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PNNL-14515

Demonstration of the Whole Building Diagnostician for the Federal Building & U.S. Courthouse at Milwaukee, Wisconsin, and for the University of Wisconsin at Madison

NN Bauman
JC Hail

December 2003

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Demonstration of the Whole Building Diagnostician for the Federal Building & U.S. Courthouse at Milwaukee, Wisconsin, and for the University of Wisconsin at Madison

N. N. Bauman
J. C. Hail

December 30, 2003

Prepared for the Wisconsin Division of Energy under a grant from the U.S. Department of Energy Federal Energy Management Program's 2001 State Energy Program Special Projects and a grant from the Rebuild America Program

Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

The Wisconsin Division of Energy obtained funding through the Federal Energy Management Program (FEMP) to install the Whole Building Diagnostician (WBD) software program as a test bed project to expand the energy savings programs within Wisconsin. The DOE Rebuild America program provided limited additional funding assistance to install the WBD in a University of Wisconsin building.

The WBD is a pre-commercial, production-prototype software package that connects to digital facility management and control systems (FMCS) (a.k.a. energy management systems) to analyze overall building and system performance. Results from the WBD's Outdoor-Air Economizer (OAE) module, the subject of this report, are used by the building operators to determine operational or mechanical problems with the air-handling units (AHUs) operations, as well as providing estimates for the energy savings potential should these problems be corrected. The WBD was developed by the DOE's Pacific Northwest National Laboratory with Honeywell, Inc., and the University of Colorado.

The selected sites were the Milwaukee Federal Building and U.S. Courthouse (517 East Wisconsin Avenue, Milwaukee, Wisconsin) operated by the U.S. General Services Administration (GSA), and Grainger Hall on the University of Wisconsin-Madison campus. Each building was greater than 400,000 square foot, with multiple heating, ventilation, and air-conditioning (HVAC) systems operated and managed from a central FMCS. The Federal Building was selected because of the building's proactive energy management staff. The University building was selected because of its proactive staff and because the building's control system was one for which the WBD already had existing drivers (e.g., the WBD-to-building communication programs).

Prior to the WBD installation, PNNL and building staff verified that each facility could provide the required data points from each AHU for the WBD through direct digital data exchange at the University building and through a modified data collection scheme at the Federal building. However, each site installation later proved to have software and human operator problems with the continuous data collection needed to obtain accurate and reliable diagnostic results. Data was collected for only 12 hours after the initial start up of the WBD at the Federal Building. At the University building, data was collected for approximately 120 hours.

Firm energy and cost saving recommendations could not be provided because of the insufficient data collected at each site. However, the limited data and diagnostics did indicate that HVAC problems at each site and that corrective action would provide energy savings. The WBD as installed can help each site operate facilities in a way that will benefit the building occupants and save energy and other operational costs. The following actions are recommended to use the installed WBD to help achieve each site's potential energy savings and operational improvements:

1. Identify at least one individual to be responsible for the weekly monitoring and simple maintenance of the data collection system.

2. Provide that individual with the resources necessary to verify problems identified by the WBD and then to implement or request correction actions.
3. Identify funding through FEMP, RBA, or the State of Wisconsin to obtain additional and training on the WBD software and on related HVAC engineering.
4. In the case of the Federal Building, provide funding for the support needed from their FMCS contractor.

In addition to using the WBD as installed, a site may want to apply the WBD in one or more of the following ways:

1. Extend the WBD to monitor and diagnose additional building air handlers at the University of Wisconsin.
2. Implement the WBD module that evaluates the daily energy performance of a building or component against their multiyear baseline. Use this module to do the following evaluations:
   A. Measure and verify the general effectiveness of an operation and maintenance (O&M) program for a campus, building, or building component,
   B. Measure and verify the energy performance of an energy project such as lighting retrofits and chiller replacements, and/or
   C. Independently measure and verify the performance guarantees of an energy savings performance contract or a utility energy savings contract.

Site staff have the necessary expertise to extend and manage the WBD with limited additional planning, training, and support by PNNL. The planning would include determining the data flow between a building's metering or FMCS system to the WBD. The support can also include mechanical engineers and building controls experts who can trouble-shoot building problems identified by the WBD and other means. Lastly, the support can include experts in recommissioning and in energy savings performance contracting.

GSA sites may want to participate in a planned demonstration program of a commercialized web-based suite of essential facility management tools for maintenance management, asset management, and project management. One of the essential tools will be the next generation of the WBD. The demonstrations may begin as soon as the spring of 2004.

These recommendations and opportunities will help the General Services Administration and the State of Wisconsin improve their energy and operational effectiveness. The first next step is to discuss interests and approaches with FEMP's regional program office representative Melinda (Mindy) Latimer at (312) 886-8582.

Contacts

State of Wisconsin Grant Manager

Barbara Smith
Division of Energy
Department of Administration
P.O. Box 7868
Madison, WI 53702
(608) 266-7554
Barbara.Smith@doa.state.wi.us

Federal Courthouse

GSA Supervisory Property Manager:
Tony Lillibridge
Room 230
517 East Wisconsin Avenue
Milwaukee, Wisconsin 53202
(414) 297-1125

GSA Project Manager for WBD:
John Ozburn
Room 230
517 East Wisconsin Avenue
Milwaukee, Wisconsin 53202
(414) 297-3320
john.ozburn@gsa.gov

University of Wisconsin

Statewide Building Controls Manager:
Ron Bristol
Division of Facilities Development
Department of Administration
PO Box 7866
Madison, WI 53707-7866
608 266-3051
ron.bristol@doa.state.wi.us

DOE Grant Manager

Mindy Latimer
FEMP Program Representative
DOE Midwest Regional Office
One South Wacker Drive, Suite 2380
Chicago, Illinois 60606
(312) 886-8582
melinda.latimer@ee.doe.gov

DOE Rebuild America

PNNL Program Manager:
Michael Baechler
Pacific Northwest National Laboratory
620 SW Fifth Ave., Suite #810
Portland, OR 97204
(503) 417-7553
michael.baechler@pnl.gov

DOE Pacific Northwest National Laboratory

WBD Installation and Report:
Nathan Bauman
Box 999, K5-16
Richland, WA 99352
(509) 375-6756
nathan.bauman@pnl.gov

WBD-Wisconsin Project Manager:
John Hail
Box 999, K5-16
Richland, WA 99352
(509) 372-4799
john.hail@pnl.gov

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1 Purpose of This Task Report

In May 2003, the Wisconsin Division of Energy (Wisconsin) initiated a Federal Energy Management Program (FEMP) funded project to demonstrate the Whole-Building Diagnostician (WBD), for automatically and continually diagnosing operational problems in the GSA-managed Federal Courthouse in Milwaukee, Wisconsin's building heating, ventilation, and air-conditioning (HVAC) systems. The DOE Rebuild America (RBA) program provided funds to install the WBD in a few of the University of Wisconsin-Madison facilities in the same effort.

Developed by the DOE's Pacific Northwest National Laboratory with Honeywell, Inc. and the University of Colorado, the WBD is a pre-commercial, production-prototype software package that connects to building control systems (e.g., energy management systems), utilizing data from the control system's sensors to analyze overall building and system performance.

The WBD currently consists of two diagnostic tools, or modules, with a user interface designed to readily identify problems and provide potential solutions to building operators. The Outdoor-Air Economizer module (OAE) (the subject of this demonstration), diagnoses whether each 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 outside air when appropriate and not wasting energy by supplying excess outside air. In addition to the two diagnostic modules, the WBD also has a data collection module to automatically retrieve data from some building automation systems.

The results of the on-line demonstration are presented in this report. In the section following this, the need for diagnostics in building systems is briefly discussed, followed by a section on basic information about what the WBD is, how it works, and a detailed description and capabilities of the OAE module. The Wisconsin state facilities in which the software was utilized are described next. Technical discussions including installation of the WBD, the WBD's operation, problems encountered, recommendations, and opportunities and next steps are also presented.

2 The Selected Facilities

2.1 Milwaukee Federal Building and U.S. Courthouse

The Milwaukee Federal Building, originally built from 1892 through 1899 to serve as a post office, is a 426,891 square foot facility, which now serves primarily as the U.S. Bankruptcy Court. The Annex (rear wing) of the building was added, through the fifth floor from 1929 until 1932, with the sixth and seventh floors added in the early 1940s. The most current renovation (approximately $10,000,000) took place from 1973 until 1978. Figure 1 shows exterior and interior photos of the building.

The U.S. General Services Administration (GSA) provides primary support and maintenance for the heating, ventilation, and air-conditioning (HVAC) systems within the facility. The facility utilizes Andover controls as their facility management and controls system (FMCS), with ECC

Controls as the contractor responsible for the FMCS control algorithms, including scheduling, upgrades, and maintenance.

The FEMP grant project included the set up of the data collection process, monitoring and diagnostics for 18 of the facilities' air-handler units, and assistance with interpretation of the diagnostic results including recommendations for corrective actions. The unit which served the atrium was not included because its data would not have provided meaningful diagnostic results.

Figure 1. Milwaukee Federal Building and U.S. Courthouse and interior view of the Atrium

2.2 University of Wisconsin-Madison School of Business

Opening in 1993, Grainger Hall is a 449,250 square foot facility, which houses the Center for Arts Administration, the School of Business, the Journal of Consumer Research, the Small Business Development Center, the Center for the Study of Organizational Performance, the Weinert Center for Entrepreneurship, and the Wisconsin Public Utility Institute. This $40,000,000 facility, named after David W. Grainger, includes 30 modern classrooms, 3 auditoriums with multi-media broadcast capabilities, as well as the 30,000 square foot Business Library. Figure 2 shows an exterior photo of the building.

The operations and maintenance (O&M) group provides the primary support for the HVAC systems within Grainger Hall. The facility utilizes Johnson's METASYS controls as their FMCS with O&M staff responsible for the control system algorithms, including scheduling, upgrades, and maintenance.

Funding from the Rebuild America Program (RBA) provided the support to set up the data collection process, monitoring and diagnostics for the six air-handler units, and assistance with interpretation of the diagnostic results including recommendations for corrective actions during follow-up conference calls after enough data had been collected.

Figure 2. Grainger Hall (Univ. of Wisconsin-Madison School of Business)

3 The Need for Diagnostics in Building Systems

Automated commissioning and diagnostic technologies are designed to ensure the ongoing performance of buildings at the highest possible levels of efficiency. Evidence of extensive performance problems in buildings shows that an efficient building stock will not result solely from designing efficient buildings and installing efficient equipment in them (Lunneberg 1999).

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 even more common in existing buildings because they arise over time from operational changes and lack of maintenance (Claridge et al. 2000). They often result in problems with comfort control and indoor-air quality that 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[1] of buildings is valuable in terms of both finding problems and developing the techniques for doing so, but it is expensive. With only one to two percent of total construction costs devoted to commissioning (see the commissioning resources at http://www.peci.org) and the few experts available to provide such services in high demand, commissioning is not done adequately for most commercial buildings. Commissioning is difficult to sell in a low-bid

[1] Commissioning is the process of systematically putting a building "through its paces," checking that it performs as expected in terms of sensor and actuator connectivity and calibration, system modes, control sequences, and equipment capacities and conversion efficiencies. The term derives from the traditional acceptance process for naval ships, which must undergo a shakedown cruise to prove their speed, range, stability, maneuverability, communications, etc., to meet design specifications before they are accepted into service.

