Automated Diagnostics: Improving Building System and Equipment Performance

By Srinivas Katipamula and Mike Brambley

Srinivas Katipamula and Mike Brambley work for Pacific Northwest National Laboratory[1] as a Senior Research Scientist and Staff Scientist, respectively.

Richland –According to the Energy Information Agency (EIA), in 1995, 5.3 quadrillion Btu (quad = 10^{15} Btu) of energy were consumed by commercial buildings in the United States at cost of about 70 billion dollars. Many detailed studies over the past decade have shown that a significant amount, as much as 30%, of this energy consumption is wasted. Much of the waste can be related to our inability to optimally control, maintain, detect, and diagnose operational problems with the buildings and their systems (HVAC and others). Also, recent studies (ELCAP and Texas LoanSTAR) have shown that metering and monitoring energy end-uses and analyzing them on an continuos basis can have an enormous benefit in terms of detecting and correcting problems. However, metering, monitoring and analyzing the end uses and system performance continuously is costly and time consuming, unless automated. Existing building automation systems (BASs) could be used for monitoring performance along with special software applications that automate data analysis.

Widespread use of computers for supervisory control in buildings started in the late 1960s and early 1970s. Since then, controls have evolved from primarily pneumatics to electromechanical to direct digital controls. In recent years, exponential growth in the computer, telecommunications, and information technology industries has stimulated changes in the building automation and controls industry as well. Although the computing power of the BASs has increased several fold in the last decade, the functionality of the BASs from an applications perspective has changed very little. Traditionally, BASs provided loop control, alarm reporting, dynamic control, and energy management (start/stop, duty cycling, load shedding, demand limiting, temperature setback, economizer control, and boiler and chiller optimization). BASs could provide valuable additional services to building managers and operators beyond these traditional functions by collecting, storing, and continuously and systematically analyzing and drawing conclusions from key energy, temperature, and flow data. The conclusions could be in the form of adjustments to the set points, tracking energy use for performance contracting, detecting faults , and pinpointing the root causes of the faults. Specialized software applications to detect faults and diagnose problems with buildings and systems are absent from most BASs.

Where are the applications?

The November 1996 issue of Energy User News reported a market research firm's finding that much of the control industry's growth through the end of the century will come in the areas of software and services. Yet there are only a handful of nontraditional applications. This is because users (building owners/designers) generally specify BASs on their traditional technical features and not by looking at the overall system's capability to provide applications that would improve comfort, increase efficiency and lower operating costs. Manufacturers are reluctant to bid for anything more than what the specifications call for because of cost, and they are unwilling to bundle additional applications as part of the BAS. In the past, third-party or in-house development of such applications were hindered by the complexity of programming BASs, lack of suitable means to acquire data easily from them, and lack of interoperability between different BASs. The only mechanism available to retrieve data was to use trend logs provided by the manufacturers, which were not always easy to implement or use.

In recent years, many manufacturers have started supporting standard protocols such as object linking and embedding (OLE) and its predecessor dynamic data exchange (DDE) for application-to-application data exchange and communication using data objects. These protocols provide simpler ways of data collection from BASs. Also standard protocols, such as Building Automation and Control Network (BACnet™), ASHRAE/ANSI Standard 135-1995 (developed by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) and adopted by the American National Standards Institute (ANSI)), are contributing to easier implementation by providing standard mechanisms by which applications can communicate with field devices and different BASs can communicate with each other.

This article describes the need for building level diagnostics. In also reports how whole-building systems and equipment effectiveness can be increased using automated diagnostic techniques coupled with automated data collection from BASs over the existing local area and Internet networks now that the some of the old barriers (data exchange and communication) no longer exist. The results from field installation of a diagnostic module are also presented.

How can whole-building level diagnostics help?

Operational problems associated with degraded equipment, failed sensors, improper installation, poor maintenance, and improperly implemented controls plague most commercial buildings. Some problems are detected as a result of occupant complaints or alarms provided by the BAS. Building operators often respond by checking space temperatures, adjusting thermostat set points or changing control settings without clearly understanding the energy impacts. Often the root cause of the problem goes undetected, so when the problem reoccurs the response is repeated. But in other instances, problems go undetected because they do not affect occupant comfort or trigger an alarm. For example, an airside economizer operating when the zone thermostat requests heat or lights being ON during unoccupied hours are both failures that waste valuable energy, but may go undetected. To detect and diagnose problems carefully by inspecting trends, equipment, controls, or control algorithms, is time consuming and costly.

