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Automatic Identification of Retro-commissioning Measures

February 2018

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RG Lutes
RM Underhill
S Huang

U.S. DEPARTMENT OF
ENERGY

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

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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 optimally, which leads 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, including air handing units (AHUs), economizer systems, and hot-water and chilled-water central plants, and to provide actionable real-time information to building operation staff. 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 along with occupant comfort issues. 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.

1. Detection, diagnosis, and correction of high duct static pressure in variable air volume (VAV) 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.

Five hot-water central plant RCx measures will be implemented.

1. Detection and diagnosis of low hot-water loop delta-T (difference between supply and return water temperatures).
2. Detection and diagnosis of constant hot-water loop supply temperature (no reset).
3. Detection and diagnosis of constant hot-water loop differential pressure (no reset).

[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

4. Detection and diagnosis of high hot-water loop differential pressure set point.
5. Detection and diagnosis of high hot-water supply temperature set point reset.

Five economizer control RCx measures will be implemented.

1. Detection of AHU sensor faults (outdoor-air, mixed-air, and return-air temperature sensors).
2. Detection that the AHU is not economizing when it should.
3. Detection that the AHU is economizing when it should not.
4. Detection that the AHU is using excess outdoor air.
5. Detection that 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.

Acknowledgments

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; Woohyun Kim for the technical review of the report; and Heather Culley for editorial support.

Acronyms and Abbreviations

°F	degree(s) Fahrenheit
AHU	air-handling unit
BAS	building automation system
CSV	comma-separated variable
CFM	cubic feet per minute
DDB	differential dry-bulb
DP	differential pressure
HI	high limit
HVAC	heating, ventilation, and air-conditioning
HW	hot water
HWRT	hot water loop return temperature
HWST	hot water supply temperature
HWSTSP	hot water loop supply temperature set point
in. w.g.	inch(es) water gauge
MAT	mixed-air temperature
MaxDP	maximum differential pressure
MinDP	minimum differential pressure
OAD	outdoor-air damper
OAF	outdoor-air fraction
OAT	outside-air temperature
PNNL	Pacific Northwest National Laboratory
RAT	return-air temperature
RCx	retro-commissioning
RTU	rooftop unit
SAT	supply-air temperature
VAV	variable air volume
VFD	variable-frequency drive

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1.0 Introduction

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

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 respond to control 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 have occurred. Human factors also influence building performance and necessitate the need for building retuning. These human factors 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 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)[1,2,3] of existing buildings saves energy; most reported savings are in in the range of 10% to 30% of the total building energy consumption. However, RCx as it is practiced today is perceived as not being cost-effective and also does not guarantee the persistence of optimum building operations. Many of the operational problems typically detected during the RCx process can be detected automatically and continuously day-to-day, thereby allowing the buildings to operate near optimally. Pacific Northwest National Laboratory (PNNL) developed a re-tuning process to address some of the issues associated with RCx. However, to ensure the persistence of optimum building operations, the re-tuning process has to be applied periodically. The algorithms

[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 a number definitions of RCx exist, 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

[2] 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, Washington.

[3] 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.

described in this document will allow continuous and automatic re-tuning, thereby leading to and ensuring persistence of desired operations. These diagnostics will reduce the cost of implementing RCx.

Re-tuning is a systematic process of identifying and correcting operational problems that plague commercial buildings that have BASs. Correction of many of these problems requires no or very little cost. The problems identified as part of this process can include the following.

- Excessive temperatures (too high, too low) for various 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 (SATs) and static pressures that are not working or are 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 are 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 are 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 (AHU, chiller plant, heating hot-water plant, etc.).

The re-tuning process can be applied using a semi-automated process to identify operational problems and to correct these 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 RCx, but to ensure persistence of optimum building operations, 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 identified during re-tuning can be detected automatically and continuously, allowing the buildings to operate near optimal, which leads to lower RCx cost and increased persistence. A number of re-tuning measures can be detected automatically. Similar to a 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 identification of retro-commissioning (AIRCx) uses computer algorithms to ensure that buildings operate continuously at peak efficiency. AIRCx ensures that the building staff focus on activities for which their intervention is essential (e.g., replacing components that have physically failed or degraded, thereby reducing efficiency and increasing the cost of operation) and corrects operational problems that can be corrected without operator intervention leading, the 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 be detected and diagnosed automatically, *some* of which 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, the following nine re-tuning measures were selected for automation.

- Detection, diagnosis, and correction of high duct static pressure in variable air volume (VAV) air-handling units (AHUs).
- Detection, diagnosis, and correction of low duct static pressure in VAV AHUs.
- Detection, diagnosis, and correction of high SAT in VAV AHUs.
- Detection, diagnosis, and correction of low SAT in VAV AHUs.
- Detection and diagnosis of low hot-water loop delta-T (difference between supply and return water temperatures).
- Detection and diagnosis of constant hot-water loop supply temperature (no reset).
- Detection and diagnosis of constant hot-water loop differential pressure (no reset).
- Detection and diagnosis of high hot-water loop differential pressure set point.
- Detection and diagnosis of high hot-water supply temperature set point reset.

The first four algorithms include automated detection, diagnosis, reporting, and *correction*, while the remainder include automated detection, diagnosis, and reporting (no correction).

1.2 Deployment of the Algorithms

All of the algorithms are coded in the Python programming language and made compatible with the Transactional (VOLTTRON[4]) Network[5] framework and the OpenEIS framework. The AIRCx 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.
5. Automatically correct the problem.

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

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[4] For more information on VOLTTRON, 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.

[5] 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.

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.