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.

By embedding the expertise required to detect and diagnose operation 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. Further, this detection and diagnostic expertise remains as a legacy in buildings after they are constructed, protecting the building systems against slow mechanical degradation, as well as faults inadvertently introduced by operators seeking to resolve complaints without finding root causes. The principal technical challenges are the construction of diagnostic techniques that 1) can be automated, 2) comprehensively diagnose the range and diversity of building systems and equipment, 3) make use of a minimal set of additional sensors beyond those used for control, and 4) are applicable for building commissioning, as well as ongoing diagnostics.

Currently, most building owners are not aware of the power of automated commissioning and diagnostic technology to provide them more cost effective, comfortable, and productive buildings. The technology is in its infancy and not yet well known in practice. Finally, energy service companies who may eventually offer commissioning and diagnostic services are slow to expand their business practices beyond their current focus on lighting and cooling equipment retrofits. Despite this current state, automated diagnostic technology offers a future with improved facility operation, better indoor environments, and enhanced and higher-quality offerings by service companies.

4 Background on the WBD

Developed by the Pacific Northwest National Laboratory (PNNL)[2] under funding from the Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy, with Honeywell, Inc. and the University of Colorado as subcontractors, the Whole-Building Diagnostician (WBD) is a production-prototype software package with two modules providing automated diagnostics for buildings based on data collected by direct digital control (DDC) systems. These tools are deployed in the WBD's user interface and data and process management infrastructure.

The WBD's Outdoor-Air Economizer (OAE) module diagnoses whether each 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

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

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 low cost. Early experience with the OAE in new and existing buildings in Washington and California has confirmed the broadly held suspicion that problems with outdoor-air ventilation control and economizing are endemic. The OAE has discovered problems in virtually all of air handlers examined to date, in existing and newly commissioned buildings.

The WBD also contains a Whole-Building Efficiency module that monitors whole-building and major subsystem (end-use) performance. It does this by tracking actual energy consumption and comparing it to estimated expected consumption as a function of time of day, day of week, and weather conditions. Using these data, it automatically constructs a model based on actual past system performance for a baseline period, and then alerts the user when performance is no longer as good as or, in the case of retrofits or operations and maintenance (O&M) programs, is better than past performance. The tool continuously updates its model with recent energy consumption to provide feedback during the initial training period after a period of about 4 to 6 weeks. Electricity or gas consumption sensors typically must be connected to the building's direct digital control (DDC) system to obtain the consumption data. This, however, is not an absolute requirement.

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. These tools are available for commercialization through special use licenses from Battelle. The WBD's infrastructure is an open-protocol, public-domain framework designed to support the ready incorporation of new diagnostic tools from other developers in the future.

4.1 The WBD Infrastructure

The WBD currently consists of 4 primary modules: the two diagnostic modules, the user interface, and a database that stores measured data, as well as diagnostic results. The diagnostic modules are 1) the Outdoor Air Economizer Diagnostician module and 2) Whole-Building Energy module. The 4 modules are connected by an infrastructure that provides data transfer, data management, and process control, as shown in Figure 3. Boxes represent major components; lines represent flows of data. Data is automatically obtained at a user-specified sub-hourly frequency and averaged to create hourly values. As new hourly values become available in the database, the diagnostic modules automatically process them and produce diagnostic results that are also placed in the database. The user can then open the WBD user interface at any time to see the latest diagnostic results, and can also browse historical results.

Raw data (e.g., sensor measurements) may be obtained from a variety of data sources: a data logger or building management system, another database, or some other analytic software tool. The system also requires one-time entry of set up data that customizes the WBD modules to each specific building and heating/cooling/ventilation system. The system is written in the C++ language and uses an SQL database. The term DDE in Figure 3 refers to Microsoft's dynamic data exchange protocol.

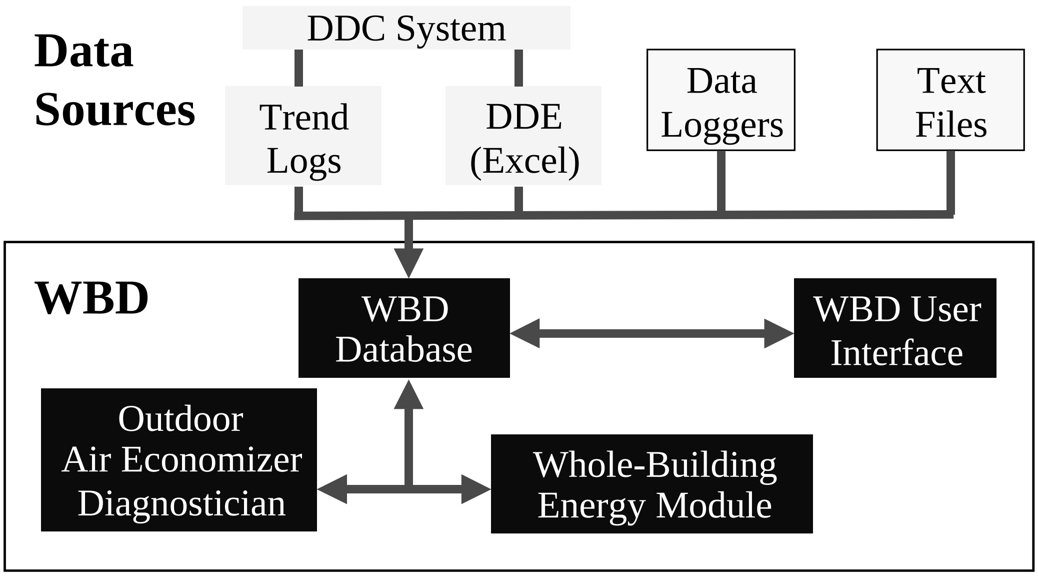

Figure 3. Schematic diagram of the WBD software

5 The Outside-Air Economizer (OAE) Diagnostic Module

This section provides a brief overview of the Outdoor-Air Economizer (OAE) module. Additional information about the WBD and the OAE can be found in Brambley et al. (1998) and Katipamula et al. (1999). The OAE 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. (2003)]. 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 waterside or the refrigerant side of the air handler; it only detects problems on the airside (i.e., economizer operation and ventilation). If the air handler does not have an economizer, the OAE module can still detect problems with the outdoor-air ventilation.

5.1 Types of Economizer Controls Supported

The OAE module can diagnose abnormal operations or problems with several different types of economizer controls including differential dry-bulb temperature-based, differential enthalpy-based, high-limit dry-bulb temperature-based, and high-limit enthalpy-based.

With differential control strategies, the outside-air condition is compared with the return-air condition. As long as the outside-air condition is more favorable (for example, with dry-bulb temperature control, the outside-air dry-bulb temperature is less than the return-air temperature), outside air is used to meet all or part of the cooling demand. If the outside air alone cannot satisfy the cooling demand, mechanical cooling is used to provide the remainder of the cooling load.

With high-limit control strategies, the outside-air condition is compared to a single or fixed set point (usually referred to as a high limit). If the outside-air condition is below the set point, outside air is used to meet all or part of the cooling demand. Mechanical cooling provides any remaining cooling load.

In addition to these economizer control strategies, the OAE supports fault detection with both integrated and nonintegrated economizers. An integrated economizer, as its name implies, is fully integrated with the mechanical cooling system such that it can either provide all of the building's cooling requirements if outdoor conditions allow, or it can be supplemented by mechanical cooling when outdoor conditions are not sufficiently favorable to handle the entire cooling load. An economizer often has the ability to throttle outdoor-air intake rates between minimum and maximum levels to prevent the delivered air from being cooler than the supply-air set point.

Conversely a nonintegrated economizer does not operate when the mechanical cooling system is operating. If outdoor conditions are not sufficiently favorable to allow 100 percent economizing, no economizing is used. A two-stage thermostat often controls a nonintegrated economizer. The first stage opens the economizer; the second stage locks out the economizer and turns on the mechanical cooling.

5.2 Types of Air-Handling Systems Supported

The OAE tool supports the following types of single-duct air handlers:

- constant-air-volume systems
- variable-air-volume (VAV) systems with no volume compensation (i.e., outside-air intake is a constant fraction of the supply-air flow rate rather than changing it to maintain a constant outside-air volume).

Air handlers that the OAE tool does <u>not</u> support include:

- VAV systems that maintain constant outside-air volume flow through volumetric flow measurements (commonly using air-monitoring stations consisting of pitot-tube arrays)
- VAV systems that attempt to approximately provide constant outside-air volumetric flow by increasing the outside-air fraction (e.g., by opening the outside-air damper system) as the fan speed decreases
- systems that utilize CO_2-based outside-air control strategies
- dual-duct air-handling systems.

5.3 Metered Data Requirements for the OAE Module

The OAE requires 7 periodically measured/collected (currently at sub-hourly increments) variables, as shown in Table 1. In addition to the 7 variables, the damper-position signal is also required for air handlers with damper-position-signal control (i.e., if the damper-position signal is controlled directly to maintain the ventilation or to control the supply- or mixed-air temperatures when the air handler is economizing). For economizers with enthalpy-based control, outside- and return-air relative humidity (only for differential enthalpy control) or dew point temperatures are required. If the supply- or mixed-air temperature set point is reset, the reset value at each hour is also needed.

Table 1. Typical required data points for the OAE module

AHU Signals	Data Point(s)	Units	Integration
Date/time Stamp	Date/time stamp (end of hour)	Date/time	None
Fan Status	Fan on fraction	Ratio (0 to 1)	Average hourly
Damper Status	Damper position	Percent open	Average hourly when fan is on
AHU Status	Chilled water valve position	Percent open	Average hourly when fan is on
	Hot water valve position		
Air Temperatures	Discharge-air temperature	Degrees F	Average hourly when fan is on
	Return-air temperature		
	Mixed-air temperature		
	Outdoor-air temperature		

5.4 Set up Data Requirements

The OAE module requires several one-time (set up or configuration) data inputs to characterize the existing systems and how they are controlled. The engineering units for all inputs (both set up and measured) are assumed to be in British units unless otherwise specified.

The OAE is capable of detecting and diagnosing faults with most commonly found air handlers using almost all outside-air and economizer control strategies. However, the user must describe the control strategies used to the OAE with the set up information. In addition, the OAE is designed to be flexible in accepting status inputs. For example, the WBD can accept any one of 4 different types of signals to indicate whether the supply fan is ON. Once the OAE module is configured, the detection and diagnosis is fully automated.

The set up data are required for all air-handler systems with economizers. These data describe:

1. The basic air-handling system
2. The minimum, maximum, and required (building fully-occupied) outdoor-air fractions
3. The occupancy schedule, defining when the required outdoor air must be supplied
4. Data needed to estimate energy and cost impacts of problems.

There are 17 items of user-supplied set up data that must be supplied for every air-handler system. In addition, there are a number of additional set up data inputs, along with the types of air handler and economizer controls to which they are applied. As few as 3 to as many as 15 additional inputs may be required to describe any given system type. For a typical system with an outdoor-air-fraction-based differential temperature economizer with low-limit control, 9 of these setup items are required. Almost all of these inputs are provided with defaults that enable the OAE module to be initialized without the user providing them; however, it will not provide correct diagnoses unless the setup values are correct. Potential errors in the setup data are sometimes identified by the OAE as candidate causes of problems it detects with the air-handler operation. Generally, these then need to be reconciled by the building operator and setup data changed to correct any differences between the actual and default values.

