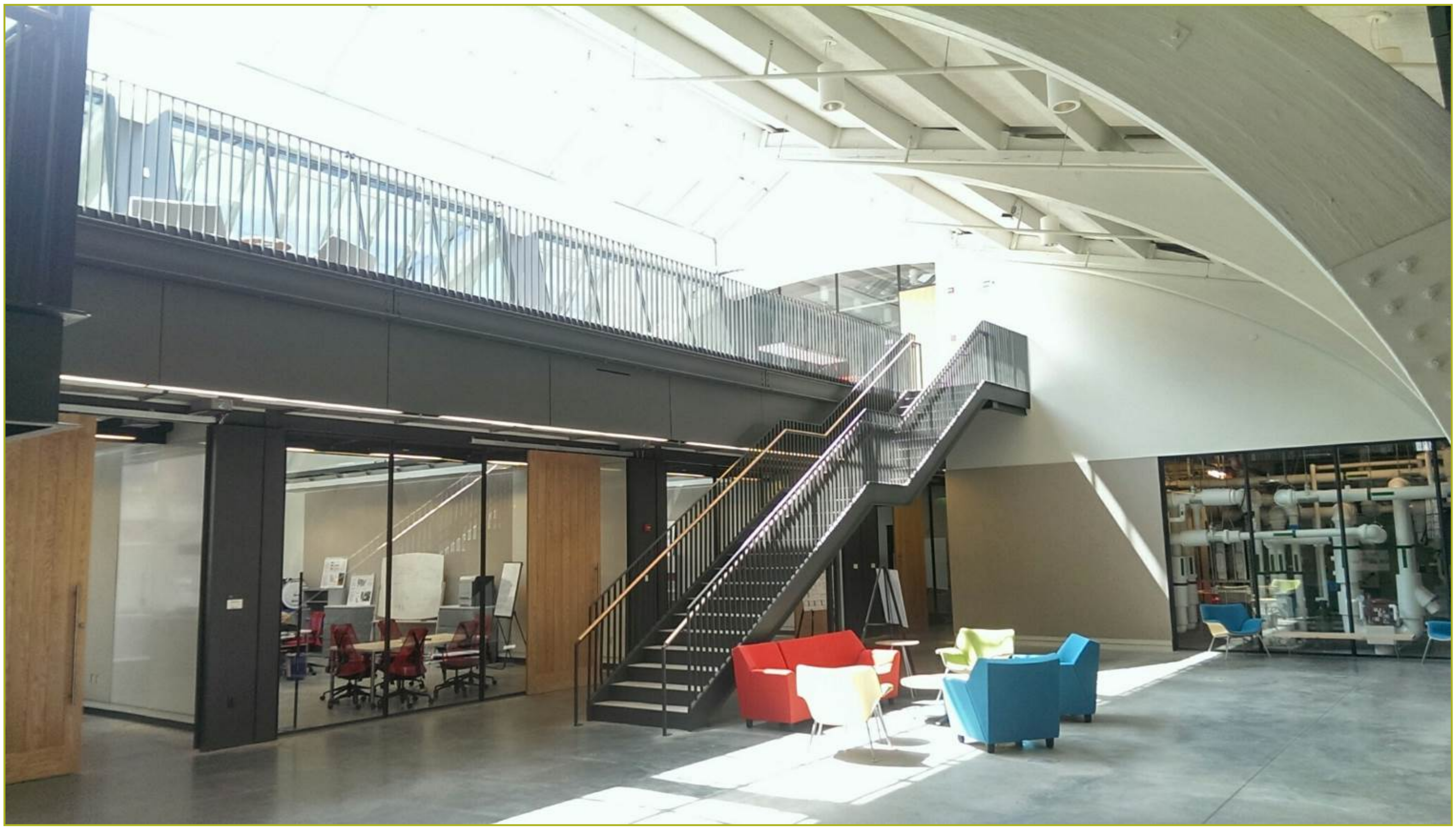
CONSORTIUM for
BUILDING ENERGY
INNOVATION

REPORT

Title: Demonstration and Commercialization of VOLTTRON Compatible AHU Diagnosis

Report Date: April 30, 2016

Report Author: Dr. Jin Wen, Adam Regnier, Yimin Chen, and Dr. Srinivas Katipamula



Funded by U.S. DOE

Report Abstract

Market available AHU diagnosis solutions often suffer from long payback time due to the needs to manually customize diagnosis solutions, collect extensive training data, or install additional instruments. Through the previous small scale real building demonstrations, the solutions developed in this task have been shown to be highly automated and require minimum engineering hours and no additional instrument. In BP5, the AHU VAV/CAV fault diagnosis solutions developed in previous budget periods are further advanced to include the retro-commissioning feature to accelerate their market adoption process. The performance and cost-effectiveness of the solutions are demonstrated in five SMSCB buildings in this project. Among the five demo buildings, two buildings are used as active testbed, in which, over five hundreds of fault tests have been conducted over three different seasons. The other three buildings are used to examine the performance of the retro-commissioning feature.

Overall speaking, the diagnostic accuracy of our solution is over 95% with less than 1% of the false alarm rate. The average magnitude of the fault energy impacts included in this study is found to be $0.07/sf /year. This would indicate that the use of our technology would typically pay for itself in less than two years by just detecting a single fault.

Two companies, KGS Buildings (a well-established building energy management company) and Kinetic Buildings (a start up company), have licensed the AHU AFDD solutions developed in this project.

Contact Information for lead researcher

Name: Dr. Jin Wen
Institution: Drexel University
Email address: jinwen@drexel.edu
Phone number: 215-895-4911

Contributors

Drexel University: Dr. Jin Wen, Adam Regnier, Yimin Chen, Jesse Schwakoff, and Taylor Castonguay

PNNL: Srinivas Katipamula, Jeremy N. Haack

1. Introduction

It is well known that the monetary and energy costs of buildings operation are high. Estimates have found that the HVAC systems of buildings are responsible for 14% of primary energy consumption in the U.S., and 32% of all electricity generated in the U.S. Energy use in the built environment is projected to grow at an average rate of 1.5% annually. HVAC energy makes up a large portion of the overall building energy consumption, in offices comprising 48% of the total energy used (Pérez-Lombard et al., 2008). While HVAC will always comprise a large portion of our overall energy consumption, there is a significant amount of energy wasted as a result of faulty operation of these systems. Previous studies have indicated that as much as 30% of energy consumption in commercial buildings is wasted due to inefficient operation. However, through the use of effective automated fault detection and diagnosis (AFDD), this waste can be largely avoided.

Air handling units (AHUs) are used in over 30% of all commercial buildings. AHUs are also the central location for managing heat exchange between primary and secondary systems and ventilation of the building. Hence, faulty operation of AHUs can result in significant energy waste and adverse impacts on indoor air quality.

With the advent of more advanced building control systems, and the continuous reduction of sensor costs and computational costs, there is an emergent opportunity to implement systems for early and effective detection and diagnosis of faults. Without AFDD strategy, faults in AHUs are typically identified only via occupant complaints. As a result, only faults resulting in inadequate conditioning of the occupant space's temperature are commonly detected and repaired. However, control systems are able to compensate for many AHU faults without impacting occupant comfort, leading to many energy-wasting faults persisting in an AHU-VAV system perpetually or for extended periods of time.

AFDD for HVAC applications has been an active area of research for more than two decades (more details in the following section), yet there remains a lack of reliable, affordable, and scalable AFDD solutions for AHUs.

AHU-VAV systems pose a number of unique challenges to the typical fault detection paradigm.

- These systems are "built-up" systems, which are custom designed for each particular implementation. As a result, methods requiring extensive modeling or heuristics can be impractical due to the high engineering costs associated with the customization requirements for each individual system.
- They operate across multiple modes in a continuously transient manner. As depicted in Figure 1, there are 4 typical and distinct operational modes in a AHU: heating, cooling, economizing, and economizing with cooling. However, within each of these modes there are innumerable combinations of valve positions, fan speeds, and damper positions that modulate continuously to adapt to constant changes in weather and internal building loads. Additionally, many buildings are now equipped with demand-controlled ventilation (DCV), resulting in additional damper

modulation in all modes of AHU operation. Other control strategies that can cause variations from normal modes of operation include humidification-based control strategies, demand-response control signals, energy recovery units, and dedicated outdoor air systems – all of which are quite common in practice.

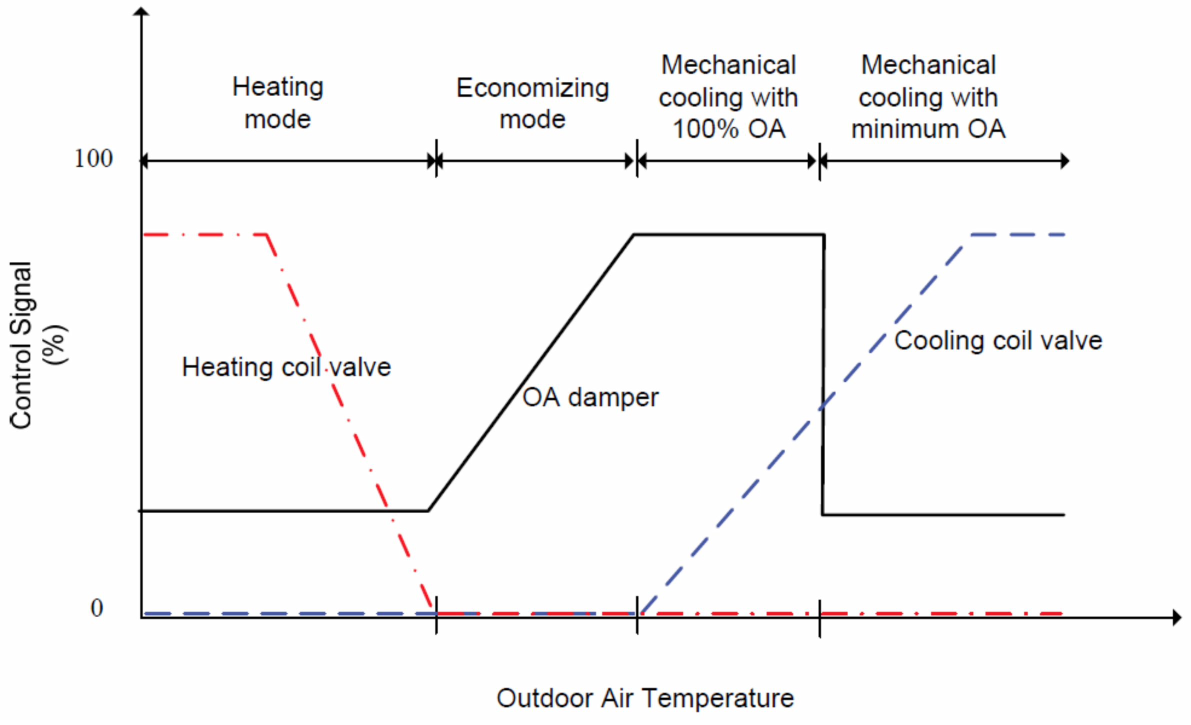


Figure 1: AHU Operational Modes.

- The sensor configurations typically installed in AHU-VAV systems are designed for control purposes, and not for the detection of faults. This lack of measurement or measurement accuracy often leads to ambiguity during an AFDD process.
- Although there is the potential for significant energy and cost savings, there is a general lack-of-willingness by industry to invest in AFDD technologies, so viable solutions must have lower upfront costs than what is currently available commercially. This problem is exacerbated by the difficulty in accurately quantifying the benefits of AFDD, and by the fact that many building tenants are responsible for utility bills, reducing building owners' financial incentives to incorporate these tools.
- Control strategies vary widely between different buildings, and effective AFDD solutions must be adaptable to all of them.

In this project, a cost-effective AHU AFDD strategy that employs pattern-matching principle component analysis method for fault detection and diagnostic Bayesian network (DBN) method for fault isolation is examined. This solution is developed in previous years and has been studied over several test buildings (Li and Wen, 2014, Zhao et al., 2015 and 2016, Regnier, et al., 2014). In this year, the focus of the project includes: 1) the AFDD solution developed in previous budget periods will be further advanced to include retro-commissioning features to accelerate their market adoption process; 2) the solution will be demonstrated in five SMSCB buildings and the cost-effectiveness of the solution will be analyzed; and 3) A market analysis and commercialization plan will be developed with the help from our market partners. Manufacturing/licensing agreement(s) will be signed with commercialization partner(s).

In this report, Section 2 describes the selected demonstration buildings and active tests performed in these buildings. Section 3 summarizes the retro-commissioning feature (retro-DBN) and the overall accuracy of the solutions (PM-PCA, DBN, and retro-DBN) using demonstration data. Section 4 summarizes our cost-effectiveness analysis of the solutions. And Section 5 provides a market analysis and commercialization status.

2. Demonstration Buildings and Active Fault Tests

2.1 Demonstration Buildings

During BP5, we have performed demonstrations of our AFDD solutions in five buildings to demonstrate the effectiveness of the tool, and to identify if there are any potential pathways to commercialization. The process to select the AHUs and variable air volume boxes (VAVs) was to first identify a set of “candidate” systems in which data could be readily acquired. This was done by utilizing relationships with West Chester University, Drexel University, and KGS Buildings (KGS). From these different sources, 15 candidate buildings were identified as potential demonstration sites. To winnow this list down, a set of selection criteria were identified as follows:

1. Experimental testing capabilities
2. Variety of physical system characteristics.
3. Variety of control strategies.
4. Facilitating commercialization.
5. Variety of modes of operation.
6. Located domestically.

Based on these criteria, the following sites are selected as demonstration sites:

1. Swope Building, Westchester, USA (music school)
2. Stratton Building, Philadelphia, USA (classrooms and offices)
3. Commonwealth Building, Philadelphia, USA (classrooms and offices)
4. Anonymous Building, Cambridge, USA (laboratory)
5. Anonymous Building, Joliet, USA (manufacturing plant)

The summary of these selections is included in Table 1. Details about the selection process and criteria are summarized in the G/NG 2.4.1 report.

Table 1: Overview of Selected AHUs

No.	Location	AHU Configuration	Fan Capacity	VAVs	System Age	Mean Winter Low	Mean Summer High	Climate Zone
1	West Chester, PA, USA	Economizer, DOAS, DCV, Humd	30,000 CFM	45 w. rht	2007	-4°C (24°F)	29°C (84°F)	4
2	Philadelphia, PA, USA	Economizer, DR	20,000 CFM	31 w. rht	2013	-4°C (25°F)	31°C (87°F)	4
3	Philadelphia, PA, USA	Tri-fan, Humd, ERU	40,000 CFM	99 w. rhts 2 FP w. rhts	2004	-4°C (25°F)	31°C (87°F)	4
4	Cambridge, Massachusetts, USA	Economizer	50,000 CFM	n/a	2005	-6°C (22°F)	28°C (82°F)	5
5	Joliet, Illinois, USA	Economizer	30,000 CFM	n/a	2004	-9°C (16°F)	29°C (85°F)	5

Rht = VAV-box reheats; FP = fan-powered VAV-boxes; DOAS = dedicated outdoor air system; DCV = demand-controlled ventilation; Humd = humidification unit in AHU; DR = demand-response signal; ERU = energy recovery unit (e.g. heat-wheel)

AHU 1 from above is on the campus of West Chester University, and has been used in previous demonstrations during B.P.4. It is a good choice for demonstration because the building utilizes a number of advanced and unique control strategies (DCV, humidification-based control), and because the AHU has a unique configuration as well (DOAS, humidifier). As faults are detected and diagnosed in this building, the information will be passed to the building operator to perform verification of any faults identified.

AHUs 2 and 3 are on Drexel's campus, and were selected because they can be monitored online in real-time using the Volttron platform, and because they can be used to conduct fault-testing experiments. As mentioned above, it is necessary to be able to artificially implement faults some of the AHUs and VAV-boxes to fully demonstrate and measure the efficacy of the diagnostic tool. The measurement and verification of the technology at these buildings will be performed in two ways. Firstly, if a naturally-occurring fault is identified, the equipment will be inspected by our team and the information will be passed to the Drexel facilities office to verify the findings. The second way the tool will be validated at these buildings is by artificially introducing faults into the systems. This process has already begun for the cooling season.

Experiments will consist of testing mechanical, controls, maintenance, and operator faults. All faults are tested in "both directions" (e.g. if a fault is tested "too far open", it will also be tested as "too far closed"), as well as with multiple severities in each fault direction. An overview of the faults that will be introduced can be summarized as follows:

- Mechanical faults, including dampers, valves, fans, sensors, etc.
- Control faults, including instability, and cycling faults
- Maintenance faults
- Operator faults

The fourth and fifth AHUs were provided by our commercialization partner, KGS. Since these are real customers of KGS who are not involved with the research, the data have to be anonymized and the analysis will be performed offline. KGS has recently provided these data, and analysis will commence soon. Presently, little information has been provided about the physical configurations and control strategies of these buildings, so this will be an opportunity to demonstrate the automation and flexibility of the use of our strategy in a building where little additional information is available.

The measurement and verification of these buildings will be performed by comparing our findings with the findings of KGS, and identifying the strengths and weaknesses of the different approaches. This comparison is expected to facilitate the incorporation of our technology by KGS into their existing diagnostic tools.

The manner in which each of the selected buildings pertains specifically to the selection criteria is described in 2.2 Active Fault Testing

In order to test, refine, and demonstrate the accuracy and cost-effectiveness of our AFDD strategies, experiments were conducted to artificially introduce faults into different demonstration buildings and record how the AFDD algorithms performed. For this project, the focus is on air handling units (AHUs) and variable air volume terminal units (VAVs). During the summer and fall seasons, the majority of the testing was performed at Stratton Hall. During the winter seasons, the testing was mostly performed at the Commonwealth building.

2.2.1 Building description

Stratton Hall is a three story building located on Drexel University's campus in the city of Philadelphia. The original building was constructed in 1955 but has recently undergone a major renovation that was completed in late 2013. This renovation included fully reconfiguring the interior space, as well as numerous repairs to the building façade/envelope and window replacement. Additionally, the mechanical systems were almost entirely replaced, including 2 new AHUs – AHU-2 and 3. AHU-2 serves 31 VAV-boxes located on the second floor and AHU-3 serves the 16 VAV-boxes on the third floor. The AHUs in Stratton Hall are considered to be of "typical" configuration.

The control strategies utilized at the Stratton Building are also considered to be typical and are well-aligned with the best practices for energy savings by utilizing supply air temperature and pressure resets. Each of the VAV-boxes is controlled by the zone temperatures, contains a reheat coil, and none of the VAV-boxes in this building are fan-powered. The AHU-VAV system is controlled by Automated Logic's WebCTRL building automation system (BAS) software.

Table 2. Due to the nature of the buildings, AHUs 1 to 3 (Swope building, Stratton Hall building and Commonwealth building) are selected for active fault testing. These data can be used for demonstrating all of our AFDD solutions. The other two buildings are used for retro-commissioning DBN demonstration since no active fault testing can be performed.

2.2 Active Fault Testing

In order to test, refine, and demonstrate the accuracy and cost-effectiveness of our AFDD strategies, experiments were conducted to artificially introduce faults into different demonstration buildings and record how the AFDD algorithms performed. For this project, the focus is on air handling units (AHUs) and variable air volume terminal units (VAVs). During the summer and fall seasons, the majority of the testing was performed at Stratton Hall. During the winter seasons, the testing was mostly performed at the Commonwealth building.

2.2.1 Building description

Stratton Hall is a three story building located on Drexel University's campus in the city of Philadelphia. The original building was constructed in 1955 but has recently undergone a major renovation that was completed in late 2013. This renovation included fully reconfiguring the interior space, as well as numerous repairs to the building façade/envelope and window replacement. Additionally, the mechanical systems were almost entirely replaced, including 2 new AHUs – AHU-2 and 3. AHU-2 serves 31 VAV-boxes located on the second floor and AHU-3 serves the 16 VAV-boxes on the third floor. The AHUs in Stratton Hall are considered to be of "typical" configuration.

The control strategies utilized at the Stratton Building are also considered to be typical and are well-aligned with the best practices for energy savings by utilizing supply air temperature and pressure resets. Each of the VAV-boxes is controlled by the zone temperatures, contains a reheat coil, and none of the VAV-boxes in this building are fan-powered. The AHU-VAV system is controlled by Automated Logic's WebCTRL building automation system (BAS) software.

Table 2: Selected AHUs with Selection Criteria

No.	Location	System, Controls, Size Variety	Experimental Testing Capable	Facilitates Commercialization Partnerships	Operational Mode Variety	Located in the United States
1	West Chester, PA, USA	Unique from other demo buildings	Maybe	3rd-party verification	Full spectrum of seasons	Yes
2	Philadelphia, PA, USA	Unique from other demo buildings	Yes	Internal verification	Full spectrum of seasons	Yes

3	Philadelphia, PA, USA	Unique from other demo buildings	Yes	Internal verification	Full spectrum of seasons	Yes
4	Cambridge, Massachusetts, USA	Unique from other demo buildings	No	KGS verification	Full spectrum of seasons	Yes
5	Joliet, Illinois, USA	Unique from other demo buildings	No	KGS verification	Full spectrum of seasons	Yes

Commonwealth Building is a seven story building located on Drexel University's campus. The original building was a warehouse. In 2003, it was renovated again to become part of the Bossone Research Center. There is one AHU and 105 VAVboxes in this building. Compared with AHU in Stratton Hall, AHU in Commonwealth Building has two supply air duct with two supply air fan and energy recovery configuration. There are two types of VAVbox in Commonwealth Building. One is normal VAVbox with reheating component. Another is fan powered VAVbox. In winter test, the normal VAVbox fault test was conducted.

2.2.2 Experimental Methods

The methods used to simulate faults encountered in the real world can be defined in two different primary categories:

Override setpoints or control logic via the BAS web interface. This is the preferred implementation for most faults since it is the least intrusive method of introducing faulty operation into the system. The overrides that were performed included overriding actuator positions for dampers and valves, overriding fan speeds, fixing and biasing sensor values, and manipulating PID control values. Overriding the system via the BAS was used in all instances except when it was not possible to accurately simulate the way a fault would naturally occur.

Manually apply a control signal to the actuators. This second fault simulation method is to inject the voltage signal to the actuators instead of using the Direct Digital Controller (DDC) to send the signal to the actuator. During the winter fault test, the outdoor air (OA) damper and exhaust air damper positions were manually overridden by sending a voltage signal directly to the actuator. During the course of the test, the team cut off the DDC connection to the actuator and used a voltage generator to connect directly to the OA and relief air damper actuators. Figure 2 shows an implementation of this type of fault. The team originally planned to implement this type of fault test to Return Air (RA) fan – stuck the fan speed instead of controlling it

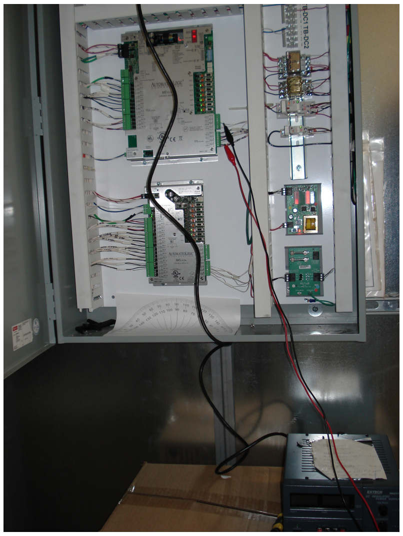


Figure 2 – Manual application of the control signal

via Variable Frequency Driver (VFD). But the test was cancelled because it will cause the Supply Air (SA) fan speed to fluctuate tremendously.

2.2.3 Implemented Faults

The summer and fall experiments were conducted from June 2015 through November 2015. A total of 94 fault experiments in Stratton Building were conducted during this period. During these testing seasons, there were 71 faults artificially introduced to AHU-2 and 23 faults artificially introduced to different VAV-boxes. The winter fault experiments were conducted through November 2015 to February 2016. A total of 27 fault experiments in Stratton Building and 13 fault experiments in Commonwealth were conducted during this period. During these testing seasons, there were 36 faults artificially introduced to AHU and 4 faults artificially introduced to different VAV-boxes. An overview of the different experiments is provided in Tables in Appendix A.

2.3 PNNL's Proactive FDD Method Development

Pacific Northwest National Laboratory (PNNL) has contributed the research, development and deployment effort associated with this project. PNNL's contributions included general VOLTTRON technical support, , sharing performance data from a number of AHUs and implementation and testing of the AHU/RTU proactive diagnostics in VOLTTRON using Python scripts. Much of the AHU/RTU proactive diagnostics were developed through a separate funding from DOE. For the BP5 efforts, PNNL implemented and tested the proactive diagnostics on a selected RTU/AHUs on the VOLTTRON platform. The details of the proactive diagnostics algorithms are documented in Appendix C of this report.

3. Retro-commissioning DBN and Overall Solutions' Performance

This section provides an overview of the fault detection and diagnostic results to date. This consists of three main items:

1. Automated fault detection (anomaly detection)
2. Retro-commissioning (RCx) diagnostics
3. Continuous-commissioning (CCx) diagnostics

For the 65 faults that were studied using the fault detection algorithm, a summary of the results is included in Table 3, below. A detailed list of these fault experiments, and the results obtained using the detection algorithm is included in *Appendix B*, at the end of this document. The detection algorithm for BP5 was primarily tested at the buildings at Drexel University, since the research team had physical access to these building systems and was able to carefully monitor the experiments. The overall detection rate was found to be 85%. This is a slightly lower detection rate than previously observed, but this is expected due to the fact that faults of lower magnitude were being tested. The less severe a fault is, the impact on the system variables is reduced and it becomes more difficult to accurately detect the anomalies. Faults that do not cause any fault symptoms are not intended to be detected due to the fact that building operators are not typically interested in these faults.

Table 3: Overall Detection Rate

Accurately Detected	No Symptoms	Missed Detection
34	25	6

At the time of writing, the diagnostic Bayesian network algorithms have been tested on 3 different buildings, encompassing a total of 45 different faults. The key advance demonstrated in these results is the fact that the Bayesian network has been improved to function across a wide variety of buildings and system types without any modification, as the results demonstrate. In the below tables, Building 1 is Building 101 at the Philadelphia Naval Yard, Building 2 is Swope Hall at West Chester University, and Building 3 is Stratton Hall at Drexel University.

To analyze the diagnostic results, the day during which each fault was implemented was analyzed, and the results of the Bayesian network were summarized over the duration of each fault experiment. If a fault was identified with an average probability exceeding 60% during the time in which it was implemented, it was considered to be *accurately diagnosed*. If a different fault was diagnosed with higher than 60% confidence, and this incorrect diagnosis was in-part due to the effects of the fault that was artificially introduced, it was categorized as *misdiagnosed*. If a different fault was identified during the course of the fault experiments that was not due to the fault experiment, it was categorized as a *false-alarm*. If no fault was detected with greater than 60% confidence, the fault was categorized as *not detected*. The faults that were not detected were also sub-classified as either *impactful* faults of faults with *no impact.* A fault is only categorized as having no impact if:

- It is not in the control-loop of the system, so it does not directly impact any operation
- If an experienced building operator was reviewing at the building data, with knowledge that the fault exists, it would not be apparent from the BAS data.

The first bullet above is objectively determined, but the second bullet requires a subjective assessment of whether the fault has any system impact. The faults that were found to have no impact were sensors with very small biases (2-3°F), and dampers or valves that were "stuck" at their normal operational range for a given operational mode. For example, if an outdoor air damper control signal is requesting the damper to be 45% open, but the fault experiment has the value fixed at 50% open, the difference in the data would be very difficult to discern and the energy, cost, and comfort impacts would be negligible. However, when the system shifts to a different mode and requests that the damper is closed, or moved to 100% open, then the fault would become immediately apparent to a building operator, and would have measurable impact on the system operation.

A summary of the results of the faults utilizing the RCx approach (baseline threshold values) is included in Table 4, and a summary of results utilizing the CCx approach (training the Bayesian network thresholds based on known fault-free operation) is included in Table 5.

Note that in these tables, there were not fault experiments conducted at buildings 4 or 5. Historical data for these buildings were provided offline for analysis of normal operation in order to identify the faults. Since our research group did not have direct access to these physical systems, a definitive ground truth was not possible to identify; however, the data for these buildings were analyzed manually to ensure the accuracy of the results that were obtained. For each of these buildings, one week of data were analyzed for each of the system operational modes (heating, cooling, and shoulder/economizer operation). Additionally, continuous-commissioning studies for these buildings did not yield useful information, since the faults that were studied were present throughout the duration of the data, and new faults were not observed.

Table 4: Retro-commissioning summary of results

Retro-Commissioning Results						
Building	Total Fault Experiments	Accurately Diagnosed	Misdiagnosed	False Alarms	Not Detected	
					Impactful	No Impact
Building 1	15	10	1	1	0	4
Building 2	15	9	2	2	0	4
Building 3	15	12	0	0	0	3
Building 4	n/a	1	0	0	n/a	n/a
Building 5	n/a	2	0	0	n/a	n/a

Table 5: Continuous-commissioning summary of results

Continuous-Commissioning Results						
Building	Total Fault Experiments	Accurately Diagnosed	Misdiagnosed	False Alarms	Not Detected	
					Impactful	No Impact
Building 1	15	11	0	0	0	4
Building 2	15	11	0	0	0	4
Building 3	15	13	0	0	0	2
Building 4	n/a	n/a	n/a	0	n/a	n/a
Building 5	n/a	n/a	n/a	0	n/a	n/a

From these tables, it can be firstly observed that no *impactful* faults were missed in either network, and that when using the continuous commissioning network, all faults that impacted energy, comfort or indoor air quality were accurately detected and diagnosed. To illustrate the concept of a fault that is not impactful, the operational data for the fault in which the Building 2 return fan was stuck at a fixed speed is shown in Figure 3 and the diagnostic result is included in Figure 4. As observed in Figure 3, the fan speed was fixed at the normal operational range, resulting in negligible impact to the system, and limited evidence to use for diagnosis.

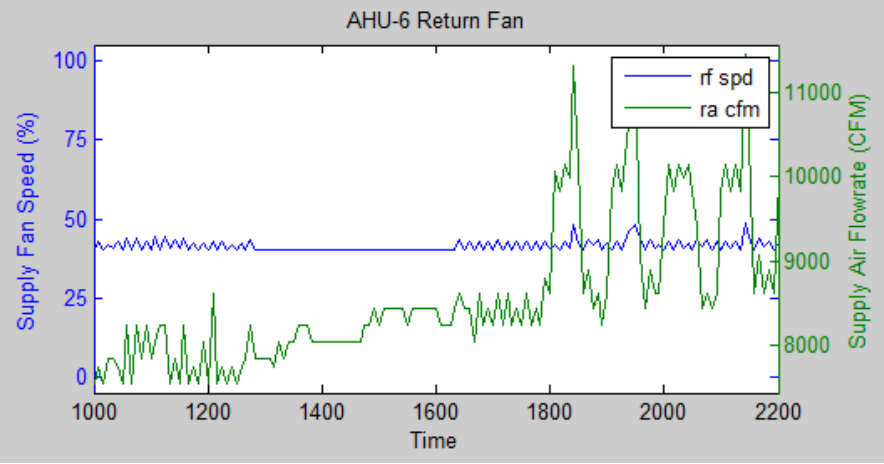


Figure 3: Return fan stuck at fixed speed (minimal impact)

In the above figure, "rf spd" refers to the return fan speed, and "ra cfm" refers to return air flowrate.

As demonstrated in Figure 4, below, the most likely diagnosis was correctly found to be a fan stuck at fixed speed ("frozen"), but due to the limited impact the diagnosis was not strong enough to meet the 60% threshold used to evaluate the efficacy of the fault diagnostic algorithm.

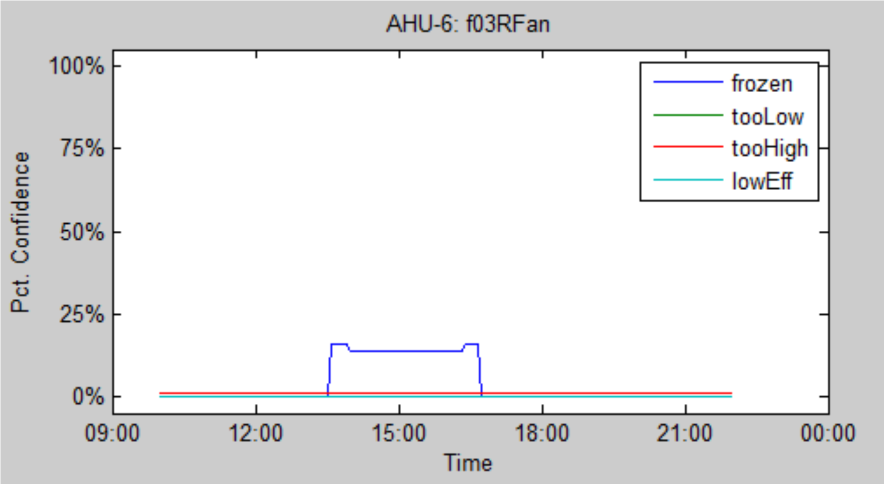


Figure 4: Return fan diagnostic result, 2015-12-17 (Swope AHU-6)

In the retro-commissioning network, there were three false alarms and three misdiagnosed faults. In reviewing the results, it was found that the misdiagnoses corresponded directly with the false alarms. The false alarm and misdiagnosis in Building 1 were due to the fact that there is no return air (RA) or mixed air (MA) damper. As a result, when economizing is expected, little to no outdoor air is actually being introduced into the system. While this was not technically a fault (since no piece of equipment was malfunctioning), it is behavior that differs from typical AHU operation, so it is useful information for a building operator or service provider. However, when previous operational data was used to train the thresholds, these faults were not falsely flagged.

Similarly, the misdiagnoses and false alarms identified in Building 2 were due to the non-traditional humidity-based control that was utilized in this building. In one instance a fault was flagged due to simultaneous operation of the heating and cooling coils. While this was done intentionally at this site for the purpose of dehumidification, this is indicative of faulty operation in many buildings and is a reasonable operational condition of which to alert a building operator or service provider. The other false alarm, and associated misdiagnosis was due to the temperature differential created by the steam humidification. Again, once these items were incorporated in the training data as "normal" operation, the faults were properly diagnosed.

4. Cost-effectiveness

In order to fully quantify the cost-effectiveness of our AFDD strategies, it is necessary to include a number of metrics, many of which are difficult to accurately quantify. The complete cost-benefit paradigm would include all of the following metrics listed in Table 6.

However, a key variable required for accurate economic analysis is not available: data regarding the frequency of fault occurrences. As a result, a comprehensive analysis of paybacks for the entire building stock impossible. In lieu of this type of analysis, the costs and benefits of specific fault occurrences are provided to demonstrate the paybacks under a wide variety of commonly observed circumstances.

- The cost to deploy the solution
- The cost savings identified due to energy savings

Table 6 Costs and benefits of an AFDD strategy.

