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EVALUATION OF EMERGING DIAGNOSTIC TOOLS FOR COMMERCIAL HVAC SYSTEMS

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ABSTRACT

This paper compares and evaluates the capabilities of six emerging diagnostic tools for commercial HVAC systems. We present a brief description of the diagnostic tools, and then focus on evaluating the features of the tools. We include the following six tools in our analysis: Architectural Energy Corporation's ENFORMA® software, Facility Dynamics Engineering's Performance And Continuous Re-commissioning Analysis Tool (PACRAT), Pacific Northwest National Laboratory's Whole Building Diagnostician (WBD), Pacific Gas and Electric's Universal Translator, UC Berkeley's Fan System Tools, and Silicon Energy's Enterprise Energy Management Suite. The air-side economizer operation is the most common diagnostic across the tools, so this diagnostic function is evaluated in detail. We outline the key strengths and weaknesses of each tool, while keeping in mind the tool intent and current extent of commercialization. Each tool has unique features for data management and analysis, which can be beneficial for different applications and users.

INTRODUCTION

Studies have shown opportunities for significant energy savings from "tuning up" existing heating, ventilating, and air-conditioning (HVAC) systems (Gregerson, 1997, Claridge et al., 2000). If these energy savings are clearly available, what prevents building owners and managers from retro-commissioning or continuously assessing building performance? The difficulty in detecting and diagnosing operational problems is a main factor. Building operators and energy managers rarely have adequate training, time, or tools to continually assess performance.

To address these needs and issues, new diagnostic software tools are becoming available to facilitate the detection and diagnosis of energy and other performance problems in commercial buildings. For over twelve years, researchers have developed diagnostic methods for HVAC systems. Automated diagnostics research has produced model-based methods for detecting deviations from normal operation and rule-based expert systems to detect and diagnose problems (Anderson et al. 1989, Haberl, et al. 1989, Culp 1989, Norford et al. 1990, Kreider and Wang 1991, Benouarets et al. 1994). With varying degrees, commercial tools have drawn upon this research.

Beyond their diagnostic capabilities, the tools provide a data management framework by organizing information from volumes of underutilized time-series data from energy management control systems (EMCS), utility demand metering, and dedicated monitoring systems. By combining newer EMCS logging capabilities with advances in information technology, there is great potential to use the data to assess building performance. Using these data, diagnostic tools can summarize relevant performance metrics, display plots for manual analysis, and perform automated diagnostic procedures.

Objective

Although there have been research efforts to develop diagnostic methodologies for building HVAC systems for over a decade, only recently have commercial tools become available. Consequently, there has been little detailed characterization of the tools and a limited awareness of their differences and capabilities by potential users. This paper assesses diagnostic tools for use with large commercial building EMCS data, comparing the features of the tools for two audiences. First, we give an overview of the side-by-side tool comparison detailed in our recent companion paper (Friedman and Piette, 2001a). Next, we focus on an evaluation of a common diagnostic, the air-side economizer, as well as an assessment of the general strengths and limitations of each tool. Our overall study, which includes a literature review, detailed tool descriptions, tool evaluation, and future research perspectives, will be available on the internet (Friedman and Piette, 2001b). The tool comparison and evaluation attempts to give potential users (operators, energy managers, engineers, service companies, or commissioning agents) an understanding of tool capabilities to simplify their assessment of implementation options. Tremendous potential exists for the utilization of visualization and diagnostic techniques, and each tool offers valuable features for diagnostic analysis.

Manual and Automated Diagnostics

The distinction between manual and automated diagnostic tools is not straightforward, since tools have various levels of automation for data collection, management, processing, and diagnostics. The term 'diagnostics' encompasses both the detection of operational problems and the diagnosis of their cause (Haves, 1999). Here, we define manual diagnostic tools as aids to diagnostics that help extract information from raw data. Manual diagnostic tools require a knowledgeable user to identify problems using plots and information automatically generated by the tool. In contrast, automated diagnostics reduce or eliminate the need for human reasoning in detection and diagnosis of problems by automating the process of analyzing data (Brambley and Pratt, 2000). Automated diagnostic tools use a combination of models, statistical methods, and expert rules to detect operational problems.