5.5 Basic Operating Sequence of Air Handlers

The OAE module 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 logic tree is based on the basic air-handler operating sequence, as described below.

An air handler typically has two main controllers: 1) to control the outdoor-air intake and 2) to control the supply-air temperature (in some cases mixed-air temperature is controlled rather than supply-air temperature). The basic operation of the air handler is to draw in outdoor air and mix it with return air from the zones and, if necessary, condition it before supplying the air back to the zones, as shown in Figure 4.

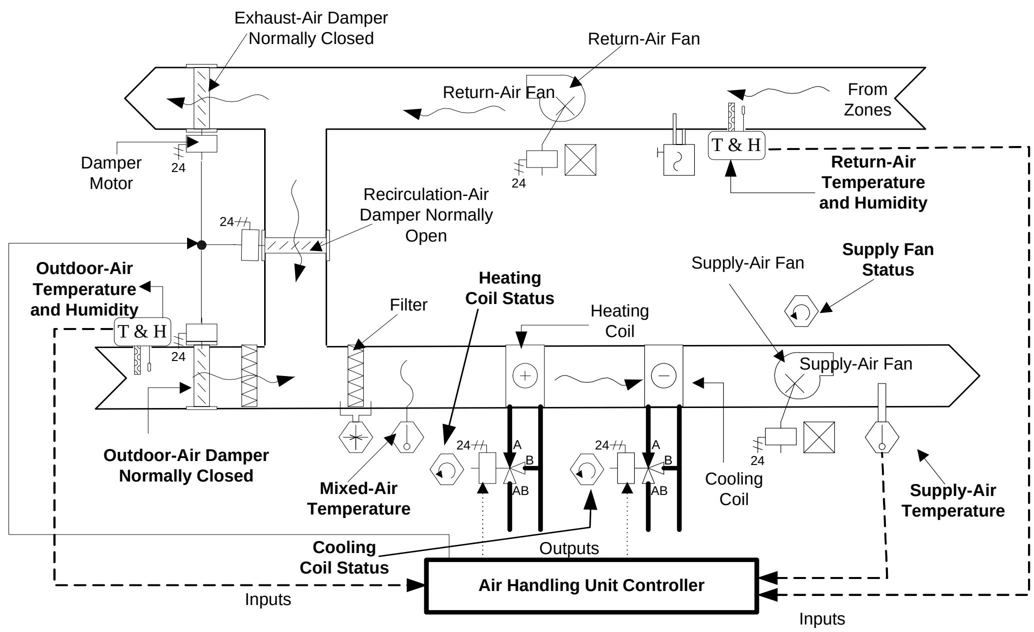

Figure 4. Schematic diagram of an air-handler showing typical sensor locations

An air handler typically has four primary modes of operation during a building's occupied periods, for maintaining ventilation (fresh-air intake) and comfort (the supply-air temperature at the set point), as shown in. The operating sequence determines the mode of operation and is based on the ventilation requirements, the internal and external thermal loads, and indoor and outdoor conditions.

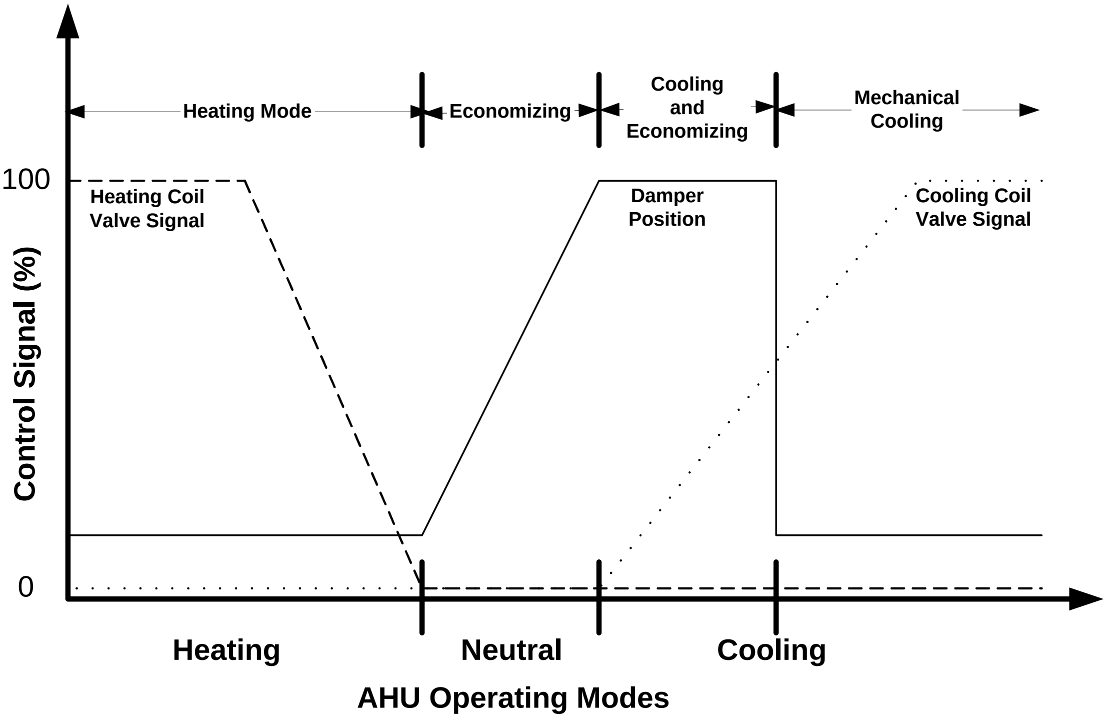

Figure 5. Basic operating sequence of an air-handling unit

When indoor conditions call for heating, the heating-coil valve is modulated (i.e., controlled) to maintain the supply-air temperature at its set point (heating mode in). When the air handler is in the heating mode, the cooling-coil valve is fully closed, and the outdoor-air damper is positioned to provide the minimum outdoor air required to satisfy the ventilation requirements. As heat gains increase in the zone and the need for cooling increases, the air handler transitions from heating to cooling. Before mechanical cooling is provided, the outdoor-air dampers are opened fully to use the favorable outdoor conditions to provide 100 percent cooling (economizer mode in). In this mode, the heating- and the cooling-coil valves are fully closed and the outdoor-air dampers are modulated to meet the cooling requirements.

As the heat gains in the zone continue to increase, the outdoor air alone cannot provide all the cooling necessary, and the air handler changes modes by initiating mechanical cooling (cooling and economizing mode in) to supplement the economizer. In this mode, the outdoor damper is fully open, the heating-coil valve is fully closed, and the cooling-coil valve is modulated to maintain the supply-air temperature. As the outdoor conditions become unfavorable (i.e., too hot and humid) for economizing, the air handler changes mode again. This time the outdoor-air dampers are modulated to the minimum position to provide the minimum outdoor air required to satisfy the outdoor-air ventilation needs, the heating-coil valve continues to be fully closed, and the cooling-coil valve is modulated to maintain the supply-air temperature at its set point.

If an air handler does not have an economizer, there are two basic modes of operation (heating and mechanical cooling). If the economizer is not integrated with mechanical cooling (i.e., it cannot economize and provide mechanical cooling simultaneously), there are 3 basic modes of operation (heating, economizing, and mechanical cooling).

5.6 Diagnostic Approach

The OAE 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 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. Tolerances are assigned to each data point, and uncertainty is propagated through all calculations.

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 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 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. In the example above, a stuck outdoor-air damper, an economizer controller failure, or perhaps a misconfigured setup could cause the economizer to be off. Thus, at each metered time period, a list of possible causes is generated.

An overview of the logic tree used to identify operational states and to build the lists of possible failures is illustrated in Figure 6. The boxes represent major sub-processes necessary to determine the operating state of the air handler; diamonds represent tests (decisions), and ovals represent end states and contain brief descriptions of OK and problem states. Only selected end states are shown in this overview, and the details of processes and decisions are excluded because of space constraints.

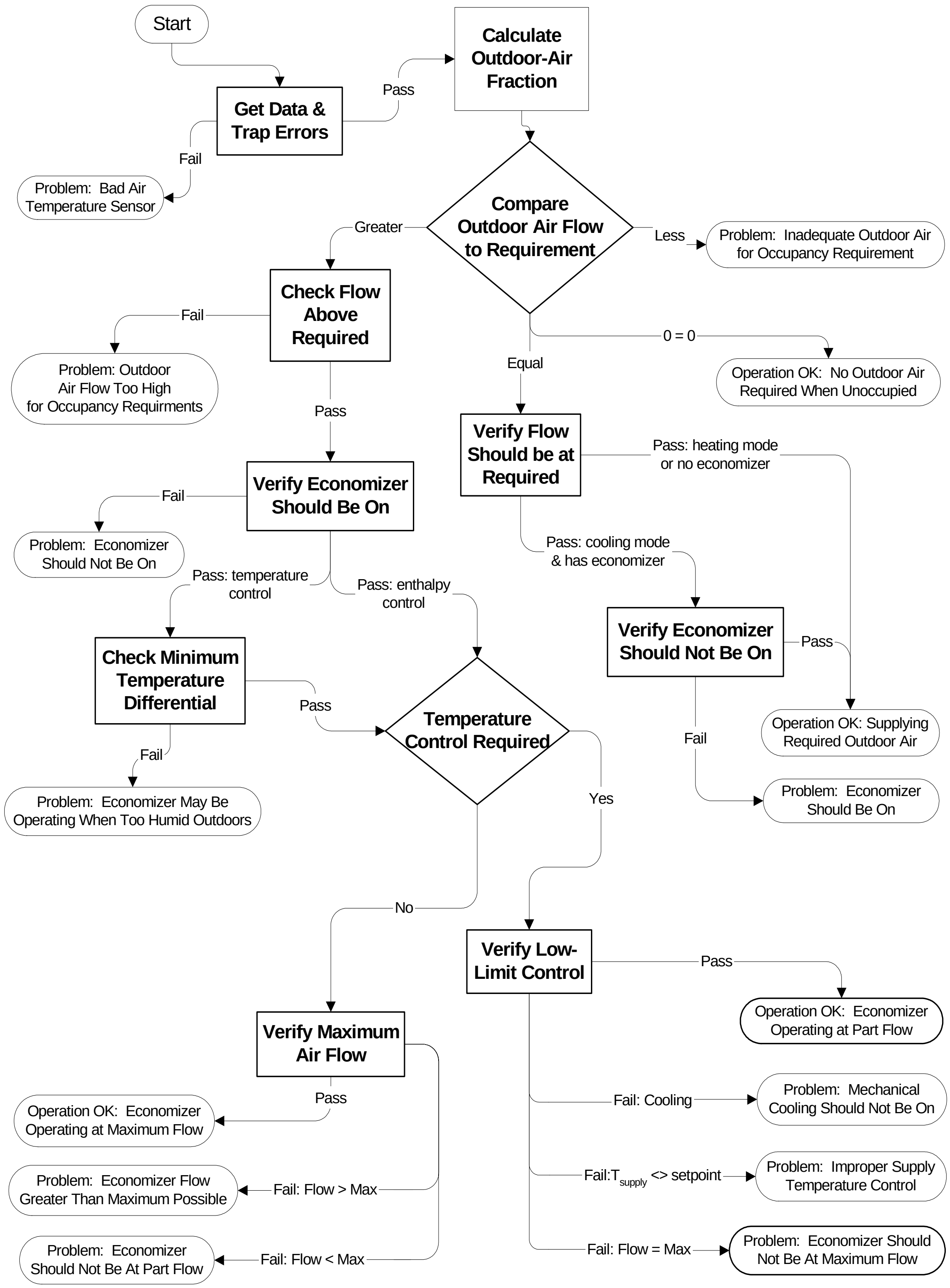

Figure 6. Overview of the OAE diagnostic logic tree showing key decision processes (boxes) and operating states (ovals)

5.7 Basic OAE Functionality

The OAE user interface uses color-coding 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 7, 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, results for air handler 2 (AHU-02 TP) are 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 state. White cells identify OK states, for which no problems were detected. Other colors represent problem states. Clicking the computer mouse on any shaded cell brings up the specific detailed diagnostic results for that hour.

