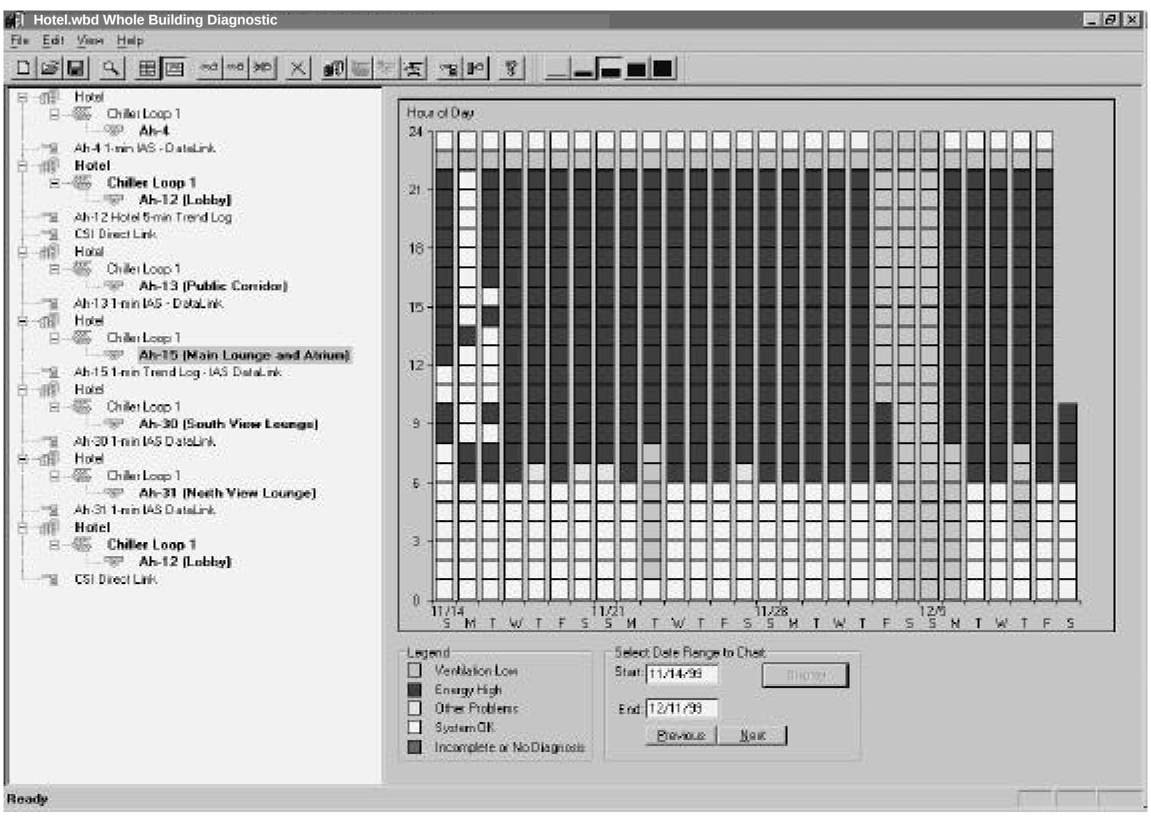

Figure 5. An example OAE color map is shown for air handler 15 for November 14 through December 11. A high energy-consumption problem is clearly evident throughout this time period.

