Performance Monitoring of Chilled-Water Distribution Systems Using HVAC-Cx

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ABSTRACT

In this research we develop, test, and demonstrate the newest extension of the software HVAC-Cx (NIST and CSTB 2014), an automated commissioning tool for detecting common mechanical faults and control errors in chilled-water distribution systems (loops). The commissioning process can improve occupant comfort, ensure the persistence of correct system operation, and reduce energy consumption. Automated tools support the process by decreasing the time and the skill level required to carry out necessary quality assurance measures, and as a result they enable more thorough testing of building heating, ventilating, and air-conditioning (HVAC) systems. This paper describes the algorithm, developed by National Institute of Standards and Technology (NIST), to analyze chilled-water loops and presents the results of a passive monitoring investigation using field data obtained from BACnet® (ASHRAE 2016) controllers and presents field validation of the findings. The tool was successful in detecting faults in system operation in its first field implementation supporting the investigation phase through performance monitoring. Its findings led to a full energy retrocommissioning of the field site.

INTRODUCTION

Building owners are gaining a better understanding of the benefits of building commissioning. Investing in the commissioning process1 can reduce life-cycle costs, decrease energy use, improve occupant comfort and productivity, and support cost-effective maintenance (Frank et al. 2007; Effinger et al. 2009; Friedman et al. 2012; Mills 2009; Winters 2014). It also forms a foundation for effective operation and maintenance (O&M), providing valuable feedback to the operator on an ongoing basis to maintain system performance, particularly in the case of ongoing commissioning. However, costs are still high and commissioning is not standard practice, with common exceptions for government buildings and schools. The buildings industry, including those involved in commissioning activities, recognizes the need for tools that can automate some of the labor-intensive steps in the commissioning process to detect and diagnose mechanical equipment faults (Heinemeier 2012; Milesi Ferretti et al. 2014). Commissioning tools for ongoing monitoring include model-based approaches (Kelso and Wright 2004; Haves and Khalsa 2000) and expert rules (Castro and Vaezi-Nejad 2009; Milesi Ferretti et al. 2015; Santos et al. 2014) or hybrid approaches (Canmet ENERGY 2009). One of the largest collections of tools was presented by the Energy in Buildings Program of the International Energy Agency (IEA), which published the results of Annex 47, Cost-Effective Commissioning for Existing and Low Energy Buildings (Neumann et al. 2010). These results include both commercialized tools as well as tools in development, such as the prototype for the software HVAC-Cx (NIST and CSTB 2014). These automated commissioning tools were developed to facilitate the commissioning process described by Legris et al. (2010) and enable the realization of the persistence of commissioning benefits. Case studies

1. Commissioning (Cx): Clarifying building system performance requirements set by the owner, auditing different judgments and actions by the commissioning related parties in order to realize the performance, writing necessary and sufficient documentation, and verifying that the system enables proper operation and maintenance through functional performance testing. Commissioning should be applied through the whole life of the building (IEA 2004).
showed an initial savings of 15% or better, based on the availability of operational and performance history. The capabilities of these commissioning tools have grown significantly as they scale up to meet the demands of networks of buildings. However, many tools are proprietary and information about their methodologies is limited (KGS Buildings 2014; Arney et al. 2003; Santos et al. 2014; CanmetENERGY 2009; Accenture 2011).

In 2015, ASHRAE published Guideline 0.2 on the existing building commissioning (EBCx) process used to optimize the operation of facilities and systems to meet the current facility requirements (ASHRAE 2015). The guideline builds on the quality principles of Guideline 0-2013, The Commissioning Process (ASHRAE 2013).

