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Comparison of Emerging Diagnostic Tools for Large Commercial HVAC Systems

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Comparison of Emerging Diagnostic Tools for Large Commercial HVAC Systems

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Synopsis

Diagnostic software tools for large commercial buildings are being developed to help detect and diagnose energy and other performance problems with building operations. These software applications utilize energy management control system (EMCS) trend log data. Due to the recent development of diagnostic tools, there has been little detailed comparison among the tools and a limited awareness of tool capabilities by potential users. Today, these diagnostic tools focus mainly on air handlers, but the opportunity exists for broadening the scope of the tools to include all major parts of heating, cooling, and ventilation systems in more detail. This paper compares several tools in the following areas:

- Scope, intent, and background

- Data acquisition, pre-processing, and management

- Problems detected

- Raw data visualization

- Manual and automated diagnostic methods

- Level of automation

This comparison is intended to provide practitioners and researchers with a picture of the current state of diagnostic tools. There is tremendous potential for these tools to help improve commercial building energy and non-energy performance.

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Introduction

New diagnostic software tools are available to streamline the detection and diagnosis of energy and other performance problems in commercial building operations. These tools provide a framework for data management by organizing information from volumes of underutilized energy management control system (EMCS) trend logs and other time-series data. Some of the tools can extract and summarize relevant performance metrics, display plots for manual analysis, and perform automated diagnostic procedures. In combining newer EMCS data logging capabilities with advances in information technology, there is great potential to use EMCS data to assess building performance. Such tools are needed because EMCS have extremely limited embedded diagnostic capabilities. Given the limited tools available, building operators rarely have the time required to collect and analyze trend logs for performance problems. Building operators and energy engineers need better tools to streamline and guide the use of EMCS data.

Since diagnostic software tools have only recently been developed, there has been little detailed characterization of, or comparison among, the tools and a limited awareness of their differences and capabilities by potential users. We present a review of seven tools for use with large commercial buildings. The assessment attempts to give potential users (building operators, energy managers, engineers, energy service companies, or commissioning agents) an understanding of each tool's capabilities to help the user better assess options for implementation. There is tremendous potential for utilization of data visualization and diagnostics techniques, and each tool offers valuable capabilities for diagnostic analysis. This paper is one piece of a larger forthcoming report developed by LBNL as part of the California Energy Commission's Public Interest Energy Research program (http://buildings.lbl.gov/cec/).

The distinction between manual and automated diagnostic tools is not straightforward, since tools have various levels of automation in their data collection procedures, management and processing of data, and diagnostic use. The term 'diagnostics' encompasses both the detection of operational problems and the diagnosis of their cause (Haves, 1999). Diagnostic tools can be used to assess existing building operations for retro-commissioning as a one-time event or continuously over time. 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 the plots and information automatically generated by the tool. In contrast, *automated diagnostic tools* reduce or eliminate the need for human reasoning in detection and diagnosis of problems by automating the process of analyzing data.

This review begins with a presentation of the tools and selection criteria, followed by an overview of their scope, intent, and background. Next we present summary charts and details of operational use focused on three steps for diagnostic tool operation. We conclude with a summary of the level of automation provided by each diagnostic tool.

Tools and Selection Criteria

This section introduces the tools selected in our comparison. We have focused on the implementation of the tools with an existing EMCS, even though some tools are intended mainly for short-term use with data loggers. While inputting EMCS data into these short-term tools is a less streamlined process than with the continuous monitoring tools, using the short-term tools to continuously detect performance problems is valuable. The tools studied have varying scope and depth in their treatment of detection and diagnosis. The following list shows the core tools for comparison organized by the primary level of diagnostic automation.