Costs	Benefits
• Hardware gateway • Gateway set-up/configuration • Point-mapping/data-tagging • Site-specific algorithm customization • Threshold customization ○ Initial set-up ○ With season/mode changes • Hosting of data/algorithms	• Energy cost savings ○ Heating energy ○ Cooling energy ○ Fan energy • Worker productivity savings ○ Due to increased comfort ○ Due to improved indoor air quality (IAQ) • Savings from improved service scheduling • Savings from reduced manual diagnostic time

Comparing these two items with the full benefit-cost structure identified above, one notices that the "cost to deploy" includes all of the key cost items, while the cost savings analyzed in this report only includes the energy costs. This is due to the fact that all of the fault experiments were conducted in occupied buildings, so occupant comfort and proper ventilation were maintained during all of the conditions included in this dataset. As a result, the largest cost-saving metric – occupant productivity – is not included in this analysis. Also, comprehensive analysis of the time savings due to reduced diagnostic effort and service scheduling prioritization fall outside the scope of this investigation. However, as a result, it can be assumed that the actual cost savings observed in practice will far exceed the cost savings identified solely due to energy waste.

By utilizing only faults that do not significantly impact occupant comfort, this study investigates the most important faults to analyze in terms of energy waste. Faults that significantly impact occupant comfort are likely to have a much greater energy impact on a daily or hourly basis, but these types of faults are typically promptly addressed by building maintenance or the building service provider. However, there presently exist no widely-adopted tools for diagnosing faults, so faults that to not garner occupant complaints will persist indefinitely unbeknownst to building owners and operators.

4.1 Estimating Deployment Costs

To estimate deployment costs, two metrics were investigated: the number of hours required for our team to deploy the solution, and the typical costs presently associated with deploying manual retro-commissioning by service providers. Deployment costs are a function of the quantify of equipment and the quantity of data points collected from a given building, but with a standard AHU-VAV configuration, this value can be accurately estimated in terms of cost per square foot.

Based on conversations with many of our industrial partners, a standard estimate for a service provider to perform retro-commissioning analysis is $0.20/square foot, exclusive of performing any repairs. Comparing the time-savings that can be realized by deploying a more automated strategy, and by studying the time required to deploy our solution, it is found that utilizing this AFDD technology can save approximately 40% of this cost by removing the requirements for site-specific algorithm customization and threshold customization. As a result, the deployment cost is estimated at $0.12 per square foot.

4.2 Estimating Energy Cost Savings

The present HVAC fault monitoring paradigm is to respond to occupant complaints and to routinely perform a more comprehensive retro-commissioning effort. This retro-commissioning is not performed frequently, however, so many faults that do not affect occupant comfort can persist indefinitely in buildings. Even as awareness has grown of the problems associated with undiagnosed faults, the cost of retro-commissioning is prohibitive to perform frequently. For example, new legislation is starting to be passed in some cities around the country, starting in New York City and now potentially in Seattle, but the program in New York City only requires a retro-commissioning to be performed once every ten years. So without some ongoing monitoring, it is still possible for numerous energy-wasting faults to persist in buildings for a decade, even under the state-of-the-art scrutiny. For this reason, as will be demonstrated with the energy waste observed in this study, it is essential that buildings implement some form of continuous commissioning in order to avoid this costly problem. The detailed methods of estimating energy impacts in this project are introduced in our milestone report 2.4.C. Here a brief summary of the energy impact results is presented here.

For this study, there was limited data available for the fan power for much of the data, so it was excluded when not available and included when it was available. All of the energy impact of the various faults was measured during the course of the experiment. These results were then pro-rated to be converted to energy impact on a daily basis, and energy impact on an annual basis in terms of square footage. An overall summary of the results is included in Table 7.

Table 7 Energy impacts of the selected faults tested in this project.

Date	**Description**	**Fault Severity**	**Op. Mode**	**Daily Energy Impact (Δ)**			**Energy Impact**	**Daily Cost**	**Annual Cost/sf**
				Fan	**CW Coil**	**HW Coil**			
				kWh	*kBtu*	*kBtu*	*%*	*$*	*$*
8-Jun-15	OA damper, too far open	25%	Clg		200	0	6%	$1.40	$0.02
25-Jun-15	OA damper, too far open	10%	Clg		600	0	17%	$4.40	$0.05
9-Jul-15	OA damper, too far closed	-15%	Clg		140	0	4%	$1.00	$0.01
26-Jul-15	OA damper, too far open	25%	Clg		2,970	0	103%	$21.80	$0.27
11-Nov-15	OA damper, too far closed	-8%	Econ.	7	0	0	10%	$7.70	$0.09
23-Nov-15	OA damper, too far closed	-25%	Econ.	4	0	0	5%	$9.10	$0.11
16-Sep-15	CHW valve, too far open	20%	Clg		490	0	14%	$3.60	$0.04
17-Sep-15	CHW valve, too far open	35%	Clg		200	0	6%	$1.50	$0.02
19-Sep-15	CHW valve, too far closed	-35%	Clg		-670	0	-25%	($4.90)	($0.06)
22-Sep-15	CHW valve, too far closed	-30%	Clg		-760	0	-28%	($5.60)	($0.07)
15-Sep-15	CHW valve, stuck at normal	0%	Clg		-80	0	-3%	($0.60)	($0.01)
23-Sep-15	CHW valve, stuck at normal	0%	Clg		50	0	2%	$0.30	$0.00
26-Aug-15	SA fan, too high	10%	Clg		-110	0	-3%	($0.80)	($0.01)
12-Jun-15	SA fan, normal	5%	Clg		710	0	16%	$5.20	$0.06
30-Aug-15	SA fan, too low	-25%	Clg		-130	0	-4%	($0.90)	($0.01)
8-Sep-15	MA temp. sensor, negative bias	11 °F	Clg		220	0	5%	$1.60	$0.02
30-Sep-15	MA temp. sensor, negative bias	11 °F	Clg		-1,540	0	-41%	($11.30)	($0.14)
18-Nov-15	MA temp. sensor, positive bias	-9 °F	Econ.	3	0	0	5%	$6.30	$0.08
30-Jul-15	SA SP sensor, negative bias	8%	Clg		1,970	0	42%	$14.50	$0.18
9-Sep-15	SA SP sensor, positive bias	-8%	Clg		330	0	7%	$2.40	$0.03
30-Dec-15	SA SP sensor, negative bias	8%	Econ.	-1	0	0	-2%	$5.30	$0.06
1-Jul-15	SA temp sensor, negative bias	10 °F	Clg		-1,020	0	-29%	($7.50)	($0.09)
12-Sep-15	SA temp sensor, frozen	10 °F	Clg		-90	0	-3%	($0.70)	($0.01)
20-Nov-15	SA temp. sensor, positive bias	-5 °F	Econ.	5	0	0	6%	$8.50	$0.10

Notice that Table 7 was calculated following the following rules/processes:

- Daily energy impact and daily cost values compare the experimentally observed values minus the calculated baseline values, and are pro-rated to simulate the fault over a single full day of operation. (The fault experiments were 6 to 8 hours in duration, but the system is on for 16 hours per day. Of the buildings studied, the systems were typically on for between 12 and 24 hours per day, so this is a reasonable estimate to use.)
- The annual cost per square foot was estimated by multiplying the daily cost by the number of days per year that the system was operating in the associated mode, and then dividing by the square footage of the space conditioned area. For this building, the system is in cooling mode for approximately half of the year, and in economizing mode for approximately half of the year.
- Empty cells for fan power indicate experiments for which fan power data were not available.
- Negative numbers indicate cost savings.

4.3 Overall Cost-effectiveness Analysis

Overall the results correspond correctly with the expected behavior of the system in terms of the times when energy is being saved and wasted, and within the order of magnitude expected. Additionally, a number of fault-free days were studied and the overall accuracy of these results is found to be typically within 3% error.

The average magnitude of the faults included in this study was found to be $0.07/sf /year. This would indicate that the use of this technology would typically pay for itself in less than two years by just detecting a single fault, but this is an extremely conservative estimate due to a variety of additional factors:

- For many of these calculations, only the coil power was taken into account since the fan power data were not yet available. Including the fan power in the calculations can impact the results by the same order of magnitude as the coil power, so the effect of some faults would be significantly greater.
- The annual impact was estimated utilizing only the mode during which each fault experiment was conducted. However, many of the faults would have energy impacts throughout the year, so there is a potential for a much greater overall impact.
- From our experience, and the experience of the service providers and building operators who assisted with this analysis, multiple faults typically occur during the course of a given year, even in new systems, so the combined cost of multiple faults should be included in any cost-effectiveness analysis.
- As can be observed, faults are about half as likely to save energy as they are to waste energy, however when energy is being saved it is always at the expense of occupant comfort or health, due to inability to maintain zone temperatures, or lack of proper ventilation. Additionally, certain faults that save energy at the AHU-level, can result in additional energy expended at the zone level, which was not included in this study.

5. Market Analysis and Commercialization

5.1 Market Analysis

A very detailed market analysis is provided in our G/NG 2.4.2 report. Here is a brief summary of some of the key information.

Over the past five years, the market for AFDD in commercial buildings has experienced significant growth. This has been driven by an increasing ability to connect to building automation systems, improved networking capabilities, and more affordable computation.

The products presently available on the market provide a variety of services to help buildings owners and operators identify energy waste and inefficiencies, and go by a variety of names like building analytics, AFDD, and monitoring-based commissioning. Across the market, many competing products promise similar results, but the marketplace is quite difficult for a customer to navigate due to the lack of consistent terminology. (The same words used to describe two different technologies may refer to wholly different sets of functionalities.)

While many new AFDD solutions are continuing to come to market, the overall rate of adoption for these technologies is still relatively low as a percentage of the overall building stock. In discussions with buildings owners and operators, the key barriers to more widespread adoption frequently mentioned are:

- Inadequate ROI/payback. The high upfront/setup costs of many of these technologies makes the required investment and associated payback period too high when compared with alternative corporate investments.
- Low accuracy/reliability.
- Lack of interoperability.
- Inability to accurately quantify benefits. Performing effective measurement and verification (M&V) of these solutions is difficult and inexact, so owners and operators have a difficult time substantiating investments.
- Lack of knowledge/understanding of solutions. With new options for energy saving technologies being added each year, and the complete lack of industry standards, it is understandable that the typical building owner or operator has a difficult time sorting through the options to find the solution that fits their building(s).
- Poor previous experience. This market is not new, but it has gone through a significant evolution over the past decade. There is a shift away from energy "dashboards" and toward more detailed analytics, however many of the early adopters of these technologies were underwhelmed by the efficacy.
- Customer is disconnected from the issue. From a building operator's perspective, as long as the occupants aren't complaining about comfort too much then the building is operating adequately. Even sophisticated building operators who have some understanding that the building HVAC systems could be operated with less energy is probably not aware of the quantity of expended energy that is actually avoidable in the buildings, or where this energy is being expended.

As a result of the above factors, the primary drivers for growth of adoption of AFDD solutions can be considered to be:

- Reduction of implementation costs
- Education of customers
- Industry standards, including standardized terminology and benchmarks or ratings that can be used for the evaluation of competing technologies.

The first two drivers of adoption are well understood by the market, and as technology progresses and time passes they are both expected to be addressed by the market and the state of research. Industry standards can take longer to be implemented, accepted, and understood. While there is presently some movement in the standards conversation at ASHRAE, there is presently no expected timeline or concrete understanding of what these standards may or may not entail. With the assumption that many of these barriers will be gradually addressed in the coming decades, Navigant Research has projected that the market for energy management systems will grow from its present size of about $2.4B to $10.8B within the next decade.

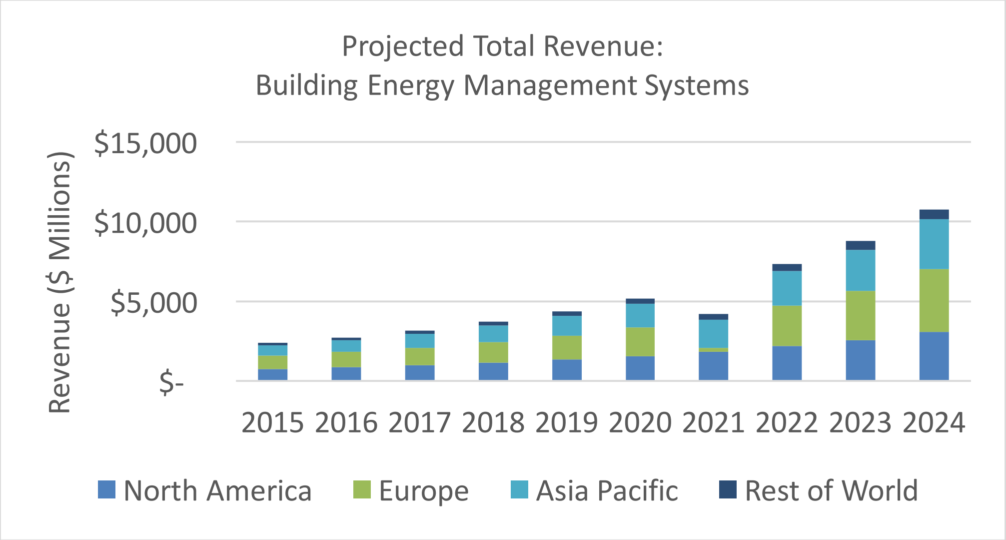


Figure 5 Projected total revenue in building energy management systems.

This expected rapid market expansion of 350% over the next decade is, of course, contingent upon the required investments in R&D, and the expectation that customers will be adequately educated and guided to make the decision to implement these types of technologies. Presently, based on the CBECS data, there are approximately 800,000 buildings in the US with some type of Building automation systems. This number is rapidly growing with new construction of commercial buildings typically including some BAS/networking capabilities, and retrofits adding these capabilities to new buildings.

In this document, we provide a brief listing of some of the most popular energy management solutions on the market, with a focus on diagnostic tools. These are the tools upon which some of the analysis provided in this report included. This list is based upon market research and industry feedback regarding the technologies most relevant to this market - and is in not a comprehensive itemization of all energy management solutions on the market. The focus of this report is on fault diagnostics, but some additional energy management products of note have also been included.

The authors of this paper have only used five of the technologies discussed below, and as mentioned above it is very difficult to understand the capabilities of these competing solutions without actually using them. As a result, this list of products is divided into three different categories – FDD, re-tuning, and data analytics – based on the core competency of the solution. Note that most of the products have some crossover into the other areas. For example, nearly all of the AFDD tools have some re-tuning capabilities, and many of the data analytics tools can be used for some building diagnostics with a knowledgeable operator or with special customizations.

Table 8 Existing building energy management products.

Company	Product	Category
KGS Buildings	Clockworks	FDD
Ezenics	AFDDI	FDD
SkyFoundry	SkySpark	FDD
CopperTree (Delta Controls)	Kaizen	FDD
IFCS	DABO	FDD
Iconics	FDDWorX	FDD
BuildingIQ	Predictive Energy	Re-tuning
Siemens	InfoCenter	Data
Cimetrics	Analytika	Data
KMC	Commander	Data
SCIenergy	EnergyScape	Data
Gridium	RCx	Data
Agentis	Ecosystem	Data
Field Diagnostics	SAMobile	Data
FirstFuel	FirstAdvisor	Data
Retroficiency	Efficiency Intelligence	Data
Energent	Energy Analysts	Data
Lucid	BuildingOS	Data
Johnson Controls	Metasys	Data
Niagara	Analytics Framework	Data

5.2 Commercialization

The diagnostic algorithms developed at Drexel University as part of the CBEI project are commercialized in two separate ways, through licensing agreements with two companies:

1. KGS Buildings has licensed the use of the algorithms as an additional tool that can be deployed with their existing Clockworks software. Drexel University is preparing user manuals and well-documented code to facilitate the testing and adoption of these algorithms. While the exact scope and business

plan are proprietary information, the algorithms provided can be utilized across a wide range of anomaly detection and continuous-commissioning applications.

2. Additionally, a startup was recently launched by one of the Drexel University researchers (Adam Regnier, one of the authors of this document) who was involved in developing these diagnostic algorithms. Kinetic Buildings is a software company focused on low-cost deployment of energy saving technologies in commercial buildings. The methods and algorithms developed as a part of this project will be included as part of their software offering.

Direct commercialization of federal R&D can be difficult to achieve, but this project has identified the key business drivers early on in the development process to facilitate this task. Firstly, it was identified that smaller companies were more likely to be interested in investing in externally developed technology than larger firms and are more likely to take risks with innovative new approaches. As a result, all of the firms that were approached for initial commercialization were smaller diagnostics and controls companies. With further development and demonstration, it would open up the potential to engage larger companies, but they are more likely to adopt more mature solutions.

Reference

Li, S. and J. Wen, “Application of Pattern Matching Method for Detecting Faults in Air Handling Unit System”, Automation in Construction, 43:49–58, 2014.

Pérez-Lombard, L., J. Ortiz, and C. Pout, “A Review on Buildings Energy Consumption Information,” Energy and Buildings, 40, 394-398, 2008.

Regnier, A., J. Wen, J. Schwakoff, “Automated Diagnosistics for AHU-VAV Systesm using Pattern Matching”, Proceedings of the 1st ACM Conference on Embedded System for Energy-Efficient Buildings, Novebmer, 2014, Memphis, TN.

Zhao, Y., J. Wen, and S. Wang, “Diagnostic Bayesian networks for diagnosing air handling units faults - Part II: Faults in coils and sensors,” Applied Thermal Engineering, 90, 2015, 145-157.

Zhao, Y., J. Wen, F. Xiao, X. Yang, and S. Wang. " Diagnostic Bayesian networks for diagnosing air handling units faults -Part I: faults in dampers, fans, filters and sensors." *Applied Thermal Engineering, Accepted. 2016*

Appendix A Fault Tests Summary

Table A.1 Injected Faults during Summer and Fall Test Period in Stratton Building

Date	System	Start Time	End Time	Test Performed
6/3/2015	AHU-2	1058	1750	SA temp sensor frozen (60°F)
6/4/2015	AHU-2	952	1725	SA temp sensor bias (-4°F)
6/6/2015	VAV 2-17	1424	2300	Zone temp bias (5°F)
6/7/2015	VAV 2-17	1029	1859	Zone temp bias (negative 4°F)
6/8/2015	AHU-2	1330	1750	OA damper stuck too far open (40%)
6/10/2015	AHU-2	1217	2258	SA temp sensor bias (-5°F)
6/12/2015	AHU-2	1124	1630	SF overridden (too low - 68%)
6/13/2015	VAV 2-10	1230	1821	Damper stuck close to norm (~30%)
6/14/2015	AHU-2	1015	1713	SF overridden (too high - 80%)
6/15/2015	AHU-2	1056	2008	SF positive bias (-8%)
6/21/2015	AHU-2	1310	2127	RF stuck (60% - low)
6/22/2015	AHU-2	1113	1935	RF stuck (85% - high)
6/24/2015	VAV 2-10	1335	2001	Damper stuck too far open (40%)
6/25/2015	AHU-2	1148	2000	OA damper stuck too far open (25%)
6/26/2015	VAV 2-22	1154	220	Flow sensor positive bias (+20%)
6/27/2015	AHU-2	1254	1841	OA damper stuck 100% open
6/29/2015	VAV 2-22	1144	2248	Flow sensor negative bias (-20%)
7/1/2015	AHU-2	1143	1745	SA temp sensor frozen (70°F)
7/2/2015	VAV 2-6	1130	1700	Flow sensor negative bias (-30%)
7/7/2015	VAV 2-5	1020	1645	Flow sensor positive bias (+30%)
7/8/2015	AHU-2	1311	2213	SA Static pressure positive bias (+.20in)

7/9/2015	AHU-2	1230	1911	OA damper stuck closed (0%)
7/10/2015	AHU-2	1216	1712	SF controller negative bias (-4%)
7/10/2015	VAV 2-23	1344	2319	Zone temp bias (positive 3 °F)
7/11/2015	AHU-2	833	1242	MAT sensor frozen low (60°F)
7/11/2015	VAV 2-2	852	1243	Zone temp bias (negative -3°F)
7/12/2015	VAV 2-23	1329	1855	Damper override shut (0%)
7/13/2015	AHU-2	1111	2032	Unstable CHW valve operation (Proportional gain 0.75/1/2)
7/14/2015	AHU-2	1210	1934	SA flow sensor frozen (15,750 cfm)
7/15/2015	AHU-2	1205	1653	Unstable CHW valve operation (integral gain 0.4)
7/15/2015	VAV 2-10	1221	1653	Zone temp sensor frozen (warm 74.5°F)
7/16/2015	AHU-2	1255	1658	SA Static pressure negative bias (-0.25 in H2O)
7/17/2015	AHU-2	1140	1335	SA temp sensor frozen (52F)
7/20/2015	AHU-2	1410	2207	OA flow sensor frozen (1,000 cfm)
7/21/2015	VAV 2-5	1130	1855	Zone temp sensor frozen (cool 69°F)
7/23/2015	AHU-2	1010	1737	Preheat Discharge Air Temp frozen (55°F)
7/24/2015	AHU-2	1345	1740	Preheat Discharge Air Temp frozen (85°F)
7/26/2015	AHU-2	1310	1714	OA damper stuck to 50%
7/28/2015	VAV 2-18	1155	1727	Damper stuck too far open (70%)
7/29/2015	AHU-2	1035	2002	RF stuck at nominal value (75%)
7/30/2015	AHU-2	1206	1717	SA SP sensor frozen (too high 1.3 in H2O)
8/3/2015	AHU-2	1445	2105	RA damper stuck (95%)
8/4/2015	AHU-2	946	1740	RA damper stuck (80%)
8/5/2015	VAV 2-25	1125	2130	Discharge temp sensor slightly high (60°F)
8/6/2015	VAV 2-1	1050	1804	Discharge temp sensor slightly low (51°F)
8/8/2015	AHU-2	1055	2042	Relief Air damper stuck (50%)
8/10/2015	AHU-2	1445	1943	OA temp sensor frozen (81%)
8/12/2015	AHU-2	1814	2105	RA damper stuck (too low50%)
8/13/2015	VAV 2-16	1845	2203	Discharge temp sensor frozen (too low 55°F)

8/14/2015	AHU-2	1534	2023	SA flow sensor frozen (too high 18,000cfm)
8/15/2015	AHU-2	1207	2042	SA temp sensor negative bias (-1°F)
8/15/2015	VAV 2-12	1518	2041	Damper stuck too far closed (10%)
8/16/2015	AHU-2	1532	2026	RA temp sensor frozen (too low 60°F)
8/17/2015	VAV 2-2	1923	2216	Discharge air temp sensor (too high 75°F)
8/18/2015	AHU-2	1439	2131	RA humidity sensor frozen (too high 75%)
8/18/2015	VAV 2-22	1728	2132	Damper override shut (0%)
8/19/2015	AHU-2	1641	2144	RA temp sensor frozen (too high 85°F)
8/21/2015	AHU-2	1630	2158	RA flow rate sensor frozen (15,500 cfm)
8/23/2015	AHU-2	1512	2102	RA humidity sensor frozen (25%)
8/23/2015	VAV2-11	1601	2101	Damper override stuck (50%)
8/24/2015	AHU-2	1649	2142	Relief air damper (stuck to 50%)
8/25/2015	AHU-2	1449	2141	RA damper (stuck to 50%)
8/26/2015	AHU-2	1623	2214	SF overridden to 85%
8/28/2015	VAV 2-5	1658	2154	Discharge temp sensor frozen (55°F)
8/29/2015	AHU-2	1445	2137	Unstable CHW valve operation (proportional gain 2/4/8)
8/30/2015	AHU-2	1609	1832	SF overridden to 50%
9/5/2015	AHU-2	1545	1919	Relief air damper stuck to 50%
9/8/2015	AHU-2	1020	2144	Mixed air sensor frozen (85°F)
9/9/2015	AHU-2	1004	2119	SA SP sensor frozen (too low 1.1 in H2O)
9/10/2015	AHU-2	1200	1847	SF frozen (much too low - 30%)
9/11/2015	AHU-2	1115	2105	RF stuck (too low 50%)
9/12/2015	AHU-2	1015	1502	SA temp sensor frozen (too low 55°F)
9/13/2015	AHU-2	1538	2002	SA flow sensor frozen (too low 13,000cfm)
9/14/2015	AHU-2	1121	1800	SF unstable (proportional gain 2/4/8)
9/14/2015	AHU-2	1403	2114	CHW_valve_stuck (34%)
9/15/2015	AHU-2	1356	2046	CHW_valve_stuck (50%)
9/16/2015	AHU-2	1616	2130	CHW_valve_stuck (75%)

9/17/2015	AHU-2	1538	2115	CHW_valve_stuck (90%)
9/18/2015	AHU-2	1718	2135	CHW_valve_stuck (100%)
9/19/2015	AHU-2	1028	1535	CHW_valve_stuck (20%)
9/20/2015	VAV 2-10	1521	2027	Damper stuck too far closed (20%)
9/21/2015	AHU-2	1033	1724	SF overridden to (90%)
9/22/2015	AHU-2	1132	1703	CHW_valve_stuck (25%)
9/23/2015	AHU-2	1608	2143	CHW_valve_stuck (40%)
9/25/2015	AHU-2	1757	2107	SF fan stuck (80%)
9/29/2015	AHU-2	1046	1635	CHW_valve_stuck (80%)
9/30/2015	AHU-2	1511	2152	Mixed air temperature sensor frozen (85°F)
10/1/2015	AHU-2	1403	2037	Return air temperature sensor frozen (70°F)
10/3/2015	AHU-2	1007	1558	SF overridden (80%)
10/6/2015	AHU-2	1322	2057	Unstable chilled water valve operation (proportional gain = 2)
10/7/2015	AHU-2	1408	1951	SA temp sensor frozen (70°F)
10/17/2015	AHU-2	942	1847	OA damper stuck too far open (20%)
10/24/2015	AHU-2	845	1711	OA damper stuck too far open (50%)
10/25/2015	AHU-2	1210	1627	OA damper stuck too far open (60%)

Table A.2 Injected Faults during Winter Test Period in Stratton Hall

Date Start	Day	Start Time	Date End	End Time	Building	Sys.	Mode	Category	Component	Description	Direction	Fault Value	Normal Operation	Severity
11/11/15	Wed	1611	11/11/15	2200	Stratton Hall	ahu2	Econ	Damper	OA damper	Manual inject signal	Stuck	50%	58% (15%-100%)	-8%
11/15/15	Sunday	1417	11/15/15	1652	Stratton Hall	ahu2	cooling	Operator	SA fan	override to fixed value	Too high	70%	50%(30%-60%)	20%(10%)
11/15/15	Sunday	1417	11/15/15	1652	Stratton Hall	ahu2	cooling	Fan	SA fan	Fan not at controlled speed.	Too high	70%	50%(30%-60%)	20%(10%)
11/16/15	Monday	1535	11/16/15	2107	Stratton Hall	ahu2	Econ	Sensor	SA temperature sensor	Frozen	Too low	58F	65F	-7F
11/16/15	Monday	1645	11/16/15	1000	Stratton Hall	ahu2	Econ	Damper	OA damper	The operator closed it	Closed	0%	15%	-15%
11/18/15	Wednesday	1100	11/18/15	1907	Stratton Hall	ahu2	Econ	Sensor	Mixed air temperature senor	Frozen	Too low	58F	67.5F(65-70F)	-10F(-7)F
11/20/15	Friday	1417	11/20/15	2253	Stratton Hall	ahu2	Econ	Sensor	SA temperature sensor	Frozen	Too high	78F	65F	13F
11/23/15	Wednesday	1418	11/23/15	2137	Stratton Hall	ahu2	Econ	Damper	Outside air damper	Stuck (manual)	Too far close	30%	55%(40%-70%)	-10%(-25%)

11/27/15	Friday	1305	11/27/15	2010	Stratton Hall	ahu2	Econ	Controller	SF Integral gain	Manual override in software	high	2	0.3	0.5
11/29/15	Sunday	1229	11/29/15	2012	Stratton Hall	ahu2	Econ	Controller	OA damper	Far too closed	Too low	50%	65%(60%-70%)	-15%(-10%)
12/04/15	Friday	1250	12/04/15	1900	Stratton Hall	vav215	Econ	Sensor	VAVbox discharge temp sensor	Frozen	Too high	60F	67.5F(55F-60F)	5F(2.5F)
12/11/15	Friday	1130	12/11/15	2033	Stratton Hall	ahu2	Econ	Fan	SF fan	manual override in software	Too low	45%	60%(50%-70%)	-15%(-5%)
12/14/15	Monday	1212	12/14/15	2130	Stratton Hall	ahu2	Econ	Damper	Relief damper	Stuck (manual)	too low	30%	67.5%(60%-75%)	-27.5%(-20%)
12/16/15	Wednesday	1014	12/16/15	1915	Stratton Hall	ahu2	Econ	Damper	Relief damper	Stuck (manual)	Much too low	40%	67.5%(60%-75%)	-27.5%(-20%)
12/21/15	Sunday	1008	12/21/15	2115	Stratton Hall	ahu2	Econ	Damper	OA damper	Stuck (manual)	Too high	60%	50%(40%-60%)	10%(0%)
12/28/15	Monday	1044	12/28/15	2122	Stratton Hall	Vav-2-5	Econ	Damper	Discharge air damper	Manual override in software	Too far closed	15%	65%(30%-100%)	-50%(-15%)
12/30/15	Wednesday	1411	12/30/15	2221	Stratton Hall	ahu2	Econ	SA pressure	SA Static pressure frozen	Manual override in software	Too high	1.3	1.2	0.1
01/05/16	Tuesday	1154	01/05/16	2135	Stratton Hall	ahu2	Econ	Sensor	Preheat temp sensor	Frozen	Too high	80F	55F(50-60F)	25F(20F)
01/08/16	Friday	1152	01/08/16	2150	Stratton Hall	ahu2	Econ	Damper	OA damper	Stuck	Too low	20%	60%(40%-80%)	-40%(-20%)
01/09/16	Saturday	1121	01/09/16	2140	Stratton Hall	ahu2	Econ	Damper	Relief damper	Stuck	Too low	15%	60%(40%-80%)	-45%(-25%)
01/11/16	Monday	857	01/11/16	2208	Stratton Hall	ahu2	Heating	Valve	Heating water valve	Leaking	Too low	5%	0	5%
01/18/16	Sunday	1030	01/18/16	2019	Stratton Hall	VAV-2-4	Econ	Valve	Reheat water valve	Manual override in software	Near normal	15%	15%(10%-20%)	
01/27/16	Wednesday	1048	01/27/16	2037	Stratton Hall	ahu2	Econ	Operator	SA fan	Manual override in software	Too high	80%	70%	10%
02/05/16	Friday	1015	02/05/16	2218	Stratton Hall	ahu2	Econ	Damper	OA damper	Manual override in software	Too low	20%	30%	-10%
02/12/16	Friday	815	02/10/16	2037	Stratton Hall	ahu2	Heating	Valve	Heating water valve	Manual override in software	Too low	20%	25%(20%-30%)	-5%
02/17/16	Wednesday	1159	02/17/16	2015	Stratton Hall	ahu2	Econ	Valve	Heating water valve	Heating water valve	Large	10%	0%	10%
02/27/16	Saturday	1451	02/27/16	2125	Stratton Hall	VAV-2-6	Econ	Valve	Reheat water valve	Leaking	Large	10%	0%	10%

Table A. 3 Injected Faults during Winter Test Period in Commonwealth Building

Date Start	Day	Start Time	Date End	End Time	Building	Sys.	Mode	Category	Component	Description	Direction	Fault Value	Normal Operation	Severity
11/22/15	Sunday	1658	20151122	2128	Commonwealth	AHU	Econ	Sensor	SA temperature sensor	Frozen	Too low	65F	70F	-5F
12/18/15	Friday	1110	12/18/15	1752	Commonwealth	AHU	Econ	Sensor	Mixed-air temp	Frozen	Too high	60F	55F(50-60F)	5F(0F)
12/20/15	Sunday	931	12/20/15	1902	Commonwealth	AHU	Econ	Sensor	Static pressure sensor	Frozen	Too low	0.3"wc	0.44 "wc	-0.13 "wc
12/26/15	Tuesday	1034	12/26/15	2253	Commonwealth	AHU	Econ	Operator	SA fan	Frozen	Too low	70% (42HZ)	47.5 (45-50 HZ)	-5.5(-3)HZ
01/01/16	Thursday	1109	01/01/16	2055	Commonwealth	AHU	Econ	Sensor	Supply air temperature	Frozen	Too low	90% normal	60F(55-65F)	
01/05/16	Tuesday	1425	01/05/16	2140	Commonwealth	AHU	Econ	Sensor	Mixed air temperature	Frozen	Too low	55F		
01/25/16	Monday	858	01/26/16	832	Commonwealth	VAV	Econ	Sensor	Mixed air temperature	Frozen	Too high	70F	60F	10F
02/03/16	Wednesday	1150	02/03/16	2113	Commonwealth	AHU	Econ	Sensor	Static pressure sensor	Frozen	Too low	1.6	1.9	-0.3
02/10/16	Wednesday	948	02/10/16	2055	Commonwealth	AHU	Econ	Sensor	Static pressure sensor	Frozen	Too high	1.95	1.9	0.05
02/15/16	Monday	900	02/15/16	2128	Commonwealth	AHU	Econ	Valve	Heating water valve	Leaking	Too low	5%	0%	5%
02/24/16	Wednesday	1456	02/25/16	635	Commonwealth	AHU	Econ	Valve	Heating water valve	Leaking	Too low	10%	0%	10%
02/26/16	Friday	941	02/26/16	2029	Commonwealth	AHU	Econ	Sensor	SA static pressure sensor	Bias	Negative	-0.2	1.9	-0.2
02/27/16	Saturday	1128	02/27/16	2103	Commonwealth	VAV-2-	Econ	Valve	Heating water valve	Leaking	Large	10%	0%	10%

Appendix B: Summary of Detection Results

Date Start	Category	Component	Description	Direction	Fault Value	Normal Operation	% Severity	Symptoms	Detection result
2015-06-04	Sensor	SA temp	Bias	Negative	-4F	65F	-7%	No symptoms observed.	Not Detected
2015-06-08	Damper	Outside air damper	Stuck	Too far open	Stuck at 40%	15%	167%	supply air flowrate, SA temperature, SA and RA fan, Cooling coil valve, Out air flowrate too high	Detected
2015-06-12	Fan	SF	Fixed	Normal	68%	70%	-3%	SF and RF speed, SA flowrate, SA SP slightly low	Detected
2015-06-14	Fan	SF	Fixed	Too high	80%	70%	14%	SF and RF speed, SA flowrate, SA SP too high	Detected
2015-06-15	Fan	SF	Bias	Negative	-8%	70%	-11%	No symptoms observed.	Not Detected
2015-06-21	Operator	RF	overridden to fixed value	Too low	60%	75%(70%-80%)	-14%	RF speed RA flowrate too low	Detected
2015-06-21	Fan	RF	Stuck	Too low	60%	75%(70%-80%)	-14%	RF speed RA flowrate too low	Detected
2015-06-22	Operator	RF	overridden to fixed value	Too high	85%	75%(70%-80%)	18%	RA flowrate too high	Not Detected[1]
2015-06-22	Fan	RF	Stuck	Too high	85%	75%(70%-80%)	18%	RA flowrate too high	Not Detected

---

[1] In this test case, only RA flowrate too high was found, and this value is not surpass the baseline data.

