

NIST Technical Note 1924

Evaluating the Initial Field Performance of HVAC-Cx for Air-Handling Units

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This publication is available free of charge from:
<http://dx.doi.org/10.6028/NIST.TN.1924>

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August 2016



U.S. Department of Commerce
Penny Pritzker, Secretary

National Institute of Standards and Technology
Willie May, Under Secretary of Commerce for Standards and Technology and Director

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National Institute of Standards and Technology Technical Note 1924
Natl. Inst. Stand. Technol. Tech. Note 1924, 14 pages (August 2016)
CODEN: NTNOEF

This publication is available free of charge from:
<http://dx.doi.org/10.6028/NIST.TN.1924>

Abstract

Automated commissioning tools facilitate the ongoing commissioning process to improve occupant comfort, ensure the persistence of correct system operation, and reduce energy consumption. These tools decrease 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. The purpose of the research effort described in this paper is to develop, test and demonstrate an automated commissioning tool that detects common mechanical faults and control errors in air handling units (AHU's). This paper presents the HVAC-Cx software, a tool developed by the U.S. National Institute of Standards and Technology (NIST). It utilizes actual air-handling unit data obtained from a building automation system and analyzes the data for proper operation by comparing the actual performance of the installed system against a set of expert rules for the system. This paper examined the effectiveness of the tool in detecting faults and documents the results from the first field application to air-handling units.

Keywords: automated commissioning, HVAC-Cx air-handling units, expert rules, fault detection

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1. Introduction

Building commissioning¹ (Cx) is a process designed to verify that the building meets the owner's needs and operates efficiently. Investing in building commissioning can reduce lifecycle costs, decrease energy use, improve occupant comfort and productivity, and support cost-effective maintenance [1-5]. It ensures that the building is operating as intended at handover and also ensures that documentation is complete and that operators are well trained, a necessary foundation for effective operations and maintenance (O&M). In the buildings industry, there is a need for tools that can automate the labor intensive commissioning process, specifically to detect and diagnose mechanical equipment faults [6, 7]. The aim is to obtain proper performance across the building stock and to improve commissioning service quality and establish consistency.

Ongoing commissioning provides valuable feedback to the operator on an ongoing basis to maintain system performance. Software tools can assist operators in the ongoing evaluation of building systems, combining fault detection and diagnostic capabilities with expert knowledge of the strategies for operating equipment in a way that can help determine whether the equipment is performing correctly. Tools can be implemented to support both ongoing monitoring and active testing. Ongoing monitoring involves evaluating systems over a wide range of normal operating conditions. Active testing involves presenting commands to invoke a certain mode of operation and evaluating the system's response to confirm that the response is appropriate [8]. By applying expert rules to evaluate data from the building automation system, building operators have a good mechanism for feedback on the performance of operations, independent of comfort complaints and service issues. Improving the quality and the efficiency of commissioning also enables more thorough testing of building HVAC systems.

NIST has developed HVAC-Cx, a free, open-source commissioning tool to facilitate on-going commissioning of small commercial buildings having a building automation system [9]. It applies an expert rule analysis to evaluate system performance as a tool for commissioning agents and building operators. The tool validation is structured in three phases. In Phase 1, the software was validated in a laboratory environment using the Virtual Cybernetic Building Testbed [10, 11]. In Phase 2, the subject of this report, the objective was to evaluate the field performance of HVAC-Cx for air-handling units. The analysis was limited to the ongoing monitoring or passive surveillance of a field system over a one-month period in a community college. The performance of HVAC-Cx is evaluated for its ability to correctly identify faults and significant attention is paid to false alarms that can erode user confidence in the tool. The third phase will focus on active testing, including pre-functional testing and functional performance testing in a retro-commissioning project.

2. HVAC-Cx

The purpose of the HVAC-Cx tool is to facilitate the testing and analysis of HVAC systems. The tool has a graphical user interface that enables the commissioning agent or building operator to monitor the performance of the air handling units (AHUs) in a building or set of buildings. Testing can be carried out by passive surveillance of system operation or, in the case of BACnet building automation systems (BAS), active testing by using

¹ ASHRAE defines commissioning as 'A quality-focused process for enhancing the delivery of a project. The process focuses upon verifying and documenting that the facility and all of its systems and assemblies are planned, designed, installed, tested, operated, and maintained to meet the owner's project requirements'. See http://wiki.ashrae.org/index.php/Commissioning_process

customizable test scripts commanding the system into its various normal modes of operation and then applying expert rules that are capable of detecting improper system operation [9]. The tool enables users to interact with historical building data and real-time data from BACnet systems.

The basis for the fault detection analysis used by HVAC-Cx in this study is the AHU Performance Assessment Rules (APAR), a set of expert rules designed to assess the performance of AHUs using data from existing sensors in the BAS [12-14]. The APAR rules are briefly described in Table 2 using the nomenclature presented in Table 1. The extent of the AHU performance assessment is generally limited by the availability of design data (e.g., ventilation requirements and sequencing strategy), and basic system metrics such as operational data including occupancy information, setpoint values, sensor measurements, and control signals. Typical commercial grade sensors installed for control purposes have sufficient accuracy to conduct this study; laboratory grade instruments are not required.