Manual Diagnostic Tools

- **ENFORMA® Portable Diagnostic Solutions (ENFORMA software)**, Architectural Energy Corporation (AEC) (Frey, 1999)
- **Universal Translator (UT)**, Pacific Gas and Electric's (PG&E) Pacific Energy Center (Stroupe, 2000)
- **UC Berkeley, Analysis Tools for Built-up Fan Systems (UCB Tools),** University of California at Berkeley, Center for Environmental Design Research (Webster et al, 1999)
- **Enterprise Energy Manager Suite (EEM Suite™)**, Silicon Energy (Silicon Energy, 2001)

Automated Diagnostic Tools

- **Whole Building Diagnostician (WBD)**, Pacific Northwest National Laboratory (Brambley et al, 1998)
- **Performance and Continuous Recommissioning Analysis Tool (PACRAT)**, Facility Dynamics Engineering (Santos and Brightbill, 2000)

The tools selected for comparison were narrowed from a larger set of diagnostic tools based on the following criteria:

- The tool aids heating, ventilating, and air conditioning (HVAC) diagnostics with, at minimum, automatically created diagnostic plots or programmable alarms.
- The tool serves large commercial building HVAC systems and 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).

Silicon Energy's EEM Suite was selected as an example of a web-based energy management tool, even though it does not have pre-defined HVAC diagnostics. EEM Suite brings together remote data acquisition from EMCS and utility meters with visualization tools for manual diagnostics.

Additionally, the Information Monitoring and Diagnostic System (IMDS) (Piette et al, 2000) developed by Supersymmetry and demonstrated by LBNL and partners through a CIEE project[1] is briefly touched upon. The IMDS consists of a set of high-quality sensors and data acquisition and visualization systems, including a web interface. Electric Eye, an advanced data visualization tool utilized by the IMDS, is included in the data visualization comparison.

Diagnostic Tool Overview

This section presents an overview of the scope, intent, and background of each tool. Since tools have different levels of commercialization and different diagnostic purposes, it is important to approach the analysis of the diagnostic tools with an understanding of these overview issues to discourage unfair comparisons. This overview sets the context for the comparisons of operational use in the next section.

Tool Scope and Intent

Since the focus of this 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 following list is an overview of the major systems served by the tools.

- The **ENFORMA** software is used for short-term analysis to aid problem detection in many system types. The tool includes air handlers, cooling plants (cooling towers, chillers), heating plants, and zone distribution systems.
- The **UC Berkeley Fan Tools** have unique capabilities to benchmark fans using one-time measurements, but since we have limited our analysis to time-series data, we do not review this feature. We will focus on UC Berkeley's spreadsheet modules for time-series data that include data visualization and statistics for the analysis of fan power, system temperatures, zone temperatures, reheat, and duct static pressure.
- The **Universal Translator's** primary strength is in synchronization of multiple data sources for use with both EMCS data and data loggers. The tool also has diagnostic modules for outdoor air economizers and equipment run-time and cycling.
- The **WBD** is an automated tool for continuous analysis of economizers (outdoor air economizer module – OA/E) and whole building or central plant energy consumption (whole building energy module - WBE).

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[1] California Institute for Energy Efficiency, Diagnostics for Building Commissioning and Operation Project. Collaborators include Lawrence Berkeley National Laboratory (LBNL), Supersymmetry, A. Sebald, and C. Shockman. See http://eetd.lbl.gov/ea/iit/diag/index.html

- **PACRAT** provides continuous analysis and is both broad and in-depth in its automated diagnostic capabilities. PACRAT's automated diagnostics address the air handlers, chillers, hydronic system, whole building energy, and zone distribution.

- The **EEM Suite** uses a web-interface for continuous display and manipulation of utility and EMCS data connected through gateways. EEM Suite can help visualize the performance of any systems for which data is linked, but there are no pre-defined diagnostic modules.

The short-term tools (ENFORMA, UT, UCB Tools) 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, the WBD, PACRAT, and EEM Suite were designed to continuously evaluate EMCS data, and they include vendor-specific algorithms to aid importing data. The tools have differing degrees of automation, which are directly related to the intended function. If the tool is intended for short-term use, automated features have a less important role. If tool users are experienced in energy analysis or if the tool is used for one-time commissioning or retrofit projects, there is less need for automated methods of diagnosis. Conversely, for continuous data analysis, it is appropriate to have fully automated diagnostic procedures. Automated problem detection is important to all users since examining data manually is tedious. The automated tools can greatly reduce the time needed to both detect and diagnose problems.

