Diagnostics for Monitoring-Based Commissioning

Michael R. Brambley and Srinivas Katipamula
Battelle Pacific Northwest Division

Patrick O'Neill
NorthWrite Inc.

Synopsis

This paper presents a case for application of automated monitoring, analysis and diagnostic tools for monitoring-based commissioning. Selected examples are presented in which such tools have been used successfully to support commissioning activities in southwestern Canada and the U.S. Pacific Northwest. The first example involves use of spreadsheet-based tools to automatically generate diagnostic plots that are visually examined for specific features that reveal operational problems in space conditioning systems of large commercial buildings. The findings then guide re-tuning actions to increase building energy efficiency. This is followed by application of a tool for continuous monitoring of whole-building energy use to automatically track energy savings resulting from a utility commissioning program. This tool also provides a means by which to detect degradation of savings and performance to guide monitoring-based commissioning actions. The potential use of automated diagnostic tools for chillers and packaged air conditioners is then described for continually commissioning these units. The paper concludes with a discussion of the impacts of this approach on commissioning, including potential time savings, associated cost savings, and improvements in the quality of commissioning.

About the Authors

Michael Brambley, Ph.D., a Staff Scientist with Battelle, has over 30 years of experience related to energy technologies and policy, focusing for the last 20 years on developing technologies for improving building energy efficiency. Before joining PNNL, he was a faculty member in the Engineering School at Washington University in St. Louis.

Srinivas Katipamula, Ph.D., is a Staff Scientist with Battelle and has extensive technical experience in development of automated fault detection, diagnostics and commissioning techniques, building energy system simulations, analysis/evaluation of energy efficient technologies, analytical modeling techniques, tools and techniques to verify energy saving from building and equipment retrofits, and development and deployment of re-tuning.

Patrick O'Neill, Ph.D., is the co-founder and Chief Executive Officer of NorthWrite, Inc., an Internet-based facility, security, and energy management software company. Before NorthWrite, Patrick spent 10 years at Honeywell International, where he most recently served as Vice President of Technology and Development for e-Business. Prior to Honeywell, O'Neill worked at Battelle and the University of Illinois at Urbana-Champaign.

Introduction

Monitoring-based commissioning (MBCx) uses energy consumption and system-performance monitoring to guide the re- and retro-commissioning processes for existing buildings and to verify the energy savings achieved. Furthermore, monitoring is used to help ensure the persistence of savings by alerting building staff and management to degradation in performance and to detect faults in operation. Monitoring also can help identify improvement opportunities during re- and retro-commissioning and, when implemented to continuously provide data during building operation, can support continual commissioning and renewal of building systems.

A major project that is applying monitoring-based commissioning across a large number of state university campuses in California is showing the value of this approach for existing buildings.[1,2] That project involves the installation and "upgrade of permanent energy meters and other instrumentation, augmentation of energy information systems, benchmarking of building energy performance, assistance with initial commissioning efforts, and training of in-house staff."[3] The partnership performing this project has defined MBCx as the "adjustment, maintenance or repair of existing equipment as opposed to upgrade of equipment."[4] In this paper, we use a broader definition of MBCx, which includes re- and retro-commissioning projects in which retrofits might be included. Monitoring is used to identify opportunities for operational improvements, to verify savings from re- and retro-commissioning, and to provide information to support maintaining building performance after commissioning to ensure the persistence of savings.

Over the last decade or so, diagnostic techniques and automated tools (e.g., PACRAT, the NIST APAR and VAV algorithms, and the WBD; see Friedman and Piette[5]) have been developed that assist in detecting operational faults and degradation in the performance of building systems and diagnosing their causes. These techniques and tools can significantly reduce the time, effort and level of knowledge required to acquire and analyze data to reveal energy-consuming operational faults, such as failed sensors, inoperable economizer dampers, poorly implemented schedules, and improperly charged direct expansion equipment, to name few. These tools provide information valuable for identifying opportunities for saving energy through improved operations and detecting faults and performance degradation as they occur, enabling their timely correction, thus helping ensure persistent savings.

This paper presents a case for application of monitoring, analysis and diagnostic tools and techniques through selected examples, where such tools have been used successfully in support of commissioning activities in southwest Canada and the U.S. Pacific Northwest. The examples start with applications across many buildings in two commissioning programs. The next section describes the use of spreadsheet-based tools to format trend-log data from building automation systems and to automatically generate diagnostic plots that are visually examined for specific features that reveal operational problems in space conditioning systems of large commercial buildings. This is followed by a section in which continuous monitoring of whole-building energy use is used to automatically track daily energy savings resulting from a utility commissioning program. This tracking also provides a means by which to detect degradation of savings and performance to guide monitoring-based commissioning actions. The potential use of automated diagnostic tools for chillers and packaged air conditioners is then described for continually commissioning these units based on monitoring. The paper concludes with a discussion of the impacts of this approach to commissioning, including potential time savings, associated cost savings, and improvements in the quality of commissioning.