In 2013, National Institute of Standards and Technology (NIST) developed the first version of HVAC-Cx, a free, open-source tool that could be implemented by the commissioning team to facilitate the investigation phase of the EBCx process and be used by building operators on an on-going basis for performance monitoring. NIST and CSTB had conducted joint research as a part of IEA Annex 40 (IEA 2004) with the aim of providing a simple tool that could address an underserved segment of the building stock to improve the performance of mechanical systems. The tool validation is structured in three parts. In Part 1, the software was validated in a laboratory environment using the Virtual Cybernetic Building Testbed (Bushby et al. 2010; Milesi Ferretti et al. 2015). In Part 2, field validation of HVAC-Cx for the performance monitoring of a performing arts center, HVAC-Cx for chiller loops was evaluated for its ability to correctly identify faults in operations data that would be useful in the investigation phase. Part 3 is the energy retrocommissioning of the performing arts center using HVAC-Cx to support site investigation and testing in the investigation phase and to help verify achievement of the current facility requirements in the ongoing commissioning phase.

**HVAC-Cx**

The purpose of the HVAC-Cx tool is to facilitate the testing and analysis of mechanical systems in buildings (NIST and CSTB 2014). It is software that enables users to interact with both real-time and historical data from buildings with a BACnet® (ASHRAE 2016) enabled building automation system (BAS). Through HVAC-Cx, commissioning agents and building operators can monitor the performance of the systems in a building or set of buildings. Testing can be carried out by passive surveillance of system operation or, in the case of BACnet-enabled BAS, by active testing using customizable test scripts commanding the system into its various normal modes of operation and then applying expert rules that can detect improper system operation (Milesi Ferretti et al. 2015).

The analysis is performed by recording device data, including sensors, motors, dampers, alarms, and mode status from the BAS, and applying a set of logical expert rules to the data to identify operational faults. The logical rules are derived from determining expected values during modes of operation, from transcribing expectations outlined in the documented sequence of operations, and from recording fault reports and alarms from the devices themselves. When a rule condition has been met, a fault detection alarm is generated and potential causes of the fault are presented to the user for further diagnostic assistance. The comparison of values is performed on a minute-by-minute basis and examines the readings to determine the operational mode and applies rules that determine whether values are too far off set point or if there is inconsistency with the mode of operation. A diagnostic report is prepared and shown via a graphical user interface (GUI) in HVAC-Cx. This report shows the faults that occur in a minute, in an hour, and on average over a day. The graphical capabilities of HVAC-Cx provide the user with the ability to look at data to provide further insight. The detection and diagnostic methodology was originally developed for application to single-duct variable-air-volume (VAV) and constant-volume air-handling units (AHUs) (Schein et al. 2006).

In 2015, a new set of expert rules was developed to assess the performance of chiller loops using data from existing sensors in the BAS. The extent of the chiller loop performance assessment is generally limited by the availability of design data (e.g., control requirements and sequencing strategy) and operational data including set point values, sensor measurements, and control signals. Typical commercial-grade sensors installed for control purposes have sufficient accuracy to conduct the performance assessment. HVAC-Cx provides a set of rules that can be applied along with the ability to create custom rules. Once configured, users can easily look at historical data for relevant values or apply rules to that historical data.

The 71 chiller loop rules fall into four categories: parametric values, temperature relationships, control logic, and potential safety concerns. The first eight rules are parametric checks of the plant chilled-water and building chilled-water supply and return temperatures. They compare the minute data to the acceptable range of values that were configured for the system. Rules 9 to 19 are based on the expected temperature relationships that must be maintained during normal operation. When these relationships are violated, the system is not operating as intended. Rules 20 to 62 screen for logic faults by comparing the actual operation of valves and pumps against the sequence of operations outlined in the control documentation. These would typically be introduced as custom rules. Finally, Rules 63 to 71 monitor the BAS for reported equipment faults and alarms. Table 1 presents the nomenclature used in the chiller loop rules. Table 2 shows a representative

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2 Certain commercial equipment, instruments, and materials are identified in this paper. Such identification is not intended to imply recommendation or endorsement by National Institute of Standards and Technology (NIST), nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.
Table 1. Nomenclature Used in the Chilled-Water Loop Rules