Table 1. Nomenclature used in the APAR rules

MT_{max}	maximum number of mode changes per hour
T_{co}	changeover air temperature for switching between Modes 3 and 4
T_{ma}	mixed air temperature
T_{oa}	outdoor air temperature
T_{ra}	return air temperature
T_{sa}	supply air temperature
$T_{sa,s}$	supply air temperature set point
ΔT_{min}	threshold on the minimum temperature difference between the return and outdoor air
ΔT_{rf}	temperature rise across the return fan
ΔT_{sf}	temperature rise across the supply fan
Q_{oa}/Q_{sa}	outdoor air fraction = $(T_{ma} - T_{ra}) / (T_{oa} - T_{ra})$
$(Q_{oa}/Q_{sa})_{min}$	threshold on the minimum outdoor air fraction
u_{cc}	normalized cooling coil valve control signal [0,1], where $u_{cc} = 0$ indicates the valve is closed and $u_{cc} = 1$ indicates it is 100 % open
u_d	normalized mixing box damper control signal [0,1], where $u_d = 0$ indicates the outdoor air damper is closed and $u_d = 1$ indicates it is 100 % open
u_{hc}	normalized heating coil valve control signal [0,1], where $u_{hc} = 0$ indicates the valve is closed and $u_{hc} = 1$ indicates it is 100 % open
Greek Symbols	
ε_{cc}	threshold parameter for the cooling coil valve control signal
ε_d	threshold parameter for the mixing box damper control signal
ε_f	threshold parameter accounting for errors related to airflows (function of uncertainties in temperature measurements)
ε_{hc}	threshold parameter for the heating coil valve control signal
ε_t	threshold for errors in temperature measurements

Table 2. APAR Rule Set [14]

Mode	Rule #	Rule Expression (true implies existence of a fault)
Heating (Mode 1)	1	$T_{sa} < T_{ma} + \Delta T_{sf} - \epsilon_t$
	2	For $ T_{ra} - T_{oa} \geq \Delta T_{min}$: $ Q_{oa}/Q_{sa} - (Q_{oa}/Q_{sa})_{min} > \epsilon_f$
	3	$ u_{hc} - 1 \leq \epsilon_{hc}$ and $T_{sa,s} - T_{sa} \geq \epsilon_t$
	4	$ u_{hc} - 1 \leq \epsilon_{hc}$
Cooling with Outdoor Air (Mode 2)	5	$T_{oa} > T_{sa,s} - \Delta T_{sf} + \epsilon_t$
	6	$T_{sa} > T_{ra} - \Delta T_{rf} + \epsilon_t$
	7	$ T_{sa} - \Delta T_{sf} - T_{ma} > \epsilon_t$
Mechanical Cooling with 100 % Outdoor Air (Mode 3)	8	$T_{oa} < T_{sa,s} - \Delta T_{sf} - \epsilon_t$
	9	$T_{oa} > T_{co} + \epsilon_t$
	10	$ T_{oa} - T_{ma} > \epsilon_t$
	11	$T_{sa} > T_{ma} + \Delta T_{sf} + \epsilon_t$
	12	$T_{sa} > T_{ra} - \Delta T_{rf} + \epsilon_t$
	13	$ u_{cc} - 1 \leq \epsilon_{cc}$ and $T_{sa} - T_{sa,s} \geq \epsilon_t$
	14	$ u_{cc} - 1 \leq \epsilon_{cc}$
Mechanical Cooling with Minimum Outdoor Air (Mode 4)	15	$T_{oa} < T_{co} - \epsilon_t$
	16	$T_{sa} > T_{ma} + \Delta T_{sf} + \epsilon_t$
	17	$T_{sa} > T_{ra} - \Delta T_{rf} + \epsilon_t$
	18	For $ T_{ra} - T_{oa} \geq \Delta T_{min}$: $ Q_{oa}/Q_{sa} - (Q_{oa}/Q_{sa})_{min} > \epsilon_f$
	19	$ u_{cc} - 1 \leq \epsilon_{cc}$ and $T_{sa} - T_{sa,s} \geq \epsilon_t$
	20	$ u_{cc} - 1 \leq \epsilon_{cc}$
Unknown Occupied Modes (Mode 5)	21	$u_{cc} > \epsilon_{cc}$ and $u_{hc} > \epsilon_{hc}$ and $\epsilon_d < u_d < 1 - \epsilon_d$
	22	$u_{hc} > \epsilon_{hc}$ and $u_{cc} > \epsilon_{cc}$
	23	$u_{hc} > \epsilon_{hc}$ and $u_d > \epsilon_d$
	24	$\epsilon_d < u_d < 1 - \epsilon_d$ and $u_{cc} > \epsilon_{cc}$
All Occupied Modes (Modes 1,2,3,4,5)	25	$ T_{sa} - T_{sa,s} > \epsilon_t$
	26	$T_{ma} < \min(T_{ra}, T_{oa}) - \epsilon_t$
	27	$T_{ma} > \max(T_{ra}, T_{oa}) + \epsilon_t$
	28	Number of mode transitions per hour $> MT_{max}$

HVAC-Cx helps the user to detect and to diagnose AHU faults; when a rule condition has been met, a fault has been detected and suggestions for the cause of the fault are presented to the user in a hierarchical way for further diagnostic assistance. The detection and diagnostic methodology was developed for application to single-duct, variable air volume (VAV) and constant volume AHUs. There are four modes of operation defined by the APAR rules: heating (Mode 1), free cooling with mixed outdoor air (Mode 2), mechanical cooling with 100 % outdoor air (Mode 3), and mechanical cooling with minimum outdoor air (Mode 4). Rules pertaining to each of these predefined modes, listed in Table 2, are evaluated once the system data is categorized based on its control actions and space conditions.

HVAC-Cx provides the results of the analysis through a graphical user interface. Figures 1 through 3 present screenshots from the software tool. Figure 1 summarizes the number of faults found. The two calendar blocks on the right display the faults detected in the month of March 2014. Each day has a number displayed that indicates the number of

individual 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. 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 over the full month.