Guiding Commercial Building Re-Tuning with Control System Data

Retro-commissioning studies place the potential energy savings from improved operation and maintenance (O&M) of commercial buildings between 5% and 30%. A pilot program has been initiated in the State of Washington focused on capturing a significant portion of this potential through transformation of building O&M professionals' practices.[6,7] One major component of the program focuses on re-tuning large commercial buildings. It is intended to change the way HVAC systems in large commercial buildings are operated, serviced and maintained by targeting high-impact energy efficiency measures that can be delivered immediately, at low or no cost. As part of this effort, companies providing HVAC servicing were trained to provide HVAC and controls re-tuning services. While providing the training, HVAC systems in selected large commercial buildings were "tuned" for efficient operation, and then each trained team re-tuned five additional buildings.

Many large[†] commercial buildings today use sophisticated EMCSs to manage a wide range of building systems. Although the capabilities of the EMCSs have increased over the last 2 decades, the capabilities of these systems are not fully utilized, and many buildings are not properly commissioned, operated or maintained. Lack of proper commissioning, the inability of the building operators to understand complex controls, and lack of proper maintenance leads to inefficient operations and reduced equipment lifetimes. Tuning building controls using EMCSs helps ensure maximum building energy efficiency and the comfort of building occupants. A poorly tuned system can sometimes maintain comfortable conditions, but at a high energy cost to overcome unrecognized inefficiencies.

Periodic re-tuning of building controls and HVAC systems will enhance building operations and improve building efficiency. Re-tuning, as used in this project, is a systematic, semi-automated process of detecting, diagnosing and correcting operational problems with building systems and their controls. The process can significantly increase energy efficiency at low or no cost – and the impact is immediate. Unlike the traditional retro-commissioning approach, which generally has a broader scope, re-tuning primarily targets HVAC systems and their controls. In addition, re-tuning uses monitored data to assess building operations even before conducting a building walk through. This process is similar to MBCx as implemented in other work cited earlier. However, in contrast to monitoring-based approaches using newly-installed or enhanced permanent meters and energy information systems, our re-tuning approach leverages existing EMCSs to trend data and identify operational faults and opportunities to save energy.

[†] For this project, a large commercial building is defined as a building with 100,000 square feet (sf) or more of conditioned space, having an energy management and control system (EMCS).

Re-tuning Methodology

An early version of the re-tuning methodology was initially developed during the electricity crisis of 2000–2001 for the Federal Energy Management Program (FEMP). The procedures were adopted by FEMP and rolled out as part of the U.S. Department of Energy (DOE) ALERT (Assessment of Load- and Energy-Reduction Techniques) Program for federal facilities. The procedures were further refined and formalized for use in the current project. The re-tuning method consists of six primary steps: 1) initial collection of relevant building information, 2) pre-re-tuning, 3) building walk through, 4) re-tuning, 5) post-tuning and 6) savings analysis. For more details on how to execute each of these primary steps, refer to references 6 and 7. A more detailed description of the pre-re-tuning phase (step 2), which is the focus of this paper, follows.

The pre-re-tuning phase involves setting up trend logs in the EMCS, collecting trend data for at least 1 week (preferably 2 weeks) for key points in the mechanical system, and analyzing the data to learn more about current building operations. This analysis helps identify operational problems such as: systems running during unoccupied hours, poor economizer operation, outdoor-air ventilation during morning warm-up or cool-down, incorrect “optimal” start and stop of systems, excessive equipment cycling, leaky valves, exhaust fans running continuously, faulty sensors, and high supply-air static pressure, which leads to poor zone control.

Before starting collection of trend data, a monitoring plan is prepared, which is based on the building information gathered in the previous step. To help the service providers, monitoring templates and a list of points to trend on common HVAC systems are provided. The plan identifies trend logs that need to be set up in the EMCS and how the trend data will be analyzed. For each trend log (i.e., sensor or control point), the plan specifies the duration of the logging period (number of days) and the measurement period (time interval between logged values). The monitoring plan depends on the specific HVAC systems in the building[¥].