Tool Overview

Since the focus of our study is large commercial buildings, the comparison is limited to the diagnostics that apply to the typical systems found in these buildings: built-up air handlers, central cooling plants, and distribution systems. The tools selected for comparison were narrowed from a larger set of diagnostic tools based on the following criteria:

- The tool aids HVAC diagnostics with, at minimum, automatically created diagnostic plots or programmable alarms.
- The tool has diagnostic capabilities for central plants and/or built-up air handlers.
- The tool has the ability to import EMCS data (as opposed to only using data loggers).

Rossi and Braun (1997) have developed a statistical, rule-based diagnostic tool for rooftop air conditioners, but this tool does not fit our criteria. Next we present an overview of the tools.

TOOL A.

The University of California-Berkeley, Center for Environmental Design Research has developed **Built-up Fan System Tools** that have the unique capability to benchmark fans using one-time measurements, but since we have limited our analysis to time-series data, we do not review this feature. Instead, we focus on five spreadsheet modules for time-series data that include data visualization and statistics for the analysis of fan power, air-side economizer, zone temperatures, reheat, and static pressure. The tool, created in 1999, is currently in a prototype phase (Webster et al., 1999)

TOOL B.

The **ENFORMA® Portable Diagnostic Solutions** software is used for short-term analysis to aid diagnostics in many system types. The tool processes data for manual comparison to pre-defined reference plots for air handlers, cooling towers, chillers, heating plants, and zone distribution systems. The software was commercialized in 1996 by Architectural Energy Corporation and has sold over 50 licenses. (Frey, 1999)

TOOL C.

The **Universal Translator's** primary strength is in synchronization of multiple data sources for use with both EMCS data and data loggers (Stroupe, 2000). The tool also has a semi-automated diagnostic module for economizers and a manual diagnostic module for equipment run-time and cycling. This tool was created by Pacific Gas and Electric's Pacific Energy Center and is currently in beta testing phase with over 50 users.

TOOL D.

The **Whole Building Diagnostician (WBD)** is an automated tool for continuous analysis of economizers (outdoor air economizer module) and whole building or central plant energy consumption (whole building energy module) (Brambley et al., 1998). The WBD has been developed and installed in multiple buildings at ten sites since 1998 by Pacific Northwest National Laboratory.

TOOL E.

Performance and Continuous Re-commissioning Analysis Tool (PACRAT) provides continuous analysis and is both broad and in-depth in its automated diagnostic capabilities (Santos and Brightbill, 2000). The tool's automated diagnostics address the air handlers, chillers, hydronic system, whole building energy, and zone distribution. PACRAT was first developed by Facility Dynamics Engineering for internal use, then sold commercially in 1999. The tool has been installed at about 10 sites.

TOOL F.

The **Enterprise Energy Management Suite** uses a web-interface for the continuous display and manipulation of utility, EMCS and related time-series data connected through gateways (Silicon Energy, 2001). This tool provides data visualization and programmable alarms, but there are no pre-defined diagnostic plots. Since its commercialization in 1999, this tool has been sold to about 15 end-users and installed in mainly large campuses of buildings.

Tool Scope and Intent

One purpose for comparing diagnostic tools is to present the spectrum of tool capabilities and place each tool within that spectrum. The following graphic (Figure 1) describes the different pieces of a diagnostic system. The EMCS provides the data for the tools studied and, therefore, the tool scope begins with the acquisition of this data from EMCS control points. Some tools acquire and archive data from the EMCS in databases. Pre-processing prepares the data for analysis through synchronization, averaging, and filtering for erroneous data.