Automating data gathering and diagnostics for building systems and equipment will help remedy these problems and improve building operations by automatically and continuously detecting performance problems and bringing them to the attention of building operators. With increased use of BASs, the prevalence of inexpensive, but powerful, personal computers and computing infrastructures (LANs and the Internet), and emergence of standard protocols (e.g., BACnet™ and LonMark) make it easier to deploy new automated diagnostic tools for building operation.

An approach to whole-building diagnostics

As part its mission in commercial buildings research and development, the U.S. Department of Energy (DOE) in collaboration with industry is developing a tool that automates detection and diagnosis of problems associated with energy consumption in buildings and systems. The tool, known as the whole-building diagnostician (WBD), currently has two modules the whole-building efficiency (WBE) indicator and the outdoor air/economizer (OAE) diagnostician. The WBE provides diagnostics related to aggregated energy end uses, namely building total electric energy, building total thermal energy, HVAC electric energy other than chiller energy, and chiller/package unit energy. The OAE module monitors the performance of air-handling units (AHUs) and detects problems with outside air ventilation control and economizer operation, using sensors that are commonly installed for control purposes.

How does the WBE tool detect problems?

The WBE module comprises two distinct tools: the WBE diagnostic tool and the WBE baseline tool. The diagnostic tool does all the energy-related computations and generates diagnostic messages. The baseline tool provides a mechanism to train neural networks (NN) to model and predict the energy end uses of the building. The WBE generally provides diagnostics related to four aggregated energy end uses: whole-building total electric energy, whole-building total thermal energy, HVAC-other-than-chiller-electric, and chiller/package unit energy. The diagnostics are based on comparison of the actual energy consumption to the expected energy consumption predicted by the neural network model. In general, the NN model uses time of day, day of the year, day of the week, outdoor air dry-bulb temperature, and relative humidity as independent variables. Other independent variables such as occupancy and plug loads can also be added to the model, if needed.

Whenever there is a statistically significant difference between actual and expected energy use or a sufficiently high probability that a sensor has malfunctioned, a diagnostic message is generated by the WBE. The WBE module uses probabilistic inference in the form of a belief network with continuous and discrete variables for diagnosis. The belief network uses a cost matrix to relate risk to the probability of a problem existing. By using this belief network, false diagnostics can be minimized. The WBE tool has been tested using simulated data and will soon be tested in the field.

How does the OAE tool detect problems?

As with any mechanical system, faults can occur that diminish or eliminate an airside economizer's effectiveness. However, unlike the primary (mechanical) cooling system, a failure of the economizer may go completely unnoticed. Any failure, for example, that prevents outdoor air from being used for cooling when outdoor conditions are favorable may go unnoticed because the mechanical cooling system will pick up the load and occupants will suffer no discomfort. Similarly, a failure that results in too much outdoor air may not be apparent in a reheat system. Reheating will ensure that the air supplied to the space is at a comfortable temperature. In both of these examples, however, the system would use more energy (and cost more to operate) than necessary.

The OAE diagnostician is designed to monitor conditions of an AHU not normally affecting occupants and alert the building operator when there is evidence of a failure. The common types of outdoor-air ventilation and economizer problems handled by the module include stuck outdoor-air dampers, failures of temperature and humidity sensors, economizer and ventilation controller failures, supply-air controller problems, and air-flow restrictions that cause unanticipated changes in overall system circulation. The tool uses rules derived from engineering models of proper and improper AHU performance to diagnose operating conditions. The rules are implemented in a decision tree structure in software. The diagnostician uses periodically measured conditions (temperature or enthalpy) of the various air-flow streams, measured outdoor conditions, and information on the status of equipment and systems 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.