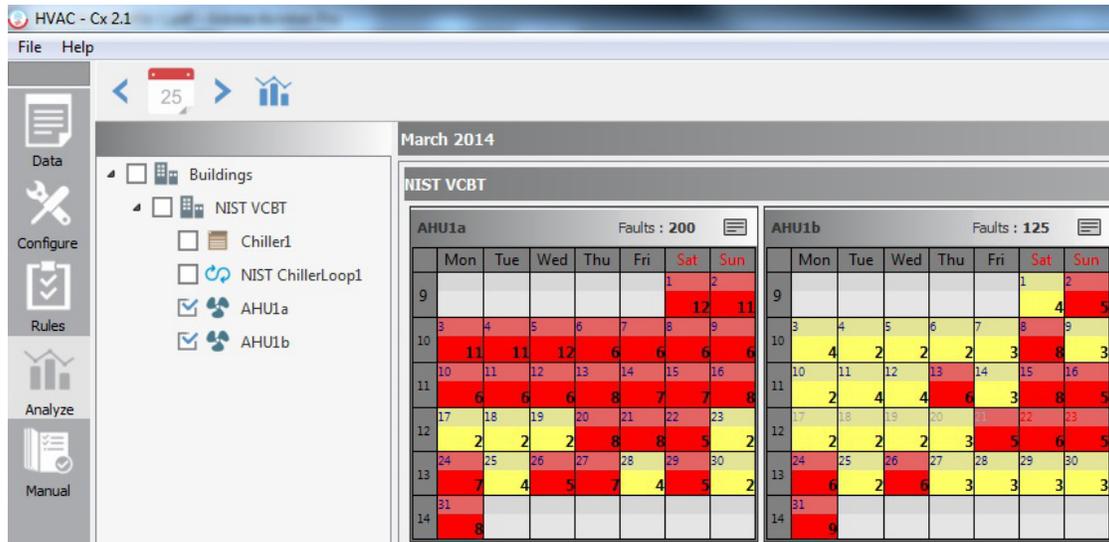


Figure 1. HVAC-Cx high-level summary of the number of faults detected.

Figure 2 presents the results summary for one hour for where the y-axis displays the number of faults identified over the period. Each bar indicates the results for one minute of data. The colored cells under the yellow fault bars indicate the mode in which the system is operating. Red and white diagonal stripes indicate heating mode (Mode 1), blue and white vertical stripes indicate cooling with outdoor air (Mode 2), and the purple and white horizontal stripes indicate mechanical cooling with minimum outdoor air (Mode 4). By hovering the computer mouse over one of the yellow, vertical fault bars, a pop-up window appears with details on the faults identified and associated fault causes.

Figure 3 presents the tool's capability to display relevant sensor data including commands in a graphical manner to assist operators in reviewing the system data. The x-axis is the number of minutes past the beginning of the hour. The y-axis on the left shows the temperature, and the y-axis on the right shows the control signals.