2015-06-25	Damper	Outside air damper	Stuck	far open	Stuck at 25%	15%	60%	No symptoms observed.	Not Detected
2015-06-27	Damper	Outside air damper	Stuck	Too far open	100%	15%	567%	MA temp too low, Between coil temp too low, outdoor air flowrate too high	Detected
2015-07-01	Sensor	SA temp	Frozen	Higher	70F	60F (55F-65F)	17% (8%)	No symptoms observed.	Not Detected
2015-07-08	Sensor	SA static pressure	Bias	Positive	1.05 in. H2O(84%)	1.25 in. H2O	-8%	No symptoms observed.	Not Detected
2015-07-09	Damper	Outside air damper	Stuck	Close	0%	15%	-100%	No symptoms observed.	Not Detected
2015-07-10	Fan	SF PID controller	Bias	Negative	-4%	75%	-5%	No symptoms observed.	Not Detected
2015-07-13	Valve	PID controller	Controller	higher Proportional	0.75/1/2	Proportional normal value= 0.5	300%	No symptoms observed (except mixed air temp too high)	Not Detected
2015-07-14	Sensor	Supply air flowrate sensor	Frozen	Normal	15,750cfm	15745cfm	0%	No symptoms observed.	Not Detected
2015-07-15	Valve	PID controller	Controller	higher Integral	0.4	Integral normal value= 0.2		No symptoms observed.	Not Detected
2015-07-20	Sensor	Outside air flowrate sensor	Frozen	Lower	1,000cfm	0-2000cfm	-33%	No symptoms observed.	Not Detected
2015-07-23	Sensor	Preheat discharge air temp	Frozen	Lower	55F	70F(65-75F)	-15%	Preheat temperature too low	Detected

2015-07-24	Sensor	Preheat discharge air temp	Frozen	Higher	85F	70F(65-75F)	30%	Preheat temperature too low	Detected
2015-07-26	Damper	Outside air damper	Stuck	Too far open	50%	Normal at 15%	230%	Preheat temperature and outdoor air flowrate too high	Detected
2015-07-26	Operator	Outside air damper	overridden to fixed value	Too far open	50%	Normal at 15%	230%	Preheat temperature and outdoor air flowrate too high	Detected
2015-07-29	Operator	Return fan	overridden to fixed value	Normal	75%	Linked to supply air fan	0	Mixed air and preheat temp are too high	Detected
2015-07-29	Fan	Return fan	stuck	Normal	75%	Linked to supply air fan	0	Mixed air and preheat temp are too high	Detected
2015-07-30	Sensor	SA static pressure	Frozen	Higher	1.3inch (104%)	1.25inch	4%	RA temp and MA temp too high, SF SA flowrate, RF,RA flowrate too low	Detected
2015-08-03	Damper	RF	Stuck	Too high	95%	Normal at 85%	11%	MA temp too high	Detected
2015-08-04	Damper	RF	Stuck	Too low	80%	Normal at 85%	-6%	MA temp too high	Detected
2015-08-08	Damper	Relief air damper	Stuck	Higher	25%	Normal at 15%	67%	No symptoms observed.	Not Detected
2015-08-12	Damper	RF	Stuck	Too much lower	50%	Normal at 85%	-40%	No symptoms observed.	Not Detected
2015-08-14	Sensor	SA flow rate sensor	Frozen	Higher	18,000cfm	16,000 cfm	12.50%	SA flowrate meter frozen	Not Detected
2015-08-15	Sensor	SA temperature sensor	Bias	Negative	-1F	60F (55F-65F)	-2%	No symptoms observed.	Detected

2015-08-16	Sensor	RA temp sensor	Frozen	Lower	60F	75F	-20%	RA temp too low	Detected
2015-08-18	Sensor	RA humidity sensor	Frozen	Higher	75%	Normal at 50%	50%	RA humidity too high	Not Detected[2]
2015-08-19	Sensor	RA temp sensor	Frozen	Higher	85F	75F (70F-80F)	13%(6%)	RA temp too high	Detected
2015-08-23	Sensor	RA humidity sensor	Frozen	Lower	25%	Normal at 50%	-50%	RA humidity too low	Not Detected[3]
2015-08-24	Damper	Relief air damper	Stuck	Higher	50%	Normal at 15%	230%	No symptoms observed.	Not Detected
2015-08-25	Damper	Return air damper	Stuck	Lower	50%	Normal at 85%	-40%	No symptoms observed.	Not Detected
2015-08-26	Fan	Supply air fan	Frozen	Higher	85%	75% (70%-80%)	12.50%	SA SP too high, SF speed too high	Detected
2015-08-29	Controller	Chilled water valve	Unstable	Proportional gain	2/4/'8	0.5	300%-1500%	No symptoms observed.	Not Detected
2015-08-30	Fan	Supply air fan	Frozen	Lower	fix at 50%	75% (70%-80%)	33%(-29%)	SF, RF speed RA flowrate too low	Detected
2015-09-05	Damper	Relief air damper	Stuck	Higher	50%	15%	230%	No symptoms observed.	Not Detected
2015-09-08	Sensor	Mixed air temp	Frozen	Higher	85F	74F (72-76F)	13%(11%)	MA temp too high	Detected
2015-09-09	Sensor	SA static pressure	Frozen	Lower	1.1in	Normal at 1.25in	-8%	SF and RF speed, SA and RA flowrate too high	Detected

---

[2] In this test case, the humidity sensor was not included in the control loop in cooling mode. Therefore, no other abnormity was found.

[3] In this test case, the humidity sensor was not included in the control loop in cooling mode. Therefore, no other abnormity was found.

2015-09-10	Fan	SA fan	Frozen	Much too low	fix at 30%	B4 value 74%	-59%	SF, RF speed RA flowrate too low, SA Sp too low	Detected
2015-09-11	Fan	Return air	Stuck	Too low	fix at 50%	75% (70% to 80%)	-33%(-29%)	RF speed RA flowrate too low	Detected
2015-09-11	Operator	Return air	overridden to fixed value	Too low	fix at 50%	75% (70% to 80%)	-33%(-29%)	RF speed RA flowrate too low	Detected
2015-09-12	Sensor	SA temp sensor	Frozen	Too low	55F	60F (55F-65F)	-8%(0)	CHW valve too low	Detected
2015-09-13	Sensor	SA flow rate sensor	Frozen	Too low	13,000 cfm	16,000 cfm (15,000-17,000 cfm)	-18%(-13%)	No symptoms observed.	Not Detected
2015-09-15	Valve	CHW valve	Stuck	Near normal	50% open	55% (40%-70%)	-9%(0%)	No symptoms observed.	Not Detected
2015-09-16	Valve	CHW valve	Stuck	Too high	75% open	55% (40%-70%)	10%	CHW valve too low, SA temp too low	Not Detected[4]
2015-09-17	Valve	CHW valve	Stuck	Much too high	90% open	55% (40%-70%)	63%(29%)	SA temp, CHW valve RA temp too low, SA setpoint too high	Detected
2015-09-18	Valve	CHW valve	Stuck	Much too high	100% open	55% (40%-70%)	81%(43%)	SA temp, CHW valve RA temp too low, SA setpoint too high	Not Detected

---

[4] In this test case, the baseline data was checked to find the lower SA temperature. Therefore, the fault was not detected.

2015-09-19	Valve	CHW valve	Stuck	Much too low	20% open	55% (40%-70%)	-63%(-50%)	SA temp too high	Not Detected
2015-09-22	Valve	CHW valve	Stuck	Much too low	25% open	50% (40%-60%)	-60%	SA temp too high	Not Detected
2015-09-23	Valve	CHW valve	Stuck	higher	40% open	35% (30%-40%)	14%(0%)	SA temp slightly high, CHW valve high	Not Detected
2015-09-25	Fan	SF Fan	Frozen	Variable	80%,70%, 60%,50%	70%	14%,0,-14%,-28%	SA flowrate varies	Detected
2015-09-29	Valve	CHW valve	Stuck	Too high	80%	median value 40%	100%	SA temp slightly low, CHW too low, RF temp and mixed air temp too low	Detected
2015-09-30	Sensor	Mixed air temp	Frozen	Much too high	85F	74F (72-76F)	15%	Mixed air and preheat temp are too high, CHW Valve too low	Detected
2015-11-11	Damper	OA damper	Manual inject signal	Stuck	50%	58% (15%-100%)	-16%	No symptoms observed.	Not Detected
2015-11-15	Fan	SA fan	Fan not at controlled spd.	Too high	70%	50%(30%-60%)	40%(13%)	Static pressure fluctuates	Detected
2015-11-16	Sensor	SA temperature sensor	Frozen	Too low	58F	65F	-11%	SA temperature sensor	Detected
2015-11-18	Sensor	Mixed air temperature senor	Frozen	Too low	58F	67.5F(65-70F)	-15%(-10%)	No symptoms observed.	Detected
2015-11-20	Sensor	SA temperature sensor	Frozen	Too high	65F	70F	-20%	No symptoms observed.	Detected

2015-11-23	Damper	OA damper	Stuck (manual)	Too far close	30%	55%(40%-70%)	-18%(62.5%)	No symptoms observed.	Not Detected
2015-12-30	SA pressure	SA Static pressure frozen	Manual override in software	Too high	1.3	1.2	8%	SA fan speed decreases	Detected

Appendix C: PNNL Proactive FDD Method Summary

Automation of Retro-commissioning Measures

S Katipamula
RG Lutes
R Underhill
G Liu

Prepared for
U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99352

Executive Summary

There is a general agreement that retro-commissioning (RCx)[1] of existing buildings saves energy, with most reported savings in the range of 10% to 30%. However, RCx as it is practiced today is perceived as expensive with no guarantee of persistence.

Many operational problems that are identified during RCx can be detected automatically and continuously, allowing the building to operate near optimally, leading to a lower RCx cost and increased persistence. Pacific Northwest National Laboratory (PNNL) developed a set of software applications to perform continuous RCx diagnostics. These continuously running software applications can be integrated with building automation systems to monitor key building systems; air handing units (AHUs), economizer systems, hot water central plants, and chilled water central plants and provide actionable real-time information to building operators. These applications can detect operational and equipment problems that might otherwise go undetected, compromising the efficiency of equipment and wasting energy. Many operational problems can be auto-corrected. This seamless integration of detection and correction allows facilities personnel to focus on maintenance and up-keep of equipment. Automation of RCx has the potential to tap into 60 to 80% of the savings attributed to RCx with very little investment.

This report describes the RCx software applications developed by PNNL. These applications perform RCx diagnostics on AHUS, economizer systems and hot water central plants. In the future chilled water central plant diagnostics will be added.

Initially, seven AHU RCx measures will be implemented, these include:

1. Detection, diagnosis and correction of high duct static pressure in variable air volume (VAV) air handling units (AHUs)
2. Detection, diagnosis and correction of low duct static pressure in VAV AHUs
3. Detection and diagnosis of No duct static pressure reset in VAV AHUs
4. Detection, diagnosis and correction of high supply-air temperature (SAT) in VAV AHUs
5. Detection, diagnosis and correction of low SAT in VAV AHUs
6. Detection and diagnosis of no SAT reset in VAV AHUs
7. Detection and diagnosis of unoccupied operation in VAV AHUs

Seven economizer control RCx measures will be implemented, these include:

---

[1] Commissioning is a systematic quality assurance process that spans the entire design and construction process, helping ensure that the new buildings' performance meets owners expectations - http://www.documents.dgs.ca.gov/green/commissionguidenew.pdf

Although there are number definitions of RCx, the commonly used definition is a systematic method for investigating how and why existing buildings' systems are operated and maintained, and identifying ways to improve overall building performance. http://www.documents.dgs.ca.gov/green/commissionguideexisting.pdf

1. Detect if the mixed-air and discharge air temperature sensors are consistent (
2. Detect if the outdoor-air damper is not modulating correctly
3. Detect AHU sensor faults (outdoor-air, mixed-air and return-air temperature sensors)
4. Detect if the AHU is not economizing when it should
5. Detect if the AHU is economizing when it should not
6. Detect if the AHU is using excess outdoor air
7. Detect if the AHU is not providing insufficient ventilation air.

In the subsequent sections of this report implementation details for the above mentioned RCx measures will be provided including flow charts, detailed list of inputs and outputs, and possible corrective actions for non-auto-correcting RCx measures.

Acknowledgements

The authors would like to acknowledge the Buildings Technologies Office of the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy for supporting the research and development effort. The authors would also like to thank Joseph Hagerman, Senior Advisor and Technical Development Manager at DOE; George Hernandez, staff scientist at PNNL, for thoughtful comments and insights; Andrew Nicholls Program Manager at PNNL for his thoughtful guidance; Woohyun Kim for the technical review of the report; and Sue Arey for editorial support.

Table of Contents

List of Figures

1 Introduction

Today, many large (>100,000 sf) commercial buildings use sophisticated building automation systems (BASs) to manage a wide range of building heating, ventilation and air conditioning (HVAC) equipment. While the capabilities of BASs have increased over time, many buildings still do not fully utilize their capabilities and are not properly commissioned, operated, or maintained. This leads to inefficient operations, increased energy use and cost, and reduced lifetimes of the equipment. "Tuning" buildings, much like tuning automobiles periodically, ensures maximum building energy efficiency and the comfort of building occupants. A poorly tuned system can (but not always) maintain comfortable conditions but at a higher energy cost to overcome inefficiencies.

In many cases, the BAS controls were never configured properly to "optimize" set points. Often, set points are configured to respond to worst-case outdoor air conditions (or design conditions), instead of internal zone conditions. Equipment vendors often use outdated "rules of thumb" that do not allow their equipment to be "optimized" or sequenced properly. Older buildings with BASs are often configured to have their controls respond to sequences that are no longer relevant because equipment with better performance is installed, building envelopes (newer windows, roof, etc.) are improved or other similar changes occur. Human factors also play into this as well. This can include space loading and mission (use) changes; poorly trained operations staff; who often make the final determination on how to operate the various systems (including manual set points and overrides); or poorly designed systems (sizing, control sequences, etc.).

BASs have been sold as an improvement over mechanical (pneumatic) controls and electric/electronic controls with the promise of better control response, more accurate sensing and the ability to operate with fewer human resources. While this is true, many BASs are often found with fixed set point values, modified alarm settings (that no longer provide alarms when equipment or systems are not operating as designed), numerous overrides on equipment schedules, set points, commanded values and other man-made anomalies. Within a short period of time (often within a few months after the BAS installation), these BAS operational changes become the "legacy" (standard) mode of operation. This mode of operation cannot succeed in "optimizing" building systems and equipment or in creating improvements that are sustained or significant.

There is general agreement that retro-commissioning (RCx)[2,3,4] of existing buildings saves energy, with most reported savings in the range of 10% to 30% of the total building energy consumption. However,

---

[2] Commissioning is a systematic quality assurance process that spans the entire design and construction process, helping ensure that the new buildings' performance meets owners expectations - http://www.documents.dgs.ca.gov/green/commissionguidenew.pdf

Although there are number definitions of RCx, the commonly used definition is a systematic method for investigating how and why existing buildings' systems are operated and maintained and identifying ways to improve overall building performance. http://www.documents.dgs.ca.gov/green/commissionguideexisting.pdf

[3] For more information refer to Fernandez N, S Katipamula, W Wang, Y Huang, and G Liu. 2012. Energy Savings Modeling of Standard Commercial Building Re-tuning Measures: Large Office Buildings. PNNL-21569, Pacific Northwest National Laboratory, Richland, WA.

RCx as it is practiced today is perceived as not cost effective and also does not guarantee persistence. Many of the operational problems that are detected during the RCx process can be detected automatically and continuously allowing the buildings to operate near optimally. PNNL developed the re-tuning process to address some of the issues associated with RCx. However, to ensure persistence, the re-tuning process has to be applied periodically. The algorithms described in this document will allow continuous and automatic re-tuning leading to and ensuring persistence of operations. These diagnostics will reduce the cost of implementing RCx. This document provides the details of algorithms that will be developed as part of this task and a deployment scenario.

Re-tuning is a systematic process to identify and correct operational problems that plague commercial buildings with BASs. Correction of many of these problems requires no cost or very little cost. The problems identified as part of this process can include:

- Excessive temperatures (too high, too low) for various heating ventilation and air conditioning (HVAC) systems including supply air, chilled water and hot-water systems
- Overrides on set points and equipment (intended for short periods of time), but forgotten and left in place (for long periods of time)
- Resets on set points for supply-air temperatures (SAT) and static pressures that are not working or locked (too high, too low, fixed)
- Resets on set points for chilled water supply temperatures and chilled water loop differential pressures that are not working or locked (too high, too low, fixed)
- Resets on set points for heating hot-water supply temperatures and heating hot-water loop differential pressures that are not working or locked (too high, too low, fixed)
- Equipment running under low load conditions (low Delta T – difference between supply and return water) for hot-water and chilled-water systems
- Equipment running when the building is not occupied and there is no demand for those systems (air handling units, chiller plant, heating hot-water plant, etc.).

The re-tuning process can be applied using a semi-automated process to identify operational problems and correcting the problems (i.e., for operational faults where set point or controls adjustments or removing operator overrides will remedy the problem). This approach can lower the cost for retro-commissioning; however, to ensure persistence, the re-tuning process has to be applied periodically. In some cases, these efforts may require re-programming of existing control sequences or adding new control sequences to remedy problems identified above (manual correction or replacement of faulty equipment).

Many operational problems that are identified during re-tuning can be detected automatically and continuously, allowing the buildings to operate near optimally, leading to a lower RCx cost and increased persistence. There are a number of re-tuning measures that can be detected automatically. Similar to a

---

[4] See Evan Mills. 2009. "Building Commissioning: A Golden Opportunity for Reducing Energy Costs and Greenhouse-gas Emissions." The reported median whole-building savings were 16% from retro-commissioning.

semi-automated/manual re-tuning process, the automation of detecting re-tuning measures for the re-tuning process relies upon analysis of real-time or near real-time data collected from the BAS to detect and diagnose operational problems that can be corrected with no- or low-cost actions. The automation of detecting these re-tuning measures has the potential to tap into 60 to 80% of the savings attributed to RCx with very little investment; it also ensures the long-term persistence of savings.

Automatic retro-commissioning (auto RCx) uses computer algorithms to ensure that buildings operate continuously at peak efficiency. Auto RCx ensures that the building staff focus on activities for which their intervention is essential (e.g., replacing components that have physically failed or degraded reducing efficiency and increasing the cost of operation) and correcting operational problems that can be corrected without operator intervention leading a way to self-healing control systems.

1.1 Selection of Algorithms

A number of algorithms were developed in 2010 as part of a Cooperative Research and Development Agreement (CRADA) with KGS Buildings LLC (KGS). Using the 2010 diagnostic algorithms as a basis, PNNL reviewed and prioritized a list of common problems that can not only be detected and diagnosed automatically but *some* can be corrected automatically as well. These enhanced algorithms, when deployed in buildings, will allow for continuous and automated re-tuning of commercial buildings.

Initially, nine re-tuning measures are selected for automation, these include:

1. Detection, diagnosis and correction of high duct static pressure in variable air volume (VAV) air handling units (AHUs)
2. Detection, diagnosis and correction of low duct static pressure in VAV AHUs
3. Detection, diagnosis and correction of high supply-air temperature (SAT) in VAV AHUs
4. Detection, diagnosis and correction of low SAT in VAV AHUs

The first four algorithms include automated detection, diagnosis, reporting and *correction*, while the remainder will only involve automated detection, diagnosis and reporting.

1.2 Deployment of Algorithms

All algorithms are coded in the Python programming language and made compatible with the Transactional (VOLTTRON[5]) Network[6] framework and the OpenEIS framework. The auto RCx process involves five basics steps:

1. Collect relevant data/information
2. Detect the problem or re-tuning measure
3. Diagnose the cause of the problem or re-tuning measure
4. Report the problem to the operator, and
5. Automatically correct the problem.

---

[5] For more information on VOLTTRON, see Footnote 3. Also see Lutes RG, S Katipamula, BA Akyol, ND Tenney, JN Haack, KE Monson, and BJ Carpenter. 2014. VOLTTRON: User Guide. PNNL-23182, Pacific Northwest National Laboratory, Richland, WA.

[6] For information on the Transactional Network, see Haack JN, S Katipamula, BA Akyol, and RG Lutes. 2013. VOLTTRON Lite: Integration Platform for the Transactional Network. PNNL-22935, Pacific Northwest National Laboratory, Richland, WA.

To collect data and to deploy the auto RCx part of the algorithm the BACnet driver from the VOLTTRON agent execution platform is critical. This driver was developed as part of a separate project. The driver allows for two-way communication to BACnet compatible controllers and BASs.

The following convention is used in this report to identify the various variables used for diagnostics:

- *Italics* style: configurable constant value
- **Bold** style: data measurement
- ***Bold*** italic style: data array of measurement
- Normal Style: calculated value

Although the BACnet driver is essential for the auto-correction, the detection and the diagnostics steps can be deployed using data collected from offline processes (i.e., CSV text files) as well. So, there are number of different ways these algorithms can be deployed, as shown in Figure 1. The remainder of this report will be dedicated to documenting the re-tuning diagnostics.

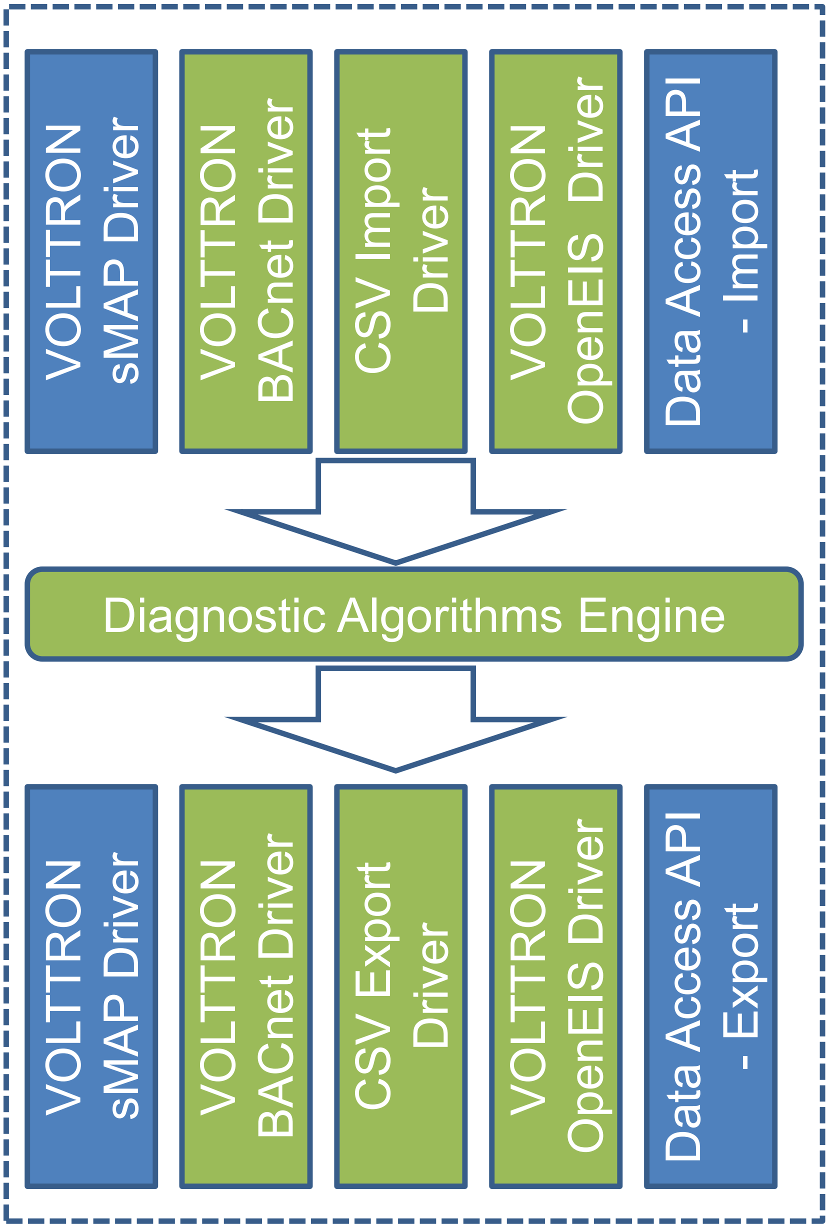


Figure 1: Deployment Options for Auto RCx Algorithms

2 Air-side Auto-Detect and Auto-Correct RCx Algorithms

The air-side auto-detect and auto-correct RCx processes utilize a decision tree structure to detect, diagnose and automatically provide corrective actions to the problems associated with an AHU's operation.

Detecting and diagnosing problems within an AHU is crucial because they can increase system energy expenditures and affect the comfort of occupants. The air-side re-tuning diagnostics are designed to monitor conditions within the AHU and the zones served by the AHU using sensors and control points that are typically associated with the AHU and zone controllers. When a problem is detected, the diagnostic identifies the problem and notifies the operator of the problem and the potential cause.

The air-side diagnostics detect the following operational problems: 1) low SAT, 2) high SAT, 3) no reset for the SAT set point, 4) fan operation during unoccupied time periods, 5) low duct static pressure, 6) high duct static pressure, and/or 7) no reset for the duct static pressure set point.

The diagnostic algorithms utilize rules derived from engineering principles of proper and improper AHU operations. There are seven air-side diagnostics corresponding to the seven operational problems; the air-side diagnostics include:

1. Detect whether the SAT for an AHU is too low
2. Detect whether the SAT for an AHU is too high
3. Detect whether the SAT set point for an AHU is reset or fixed
4. Detect whether the fan is operational during unoccupied time periods
5. Detect whether the duct static pressure for an AHU is too low
6. Detect whether the duct static pressure for an AHU is too high
7. Detect whether the duct static pressure set point for an AHU is not reset.

The intent of these algorithms is to provide actionable information to building owners and operations staff while minimizing false alarms. In addition to providing actionable information, these algorithms can be configured to provide automated corrective actions. The remainder of this section will provide a more detailed summary of the seven algorithms to detect, diagnose and provide automated corrective actions.

2.1 Air-side Automated RCx Main Diagnostic Process

For the automatic RCx process to be initiated, the following condition must be met:

- The AHU supply-fan status shows that the fan is ON. If the supply-fan status is not available the suuply-fan speed signal can be used as an indicator of the fan status (i.e., if the supply-fan speed is greater than the minimum fan speed (*LowFanSpeed* = 20%), consider the fan to be ON).

A list of configuration parameters for the air-side diagnostics include (with default values):

1. Automatic RCx (*AutoRCx flag*) flag = False

2. Number of required data points for RCx (*NRequiredData*) = 10
3. Minimum elapsed time for analysis (*MinAnalysisTime*) = 15 minutes
4. High supply fan (*HighFanSpeed*) threshold = 95%
5. Low supply fan (*LowFanSpeed*) threshold = 20%
6. Allowable set point deviation (*Allowable SPDev*) = 10%
7. SAT set point RCx increment/decrement (*RCxSAT*) = 1 ^{o}F
8. Duct static pressure RCx increment/decrement (*RCxStcPr*) = 0.15 inch w.g.

Low SAT auto-correct RCx adjustable parameters:

9. Maximum SAT set point (*MaxSATSP*) = 75 ^{o}F
10. Percent reheat (*PercentRht*) threshold = 25%
11. Reheat “ON” (*RhtON*) threshold = 10%
12. Reheat valve (*ZRhtVlv*) threshold = 50%

High SAT auto-correct RCx adjustable parameters:

13. High damper (*HighDmp*) threshold = 80%
14. Reheat ON (*RhtON*) threshold = 5%
15. Minimum SAT set point (*MinSATSP*) = 50 ^{o}F
16. Percent damper (*PercentDmp*) threshold = 50%
17. Zone high damper (*ZHighDmp*) threshold = 90%
18. Percent reheat (*PercentRht*) threshold = 25%

No SAT set point reset auto-detect RCx adjustable parameters:

19. SAT reset (*ResetSAT*) threshold = 5 ^{o}F

Unoccupied fan operation auto-detect RCx adjustable parameters:

- Unoccupied time (*UnnoccTime*) threshold = 30%
- Unocuppied static pressure (*UnoccStcPr*) threshold = 0.25 inch w.g.
- Building schedule (*BldSch*) = [6:00 AM - 8:00 PM]
    - Monday = [6:00 AM – 8:00 PM]
    - Tuesday = [6:00 AM – 8:00 PM]
    - Wednesday = [6:00 AM – 8:00 PM]
    - Thursday = [6:00 AM – 8:00 PM]
    - Friday = [6:00 AM – 8:00 PM]
    - Saturday = Unoccupied

- Sunday = Unoccupied

Low duct static pressure auto-correct RCx adjustable parameters:

20. Zone low damper (*ZLowDmp*) threshold = 10%
21. Zone high damper (*ZHighDmp*) threshold = 90%
22. Maximum duct static pressure set point (*MaxStcPrSP*) = 3.0 inch w.g.

High duct static pressure auto-correct RCx adjustable parameters:

23. High duct (static pressure) zone damper (*HDZDmp*) threshold = 30%
24. Minimum duct static pressure set point (*MinStcPrSP*) = 0.5 inch w.g.

No duct static pressure set point reset auto-detect RCx adjustable parameters:

25. Static pressure reset (*StcPrReset*) threshold = 0.25 in. w.g.

In subsequent sections, when describing RCx measures AVG(), MIN(), MAX(), and LEN() will be used to indicate array operations that return the average value, minimum value, maximum value, and length (number of elements) of an array or list of elements. ABS() will be used to indicate a mathematical operation that returns the absolute value of a number.

The air-side automated RCx main process handles the diagnostics pre-requisites (i.e., pre-requisites that apply to all the air-side diagnostics) and data management (passing thresholds values to the diagnostics and initializing the analysis dataset arrays) for all seven diagnostics sub-processes (Figure 2).

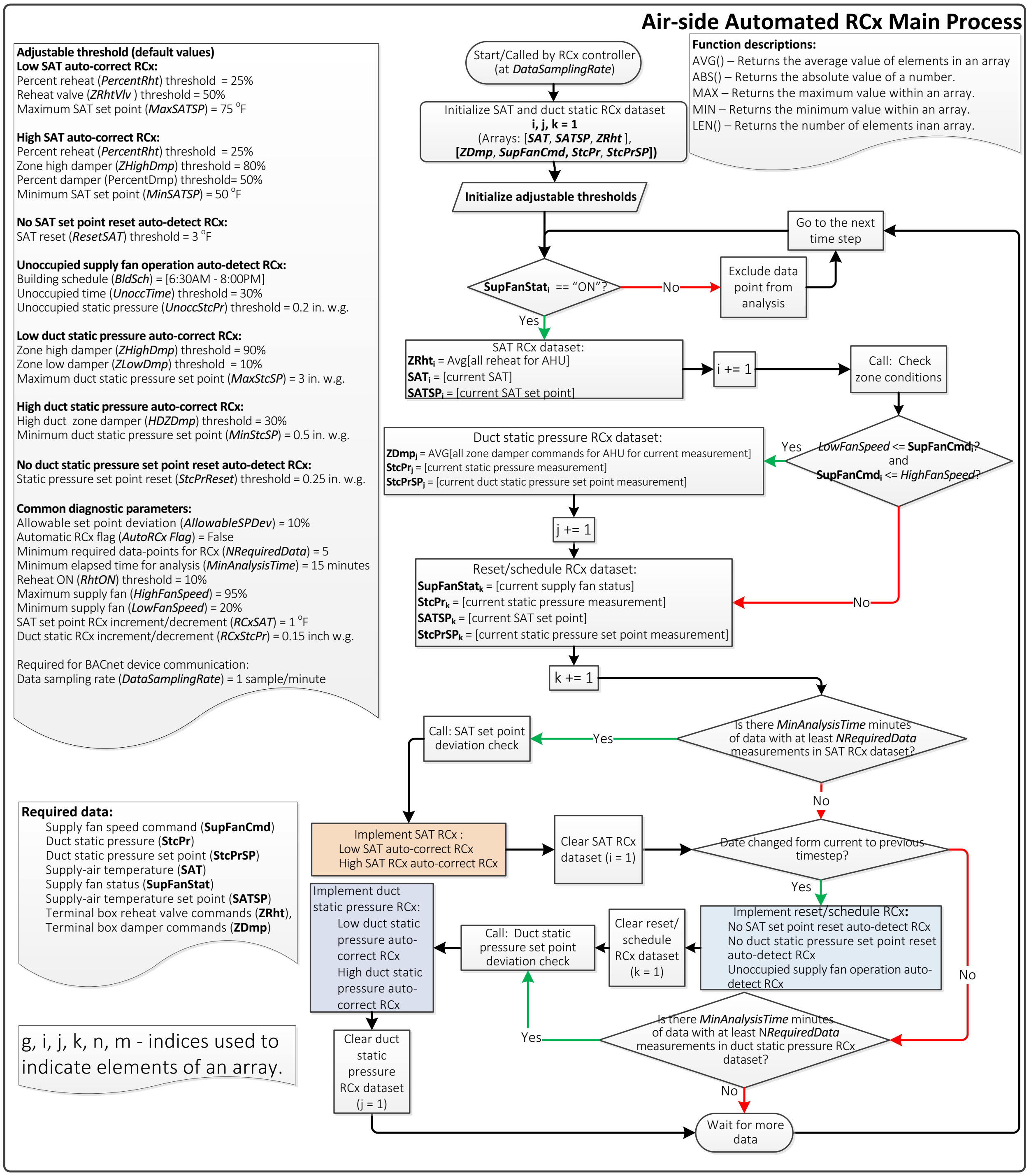


Figure 2: Flow chart for Air-side Automated RCx Main Process

Figure 3 contains three diagnostic functions called within the main air-side automated RCx main process. These checks verify that the duct static pressure is not deviating significantly from the duct static pressure set point, confirms the SAT is not deviating significantly from the SAT set point, and check zone conditions that will be used in the subsequent SAT and duct static pressure auto-correct RCx diagnostics.