The monitoring plan is then implemented, first by creating trend logs in the EMCS. After sufficient data are collected in the logs (as specified by the logging periods in the plan), they are analyzed, using a semi-automated spreadsheet tool and analysis guidelines, to gain insight into current operations and to detect problems with the building systems and their controls. The spreadsheet reads EMCS trend log files and automatically produces a set of plots that the re-tuning technicians are taught to use for detecting operational issues.

Analysis of EMCS Trend Log Data

Although most EMCSs can trend and export data to files, the formats of trend logs vary from one EMCS to another. There is no standard for such output, and each EMCS vendor exports the data in a different format. While some vendors provide multiple columns of data, each column for a

[¥] A sample monitoring plan for a building with variable-air-volume air-handling units with a central plant consisting of chillers and boilers can be found at http://buildingefficiency.labworks.org/media/large_building_trending_requirements_for_retuning.pdf.

separate variable, in a single file, others provide values for only one data point per file. Most vendors, however, provide some type of ASCII output, either space or comma delimited.

The spreadsheet developed for use in the project works with many formats but not all. In some cases, some pre-processing is necessary to prepare the inputs so they are compatible with the spreadsheet. The spreadsheet supports both the single-column and the multiple-column data formats, as long as the data columns are separated by commas. When the columns are space or tab delimited, the data can be pre-processed and converted to the compatible format by opening them in Microsoft Excel© and then saving the files in comma separated variable (csv) format.

The spreadsheet tool is tailored to analyze and produce graphs that provide information on the operations of air-handling units, zone variable-air-volume boxes, and chiller and boiler plant operations. As part of training, the service providers are taught how to process the data using the spreadsheet and, more importantly, how to interpret the graphs that the spreadsheet generates. The user enters basic information such as the names of files where the data can be found, the columns where the values of particular data points are located, and the starting row position of the data (see Figure A). Once all relevant information for the various data points is entered in the input sheet, the user clicks on the "Start Analysis" button to generate a set of plots automatically.

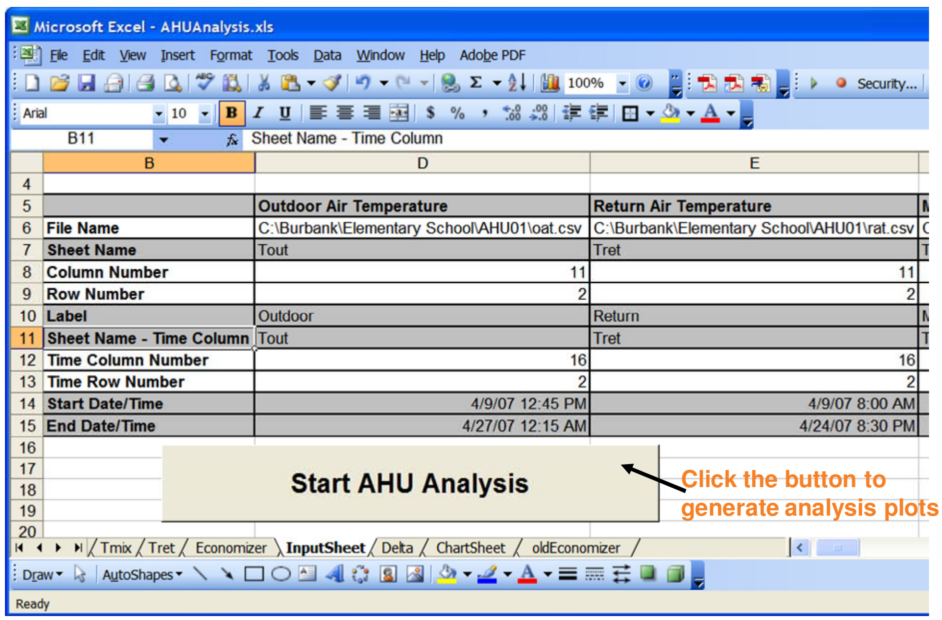

Figure A: Screenshot of the Spreadsheet Analysis Input

The plots can be reviewed visually to detect many common operational problems. Two example plots are shown in Figure B. The first plot (a) shows an improperly working economizer on an air-handling unit (AHU). The mixed-air temperature tracks the outdoor-air temperature, indicating that the outdoor-air damper is continuously fully open while the return-air damper is fully closed. The discharge-air temperature is always greater than the mixed-air temperature, indicating that that the unit is heating the mixed air more than necessary. By modulating the outdoor-air damper and enabling some of the return-air to be recirculated, the desired discharge-air temperature could be reached with no heating or cooling energy required. The second plot (b) shows properly operating chilled- and hot-water valve signals (no simultaneous heating and cooling). When the hot water valve signal is non-zero, the chilled water valve signal is zero and vice versa, as indicated by the data points on the two axes. Data points in the yellow region