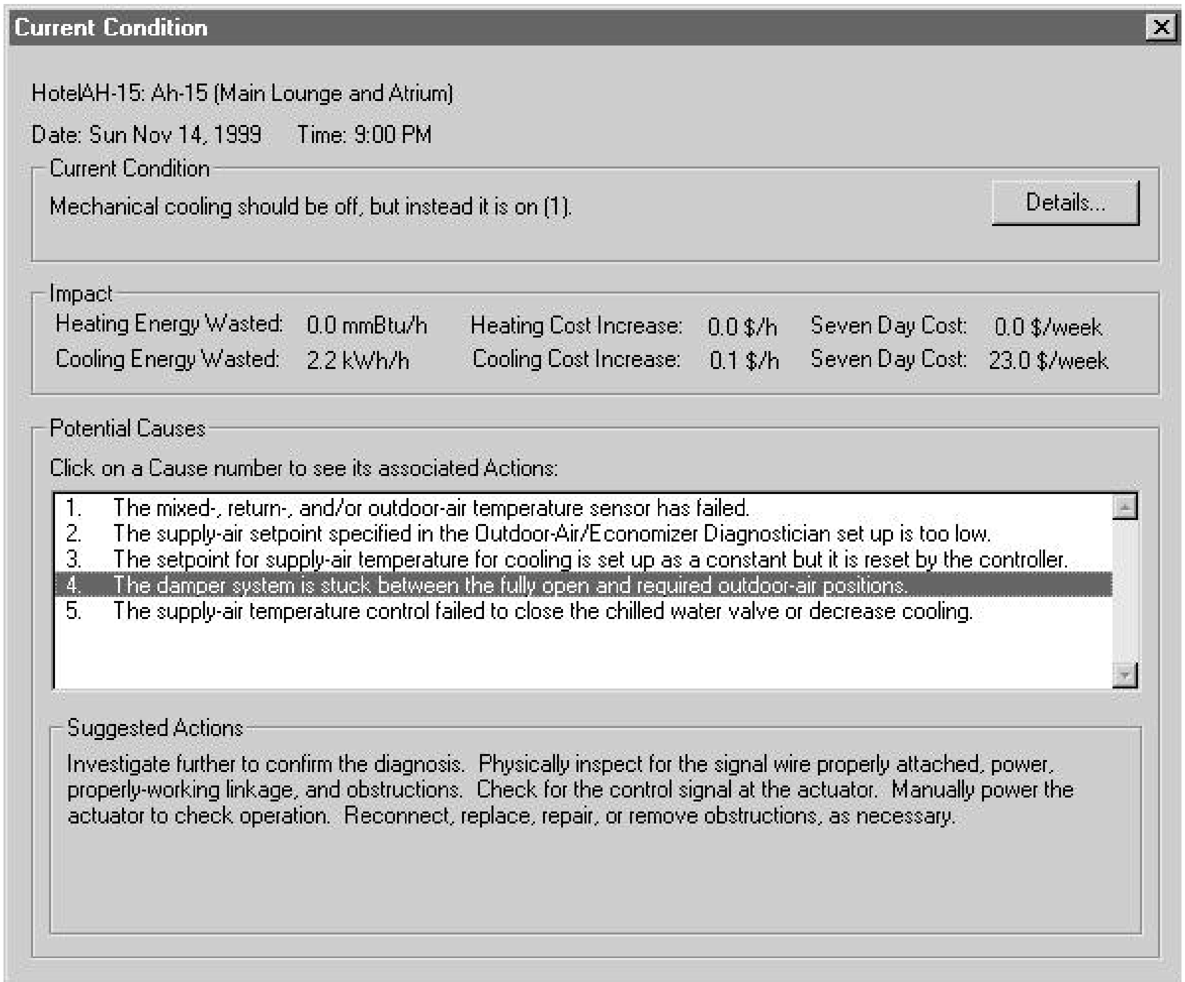

Figure 6. The conditions screen for air handler 15 on November 14 at 9 p.m. is shown. The OAE diagnostician found the problem to be that the cooling system is operating when it should be off, causing the high energy consumption shown in Figure 5. The cost penalty of this problem is relatively small, however.

tool applicable to a large percentage of buildings without requiring the addition of new sensors. However, the diagnosis is also limited by the second factor—the knowledge and methods used by the tool. In this section, we provide examples that show how the data collected can be used to "manually" extend the diagnosis beyond that provided by the OAE tool. These examples serve to illustrate methods that knowledgeable engineers can use to further isolate the cause of a problem detected by the OAE and to provide a peak at the future by describing additional air handler diagnostics that we anticipate will be implemented in future versions of this tool and in tools developed by others.

Returning to air handler 12, when the return-air, mixed-air, and outdoor-air temperatures are plotted together versus time (see Figure 7), the mixed-air temperature appears on average to exceed both the return-air and outdoor-air temperatures. This is thermodynamically impossible. None of the values is unrealistic, however, indicating that no sensor has completely failed. One