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{wcps}$</td>
<td>Plant chilled-water supply temperature</td>
</tr>
<tr>
<td>$T_{wcp}$</td>
<td>Plant chilled-water return temperature</td>
</tr>
<tr>
<td>$T_{wcps,min}$</td>
<td>Specified minimum plant chilled-water supply temperature</td>
</tr>
<tr>
<td>$T_{wcps,max}$</td>
<td>Specified maximum plant chilled-water supply temperature</td>
</tr>
<tr>
<td>$T_{wcb}$</td>
<td>Building chilled-water supply temperature</td>
</tr>
<tr>
<td>$T_{wcb}$</td>
<td>Building chilled-water return temperature</td>
</tr>
<tr>
<td>$T_{wcb,min}$</td>
<td>Specified minimum building chilled-water supply temperature</td>
</tr>
<tr>
<td>$T_{wcb,max}$</td>
<td>Specified maximum building chilled-water supply temperature</td>
</tr>
<tr>
<td>$T_{wcb,s}$</td>
<td>Building chilled-water supply temperature set point</td>
</tr>
<tr>
<td>$\Delta P_{wp}$</td>
<td>Plant differential water pressure</td>
</tr>
<tr>
<td>$\Delta P_{wb}$</td>
<td>Building differential water pressure</td>
</tr>
<tr>
<td>$\Delta P_{wb,sp}$</td>
<td>Building differential water pressure set point</td>
</tr>
<tr>
<td>$\Delta P_{wb,min}$</td>
<td>Building differential water pressure, minimum</td>
</tr>
<tr>
<td>$\Delta P_{wb,max}$</td>
<td>Building differential water pressure, maximum</td>
</tr>
<tr>
<td>$U_{CBFX}$</td>
<td>Control signal to chilled-water pump $X$ (1-3)</td>
</tr>
<tr>
<td>$U_{1X}$</td>
<td>Control signal to chilled-water valve $X$ (1-5)</td>
</tr>
<tr>
<td>$OpModeX$</td>
<td>Chiller operational mode $X$ (1-4)</td>
</tr>
<tr>
<td>PumpEnable</td>
<td>Building pump enabled ($0 = off, 1 = on$)</td>
</tr>
<tr>
<td>FaultVFDX</td>
<td>Chilled-water pump $X$ (1-3) variable frequency drive (VFD) fault indicated ($0 = fault free, 1 = fault$)</td>
</tr>
<tr>
<td>AlarmPumpX</td>
<td>Pump $X$ (1-3) indicates alarm ($0 = no alarm, 1 = alarm$)</td>
</tr>
<tr>
<td>FaultChiller</td>
<td>Chiller indicates unspecified fault ($0 = fault free, 1 = fault$)</td>
</tr>
<tr>
<td>$\varepsilon_p$</td>
<td>Threshold parameter for the pump control signal</td>
</tr>
<tr>
<td>$\varepsilon_t$</td>
<td>Threshold for errors in temperature measurements</td>
</tr>
</tbody>
</table>