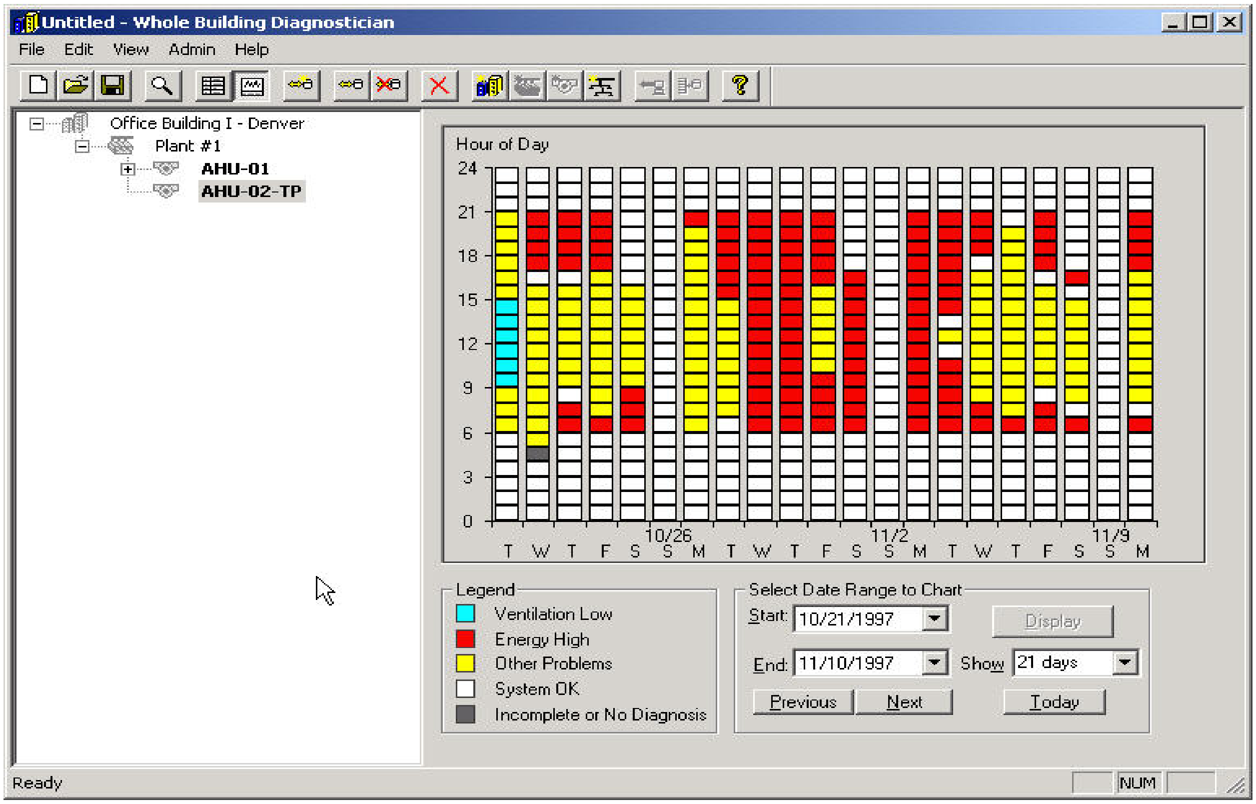

Figure 7. Screen image of example OAE diagnostic view

Figure 8 shows a pop-up window providing a short description from a selected problem hour from Figure 7. Figure 9 shows the detailed explanation of the problem, energy impacts of the problem, potential causes, and suggested corrective action(s). Clicking" on the *Details* button in the *Current Condition* window (Figure 8) reveals this "Details" window. Although in this case the problem appears to be with the mixed-air temperature sensor, the OAE diagnostician cannot, by itself, isolate that specific sensor, because both the return- and outdoor-air sensors may also be out of calibration. A manual inspection of the three sensors and their wiring would be needed to identify the specific problem.

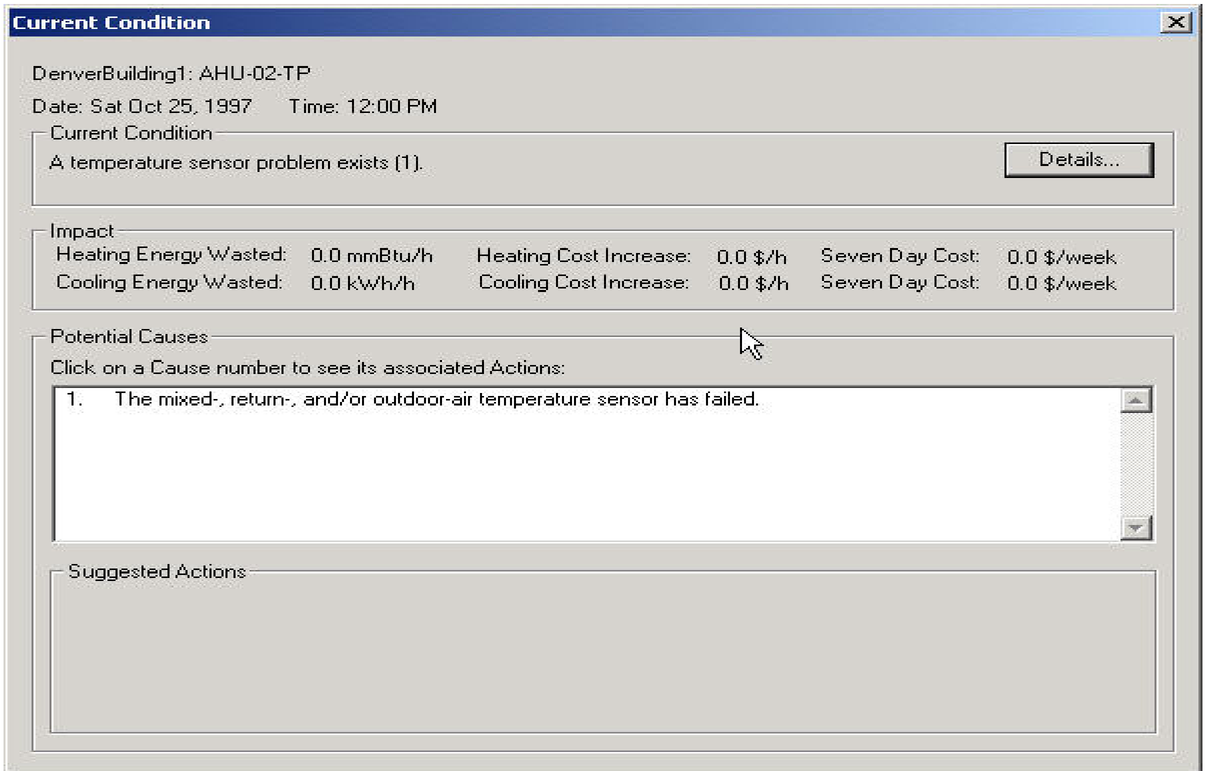

Figure 8. Current condition screen for example problem hour

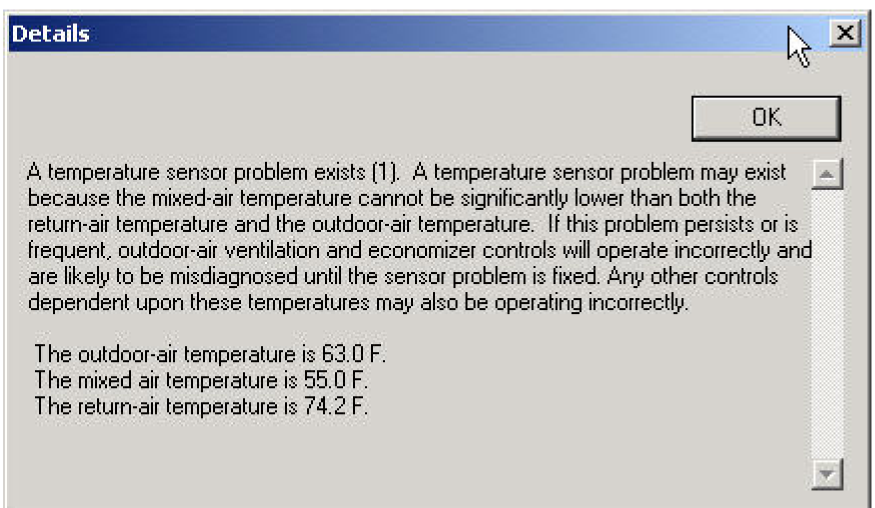

Figure 9. Details screen example problem hour

5.8 Requirements for Using the WBD and OAE

The WBD and its diagnostic modules were developed for a personal computer running any Microsoft Windows operating system (98/ME/NT/2000/XP)[3]. The WBD can be run in a fully automated/unattended mode or can be used to batch process the data. To run the WBD in a fully automated (unattended) mode, the data collection from the air handlers to the WBD database must be fully automated. A companion data collection module can be used to collect the data from air handlers that are controlled by central building automation systems. To use this data collection module, the site needs a networked computer operating under Windows 98/NT/2000/XP (preferably NT or 2000 to avoid problems with the computer's clock) and a building automation system (BAS) that support Microsoft DDE protocols. There are other methods available for data collection; however, several of the current methods may require increased levels of human intervention.

Although the underlying methodology used by the OAE is independent of the time interval at which data are collected, the user interface only displays results at hourly intervals. Data should be, at a minimum, collected once an hour, however, the data collection module can process data that is collected at a more frequent interval and average it to hourly values (instantaneous values obtained on 5-minute intervals are recommended). It is recommended to have all measured data either instantaneous or averaged, as mixing instantaneous and averaged data may introduce false alarms.

6 Summary of On-line Data Collection, Testing and Results

6.1 Milwaukee Federal Building & U.S. Courthouse

This demonstration project included the set up of the data collection process, monitoring and diagnostics for 18 of the facilities air-handler units, and assistance with interpretation of the diagnostic results including recommendations for corrective actions. The unit, which served the atrium, was not included, as its data would not have provided meaningful diagnostic results.

6.1.1 Configuring the Diagnostician

There are two aspects of the air-handler's operation that must be specified for the OAE: the control strategy for the outdoor-air and economizer, and the schedule (times of day and days of week) for which the minimum outdoor air must be supplied for the occupants (i.e., the occupancy schedule).