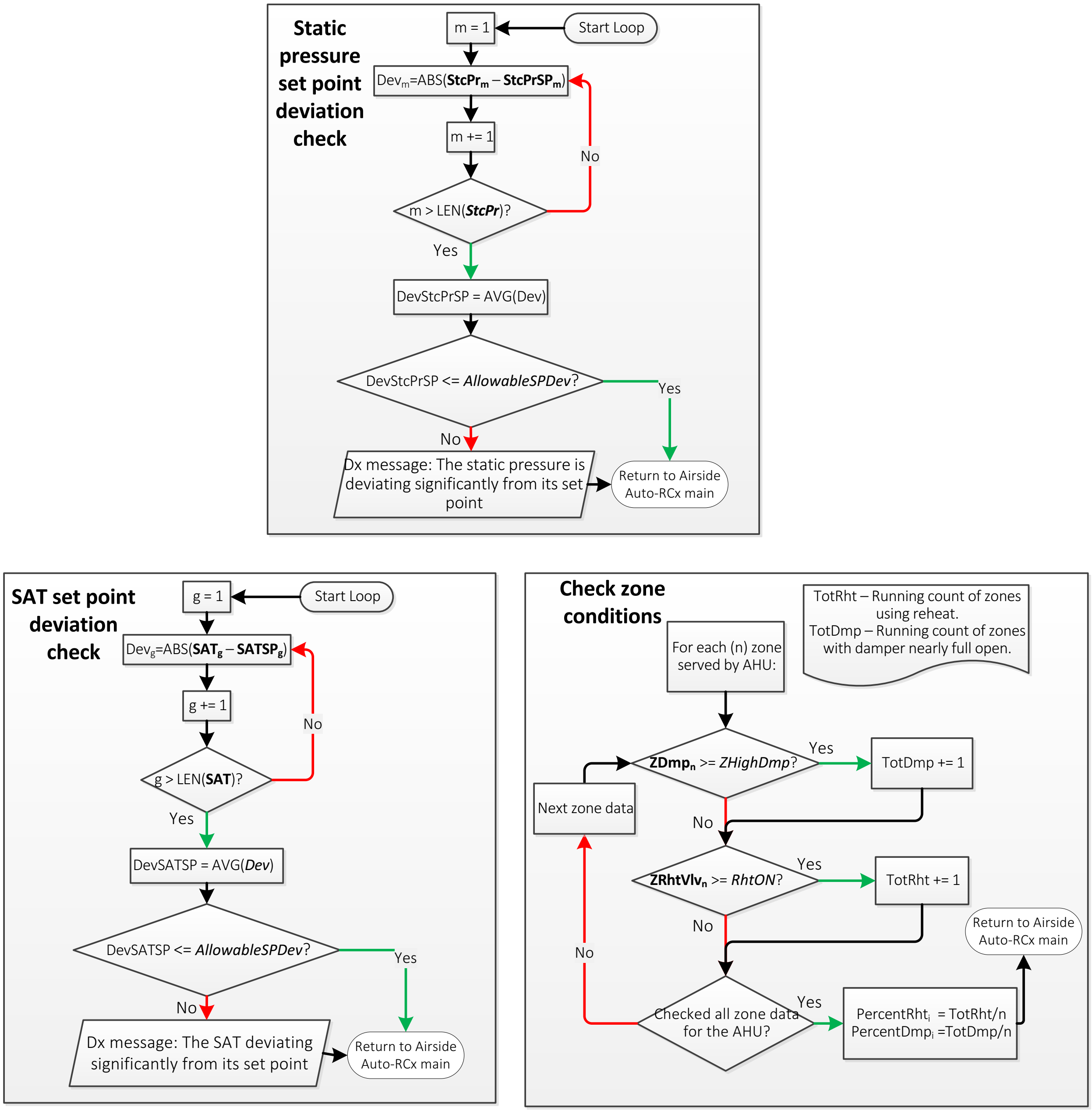


Figure 3: Functions Called within Air-side Automated RCx Main Process

2.2 Low Supply-air Temperature Auto-Correct RCx Process

The purpose of the low SAT auto RCx measure is to identify the re-tuning opportunities within the SAT control strategy. This auto-correct RCx process can be implemented on single duct VAV AHUs where the AHU does not have a heating coil. For this type of an AHU, the heating or reheating of air usually occurs at the zone level within the zone terminal box.

Conditions at the zone level can be used to diagnose operational issues at the AHU. When AHU's supply fan is ON, the zone reheat valve positions can be used to determine if the SAT is too low. When air supplied to the zone is too cold a reheat valve is opened to allow hot-water to circulate through the valve (electric resistance reheat is also common) and warm the air before it is discharged into the zone. If a large percentage of zones served by an AHU during the occupied period are using reheat, it is an indicator that the AHU's SAT set point is too low.

Increasing the SAT set point will decrease energy consumption but may increase the humidity ratio of the supply air. High humidity ratio of the supply air can lead to discomfort in the zones served by the AHU. For deployment in climate zones where high humidity is a concern, it is advisable to run this diagnostic without auto-correction enabled (*AutoRCx flag* = True) or change the auto-correction flag seasonally or use outdoor humidity measurement to automatically limit auto-correction when outdoor humidity levels are greater than 75% RH.

2.2.1 Proposed Auto-Correct RCx Action for Low SAT

When the user has configured the *AutoRCx flag* = True, and the diagnostic measure has detected a re-tuning opportunity, the existing SAT set point will be adjusted to a higher value. If the *AutoRCx flag* = False, then no automatic action(s) will occur. Automatic actions are based upon the following parameters and assumptions:

- There are no overrides pertaining to the SAT set point.
- There are no overrides pertaining to related equipment (heating or cooling coil commands, etc.). If overrides are in place and can be detected, there will be no attempt to adjust the set point. An automatic re-tuning error/fault message (indicating that the automatic correction could not be executed) will be generated.

A maximum SAT set point (*MaxSATSP*) is required as an input. The maximum SAT set point sets a high limit on the SAT. If the maximum SAT set point is reached during auto-correction and the algorithm determines that the SAT set point is still too low, a message will be generated for the user that specifies that the maximum value for the SAT set point has been reached and the SAT is still too low. The building operator/user can then choose whether the configurable parameter, *MaxSATSP,* should be increased further. Setting a maximum value for the SAT set point will help to ensure that the cooling needs for the zones served by this AHU are met. While increasing the SAT set point will save energy (lower pumping requirements for chilled water in AHU cooling coil and can reduce supply-fan energy in some cases), it may also compromise occupant comfort. Generally, the maximum SAT set point should not exceed 70^{o}F.

The high SAT auto-correct RCx measure will adjust the SAT set point to a higher value at a rate that does not create system instability. This rate is a configuration parameter and its value is adjustable by the user. This diagnostic should be run, once every 15 minutes (at most, adjustable by modifying parameter called *MinAnalysisTime*).

This continuous diagnostic will automatically apply the re-tuning measure, increasing the SAT set point, until the diagnostic determines that zones conditions indicate a suitable SAT set point has been achieved or the maximum SAT set point is reached.

2.2.2 Monitored Data for Low SAT Auto-Correct RCx

This section describes the required input data for this auto RCx diagnostic. The following data points are required for the execution of this diagnostic:

1. Supply-fan status (**SupFanStat**) or the supply-fan speed command (**SupFanSpeed**)
2. All reheat valve commands from the terminal box controllers or BAS (**ZRht**)
3. Running total of the number of zones that are reheating during the current analysis dataset (TotRht)
4. SAT set point (**SATSP**)
5. **SAT**
1. SAT set point control point priority (optional)
2. AHU cooling coil valve command control point priority (optional)
3. Supply fan variable-frequency drive (VFD) command control point priority (optional)

2.2.3 Low SAT Auto-Correct RCx Diagnostic Process

This section provides the RCx diagnostic details including a detailed flow chart (Figure 4).

The following steps are used to detect the re-tuning opportunity (step 1 and step 2 occur in the air-side automated RCx main diagnostic Process but are included here to add clarity to the RCx process):

1. Calculate the percent of zones where the terminal box reheat valve command is greater than the *RhtOn* threshold and append this value to the PercentRht array.

2. If the *MinAnalysisTime* has been reached and there are at least *NRequiredData* measurements in the analysis dataset,
    - Proceed to step 3.

   Else, the *MinAnalysisTime* has not been reached or there are not at least *NRequiredData* measurements in the analysis dataset,
    - Proceed to step 8.

3. Calculate the average percent of zones over the analysis period (AvgPercentRht) where the terminal box reheat valve command is greater than the *RhtOn* threshold,
    - AvgPercentRht = AVG(PercentRht)

4. Check zone conditions, terminal box reheat valve command, to detect operational problems:
    - If AvgPercentRht > *PercentRht* (percent reheat threshold):
        - Proceed to step 5.
    - If AvgPercentRht ≤ *PercentRht* (percent reheat threshold):
        - Generate diagnostic message: No problems detected for low SAT auto-correct RCx.
        - Proceed to step 7.

5. Calculate AvgRht (average zone reheat valve command) in the current analysis dataset,
    - If AvgRht > *ZRhtVlv* (zone reheat valve threshold):
        - Proceed to step 6.

- If AvgRht ≤ *ZRhtVlv* (zone reheat valve threshold):
    - Generate diagnostic message: No problems detected for low SAT auto-correct RCx.
    - Proceed to step 7.

6. If *AutoRCx flag* == True:
    - Ensure that auto-correction will not increase the SAT set point above the maximum configured SAT set point (*MaxSATSP*). Calculate the intended auto-corrected SAT set point (RCxSATSP).
    - RCxSATSP = **SATSP** + *SATSPInc* (**SATSP** is the current SAT set point)
        - If RCxSATSP ≥ *MaxSATSP:*
            - Generate diagnostic message: The SAT set point has reached the maximum configured SAT set point but zone conditions still indicate that the SAT is too high.
            - **SATSP** = *MaxSATSP*
        - If RCxSATSP < *MaxSATSP:*
            - Generate diagnostic message: The SAT has been detected to be too low. The SAT set point has been increased during the auto-correct RCx process.
            - **SATSP** = RCxSATSP
    - Proceed to step 7.

    If *AutoRCx flag* == False:
    - Generate diagnostic message: The SAT has been detected to be too low but auto-correction is not enabled.
    - Proceed to step 7.

7. Send the command to the BAS or AHU controller, set the new **SATSP** (if a re-tuning opportunity was detected and auto-correction is enabled) and make diagnostic message(s) available for operator.

8. Return to the air-side automated RCx main diagnostic, and wait for next available data.

The BACnet data interface queries data off the local controller or BAS every **"**Data Sampling Rate" minutes. The data is then supplied to the algorithm, which executes every "Data Sampling Rate". The execution of the diagnostic is identical for metered data provided via csv file except no auto-correction can be applied.

The following list contains the adjustable thresholds and parameters for this diagnostic:

- Minimum elapsed time for analysis (*MinAnalysisTime*) = 15 minutes
- Number of required data points for RCx (*NRequiredData*) = 5
- Maximum SAT set point (*MaxSATSP*) = 75 ^{o}F
- SAT set point auto-correct increment/decrement (*RetuningSAT*) = 1 ^{o}F
- Percent reheat (*PercentRht*) Threshold = 25%
- Reheat valve (*ZRhtVlv*) threshold = 50%
- Reheat is ON (*RhtOn*) threshold = 10%

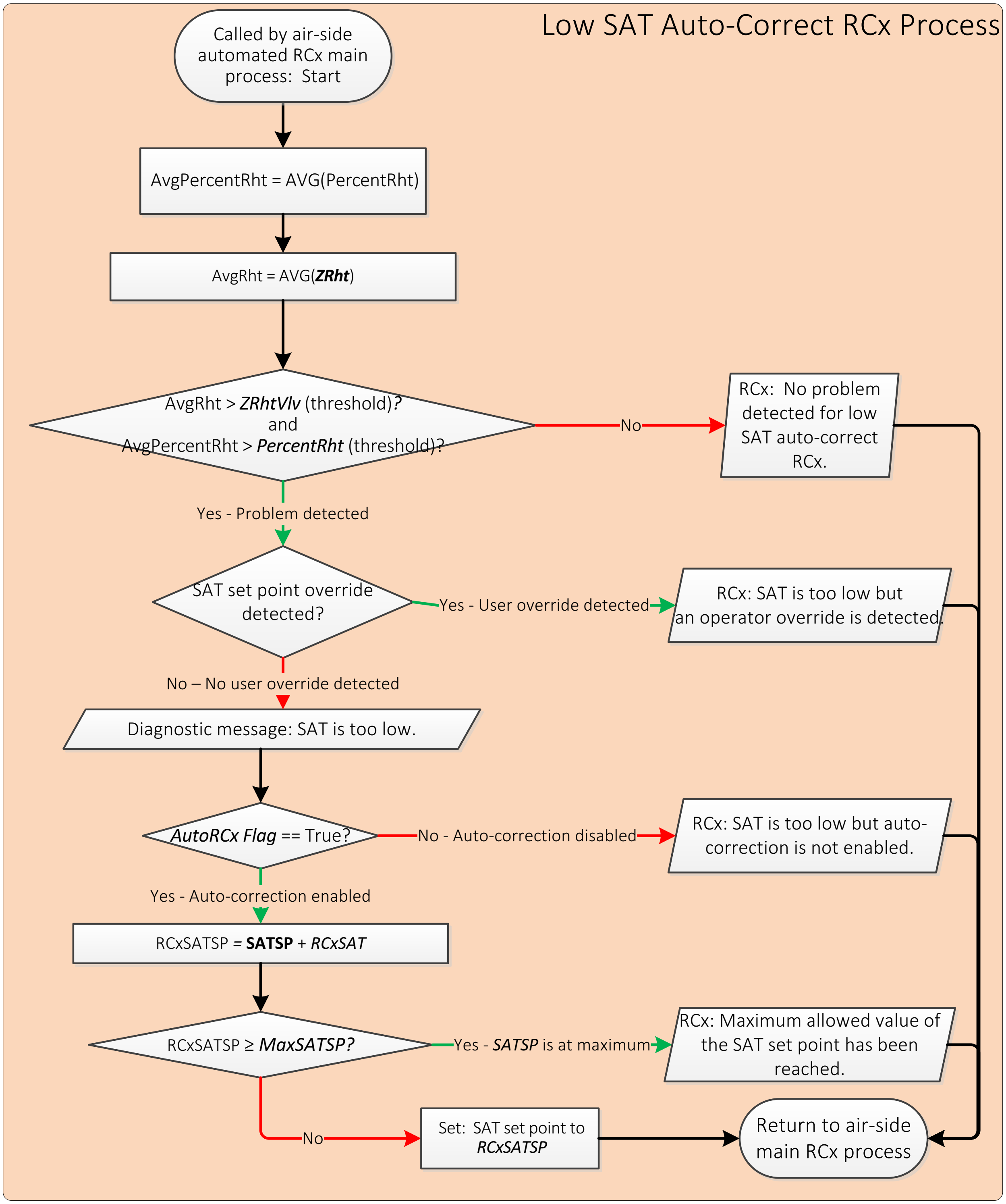


Figure 4: Flow Chart for Low SAT Auto-Correct RCx Process

2.3 High Supply-air Temperature Auto-Correct RCx Process

The purpose of the high SAT auto-correct RCx process is to identify re-tuning opportunities with the SAT control strategy. This auto-correct RCx process is intended for use on single-duct VAV AHUs, where the

AHU does not have a heating coil. For this type of an AHU, the heating or reheating of air usually occurs at the zone level within the zone terminal box.

When the supply fan is ON, the zone damper commands coupled with the zone reheat commands can be used to detect if the SAT is too high. When a large percentage of zones have dampers that are fully open, in an attempt to maintain space temperatures, it is indicative of a SAT that is too high. If a large percentage of zones have dampers that are fully open, it is also important to verify that very few zones are utilizing reheat. Zone reheat is used to heat air supplied by the AHU that is too cold for the space (common zone reheat methods include hot-water reheat and electric resistance reheat). If more than 25% (adjustable threshold) of zones are using reheat, the SAT set point should not be lowered. A high SAT could indicate an equipment failure within the AHU (chilled water valve is not modulating) or the chilled water system (chiller is off, not functioning properly, or chilled water supply pumps are malfunctioning). If the AHU is unable to maintain the SAT near the SAT set point, the diagnostic will alert the building operator/user.

Lowering the SAT set point may allow the system to deliver a lower supply air flow while still maintaining space temperatures. This reduction in air flow can lead to fan energy savings. Lowering the SAT will also lead to drier air; this results in improved comfort, especially in climate regions that experience humid weather. Lowering the SAT set point may increase the load on the chiller.

2.3.1 Proposed Auto-Correct RCx Action for High SAT

When the user has configured the *AutoRCx flag* = True, and the diagnostic measure has detected a re-tuning opportunity, the existing SAT set point will be adjusted to a higher value. If the *AutoRCx flag* = False, then no automatic action(s) will occur. Automatic actions are based upon the following parameters and assumptions:

- There are no overrides pertaining to the SAT set point.
- There are no overrides pertaining to related equipment (cooling coil commands, etc.). If overrides are in place and can be detected, the SAT will not be modified. An automatic re-tuning error message will be generated that informs the software user that auto-correction cannot be performed while the equipment is in an override state.

A minimum SAT set point (*MinSATSP*) is required as an input by the software user. The *MinSATSP* sets a limit on the auto-correct RCx process and the amount the SAT set point can be reduced. This ensures that safety components (low temperature thermostats, etc.) are not tripped and that excessively cold air is not allowed to be introduced into the AHU from outside via the economizer damper. If the minimum SAT set point is reached during auto-correction and the algorithm determines that the SAT set point is still too high, a message will be generated for the user that specifies that the minimum value for the SAT set point has been reached and the SAT set point is still too high. The software user can then choose whether the configurable parameter *MinSATSP* will be reduced further. Exercise caution to ensure that safety components (low temperature thermostats, etc.) are not tripped inadvertently or that excessively cold air is allowed into the air handler during cold weather, as a result of improper SAT set points.

The automatic re-tuning measure will adjust the SAT set point to a lower value at a rate that does not create system instability. This diagnostic should be run, once every 15 minutes (at most, adjustable by modifying parameter called *MinAnalysisTime*).

This continuous diagnostic will automatically apply the re-tuning measures, lowering the SAT set point, until the diagnostic determines that zones conditions indicate a suitable SAT set point has been achieved or the *MinSATSP* is reached.

2.3.2 Monitored Data for High SAT Auto-Correct RCx

This section describes the required input data for this auto RCx diagnostic. The following data points are required for the execution of this diagnostic:

4. Supply-fan status (**SupFanStat**) or the supply-fan speed command (**SupFanSpeed**)
5. All reheat valve commands from the terminal box controllers or BAS (**ZRht**)
6. All damper position commands from the terminal box controllers or BAS (**ZDmp**)
7. Running total of the number of zones that are reheating during the current analysis dataset (TotRht)
8. Running total of the number of zones where the terminal box damper command exceeds the *ZHighDmp* during the during the current analysis dataset (TotDmp)
9. SAT set point (**SATSP**)
10. **SAT**
11. SAT set point control point priority (optional)
12. AHU cooling coil valve command control point priority (optional)
13. Supply fan variable-frequency drive (VFD) command control point priority (optional)

2.3.3 High SAT Auto-Correct RCx Diagnostic Process

This section provides the RCx diagnostic details including a detailed flow chart (Figure 5).

The following steps are used to detect the re-tuning opportunity (step 1 through step 3 occur in the air-side automated RCx main diagnostic process but are included here to add clarity to the RCx process):

1. Calculate the percent of zones where the terminal box reheat valve command is greater than the *RhtOn* threshold and append this value to the PercentRht array.

2. Calculate the percent of zones where the terminal box damper command is greater than the *HighDmp* threshold and append this value to the PercentDmp array.

3. If the *MinAnalysisTime* has been reached and there are at least *NRequiredData* measurements in the analysis dataset,
    - Proceed to step 4.

   Else, the *MinAnalysisTime* has not been reached or there are not at least *NRequiredData* measurements in the analysis dataset,
    - Proceed to step 10.

4. Calculate the average percent of zones over the analysis period (AvgPercentRht) where the terminal box reheat valve command is greater than the *RhtOn* threshold,
    - AvgPercentRht = AVG(PercentRht)

5. Calculate the average percent of zones over the analysis period (AvgPercentDmp) where the terminal box damper command is greater than the *HighDmp* threshold,
    - AvgPercentDmp = AVG(PercentDmp)

6. Check zone conditions, terminal box damper command, to detect operational problems:
    - If AvgPercentDmp > *PercentDmp* (percent terminal box damper threshold):
        - Proceed to step 7.
    - If AvgPercentDmp ≤ *PercentDmp* (percent terminal box damper threshold):
        - Generate diagnostic message: No problems detected for high SAT auto-correct RCx.
        - Proceed to step 9.

7. Check zone conditions, terminal box reheat valve command, to detect operational problems:
    - If AvgPercentRht < *PercentRht* (percent reheat threshold):
        - Proceed to step 8.
    - If AvgPercentRht ≥ *PercentRht* (percent reheat threshold):
        - Generate diagnostic message: No problems detected for low SAT auto-correct RCx.
        - Proceed to step 9.

8. If *AutoRCx flag* == True:
    - Ensure that auto-correction will not reduce the SAT set point below the minimum configured SAT set point (*MinSATSP*). Calculate the intended auto-corrected SAT set point (RCxSATSP).
    - RCxSATSP = **SATSP** - (**SATSP** is the current SAT set point)
        - If RCxSATSP ≤ *MinSATSP:*
            - Generate diagnostic message: The SAT set point has reached the minimum configured SAT set point but zone conditions still indicate that the SAT is too high.
            - **SATSP** = *MinSATSP*
        - If RCxSATSP > *MinSATSP:*
            - Generate diagnostic message: The SAT has been detected to be too high. The SAT set point has been reduced during the auto-correct RCx process.
            - **SATSP** = RCxSATSP
    - Proceed to step 9.

    If *AutoRCx flag* == False:
    - Generate diagnostic message: The SAT has been detected to be too high but auto-correction is not enabled.
    - Proceed to step 9.

9. Send the command to the BAS or AHU controller, set the new SAT set point to *SATSP* (if a re-tuning opportunity was detected and auto-correction is enabled) and make diagnostic message(s) available for operator.

10. Return to air-side automated RCx main diagnostic, and wait for next available data.

The BACnet data interface queries data off the local controller or BAS every **“**Data Sampling Rate” minutes. The data is then supplied to the algorithm, which executes every “Data Sampling Rate”. The execution of the diagnostic is identical for metered data provided via csv file except no auto-correction can be applied.

The following list contains the adjustable thresholds and parameters for this diagnostic:

- Minimum elapsed time for analysis (MinAnalysisTime) = 15 minutes
- Number of required data points for RCx (NRequiredData) = 5
- Reheat ON (RhtON) threshold = 10%
- Minimum SAT set point (MinSATSP) = 50 ^{o}F
- Percent damper (PercentDmp) threshold = 50%
- Zone high damper (ZHighDmp) threshold = 90%
- Percent reheat (PercentRht) threshold = 25%
- SAT set point auto-correct increment/decrement (RetuningSAT) threshold = 1 ^{o}F

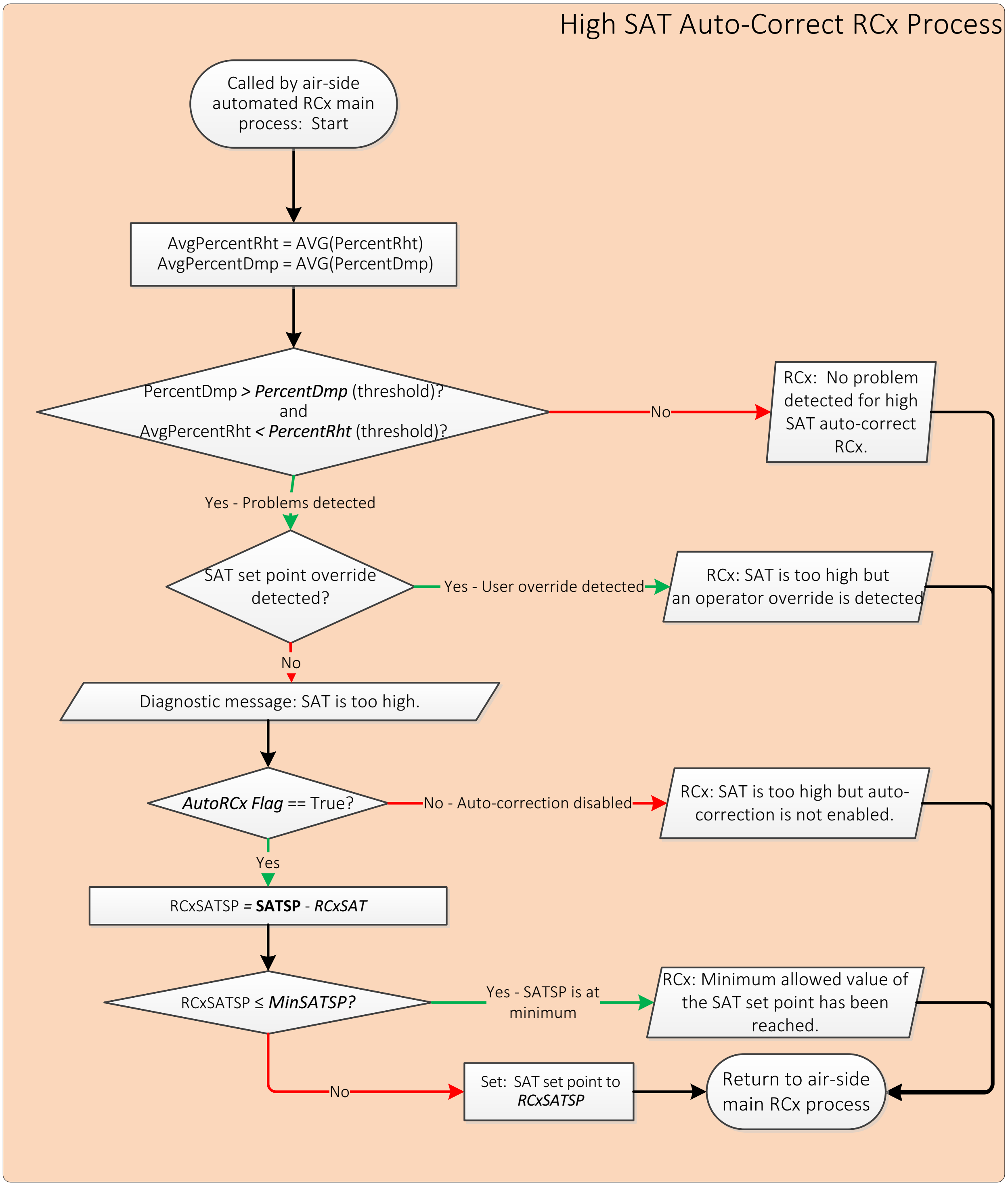


Figure 5: Flow Chart for High SAT Auto-Correct RCx Process

2.4 No Supply-air Temperature Set Point Reset Auto-Detect RCx Process

The purpose of this (No SAT Set Point Reset) diagnostic measure is to identify opportunities with the SAT control strategy. When the supply fan is ON, the SAT set point can be automatically adjusted to the load conditions, which will allow the supply fan and chiller to operate more efficiently.

Throughout the course of a day, the SAT set point for an AHU should show some variation to indicate that a SAT reset is being utilized. Typical AHU operations include morning startup, mid-day peak cooling loads, and evening shutdown. Resetting the SAT can be beneficial and save significant amounts of energy. If occupancy is low, or the zone cooling load is reduced, resetting (increasing the SAT set point) will save energy and still maintain occupant comfort. If the AHU is serving a specialized zone, like a data center, that has a nearly constant cooling load and therefore a constant SAT set point, this diagnostic should not be used.

Figure 6 shows an example of good operation where the SAT set point varies (i.e. it is reset) throughout the day. Common methods for resetting the SAT set point include reset based on the OAT, reheat valve commands, or a set schedule.

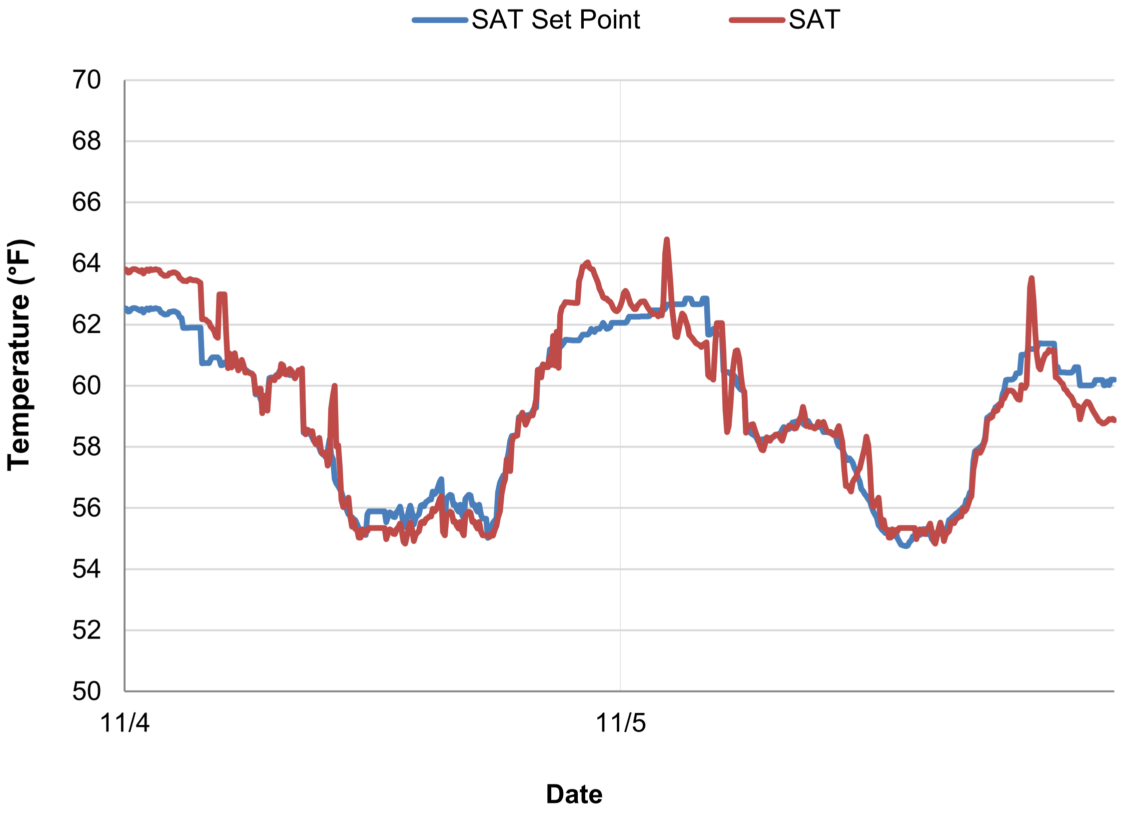


Figure 6: Example of Good Operation, SAT Set Point Shows Variation

The diagnostic presented in this section will alert the building operator/user if there is an opportunity for re-tuning and resetting the SAT set point.

2.4.1 Monitored Data for No SAT Set Point Reset Auto-Detect RCx

This section describes the required input data for this auto RCx diagnostic. The following data points are required for the execution of this diagnostic:

1. Supply-fan status (**SupFanStat**) or the supply-fan speed command (**SupFanSpeed**)
2. SAT set point (**SATSP**)
3. SAT set point control point priority (optional)

2.4.2 No SAT Set Point Reset Auto-Detect RCx Diagnostic Process

This section provides the re-tuning diagnostic details including a detailed flow chart (Figure 7). This diagnostic is executed daily, at midnight, to ensure accurate results and allow sufficient time for variation in the supply-air temperature set point to occur.

The following steps are used to detect the re-tuning opportunity (step 1 in this diagnostic occurs in the air-side automated RCx main diagnostic process but is included here to add clarity to the RCx process):

1. Upon the completion of day (i.e., midnight),
    - If there are *NRequiredData* measurements in the analysis dataset:
        - Proceed to step 2.

      Else, there is insufficient data to conduct this diagnostic.
        - Proceed to step 4.

2. Check if the SAT set point varies throughout the day,
    - If MAX(**SATSP**) - MIN(**SATSP**) ≤ *ResetSAT* (SAT set point reset threshold):
        - Generate diagnostic message: A SAT set point reset was not detected. Implementation of a SAT set point reset will save energy and improve the AHUs performance.
        - Proceed to step 3.
    - Else, generate diagnostic message: No problems detected, A SAT set point reset was not detected.
        - Proceed to step 3.

3. Make diagnostic message(s) available to operator.

4. Return to air-side automated RCx main diagnostic, and wait for next available data.

The BACnet data interface queries data off the local controller or BAS every **“**Data Sampling Rate” minutes. The data is then supplied to the algorithm, which executes every “Data Sampling Rate”. The execution of the diagnostic is identical for metered data provided via csv file except no auto-correction can be applied.

The following list contains the default but adjustable thresholds and parameters for this diagnostic:

- SAT reset (*ResetSAT*) threshold = 1 ^{o}F
- Number of required data points for RCx (*NRequiredData*) = 5

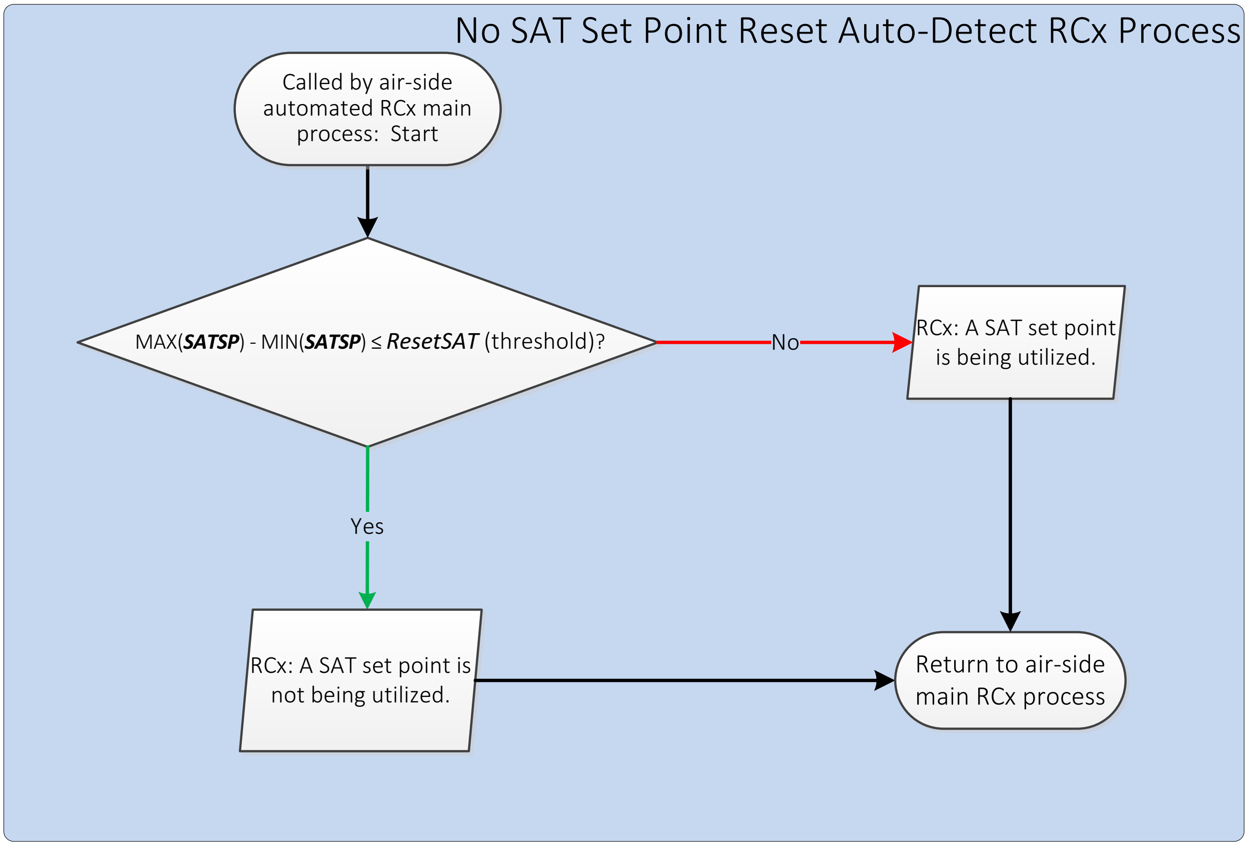


Figure 7: Flow Chart for No SAT Set Point Reset Auto-Detect RCx Process

2.5 Unoccupied Supply Fan Operation Auto-Detect RCx

The purpose of this (unoccupied period fan operation) diagnostic measure is to identify unscheduled operation of AHUs – AHUs running continuously or running during unoccupied periods. Turning off the fan, when a building or area served by an AHU is unoccupied, will yield fan energy savings and potential cooling and heating energy savings as well.