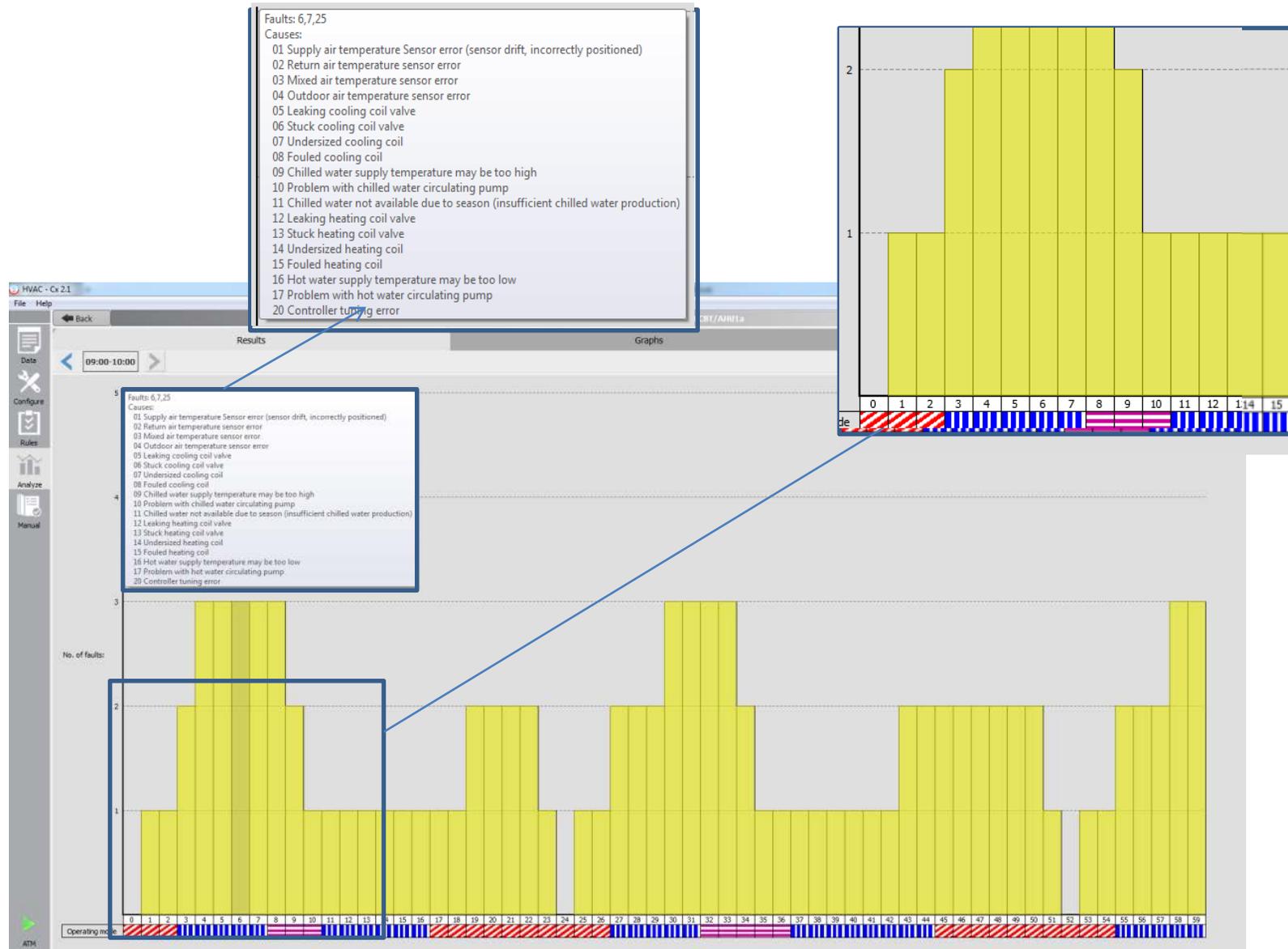


Figure 2. HVAC-Cx daily summary identifying mode of operation for each hour, faults detected and potential causes.

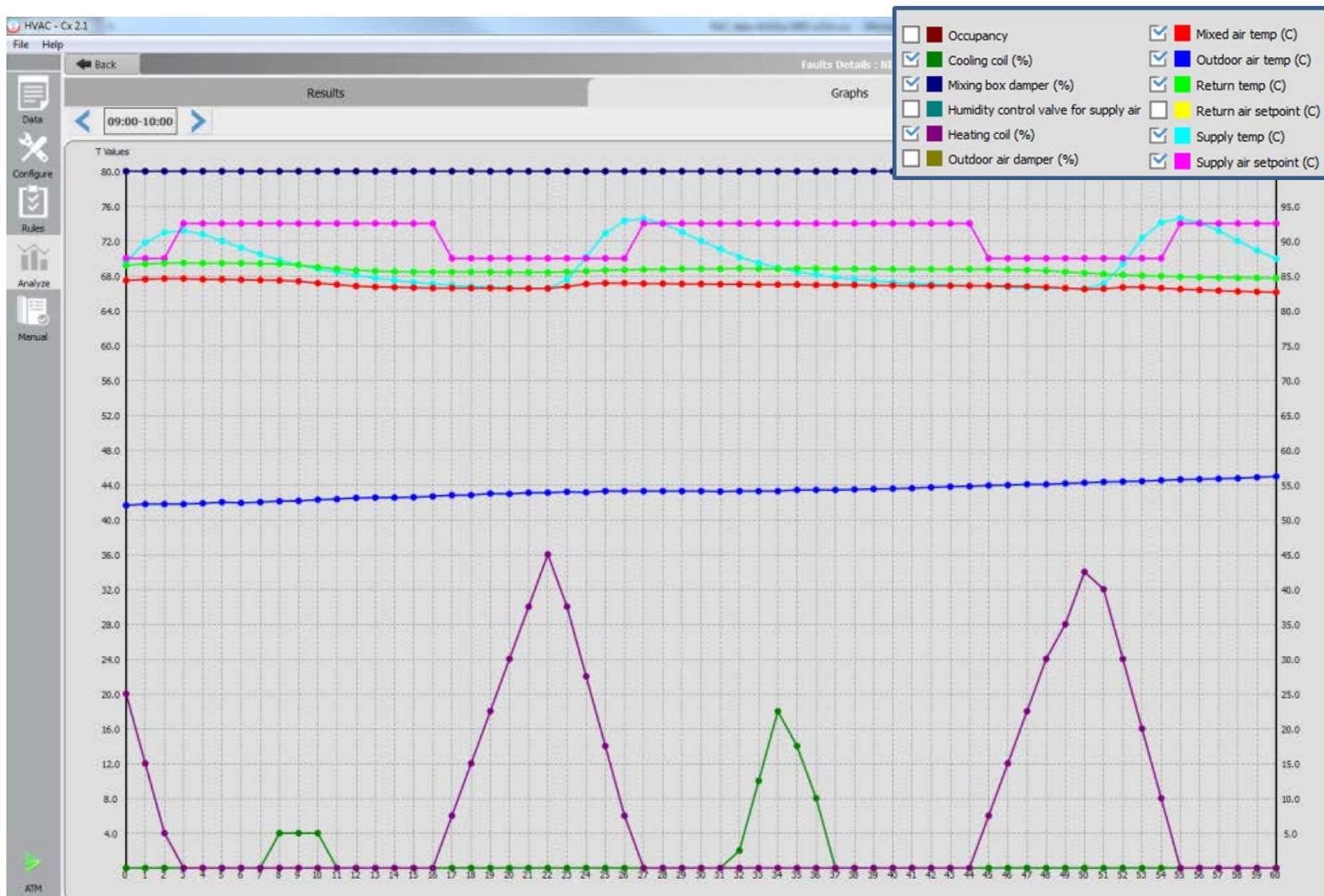


Figure 3. Graphical capabilities of HVAC-Cx showing system temperatures and command signals.

3. HVAC System Description

The field site is a community college campus located in Rockville, Maryland. Data were collected from two air-handling units that serve a performing arts center. Data was collected every 10 s from March 1, 2014 to April 30, 2014 by facility personnel and made available to the researchers. It was originally intended that the data would be obtained using the university’s advanced control system, which would allow the researchers to remotely access the equipment controllers via the Internet. Due to time and personnel constraints, it was not possible to establish this mode of data collection. Instead, researchers installed the BACnet Data Source a data collection software tool to collect data from the BACnet controllers [15,16].

The variable-air-volume AHUs (AHU-1A and AHU-1B) were identical and were configured with enthalpy-based economizers. The AHUs serve an auditorium, operating 24 hours per day, seven days per week without occupancy-based scheduling. Figure 4 shows the flow diagram for AHU-1A.