The diagnostic tools use various raw data visualization techniques and diagnostic procedures. Figure 1 depicts how the tools fit into this representation of architecture. Tools D, E, and F have automated data acquisition and archiving for continuous analysis. By contrast, Tools A, B, and C require manual data acquisition and do not have archiving capabilities. Tools D and E create links to the location of the data that is collected in trend files by the EMCS. Tool F is the only tool studied that uses data gateways for remote implementation of two-way building control.

The shaded region for Tool D represents this tool's limited data visualization capabilities compared to the other tools. Tool C's treatment of diagnosis is much less complex than Tools D and E, and therefore this area is also shaded. Tools D and E and the are the main tools that provide automated detection and diagnosis. The other tools aid manual problem detection through techniques such as standard plots, reference lines, and statistics. Even though most tools do not diagnose the causes of problems, they are still considered diagnostic tools since they provide aid to problem detection.

The scope of each diagnostic tool is directly related to its intended use. Some of the tools are not intended for utilization with EMCS data, but they all have the capability to analyze such data. The short-term tools (Tools A, B, and C) are intended for commissioning or retrofit analysis using data loggers, but these tools can also import formatted data files from any source, including EMCS data. In contrast, Tools D, E, and F were designed to continuously evaluate EMCS data, and they include vendor-specific algorithms to access this data. Tool F's web-based platform allows comparisons across campuses of buildings from a remote location. Tool E is able to assess multiple buildings connected to a network or through file transfer protocol (ftp) sites.

Our related paper elaborates on each tool's features for data acquisition, archiving, and pre-processing (Friedman and Piette, 2001). A list of problems detected by each tool is provided, as well as the specific methods used for data visualization. Finally, the paper presents each tool's automated and manual diagnostic methods.

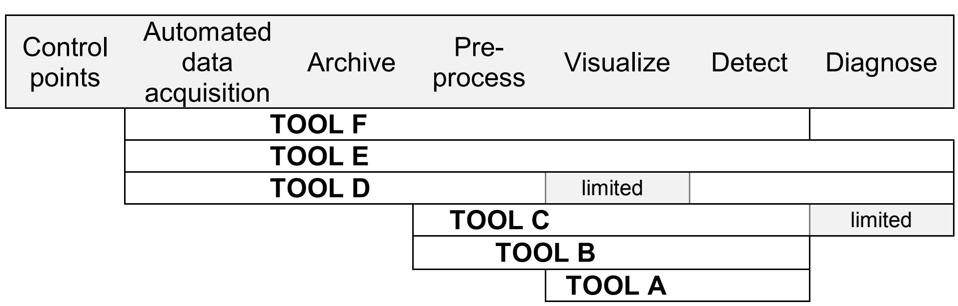

Figure 1. Tool Scope

TOOL EVALUATION

The introduction gave an overview of tool characteristics. While it is difficult to evaluate tools with differing intent and scope in a direct comparison, it is important to understand each tool's strengths and limitations. Based on our experience operating the tools and detailed demonstrations, we inform tool users and developers of important strengths as well as the areas that limit the usability of the tool.

We have not studied the appropriateness of tool features, since this depends on the goals of the user. For example, expert users may value a low-cost manual tool with less diagnostic applications over an automated high-cost tool if they have diagnostic experience and are interested in only specific applications. Our evaluation does not assess the level of tool sophistication appropriate for and valued by different users, but focuses on presenting the overall capabilities of the tools. We first assess the air-side economizer diagnostic specifically, since the economizer analysis is the most common tool diagnostic. Next, a general set of strengths and limitations are discussed.

Economizer Diagnostic

Five of the six tools perform economizer diagnostics, each with different analysis methods. Our evaluation of the economizer diagnostic focuses on assessing the treatment of three categories:

- diagnostic methods
- visualization and notification
- cost analysis

While it would be valuable to assess the ease of configuration and use of the economizer diagnostic, such an assessment is not within the scope of this study. Ease of use would depend on several factors such as the user's knowledge of the tool and the training they received, diagnostic expertise, and familiarity with the building. Therefore, this analysis would require interviews of tool users. First, we describe the proper operation of an airside economizer. Then we discuss the diagnostic features of each tool.