The supply fan should be turned off when the building is not occupied. There may be circumstances when the supply fan may have to run during the unoccupied periods, including warm-up events, nighttime set back (low/high space temperature events) and/or OAT events (cold or hot weather). These events could be provided as a part of building schedule, e.g., if a building working schedule is 8:00 AM-8:00 PM and the building needs to be warmed up for an hour before the working schedule, the building working scheduled can be changed to 7:00 AM-8:00 PM to accommodate that event.

In this diagnostic, the supply-fan status is used to determine the total time when the fan is running during the non-working hours. If the fan total run time exceeds a threshold, this diagnostic will alert the building operator/user that an operational fault has occurred or there is currently an opportunity for improvement. Failure to correct will result in excess energy consumption and additional wear/tear on equipment.

If the supply-fan status is not available, the duct static pressure will be used as an alternative. If the average duct static pressure during the unoccupied hours exceeds a threshold, an alert will be sent to the building operator. Because the BAS schedules and external situations that determine fan operations are subjected to change weekly, this diagnostic will need to be reviewed on a regular basis to mitigate false alarms.

2.5.1 Monitored Data Unoccupied Supply Fan Operation Auto-Detect RCx

This section describes the required input data for this auto RCx diagnostic. The following data points are required for the execution of this diagnostic:

1. AHU supply-fan speed status (**SupFanStat**) or AHU supply-fan speed (**SupFanSpeed**)
2. Duct static pressure (**StcPr**)

2.5.2 Unoccupied Supply Fan Operation Auto-Detect RCx Diagnostic Process

This section provides the re-tuning diagnostic details including a detailed flow chart (Figure 8). The following steps are used to detect the re-tuning opportunity (step 1 in this diagnostic occurs in the air-side automated RCx main diagnostic process but is included here to add clarity to the RCx process):

1. Upon the completion of day (i.e., midnight),
    - If there are *NRequiredData* measurements in the analysis dataset:
        - Proceed to step 3.

      Else, there is insufficient data to conduct the diagnostic.
        - Proceed to step 7.

2. Iterate over **SupFanStat** array and increment a counter when the supply-fan status indicates the supply fan is ON and the timestamp associated with the point indicates the building is in an unoccupied state (initialize: counter = 0).
    - For each element k in **SupFanStat** if $\mathbf{SupFanStat}_k$ == 1 and timestamp ∈ unoccupied schedule, then counter = counter + 1.

3. Calculate the percent of unoccupied time the supply fan was in operation.
    - PercentUnoccOp = (counter/LEN(**SupFanStat**)) × 100

4. Check if supply fan is excessively operating during unoccupied periods,
    - If PercentUnoccOp > *SupplySched* (supply-fan unoccupied schedule threshold)*:*
        - Generate diagnostic message: Data indicates the AHU is operating during unoccupied periods.
        - Proceed to step 6.
    - Else, proceed to step 5.

5. Check whether the average duct static pressure exceeds a threshold.
    - If AVG(**StcPr**) < *StcPrSched* (duct static pressure unoccupied schedule threshold):
        - Generate diagnostic message: No problems detected for unoccupied fan operation auto-detect RCx.
        - Proceed to step 6.

Else, generate diagnostic message: Data indicates the AHU is operating during unoccupied periods.
    - Proceed to step 6.

6. Make diagnostic message(s) available for operator.

7. Return to air-side automated RCx main diagnostic, and wait for next available data.

The BACnet data interface queries data off the local controller or BAS every **"**Data Sampling Rate" minutes. The data is then supplied to the algorithm, which executes every "Data Sampling Rate". The execution of the diagnostic is identical for metered data provided via csv file except no auto-correction can be applied.

The following list contains the adjustable thresholds and parameters for this diagnostic:

- Default Building Schedule:
    - Monday = [6:00 AM - 8:00 PM]
    - Tuesday = [6:00 AM - 8:00 PM]
    - Wednesday = [6:00 AM - 8:00 PM]
    - Thursday = [6:00 AM - 8:00 PM]
    - Friday = [6AM-8PM]
    - Saturday= Unoccupied
    - Sunday = Unoccupied
- Supply-fan unoccupied (*SupplySched*) threshold = 30%
- Duct static pressure unoccupied schedule (*StPrSched*) threshold = 0.2 inch w.g.
- Number of required data points for RCx (NRequiredData) = 5

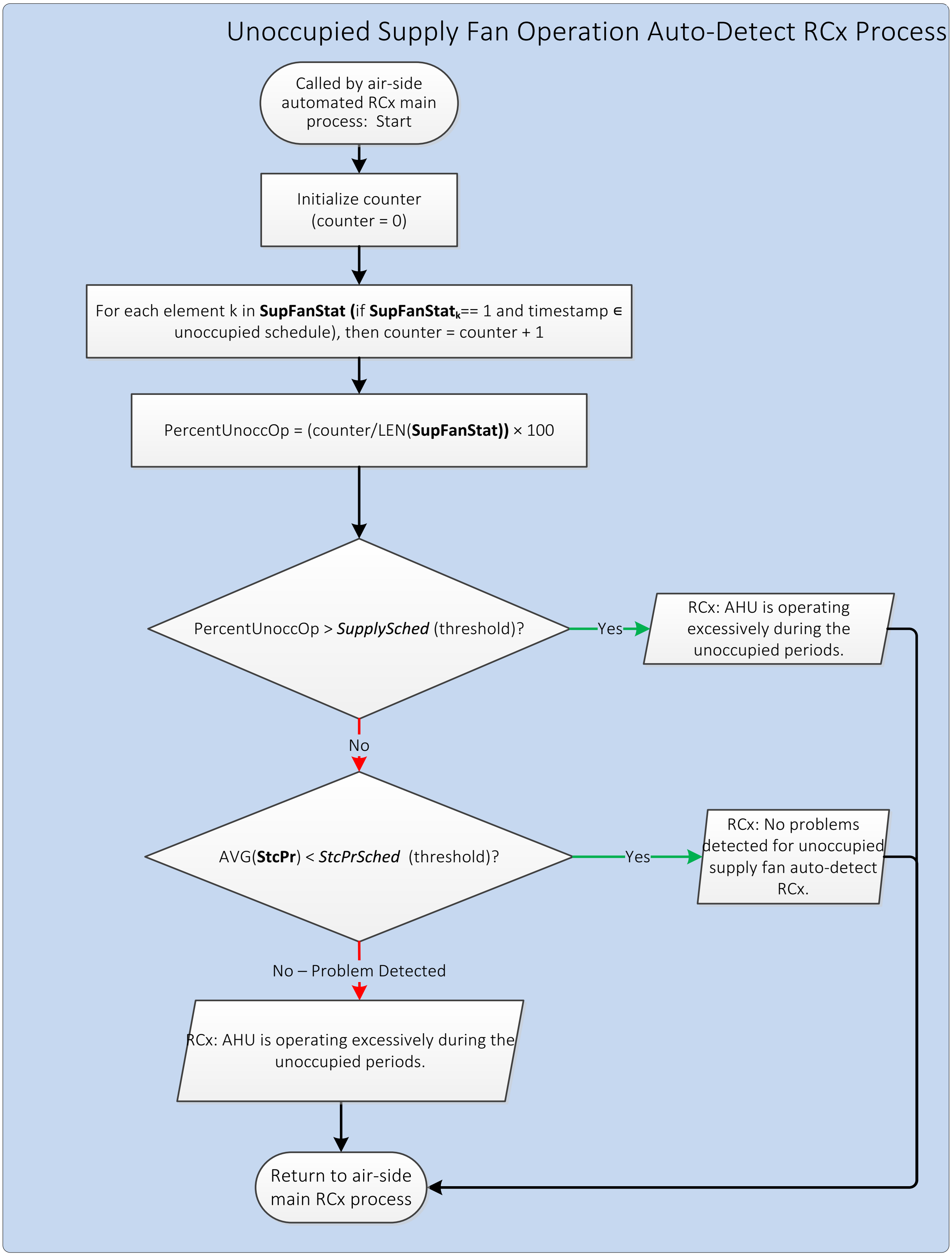


Figure 8: Flow Chart for Unoccupied Supply Fan Operation Auto-Detect RCx Process

2.6 Low Duct Static Pressure Auto-Correct RCx Process

The purpose of the low duct static pressure auto-correct RCx process is to identify conditions when the AHU duct static pressure is too low. There can be many reasons for low duct static pressure including building operator adjustments, overrides, or equipment configuration issues. A duct static pressure that is too low, if not identified and increased, will cause other system problems including “starved box” (a condition of the VAV box where the actual flow is less than the desired flow, even when the damper is 100% open) and an inability to maintain space temperatures. Fixing the low duct static pressure condition will not conserve fan energy (it may actually consume more fan energy) but it may improve occupant comfort. Other auxiliary system effects that stem from low supply-fan duct static pressure (additional run hours at the supply fan, lowered SAT set point and related efforts to solve comfort problems) can also be mitigated when low supply-fan duct static pressure is fixed.

If duct static pressure is too low and the supply fan is running at low speed (less than 100%), the result could be that the fan is providing less air flow than required. This mismatch can cascade into other areas that affect equipment performance and occupant comfort. Building operator actions (set point overrides, etc.) can have an adverse impact on the supply-fan system.

When the time-average value for zone VAV damper command(s) is greater than a given threshold value for a known time period, the diagnostic will alert the building operator/user that a re-tuning opportunity has been detected, and there is currently an opportunity for improvement (increase the supply-fan duct static pressure set point). Figure 9 shows an example of poor operations. Nearly all the zone dampers are fully open indicating that the zones need more air flow. This is indicative of a static pressure set point that is too low. This can also indicate duct work that has breached (failed) and may necessitate the operations and maintenance staff to identify possible duct failures (either above the drop ceiling or in other hard-to-reach areas where duct work is located or ran). Figure 10 shows an example of good operations. Most of the zone dampers are between 50% and 75% open.

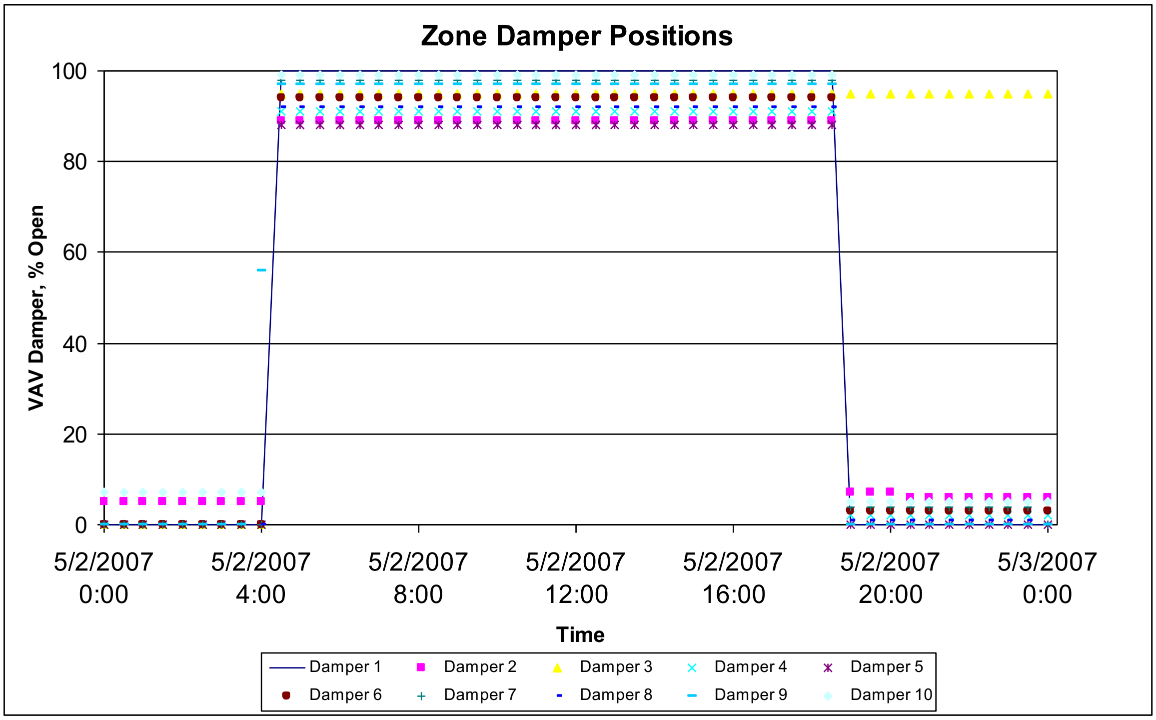


Figure 9: Example of Bad Operation – All Zone Dampers Are nearly 100% Open

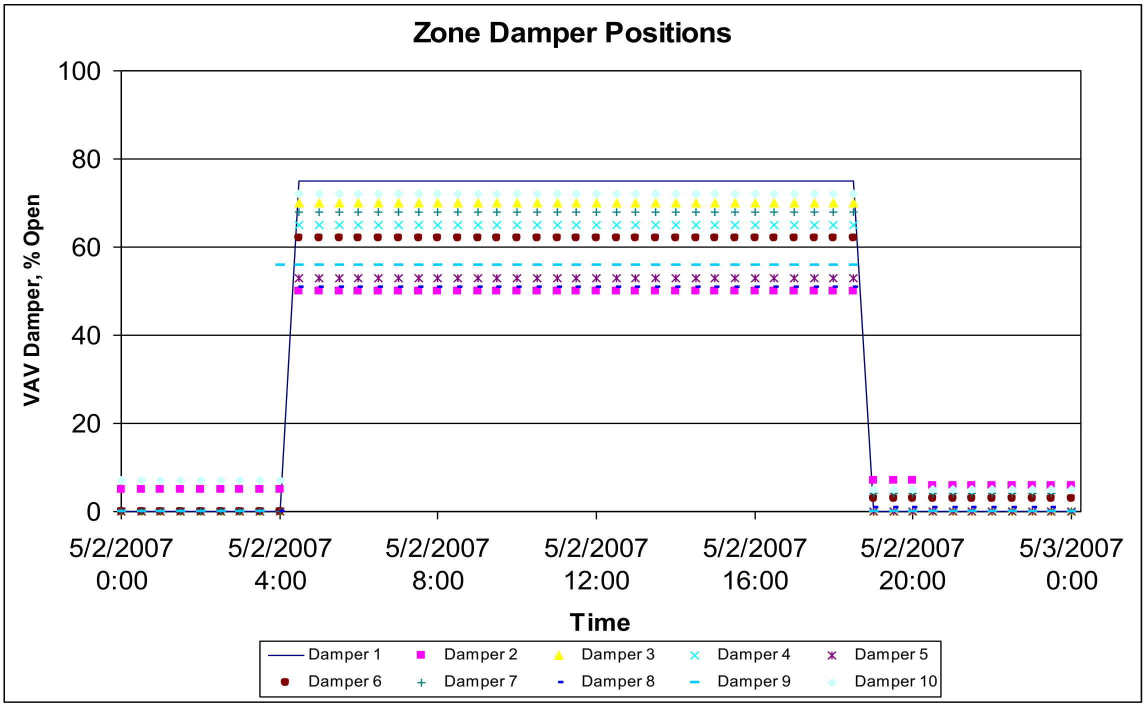


Figure 10: Example of Good Operations – Most Zone Dampers Are Open Between 50% and 75%

2.6.1 Proposed Auto-Correct RCx Action for Low Duct Static Pressure

When the user has configured the *AutoRCx flag* = True, and the diagnostic measure has detected a re-tuning opportunity, the existing duct static pressure set point will be adjusted to a higher value. If the *AutoRCx flag* = False, then no automatic action(s) will occur. Automatic actions are based upon the following parameters and assumptions:

- There are no overrides pertaining to the duct static pressure set point.
- There are no overrides pertaining to related equipment (inlet vane command/VFD speed command, etc.). If overrides are in place and detected, there will be no attempt to adjust the set point. An automatic re-tuning error/fault message (indicating that the auto-correction response could not be executed) will be generated.

This diagnostic measure includes a maximum high limit value for the duct static pressure set point that the auto-corrected value can never exceed. For instance, a maximum value of 2.0 inches w.g. should be configured as the maximum allowable duct static pressure set point to ensure equipment protection.

The auto RCx algorithm will adjust the duct static pressure set point to a higher value at a rate that does not create system instability. This diagnostic should be run, once every 15 minutes (at most, adjustable by modifying parameter called *MinAnalysisTime*).

This continuous diagnostic will automatically apply the re-tuning measures, increasing the duct static pressure set point, until the diagnostic determines that zone conditions indicate a suitable duct static pressure set point has been achieved or the maximum duct static pressure set point is reached.

2.6.2 Monitored Data for Low Static Pressure Auto-Correct RCx

This section describes the required input data for this auto RCx diagnostic. The following data points are required for the execution of this diagnostic:

1. AHU supply-fan status (**SupFanStat**) or supply-fan speed command (**SupFanSpeed**)
2. Duct static pressure (**StcPr**)
3. Duct static pressure set point (**StcPrSP**)
4. All damper position commands from the terminal box controllers (**ZDmp***)*
    - The diagnostic is performed at the AHU level so all terminal box damper commands from zones served by the AHU of interest (AHU that the diagnostic is running on)
5. Duct static pressure set point control point priority (optional)

2.6.3 Low Duct Static Pressure Auto-Correct RCx Diagnostic Process

This section provides the re-tuning diagnostic details including a detailed flow chart (Figure 11).

The following steps are used to detect the re-tuning opportunity (step 1 in this diagnostic occurs in the air-side automated RCx main diagnostic process but is included here to add clarity to the RCx process):

1. If the *MinAnalysisTime* has been reached and there are at least *NRequiredData* measurements in the analysis dataset,

    - Proceed to step 2.

   Else, the *MinAnalysisTime* has not been reached or there are not at least *NRequiredData* measurements in the analysis dataset.
    - Proceed to step 6.

2. Sort the terminal box damper commands from largest to smallest. Use the largest 50% of the zone terminal box damper commands to calculate an average zone terminal box damper command (AvgDmpHigh). Use the smallest 50% of the zone terminal box damper commands to calculate an average zone terminal box damper command (AvgDmpLow).

3. If AvgDmpHigh > *ZHighDmp* (zone high damper threshold) and AvgDmpLow > *ZLowDmp* (zone low damper threshold):
    - Proceed to step 4.

   Else, generate diagnostic message: No re-tuning opportunities were detected for the low duct static pressure auto-correct RCx process
    - Proceed to step 5.

4. If *AutoRCx flag* == True:
    - Ensure that auto-correction will not increase the duct static pressure set point above the maximum configured static pressure set point (*MaxStcPrSP*). Calculate the intended auto-corrected static pressure set point (RCxStcPrSP).
    - RCxStcPrSP = **StcPrSp** + *RCxStcPr* (**StcPrSP** is the current static pressure set point)
        - If RCxStcPrSP ≥ *MaxStcPrSP:*
            - Generate diagnostic message: The duct static pressure set point has reached the maximum static pressure set point but zone conditions still indicate this value may be too low.
            - **StcPrSP** = *MaxStcPrSP*
        - If RCxStcPrSP < *MaxStcPrSP:*
            - Generate diagnostic message: The duct static pressure set point has been detected to be too low. The duct static pressure set point has been increased during the auto-correct RCx process.
            - **StcPrSP** = RCxSATSP
    - Proceed to step 5.

   If *AutoRCx flag* == False:
    - Generate diagnostic message: The duct static pressure has been detected to be too low but auto-correction is not enabled.
    - Proceed to step 5.

5. Send the command to the BAS or AHU controller, set the new **StcPrSP**, (if a re-tuning opportunity was detected and auto-correction was enabled) and make diagnostic message(s) available for the operator.

6. Return to air-side automated RCx main diagnostic, and wait for next available data.

The BACnet data interface queries data off the local controller or BAS every "Data Sampling Rate" minutes. The data is then supplied to the algorithm, which executes every "Data Sampling Rate". The execution of the diagnostic is identical for metered data provided via csv file except no auto-correction can be applied.

The following list contains the default but adjustable thresholds and parameters for this diagnostic:

- Minimum elapsed time for analysis (MinAnalysisTime) = 15 minutes
- Number of required data points for RCx (NRequiredData) = 5
- Zone high damper (ZHighDmp) threshold = 90%
- Zone low damper (ZLowDmp) threshold = 10%
- Maximum duct static pressure set point (MaxStcPrSP) = 3.0 in. w.g.
- Static pressure set point auto-correct increment/decrement (RCxStcPr) = 0.15 in. w.g.

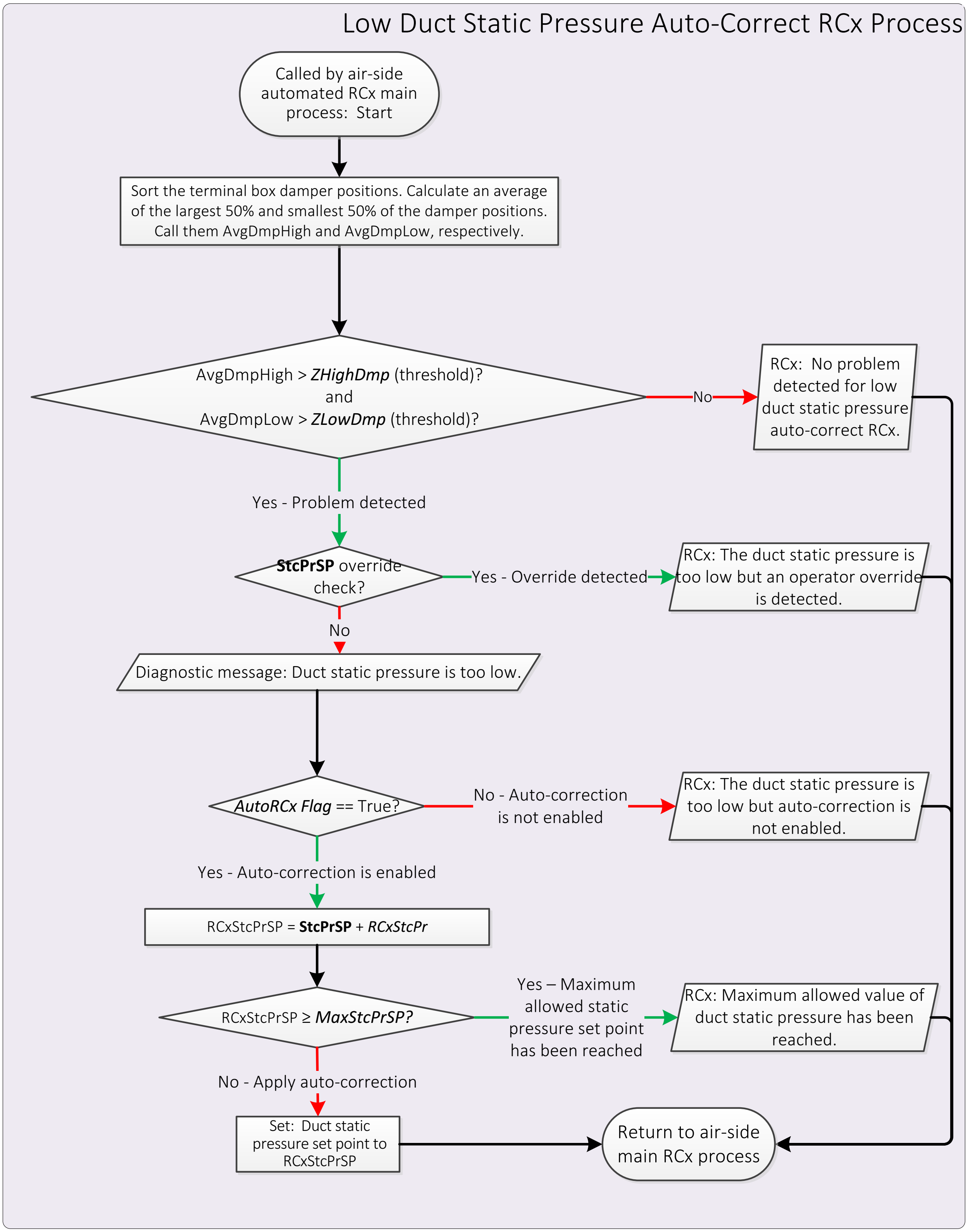


Figure 11: Flow Chart for Low Duct Static Pressure Auto-Correct RCx Process

2.7 High Duct Static Pressure Auto-Correct RCx Process

The purpose of the high duct static pressure auto-correct RCx process is to identify conditions when the AHU duct static pressure is too high. There can be many reasons for high static pressure including building operator adjustments, overrides or equipment configuration issues. A duct static pressure set point that is too high, if not identified and reduced, will cause other system problems and will result in energy waste.

The supply fan modulates to maintain the duct static pressure at the set point. The set point is usually determined based on design conditions; often it is configured to satisfy the most demanding zone, which leads to excess ventilation and excessive pressure for the remainder of the system. When the supply fan is ON and the duct static pressure is too high, the supply fan(s) are running at a higher speed, using more energy than required. This mismatch can cascade into other areas that impact equipment performance and energy efficiency. Building operator actions (set point overrides, etc.) can have an adverse impact on the supply-fan system.

Zone information is critical in detecting if the static pressure is too high. Generally, it is desirable to have most zone dampers between 50% and 75% open. When the average, time-weighted value for zone terminal box damper command(s) is less than a given threshold value for a known time period, the diagnostic will alert the user that a re-tuning opportunity has been detected and there is currently an opportunity for improvement (lower the supply-fan duct static pressure set point). Figure 12 shows an example of poor operations. All of the zone dampers are nearly closed and there is too much air flow going to the zones; this is indicative of a static pressure set point that is too high.

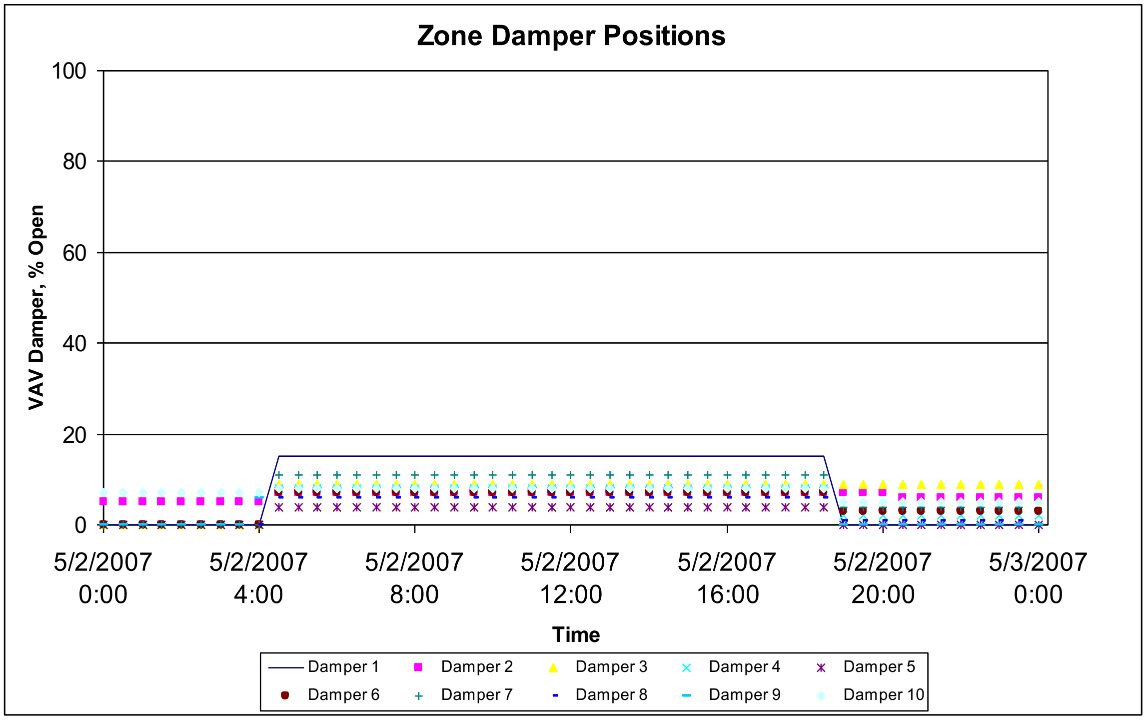


Figure 12: Example of Bad Operation – All Zone Dampers Are Nearly Closed

Figure 13 shows an example of good operations. Most of the zone dampers are between 50% and 75% open. This indicates that that the static pressure set point is not too high; zones are not receiving excess air flow.

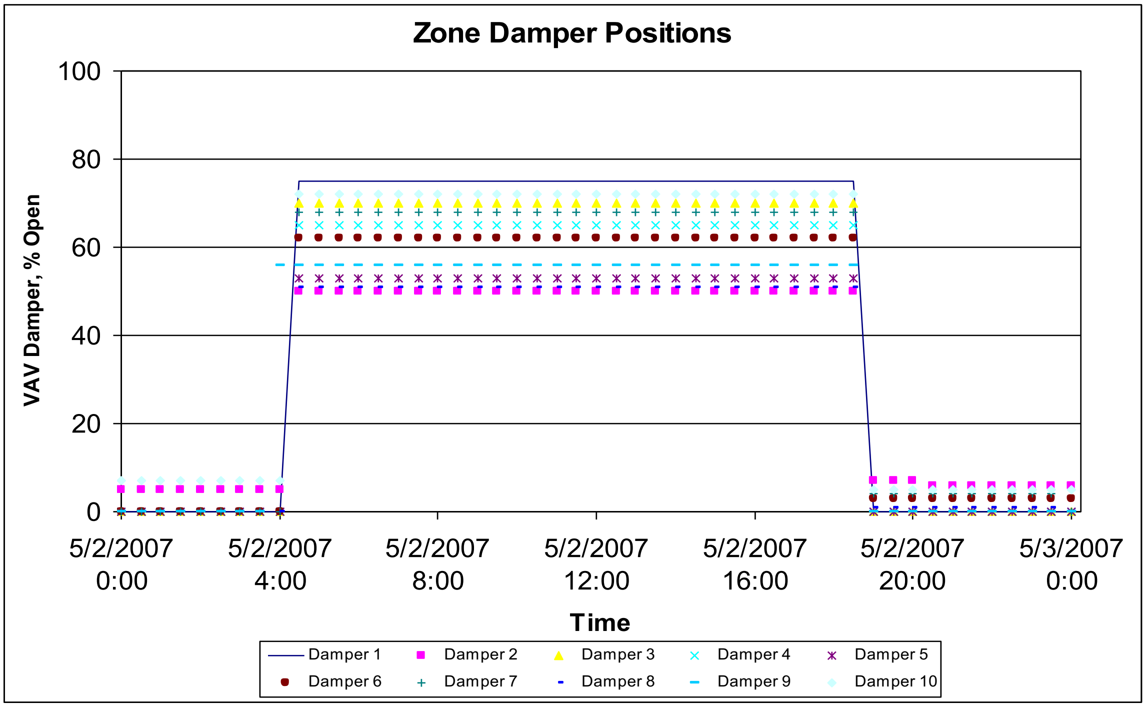


Figure 13: Example of Good Operations – Most Zone Dampers Are Open Between 50% and 75%

2.7.1 Proposed Auto-Correct RCx Action for High Duct Static Pressure

When the user has configured the *AutoRCx flag* = True, and the diagnostic measure has detected a re-tuning opportunity, the existing duct static pressure set point will be adjusted to a lower value. If the *AutoRCx flag* = False, then no automatic action(s) will occur. Automatic actions are based upon the following parameters and assumptions:

- There are no overrides pertaining to the duct static pressure set point.
- There are no overrides pertaining to related equipment (inlet vane command/VFD speed command, etc.). If overrides are in place and detected, there will be no attempt to adjust the set point. An automatic re-tuning error/fault message (indicating that the automatic re-tuning response could not be executed) will be generated.

This diagnostic measure includes a minimum low limit value for the duct static pressure set point that the auto-corrected value can never exceed. For instance, a minimum value of 0.5 inches w.g. should be configured as the minimum allowable duct static pressure set point to ensure equipment protection.

The auto RCx algorithm will adjust the duct static pressure set point to a lower value at a rate that does not create system instability. This diagnostic should be run, once every 15 minutes (at most, adjustable by modifying parameter called *MinAnalysisTime*).

This continuous diagnostic will automatically apply the re-tuning measures, increasing the duct static pressure set point, until the diagnostic determines that zone conditions indicate a suitable duct static pressure set point has been achieved or the maximum duct static pressure set point is reached.

2.7.2 Monitored Data for High Static Pressure Auto-Correct RCx

This section describes the required input data for this auto RCx diagnostic. The following data points are required for the execution of this diagnostic:

1. AHU supply-fan status (**SupFanStat**) or supply-fan speed command (**SupFanSpeed**)
2. Duct static pressure (**StcPr**)
3. Duct static pressure set point (**StcPrSP**)
4. All damper position commands from the terminal box controllers (**ZDmp***)*
    - The diagnostic is performed at the AHU level so all terminal box damper commands from zones served by the AHU of interest (AHU that the diagnostic is running on)
5. Duct static pressure set point control point priority (optional)

2.7.3 High Duct Static Pressure Auto-Correct RCx Diagnostic Process

This section provides the re-tuning diagnostic details including a detailed flow chart (Figure 14). The following steps are used to detect the re-tuning opportunity (step 1 in this diagnostic occurs in the air-side automated RCx main diagnostic process but is included here to add clarity to the RCx process):

1. If the *MinAnalysisTime* has been reached and there are at least *NRequiredData* measurements in the analysis dataset,
    - Proceed to step 2.

   If the *MinAnalysisTime* has not been reached or there are not at least *NRequiredData* measurements in the analysis dataset,
    - Proceed to step 6.

2. Sort the values in ZDmp (array containing terminal box damper commands for the zones served by the AHU of interest) from largest to smallest. Use the largest 50% of the zone terminal box damper commands to calculate an average zone terminal box damper command (AvgDmpHigh).

3. If AvgDmpHigh ≤ *ZHighDmp* (zone high damper threshold):
    - Proceed to step 4.

   Else, generate diagnostic message: No re-tuning opportunities were detected for the high duct static pressure auto-correct RCx process
    - Proceed to step 6.