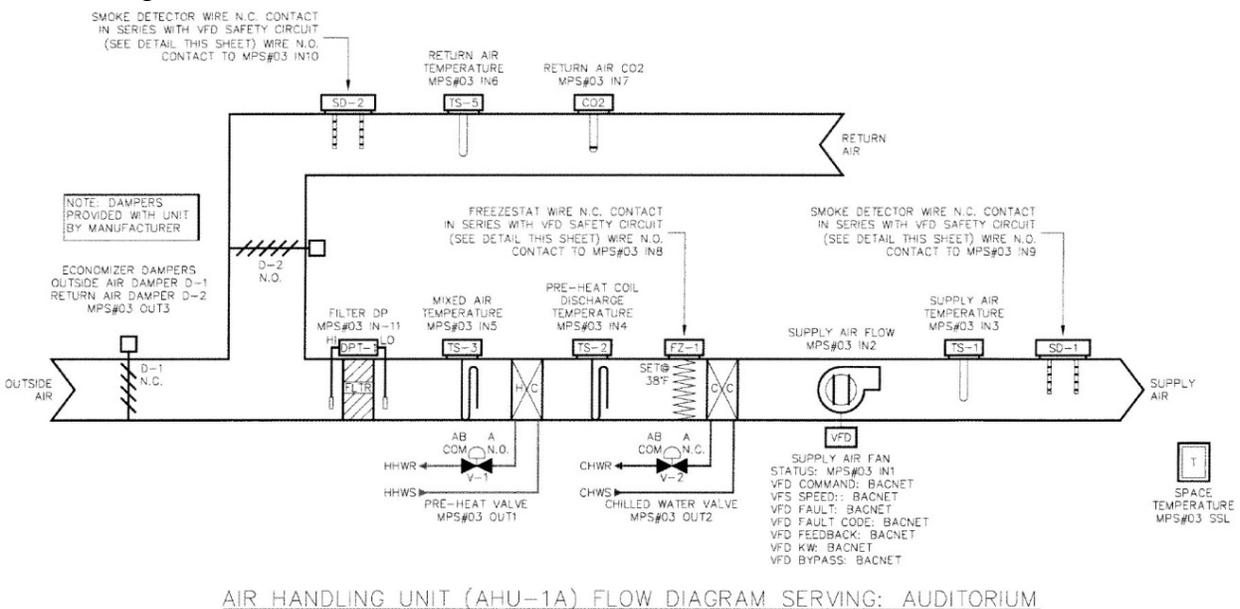


Figure 4. The flow diagram for AHU-1A.

The sequence of operations programmed in the AHU controller specifies that the system maintain the supply air temperature (TS-1) downstream of the supply air fan at a setpoint temperature of 20.5 °C (69 °F). Beginning from the left side of Figure 4, unconditioned outside air enters the AHU and mixes with the air returned from the auditorium. The outside air fraction is controlled by the position of the outside air damper and the return air damper, which are enthalpy-based economizing dampers controlled to make use of favorable outdoor air conditions (an outdoor enthalpy below 29.5 kJ (28 Btu) and outdoor air temperature at least 1.1 °C (2°F) below the return air temperature). The minimum outdoor air damper position is 10 % open to maintain minimum ventilation requirements and will be increased if the return air CO₂ levels exceed 1440 mg/m³ (800 ppm). A mixed air temperature low limit will prevent mixed air dropping below 7.2 °C (45 °F). The mixed air is filtered before passing over the heating coil and the cooling coil where the air temperature may be adjusted to meet the desired setpoint temperature. The supply fan runs continuously during occupied periods and the

control sequence modulates the output of the variable frequency drive to maintain the calculated cooling standard cubic feet per minute (SCFM) supply air setpoint airflow. Depending on the call for cooling, the values are reset between the minimum 0.92 m³/s (1950 SCFM) and maximum 2.6 m³/s (5480 SCFM) design values.

4. Air-handling Unit Commissioning Analysis Results

The results of the data analyses for the two AHUs are presented in this section. One month of data in the swing season was analyzed for each air-handling unit. This enabled the evaluation of system operation under a variety of modes. Figure 1 shows the results summary for the evaluation period.

4.1. AHU-1A Commissioning Report

AHU-1A triggered a total of 200 faults in March 2014. A review of the first two weeks of operating data showed that HVAC-Cx detected an average of eight faults per day. A high number of faults were detected in the first five days, over ten faults per day. During the first five days, the system was primarily in heating mode as the outdoor air temperatures were low, approximately -6.6 °C (20 °F), and the return air temperature, 16.1 °C (61 °F), was well below the supply air temperature setpoint, 20.5 °C (69 °F). The supply air temperature spiked out of control as the heating coil tried to provide sufficient heat to meet the setpoint temperature. The system exhibited temperature sensor faults as the mixing box temperature did not correspond with the thermal balance of the mixing box conditions. In analyzing the month of data, HVAC-Cx detected temperature inconsistencies, improper economizing, and not meeting comfort requirements.

AHU-1A temperature inconsistencies. The system was cycling between heating mode (Mode 1) and mechanical cooling with 100 % outdoor air (Mode 3). The corresponding faults triggered during these periods included inconsistencies in heating mode when the temperature of the supply air was not greater than that of the mixed air (Rule 1) and inconsistencies in cooling mode when the supply air temperature exceeded the return air temperature (Rule 12). The HVAC-Cx diagnosis is a supply air temperature sensor error.

AHU-1A control error, improper economizing. During the initial two-week period, HVAC-Cx also identified a fault when the outdoor air fraction was above the minimum ventilation requirements, when the outdoor temperature was approximately -6.1 °C (21 °F). The HVAC-Cx diagnosis is a control logic error that effected the economizer operation.