With the purchase of some tools, the user also receives the HVAC expertise of the developers in the configuration process. This service aspect is especially true with PACRAT, as the developers guide the configuration and initial use of the tool. The EEM Suite requires installation support, but diagnostics support is not included. The ENFORMA software provides engineering consulting with the initial tool configuration. The WBD developers have had extensive involvement with pilot installations and the interpretation of diagnostic results.

Many of the tools perform functions in addition to diagnostics, including rate structure cost analysis, monitoring and verification for performance contracting, design decision information, fan benchmarking, and retrofit analysis. These features give more versatility to the tools, but they are outside the scope of this study.

Tool Background

A summary of the history of the tools is presented in Table 1 to indicate the level of commercialization and the funding that has supported development. It is important to note that all the tools are relatively new and are continuing to be enhanced.

Table 1. Diagnostic Tool Background

	Developer	Stage	Funding
ENFORMA	Architectural Energy Corporation	Commercialized in 1996	EPRI* cost-share and private
UCB Tool	Center for Environmental Design Research, UC Berkeley	Prototype in 1999	CIEE, CEC**
UT	Pacific Energy Center, Pacific Gas & Electric Company	Beta testing in 2000	California public goods charges
WBD	Pacific Northwest National Laboratory, Honeywell, and Univ. of Colorado	Prototype with pilot projects, began in 1998	U.S. Dept. of Energy
PACRAT	Facility Dynamics Engineering	Commercialized in 1999	Private
EEM Suite	Silicon Energy	Commercialized in 1998	Private
IMDS	Supersymmetry, LBNL, En-Wise, C. Shockman, A. Sebald	Prototypes, 1998 and 2000	CIEE, U.S. Dept. of Energy

* Electric Power Research Institute
** California Institute for Energy Efficiency, California Energy Commission

The ENFORMA software was one of the first diagnostic tools commercially available and has been utilized for commissioning and retrofits using the AEC MicroDataLogger® product. The UC Berkeley Fan Tools are a part of a research project to develop measurement and analysis protocols for detecting problems in built-up air handling systems. The UT is intended for use with data loggers, which are available through the Tool Lending Library at PG&E's Pacific Energy Center. The WBD was built by researchers led by PNNL, who saw the need for automated diagnostic tools for use with EMCS data. PACRAT was developed by HVAC controls engineers, for streamlining the manual process of looking at data within their consulting services and for use as a stand-alone tool. Silicon Energy has developed the EEM Suite mainly for remote energy tracking and rate structure analysis at large buildings or groups of buildings. The IMDS has been demonstrated in an office building in San Francisco (Piette et al, 2000), and is currently being implemented at a second building in Sacramento.

Diagnostic Tool Operational Use

The tools utilize a progression of steps to perform diagnostics. These steps are carried out in order, with each tool's approach ranging from manual to automated. This section on operational use is organized around the following three steps:

1. Data acquisition
2. Data management and pre-processing
3. Diagnostics (problem detection and diagnosis)

Data Acquisition

Inputting the data into the diagnostic tools is the first step and may require technical assistance for new users. The short-term tools require text files for importing, while the long-term tools rely on automated data acquisition through links to the EMCS data.

The ENFORMA software requires specifically formatted headers in the data files that specify the collection frequency and time range. The UT has an interface that helps import data from text files so the date and time are not required in a predefined configuration. Unlike the ENFORMA software, the UT retains the timestamp for each point. To input data into the UCB Tools, the user simply pastes data into the input screen in the spreadsheet.

PACRAT and the WBD have routines to capture EMCS data, programmed separately for each controls manufacturer. The EEM Suite has a more sophisticated gateway with the ability for two-way communications that enables remote control of the EMCS. PACRAT and EEM Suite have implemented a flexible hierarchy of points that allows any data to be input and accessed through a user-defined tree view.