Table 2. Representative Selection of Chilled-Water Loop Rules

<table>
<thead>
<tr>
<th>Rule</th>
<th>Formula</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>$T_{wcps} &gt; T_{wcps,max} + \varepsilon_t$</td>
<td>If the plant chilled-water supply temperature is greater than the specified maximum value, then the system is operating outside of the allowable range.</td>
</tr>
<tr>
<td>6</td>
<td>$T_{wcb} &gt; T_{wcb,sp} + \varepsilon_t$</td>
<td>If the building chilled-water supply temperature is greater than the specified maximum value, then the system is operating outside of the allowable range.</td>
</tr>
<tr>
<td>9</td>
<td>$T_{wcp} &lt; T_{wcb} - \varepsilon_t$</td>
<td>If the plant chilled-water return temperature is less than the building chilled-water return temperature, then there is an inconsistency in the temperature measurements.</td>
</tr>
<tr>
<td>10</td>
<td>For Mode==2a, $\text{abs}(T_{wcb} - T_{wcb,sp}) &gt; \varepsilon_t$</td>
<td>In Mode 2a, if the building chilled-water supply temperature is significantly different than the plant chilled-water supply temperature, then there is an inconsistency in the temperature measurements.</td>
</tr>
<tr>
<td>12</td>
<td>$T_{wcb} &gt; T_{wcb,sp} + \varepsilon_{t,s}$</td>
<td>If the building chilled-water supply temperature is significantly greater than its set point, then there is a temperature sensing fault or control fault.</td>
</tr>
<tr>
<td>13</td>
<td>$T_{wcb} &lt; T_{wcb,sp} - \varepsilon_{t,s}$</td>
<td>If the building chilled-water supply temperature is significantly less than its set point, then there is a temperature sensing fault or control fault.</td>
</tr>
<tr>
<td>18</td>
<td>$\Delta P_{b} &lt; \Delta P_{b,sp} - \varepsilon_p$</td>
<td>If the building differential pressure in the chilled-water loop is less than its set point, there is a pressure sensing fault or control fault.</td>
</tr>
<tr>
<td>49</td>
<td>For Mode==3b, $U_{v2}=1$</td>
<td>In Mode 3b, if valve 2 is open, then there is a logic fault.</td>
</tr>
<tr>
<td>50</td>
<td>For Mode==3b, $U_{v3}=0$</td>
<td>In Mode 3b, if valve 3 is closed, then there is a logic fault.</td>
</tr>
<tr>
<td>71</td>
<td>FaultChiller = 1</td>
<td>If the air-cooled chiller is indicating a fault status, then there is a potential safety concern.</td>
</tr>
</tbody>
</table>
sample of these rules, listing the rule number, the formula or condition that triggers a rule violation, and a description of the rule condition.

HVAC-Cx provides the results of the analysis through a GUI. Figures 1 through 3 present screenshots from the software tool. Figure 1 summarizes the number of faults found. The calendar block on the right displays the faults detected in the month of July 2015. Each day has a number displayed that indicates the number of different faults identified that day. If the number exceeds four faults, the day is highlighted in red. If it has one to four faults, it is highlighted in yellow. If no faults are detected, it is highlighted in green. If no data are available for the day, the block remains gray. The top of the calendar block also lists the total number of faults, and a button to the right of that total will generate a report of the faults detected for the full month. Results from multiple components can be displayed for the same month, but multiple months cannot be displayed at once.

From this high-level diagnostic report, individual days may be selected and the fault occurrences are broken down by the hour. Hovering over one of the hours reveals the faults that occurred and a list of possible reasons they might have occurred. Figure 2 illustrates this.

In Figure 2, the y-axis displays the number of faults identified over the period, with each vertical fault bar indicating the results for one hour of data. There are two rows of numbered boxes under the yellow bars; the first row has a white background and shows the hour of the day, the second row has a gray background and indicates the mode in which the system is operating. Hovering the computer mouse over one of the vertical fault bars causes a pop-up window (the white box in the upper left of Figure 2) to appear with a list of the identified faults and associated fault causes. Multiple occurrences of the same fault are registered once in the summary table. In this case, it identifies three faults that occurred in the one-day period as well as five potential causes.

Figure 3 presents the tool’s capability to display relevant sensor data and control signals in a graphical manner to assist operators in reviewing the system data. The y-axis shows the temperature in degrees Celsius. Checking the “Cmd Graphs” (command graphing) box (in the lower right section of Figure 3) will display the values of the corresponding control signals and adds a y-axis on the right side of the chart.

These graphs, which can represent both chiller loops and AHUs, are an effective way of diagnosing the system performance of the component for as long as data have been recorded. With the knowledge that systems are not performing according to their documentation or are acting abnormally, an operator may choose to conduct a commissioning test on the component or system rather than wait for a regularly scheduled EBCx test or be prompted by a complaint about comfort or more significant issues.

INVESTIGATION REPORT

The field site is a community college located in Rockville, Maryland. The building undergoing retrocommissioning is a performing arts center (PAC) with one large auditorium, a lobby area, a dressing area, a green room, an administrative office, a shop area, and two mechanical rooms. There are two floors plus a partial basement. In 2008, a mechanical and electrical systems replacement project was carried out, but no formal commissioning process was performed at that time (Greenman-Pedersen 2008). The project included replacement of

- all AHUs and exhaust fans;
- the existing chiller and cooling tower (replaced by an air-cooled chiller), chilled-water and heating-water pumps, and the provision of a new chilled-water line that interfaces to the campus central plant loop;
- the fire detection/alarm system and sprinkler system;
- interior and exterior lighting (except theatrical lighting); and
- installation of a new BAS with occupancy scheduling capabilities for the equipment.