4. If *AutoRCx flag* == True:
    - Ensure that auto-correction will not decrease the duct static pressure set point below the minimum configured static pressure set point (*MinStcPrSP*). Calculate the intended auto-corrected static pressure set point (RCxStcPrSP).
    - RCxStcPrSP = **StcPrSp** - *RCxStcPr* (**StcPrSP** is the current static pressure set point)
        - If RCxStcPrSP ≤ *MinStcPrSP:*

        - Generate diagnostic message: The duct static pressure set point has reached the minimum static pressure set point but zone conditions still indicate this value may be too high.
        - **StcPrSP** = *MinStcPrSP*
    - If RCxStcPrSP > *MinStcPrSP:*
        - Generate diagnostic message: The duct static pressure set point has been detected to be too high. The duct static pressure set point has been decreased during the auto-correct RCx process.
        - **StcPrSP** = RCxSATSP
- Proceed to step 5.

If *AutoRCx flag* == False:

- Generate diagnostic message: The duct static pressure has been detected to be too high but auto-correction is not enabled.
- Proceed to step 5.

5. Send the command to the BAS or AHU controller, set the new **StcPrSP**, (if a re-tuning opportunity was detected and auto-correction was enabled) and make diagnostic message(s) available for the operator.

6. Return to air-side automated RCx main diagnostic, and wait for next available data.

The BACnet data interface queries data off the local controller or BAS every **“**Data Sampling Rate” minutes. The data is then supplied to the algorithm, which executes every “Data Sampling Rate”. The execution of the diagnostic is identical for metered data provided via csv file except no auto-correction can be applied.

The following list contains the default but adjustable thresholds and parameters for this diagnostic:

- Minimum elapsed time for analysis (MinAnalysisTime) = 15 minutes
- Number of required data points for RCx (NRequiredData) = 5
- High duct zone damper (HDZDmp) threshold = 30%
- Minimum duct static pressure set point (MinStcPrSP) = 0.5 in. w.g.
- Static pressure set point auto-correct increment/decrement (RCxStcPr) = 0.15 in. w.g.

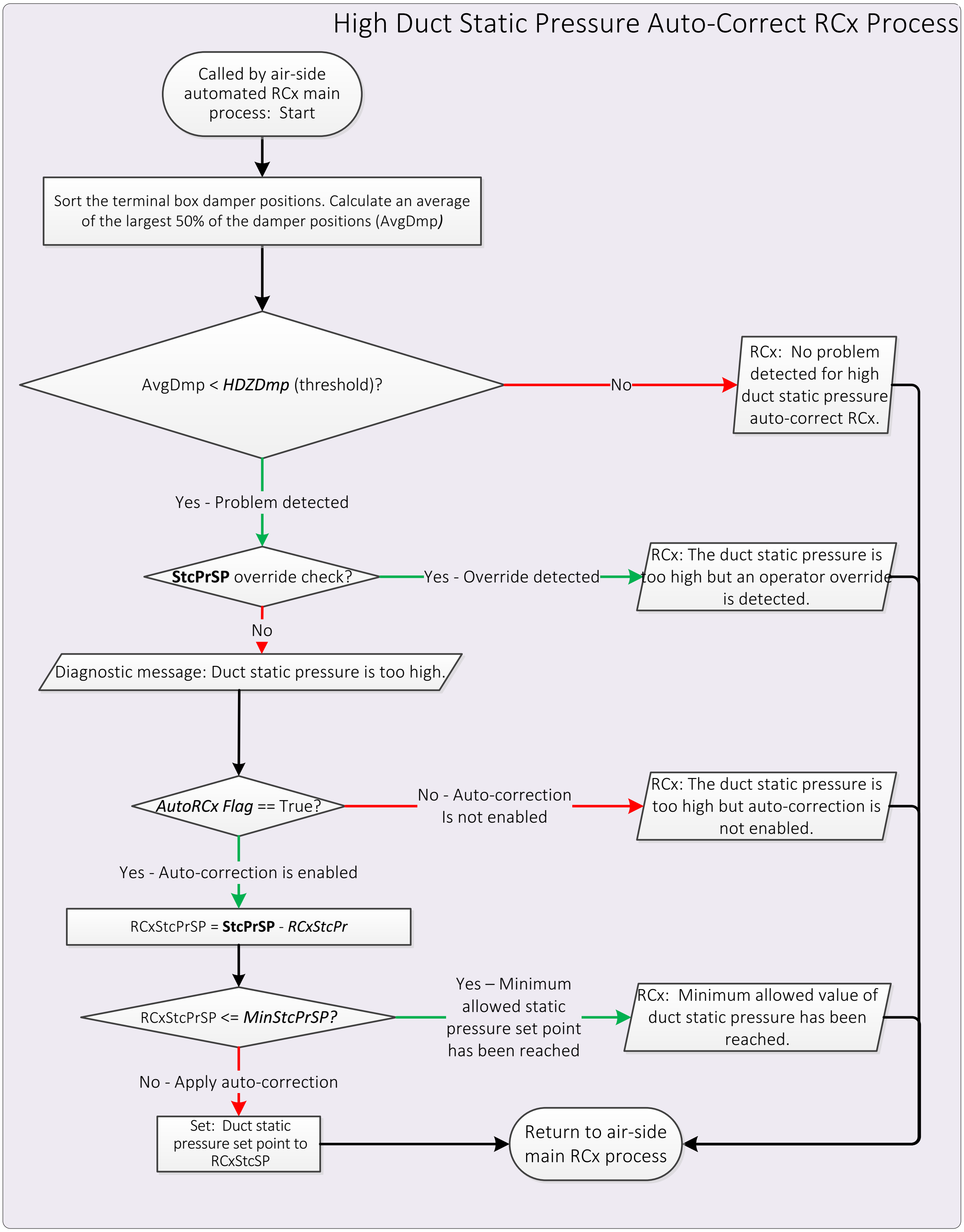


Figure 14: Flow Chart for High Duct Static Pressure Auto-Correct RCx Process

2.8 No Duct Static Pressure Set Point Reset Auto-Detect RCx Process

The purpose of the no duct static pressure set point reset auto-detect RCx process is to identify conditions when the static pressure remains constant or does not reset (change). When the supply fan is ON, the supply fan's static pressure set point can be automatically adjusted to the load conditions, which will allow the supply fan to operate more efficiently.

Throughout the course of a day, the duct static pressure set point for an AHU should show some variation to indicate that a duct static pressure set point reset is being utilized. Typical AHU operations include morning startup, mid-day peak cooling loads, and evening shutdown. Resetting the duct static pressure set point can be beneficial and save significant amounts of energy. If occupancy is low, or the zone cooling load is reduced, resetting the duct static pressure set point will save energy and still maintain appropriate air flow rates to zones to meet occupant ventilation requirements and zone cooling needs.

Figure 15 shows an example of good operation. The duct static pressure set point varies, is reset, throughout the day. Common methods for resetting the duct static pressure set point include reset based on zone damper commands or AHU schedule.

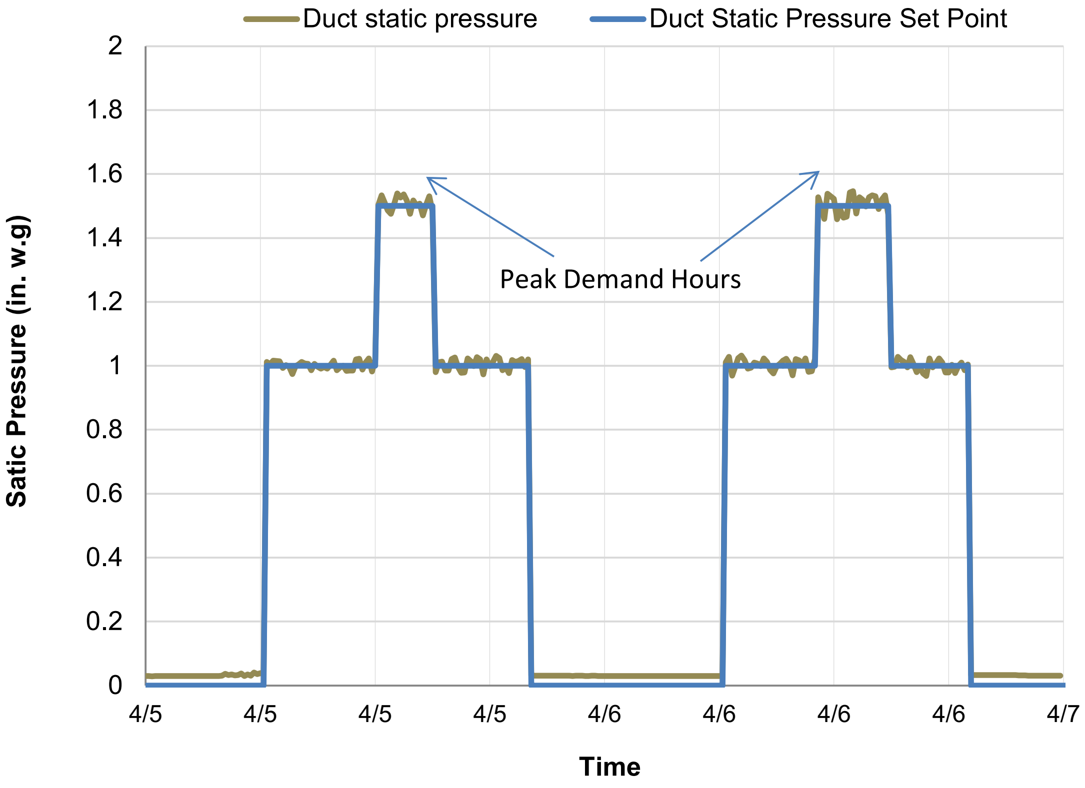


Figure 15: Example of Good Operations - The Duct Static Pressure Set Point Varies

2.8.1 Monitored Data for No Duct Static Pressure Reset Auto-Detect RCx

This section describes the required input data for this auto RCx process. The following data points are required for the execution of this diagnostic:

1. Duct static pressure set point (**StcPrSPSP**)
2. AHU supply-fan status (**SupFanStat**) or supply-fan speed command (**SupFanSpeed**)
3. Duct static pressure set point control point priority (optional)

2.8.2 No Duct Static Pressure Set Point Reset Auto-Detect RCx Diagnostic Process

This section provides the re-tuning diagnostic details including a detailed flow chart (Figure 16). This diagnostic is executed daily, at midnight, to ensure accurate results and allow sufficient time for variation in the duct static pressure set point to occur. The following steps are used to detect the re-tuning opportunity (step 1 in this diagnostic occurs in the air-side automated RCx main diagnostic process but is included here to add clarity to the RCx process):

1. Upon the completion of day (i.e., midnight),
    - If there are *NRequiredData* measurements in the analysis dataset:
        - Proceed to step 2.

      Else, there is insufficient data to conduct this diagnostic.
        - Proceed to step 4.

2. Check if the duct static pressure set point varies throughout a day,
    - If MAX(**StcPrSP**) - MIN(**StcPrSP**) ≤ *StcPrReset* (duct static pressure set point reset threshold):
        - Generate diagnostic message: A duct static pressure set point reset is not being utilized. Implementation of a duct static pressure set point reset will save energy and improve the AHUs performance.
        - Proceed to step 3.
    - Else, generate diagnostic message: A duct static pressure set point reset is being utilized.
        - Proceed to step 3.

3. Make diagnostic message(s) available to the building operator.

4. Return to air-side automated RCx main diagnostic, and wait for next available data.

The BACnet data interface queries data off the local controller or BAS every "Data Sampling Rate" minutes. The data is then supplied to the algorithm, which executes every "Data Sampling Rate". The execution of the diagnostic is identical for metered data provided via csv file except no auto-correction can be applied.

The following list contains the default but adjustable thresholds and parameters for this diagnostic:

- Static pressure set point reset (StcPrReset) threshold = 0.25 inch w.g.
- Number of required data points for RCx (NRequiredData) = 5

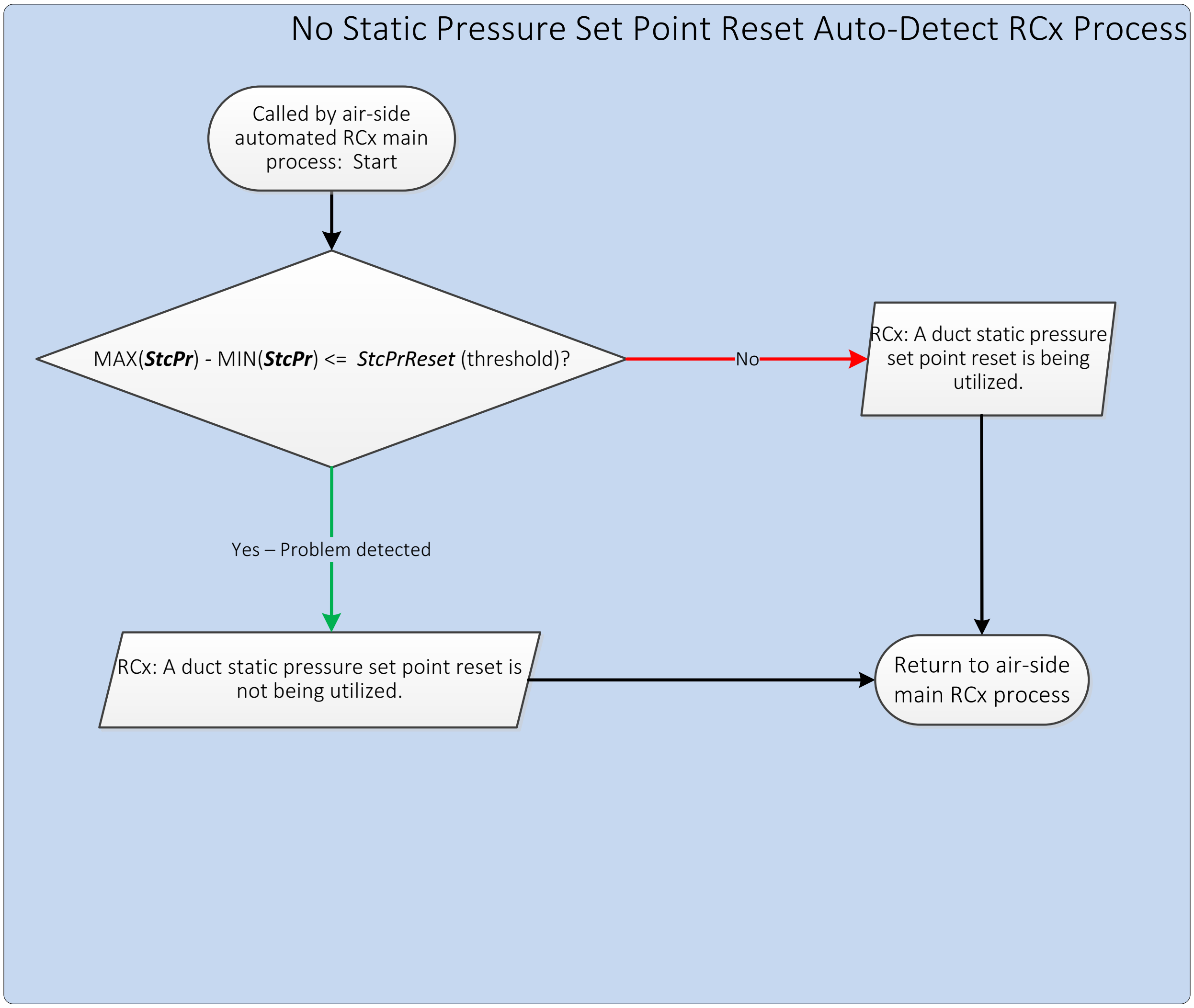


Figure 16: Flow Chart for No Static Pressure Set point Reset Auto-Detect RCx Process

3 Proactive Economizer Diagnostics

The automated fault detection and diagnostic process is a two-step process where 1) a fault with equipment operation is detected and 2) the cause of the fault is isolated (Figure 17). The process generally relies on analytical or physical redundancies to isolate faults during the diagnostic step. Most RTUs/AHUs on commercial buildings lack physical redundancy because heating, ventilation, and air conditioning (HVAC) systems in commercial buildings are considered non-critical. An AFDD process can use proactive diagnostic processes to create analytical redundancy to help isolate the cause of a fault.

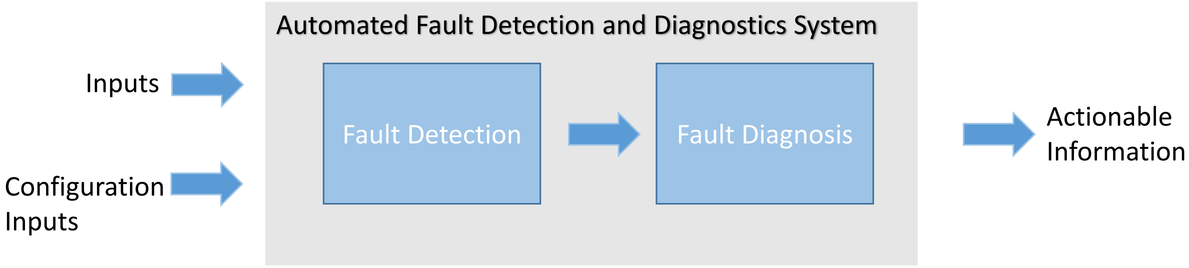


Figure 17: Illustration of the Automated Fault Detection and Diagnostic Process

Proactive AFDD is a process that involves automatically initiating changes to cause or to simulate operating conditions that may not occur for some time, thus producing results that might not be available for months otherwise. Such tests could be automated to cover a more complete range of conditions or to deepen diagnosis beyond what might be possible without this capability. The proactive diagnostic process can help diagnose and isolate faulty operations to a much greater extent than passive diagnostics, but it is intrusive. Some building owners and operators may consider this to be disruptive to the normal operation of their RTU/AHU systems. They may not, however, if such proactive tests can be conducted quickly enough to maintain acceptable control of the RTU/AHU systems. Proactive diagnostic procedures are capable of providing continuous persistence of performance if they are frequently triggered (e.g., once a day, once a week, once a month or perhaps seasonal). These procedures might be scheduled to occur during building startup hours or at the end of the day to further reduce their intrusiveness or could be scheduled on demand. The proactive diagnostic process described above is similar to functional testing that is performed during manual commissioning of systems.

The algorithms utilize rules derived from engineering principles of proper and improper RTU/AHU operations. The following is a list of the proactive economizer diagnostics:

- Compare discharge-air temperatures (DAT) with mixed-air temperatures (MAT) for consistency (AFDD0)
- Check if the outdoor-air damper (OAD) is modulating (AFDD1)

The intent of these algorithms is to provide actionable information to building owners and operations staff while minimizing false alarms. Therefore, the algorithms have been designed to minimize false alarms. On the other hand, if HVAC systems and their controls start to fail, having an indicator (a.k.a.

"check engine light") of a real problem is always helpful – especially if it allows operations and maintenance staff to be proactive, rather than reactive. The remainder of this section will provide a more detailed summary of the seven algorithms. Appendix contains more detailed information including implementation details, flowcharts, inputs required for the algorithms and the outputs from the algorithms.

To implement the algorithms, the RTU/AHU must be configured with a number of temperature sensors (including outdoor-, return-, mixed- and discharge-air) and status signals (including fan, compressor, and outdoor-air damper). The outdoor-air temperature (OAT) sensor can be installed on an individual RTU/AHU, or a shared value across the network (network from inside the building or network from outside the building). The typical location of these sensors is shown in Figure 18.

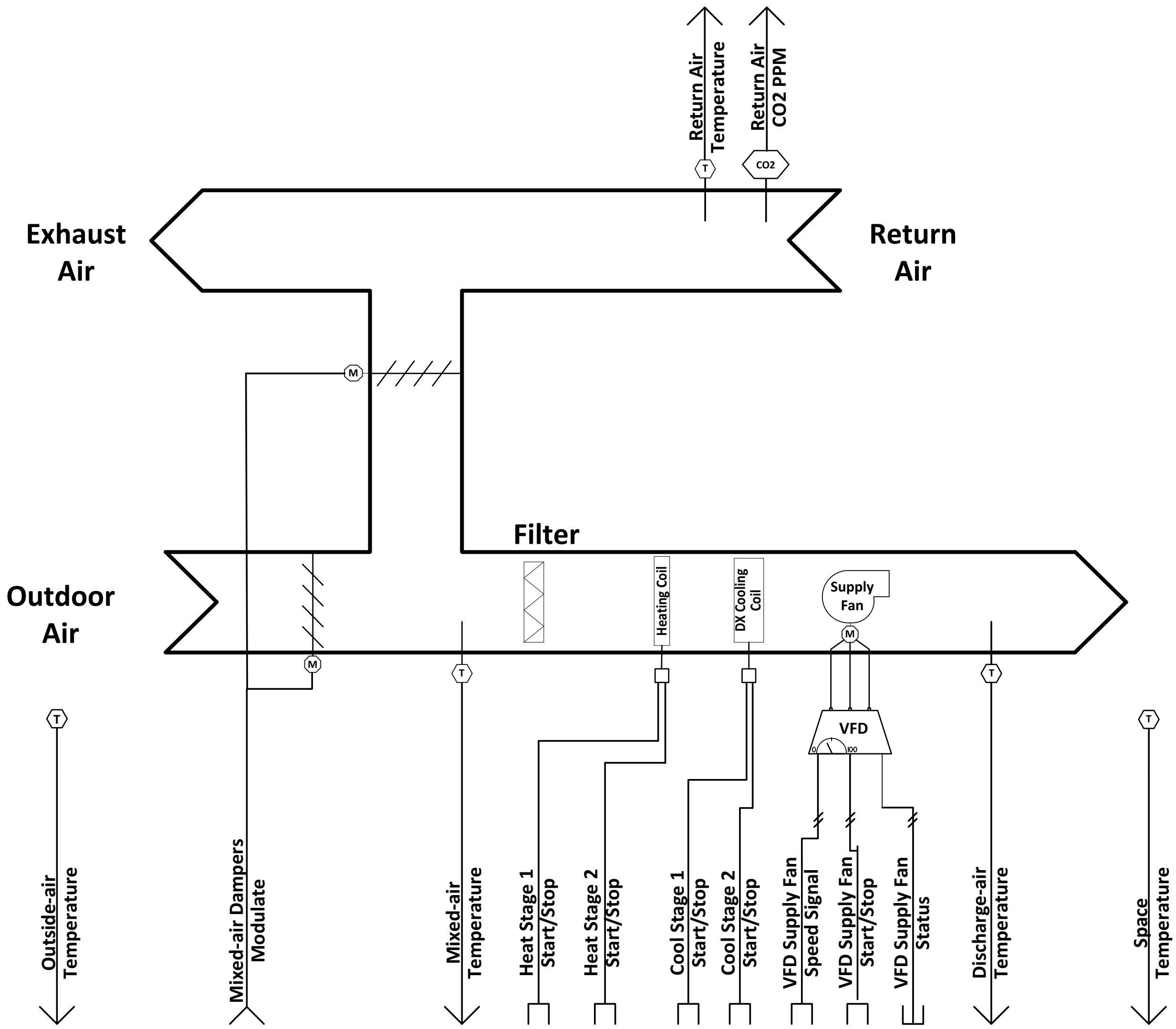


Figure 18: Schematic of RTU Showing the Various Sensor Locations

3.1 AFFD0: Compare Discharge-air Temperatures With Mixed-air Temperatures for Consistency

The first proactive diagnostic check is designed to compare the discharge-air and mixed-air temperature sensor readings with each other. When heating and cooling systems are turned off, (disabled) during this diagnostic check, the temperature sensors in the air streams upstream of the fan (mixed-air plenum) and downstream of the fan (discharge-air plenum) are compared to each other. The result of this comparison should have temperature readings within 2°F to 4°F (user-adjustable) of each other during steady-state conditions (user-adjustable time lag required after the heating and cooling systems are turned off). There usually is additional heat in the discharge–air stream from the fan and motor that would create the slight difference (higher discharge-air temperature is the expectation) when this check is made.

This test validates that these two temperature sensors are reading within a user-adjustable pre-set value (suggest 2°F to 4°F). This provides an initial confidence factor in the two sensors and their integrity. If the diagnostic check determines that the absolute value of the difference between the two temperature sensors is higher than the acceptable threshold, a fault will be generated. The fault does not identify which sensor is "faulty," only that there is a lack of confidence in one or both sensors and their accuracy.

This algorithm may consider additional fault analysis (future work) that finds that the mixed-air temperature sensor is consistently reading higher than the discharge-air temperature sensor. Typical causes include sensor fault, sensor location, sensor wiring, sensor software configuration, cooling coil control valve leak (where chilled water coils exist in the RTU/AHU), etc.

The schedule established on the TN platform determines when this fault analysis will run for an individual RTU/AHU. It is generally preferable not to schedule this test prior to normal occupancy or during morning warm up or cool down periods (because heating or cooling would be active). The best time of day to run this fault analysis is 15 to 30 minutes prior to a scheduled unoccupied period (if the intent is to not cause additional run time on the RTU/AHU). Each of the diagnostic process typically takes 20 to 30 minutes.

The building owner will determine the frequency of this fault analysis, but it is recommended at least once per week. A future enhancement of AFDD will be a data integrity flag. When the application returns a fault-free diagnostic, the flag will be set for a pre-determined amount of time. During this time, AFDD0 will not re-run and the sensors involved in that diagnostic will be assumed reliable.

If mixed-air temperature sensor value is not available because it is not typically measured, this test cannot be done.

3.1.1 Monitored Data for this Proactive Economizer Diagnostic

This section describes the required input data for this proactive diagnostic. The following data points are required for the execution of this diagnostic:

1. Mixed-air temperature (MAT)

2. Discharge-air temperature (**DAT**)
3. Supply fan status (**SupFanStat**) for RTU/AHU
4. Supply fan command (**FanSpeedCmd**) for the RTU/AHU if the **SupFanStat** is not available

3.1.2 Prerequisite

The following conditions must be met before the fault detection process can be initiated.

- Supply fan status = "ON." The proactive AFDD process will not be enabled if the supply fan status is still "OFF." If the supply fan status is not available, the supply fan command will be used in the diagnostic.

3.1.3 Fault Detection and Diagnostics Process

AFDD tests generally rely on analytical or physical redundancies to isolate faults during diagnosis. Most RTU/AHU systems in commercial buildings lack physical redundancy because HVAC systems in the commercial buildings are considered non-critical. Additionally, there is usually no outdoor-air damper feedback signal to the RTU/AHU controller. An AFDD test can use proactive diagnostic processes to create analytical redundancy to help isolate the cause of a fault. The proactive diagnostic process is similar to functional testing that is performed during manual commissioning of systems. Packaged RTU/AHU equipment for small/medium commercial applications typically have small chambers for mixing outdoor and return air and can have very non-uniform temperature and velocity distributions at the inlet to the coil. This proactive AFDD test can be initiated by the VOLTTRON schedule when all prerequisites are met. This schedule is configured in the Actuator agent (a VOLTTRON service).

Steps in this proactive economizer diagnostic:

1. AFDD agent will disable the heating and cooling (compressor(s)) for the RTU/AHU.

2. The AFDD agent will send the damper open override command to the Catalyst controller. The AFDD agent will command the OAD to a fully open position and force it to remain in that position irrespective of the Catalyst control signal. After the damper is fully open and steady-state conditions are reached (minimum 5 minutes delay time, which can be adjusted by the user), monitor and record the DAT and the MAT. If the MAT sensor is not present this test cannot be done. Compute the absolute difference between the mixed-air temperatures and discharge-air temperatures (DIFF1) averaged over 5 minutes (adjustable by the user).

3. If the difference between DAT and MAT is greater than the AFDD0 threshold, the AFDD agent can report the fault to the user and record the time of this fault. If no fault occurs, the agent will move on to next step.

4. Command the OAD to a fully closed position. After the OAD fully closes and steady-state conditions are reached (minimum 5 minutes delay time, which can be adjusted by the user), monitor and record the DAT and the MAT. Compute the absolute difference between the MAT and DAT (DIFF2) averaged over 5 minutes (adjustable by the user).

5. Step 5: If the difference between the DAT and MAT is greater than AFDD0 threshold, the AFDD agent can report the fault to the user and record the time of this fault.

6. Step 6. If performing the entire AFDD sequence (AFDD0 through AFDD6) continue to AFDD1. Otherwise, send the release commands to the local controller so the dampers return to their “normal” control configuration. The heating and cooling commands will also need to be released so they return to their normal configuration.

The following list contains the default but adjustable thresholds and parameters for this diagnostic:

- AFDD0 threshold = 5°F (adjustable by building operator).

3.1.4 Discussion

This section discusses possible causes, re-tuning opportunities, saving estimation methods, etc.

3.1.4.1 Possible Causes

The possible causes of the DAT and MAT sensor inconsistencies can be mechanical failure or a control failure:

- Sensor failure or communication failure.
- MAT sensor is out of calibration or improperly located.
- The return air and outdoor air are not well-mixed in the mixing chamber.
- The MAT sensor uses a point measurement instead of a temperature averaging sensor
- Temperature stratification: Outside air may stay at the bottom of the duct without good mixing.

3.1.4.2 Possible Corrective Actions

The following is a list of possible corrective actions:

- Use an averaging temperature sensor instead of the point measurement for mixed-air temperature.
- Possible ways to improve the mixing:
  - Rotate the damper sections so that the damper blades direct the air streams into each other as they close. This creates turbulence and helps to promote the mixing process.
  - Add baffles to divert the air stream several times before it reaches the coils. This also creates turbulence, which promotes mixing. If the baffles are arranged so that the velocity through them is low (800-1,000 fpm), then significant benefits can be realized without significant additional pressure drop.

3.1.5 Implementation Details

Error! Reference source not found. shows the fault detection flow chart for the fault “MAT and DAT are not consistent when mechanical cooling/heating is off.”

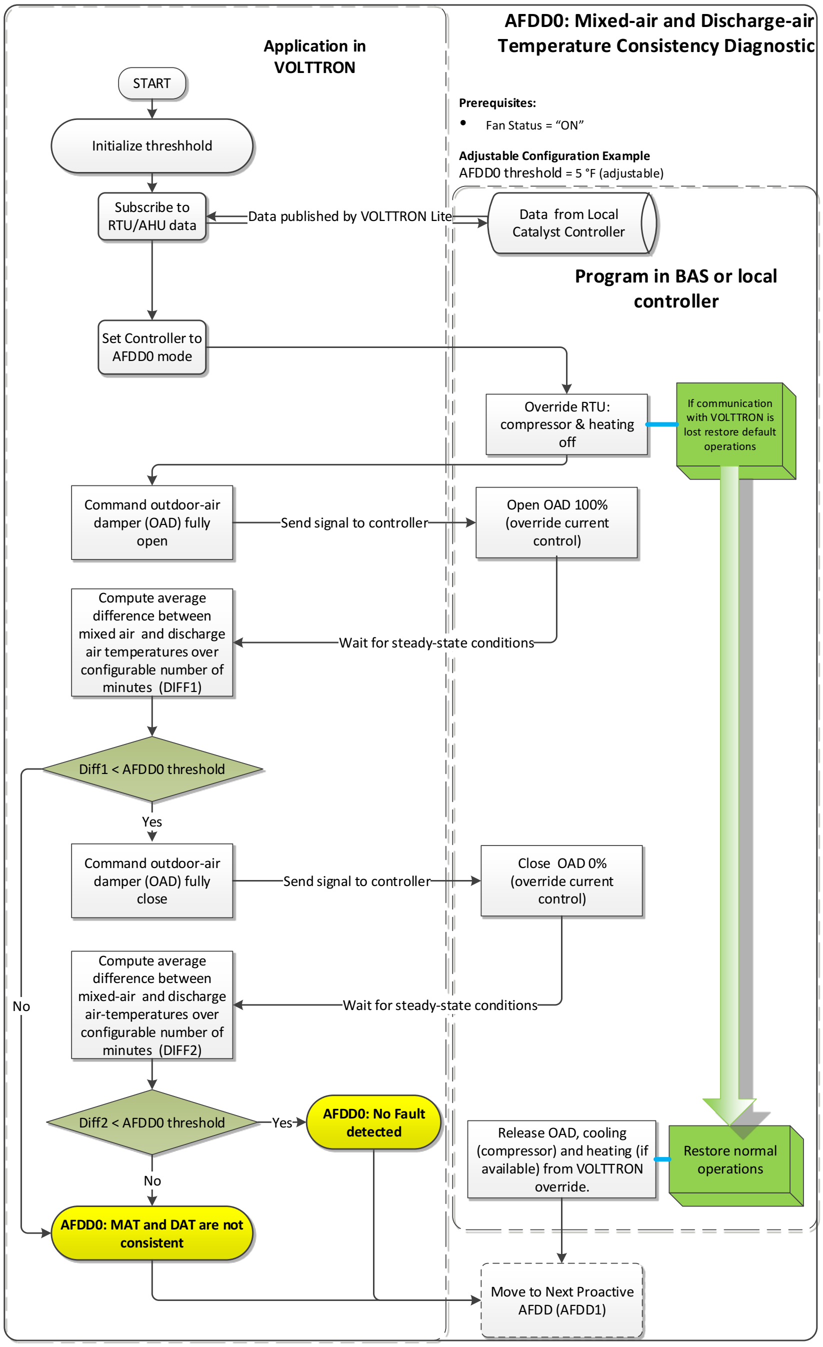


Figure 19: Mixed-air and Discharge-air Temperature Consistency Diagnostic

3.2 AFFD1: Check if the Outdoor-air Damper is Modulating

The second diagnostic check determines if the economizer damper is modulating properly. The fault analysis will use the economizer damper command to create two steady-state conditions in the mixed-air plenum.

The first steady-state condition is obtained by commanding the economizer damper to a fully open position (100% outside air). The outside-air temperature is compared to the mixed-air temperature. The time to reach steady state will be a user-adjustable parameter (recommended to be at least 5 minutes for greater accuracy and confidence in the results). If the damper is fully open, the difference between the outside air and the mixed air (discharge-air temperature if mixed-air temperature sensor is not installed) should be minimal (between 2°F and 4°F).

The second steady-state condition is obtained by commanding the economizer damper to a fully closed position (0% outside air). If the damper is fully closed, the difference between the return-air temperature (RAT) and the mixed-air temperature sensors (discharge-air temperature if mixed-air temperature sensor is not installed) should be minimal (between 2°F and 4°F).

The absolute difference between the sensor measurements is averaged over a user-adjustable number of minutes to obtain an average absolute difference for each of the steady state conditions. If the diagnostic check determines that the average absolute temperature difference is greater than the acceptable threshold, a fault is generated indicating the damper is not modulating properly.

If the RTU/AHU is missing the mixed-air temperature sensor, the discharge-air temperature sensor is used instead for both steady-state conditions with appropriate change in the threshold value. This fault test will also require that the heating and cooling functions be temporarily disabled (similar to "AFFD0" diagnostic check) for both steady-state condition checks.

The schedule established on the VOLTTRON determines when this fault analysis will run for an individual RTU/AHU. In addition to the schedule, this test will not be run if the outside-air temperatures are extreme (too hot or too cold [OAT < 50°F or OAT > 90°F]) or when the outside-air temperatures are within 4°F to 5°F of the return-air temperature value.