Figure 10 shows a portion of the configuration information of the WBD's user interface for the Federal Building as installed. The left side shows the hierarchical "configuration tree" as specified by the Administrator for this WBD installation. As shown in Figure 10, the Milwaukee Federal Building/Courthouse has a plant (which generically serves as the building's central plant), an air-handler unit, and a data collection network. The Administrator can set up a configuration tree for multiple air handlers in several ways as follows: 1) set up the tree to

[3] Although the initial version of the WBD and its components were developed and tested under the Windows 95 operating system, this operating system is not currently supported.

include all of the air-handling units under one building (that is, place all air handlers in a single WBD database), or 2) set up each air handler individually (that is, create a separate WBD database for each air handler). The current version of the WBD software does not allow the user to combine multiple databases that have a common structure, so it is more aesthetically pleasing to do the former. Because computers, networks, and electrical grids can fail in unpredictable ways, the latter is recommended because the potential for complete data loss is lessened.

PNNL staff configured each air handler as a separate WBD database as indicated in the configuration tree (Figure 10) which shows a “Milwaukee Courthouse”, a “Plant”, an “AHUxx”, and a “CSV” (data collection network). When the user selects AHU1A and the Configuration button on the toolbar is pushed, AHU1A’s configuration is displayed as shown in the right side of Figure 10. The GSA Services staff provided the information for each of the air-handler units.

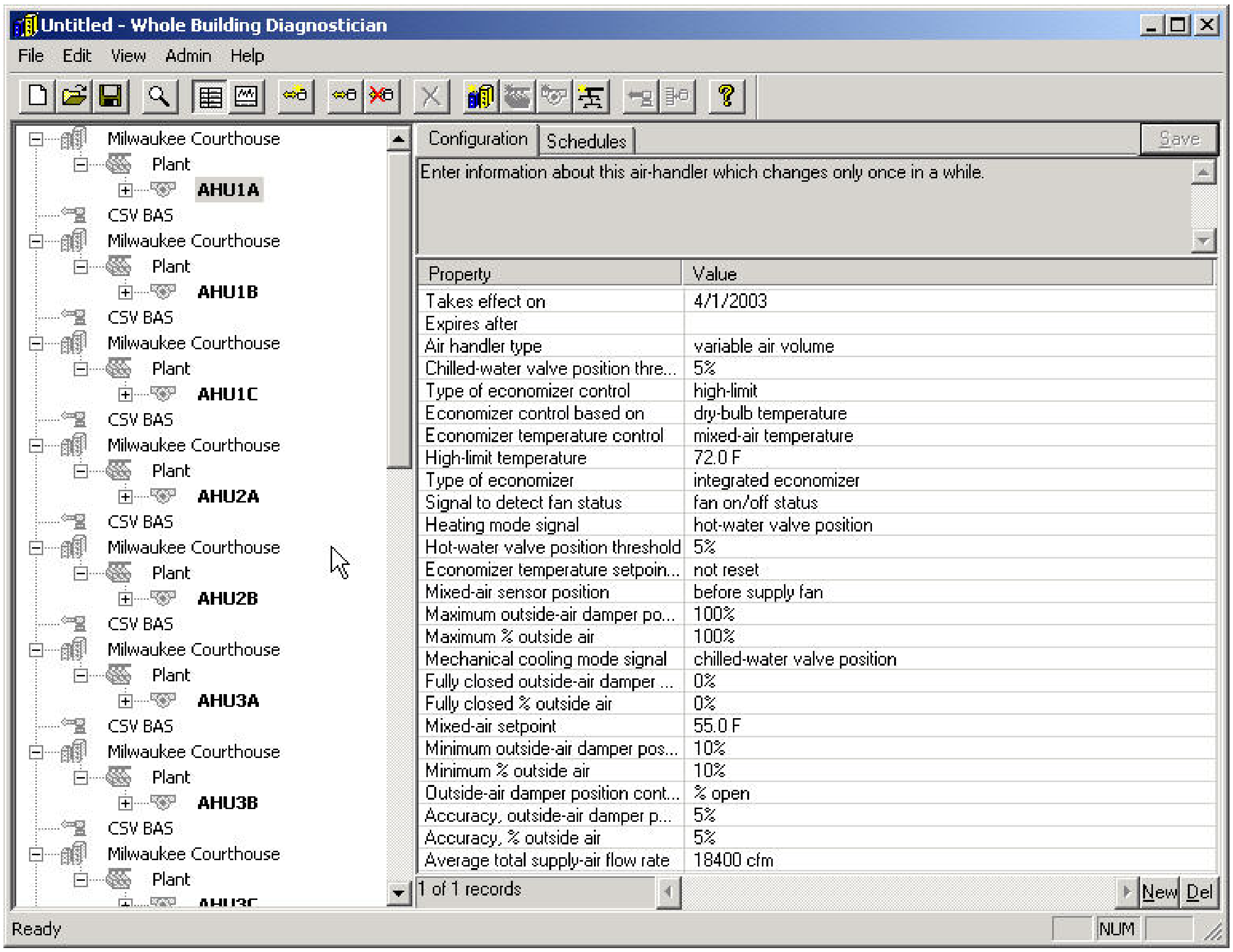

Figure 10. WBD’s AHU configuration screen for the Milwaukee Federal Building

6.1.2 Air-Handler Configuration Parameters

The Milwaukee Federal Building has 18 air-handler units - 10 variable-air volume type and 8 constant-air volume type. Each unit has an integrated economizer, controlled as a high-limit economizer based upon the mixed-air temperature set point. The supply set point for the economizer operation is not reset (i.e., it remains a constant). Table 2 provides a summary of the air-handler type, control, and nominal design air flow rates.

Table 2. Summary of Air-handler control and flow rate for the Milwaukee Federal Building

Air Handler Number	Air Handler Type	Control Basis	Control Point	Nominal Flow Rate (cfm)
AHU1A	Variable-air volume	High limit	Mixed-air temp.	18,400
AHU1B	Variable-air volume	High limit	Mixed-air temp.	20,800
AHU1C	Constant-air volume	High limit	Mixed-air temp.	1,000
AHU2A	Constant-air volume	High limit	Mixed-air temp.	25,230
AHU2B	Variable-air volume	High limit	Mixed-air temp.	27,310
AHU3A	Variable-air volume	High limit	Mixed-air temp.	24,000
AHU3B	Variable-air volume	High limit	Mixed-air temp.	14,000
AHU3C	Constant-air volume	High limit	Mixed-air temp.	7,500
AHU4A	Variable-air volume	High limit	Mixed-air temp.	21,300
AHU4B	Variable-air volume	High limit	Mixed-air temp.	18,900
AHU4C	Constant-air volume	High limit	Mixed-air temp.	3,150
AHU5A	Variable-air volume	High limit	Mixed-air temp.	21,600
AHU5B	Constant-air volume	High limit	Mixed-air temp.	19,380
AHU5C	Constant-air volume	High limit	Mixed-air temp.	3,150
AHU6A	Constant-air volume	High limit	Mixed-air temp.	23,420
AHU7A	Constant-air volume	High limit	Mixed-air temp.	User's data file unavailable
Marshal	Variable-air volume	High limit	Mixed-air temp.	10,000
Probation	Variable-air volume	High limit	Mixed-air temp.	15,000

As shown in Figure 10, AHU1A's outdoor-air damper system is controlled based on a specification of damper position (percent open), with a minimum position during occupied hours of 10 percent, a maximum position of 100 percent during economizer operation, and a fully closed position that is presumed to be 0 percent. The damper position was assumed accurate to within 5 percent of its position. These damper positions were assumed in configuration of the OAE module to correspond to outdoor-air fractions of 10, 100, and 0 percent, respectively.

The remaining parameters specify the types of signals and thresholds used to determine whether the supply fan and heating and cooling modes for the air handler are on at a given time.

6.1.3 Data Collection

The WBD's automated on-line data collection module uses the dynamic data exchange (DDE) protocol, an industry standard protocol developed by Microsoft, for exchanging data between applications. The Andover controls system installed at the Milwaukee Federal Building; however, utilizes OPC-based (OLE [object linking and embedding] for process and control) communication protocols (a client-server standard for information exchange), which are not supported with the current version of the WBD.

The development of a driver to support OPC-based communication protocols was determined to be outside the scope and budget for the current project, therefore, staff from ECC Controls, the contractor responsible for the maintenance of the Andover controls system at the Milwaukee Federal Building, and other PNNL staff were consulted to develop a method that would enable automatic data collection through alternate means.

The data collection method developed focused around one of the available methods, as seen in Figure 3. The WBD is capable of reading data from two types of text files. Staff from ECC Controls indicated that they could write and implement a module within the Andover system that would create and update a comma-delimited (CSV) text file to the dedicated data collection computer. A schematic diagram of the data collection method is illustrated in Figure 11.

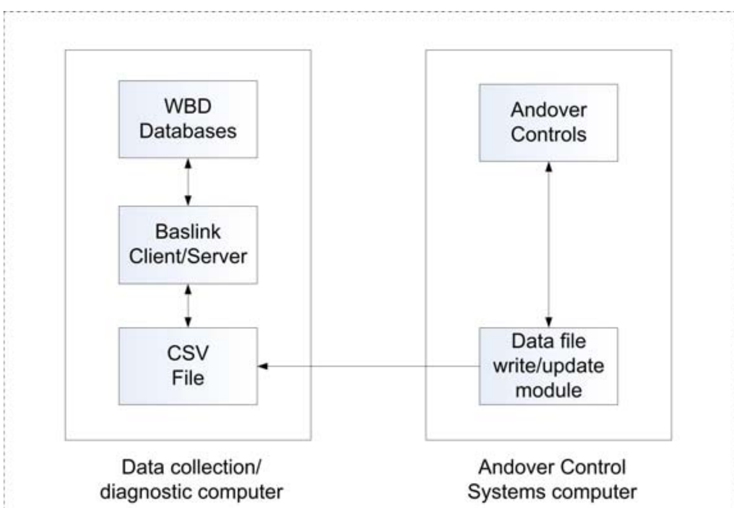

Figure 11. Schematic of the data flow/collection process at the Milwaukee Federal Building

Using its naming and communication protocols, the Andover update module polls the control system for the required data points (see Table 1), once every 5 minutes. The data are then written, in a predetermined order, to a file on the data collection computer. The WBD software program, which typically runs continuously, checks the file for updated information. When updated information is available, the WBD reads that data into storage registers until the data's time stamp indicates that it has rolled over to a new hour. The stored data is then integrated over that hour and written to the appropriate table in the WBD database. After which, the OAE diagnostician module can perform the diagnostics on the saved data.

6.1.4 Results/Diagnostics of Data Collected

This demonstration project collected limited data because independent problems surfaced during and after the site installation visit. The initial problem was that the WBD databases were configured before the site installation visit using an older version of the WBD that was not compatible with the new version of the WBD installed at the site. The advance configuration used information provided by the site staff in an effort to shorten the time required for the on-site configurations. Nonetheless, the incompatibility of the preconfigured databases prevented processing of data by the OAE diagnostics module until the databases were updated after the site visit.

Data was collected during the site installation visit from 3 pm, May 14, 2003 until after 2 am on May 15, 2003, with some databases collecting an additional hour on May 16. After discovering the problem associated with the preconfigured databases, an attempt was made to correct these at the site on the afternoon of the 16 but the available time was insufficient to make the corrections. The new error-free databases were delivered to site staff July 30, 2003, after various personnel scheduling problems were resolved.

The updated databases were loaded onto the data collection computer in mid-October after changes in the building's operations organizations and in the job responsibilities for building staff were resolved. Data was not subsequently collected and analyzed because of the lack of training for the new staff on the WBD software, the added complexity resulting from the modified automation process that was developed, and because the Andover controls contractor had made changes to a component of the data collection system (deactivation of the write/update module) that feeds the WBD.