Chilled-Water System Design Description

The Rockville Campus Central Plant provides chilled water to the PAC. Chilled water is generally available from May to September at a design temperature range of 3.3°C to 5°C (38°F to 41°F) with a temperature differential of 8.3°C (15°F) across the building inlet and outlet. The chilled-water central plant makes ice at night and melts it from noon to 8:00 p.m. to supplement the central plant chiller. Figure 4 shows the schematic diagram of the chilled-water loop for the PAC building, with connections to and from the central plant shown on the left side. An air-cooled chiller is used to supplement additional cooling loads. When a call for cooling is received, the building chiller system maintains its discharge temperature (shown in Figure 4 as New CHWS Temperature) at a set point selected by the building operator in the range of 5°C to 7.2°C (41°F to 45°F) and the chilled-water pump activates by hardware interlock from the chiller.
Figure 2  HVAC-Cx daily summary identifying the mode of operation for each hour, faults detected, and potential causes.

Figure 3  Graphical capabilities of HVAC-Cx showing system temperatures over a 24-hour period.
The chilled-water control sequence is as follows. A hand-operated position switch is provided to select plant pump or building pump operation. A four-position, hand-operated mode switch activates the modes and the position information is signaled back to the BAS. Table 3 lists the six possible modes of operation and the corresponding valve (V) and pump sequences. For Modes 2 and 3, the \textit{a} designation indicates that the plant pump is used, whereas the \textit{b} designation indicates that the building pump is used. The list of modes is as follows:

- **Mode 1**: the system is off and all valves and pumps are closed.
- **Mode 2**: the central plant cools the building. This mode was intended as the normal operating mode to leverage the more efficient central plant chiller capabilities.
- **Mode 3**: the air-cooled, 105 ton (371 kW) chiller both cools the building and feeds the distribution. This mode is intended for use when the central plant is producing ice, and the building chiller can provide supplemental cooling to the campus loop.
- **Mode 4**: the chiller exclusively cools the building. This last mode is intended for use when there is no access to the plant loop and there is limited load in the building that can be directly met by the chiller.

### Table 3. The Valve and Pump Sequencing for Chilled Water from Design Documents (Prichett Controls 2008)

<table>
<thead>
<tr>
<th>Mode</th>
<th>V-1</th>
<th>V-2</th>
<th>V-3</th>
<th>V-4</th>
<th>V-5</th>
<th>Chiller Pump</th>
<th>Building Pump</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Off</td>
<td>Off</td>
</tr>
<tr>
<td>2a</td>
<td>Modulates</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Open</td>
<td>Off</td>
<td>Off</td>
</tr>
<tr>
<td>2b</td>
<td>Modulates</td>
<td>Closed</td>
<td>Closed</td>
<td>Open</td>
<td>Closed</td>
<td>Off</td>
<td>On</td>
</tr>
<tr>
<td>3a</td>
<td>Open</td>
<td>Closed</td>
<td>Open</td>
<td>Closed</td>
<td>Open</td>
<td>On</td>
<td>Off</td>
</tr>
<tr>
<td>3b</td>
<td>Open</td>
<td>Closed</td>
<td>Open</td>
<td>Open</td>
<td>Closed</td>
<td>On</td>
<td>On</td>
</tr>
<tr>
<td>4</td>
<td>Closed</td>
<td>Open</td>
<td>Closed</td>
<td>Open</td>
<td>Closed</td>
<td>On</td>
<td>On</td>
</tr>
</tbody>
</table>

The flow diagram for building chilled water (Prichett Controls 2008).