A properly functioning airside economizer strategy uses outdoor air for ventilation when the outdoor air temperature (OAT) is cool enough to replace or reduce mechanical cooling. Dampers control the amount of outdoor and return air entering in the mixing box, which is measured as the mixed air temperature (MAT). The air from the mixing box is then cooled or heated and supplied to the building. We provide a simple diagram of an economizer in Figure 2 for reference.

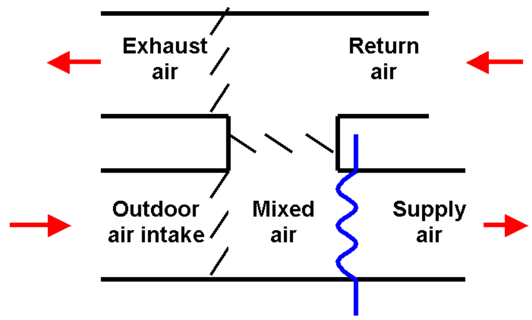

Figure 2. Air-side Economizer

Two examples of economizer control strategies are differential, where OAT is compared to RAT, and high-limit, where the OAT is compared to a setpoint. For dry-bulb temperature controlled economizers, one-hundred percent outdoor air should typically be supplied (all return air exhausted) when outdoor air temperatures are below the return air temperature (RAT), but above the supply air temperature (SAT). When the OAT is below the SAT, outdoor air dampers should be opened to help meet the cooling load, or closed to the minimum position when cooling is not needed. A third economizer strategy, enthalpy-controlled, uses relative humidity measurements to account for the cooling required for dehumidification. In all cases, when OAT is above the RAT, the outside air dampers should be closed to their minimum position required for ventilation. The state of economizer operation is most easily determined by calculating the outdoor air fraction (OAF) using system temperatures:

$$OAF = (MAT-RAT)/(OAT-RAT)$$

Each of the five diagnostic tools compares the OAT, RAT, and MAT to detect faulty economizer operation. Tools A and B do not have automated detection using the OAF, but simply help visualize economizer performance using plots. Tools C, D and E calculate outdoor air fraction for use in automated problem detection. Small uncertainties in temperature sensors lead to large uncertainty in OAF. False diagnoses are avoided using statistical methods or expert rules to determine a deadband for which the tool will not report a problem.

Using automated expert rules, Tools D and E identify the following economizer problem states:

1. **Lack of economizer cooling**: damper partially or fully closed when outdoor air should be used for cooling.
2. **Excess outdoor air** during heating mode or when OAT>RAT.
3. **Inadequate outdoor air ventilation**: less than minimum OAF for indoor air quality
4. **Mechanical cooling** used when outdoor conditions can meet full cooling load.
5. **Miscalibrated temperature sensors**

Tool E.

Tool E has a sophisticated economizer fault detection method and extensive energy cost waste analysis. The tool uses expert rules to identify problem states (anomalies) and provide possible causes and resolutions, while linking the anomalies directly to time-series graphs. Time-series data can also be viewed using a variety of plotting features. The problems detected are sorted in multiple ways over a user-defined time period. Tool E is the only tool that uses the outdoor air damper signal in addition to system temperatures in order to separate economizer control problems from mechanical problems.

Tool E calculates cost waste for each data collection interval, then sums the cost waste over time. The user can also compare cost waste across different system levels. For example, cost waste from all problems can be aggregated for each air handler or for a building over a given time period. A drawback to the diagnostic is that the logic tree is proprietary, so the methods cannot be evaluated externally. Figure 3 shows an example of a problem notification screen for the economizer diagnostic.

Tool D.