Figure 12 shows the diagnostic results for the data collected for AHU2B. Typically, a minimum of 1-week worth of contiguous data is needed to see a pattern in the AHUs response to the controls sequence and environmental conditions. If, however, the configuration data input matches the manner in which the AHU is actually being controlled, a larger set of data may indicate that this AHU has a problem with one or more of its temperature sensors.

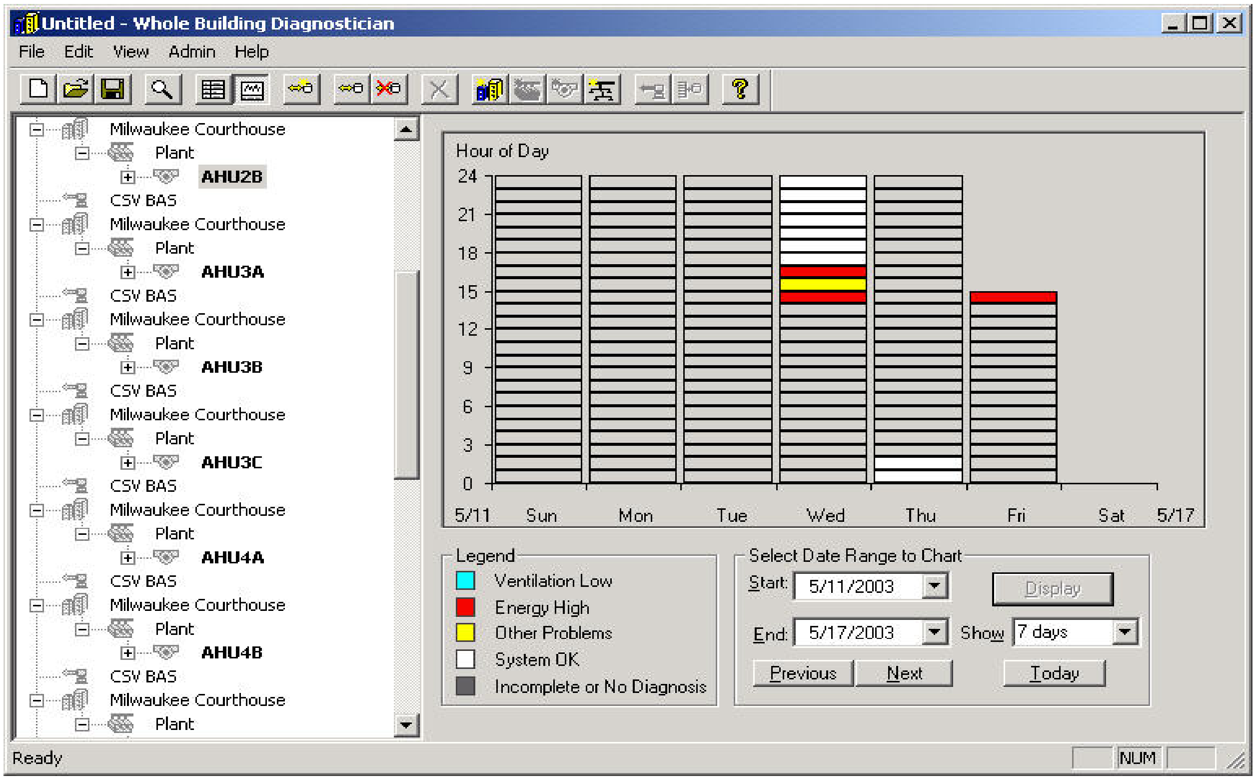

Figure 12. WBD's OAE diagnostic screen for AHU2B

Red cells, as defined in the legend in the lower center of Figure 12, indicate that energy is being wasted. Clicking on one of the red cells brings up the *Current Condition* window, shown in Figure 13, which describes possible causes for the energy waste condition. In this case, the problem identified was that there was too much outdoor-air ventilation being provided during a heating mode. Clicking on the *Details* button on the *Current Condition* window provides additional information on the nature of the problem, as shown in Figure 14. This *Details* window provides a more complete description of the problem and some key data to help interpret it.

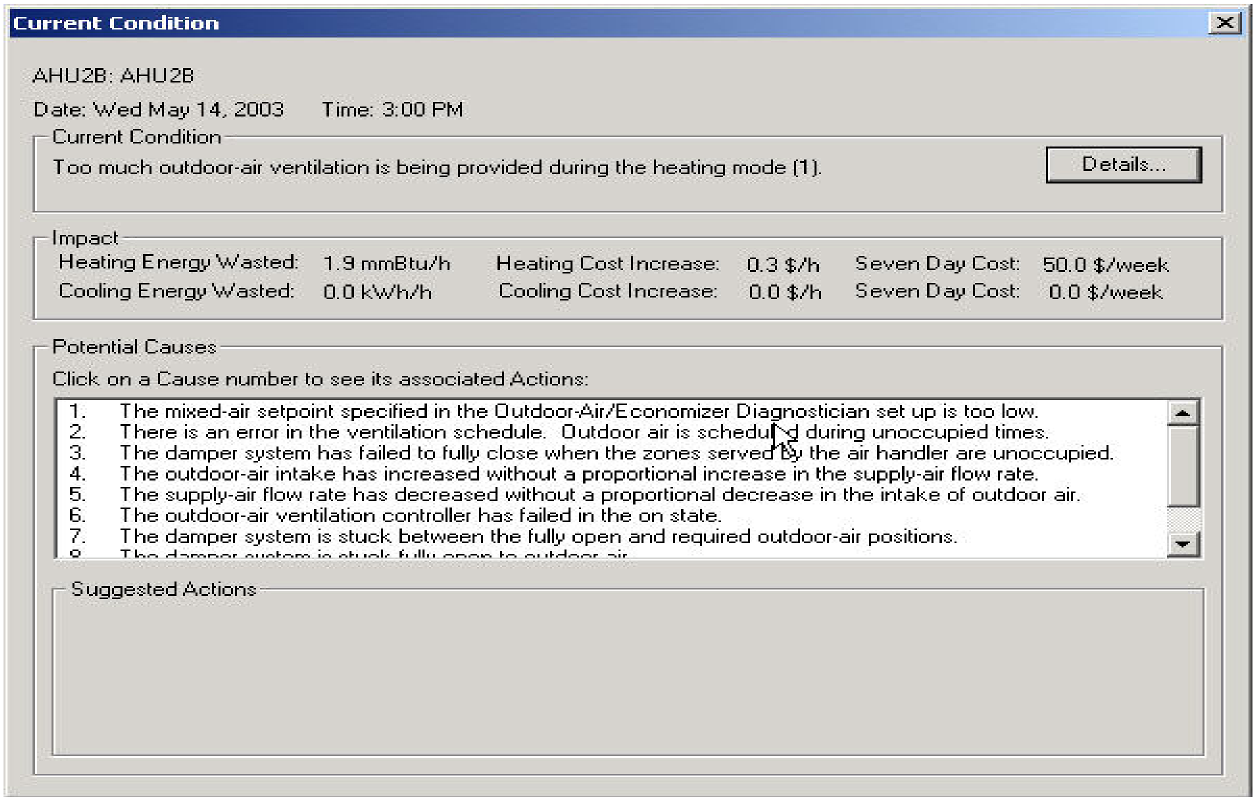

Figure 13. Current condition screen for Milwaukee Federal Building problem hour

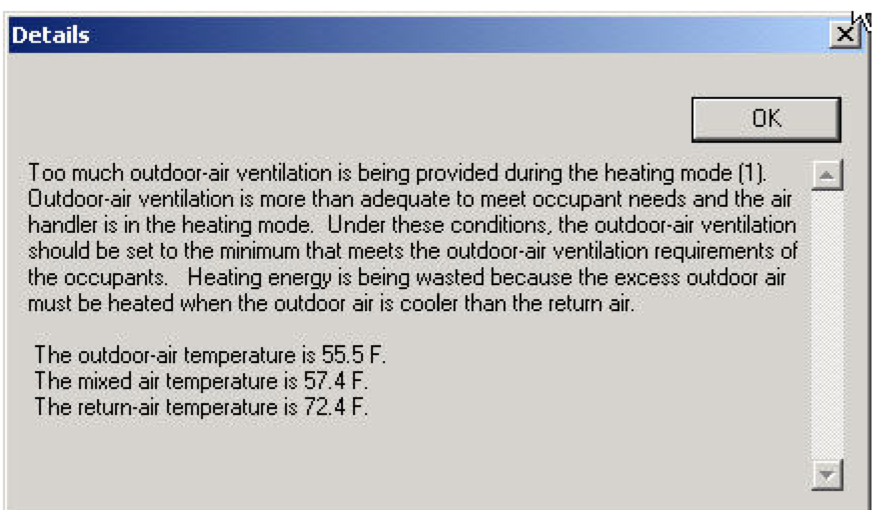

Figure 14. Details screen for Milwaukee Federal Building problem hour

As previously mentioned, a larger set of contiguous data are needed to accurately interpret the diagnostic results of the AHU. Although the problem hour noted above indicated an energy waste resulting from improper outdoor-air control, the hour following indicates “Other problem”, which by the yellow cell is indicative of a temperature sensor problem. If a more complete set of data was available and it showed a recurring pattern of “yellow” problem hours, the recommendation would be to check and calibrate or replace the faulty sensors, because no further accurate diagnoses can be determined with sensors providing bad or faulty data.

6.2 University of Wisconsin-Madison School of Business

This demonstration project included the set up of the data collection process, monitoring and diagnostics for six of the facilities air-handler units, and assistance with interpretation of the diagnostic results including recommendations for corrective actions.

6.2.1 Configuring the Diagnostician

The same specifications are required to configure the diagnostician as described in section 6.1.1. Figure 15 shows a portion of the configuration information of the WBD's user interface for Grainger Hall, as installed. When the user selects AH-1 and the *Configuration* button on the toolbar is pushed, AH-1's configuration is displayed as shown in Figure 15. The O&M staff that supports the operation and maintenance of the systems provided the configuration information for each of the air-handler units selected.