AHU-1A comfort requirements. The system was consistently unable to maintain the supply temperature setpoint (Rule 25). There were also multiple periods when the heating coil or cooling coil were at 100 % open and the setpoint temperature was still not being met. This performance fault was likely a result of the supply air temperature sensor error that was reading low, and the economizing fault that resulted in over-ventilating the system with outdoor air.

Figure 5 shows one hour of operation where the heating coil signal is under-damped and the heating coil is cycling. The supply temperature fluctuates between 14.4 °C and 23.3 °C (58 °F and 74 °F). Upon further analysis using HVAC-Cx graphing capabilities, it was evident that the system was experiencing a major system fault. It was only through a comparison of the variable frequency drive (VFD) speed and the corresponding power consumption that it became evident that there was a fan failure. Although the VFD setpoint was ramping up to meet the setpoint airflow, the power consumption of the drive was zero. This finding provides

a lesson for identifying additional rules that can be implemented to improve the capabilities of HVAC-Cx to detect this fault.

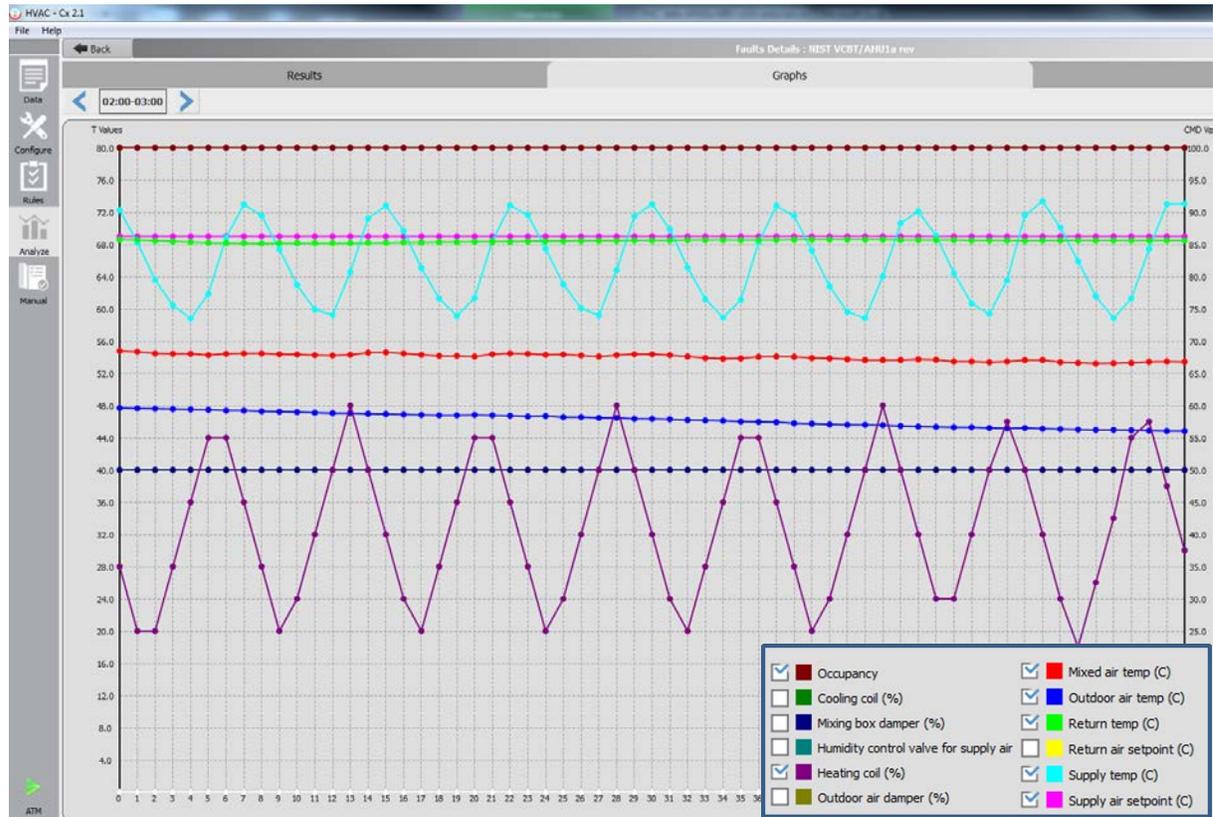


Figure 5. HVAC-Cx graphical display of AHU1a temperature instability over a one-hour period.

The system operated for five days without the proper airflow until the power to the drive was restored. Subsequently, the system operated in heating mode with the outdoor air damper at 50 % open with outdoor conditions that required minimum outdoor air, triggering alarms as HVAC-Cx detected that the system setpoint temperature was not being met (Rule 25) and that the outdoor air fraction was inappropriate for the weather conditions (Rule 2). This HVAC-Cx diagnosis indicates a control error of the mixing box subsystem.

During the second two-week period, the system control continued to exhibit improper use of the economizer function. The outdoor air damper was consistently 50 % open during periods where the system was in heating mode and the outdoor air temperature was too cold for economizing (Rule 2). Additionally, the supply air temperature was cycling between 14.4 °C and 22.2 °C (58 °F and 72 °F), indicating that the system was unable to maintain the setpoint of 20.5 °C (69 °F) while the heating coil was fully open (Rules 3 and 5).

Finally, there were periods when the building operators would reduce the fan drive output to a maximum of 25 % for noise control. Figure 3 shows the temperature and control signals for a one hour period under reduced fan output. Figure 2 shows the HVAC-Cx fault analysis for that same period. The system had a total of nine mode transitions during that one-hour

period, which was determined by HVAC-Cx to be an excessive number of mode changes in a one-hour period, indicating controller logic/tuning errors (Rule 28).