**Testing Plan and Implementation**

The goal of the EBCx project was to monitor system performance, identifying issues and opportunities for improvements to comfort, equipment reliability, and energy savings, and the campus facilities manager provided valuable support to NIST in carrying out the investigation using HVAC-Cx. The project began with an initial site visit to discuss the performance monitoring software tool and to establish data collection. Data were collected from the chiller loop that serves the PAC every minute in July and August 2015 during the cooling season. Data were collected from the BACnet-enabled controllers.
In total, five weeks of passively collected cooling-season data were analyzed, enabling the evaluation of system operation under normal conditions. These data provided a baseline of faults identified by HVAC-Cx. Information gathered at the field site was used to corroborate or dismiss findings, and the visual inspection results also added to the list of findings. Any quick fixes were implemented and documented. The following findings and recommended measures were presented to the facility manager, together with the results of an additional week of performance monitoring that was used to evaluate the implemented changes.

FINDINGS AND RECOMMENDATIONS

Eight findings and recommendations are made for the system/equipment under evaluation. Figure 5 presents the fault summary for the months of July 2015 and August 2015. Figure 2 presents a sample fault summary from July 17, which shows that three faults were triggered at different times in the day, and Figure 3 shows the corresponding temperature graphs during that period, which were used to aid in diagnosis.

Finding 1: Chilled-Water Loop Unable to Maintain Setpoint

Analysis using HVAC-Cx indicated that the chilled-water loop is unable to maintain set point consistently. Rule 12 indicates that $T_{wchbs}$, the building chilled-water supply temperature, is below the acceptable limits for 15 of the 19 days of data in July and every day in the month of August. Similarly, Rule 13 indicates that the $T_{wchbs}$ is above the acceptable limits and the fault was triggered on 10 of the 19 days of data in July and 8 days in the month of August. The temperature threshold for triggering a fault, $\varepsilon_f$, was conservatively set at 4°C (39.2°F). In both rule violations, the diagnostic report indicates a possible control logic error or a temperature sensor error. HVAC-Cx also reported a violation of Rule 6, which indicates that the $T_{wchbs}$ sensor is out of range.

When $T_{wchbs}$ rises significantly above $T_{wchbs,sp}$, it causes instability in the AHUs, which rely on chilled water to meet the cooling demands of the conditioned spaces. This fault can have a direct impact on the comfort of occupants and generate comfort complaints. Addressing comfort complaints is one of the primary goals of the commissioning project. When $T_{wchbs}$ falls significantly below $T_{wchbs,sp}$, it may cause instability in the control of the AHUs. When this occurred during the day in Mode 3, the chiller was effectively precooling the campus loop, which is not cost-effective. Additionally, in the case of a severe temperature drop, it may raise the risk of freezing the coil, which in turn would activate a defrost action. This represents a needless energy cost.

Recommendation 1

Evaluate the building chilled-water supply temperature, $T_{wchbs}$, sensor and investigate the appropriateness of the building operator’s mode selection as the first check of the control logic.

Finding 2: Continuous Operation in Mode 3b

The BAS indicates that the chiller was operating in Mode 3b continuously. In this mode, the chiller is operating to provide cooling for the building and the campus loop, and both the chiller pump and the building pump are activated. The discharge set point was fixed at 7.22°C (45°F). In July, when operating in Mode 3b, the building should be meeting its cooling load with the dedicated chiller and provide supplementary cooling to the central plant loop. Instead, the chiller is unable to meet the cooling load to bring down the temperature to its normal set point.

The facility manager reported that from May to September the building chiller was intended to be used as a backup to ensure that the building cooling load is met in the evening while the central chilling loop is making ice. In reality, the building was operating continuously in Mode 3b.

Recommendation 2

Immediately change the operating mode to Mode 4, which shifts the control of the chiller to be dedicated to meeting the building load only and to investigate the reason that the system is not operating directly off the campus loop in Mode 2a or 2b.

It was later found that the strainers had not been cleared of clay that had contaminated the system during a line repair, fouling the coils and inhibiting the necessary flow rate for proper heat transfer. As a result, building operators reduced the chiller set point temperature to maintain the loop at 3.3°C (38°F) to cool the building and eventually moved to a 24-hour operation since response times were so slow.