Tool D's economizer diagnostic uses expert rules and statistical methods to diagnose problems, using data to continuously assess and eliminate possible causes over time. The tool's extensive logic tree includes twenty different end diagnostic states (Katipamula et al., 1999). The logic tree is expected to be public information, which is important for transparency of the tool's methods.

Tool D utilizes a color map with "problem state" cells, shown in Figure 4, to notify the user of problems with economizer and ventilation operation. This method allows for visualization of the hourly diagnostic results, but a user is not able to see plots of time-series data to support the automated analysis. The "problem state" cells are linked to lists of possible causes, remedial actions, and the temperatures used in the calculation of outdoor air fraction for that hour. The color map allows the user to differentiate the results for various categories of problems, including "ventilation low", "energy high", "other problems", and "incomplete diagnosis". The high energy use (red) cell is displayed when the economizer should be fully open but is closed, when the economizer should be at minimum position but is open, and when mechanical cooling is operating unnecessarily.

Tool D presents energy cost waste for each hour, but does not aggregate the energy waste from problem states over the day. To use the cost waste presented by the tool to prioritize problems, the costs must be compared manually across problem state cells.

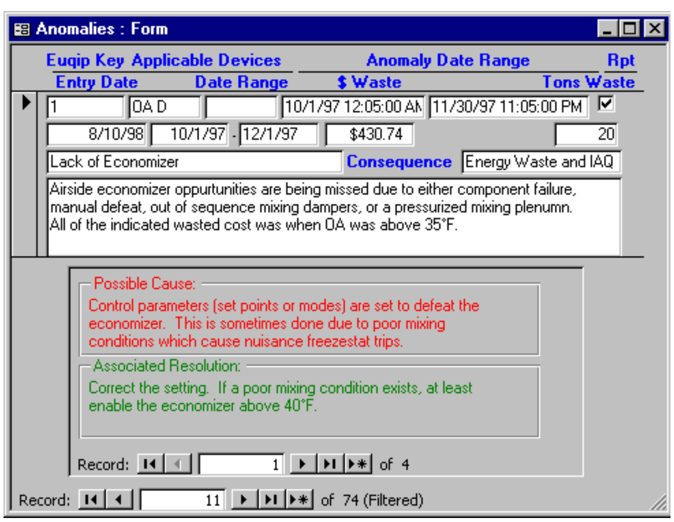

Figure 3. Tool E, Economizer Diagnostic Screen

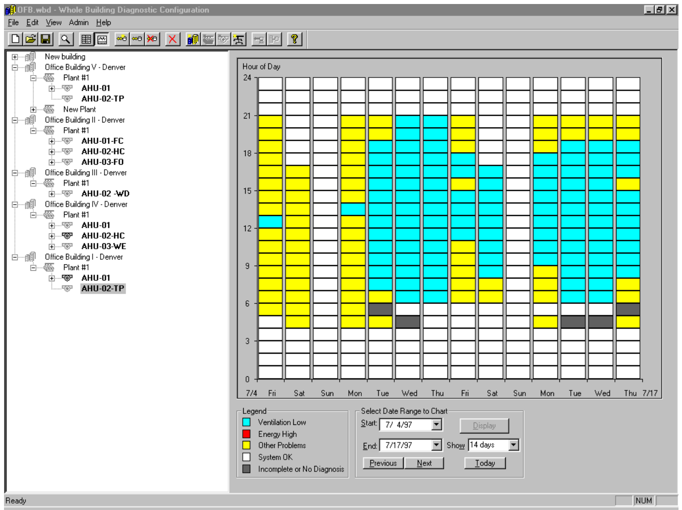

Figure 4. Tool D, Outdoor-air Economizer Color Map Problem Notification

Tool C.

Tool C's economizer diagnostic relies on its advanced filtering capabilities and produces two plots to convey diagnostic information. Filters are used to exclude data during unoccupied hours from the analysis, and the user inputs minimum outdoor air fraction and links the time-series data. Then, the analysis is run, automatically creating graphs and outputting general diagnostic phrases. Tool C reports a limited number of these phrases for each zone, such as "economizer damper is stuck open" based on a logic tree that assesses outdoor air fraction.