Data Management and Pre-processing

Once the tools access the data, data management and pre-processing occur, taking potentially unreliable EMCS data and preparing it for use in the diagnostic algorithms. We have defined this process to include time stamp synchronization, data validation, and archiving.

EMCS data may not have synchronized timestamps, which is problematic for visualizing X-Y scatter and 3-D plots, or performing diagnostic analyses. The UT is the only tool that synchronizes data through interpolation. Timestamps are synchronized across all data streams through an algorithm that examines values every second, using a time-weighted average to calculate the value at the user-specified timestamp. PACRAT and EEM Suite keep the real timestamp with each data point or can use algorithms that converge the data onto a single timestamp interval. The ENFORMA software assumes sequential data and does not import timestamps, while the WBD employs hourly averages, so timestamps do not need to be synchronized.

Data validation is essentially pre-diagnostics filtering to address the problem of erroneous data. Since EMCS data may report spikes to unreasonable values, it can be useful to pre-filter data outside a specified range for use in analysis. PACRAT, the ENFORMA software, and the EEM Suite can automatically filter data. In addition, PACRAT has algorithms that fill and recreate data through interpolation, distribution, or based on the difference between values. The UT can also build missing sections of a dataset using a manual regression routine.

To streamline the analysis of historical data and create a data management structure, some tools archive data. PACRAT archives all raw data as well as performance metrics and diagnostic results in a database. The EEM Suite archives the raw data at user-defined intervals and the alarm states on a remote server database. The WBD archives hourly average data and energy consumption in its database. The archiving capabilities of the short-term tools are limited to the amount of data run in each project and the limitations of the software platform.

Diagnostics

The last step for tool use is problem detection and diagnosis, or diagnostics. Detection requires a comparison to the "correct" operation of the system using either quantitative (modeling) or qualitative (expert knowledge) baselines. Diagnosis specifies possible causes and remedies for the problem detected.

Problems Detected

Table 2 summarizes the problems that can be detected by each tool, organized by system categories. The problems focus on energy waste, comfort control, and equipment operation, and they are detected in both manual and automated diagnostics. Again, manual diagnostics refers to the manual interpretation of results from plots that are automatically created by the tool. The column for "General across systems" is included, listing problems detected by multiple systems and referencing the systems by their column heading. PACRAT has automated detection of the largest number of problems, while the WBD focuses on a few specific diagnostics. The manual diagnostic tools also have a wide range of capabilities.

Table 2. Manual and Automated Diagnostics by System

		I. Whole building	II. Central Plant	III. Air Handler (AHU)	IV. Zones	General across systems*
AUTOMATED DIAGNOSTICS	**PACRAT**	Utility deviation from baseline model (kWh, therms, ton-hours)	Chiller diagnostics: ▪ Chilled water temp control ▪ Poor load factor ▪ Poor condenser, evaporator performance ▪ Chiller efficiency degradation ▪ Excess cycling Distribution (hydronic): ▪ Failed valve ▪ Struggling pumps, valves ▪ Primary/secondary system	▪ Simultaneous heating/cooling ▪ Lack of economizer cooling ▪ Outdoor air excess or inadequate ▪ Leaking/struggling coils ▪ Control instability, excess cycling	Space temperature deviation	▪ Failed/miscalibrated sensors (II,III) ▪ Run-time threshold met (II,III) ▪ Unoccupied operation (I,II,III) ▪ Deviation from baseline (I,II, III) ▪ Alarm occurrence (I,II, III) ▪ Override occurrence (II, III) ▪ Additional proprietary detection algorithms (I, II, III, IV) **MANUAL DIAGNOSICS** ▪ Performance metrics (I, II, III)
	WBD, WBE	Electric and gas deviation from baseline model	Chiller electric deviation from baseline model			
	WBD, OA/E			▪ Lack of economizer cooling ▪ Outdoor air excess, inadequate ▪ Failed/miscalibrated sensor		
MANUAL DIAGNOSTICS	**EEM Suite**	▪ High energy ▪ Unoccupied operation				▪ Program conditional alarms ▪ Run-time (on/off)
	ENFORMA		Boiler: see general Cooling tower (CT) capacity Chiller ▪ Condenser performance ▪ Interlock with AHU and CT ▪ Chiller kW OAT dependence	▪ Lack of economizer cooling ▪ Humidifier operation ▪ Evap cooler performance ▪ Static pressure & fan control ▪ Duct heat gain ▪ Simultaneous heating/cooling	Terminal unit operation	Unoccupied operation (II, III, IV) Temperature control (II, III, IV)
	UCB Tool			▪ Motor load factor ▪ Lack of economizer cooling ▪ Reheat operations ▪ Static pressure	Reheat operations	Temperature control (III, IV)
	UT			▪ Lack of economizer cooling		Run-time (II,III) Cycling analysis (II,III)