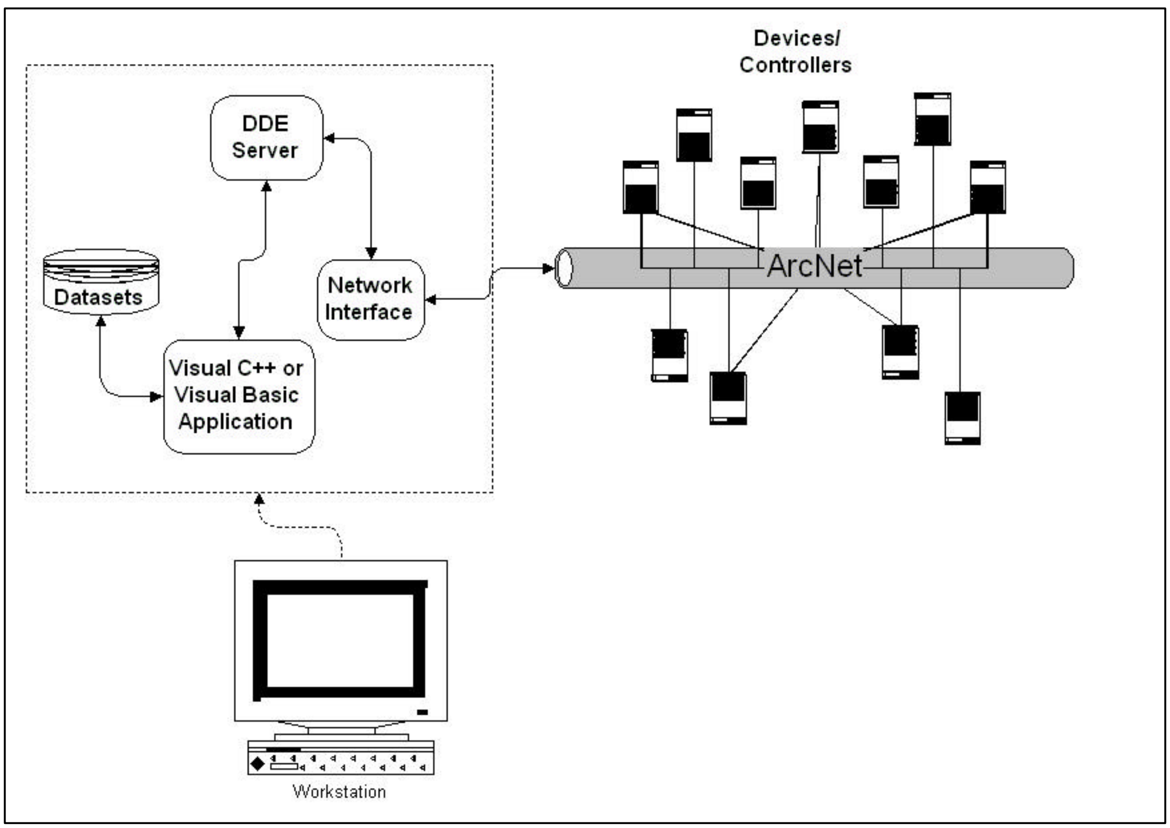
Many of the states correspond to normal operation and are dubbed "OK states." For example, one OK state is described as "ventilation and economizer OK; the economizer is correctly operating (fully open), and ventilation is more than adequate." Other states correspond to something operationally wrong with the system and are referred to as "problem states." An example problem is that the "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." Other states (both OK and problem) may be tagged as incomplete diagnoses, if the measured information is insufficient.

Each problem state known by the OAE module has an associated set 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 mistake in setting up the OAE module for this AHU could cause the economizer to be off when it should be on. Thus, at each metered time period, a list of possible causes is generated. These lists can be analyzed further over time to isolate the specific cause of the observed problems.

How did we automate a simple "data pipe" from BAS to the WBD?

The diagnosticians use periodically measured data from the BAS. These data are automatically transferred each hour from the BAS to the diagnostician's database using dynamic data exchange (DDE). The DDE is a standard Microsoft Windows 95/NT® message passing protocol that defines a mechanism for Windows applications to share information with one another. Many building automation system manufacturers provide DDE servers to facilitate data exchange between controllers/devices and application programs. A schematic diagram of the "data pipeline" is shown in the Figure. A Visual C++ or a Visual Basic program running in the background initiates a DDE conversation between the DDE server, provided by the BAS manufacturer, and the diagnostician's database to update the diagnostician's database periodically (at the beginning of each hour). The data can also be collected from a remote workstation (over the Internet) using the same DDE mechanism. We use both approaches to collect data. A set of predefined relationships is used to map data from the sensors from each of the AHUs into the database. The OAE Diagnostician then periodically processes the new data, producing diagnostic results that can be viewed.

handling units in two buildings at the Pacific Northwest National Laboratory campus in Richland, Washington. The first building is the newly constructed and occupied DOE William R. Wiley Environmental Molecular Sciences Laboratory (EMSL) in Richland, Washington. The 200,000-ft^2 (18,580-m^2) building houses laboratories, offices, conference rooms, and computer facilities. A JCI Metasys system provides monitoring and control of the facility using 3,421 sensor points. This building is more highly instrumented than most commercial buildings of similar size, but the data used by the diagnostician are commonly found in buildings with BASs. The diagnostician currently monitors three AHUs in this building. All AHUs are 20-ton (70-kW) or greater cooling capacity.