4.2. AHU-1B Commissioning Report

AHU-1B triggered a total of 125 faults in March 2014. The system had an average of four faults per day. Most days exhibited two faults that indicated that the system was not consistently maintaining setpoint, and that the cooling coil was 100 % open, an indication that the system may be out of control. There were additionally several periods where the number of faults increased to more than four faults per day. These were generally periods where the system was operating in an unknown mode, with the economizer modulating while the cooling coil or heating coil was active. HVAC-Cx detected the following fault conditions:

AHU-1B minimum ventilation requirements. For the first ten days in March, the outdoor air damper was fixed at 0 % open, violating minimum ventilation requirements for occupied periods. A new rule to detect this condition was added to the APAR rule set. Because the rule was added after the analysis, HVAC-Cx made no diagnosis on the initial fault. However, the graphing capabilities made it evident to the user that the outside air damper was at 0 % open. The anticipated diagnosis for future users would be one of a stuck damper or other fault related to the improper operation of the mixing box subsystem.

AHU-1B control error, improper cooling coil valve control. During a period when the AHU operated in mechanical cooling with minimum outdoor air, when the supply air temperature (light blue line on graph) was more than 1.1 °C (2 °F) cooler than the control setpoint (pink line on graph), the cooling coil (dark green line on graph) was approximately 100 % open, as seen in Figure 6. This was a violation of Rule 20 which indicates that the system may not be functioning properly. The diagnosis is one of improper control of the cooling coil valve and may be a secondary effect of a cooling coil discharge temperature sensor fault.

AHU-1B temperature inconsistencies. Figure 6 also shows temperature inconsistencies. Since the outdoor air damper position is at 0 %, it is anticipated that the 100 % return air would be conditioned exclusively by the cooling coil. However, two faults were identified: the supply air temperature is warmer than the return air temperature (Rule 16) and the supply air temperature is warmer than the mixed air temperature (Rule 17). This conflicts with the physical models of HVAC-Cx that describe the thermal behavior of the system, even when accounting for expected temperature increases across the fan.

The HVAC-Cx diagnosis indicates a temperature sensor fault and by reviewing the graphs that show the temperature changes over time, it is believed that the return air temperature sensor error may be likely.

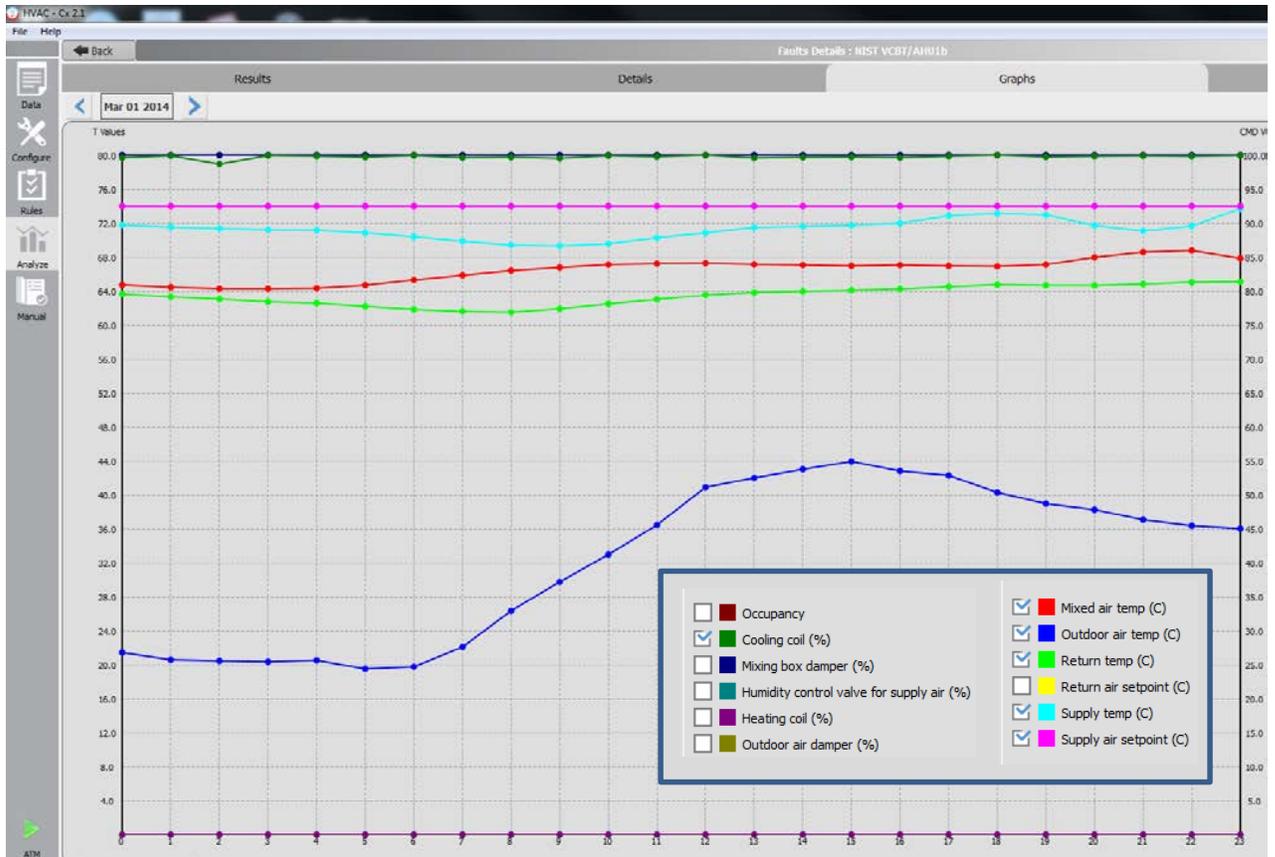


Figure 6. HVAC-Cx graphical display of AHU1b temperature inconsistencies over a 17-hour period.