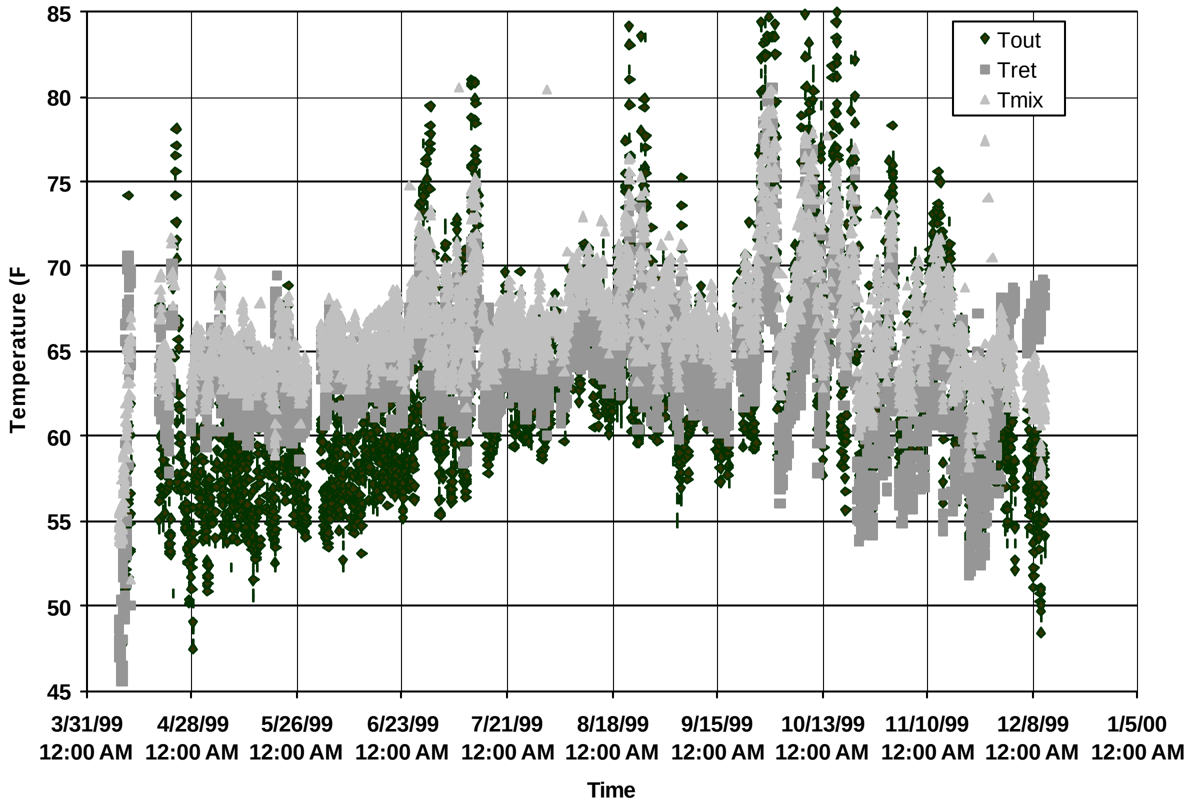

Figure 7. Return-air, outdoor-air, and mixed-air temperature data for air handler 12 are plotted against time for 11 months.

possible cause of this observed behavior is that two of the sensor connections or labels are swapped for one another. Figure 8 shows diagnostic results for the same week, when the values of the mixed-air and return-air are interchanged. Most of the display is white, indicating that behavior is close to as expected and this was probably the problem. Inspection should be used to confirm this hypothesis. Our experience indicates that these sorts of problems are not unusual in control systems and building automation systems, resulting in improper control and often going undetected for long periods of time.

For air handler 15, addition investigation is also possible using the raw data collected by the diagnostic system. Examining the outdoor-air damper signal and its relationship to the supply-air temperature and hot-water valve (for the heating deck) status reveals that the damper is operating improperly. When the air-handling unit is in the heating mode, the supply-air temperature is greater than the mixed-air temperature, as expected, but the outdoor-air damper should be closed to the minimum position that provides adequate ventilation. Instead, it is at a greater open fraction than minimum (see Figure 9). Through this additional diagnostic analysis, the problem is isolated to an outdoor-air damper control-signal problem.