* I, II, III, IV in parenthesis denote column headings that include these diagnostics.

Raw Data Visualization

The next section examines how the tools detect these problems, either manually or with a level of automation. The most basic level of manual detection is through raw time-series data visualization. Table 3 shows techniques in which the tools help users view data.

Table 3. Data visualization methods and features

		Time Series	Advance Time Series	X-Y	3D	Daily Profile	Load Duration	Filter	Real-Time	Aggregate
ENFORMA		✔	✔-	✔		✔		✔		
UCB Tool		✔		✔		✔	✔			
UT (PG&E)		✔	✔-					✔+		
WBD	**WBE**								hourly update	
	OA/E								hourly update	
PACRAT		✔	✔	✔	✔	✔+	✔	✔		✔
EEM Suite		✔	✔	✔	✔	✔+	✔	✔	✔	✔
IMDS/ Electric Eye		✔	✔	✔	✔	✔	✔	✔	✔	✔

Definitions: *Advanced time series*: Scroll and zoom capabilities. (✔-) indicates zoom only.
X-Y scatter: Plot of two points against each other to visualize relationship.
Daily profile: Data point plotted against hours of the day, overlaying multiple days(✔) or calculating average and peak profiles. (✔+)
Load duration: Sort and bin data for plotting load (or load factor) and hours at each load.
Filters: User-defined filtering by day, time, versus another point. (✔+) indicates advanced capabilities.
Real-time: Monitoring with continuous update of data.
Aggregate: Sum data across system levels or time.

Raw time-series visualization is utilized by all tools except the WBD, which uses color maps and an energy consumption index (ECI). The other tools allow for visualization of time-series (trended) data, with varying ability to scroll through or zoom for detail. The IMDS uses Electric Eye visualization software, which is compared here since Electric Eye has a unique ability to view large datasets.

Daily profiles are important in evaluating building load shapes and temperatures. The ENFORMA software, the UCB Tools, and Electric Eye include plots that overlay data from multiple days, while PACRAT and EEM Suite can calculate average and peak daily profiles for a specified date range. PACRAT and the EEM Suite include **load duration** graphs, plotting the number of hours at each binned range of load. The UCB Tools provide motor load factor duration plots.

Filtering in this context is the ability for the user to filter raw data by day type, time period, or another point, which aids in visualization of problems that do not occur in all time periods. The UT's manual filtering capabilities are the most extensive, with flexibility in creating detailed schedules and filters based on another data point. The ENFORMA software also has broad filtering capabilities, and the developers consider this a strength of the tool.

Real-time visualization of data from multiple control vendors is provided by the EEM Suite through EMCS gateways. The WBD can be implemented in real-time or semi-real-time, depending on the connection to the EMCS. PACRAT processes data in batch files, generally daily, and the IMDS has been configured for real-time data visualization for one control vendor. All short-term tools require manual data input.

Aggregating data over time (hourly, daily, and monthly) and through all levels of the hierarchy tree (building, system, and component-level) is helpful when assessing building performance. For example, cooling load (or load/sq ft) can be aggregated and compared across buildings. PACRAT and EEM Suite aggregate energy consumption using tree views, creating a new point for each layer in the hierarchy. PACRAT also aggregates energy cost waste at each level of the hierarchy. The user can aggregate data with the ENFORMA software and Electric Eye by creating calculated points.