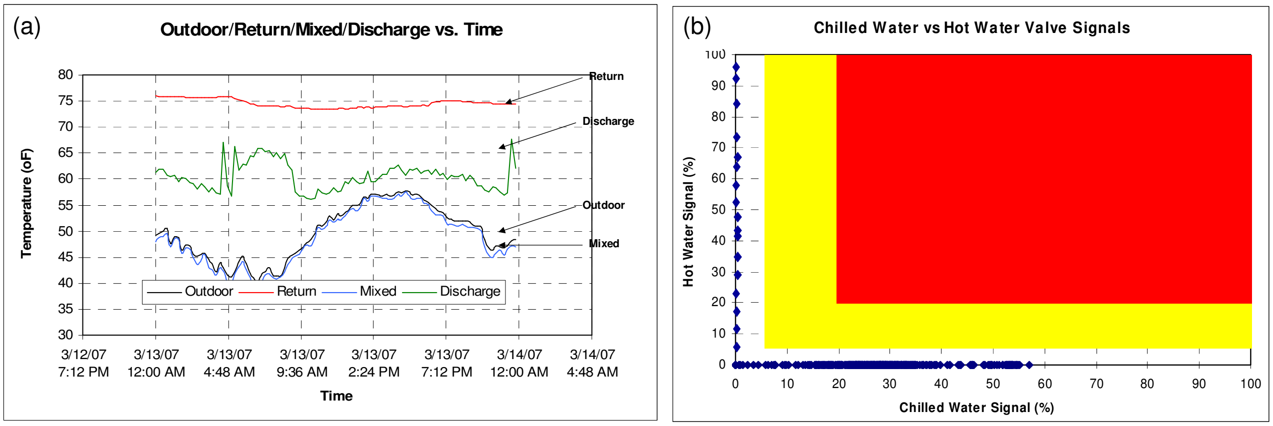

Figure B: (a) Improperly Operating Economizer and (b) Properly Operating Chilled- and Hot-Water Valves

would indicate poor valve operation causing simultaneous heating and cooling, while points in the red region would indicate even worse control.

Daily Tracking of Energy Savings: Model and Examples

O&M-based energy savings initiatives are gaining more momentum in the marketplace in large part because of the relative ease in implementing them and the commensurately lower cost. Many authors have extolled the virtues of techniques such as tune-ups, retro-commissioning, etc. These methods can yield extremely attractive paybacks (often 1 year or less). Unfortunately, they often suffer from a very practical problem — mainly, ensuring that the expected benefits are obtained and just as importantly, ensuring that the benefits persist over time. We describe below a modeling technique that is being successfully deployed by a variety of building owners, operators, and utilities to directly address the issues of measuring the savings of O&M-based efficiency improvements and also making it relatively easy to ensure that these savings persist over time.

Technical Approach

We have found the modeling methodology presented below (and commercialized by NorthWrite in their Energy Expert software application) to be effective in establishing performance baselines from which to measure energy savings associated with operational changes in buildings.[8] This method has the advantage that it can capture both linear and non-linear behavior. The method is based on the concept of data bins borrowed from the field of building energy data analysis. A bin is an interval (bin) of values of an independent variable with which a value of another (dependent) variable is associated. For example, the weather at a location can be characterized by the number of hours per year on average that the outdoor-air temperature falls into 5°F bins between some minimum temperature and some maximum temperature.

When multiple variables are used to explain the variations in energy use, multi-dimensional bins can be used where a multi-dimensional bin is defined as the intersection of one-dimensional bins based on each of the variables. This is shown in Figure C for three-dimensional bins that characterize a variable such as energy use in terms of three explanatory variables. A representative value of the dependent variable is assigned to each bin defined by the ranges of values of the independent variables. For an energy use model, the dependent variable is energy consumption.

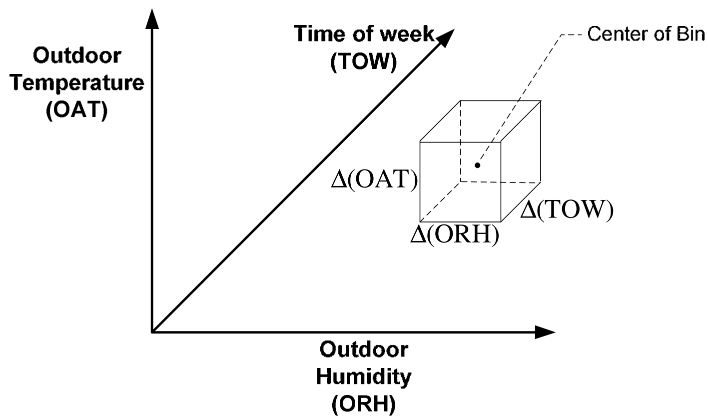

Figure C: An example three-dimensional binning scenario with bins defined by three explanatory variables: outdoor-air temperature, outdoor-air humidity, and time of week.