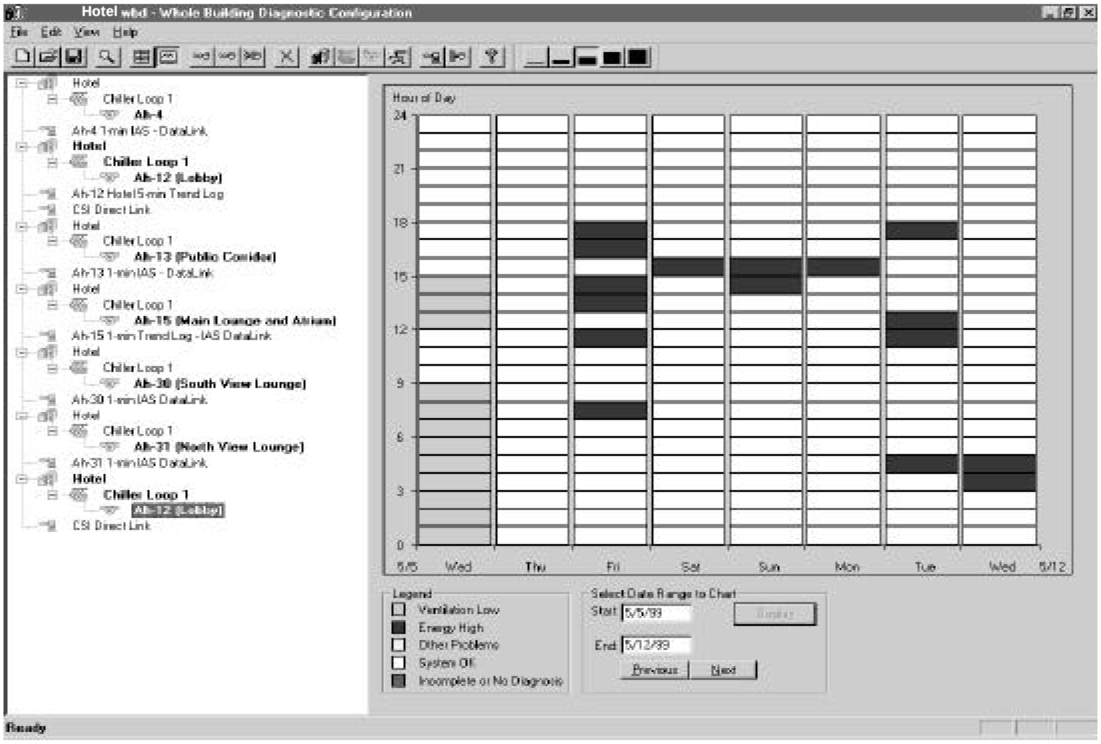

Figure 8. Diagnostic color map resulting from reprocessing the data for air handler 12 after swapping the data for the return air and the mixed air (compare to Figure 2).