The "data graph" is a time-series plot with MAT, OAT, RAT, and SAT on an upper x-axis with a percent outside air scatter plot below on a second axis. This plot is a useful presentation of all relevant data points. The "performance graph" shows MAT vs. OAT, with reference lines based on user inputs, shown below in Figure 5. This use of reference lines to visualize correct operation is a simple way to compare measured data to "ideal" operation. The comparison of raw data to the reference lines is aided by reporting of the slope and y-intercept of the actual and ideal economizer lines for each zone. These statistics coarsely quantify the difference between ideal and actual operation without calculating energy cost waste.

Tool B.

Tool B requires manual comparison of measured economizer data to reference plots, so the user must be trained in detecting economizer faults. The reference plots allow manual comparisons for a number of economizer operational states. The user is able to match the axes scales of the real data and reference plots, but since the reference plots are pre-defined using typical data and not dependent on the measured data, a literal comparison of points is not relevant. In direct comparison, Tools A and C require input of the minimum outside air percentage to create tailored reference lines. Tool B includes a plot of MAT versus OAT, shown in Figure 6, and a plot of (MAT-RAT) versus (OAT-RAT) that includes reference lines that represent 100%, 50% and 0% outside air fraction. Since the detection of economizer problems is manual with this tool, the magnitude of deviation from proper economizer operation is not calculated by the tool.

Tool A.

Tool A also assists manual detection of economizer problems through the use of reference lines that represent ideal operation. The tool includes two economizer plots. First, the MAT vs. OAT plot shows data for scheduled periods in comparison to reference lines. The references lines for ideal operation are based on user inputs of economizer high/low limits and minimum outside air fraction. Second, the scatter plot of MAT and OAT vs. hour of day shows the daily temperature profile. Summary statistics are presented (min, max, average, and standard deviation) for all system temperatures (SAT, MAT, RAT, OAT) as bar charts. In addition, the system temperatures at minimum and maximum outdoor air temperature help to quickly assess operation.