Manual Diagnostic Methods

Data visualization is a powerful method of gathering information from EMCS data, but the diagnostic tools go beyond simple data visualization techniques to aid the user in detection and diagnosis of building performance problems. Table 4 summarizes the diagnostic methods used by each tool.

Table 4. Diagnostic Methods

		Detection									Diagnosis
		Raw Data Visual	Ref. line	Bench-mark	Stats	Perf. Metric	Guide	Expert Rules	Model Base-line	Cost	Expert Rules
		Manual						Automated			
ENFORMA		✔	✔			✔	✔				
UCB Tool		✔	✔		✔	✔	✔				
UT (PG&E)		✔	✔		✔	✔-		✔-			✔-
WBD	WBE					✔			✔	✔	
	OA/E							✔		✔	✔
PACRAT		✔		✔	✔	✔+		✔+	✔	✔	✔
EEM Suite		✔		✔	✔	✔		note 1			

Note 1: The user can program conditional alarms that act as expert rules.

(✔+) indicates advanced capabilities. (✔-) indicates limited capabilities.

Definitions: Raw data visual: Manual detection using predefined plots.
Reference line: Comparison plots that help visualize correct operation.
Benchmark: Comparison across database of buildings or multiple buildings on site.
Statistics: Summary statistics (max, min, average, standard deviation, run-time)
Performance Metrics: Summarize performance (i.e., energy use intensity, chiller efficiency)
Guidelines: Companion document to aid in interpretation of plots.
Expert rules: Decision tree of expert knowledge used to detect and diagnose problems.
Modeled baseline: Baseline formulated through a model, to which measured data is compared and deviation assessed.
Cost: The cost of energy waste is calculated.

Reference plots or reference lines overlaid on data can help the user visualize correct operation for the manual detection of problems. The ENFORMA software's main aid to detection is their use of reference plots, with over 150 pre-defined plots available based on system configuration. Other tools use reference lines based setpoints or time-series data. In the UT's economizer diagnostic plot of mixed air temperature versus outside air temperature, average return air temperature and the supply air setpoint are used to create reference lines. The UCB Tool draws reference lines from user-input economizer high/low limits.

Benchmarking is a term that has been defined in a variety of ways in different contexts; we define self-benchmarking as the comparison of data across buildings within a site or company. The EEM Suite can self-benchmark across remote facilities and indexes the data by any variable. One EEM Suite module also normalizes monthly energy and cost for weather. PACRAT self-benchmarks components (e.g. chiller kW/ton) and systems across buildings using performance metrics.

Statistics provide a useful way to summarize large amounts of data. Several tools have statistics for max, min, average, and standard deviation. The UCB Tools go further to create bar graphs of system temps (SAT, RAT, MAT) at minimum and maximum outdoor air temperatures. The UT run-time analysis can be used to detect cycling and loading problems for any power measurement by calculating the number of times a point crosses a threshold and the runtime below each threshold. The EEM Suite also includes run-time analysis for use with digital points, which totals the changes in state (i.e., on/off) and the cumulative time in each state. PACRAT reports statistics within the performance characterization module for zones, ventilation rates, and cooling and heating loads.

Performance metrics are a general feature that includes calculated points such as chiller kW/ton and cooling load/sq ft. PACRAT, EEM Suite, the ENFORMA software, and the UT give the user the ability to define metrics, while the WBE generates one pre-defined metric, energy use intensity. In PACRAT, EEM Suite, and the ENFORMA sofware, the metrics are defined in the configuration as permanent calculated points, but the UT metrics must be re-defined for each processing run. A strength of PACRAT is its automated archiving of performance metrics.

Diagnostic guides and help manuals are an aid to manual detection. The ENFORMA software has extensive help files that outline diagnostic procedures, summarize the available predefined reference plots, and briefly describe relevant data patterns. The UCB tools are the only other tool that utilize written diagnostic guidelines, with short descriptions accompanying examples of each diagnostic plot.