AHU-1B control error, improper economizing. During this initial two-week period, HVAC-Cx identified several periods of unknown occupied mode operation (Mode 5). An example is shown in Figure 7. The system was not able to maintain the supply air temperature setpoint (Rule 25), and the system was exhibiting improper system control (Rule 21). The control rule was violated when HVAC-Cx detected that the cooling coil was modulating (shown in dark green on the graph) at the same time that the dampers were modulating (shown in dark yellow at 50 % open for most of the day). This control fault conflicts with the design sequence of operations.

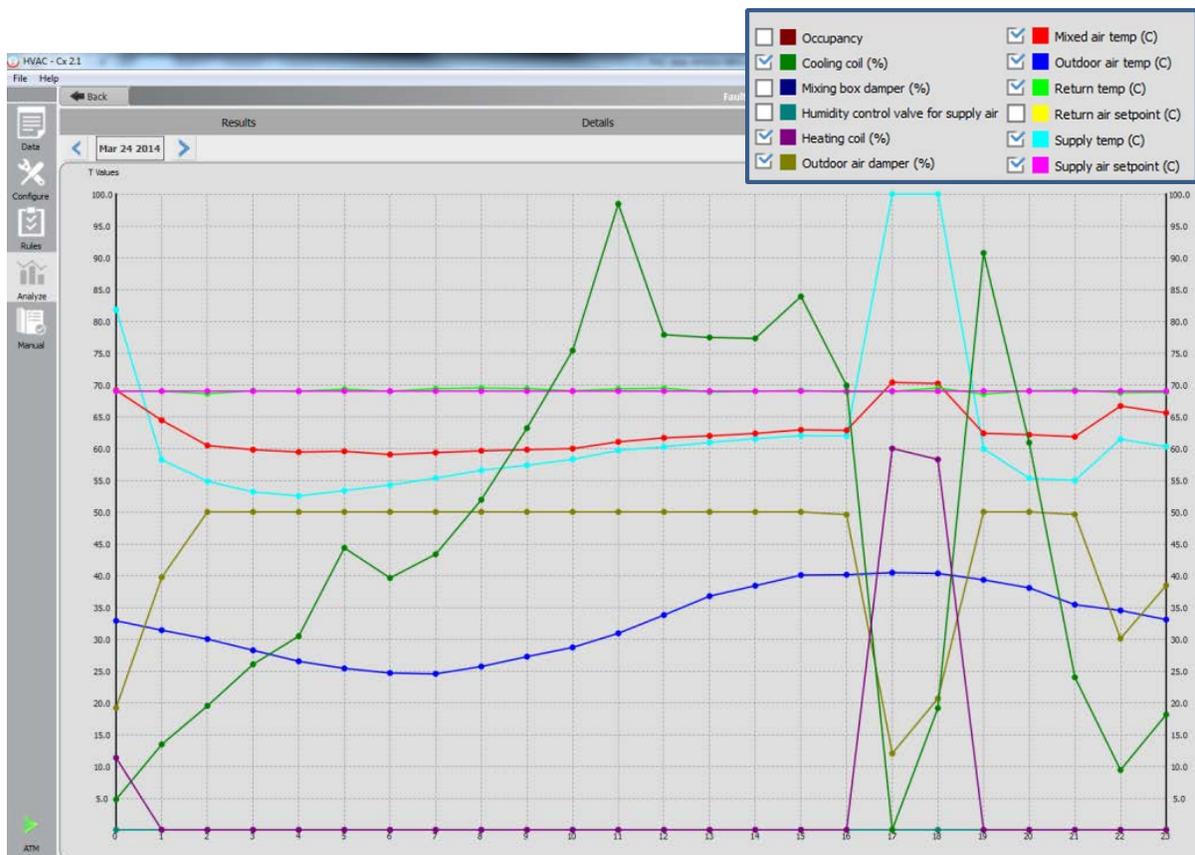


Figure 7. HVAC-Cx graphical display of AHU1b temperature inconsistencies over a 24-hour period.

AHU-1B comfort requirements. Figure 7 also shows a period when the supply air temperature dropped to more than 2.7 °C (5 °F) below the setpoint temperature and the system did not make the changes necessary to maintain temperature control. There are also several periods when the economizing dampers were commanded open at 50 % during unfavorable economizing conditions. As a result, the system was consistently unable to maintain the supply temperature setpoint (Rule 25). There were periods where the cooling coil was open with the supply air temperature consistently more than 2.8 °C (5 °F) below the setpoint temperature. This performance fault was likely a result of the economizing fault that resulted in over-ventilating the system with outdoor air and the suspected return air temperature sensor fault that would negatively effect system control.

5. Conclusions and Recommendations

The objective of this study was to evaluate the field performance of HVAC-Cx, an ongoing commissioning tool for air-handling units. The tool was evaluated using field data from a building that is located on a community college campus in Rockville, Maryland. Data was collected during the month of March 2014, under typical operation for the building.

HVAC-Cx found a variety of 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. The swing season data evaluated in this study found that AHU-1A and AHU-1B operated in all operating modes except for

mechanical cooling with 100 % outdoor air because the outdoor air damper position was limited to a maximum of 50 % outdoor air for both economizing dampers.

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 detected using HVAC-Cx graphing capabilities. The tool presently contains capabilities for passive and active testing of air-handling units and chillers. Further research is needed in applying the tool to active testing for both air-handling units and chillers, and to expand capabilities to terminal boxes. In general, the results were encouraging and valuable lessons learned can be applied to improving future performance of the software.

Further field testing is underway for HVAC-Cx and the rule-based algorithm will be modified based on the lessons learned in this study.

6. Acknowledgments

This project, like any field study, would not have been possible without those individuals who assisted with the data collection aspect of this work. Thanks are due to Christopher Karp and Michael Whitcomb of Montgomery College in Rockville, Md.

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