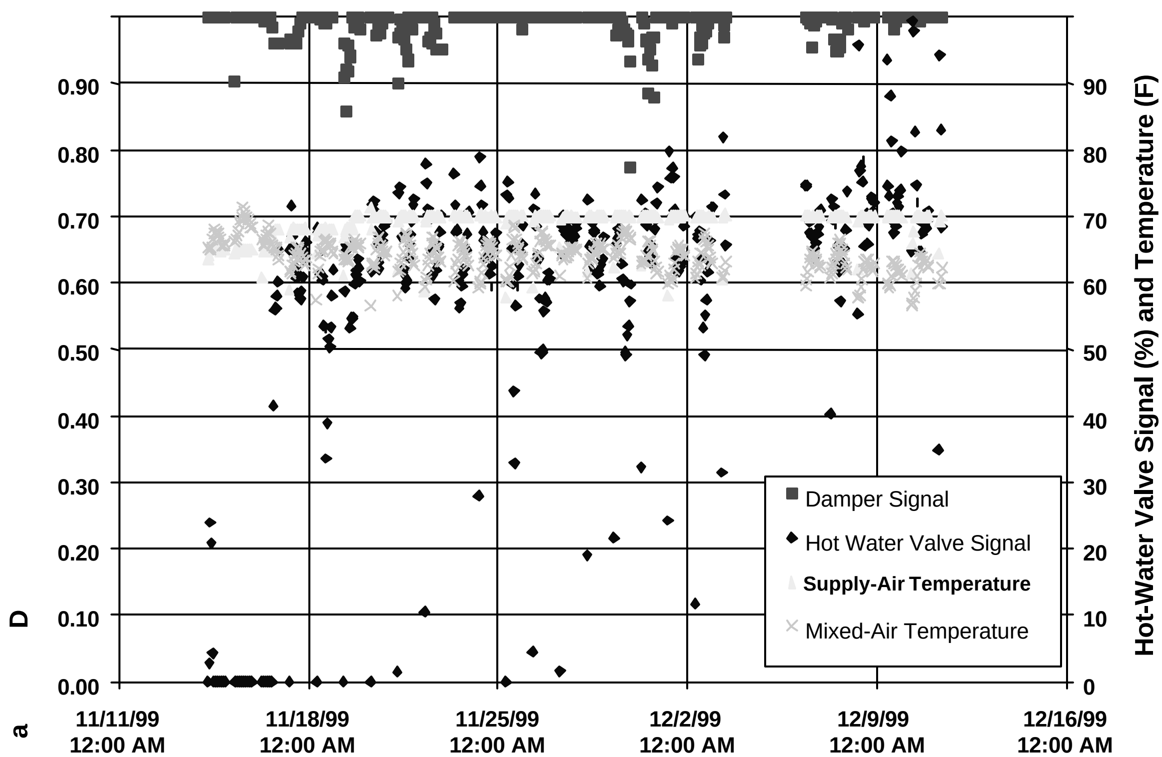

Figure 9. Outdoor-damper signal (black squares), hot-water valve signal (black diamonds), supply-air temperature (light gray triangles), and mixed air-temperature (gray x's) are shown for approximately a month for air handler 15.

Impacts

This field study resulted in two kinds of information about the problems found by the OAE: 1) how accurately it diagnosed problems, and 2) how numerous and how important the problems detected were. Both are discussed briefly here.

A summary of the functional problems identified by the OAE and the results of manually investigating them further is shown in Table 1. In each case, the extended manual diagnoses found the actual failure to be among those isolated by the OAE. Two of the three temperature sensor failures (Ahu-12 and Ahu-30) were directly identified and isolated, although manual analysis of one of them suggested that two of the sensors had likely been swapped. The third temperature sensor problem (Ahu-31) was among three possible causes isolated by the OAE module. Similarly, the failure of proper supply-air control was correctly isolated (Ahu-13) as one of two possible causes. The other, an OAE setup error, would have resulted from input of an improper description of the control scheme or setpoint value by the user in the fixed user inputs during installation.

Table 1. Comparison of functional problems identified by the OAE diagnostician and with extended engineering analysis.

Air-Handling Unit	Problems Identified	
	OAE Diagnostician	**Extended Diagnostics**
Ahu-12 [Lobby]	Temperature sensor	Swapped return- and mixed-air temperatures
Ahu-13 [Public Corridor]	OAE setup or supply-air controller	Supply-air controller
Ahu-15 [Lounge/Atrium]	Excess outdoor-air in heating mode	Damper system is stuck fully open
Ahu-30 [South Lounge]	Temperature sensor	Temperature sensor
Ahu-31 [North Lounge]	Temperature sensor, damper system, or OAE setup	Temperature sensor
Ahu-12 [Meeting Rooms]	Economizer should run but mechanical cooling is on instead	Damper system stuck fully closed

Two of the six problems identified (for Ahu-15 and Ahu-12) were stuck dampers. In both cases, stuck dampers were among fairly long lists of 8 to 10 possible causes that the OAE could not further isolate. So, the OAE correctly detected the problem but did not provide the user much further guidance in isolating the cause.

A common reason for the OAE having difficulty isolating causes is the presence of two problems simultaneously, when one or the other manifests itself at any given time. In this field test, most of the air handlers had some type of functional problem as well as some type of problem supplying outdoor air on the schedule the operators and control-system installer thought it

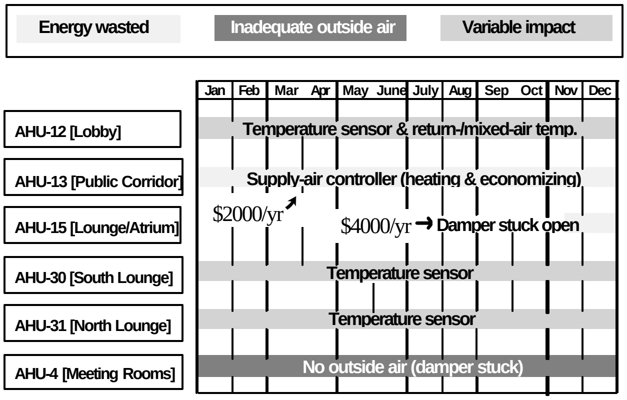

Figure 10. Duration and impact of functional problems.