Finding 3: Improper Valve Control

Analysis of the valve and pump status by HVAC-Cx had a violation of Rules 49 and 50, which indicate that Valves 2 and 3, respectively, are operating out of sequence. Specifically, the shaded valve positions in Table 4 are reversed for the Mode 3b data, with V-2 open and V-3 closed. These states are in direct conflict with the design documentation and the as-built docu-
mentation provided by the controls contractor. On the field visit, it was confirmed that the error exists in the documentation rather than in the control logic implementation.

**Recommendation 3**

Update the system documentation and make the corresponding correction in the HVAC-Cx rule list.

**Finding 4: Plant Chilled-Water Supply Temperature Out of Range**

The plant chilled-water supply temperature, $T_{wcp}$, was consistently reading approximately 21°C (69.8°F), as is shown in Figures 3 and 6. The $x$-axis shows the 24-hour period and the left $y$-axis shows the temperature value in degrees Celsius. HVAC-Cx Rule 5 was violated, indicating that the temperature reading was above its expected range. This temperature is too high to meet the supply temperature requirements of the PAC building. Using HVAC-Cx graphs, it is evident that the building supply and return temperatures, $T_{wcb}$ and $T_{wcr}$, are tracking the same temperature fluctuations exhibited by the plant supply temperature, $T_{wcp}$, but the magnitude is not reasonable. During the field visit, the BAS sensor reading was approximately 21°C (70°F), while a different analog temperature sensor indicated the temperature to be approximately 7.2°C (45°F), which was confirmed by the maintenance staff to be consistent with the campus loop temperatures at that time. Building energy use was not impacted, as the sensor reading displayed using the BAS is not an input into the control sequence for activating the building chiller.

**Recommendation 4**

Check plant supply temperature, $T_{wcp}$, sensor for proper calibration and replace if necessary.

<table>
<thead>
<tr>
<th>Mode</th>
<th>V-1</th>
<th>V-2</th>
<th>V-3</th>
<th>V-4</th>
<th>V-5</th>
<th>Chiller Pump</th>
<th>Building Pump</th>
</tr>
</thead>
<tbody>
<tr>
<td>3a</td>
<td>Open</td>
<td>Closed</td>
<td>Open</td>
<td>Closed</td>
<td>Open</td>
<td>On</td>
<td>Off</td>
</tr>
<tr>
<td>3b</td>
<td>Open</td>
<td>Closed</td>
<td>Open</td>
<td>Closed</td>
<td>Closed</td>
<td>On</td>
<td>On</td>
</tr>
</tbody>
</table>

**Table 4. Valve and Pump Sequencing Inconsistency in Chilled-Water Loop**

**Figure 6**  Graphical capabilities of HVAC-Cx showing system temperatures (solid lines) and command signals (dashed lines). The plant chilled-water supply temperature is labeled as 4.
Finding 5: Persistent Chiller Fault Alarm

The BAS has a BACnet object for the chiller that reports its fault status. Although the determination of the fault status is independent of the HVAC-Cx expert rule algorithm, the data point is monitored in HVAC-Cx by Rule 71, which when violated informs the operator that the alarm has been registered. In the data analyzed, the BAS constantly reported that the air-cooled chiller was in alarm. The maintenance staff confirmed the value in the controller but, due to a lack of documentation and or training with the building control system, no diagnosis was possible.

Recommendation 5

Contact the control system installer for information on the setting for the chiller fault to diagnose the source of the alarm.

Finding 6: Sensor Calibration Needed

Several temperature and pressure sensors need recalibration or replacement. Seven years have passed since the sensors were installed and the general reliability of several sensors is in question. The field visit also exposed several analog temperature sensors that were broken, including that of the chiller supply water temperature, and several analog pressure gauges where the needle shows that the gauge has failed, possibly due to overpressurization.

Recommendation 6

Test and recalibrate or replace all HVAC sensors and replace the analog sensors on key components to aid building operators in maintaining awareness of the system operation. This is a valuable investment because without reliable operational data the control system cannot meet comfort requirements and the building staff is restricted in its efforts to maintain good system operation.