The model is "trained" by collecting data empirically and assigning it to bins. Given a sample of empirical data with each point of the sample consisting of values for a complete set of N independent explanatory variables (x_1, x_2, x_3, …, x_N) and the corresponding measured value of the dependent variable, an N-dimensional model is created by assigning each data point in the sample to the bin in which the point defined by the values of its independent variables lies. When a sufficient number of points have been assigned to each bin, the model is considered fully "trained." A representative value of the dependent variable is then assigned to each bin, completing the model. The median of the values of the dependent variable in the bin makes a good representative value for both large and small numbers of points per bin.

The user of this tool defines a "baseline" time period over which they wish to create a model predicting energy use. This baseline can be a period of time prior to retro-commissioning, a preceding year, or other time period of significance for a facility. By using the baseline model with values for the independent variables for times in the post-training period, predictions of what the energy use of the building would have been in the absence of degradation in efficiency or actions taken to improve energy efficiency can be obtained. By comparing the actual energy use to the predictions, energy waste associated with degradation or energy savings from improvements can be determined, while controlling for changes in the independent variables (e.g., outdoor-air temperature).

Examples

Below we provide several examples where facilities have implemented O&M-based energy savings programs and have used the Energy Expert to track their results. One of the analysis features that the Energy Expert provides is called "Cumulative Sum" (CUSUM). CUSUM is simply the integration of the daily differences between the actual and expected energy use for a modeled load. A positive slope on the CUSUM chart indicates that energy is being saved relative to the baseline. A negative slope is an indication of increased consumption relative to the baseline. The days over which the facility experiences the maximum possible positive slope can be considered a "best practice" period and can serve as a model for operating your facility.

The first example is of a large refrigerated distribution center. This building underwent a facility tune-up in which approximately 30 energy savings measures were identified as appropriate for the systems and operational needs of the facility. The site visit occurred in mid-October 2008 and approximately half of the measures were implemented while the technical team was onsite. Figure D indicates that the Energy Expert immediately starts indicating positive savings following the facility tune-up. These savings are relatively consistent for a period of several months. During this time, no additional changes were made to the facility. However, early in 2009, the remaining measures were implemented by the operations staff and the slope of the CUSUM line steepened (indicating a positive step-change in savings).

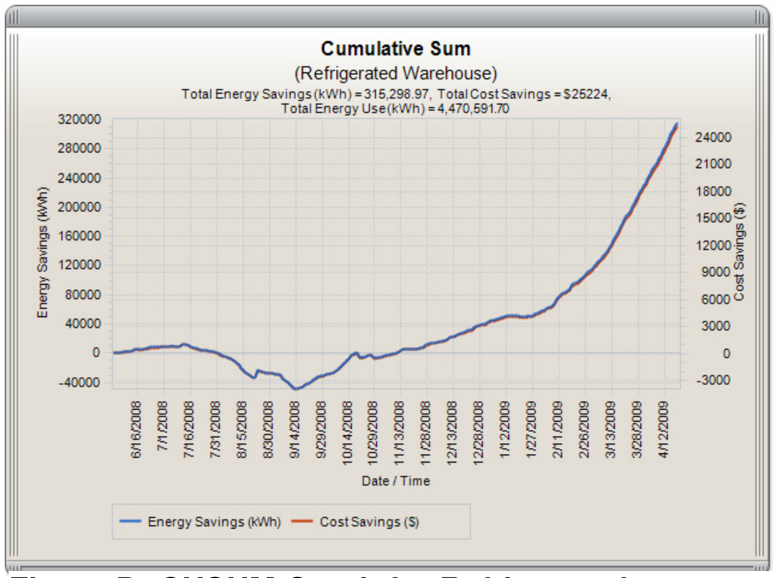

Figure D: CUSUM Graph for Refrigerated Distribution Center

Another way to see the implementation progress of an energy savings program is by viewing the daily results of the Energy Expert using the Calendar view. This feature enables you to view the days during the month where your facility uses more (red), less (blue), or about the same (green) amount of energy as the baseline.
Figure **E** shows a chronological progression for this distribution center from before the tune-up on the left, to after the tune-up on the right. The month in the middle shows the period of time in which the first phase of the tune-up occurred.