Automated Diagnostic Methods

The WBD, PACRAT, and the UT are the only tools with automation in both detection and diagnosis. These tools perform automated diagnostics through the use of expert rules or modeled baselines, shown in Table 4. The WBD and PACRAT report the associated energy cost waste to assist prioritization of action. The EEM Suite can be programmed for alarm events based on point high/low thresholds or user-defined rules. The alarm events can be sorted by chronology, severity, or priority.

Expert Rules

PACRAT, the WBD, and the UT implement expert rules to detect and diagnose problems. This process involves the comparison of datapoints in a series of rules based on knowledge of proper system operation. PACRAT outputs problems, referred to as anomalies, with a direct link to a time-series plot at the time of the event. PACRAT calculates the amount of deviation from normal operation and the energy waste associated for each data point, and sums over a specified duration. The energy cost waste is determined using a full rate schedule. In addition to aggregating the cost waste over time, PACRAT lists possible causes and associated resolutions with each anomaly.

The WBD outdoor air economizer (OA/E) module relies on a color map notification method for easy identification of problem states. Each block is shaded a color corresponding to the state for the economizer that hour (ventilation low, high energy, system ok, and incomplete or no diagnosis.) The user can drill down into each block to learn more about the problem detected, including energy cost waste for that hour and potential causes and suggested actions. The OA/E also uses expert rules to diagnose problems and has an algorithm that narrows down the cause for the

problem over time by evaluating combinations of conditions that could not exist simultaneously. For both the whole building energy (WBE) module and the OA/E, cost waste is not aggregated over time. The cost waste for each hour block is used as a rough indicator of the relative importance of the fault.

The UT utilizes a simplified expert rules that involve only system temperatures to diagnose the economizer, without calculating energy cost waste.

Modeled Baseline

PACRAT and the WBE both calculate baselines using a multi-variable binning technique and report deviations from the baselines. To use the baselines to detect deviation from correct operation, the building ideally should be commissioned. The WBD bins the energy data by hour of the week, ambient temperature, and relative humidity. PACRAT's methodology allows for any third variable in addition to the hour of day and day of the week, typically ambient temperature. PACRAT's module can create both whole building and component level energy consumption baselines.

The WBE notifies the user of a deviation from baseline energy usage by plotting the energy consumption index (ECI, where 1.0 is average). If the measured data deviates by a prescribed amount, the point is highlighted in the time-series plot of EUI. Similar to the anomalies reported using the expert rule method, PACRAT reports an anomaly when measured data deviates from the baseline created. The anomaly report includes cumulative energy cost waste linked to plots.

The automation in the steps to tool diagnostics described in this paper is summarized in Table 5.

Table 5. Summary of Tool Automation

		Data Acquisition	Management and Pre-processing	Detection	Diagnosis
ENFORMA		○	◐	○	○
UCB Tool		○	○	○	○
UT (PG&E)		○	◐	◐	○
WBD	WBE	●	◐	●	○
	OA/E	●	◐	●	●
PACRAT		●	●	●	●
EEM Suite		●	●	◐	○

Automated ●   Partially Automated ◐   Manual ○

Conclusions

Each tool has diagnostic capabilities for particular applications. For example, PACRAT has a wide range automated diagnostics that can help facility managers and operators prioritize problems by energy cost waste. Silicon Energy's EEM Suite may be most appropriate for distributed groups of large buildings due to its web-based monitoring and benchmarking functions. As a prototype tool, the WBD has important core economizer and whole building energy diagnostics for use by operators. The UT is a short-term analysis tool that focuses on synchronization of data from multiple sources. The ENFORMA software is geared toward manual detection of a wide range of system types, but requires expertise to detect and diagnose problems. The UCB Tools help automate spreadsheet analysis by generating plots and statistics for short-term data collection.

Diagnostic software tools are an emerging industry with great potential to save energy in building operations. The main value in using tools lies in reducing the data management and analysis time necessary to obtain valuable information from EMCS data, thus enabling operators, managers, and engineers to efficiently assess building performance. By using continuous time-series data and emerging software tools, the power of information technology to support building operations can be utilized to improve overall building performance.

Acknowledgements

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