Finding 7: As-Built Documentation Errors

The building chilled-water flow diagram shown in Figure 4 shows the location of the plant chilled-water supply temperature, $T_{wcps}$, sensor being downstream of the building chiller. However, the temperature logs show a significant temperature drop between the chiller and the building, $T_{wcps}$ and $T_{wchs}$. This evaluation was made using the graphical displays in HVAC-Cx. The sensor location was confirmed to be located before the chiller.

Recommendation 7

Update the as-built documentation.

Additional Findings and Recommendations

HVAC-Cx was used to analyze one week of operating data in Mode 4. In Figure 5, a significant increase in the number of faults occurs with the mode change on August 27th. The data shows that all of the faults existing before the mode change were resolved, with the exception of Fault 12, indicating that $T_{wchs}$ fell below $T_{wchs,sp}$ on many occasions and that $T_{wchbr}$ was measured as falling below the expected minimum value from time to time.

A formal EBCx process is recommended for this building and its interaction with the campus loop. Active test sequences using HVAC-Cx were designed to exercise system operation. This included testing operation under each of the possible modes of operation, many of which were not found in the performance monitoring data. Researchers discussed the general test plan with the commissioning agent and designed an approach to determine a representative series for the various modes of operation. However, the reliability of the sensors and valve actuators for a number of different systems are problematic. It is important that the function of the individual components be verified prior to conducting functional performance testing.

The following four items document findings related to systems/equipment that are outside the scope of the chiller loop analysis:

- Simultaneous heating and cooling was observed in AHU-1a, AHU-1b, and AHU-4b, and the fan belt on AHU-4b appeared in need of adjustment.
- The rolling access door to the shop area remained fully opened for several hours during the site visit. The loss of conditioned air was notable.
- The exterior lighting was off schedule and operating in full daylight conditions.
- Physical access to the air-cooled chiller was not secured.

CONCLUSION

The objective of this study was to evaluate the field performance of the chiller loop analysis portion of HVAC-Cx, an automated commissioning tool. The tool was evaluated using field data from a building that is located on a community college campus in Rockville, Maryland. Data were collected for four weeks in July and August of 2015 under typical operation for the building.

HVAC-Cx found several faults through ongoing monitoring, but a limitation to this approach is that the evaluation is dependent on the seasonal weather fluctuations and the system response to capture a variety of operating modes. Performance monitoring detected faults in two of the four operating modes. By looking at historical data and by performing active testing, researchers will be able to evaluate system operations in a more complete and systematic manner.

These tests using passive surveillance indicate that HVAC-Cx can successfully detect common HVAC faults using field data. Performance would likely improve by expanding the rule base to capture those faults that were manually detected using HVAC-Cx graphing capabilities. The tool presently has capabilities for performance monitoring and active testing of AHUs and chiller loops and exceeds the capabilities of existing BAS alarms by providing a simple user interface to create custom rules and look at historical data for.
relevant values. The field study was a success; the findings from the performance monitoring identified several important performance improvement measures and were the basis for the facility manager to initiate a full energy retrocommissioning project at the field site using HVAC-Cx to support site investigation and testing in the investigation phase.

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REFERENCES


ASHRAE. 2015. ASHRAE Guideline 0.2-2015, Commissioning process for existing systems and assemblies. Atlanta: ASHRAE.


CanmetENERGY. 2009. Le Palais des Congrès de Montréal: A more intelligent and efficient building because of DABO. Ottawa, Ontario, Canada: Natural Resources Canada, CanmetENERGY.


Greenman-Pedersen. 2008. As-built documentation for Parilla Performing Arts Center mechanical and electrical systems replacement project. Issue 3, CDD-2, 05/07/08.


NIST and CSTB. 2014. HVAC-Cx, ver. 2. National Institute of Standards and Technology (NIST), Gaithersburg, MD; and Centre Scientifique et Technique du Bâtiment (Scientific and Technical Center for Building) (CSTB), Champs-sur-Marne, France. http://www.nist.gov/services-resources/software.