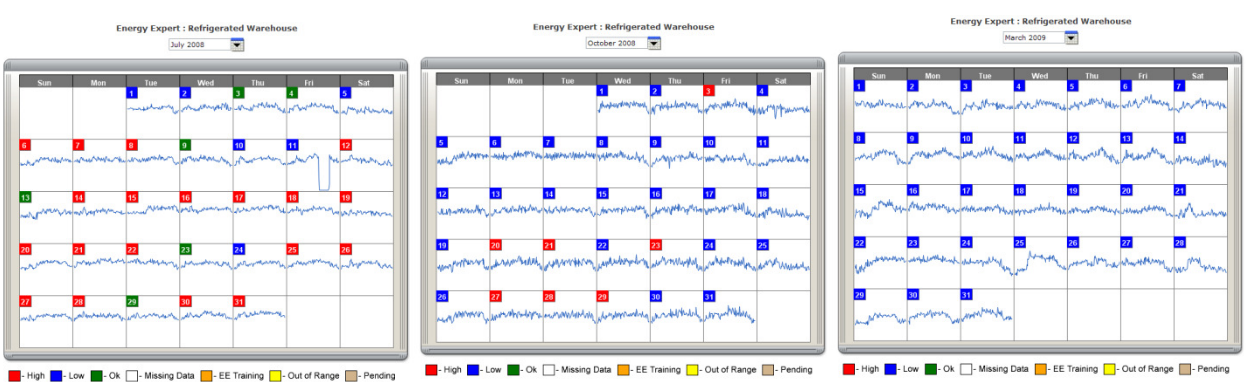

Figure E: Monthly Calendar View of Energy Expert Results

The next example (Figure F) is of a retail store that has been receiving significant energy savings as a result of implementing a number of changes to their building control system. However, in early April 2009, the controls vendor upgraded the software and overrode the tuning by resetting the set points and control strategies to an earlier version that had been archived. As a result, the store savings went from approximately $1,000 per month to $0 per month relative to the baseline (notice the decrease and overall flattening of the lines in Figure F after about April 5).

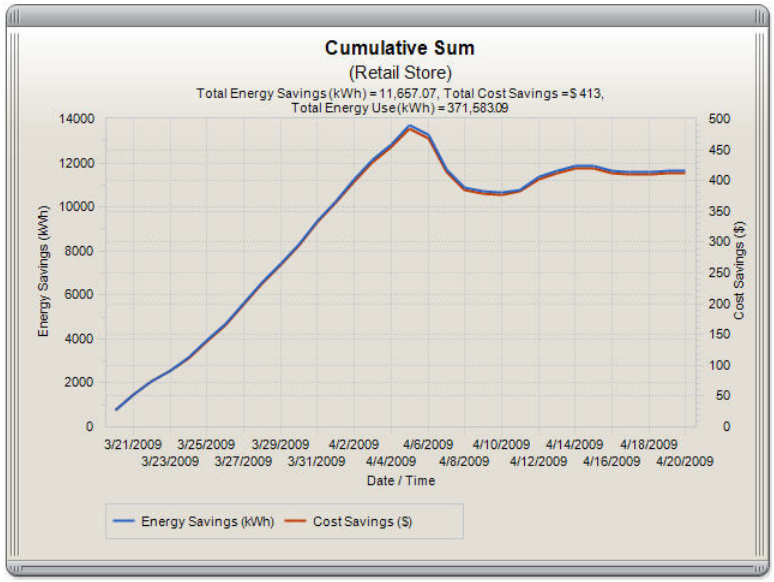

Figure F: CUSUM Graph for Retail Store

The Energy Expert provides two valuable services in this case. First, it notifies the operator that savings the building had been enjoying are no longer accruing. Second, it provides a clear and unambiguous benchmark for returning the facility to its energy saving state.

The final example is for a portfolio of nine office buildings (Figure G). Each building has an Energy Expert with a baseline set to the prior year (2008). The owners of the portfolio tasked the facility manager responsible for each building with "beating" their prior year energy use by as much as possible. The office buildings are between 75,000 and 150,000 ft^2. As you can see from the Enterprise Roll-Up Report below, all the buildings but one are making significant