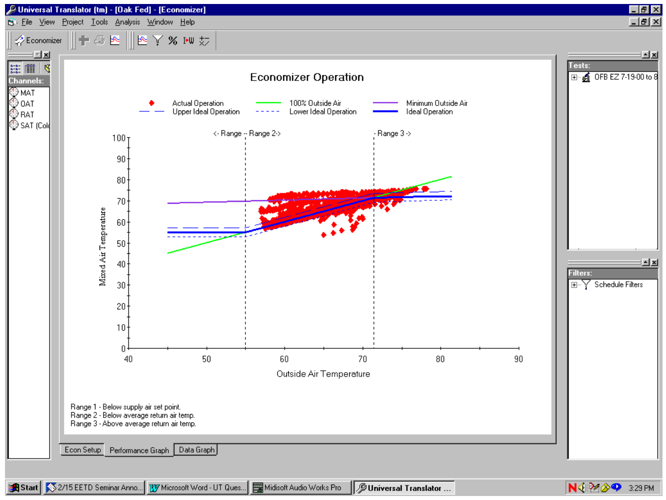

Figure 5. Tool C, Performance Graph, Economizer Diagnostic Module

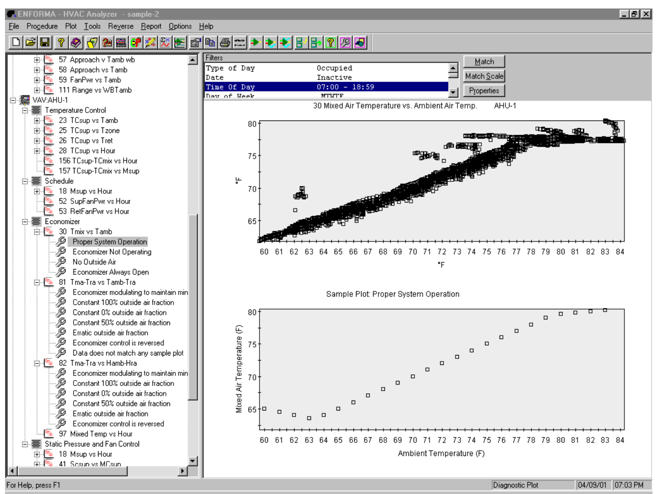

Figure 6. Tool B, Economizer Reference Plot and Measured Data

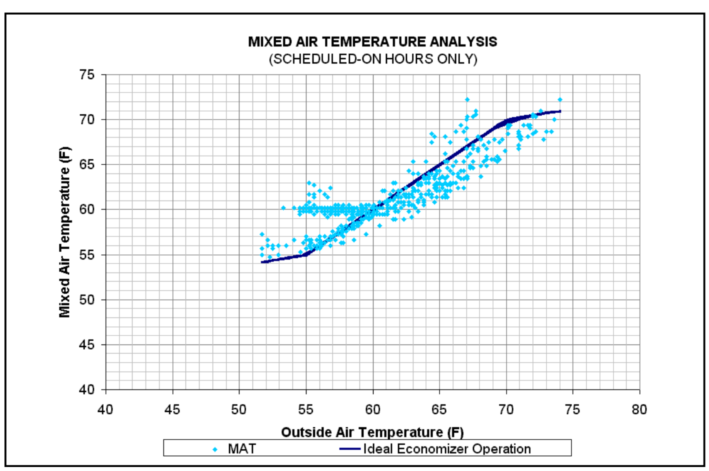

Figure 7. Tool A, Economizer Plot

General Tool Strengths and Limitations

This section sets forth areas where each tool excels, as well as features that limit use of the tool. Each user may associate different levels of importance to these strengths and limitations.

Tool A.

The strength of Tool A lies in the summary statistics and guidelines to analyzing the diagnostic plots. Fan benchmarking is the main focus of the tool, but was not assessed since it utilizes one-time performance measurements rather than time-series data. Tool A is simple to use and a straightforward framework to facilitate spreadsheet analysis, but limits a user to manual detection and diagnosis. The tool is free and available to the public.

Tool B.

Tool B is flexible for implementation with many types of systems, and provides automatic selection of reference plots from over 150 predefined diagnostic plots to use as a comparison to measured data. The software also has extensive help files that act as a diagnostic manual to guide the user through the predefined reference plots and the selection of additional plots and filters. The user-defined filtering capabilities are advanced compared with most of the diagnostic tools. Tool B's diagnostic abilities rely on manual detection and diagnosis. The user needs the technical ability and time to detect improper operation using the pre-defined reference plots. To implement the tool with EMCS data, files must be formatted in a specific way. Each data point must be listed sequentially, without a timestamp. The data are assumed to be complete, which may be problematic for EMCS data.

Tool C.

Tool C has a data processing capability that is not found in the other tools: the synchronization of time stamps through interpolation. This feature is especially useful with data from different sources or with different sampling times and frequencies. Since Tool C has limited data visualization and system diagnostics, it may be useful to run data through the tool for filtering and synchronization procedures, and then export the data to another diagnostic tool. In addition, Tool C has the most flexible user-defined filtering capabilities. In addition to the economizer analysis, the tool offers a run-time analysis that determines the data cycling rate relative to threshold values. This procedure allows cycling to be detected and quantified manually. The developers are in the process of providing documented, open code, giving users the opportunity to add their own diagnostic modules and features.

Tool D.