The frequency of this fault analysis will be determined by the building owner, but it is recommended at least once a week. A future enhancement of the AFDD will be a data integrity flag. When the application returns a fault-free diagnostic, the flag will be set for a pre-determined amount of time. During this time, AFDD1 will not rerun and the damper will be considered functional (or modulating properly).

If the fault analysis returns a fault for an economizer damper that does not open 100% or close to 0%, the platform will recommend that the building owner or designated operations and maintenance (O&M) staff physically inspect the damper movements.

3.2.1 Approach

The OAD will be commanded fully open and fully closed in sequence through a proactive diagnostic approach. Sufficient time will be allowed between opening and closing the damper to ensure conditions at the RTU/AHU have reached steady state. By comparing the temperatures, conclusions can be drawn as to the state of the OAD.

3.2.2 Input Parameters

This section describes the required input data for this proactive diagnostic. The following data points are required for the execution of this diagnostic:

1. Mixed-air temperature (**MAT**)
2. Outdoor-air temperature (**OAT**)
3. Return-air temperature (**RAT**)
4. Discharge-air temperature (**DAT**) if MAT is not available
5. Supply fan status (**SupFanStat**) for AHU/RTU
6. Supply fan command (**SupFanSpeed**) for AHU/RTU if the SupFanStat is not available

If the MAT sensor for the RTU is not available, the DAT sensor can be used and the cooling/heating systems for the RTU should be turned off temporarily during the testing.

3.2.3 Prerequisite

The following conditions must be met before the fault diagnostic process can be initiated.

- Supply fan status = "ON." The proactive AFDD process will not be enabled if the supply fan status is still "OFF." If supply fan status is not available, supply fan command will be used in the testing.

- The OAT is not too close to the RAT. For example, the proactive fault diagnostics process will not be initiated if the absolute value of (RAT-OAT) < AFDD1 temperature threshold (4 °F by default and user adjustable).

The VOLTTRON BACnet or Modbus driver will publish controller/BAS data points to the VOLTTRON message bus at 1-minute intervals. The AFDD agent will subscribe to the needed data points for use in fault diagnostics. If the MAT sensor is not available, the discharge-air temperature sensor can be used for the diagnostic. The heating and cooling (compressor) will be disabled during the diagnostic.

- Performing a limit check on temperature sensors can detect a hard failure and should be performed prior to the damper modulation diagnostic. Ensure that the current OAT is not outside the expected range for the sensor. If the OAT is above OAT high-limit or below the OAT low-limit, then the fault diagnostic should not proceed. Check that the RAT is not outside the expected range for the sensor. If the RAT is above RAT high-limit or below the RAT low-limit, the fault diagnostic should not proceed. Check that the MAT is not outside the expected range for the sensor. If the MAT is above MAT high-limit or below the MAT low-limit, the fault diagnostic should not proceed.

- All of the temperature high-limit and temperature low-limit settings for OAT, MAT, and RAT are user configurable.

- Please refer to Figure 20 for implementation of temperature limit checks.

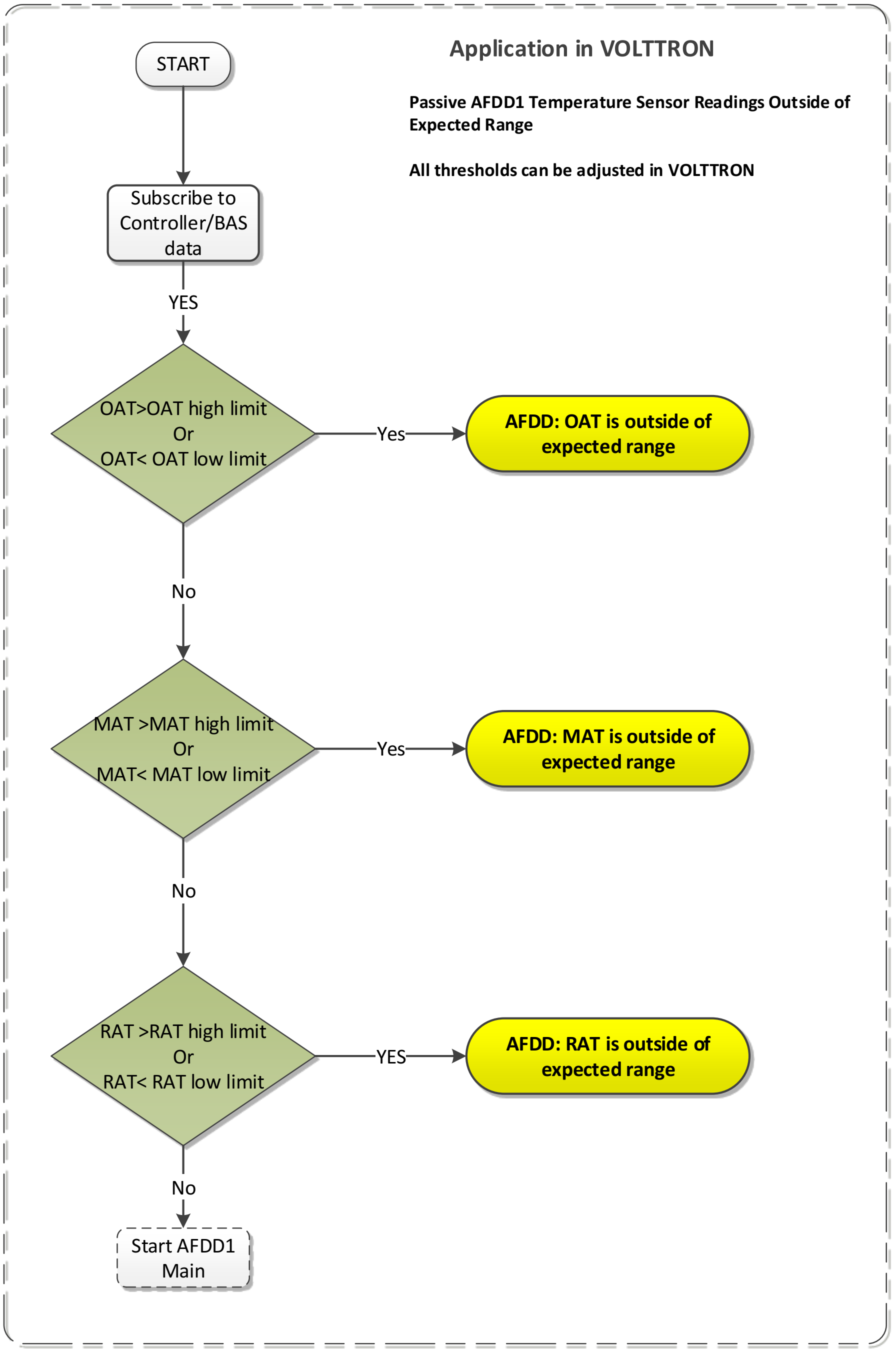


Figure 20: Flow Chart for Temperature Sensor Measurements Outside of Expected Range in Proactive AFDD1

3.2.4 Fault Detection & Diagnostics Process

AFDD tests generally rely on analytical or physical redundancies to isolate faults during diagnosis. Most RTU/AHU systems in commercial buildings lack physical redundancy because HVAC systems in the commercial buildings are considered non-critical. Also, there is usually no OAD feedback signal to the RTU/AHU controller. An AFDD test can use proactive diagnostic processes to create analytical redundancies to help isolate the cause of a fault. The proactive diagnostic process is similar to functional testing that is performed during manual commissioning of systems. If the MAT sensor is not available for the RTU/AHU, the DAT sensor can be used instead.

The proactive AFDD test can be initiated when all prerequisites are met.

Steps in the AFDD1 test:

1. AFDD agent will disable the heating and cooling (compressor) for the RTU/AHU.

2. The AFDD agent will send the damper open override command to the Catalyst controller. The AFDD agent will command the OAD to a fully open position and force it to remain in that position irrespective of the Catalyst control signal. After the damper is fully open and steady-state conditions are reached (minimum 5 minutes delay time, which can be adjusted by the user), monitor and record the OAT and the MAT (DAT if MAT is not available). Compute absolute difference between MAT and OAT (DIFF1) averaged over 5 minutes (the number of minutes the difference is averaged over is adjustable by the user).

3. Command the OAD to a fully closed position. After the OAD fully closes and steady-state conditions are reached (minimum 5 minutes delay time, which can be adjusted by the user), monitor and record the RAT and the MAT (DAT if MAT is not available). Compute absolute difference between MAT and RAT (DIFF2) averaged over 5 minutes (the number of minutes the difference is averaged over is adjustable by the user).

4. Compute the average of DIFF1 and DIFF2 (DIFF1+DIFF2)/2. If this value is greater than AFDD1 damper threshold, the AFDD agent can report the fault to the building operator and record the time the fault.

5. If no fault is detected for AFDD0 and if performing the entire AFDD sequence (AFDD0 through AFDD6) continue to AFDD2. Otherwise, send the release command(s) to the local controller so the dampers return to their normal control configuration. The heating and cooling commands are also released so they return to their normal configuration.

The following list contains the default but adjustable thresholds and parameters for this diagnostic:

- AFDD1 damper threshold = 3°F (adjustable by the user).

3.2.5 Discussion

This section discusses possible causes and corrective measures.

3.2.5.1 Possible Causes

The causes of no damper modulation can be a mechanical failure or a control failure:

- Broken linkage between damper actuator and damper.

- Damper or damper actuator mechanical (and/or electrical) failure (including damper seals, damper power or blockage/binding).

- Electrical connection (control wiring) fault between the local controller and the damper actuator (no signal or wrong signal).

- Actuator not rotating correct direction when signal is applied or not sequenced correctly with other actuator(s) when multiple actuators exist (first actuator has rotated 50% of travel before other actuator(s) start moving).

3.2.5.2 Possible Corrective Actions

This section lists some corrective actions if the outdoor-air damper is not modulating"

- Fix the damper and actuator connection.

- Make sure the control wiring and data points are mapped correctly.

- Make sure the actuator sequencing and calibration set up are correct.

3.2.6 Implementation Details

Figure 21 shows the fault detection flow chart for the fault "No outdoor-air damper modulation."

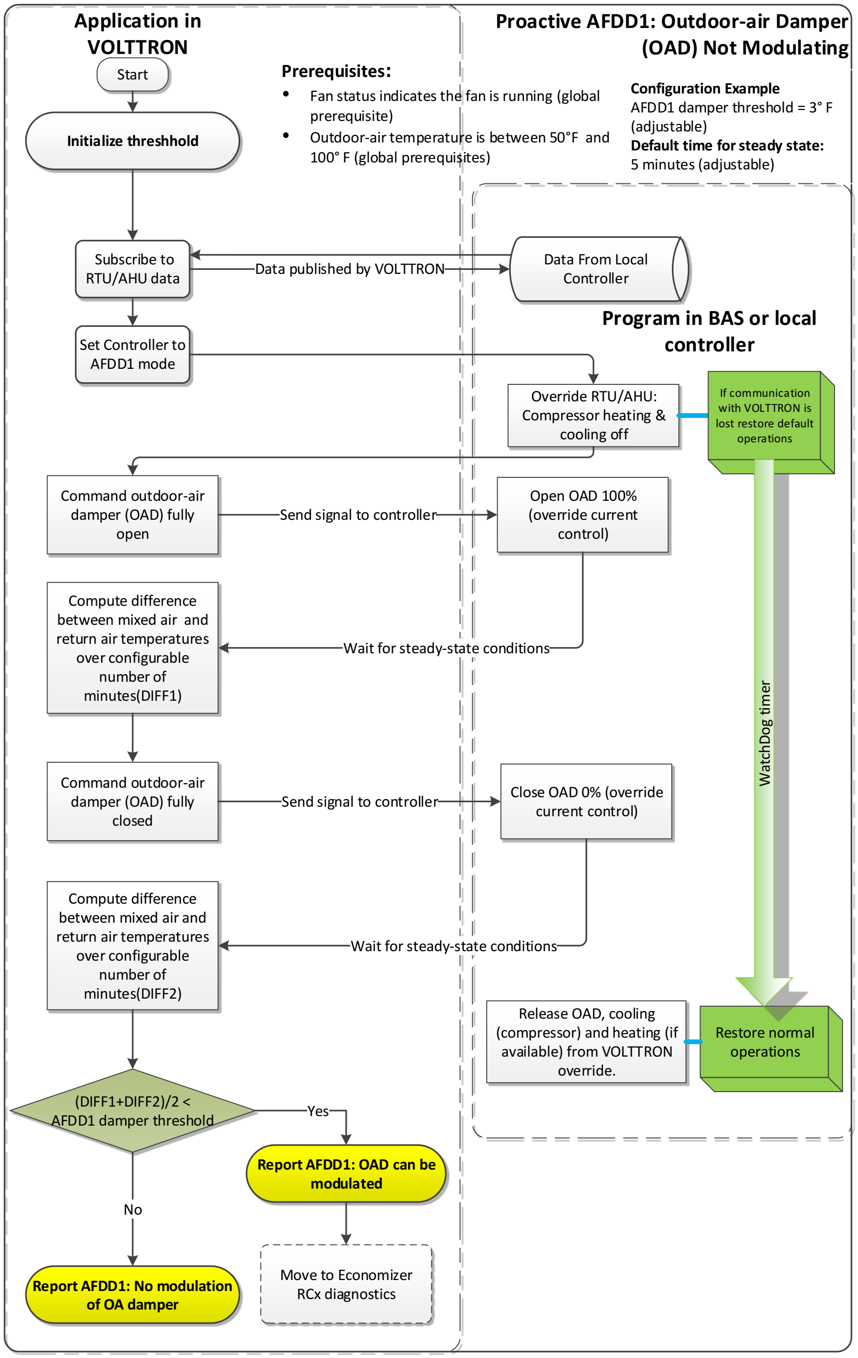


Figure 21: Flowchart to Detect Outdoor-air Damper not Modulating

4 Economizer Controls Auto-Detect RCx Algorithms

The economizer controls auto-detect RCx processes utilizes a decision tree structure derived from engineering principles to detect and diagnose problems with outdoor-air ventilation and economizer operations. The economizer control diagnostic uses two types of input data: measured data and setup data. The measured data include: mixed-, return- and outdoor-air temperatures; supply fan on/off status; outdoor-air damper command signal and the chilled water cooling valve command. The setup data include configuration details such as: economizer type (differential dry-bulb [DDB] or high OAT limit [HL]), thresholds, chiller rated energy efficiency ratio (EER), etc. The measured data can be at any interval (1-minute, 5-minute, half-hourly, or hourly, etc.).

The data for the analysis can be collected from the BAS, custom logging equipment, or from an existing database. The algorithms work on constant-volume and VAV AHUs that do not use volume compensation (metered outdoor-air flow). The auto RCx algorithm will detect and diagnose both ventilation and economizer faults.

Economizers use controllable dampers to mix outdoor air and return air in appropriate quantities to provide the right mixed-air or supply-air temperature that will either offset the entire cooling load or part of the load. An economizer that is fully integrated with the mechanical cooling system can meet all of the building's cooling requirements using both outdoor air and mechanical cooling individually or concurrently. Non-integrated economizers are operated exclusively with the mechanical cooling system. The auto RCx algorithms will work with the following economizer types: high-limit dry-bulb or differential dry-bulb. The algorithms could easily be modified to work with differential enthalpy as well.

Detecting and diagnosing problems with economizers is crucial because faulty economizer operations does not result in comfort problems and is generally masked by the system. For example, if the damper is stuck closed and is commanded to economize during conditions favorable for economizing, the occupants will not suffer because the air stream will be mechanically cooled instead. The economizer auto RCx algorithms are designed to monitor conditions of the system not normally experienced by occupants and alert the building operator when there is evidence of a fault and the potential cause of the fault.

The detected faults can be grouped into five categories: 1) inadequate ventilation, 2) energy waste, 3) temperature sensor problems, 4) miscellaneous control problems and 5) missing or out of range inputs.

The problems associated with energy waste relate to conditions when the economizer should be ON (favorable for economizing), but it is OFF and also when the economizer should be OFF, but it is ON (not favorable for economizing).

The temperature sensor problems are of two types: 1) missing and 2) out of range or incorrect values. The algorithms described in this section will identify if any of the three temperature sensor values (outdoor, return and mixed air) are inconsistent with each other, but cannot isolate the problem sensor.

The algorithms utilize rules derived from engineering principles of proper and improper AHU operations. The five algorithms include:

1. Detect AHU sensor faults (outdoor-air, mixed-air and return-air temperature sensors)
2. Detect if the AHU is not economizing when it should
3. Detect if the AHU is economizing when it should not
4. Detect if the AHU is using excess outdoor air
5. Detect if the AHU is not providing sufficient ventilation air.

The intent of these algorithms is to provide actionable information to building owners and operations staff while minimizing false alarms. As HVAC systems and their controls start to fail, having an indicator (a.k.a. "check engine light") of a real problem is always helpful – especially if it allows operations and maintenance staff to be proactive, rather than reactive. The remainder of this section will provide a more detailed summary of the five algorithms.

To implement the algorithms, the AHUs must be configured with a number of temperature sensors (including outdoor-, return-, mixed- and discharge-air) and status signals (including fan, chilled water valve command, and outdoor-air damper). The outdoor-air temperature (OAT) sensor can be installed on an individual AHU or a shared value across the network (network from inside the building or network from outside the building).

4.1 Economizer Control Auto-Detect RCx Main Diagnostic Process

For the auto RCx process to be initiated, the following conditions have to be met:

- The supply fan must be ON. If the supply-fan status is not available, the supply-fan speed can be used as an indicator of the fan status (i.e., if the supply-fan speed is greater than the minimum supply-fan speed then consider the supply fan to be ON).
- The OAT and the RAT are not too close to each other:
    - ABS(**OAT** – **RAT**) > *EconTemp*.

A cooling status flag (CoolingCall) and an economizer status flag (EconomizerFlag) are generated at each time step and made available for the five economizer diagnostics. The status flags are generated as follows:

- If **CoolingValvePos** > *CoolingEnabled* (cooling enabled threshold):
    - Set CoolingCall = True
- Else, set CoolingCall = False

- Generate the AHU economizer status flag:
    - If the *EconomizerType* = DDB:
        - EconomizerFlag = (**OAT** < (**RAT** - *TempDB*)) as a Boolean
    - Else, EconomizerFlag = (**OAT** < (*HL* - *TempDB*)) as a Boolean

A list of configuration parameters with default values for the economizer diagnostics include:

1. Low OAT (LowOAT) threshold = 30 ^{o}F
2. High OAT (HighOAT) threshold = 100 ^{o}F
3. Low MAT (LowMAT) threshold = 50 ^{o}F
4. High MAT (HighMAT) threshold = 90 ^{o}F

5. Low RAT (LowRAT) threshold = 50 °F
6. High RAT (HighRAT) threshold = 90 °F
7. Temperature dead band (TempDB) = 1 °F
8. Temperature difference (TempDiff) threshold = 4 °F
9. Chilled water valve cooling enabled (CoolingEnabled) threshold = 5%
10. Rated CFM (CFM when supply-fan is at full speed) = 500 cfm
11. Rated Energy Efficiency Ratio (EER) = 10.0 (used to estimate the energy impact)
12. Economizer temperature (EconTemp) threshold = 4 °F
13. Economizer type (EconomizerType) = DDB
14. High limit (HighLimit) temperature = 65 °F (Only needed if the economizer type is HL)
15. Data sampling rate (DataSamplingRate) = 1.0 minute(s) per sample
16. Number of required data points for analysis (NRequiredData) = 10 measurements
17. Estimated Rated CFM (when supply fan is at full speed) = 500 (site and unit specific)

The main process handles the global pre-requisites (i.e., pre-requisites apply to all five of the economizer diagnostics), the temperature sensors high and low limit checks, and data management (passing thresholds values to the diagnostics and initializing the analysis dataset arrays) (Figure 22).

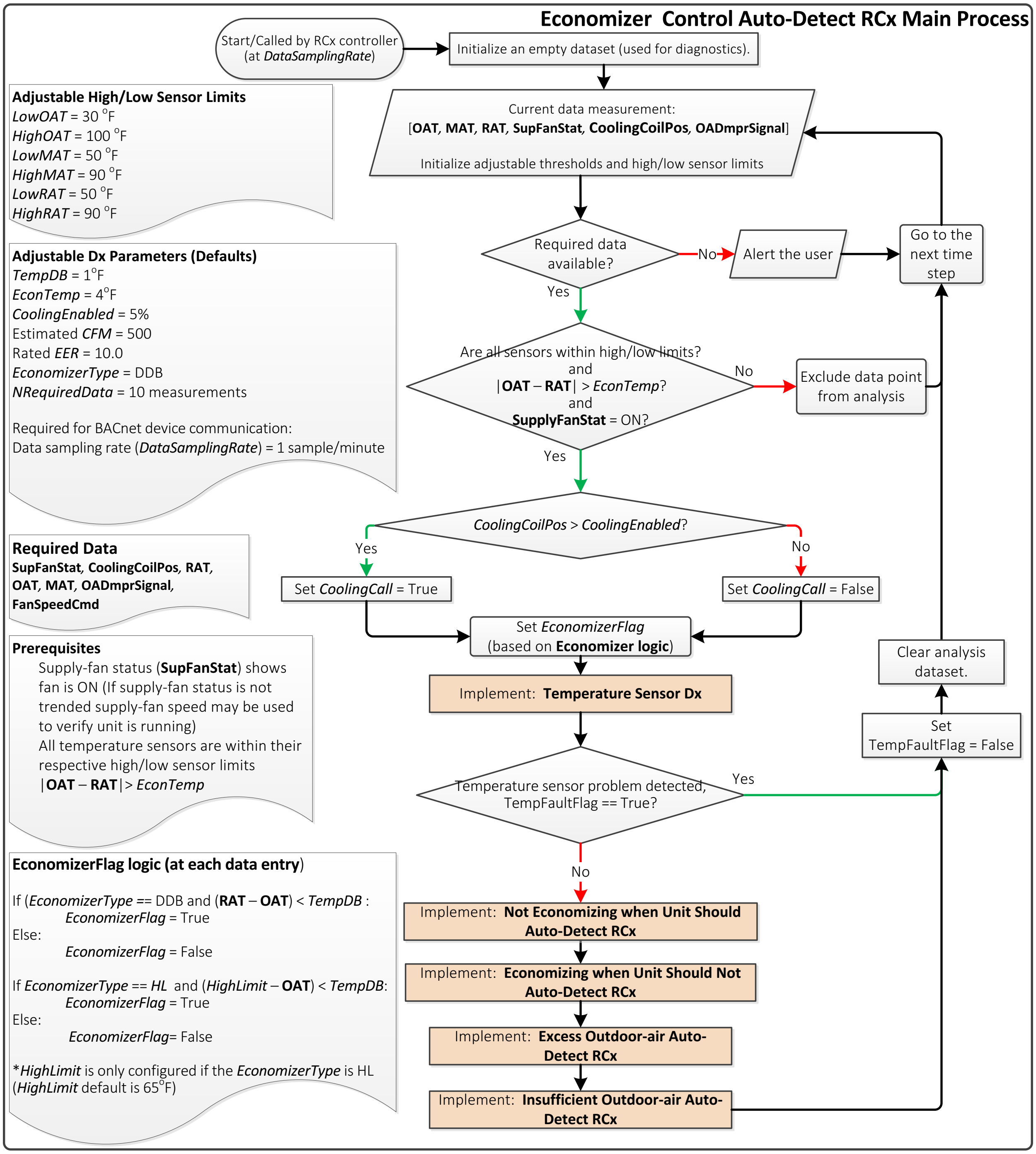


Figure 22: Flowchart for Economizer Control Auto-Detect RCx Main Process

4.2 Air Temperature Sensor Fault Auto-Detect RCx Process

The air temperature sensor fault auto-detect RCx process determines if the temperature sensors used on the AHU are reliable and within accepted tolerances. A temperature sensor fault, especially hard faults, can be detected by performing simple limit checks such as verifying the range of the measured temperature sensors data. For some temperature sensors, tight limits can be specified so the temperature sensors deviations can be easily detected. However, for the other sensors, such as outdoor-air temperature, there is a large range of valid values. In such cases, the high and the low limits must be seasonally adjusted and reset using a condition (day of year, for example), or sufficiently wide so that adjustment is not necessary (although this decreases the value of the limits). A hard failure indicated by a specific sensor reading outside the specified high/low limits can be isolated to a specific sensor.

If the sensors are operating within the specified limits, the measured temperature sensor data is used to detect whether any of the three temperature sensor values (outdoor, return and mixed air) are inconsistent with each other. The algorithm cannot isolate the faulty temperature sensors with this check. This diagnostic only alerts the building owner that one or more of the sensors is likely faulty.

4.2.1 Monitored Data for Air Temperature Sensor Fault Auto-Detect RCx

This section describes the required input data for this economizer diagnostic. The following data points are required for the execution of this diagnostic:

1. **MAT**
2. **RAT**
3. **OAT**
4. Outdoor-air damper signal (**OADmprSignal**).

If the **OADmprSignal** is measured as a voltage, or a value other than percent of fully open, then the values need to be converted to percent.

4.2.2 Temperature Sensor Fault Auto-Detect RCx Diagnostic Process

This section provides the diagnostic details including a detailed flow chart (Figure 23). The global economizer pre-requisites (checked in the main section previously) must be satisfied in order for the temperature sensor diagnostic to run.

The following steps are used for this diagnostic process (step 1 through step 3 occur in the Economizer Auto-Detect RCx Main Diagnostic process but are included here to add clarity to the RCx process):

1. Check if all prerequisites are met:
    - If all the prerequisites are met, add these data measurements to the current analysis dataset.
    - If not all the prerequisites are met, do not add these data measurements to the current analysis dataset and proceed to step 8.

2. If the **OADmprSignal** > *OpenDamper* (open damper threshold) and has been so for *OpenDamperTime* consecutive minutes:
    - Add the **OAT** and **MAT** to the OPEN-DAMPER dataset.
        - Append the current **OAT** measurement to ***OpenDmprOAT*** and append the current **MAT** to ***OpenDmprMAT***.

3. If the minimum analysis time (*MinAnalysisTime*) has been reached and there are at least *NRequiredData* measurements in the analysis dataset:

    - Proceed to the next step 4.

    Else, the minimum analysis (*MinAnalysisTime*) has not been reached or there are not at least *NRequiredData* measurements in the analysis dataset:
    - Proceed to step 8.

4. Calculate the average value of each temperature sensors' readings contained within the analysis dataset (AvgOAT, AvgMAT, and AvgRAT for ***OAT***, ***MAT***, and ***RAT***, respectively).

5. If the OPEN-DAMPER dataset has at least *NRequiredData* entries (***OpenDmprOAT***, ***OpenDmprMAT***, OATDiffMAT are arrays):
    - OATDiffMAT = [ABS(**OpenDamperMAT**$_k$ – **OpenDamperOAT**$_k$) for each point (k) in the OPEN-DAMPER dataset]
    - OpenDmprCheck = AVG(OATDiffMAT)
    - If OpenDmpCheck > *TempConsistency* (OAT and MAT consistency threshold):
        - Generate diagnostic message: The outdoor-air and mixed-air temperature readings are not consistent when the outdoor-air damper is fully open.
        - Set TempFaultFlag = True
    - Clear the OPEN-DAMPER dataset (***OpenDmpOAT*** and ***OpenDmpMAT***).

6. If (AvgOAT - AvgMAT) > *TempDiff* and (AvgRAT - AvgMAT) > *TempDiff* (temperature sensor threshold):
    - Generate diagnostic message: Temperature sensor problem detected. The mixed-air temperature is less than the outdoor- and return-air temperatures.
    - Set TempFaultFlag = True
    - Proceed to step 7.

    Else, if (AvgMAT - AvgOAT) > *TempDiff* and (AvgMAT - AvgRAT) > *TempDiff* (temperature sensor threshold):
    - Generate diagnostic message: Temperature sensor problem detected. The mixed air temperature is greater than the outdoor and return- air temperatures.
    - Set TempFaultFlag = True
    - Proceed to step 7.

    Else, if TempFaultFlag == False:
    - Generate diagnostic message: No temperature sensor problem was detected.
    - Proceed to step 7.

7. Make the diagnostic message(s) available to the operator.

8. Return to economizer control auto-detect RCx main diagnostic process; wait for next data.

The BACnet data interface queries data off the local controller or BAS every **"**Data Sampling Rate" minutes. The data is then supplied to the algorithm, which executes every "Data Sampling Rate". The execution of the diagnostic is identical for metered data provided via csv file except no auto-correction can be applied.

The following list contains the default but adjustable thresholds and parameters for this diagnostic:

- Temperature sensor (*TempDiff*) threshold = 4 °F

- OAT and MAT consistency (*TempConsistency*) threshold = 5 °F
- Open damper (*OpenDamper*) threshold = 90%
- Minimum analysis time (*MinAnalysisTime*) = 30 minutes
- Number of required data measurements (*NRequiredData*) = 20
- Time to state conditions once the OAD is fully open (*OpenDamperTime*) = 5 minutes

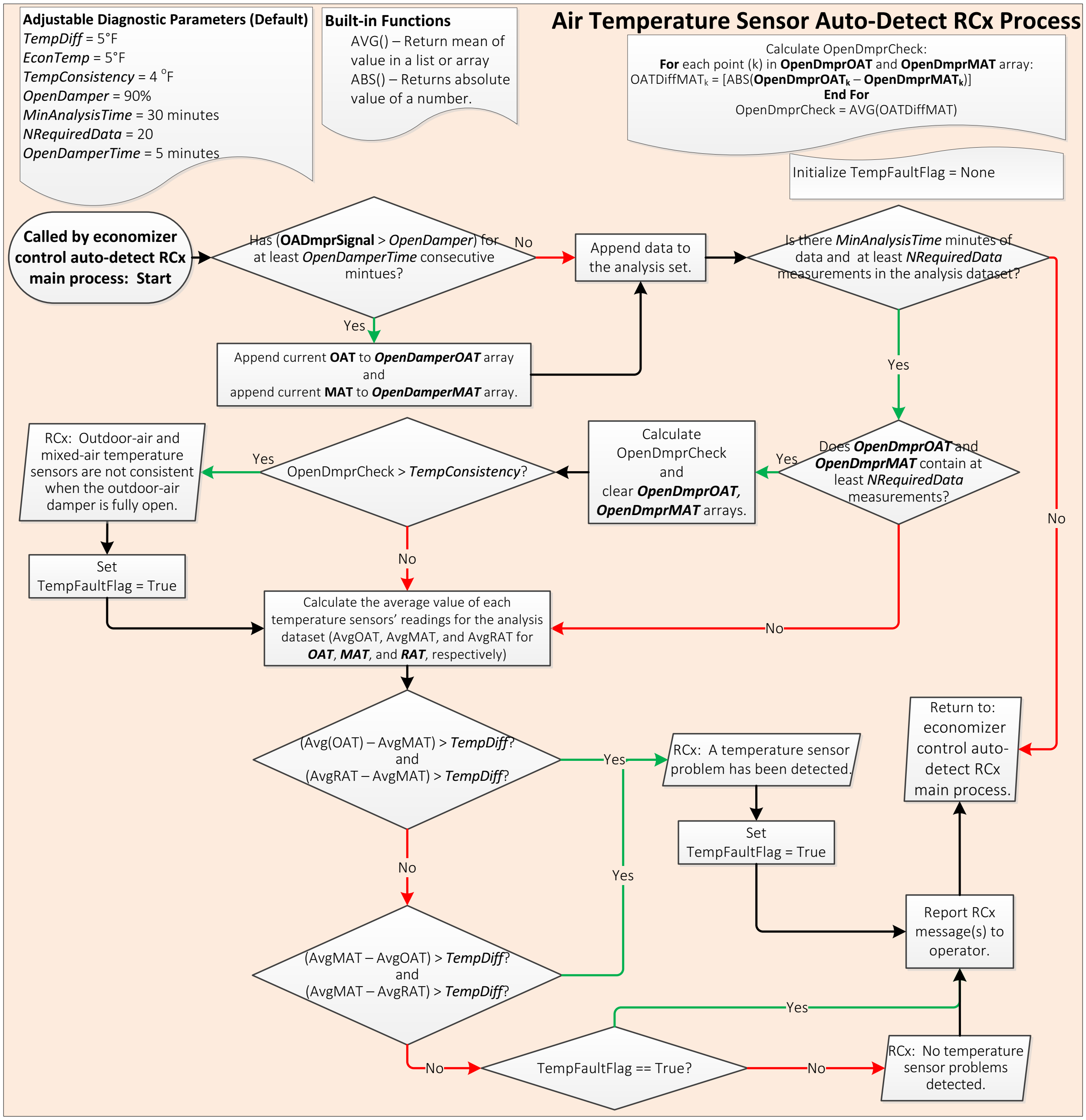


Figure 23: Flow Chart for Air Temperature Sensor Fault Auto-Detect RCx Process

4.3 AHU is not Fully Economizing When It Should Auto-Detect RCx Process

The AHU is not fully economizing when it should auto-detect RCx process determines if the economizer is ON and working properly when conditions are favorable for economizing. There are two configurations for the type of economizer: 1) differential dry-bulb economizer (economize when there is a call for cooling and OAT < RAT), and 2) high-limit economizer (economize when there is a call for cooling and OAT < high limit). The process described in this document applies to differential dry-bulb economizer only.

When the AHU is actively cooling and the outdoor-air temperature is less than the return-air temperature, the outdoor-air damper command should be close to 100%. If not, a problem is indicated by the diagnostic. When the outdoor air condition is favorable for economizing, the mechanical cooling is ON and the outdoor-air damper is less than 100% open, results in an energy waste. In many cases, outdoor air is cool enough to satisfy all the cooling loads without using mechanical cooling.

If the outdoor-air damper command indicates that the AHU is properly economizing (the outdoor-air damper is open to allow cool outdoor air into the unit), then the diagnostic will determine if the unit is bringing in nearly 100% outdoor air or at least greater than a threshold value (default 70% outdoor air). The outdoor-air fraction (OAF) is the ratio of the outdoor-air intake and the total supply-air flow rate. It can be used to determine the percentage of outdoor air being brought into the building and to diagnose over- or under-ventilation when the AHU is not in the economizer mode, and failures of the economizer mode (i.e., the AHU is in the economizer mode but the OAF shows a smaller fraction of outdoor air than expected). Because the outdoor-air intake flow rate is hard to measure, the OAF is calculated as a ratio of the difference between the mixed-air temperature and return-air temperature and the difference between outdoor-air temperature and return-air temperature, as shown in the equation below:

$$\frac{\textbf{mixed-air temperature} - \textbf{return-air temperature}}{\textbf{outdoor-air temperature} - \textbf{return-air temperature}}$$

The OAF calculation is not reliable when the outdoor-air temperature is close to the return-air temperature. Therefore, a conclusive diagnostic will only be returned when there is a significant difference between the outdoor-air and return-air temperatures, e.g., a difference of 4 to 5°F.