Energy Expert Results for: Jan 1, 2009 - Apr 20, 2009

	High Demand	Actual Consumption	Expected Consumption	Consumption Δ	Savings ($)	Low	OK	High
Office Bldg. 1	120	178,573	287,911	109,338	8,747	110	0	0
Office Bldg. 2	206	265,015	321,088	56,073	4,486	100	6	4
Office Bldg. 3	770	777,083	860,868	83,785	6,703	73	12	24
Office Bldg. 4	331	376,728	419,051	42,324	3,386	89	13	8
Office Bldg. 5	323	251,769	303,499	51,730	4,138	105	5	0
Office Bldg. 6	294	418,752	454,795	36,043	2,883	86	15	9
Office Bldg. 7	169	280,683	317,090	36,407	2,913	109	1	0
Office Bldg. 8	801	1,083,433	1,023,492	-59,941	-4,795	34	13	63
Office Bldg. 9	303	434,943	477,023	42,081	3,366	79	22	9
Total		4,066,979	4,464,817	397,838	31,827	785	87	117

Figure G: Enterprise Roll-Up Report

progress towards their year-over-year energy savings goals. The owners know exactly which site(s) need more attention by simply scanning down the savings column.

These examples demonstrate how use of the models like the one in Energy Expert for monitoring can be used to quantify savings from re- and retro-commissioning and to detect when operation practices are implemented or faults occur that reduce or eliminate savings. When used on a continuous basis, such monitoring and diagnostic tools inform building management and operations staff, enabling them to maintain the persistence of savings over time.

Automated Diagnostic Tools for Commissioning Chillers and Packaged Units

Other automated fault detection and diagnostic (FDD) tools can be used to support re- and retro-commissioning of building equipment and systems. Using data available from a building automation system or from additional sensors installed specifically for this purpose, data can be provided to FDD tools. These tools can be used to identify operational faults that can often be corrected by changes to control parameters or control code, failed components that can be repaired or replaced, and equipment and systems with degraded performance, which generally require further diagnostics or troubleshooting to identify underlying root causes. Although these tools are commonly used to continuously monitor equipment and systems in real time during operation, many can be used to also process data offline. Both approaches can be used to inform re- and retro-commissioning of existing buildings. To support continued monitoring-based commissioning or condition-based maintenance, these tools should be set up to continually process real-time data feeds from a permanently-installed EMCS or separate data acquisition system. The information from these tools can be used to maintain systems and equipment in peak operating condition preserving the savings achieved from the initial commissioning. Brief descriptions of two examples of FDD tools that could be used to support MBCx follow.

The user interface of an automated centrifugal chiller diagnostician is shown in Figure H. Using data such as the condenser refrigerant pressure, the evaporator refrigerant pressure, the entering and leaving temperatures of the condenser water, and the entering and leaving temperatures of the chilled water, this diagnostician detects operation faults, e.g., condenser fouling, evaporator fouling, system overcharge or undercharge, and high or low condenser or evaporator flow rates.

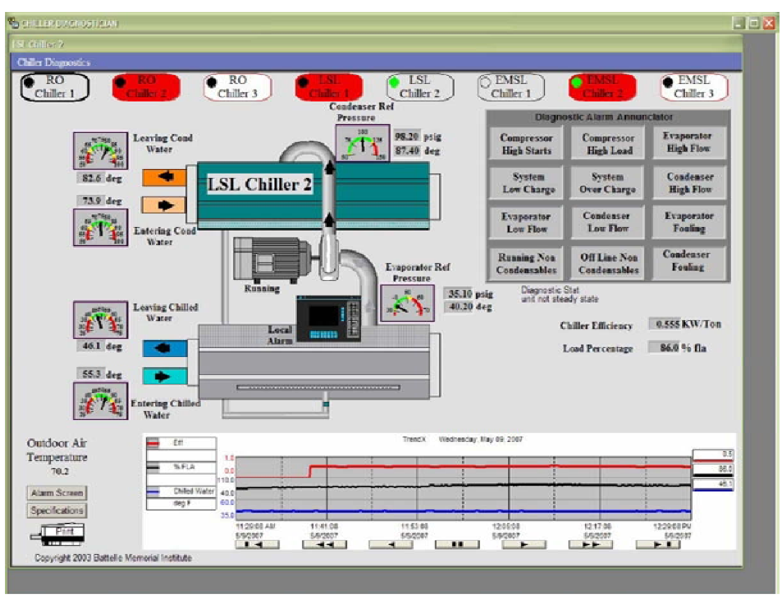

Figure H: User Interface of an Automated Centrifugal Chiller Diagnostician.

This diagnostician also tracks the chiller efficiency, providing the ability to detect and quantify degradation in efficiency over time. These are all capabilities that could be used during initial (monitoring-based) commissioning and continuously thereafter to identify operation and maintenance actions that could be taken to improve the system's operating efficiency. The benefit of such a diagnostic tool is that it automatically performs calculations often done manually offline by an analyst or not at all during retro-commissioning.