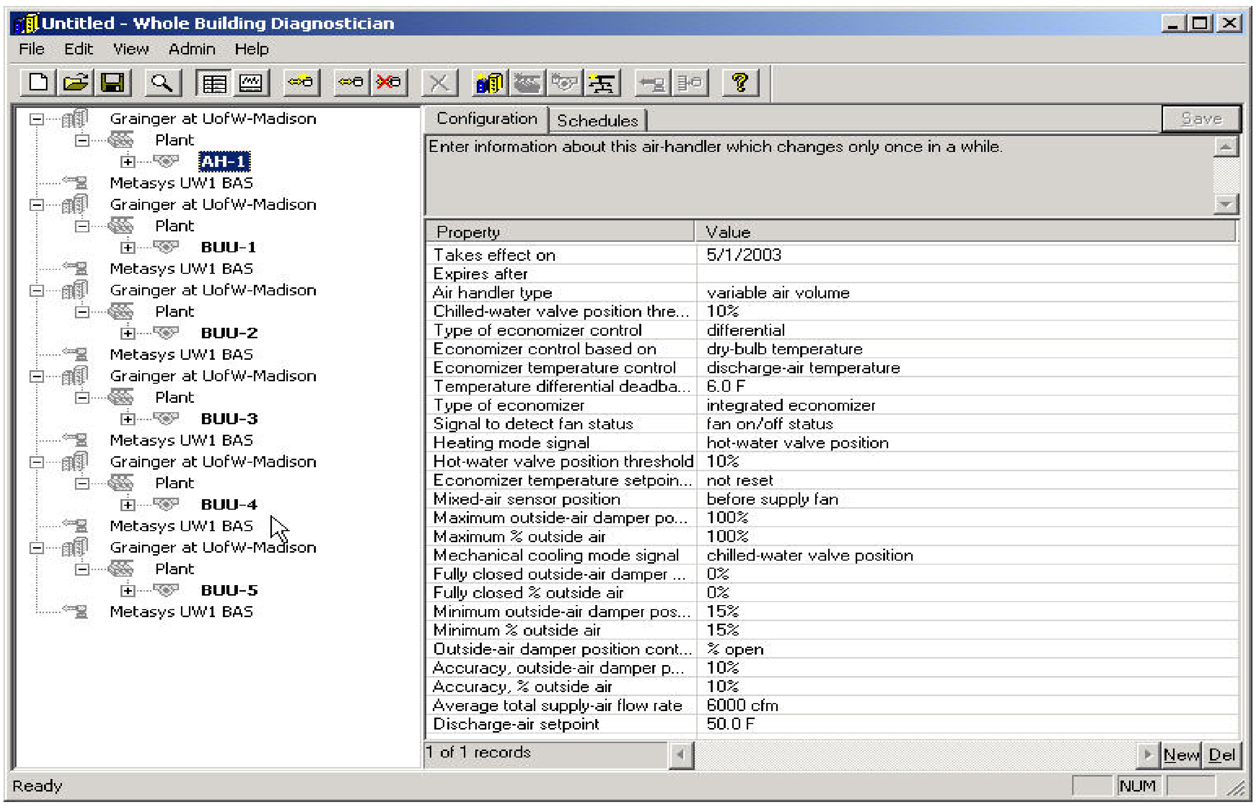

Figure 15. WBD's AHU configuration screen for Grainger Hall

6.2.2 Air Handler Configuration Parameters

There were six variable-air-volume type air-handling units set up at Grainger Hall at the University of Wisconsin-Madison. Each of the six units has an integrated economizer, controlled as a differential, dry-bulb temperature economizer based upon the supply- or discharge-air temperature set point. The set point for the economizer operation for all six units is reset. Table 3 provides a summary of the air-handler type, control, and nominal design air flow rate.

Table 3. Summary of Air-handler control and flow rate for Grainger Hall

Air-Handler Number	Air-Handler Type	Control Basis	Control Point	Nominal Flow Rate (cfm)
AH-1	Variable-air volume	Differential, dry-bulb	Discharge-air temp.	6,000
BUU-1	Variable-air volume	Differential, dry-bulb	Discharge-air temp.	29,700
BUU-2	Variable-air volume	Differential, dry-bulb	Discharge -air temp.	18,600
BUU-3	Variable-air volume	Differential, dry-bulb	Discharge -air temp.	21,500
BUU-4	Variable-air volume	Differential, dry-bulb	Discharge -air temp.	23,400
BUU-5	Variable-air volume	Differential, dry-bulb	Discharge -air temp.	17,000

As seen in Figure 15, AH-1's outdoor-air damper system is controlled based on a specification of damper position (percent open), with a minimum position during occupied hours of 15 percent, a maximum position of 100 percent during economizer operation, and a fully closed position that is presumed to be 0 percent. The damper position was assumed accurate to within 10 percent of its position. These damper positions were assumed in configuration of the OAE module to correspond to outdoor-air fractions of 15, 100, and 0 percent, respectively.

The remaining parameters specify the types of signals and thresholds used to determine whether the supply fan and heating and cooling modes for the air handler are on at a given time.

6.2.3 Data Collection

The WBD's automated on-line data collection module uses the dynamic data exchange (DDE) protocol, an industry standard protocol developed by Microsoft, for exchanging data between applications. Staff from the University's operations and maintenance group provided the network addresses and point-names for the required data for each of the six AHUs. The staff also provided the necessary information to input the proper parameters for the AHU configuration. After the databases were set up and the IP address for the server computer was known, a sample data point was "pinged" to confirm that the pathway, naming, and communication links were all set up correctly. Figure 16 shows a simplified schematic of the data flow/collection set up.

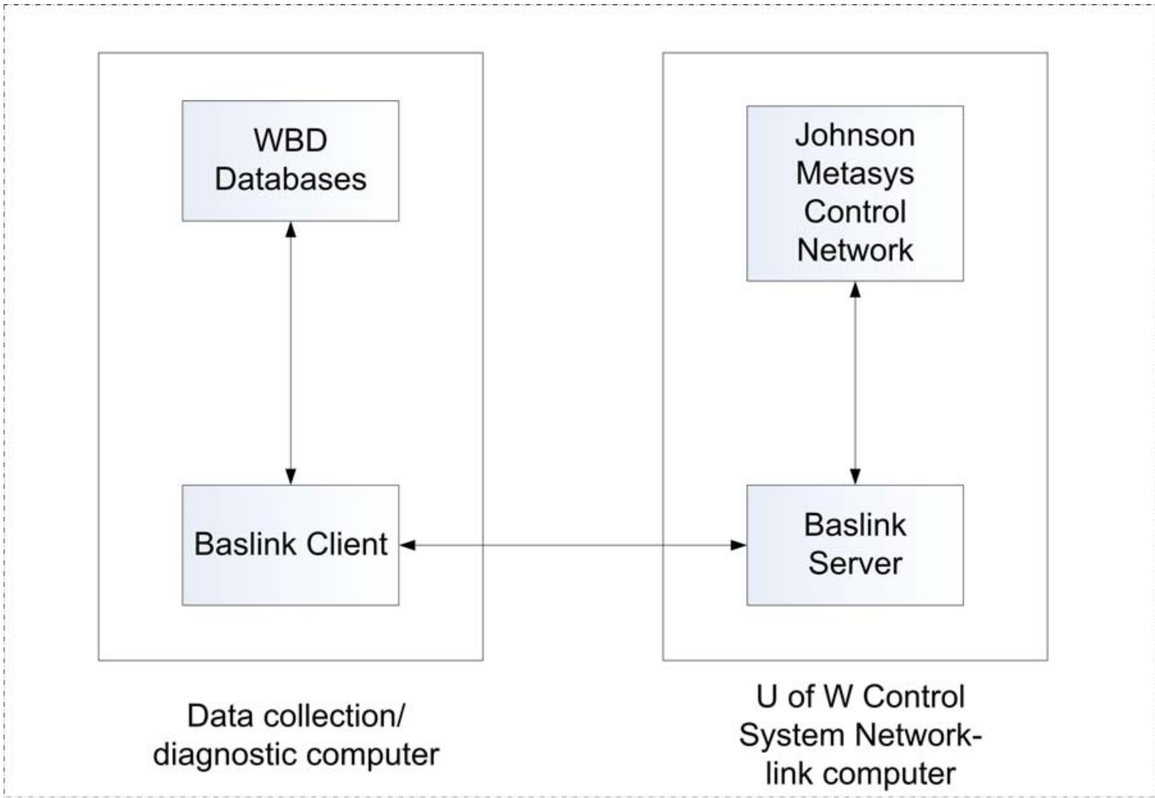

Figure 16. Schematic of the data flow/collection process for Grainger Hall

The WBD was then set up to collect data and perform the diagnostics automatically and the software was set up to turn back on automatically (when the computer was started) in the event of a computer power failure or if the computer was shut down or needed to be rebooted for some reason.

6.2.4 Results/Diagnostics of Data Collected

Although the Johnson Metasys control system can provide uninterrupted automated data collection for the WBD, site staff encountered various problems with maintaining the continuous collection and diagnostics for the six AHUs in Grainger Hall. The primary problem was in keeping the server portion of the WBD tool running on the control system network-link computer. Staff would utilize this computer for other purposes and turn the WBD collection process off or shut the computer down. The WBD collection process was enabled to automatically start upon the restart of the computer system; however, the IP address was assigned to the computer dynamically, and this changing address disrupted the data flow.

Data was collected for approximately 120 hours over the course of the following dates: May 15 through May 17, May 27, October 14 through October 21, and on November 13 and 19, 2003. As with the data collected at the Milwaukee Federal Building, the minimum contiguous data was not collected, therefore a reliable pattern in the diagnosed data was not established. The WBD is fully installed and operational such that site staff should be able run the WBD continuously (24 hours a day and 7 days a week) to collect data and diagnose HVAC performance provided that the systems (the computer and WBD processes) are left on.

Figure 17 shows the diagnostic results for the data collected for BUU2. If the configuration data input matches the manner in which the AHU is actually being controlled, then a larger set of data would likely indicate that this AHU has a problem with one or more of its temperature sensors.

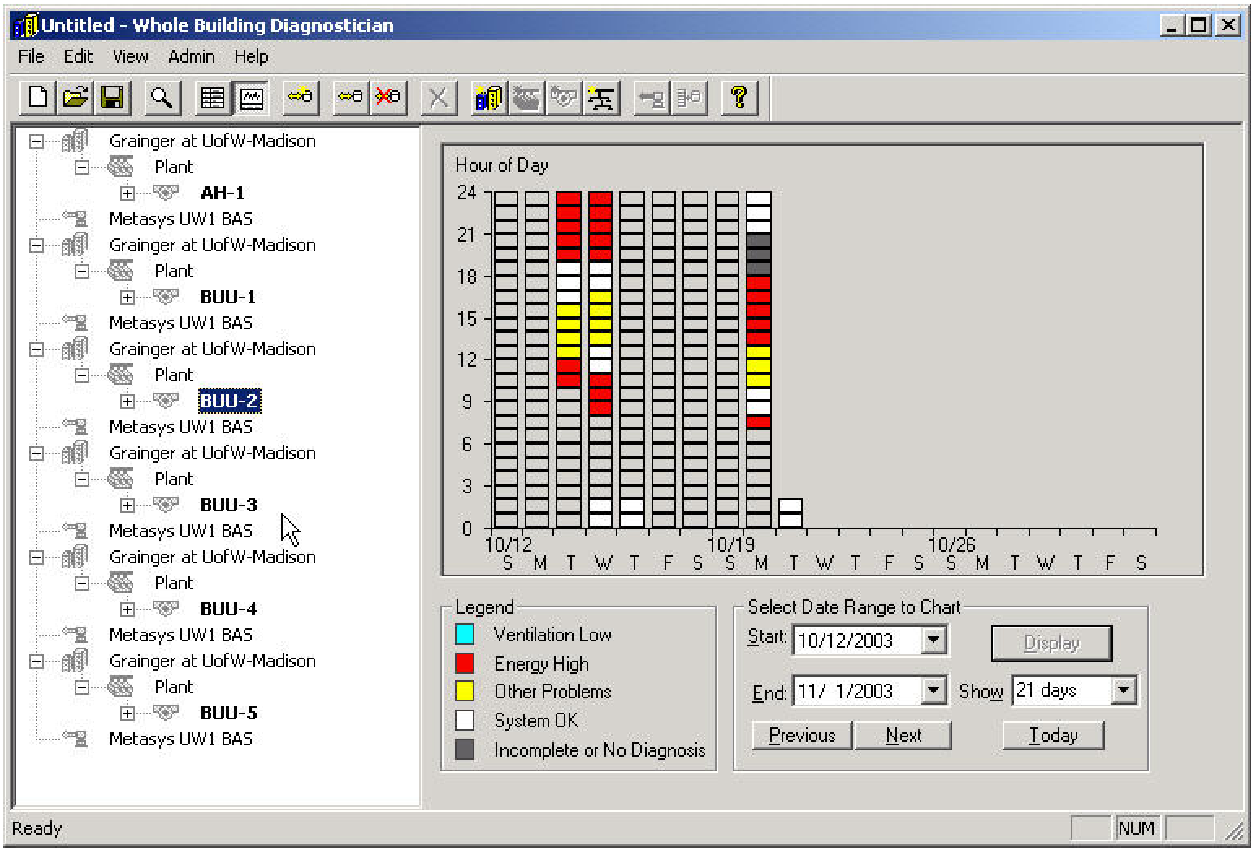

Figure 17. WBD's OAE diagnostic screen for Grainger Hall

Yellow cells, as defined in the legend in the lower center of Figure 17, indicate that some problem other than high-energy waste or excess ventilation has been diagnosed. Clicking on one of the yellow cells brings up the *Current Condition* window, shown in Figure 18, which describes the possible causes for the problem. In this case, the problem identified was that a temperature sensor problem exists. Clicking on the *Details* button on the *Current Condition* window provides additional information on the nature of the problem, as shown in Figure 19. This *Details* window provides a more complete description of the problem and some key data to help interpret it.