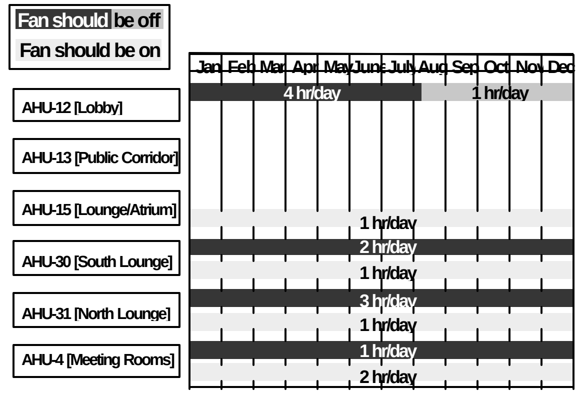

Figure 11. Air handler schedule-related problems detected by the OAE diagnostician.

should. Summaries of the nature and duration of these two classes of problems for each air handler appear in Figures 10 and 11.

Figure 10 shows that five of the functional problems in the six air handlers lasted for the entire duration of the field test (over one year). The sixth air handler's problem occurred in the final six weeks of the testing. The fact that none of these problems was noted or corrected by the operations staff supports our hypothesis that these types of problems in air handlers rarely get fixed (i.e., are "silent killers" of energy efficiency). Of the six problems found, three were temperature-sensor problems that impact both energy efficiency and the adequacy of outdoor-air ventilation. These effects are caused by poor control resulting from faulty temperature readings, but their impacts are difficult to quantify because no good temperature data are available upon which to base impact estimates. One problem affected only the outdoor-air control, but it resulted in no outdoor air being provided for the occupants. The supply-air control and damper-stuck-open problems resulted in significant energy waste, extrapolated to $2,000 and $4,000 per year, respectively. Note that these are relatively small air handlers (10,000 cfm each), so their energy problems amounted to about $0.30/cfm-yr.

Figure 11 shows that five of the six air handlers also had schedule problems, ranging from supply of too much outdoor air when it was not needed for four hours per day to under supply of outdoor air in one case for two hours per day. These schedule errors often (though not always) occurred at the beginning or end of a scheduled period and may be the result of control-design errors or failure of the operators to understand the design. Others appeared in the middle of the night, for example, and are suggestive of forgotten overrides in the control system. We did not observe any of the schedule errors get corrected during the field test, suggesting that they are extremely persistent.

Other Observations and Conclusions

During the course of our field testing of the OAE diagnostician, we made other somewhat subjective observations. The primary ones include:

- Establishing data connections to BASs can range from very difficult to easy, depending largely on the vintage of the BAS and the user-friendliness of the tools provided for logging and extracting data.
- Errors occur in setting up control systems. Tools like the OAE diagnostician can help identify these problems; however, errors can occur just as easily in setting up an automated diagnostician. Sometimes these errors are difficult to detect and distinguish from performance problems with the HVAC systems.
- Even though the interface for a diagnostic tool can be easy to use, if an operator is going to diagnose further after the tool has identified a problem and partially isolated it, good training of the operators and repair staff is crucial.
- Our examples showed how additional deeper diagnosis is valuable. In the future, it would be desirable to give automated diagnostic tools this enhanced capability so that repair actions can be more quickly targeted and implemented.
- Operators themselves can induce some problems in HVAC control systems. We have seen manually implemented temporary overrides left in place in seasons where they create energy and cost penalties. Sometimes actions taken to solve an occupant complaint quickly causes unintended effects, and often these actions don't address the root cause of operation problems. Deeper diagnosis, automated tools that assist in it, and control systems that embed diagnostic capabilities and provide explanations of control strategies will contribute to reducing these sorts of problems in the future.

In conclusion, we have found that automated diagnostics can be used successfully to find existing or newly occurring problems, in fact, many more problems than we had anticipated originally. Our field studies in other buildings show similar rates of fault occurrence. As a result automated diagnostics can be used as tools for commissioning new buildings and retro-commissioning existing buildings.

Energy and dollar savings associated with fixing problems found by the OAE diagnostician are highly variable. The OAE tool provides cost impact estimates to help guide the user in prioritizing maintenance and repair actions. Even though the savings from many problems will easily justify their repair costs, this is not true for all problems. Cost estimates are critical for identifying where actions will be most beneficial.

Automated diagnostics have limitations as shown by our examples. The additional diagnostics presented in the "Diving Deeper into Diagnosis" section involve finding correlations between data for measured variables for entire data sets and conditionally partitioned data. Although correlations were found visually in this analysis, these methods, in principle, could be automated in software in an extended version of the OAE diagnostician or a new diagnostic tool. Documenting the reasoning used to diagnose performance problems is important so that others can benefit from the knowledge and new, improved diagnostic tools can be developed.

Acknowledgements

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