Another FDD tool currently under development and field testing is a Smart Monitoring and Diagnostic System (SMDS) for packaged air conditioners and heat pumps (see Figure I). This tool consists of a hardware package, installed on each packaged HVAC unit, and diagnostic software, which runs locally on the hardware. Diagnostic results and selected data are transmitted wirelessly to a network operations center, where these data are managed and results are made available to users via a web site. Authorized users access results regarding faults detected and changes in the coefficient of performance (COP) of the HVAC unit using a web browser; no installation of special software is required. The system can be used to detect hardware and operation faults during initial retro-commissioning and then over the life of the equipment to guide maintenance and provide information critical for maintaining the savings obtained from retro-commissioning, thus supporting the MBCx process.

(a) (b)

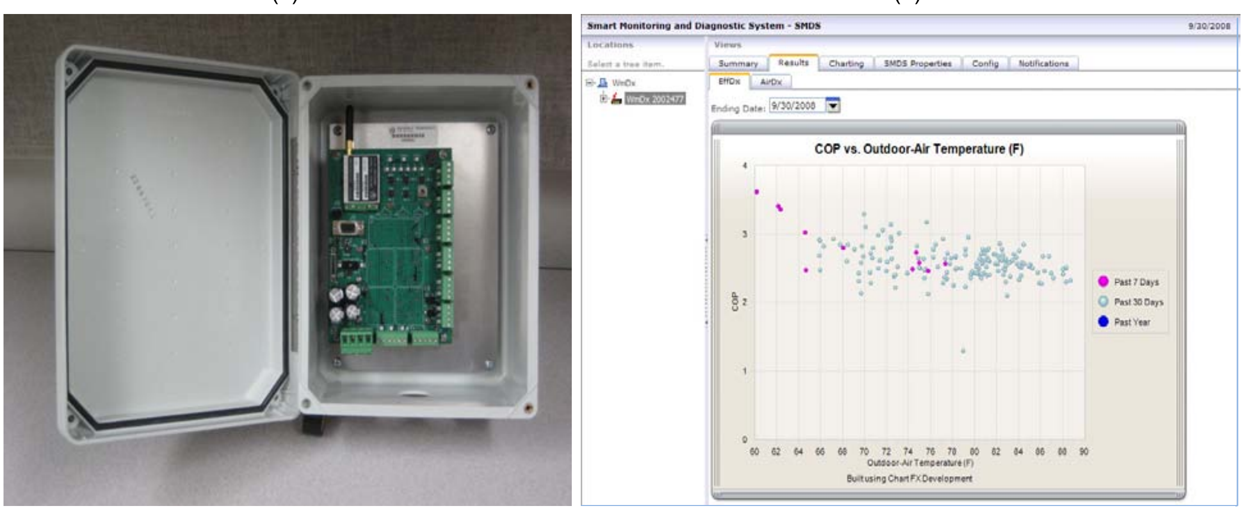

Figure I: SMDS (a) Hardware and (b) User Interface Window Showing Air-Conditioning COP Versus Outdoor-Air Temperature.

Several other diagnostic tools are available for use or are in various stages of development (see, for example, Friedman and Piette).[9] All of these could be used to enhance and streamline MBCx by automating the detection, diagnosis and quantification of impacts of operational faults in building systems and equipment.

Potential Impacts

Potential impacts of monitoring and diagnostic tools on re- and retro-commissioning include:

- time savings in collection and analysis of data compared to temporary monitoring using data loggers, manual performance of functional tests, and manual offline data analysis
- greater consistency across MBCx projects and potentially higher quality commissioning
- better detection of performance degradation and detection and diagnosis of faults, helping ensure the persistence of savings after initial commissioning.

Despite the benefits, use of these tools brings with it the cost of additional instrumentation to supplement the sensing provided by an existing EMCS. Such instrumentation may include end-use energy metering and sensors not part of the existing EMCS. Commissioning providers also require some time to learn to use the diagnostic tools, although many of the tools are user friendly and rather simple to use, possessing user interfaces that are easy to understand. Buildings without EMCS systems, which are generally smaller commercial buildings, would require the installation of sensing and data acquisition systems to provide the required data and are likely not candidates for MBCx. This problem is not unique, however, for MBCx. These same buildings are already not good candidates for retro-commissioning as conventionally done; new approaches for providing commissioning services to these small buildings are needed.

The examples provided in this paper illustrate how monitoring and diagnostic tools can be used to achieve these benefits and in some cases, the value associated with them (see, for example, Figure F). The re-tuning project described previously is collecting data to quantitatively evaluate the impacts of that monitoring-based process. At the time of writing this paper, those results were not yet available; they will be presented in future publications.

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