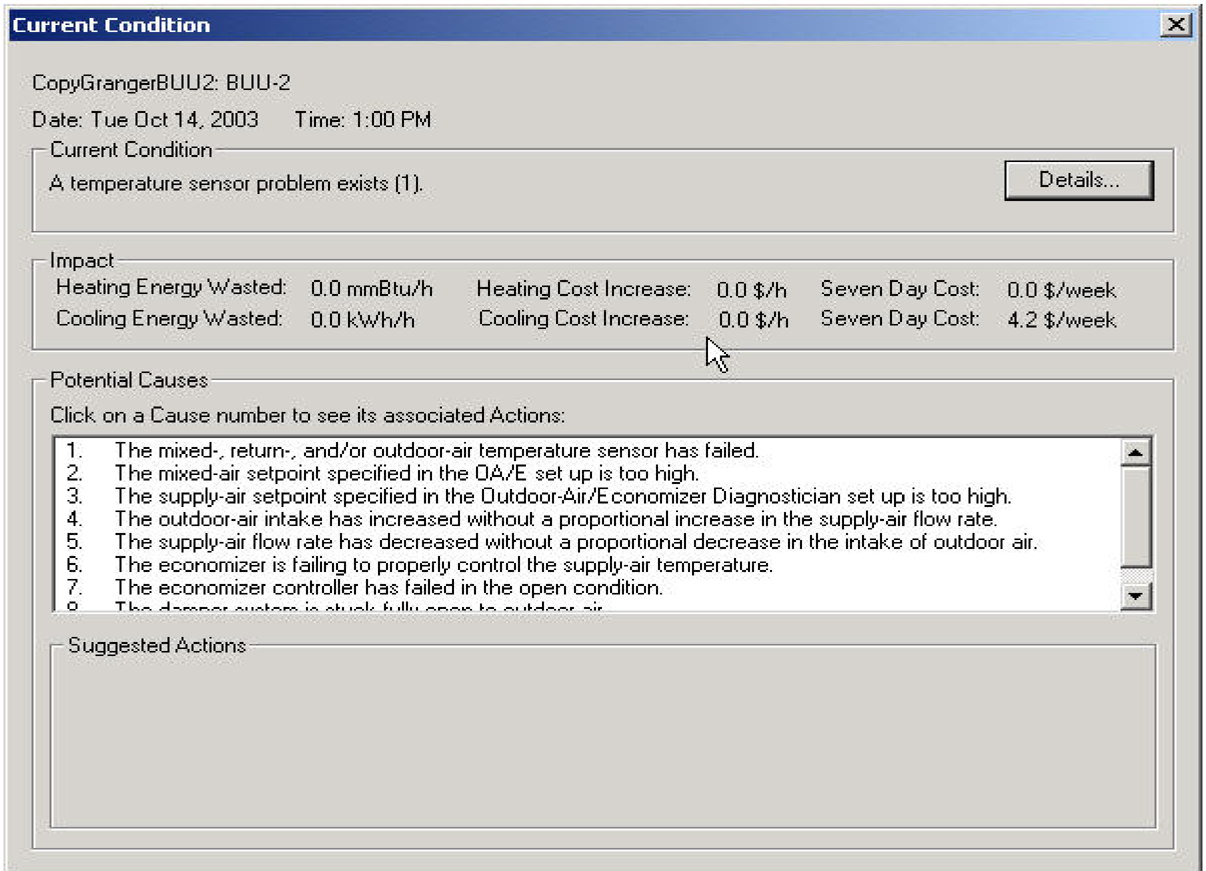

Figure 18. Current Condition screen for Grainger Hall problem hour

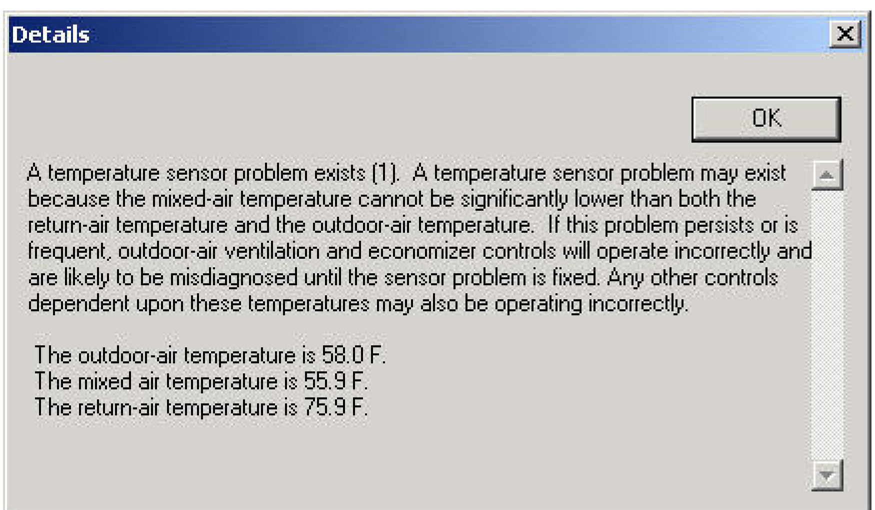

Figure 19. Details screen for Grainger Hall problem hour

As previously mentioned, a larger set of contiguous data are needed to accurately interpret the diagnostic results of the AHU. Although the problem hour noted above indicated a temperature sensor problem, if a more complete set of data was available and it showed a recurring pattern of "yellow" problem hours, the recommendation would be to check and calibrate or replace the faulty sensors, because no further accurate diagnoses can be determined with sensors providing bad or faulty data.

7 Conclusions and Recommendations

The WBD software tool, at both the Milwaukee Federal Building and at the University of Wisconsin-Madison campus, has the potential to be a very useful tool in diagnosing problems with AHU equipment and operations. Each FMCS system is able to provide the data for the automated collection and diagnostics; however, it is the "ownership" of these processes, as well as the inability to provide the needed follow-on support, that ultimately led to the meager results.

As we have observed with previous WBD demonstrations, a productive use of diagnostic tools like the WBD requires at least one individual on-site who is able and willing to monitor the data collection and diagnostic processes on a periodic basis. This individual would have the authority to make the requests for labor and materials needed to confirm and fix problems identified by the WBD. Site management must also provide the budget to support site staff in using the WBD and resolving the identified problems.

The Milwaukee Federal Building installation has the added complexity in that the automated data collection is a modified batch-process, and the site staff relies upon an outside contractor to make modifications or corrections to a portion of the data collection process as well as the FMCS control sequence. The University directly manages their Johnson Metasys system, which facilitates the automation of the data collection, and site staff makes the needed data modifications and mechanical repairs themselves.

Energy and cost saving recommendations could not be firmly provided because of insufficient data collected at each site. The limited data and diagnostics, however, did indicate that problems exist in several controls and/or equipment and that corrective action can provide energy savings. We recommend the following actions for effective use of the WBD installed at each site:

1. Identify at least one individual who will be responsible for the periodic (several times weekly) monitoring and maintenance of the data collection system and make that a supported part of the individual's weekly routine.
2. Provide that individual with the resources necessary to verify the problems identified by the diagnostic tool and make necessary corrections to the AHUs based on the cost impacts (funding, equipment, time, and authority to make/request needed corrections, etc.).
3. Identify funding (through FEMP, RBA, or the State of Wisconsin) to obtain additional and more thorough training on the WBD software and to fund follow-on support from PNNL staff.
4. In the case of the Milwaukee Federal Building, provide funding to cover the support time needed from their FMCS contractor.

Each site can achieve energy savings by using the WBD to identify HVAC problems and to guide the corrective actions.

8 Opportunities and Next Steps

In addition to using the WBD as installed, a site may want to apply the WBD in one or more of the following ways:

1. Extend the WBD to monitor and diagnose additional buildings air handlers of the University of Wisconsin. (The FEMP grant installed the WBD for all of the Courthouse's major air handlers.)
2. Implement the WBD module that evaluates the daily energy performance of a building or component. The Courthouse and University installations are currently using only the WBD's Outdoor Air Economizer (OAE) module that monitors and diagnoses just air handlers. A second WBD module, the Whole Building Energy (WBE) module, works with hourly energy use data and hourly weather data to analyze the daily performance of a building or component over a multi-year period. This WBE module can be used to do one of more of the following activities:
   A. Measure and verify the general effectiveness of an operation and maintenance (O&M) program for a campus, building, or building component.
      1) WBE can be particularly useful when an O&M department wants to see the impact of recommissioning or retuning a building or component.
      2) WBE can also help identify which buildings or components are experiencing significantly atypical energy performance problems. Atypical performance can indicate poor operations, overloaded components, and failing equipment.

   B. Measure and verify the energy performance of an energy project such as lighting retrofits and chiller replacements.

   C. Independently measure and verify the performance guarantees of an energy savings performance contract or a utility energy savings contract.

Site staff have the expertise needed to extend and manage the WBD with limited additional planning, training, and support by PNNL. The planning would include determining the data flow between the sites' metering and building control systems to the WBD. Training for the sites' senior building controls staff would build on the basic training provided under the FEMP and RBA grants and extend it to include advanced WBD administrator training. Training could also include the basic training for staff new to the WBD.

The support can include a specific number of meetings that can be conducted on site and/or by web-based online meetings. The online meetings can be done through DOE's or PNNL's online meeting tools. The online work can include the use of software for PNNL to remotely read site data for consultation purposes. The technical consultation can include PNNL mechanical engineers and building controls experts who can trouble-shoot building problems identified by the WBD or by other means. Lastly, the consultation can include PNNL experts in recommissioning and in energy savings performance contracting.

GSA sites may also be interested in participating a planned demonstration program of a commercialized web-based suite of essential facility management tools for maintenance management, asset management, and project management. One of the essential tools will be the next generation of the WBD. The demonstrations may begin as soon as the spring of 2004.

These recommendations and opportunities will help the General Services Administration (GSA) and the State of Wisconsin improve their energy and operational effectiveness. The first next step is to discuss interests and approaches with FEMP's regional program office representative Melinda (Mindy) Latimer at (312) 886-8582.

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