There can be many causes for an economizer fault or failure. It is possible that the AHU controller was not configured properly (set points) or was never programmed to utilize the economizer. This diagnostic will alert the building operator to possible failure of the economizer control function (or lack of economizer control function in cases where it was not programmed). The diagnostic will also alert the building owner if the economizer is controlled correctly but still operating poorly (not bringing in sufficient outdoor air when economizing).

This diagnostic process will continuously monitor the AHU to identify economizer operation problems and alert the building operator if they occur. Also, the diagnostic can be used with trended data via a CSV text file to identify economizer problems. If there is fault, an energy impact will be estimated using first principle relationships for sensible heat load (latent load is not considered so the energy impact estimation may be conservative).

4.3.1 Monitored Data for AHU is not Economizing When It Should Auto-Detect RCx

This section describes the required input data for this economizer diagnostic. The following data points are required for the execution of this diagnostic:

1. **MAT**
2. **RAT**
3. **OAT**
4. Supply-fan speed command (**FanSpeedCmd**)
5. Outdoor-air damper signal (**OADmprSignal**)
    - If the **OADmprSignal** or **FanSpeedCmd** are measured as a voltage or a value other than percent of fully open or full speed for **OADmprSignal** and **FanSpeedCmd** respectively, then the values need to be converted to percent.

4.3.2 AHU is not Economizing When It Should Auto-Detect RCx Diagnostic Process

This section provides the diagnostic details including a detailed flow chart (Figure 24). The following prerequisite must be met (in addition to the global pre-requisites that are checked in main process discussed previously):

- The AHU is cooling (i.e., CoolingFlag == True).
- Outdoor conditions are favorable for economizing (i.e., EconomizerFlag == True).

If the prerequisite condition is not satisfied, this diagnostic will not be executed. The following steps are used to for the diagnostic process (step 1 and step 2 occur in the economizer auto-detect RCx main diagnostic process but are included here to add clarity to the RCx process):

1. Check if all prerequisites are met:
    - If all the prerequisites are met, add these data measurements to the current analysis dataset
    - If not all the prerequisites are met, do not add these data measurements to the current analysis dataset.

2. If the minimum analysis time (*MinAnalysisTime*) has been reached and there are at least *NRequiredData* measurements in the analysis dataset:
    - Proceed to step 3.

    Else, proceed to step 10.

3. Calculate the average outdoor-air damper signal for the analysis dataset (AvgDmprSignal).

4. Calculate average outdoor-air fraction (AvgOAF) as follows (OAF is an array):
    - $OAFArray_i = [(\mathbf{MAT}_i - \mathbf{RAT}_i)/(\mathbf{OAT}_i - \mathbf{RAT}_i)$ for each point (i) in the analysis dataset]
    - AvgOAF = AVG(OAFArray) × 100
    - Proceed to step 5.

5. If AvgDmprSignal < *EconDmpr* (economizing damper threshold):

    - Generate diagnostic message: Conditions are favorable for economizing and the unit is actively cooling (mechanical cooling) but the outdoor-air damper is not fully open. The economizer is not fully utilizing the free cooling available via the outdoor air.
    - Proceed to step 8.

   Else, proceed to step 6.

6. Is the AvgOAF within acceptable limits?
    - If AvgOAF $\in$ [0, 125]:
        - Proceed to step 7.
    - Else, generate diagnostic message: The AvgOAF calculation led to an unexpected value.
        - Proceed to step 8.

7. If (100 – AvgOAF) > *EconOAF* (economizing OAF threshold):
    - Generate diagnostic message: Conditions are favorable for economizing and the outdoor-air damper is commanded open but the outdoor-air fraction indicates the unit is not bringing in near 100% outdoor-air.
    - Proceed to step 8.

   Else, generate diagnostic message: No problem was detected for this diagnostic.
    - Proceed to step 9.

8. If a problem was detected for this auto-detect economizer RCx:
    - Calculate the average supply-fan speed fraction (AvgFanSp = AVG(**FanSpeedCmd**)/100).
    - Calculate the estimated energy impact associated with the problem(s) (see Figure 26 for details).
    - Proceed to step 9.

9. Make diagnostic message(s) available to the operator.

10. Return to economizer control auto-detect RCx main diagnostic process; wait for next data.

The BACnet data interface queries data off the local controller or BAS every **"**Data Sampling Rate" minutes. The data is then supplied to the algorithm, which executes every "Data Sampling Rate". The execution of the diagnostic is identical for metered data provided via csv file except no auto-correction can be applied.

The following list contains the default but adjustable thresholds and parameters for this diagnostic:

- Economizing temperature (*EconTemp*) threshold = 4 °F
- Economizing damper (*EconDmpr*) threshold = 75%
- Economizing OAF (*EconOAF*) threshold = 30%
- Minimum analysis time (*MinAnalysisTime*) = 30 minutes
- Number of required data measurements (*NRequiredData*) = 20.

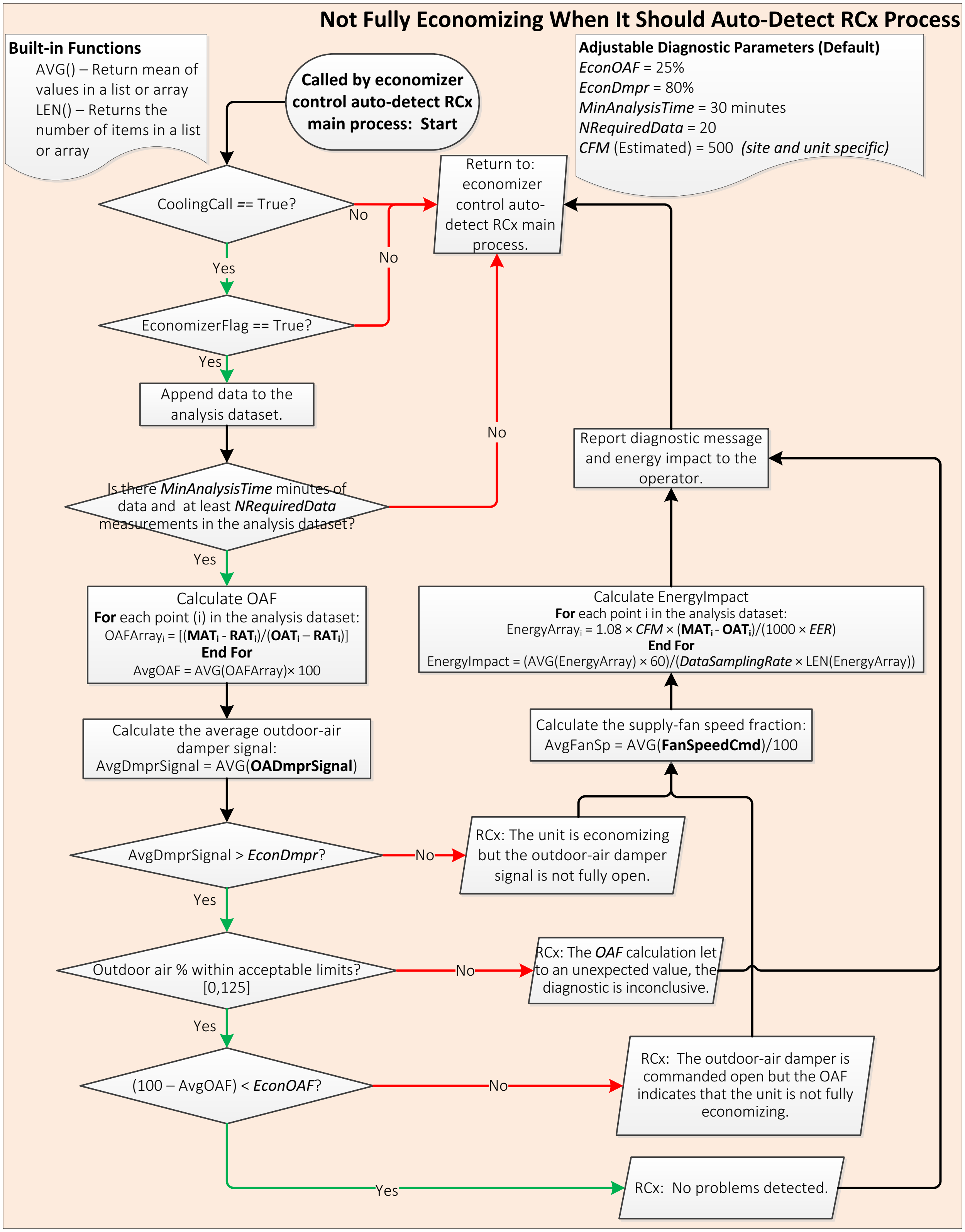


Figure 24: Flow Chart for Not Economizing When It Should Auto-Detect RCx Process

4.4 Economizing When It Should Not Auto-Detect RCx Process

The economizing when it should not auto-detect RCx process determines if the AHU is economizing when the outdoor conditions are not favorable for economizing. The AHU is considered to be in the economizer mode when the outdoor-air damper position and the outdoor-air fraction exceed their minimum threshold values. Even though economizing has potential to reduce cooling energy consumption, economizing when the conditions are not favorable has the potential to increase heating and/or cooling energy consumption. The diagnostic will use the outdoor-air damper command from the controller to determine if the damper command is appropriate during various heating and cooling events, as well as when there is no call for heating or cooling.

During occupied periods, there are at least three conditions that should be evaluated for this fault condition:

1. When there is no call for cooling or heating, the damper command should be at the minimum position.
2. When there is a call for heating, the damper command should be at the minimum position.
3. When there is a call for cooling and the conditions are not favorable for economizing (e.g. **OAT** is greater than the **RAT**), the damper position should be at the minimum position.

During unoccupied periods when the controller is trying to maintain minimum or maximum space temperatures, the damper should be closed unless the outdoor-air temperature is less than the return-air temperature, the system is in unoccupied cooling mode and the fan is running. The same is also true during morning warm-up periods and may also be true during morning cool-down periods. This fault diagnostic will alert the building owner or operator if there is a possible failure within the economizer control function.

4.4.1 Monitored Data for AHU is Economizing When it Should Not Auto-Detect RCx

The following data points are required for the execution of this diagnostic:

1. **MAT**
2. **RAT**
3. **OAT**
4. Supply-fan speed command (**FanSpeedCmd**)
5. Outdoor-air damper signal (**OADmprSignal**)
    - If the **OADmprSignal** or **FanSpeedCmd** are measured as a voltage or a value other than percent of fully open or full speed for **OADmprSignal** and **FanSpeedCmd** respectively, then the values need to be converted to percent.

4.4.2 AHU is Economizing When it Should Not Auto-Detect RCx Diagnostic Process

This section provides the re-tuning diagnostic details including a detailed flow chart (Figure 25). The following prerequisite must be met before the process is initiated:

- Outdoor conditions are not favorable for economizing (i.e., EconomizerFlag == False).

If the pre-requisite condition is not satisfied, the diagnostic will not be executed. The following steps are used to for the diagnostic process (step 1 and step 2 occur in the economizer auto-detect RCx main diagnostic process but are included here to add clarity to the RCx process):

6. Check if all prerequisites are met:
    - If all the prerequisites are met, add these data measurements to the current analysis dataset.
    - If not all the prerequisites are met, do not add these data measurements to the current analysis dataset.

7. If the minimum analysis time (*MinAnalysisTime*) has been reached and there are at least *NRequiredData* measurements in the analysis dataset:
    - Proceed to step 3.

    Else, proceed to step 7.

8. Calculate the average outdoor-air damper signal for the analysis dataset (AvgDmprSignal).

9. Calculate average outdoor-air fraction (AvgOAF) as follows (OAFArray is an array):
    - $\text{OAFArray}_i = [(\mathbf{MAT}_i - \mathbf{RAT}_i)/(\mathbf{OAT}_i - \mathbf{RAT}_i)$ for each point (i) in analysis dataset]
    - AvgOAF = AVG(OAFArray) × 100.

10. If (AvgDmprSignal – *MinOADmprSP*) > *ExcessDmpr* (excess damper threshold):
    - Generate diagnostic message: The outdoor-air damper should be at the minimum position for ventilation but is significantly above that value.
    - Calculate the average fan speed fraction (AvgFanSp = AVG(**FanSpeedCmd**)/100).
    - Calculate the estimated energy impact associated with the problem(s) (see Figure 25 for details).
    - Proceed to next step 6.

    Else, generate diagnostic message: No problem was detected during this diagnostic.
    - Proceed to step 6.

6. Make diagnostic message(s) available to the operator.

7. Return to economizer control auto-detect RCx main diagnostic process; wait for next data.

The BACnet data interface queries data off the local controller or BAS every **“**Data Sampling Rate” minutes. The data is then supplied to the algorithm, which executes every “Data Sampling Rate”. The execution of the diagnostic is identical for metered data provided via csv file except no auto-correction can be applied.

The following list contains the default but adjustable thresholds and parameters for this diagnostic:

- Excess damper (*ExcessDmpr*) threshold = 20%
- Minimum outdoor-air damper set point (*MinOADmprSP*) = 20%
- Economizing temperature (*EconTemp*) threshold = 4 °F
- Minimum analysis time (*MinAnalysisTime*) = 30 minutes

- Number of required data measurements for analysis (*NRequiredData*) = 20
- Desired outdoor-air percent (*DesiredOAF*) = 10% (when OAD is at minimum position)

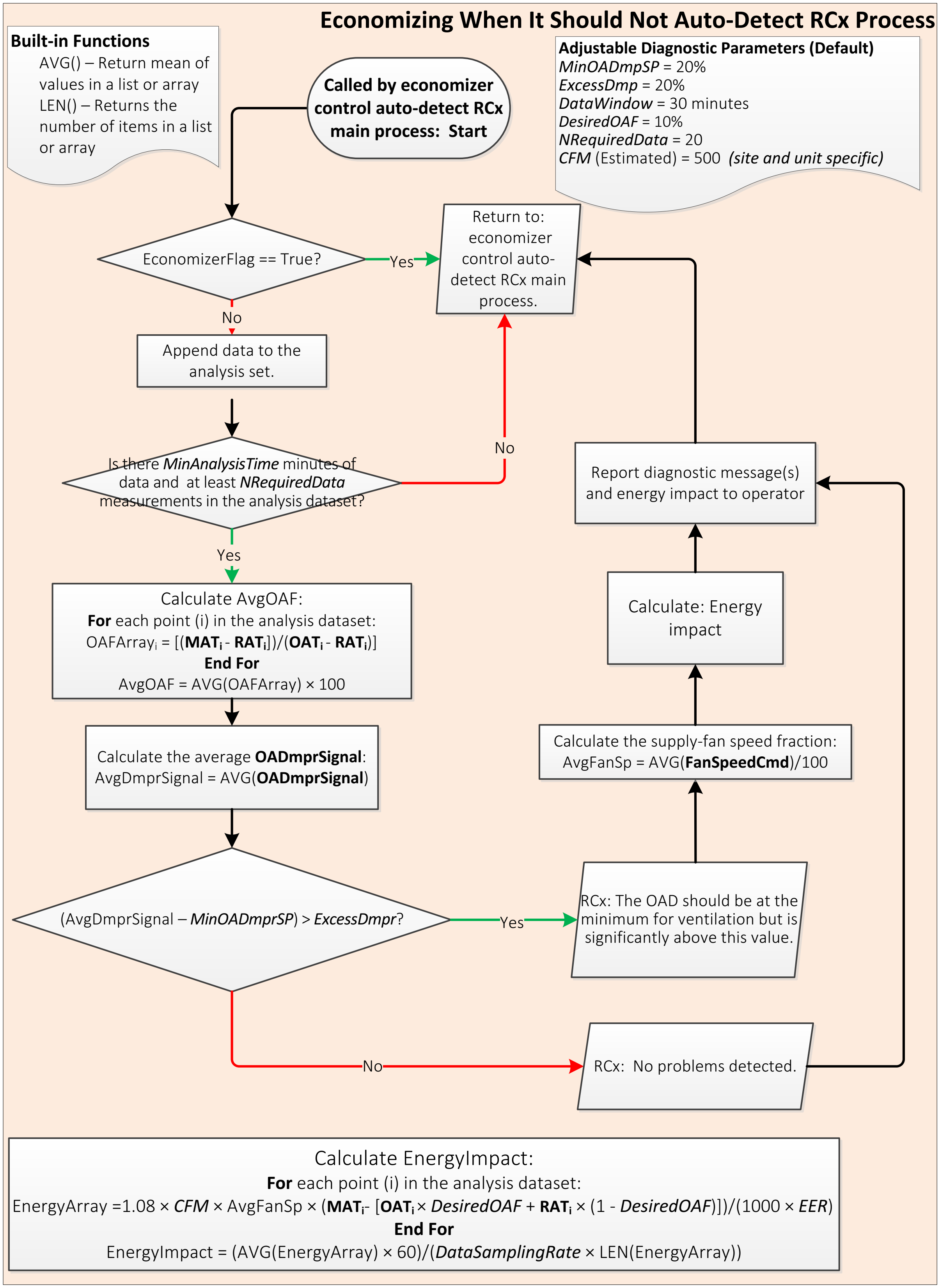


Figure 25: Flow Chart for Economizing When It Should Not Auto-Detect RCx Process

4.5 Excess Outdoor-air Intake Auto-Detect RCx Process

The excess outdoor-air intake auto-detect RCx process determines if the AHU is introducing excess outdoor air beyond the minimum ventilation requirements when the outdoor-air damper should be at the minimum position, conditions are not favorable for economizing and/or there is no call for cooling from the zones served by the unit. Excess outdoor air, when not needed, has the potential to increase heating and/or cooling energy consumption. The outdoor air fraction (OAF) will be used to determine if the AHU/RTU is providing too much outdoor air. The OAF can be calculated as a ratio of the difference between the mixed-air temperature and return-air temperature and the difference between outdoor-air temperature and return-air temperature, as shown in the equation below.

$$\frac{\textbf{mixed-air temperature} - \textbf{return-air temperature}}{\textbf{outdoor-air temperature} - \textbf{return-air temperature}}$$

The OAF calculated using the above equation is not reliable when the OAT is close to the RAT. Therefore, a conclusive diagnostic will only be returned when there is a significant difference between the outdoor-air and return-air temperatures, e.g., a difference of at least 4 to 5°F. The calculated OAF is compared to an OAF threshold (adjustable) to determine if excess outdoor air is being introduced into the space. If the calculated outdoor-air fraction exceeds a threshold, a fault is indicated.

4.5.1 Monitored Data for Excess Outdoor-air Intake Auto-Detect RCx

This section describes the required input data for this auto RCx process. The following data points are required for the execution of this diagnostic:

1. **MAT**
2. **RAT**
3. **OAT**
4. Supply-fan speed command (**FanSpeedCmd**)
5. Outdoor-air damper signal (**OADmprSignal**).

If the **OADmprSignal** or **FanSpeedCmd** are measured as a voltage or a value other than percent of fully open or full speed for **OADmpr** and **FanSpeedCmd** respectively, then the values need to be converted to percent.

4.5.2 Excess Outdoor-air Intake Auto-Detect RCx Diagnostic Process

This section provides the diagnostic details including a detailed flow chart (Figure 26). The following prerequisite must be met:

- Outdoor conditions are not favorable for economizing (i.e., EconomizerFlag == False).

If the pre-requisite condition is not satisfied, the corresponding data will not be used for this diagnostic. The following steps are used to for the diagnostic process (step 1 and step 2 occur in the economizer auto-detect RCx main diagnostic process but are included here to add clarity to the RCx process):

1. Check if all prerequisites are met:

- If all the prerequisites are met, add these data measurements to the current analysis dataset
- If not all the prerequisites are met, do not add these data measurements to the current analysis dataset.

2. If the minimum analysis time (*MinAnalysisTime*) has been reached and there are at least *NRequiredData* measurements in the analysis dataset:
    - Proceed to step 3.

   Else, proceed to step 10.

3. Calculate the average outdoor-air damper signal for the analysis dataset (AvgDmprSignal).

4. Calculate average outdoor-air fraction (AvgOAF) as follows (OAFArray is an array):
    - $\text{OAFArray}_i = [(\mathbf{MAT_i} - \mathbf{RAT_i})/(\mathbf{OAT_i} - \mathbf{RAT_i})$ for each point (i) in analysis dataset]
    - AvgOAF = AVG(OAFArray) × 100
    - Proceed to step 5.

5. Is the AvgOAF within acceptable limits?
    - If AvgOAF $\in$ [0, 125]:
        - Proceed to step 6.
    - Else, generate diagnostic message: The AvgOAF calculation led to an unexpected value.
        - Proceed to step 9.

6. If (AvgDmprSignal – *MinOADmprSP*) > *ExcessDmpr* (excess damper threshold):
    - Generate diagnostic message: The outdoor-air damper should be at the minimum position for ventilation but it is significantly above that value.

   Proceed to step 7.

7. If (AvgOAF – *DesiredOAF*) > *ExcessOAF* (excess OAF threshold):
    - Generate diagnostic message: The OAF should be at the minimum value for ventilation but it is significantly above that value.
    - Proceed to step 8.

8. If a problem was detected:
    - Calculate the average supply-fan speed fraction (AvgFanSp = AVG(**FanSpeedCmd**)/100).
    - Calculate the estimated energy impact associated with the problem(s) (see Figure 26 for details).

   Else, generate diagnostic message: No problems detected for excess outdoor-air intake RCx process.
    - Proceed to step 9.

9. Make the diagnostic message(s) available to the operator

10. Return to economizer control auto-detect RCx main diagnostic process; wait for next data.

The BACnet data interface queries data off the local controller or BAS every **“**Data Sampling Rate” minutes. The data is then supplied to the algorithm, which executes every “Data Sampling Rate”. The execution of the diagnostic is identical for metered data provided via csv file except no auto-correction can be applied.

The following list contains the default but adjustable thresholds and parameters for this diagnostic:

- *MinAnalysisTime* = 30 minutes
- *NRequiredData* = 20
- Excess damper (*ExcessDmpr*) threshold = 20%
- Excess OAF (ExcessOAF) threshold = 20%
- Minimum outdoor-air damper set point (*MinOADmprSP*) = 20%
- Minimum analysis time (*MinAnalysisTime*) = 30 minutes
- Number of required data measurements for analysis (*NRequiredData*) = 20
- Desired outdoor-air percent (*DesiredOAF*) = 10% (when OAD is at minimum position)

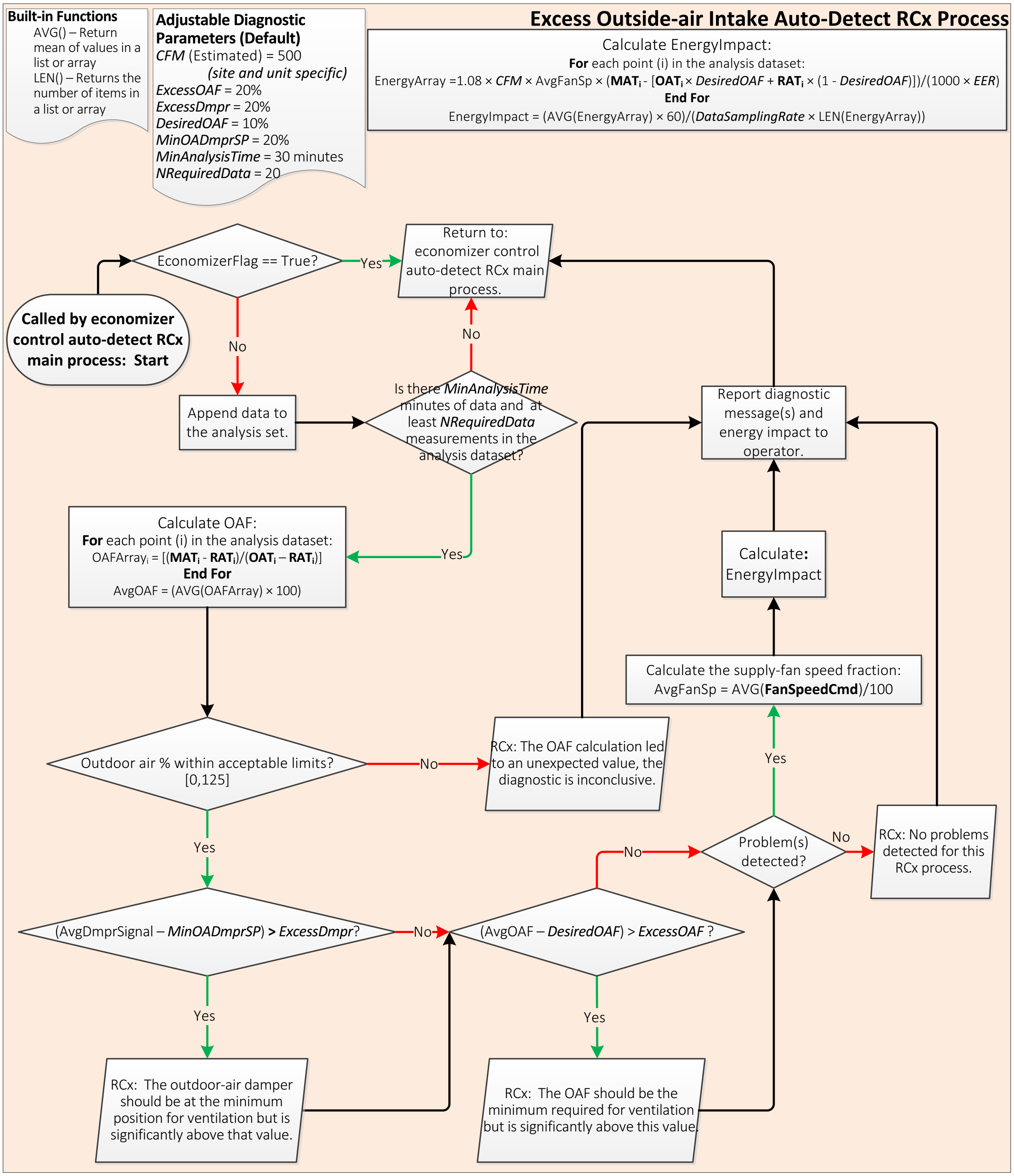


Figure 26: Flow Chart for Excess Outdoor-air Intake Auto-Detect RCx Process

4.6 Insufficient Outdoor-air Ventilation Intake Auto-Detect RCx Process

This diagnostic determines if the AHU is providing sufficient outdoor air, and therefore the minimum ventilation requirements are met.

Insufficient outdoor air has the potential to contribute to possible "sick building" syndrome. Effects of insufficient ventilation include increased levels of CO_2 gases and could lead to potentially negative building pressurization problems, which can contribute to infiltration of unwanted dust, moisture, pollens, cold air or hot air (from other parts of the building). Infiltration issues can affect occupant health and in some cases the safety of the building (cold air infiltration can freeze nearby pipes, if not adequately insulated). It is desirable to ensure that ventilation (outdoor) air is brought into the building via the AHU's outdoor-air dampers, which are designed with filtration systems, conditioning systems, and moisture capture systems. This fault analysis will determine if there is an insufficient amount of outdoor air being introduced to the AHUs.

The OAF is calculated as a ratio of the difference between the mixed-air temperature and return-air temperature and the difference between outdoor-air temperature and return-air temperature, as shown in the equation below.

$$\frac{\textbf{mixed-air temperature – return-air temperature}}{\textbf{outdoor-air temperature – return-air temperature}}$$

The OAF calculated using the above equation is not reliable when the outdoor-air temperature is close to the return-air temperatures. Therefore, a conclusive diagnostic will only be returned when there is a significant difference between the outdoor-air and return-air temperatures, e.g., a difference of at least 4 to 5^{o}F.

The calculated average OAF (AvgOAF) and the average outdoor-air damper position (AvgDmprSignal) are compared to minimum OAF and minimum damper-position thresholds, respectively, to determine if sufficient ventilation air is being introduced into the space. If the supplied outdoor air is insufficient to meet the ventilation needs of the building then a problem is indicated.

4.6.1 Monitored Data for Insufficient Outdoor-air Intake Auto-Detect RCx

This section describes the required input data for this auto RCx process. The following data points are required for the execution of this diagnostic:

1. **MAT**
2. **RAT**
3. **OAT**
4. Outdoor-air damper signal (**OADmprSignal**).

4.6.2 Insufficient Outdoor-air Intake Auto-Detect RCx Diagnostic Process

This section provides the diagnostic details including a detailed flow chart (Figure 26). The following prerequisite must be met:

- Outdoor conditions are not favorable for economizing (i.e., EconomizerFlag == False).

If the pre-requisite condition is not satisfied, the corresponding data will not be used for this diagnostic. The following steps are used to for the diagnostic process (step 1 and step 2 occur in the economizer auto-detect RCx main diagnostic process but are included here to add clarity to the RCx process):

1. Check if all prerequisites are met:
    - If all the prerequisites are met, add these data measurements to the current analysis dataset.
    - If not all the prerequisites are met, do not add these data measurements to the current analysis dataset.

2. If the minimum analysis time (*MinAnalysisTime*) has been reached and there are at least *NRequiredData* measurements in the analysis dataset:
    - Proceed to step 3.

    Else, proceed to step 9.

3. Calculate the average outdoor-air damper signal for the analysis dataset (AvgDmprSignal).

4. Calculate average outdoor-air fraction (AvgOAF) as follows (OAFArray is an array):
    - $\text{OAFArray}_i = [(\mathbf{MAT_i} - \mathbf{RAT_i})/(\mathbf{OAT_i} - \mathbf{RAT_i})$ for each point (i) in analysis dataset]
    - AvgOAF = AVG(OAFArray) × 100
    - Proceed to step 5.

5. Is the AvgOAF within acceptable limits?
    - If AvgOAF $\in$ [0, 125]:
        - Proceed to step 6.
    - Else, generate diagnostic message: The OAF calculation led to an unexpected value.
        - Proceed to step 8.

6. If (*MinOADmprSP* – AvgDmprSignal) > *InsufficientOADmpr* (insufficient outdoor-air damper threshold):
    - Generate diagnostic message: The outdoor-air damper should be at the minimum position for ventilation but is significantly below that value.

    Proceed to step 7.

7. If (*DesiredOAF* – AvgOAF) > *InsufficientOAF* (insufficient OAF threshold):
    - Generate diagnostic message: The OAF should be at the minimum value for ventilation but it is significantly below this value.
    - Proceed to step 8.

    Else, generate diagnostic message: No problems detected for insufficient outdoor-air intake RCx process.
    - Proceed to step 8.

8. Make the diagnostic message(s) available for the operator.

9. Return to economizer control auto-detect RCx main diagnostic process; wait for next data.

The BACnet data interface queries data off the local controller or BAS every **“**Data Sampling Rate” minutes. The data is then supplied to the algorithm, which executes every “Data Sampling Rate”. The execution of the diagnostic is identical for metered data provided via csv file except no auto-correction can be applied.

The following list contains the default but adjustable thresholds and parameters for this diagnostic:

- Insufficient outdoor-air damper (*InsufficientOADmpr*) threshold = 15%
- Insufficient OAF (*InsufficientOAF*) threshold = 15%
- Minimum outdoor-air damper set point (*MinOADmprSP*) = 20%
- Minimum analysis time (*MinAnalysisTime*) = 30 minutes
- Number of required data measurements for analysis (*NRequiredData*) = 20
- Desired outdoor-air percent (*DesiredOAF*) = 10% (when OAD is at minimum position).

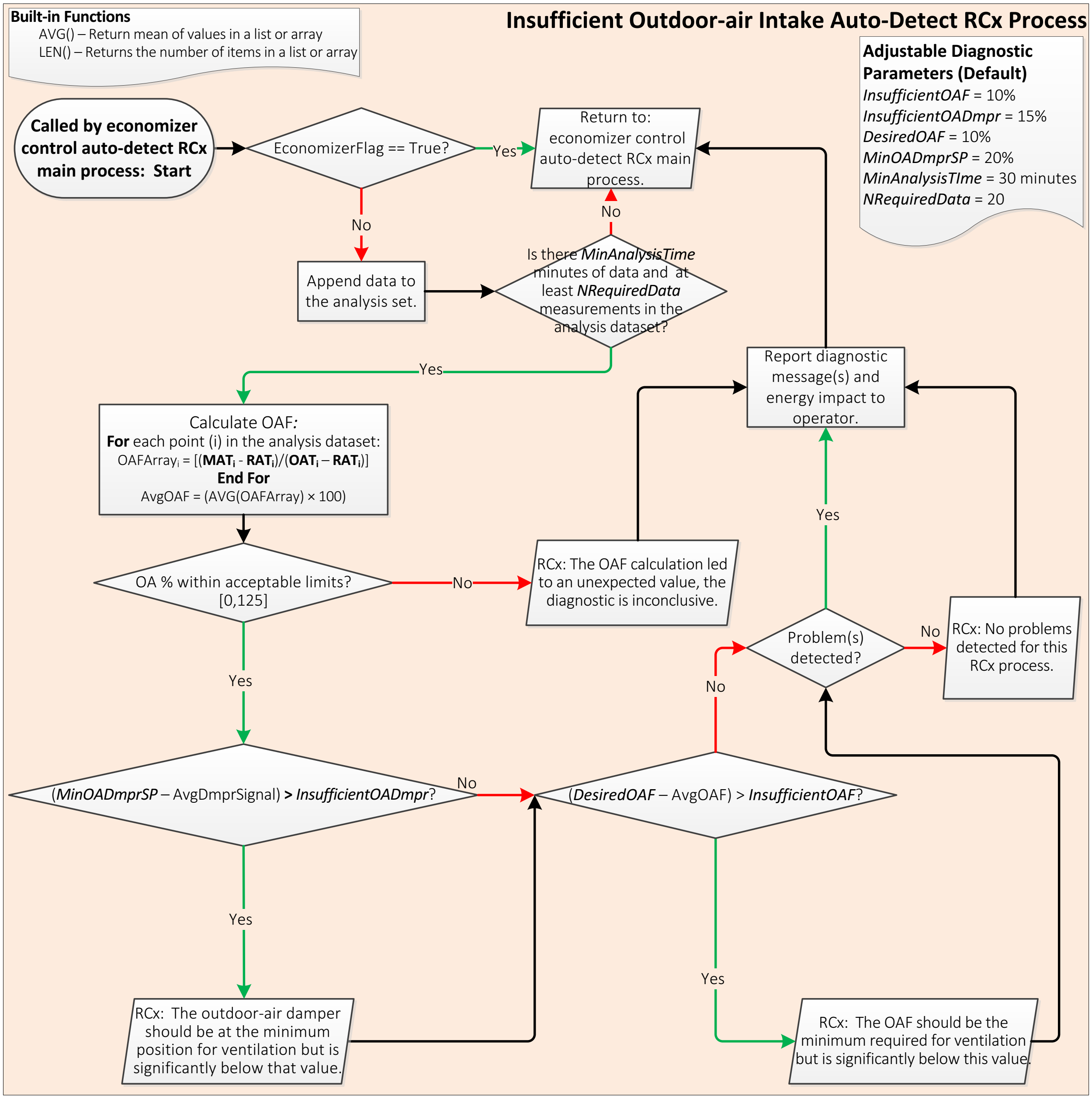


Figure 27: Flow Chart for Insufficient Outdoor-air Intake Auto-Detect RCx Process