Results from the Field

The OAE diagnostician is presently installed and operating on seven air-handling units in two buildings at the ...

The second building is the Technology Management Center (TMC), also located on the Richland campus of Pacific

Northwest National Laboratory. This 72,700-ft^2 (6754-m^2) office building constructed in 1973 has four central AHUs with economizers. A JCI Metasys system provides monitoring and control of the facility using 420 sensor points. The diagnostician monitors all four AHUs in this building.

Of the seven AHUs monitored since June 1997, four were found to have problems shortly after initial processing of data. The problems found included sensor problems, return-air dampers not closing fully when outdoor-air dampers were fully open, and a chilled-water controller problem. All problems have been confirmed by inspection of the AHUs.

The results for AHU-01 at the TMC indicated that cooling energy was being wasted because the economizer was operating partly closed even when the outside-air conditions were favorable for economizing. The possible causes reported by the diagnostician for this problem included damper system failure, temperature sensor failure, some obstruction in the outdoor-air intake duct, and an increase in supply-air flow rate without a corresponding increase in outdoor-air flow rate. Inspection of the AHU revealed that the return-air damper was not closing completely when the economizer called for 100% outside air. The diagnostician provided this as one of the possible causes.

Examination of the results from AHU-06 at EMSL building showed a failed return-, mixed-, or outdoor-air temperature sensor as a common potential cause. Inspection revealed no problem with the outside-air temperature sensor, but the location of the sensor caused it to read incorrect air temperatures. It was located in a non-aspirated tube with the top of the tube sealed and mounted in a corner under an overhang. This arrangement did not allow the air to circulate adequately. When the walls adjacent to the tube were heated by sunlight, the sensor indicated a temperature closer to the wall temperature than the air temperature.

The results for AHU-02 at TMC showed that the economizer and the ventilation system were working properly, but the supply-air controller was not controlling the supply-air temperature properly. Finally, the results from AHU-03 at TMC showed that the mixed-air temperature sensor was the problem sensor. All AHUs tested measure the mixed-air temperature across the cross-section of the mixed-air duct and average the value. Therefore, the problem is not caused by stratification but by using bad sensor data for averaging.

Where are we heading?

The OAE Diagnostician has proven effective in identifying outdoor air ventilation and economizer operation problems in air-handling units during initial field-testing. Furthermore, results for the small sample of AHUs monitored tend to confirm the widely held belief that many economizers do not work as intended. The results also indicate that automated diagnostic technology promises to help identify and eliminate these common problems.

Other uses for automated diagnostic tools include commissioning, routine building operation, and equipment servicing. During commissioning, the automated diagnostic tools could help ensure that AHUs are installed and operating properly. These tools would automatically identify problems, which would be eliminated as part of the commissioning process. For building operation, diagnosticians could be deployed as part of a control system, BAS, or supervisory software. Diagnosticians embedded in control systems would provide on-demand support to building operators or facility managers. By monitoring equipment performance continuously and diagnosing problems, diagnosticians would ensure that equipment is maintained and operated properly, providing the equivalent of continuous commissioning. For the manager of several properties or the operator of a large campus, diagnosticians could process data from several different buildings at a central location. This would reduce the frequency of site visits, improve operation and maintenance, and lower operating costs. With some minor modifications, the WBE could also be used for tracking energy savings as part of a performance contract. In addition, performance contractors could use automated diagnosticians to verify that the building systems and equipment are being used and operated as expected, ensuring profit margins.

The WBE and the OAE tools represent only two applications of automated diagnostics to building equipment and systems. In the future, this technology could be used to detect and diagnose problems with many components and systems—boilers, chillers, variable air volume boxes, heat exchangers, pumps, and fans, to name a few. Some of these applications will require more sophisticated diagnostic methods than those used by the OAE and WBE. Deployment of automated diagnostics will help improve building operation, bringing improved comfort, air quality, longer equipment life, and lower costs.