Tool D is an advanced prototype tool for a set of automated diagnostics. The tool utilizes real-time (hourly) data acquisition with an automated link to EMCS data. The economizer module employs a "cause-reduction" strategy that can save operators time in finding the cause of an identified problem. The tool also uses a diagnostic tree that is expected to be public, and is therefore useful for development of similar tools or to facilitate understanding of how the diagnostics function. The lack of visualization in the tool's economizer module may be a limitation to some users. The use of average hourly data dampens the spikes in energy and temperature, which reduces false diagnoses due to data collection problems, but also reduces the opportunity to detect peaks in usage (energy module) or oscillating economizer control. The ability to calculate energy cost waste is a strength, but Tool D does not aggregate waste over multiple data collection periods. Instead, for each fault detected in a certain hour, the tool calculates weekly cost waste by assuming the fault occurs for 24 hours a day, seven days a week.

Tool E.

Tool E has the most extensive automation of expert rules to assess HVAC system performance. Over fifty problems can be detected for air handlers, chillers, zones, and the hydronic distribution system. The tool's multi-variable baseline model can be used for any data point. The model detects deviations from baseline operation and estimates cost waste, which can alert a user to the degradation of a piece of equipment or changes in whole building energy. Another strength is the archiving of performance measures such as load shapes, chiller performance (load, lift, and power), and peak load. The hierarchy tree for system points provides flexibility in viewing and aggregating metrics both across time and across systems, such as monthly cooling load and energy cost waste at each air handler. Tool E can periodically (in batch processing) assesses system performance and can help prioritize maintenance based on cost waste.

The nature of Tool E requires commitment by building staff to help gather system information for input into the configuration. This process tends to force a detailed examination of existing operations.

Overall, Tool E can be used to assess the HVAC system operation and the root causes of many problems, summarizing relevant performance characteristics and targeting repair to the most costly problems. The automation of diagnostics coupled with visualization techniques makes the tool functional for many types of users. Experts can use the tool to streamline detection and provide data visualization capabilities for manual diagnostics, while novice users may rely entirely on the diagnostic output. The main limitation to Tool E is a lack of transparency in its methods, since the expert rules are not published.

Tool F.

Tool F has advanced web-based data acquisition with gateways linking building data to a remote server. Intra-company benchmarking is facilitated by this web platform. The tool has high quality data visualization with summation of hourly, daily, and monthly totals and the capability to visualize three years of monthly data. Aggregation also occurs for energy and demand at all levels of the system hierarchy. Average, peak, and minimum daily loads can be filtered for each day type (weekend, weekday, etc.) to aid analysis of unoccupied operation and load shape.

Tool F's main limitation is a lack of automation to diagnostics, with user-defined conditional alarms as the only method of automated detection. The tool extends beyond EMCS alarm capabilities by adding long-term archiving and advanced visualization features. Overall, Tool F provides a robust platform for whole building energy analysis and manual diagnostics.

SUMMARY

Each tool evaluated provides unique diagnostic capabilities for particular applications. There is little overlap among the current tools, as all have been developed with unique designs. For example, Tool F is a sophisticated tool for tracking energy use and related time-series data in large distributed groups of buildings due to its web-based monitoring and benchmarking capabilities. Tool E has a wide range of automated diagnostics that can help facility managers and operators prioritize problems by energy cost waste. Tool D has core economizer and whole building energy diagnostics developed specifically for use by operators. Tool C is a unique, short-term analysis tool that focuses on management of data from multiple sources. Tool B allows manual problem detection for a wide range of system types, but requires expertise to detect and diagnose problems. Tool A helps automate spreadsheet analysis by generating useful plots and statistics for short-term data collection.

Diagnostic software tools are an emerging industry with great potential to save energy in building operations. A key value in using these tools lies in reducing the data management and analysis time necessary to extract valuable information from EMCS data, thus enabling operators, managers, and engineers to efficiently assess building performance. All tools are undergoing development, streamlining configuration, and adding capabilities to detect and diagnose additional problems. By using continuous time-series data and emerging software tools, the power of information technology to support building operations has only begun to be tapped.

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