Table 1.1 contains a list of common relational operators used in this document:

Table 1.1. Relational Operators Used in this Guide

Operator	Description
==	If the values of two operands are equal, then the condition becomes true.
!=	If values of two operands are not equal, then condition becomes true.
>	If the value of left operand is greater than the value of right operand, then condition becomes true.
<	If the value of left operand is less than the value of right operand, then condition becomes true.
>=	If the value of left operand is greater than or equal to the value of right operand, then condition becomes true.
<=	If the value of left operand is less than or equal to the value of right operand, then condition becomes true.

Although the BACnet driver is essential for auto-correction, the detection and the diagnostics steps can also be deployed using data collected from offline processes (i.e., comma-separated variable [CSV] text files). Thus, there are number of different ways these algorithms can be deployed, as shown in Figure 1.1. The remainder of this report is dedicated to documenting the re-tuning diagnostics.

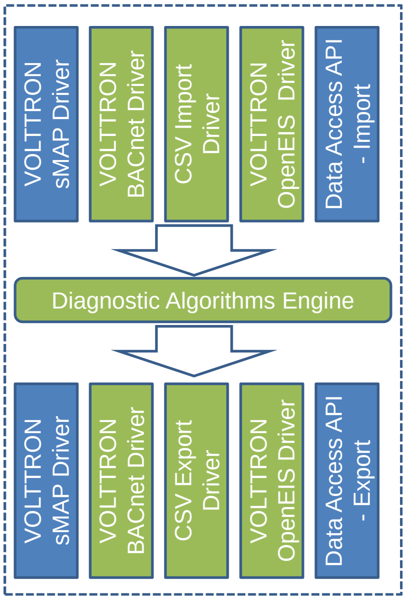

Figure 1.1. Deployment Options for AIRCx Algorithms

2.0 Air-Side AIRCx Algorithms

The air-side AIRCx (automated identification of retro-commissioning measures) processes use a decision-tree structure to detect, diagnose, and automatically provide corrective actions for the problems associated with an AHU's operation.

Detecting and diagnosing problems within an AHU is crucial because the unit can increase system energy expenditures and affect the comfort of building 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 its 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 use rules derived from engineering principles of proper and improper AHU operations. Seven air-side diagnostics correspond to the seven operational problems; the air-side diagnostics include the following.

- Detect whether the SAT for an AHU is too low.
- Detect whether the SAT for an AHU is too high.
- Detect whether the SAT set point for an AHU is reset or fixed.
- Detect whether the fan is operational during unoccupied time periods.
- Detect whether the duct static pressure for an AHU is too low.
- Detect whether the duct static pressure for an AHU is too high.
- 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 provides a more detailed summary of the seven algorithms used to detect, diagnose, and provide automated corrective actions.

2.1 Air-Side AIRCx Main Diagnostic Process

For the AIRCx 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 supply-fan speed signal can be used as an indicator of the supply-fan status (i.e., if the supply-fan speed is greater than the minimum supply-fan speed (*low_sf_threshold* = 20%), consider the fan to be ON).

Configuration parameters for the air-side diagnostics include (with default values) include the following:

- AIRCx flag (*auto_correct_flag*) = False

- Number of required data points for AIRCx (*no_required_data*) = 10
- Minimum elapsed time for analysis (*data_window*) = 15 minutes
- High supply-fan threshold (*high_sf_threshold*) = 100%
- Low supply-fan threshold (*low_sf_threshold*) = 20%
- Allowable set point deviation (*allowable_deviation*) = 10%
- SAT set point AIRCx increment/decrement (*sat_retuning*) = 1°F
- Duct static pressure AIRCx increment/decrement (*stcpr_retuning*) = 0.15 in. w.c.

Low SAT AIRCx adjustable parameters include the following:

- Maximum SAT set point (*max_sat_stpt*) = 70°F
- Percent reheat threshold (*percent_reheat_threshold*) = 25%
- Reheat "ON" threshold (*reheat_on_threshold*) = 10%
- Reheat valve threshold (*reheat_valve_threshold*) = 50%.

High SAT AIRCx adjustable parameters include the following:

- Reheat "ON" threshold (*reheat_on_threshold*) = 10%
- Minimum SAT set point (*min_sat_stpt*) = 50°F
- Percent damper threshold (*percent_damper_threshold*) = 60%
- Zone high damper threshold (*zone_high_damper_threshold*) = 90%
- Percent reheat threshold (*percent_ reheat_threshold*) = 25%.

No SAT set point reset AIRCx adjustable parameters include the following:

- SAT reset threshold (*sat_reset_threshold*) = 2°F.

Unoccupied fan operation AIRCx adjustable parameters include the following:

- Unoccupied time threshold (*unocc_time_threshold*) = 30%
- Unoccupied static pressure threshold (*unocc_stcpr_threshold*) = 0.2 in. w.g.
- Building schedule = [5:30 AM – 6:30 PM]
  - Monday (*monday_sch*) = [5:30 AM – 6:30 PM]
  - Tuesday (*tuesday_sch*) = [5:30 AM – 6:30 PM]
  - Wednesday (*wednesday_sch*) = [5:30 AM – 6:30 PM]
  - Thursday (*thursday_sch*) = [5:30 AM – 6:30 PM]
  - Friday (*friday_sch*) = [5:30 AM – 6:30 PM]
  - Saturday (*saturday_sch*) = [0:00 AM – 0:00 AM]
  - Sunday (*sunday_sch*) = [0:00 AM – 0:00 AM].

Low duct static pressure AIRCx adjustable parameters include the following:

- Zone low damper threshold (*zone_low_damper_threshold*) = 25%
- Zone high damper threshold (*zone_high_damper_threshold*) = 90%
- Maximum duct static pressure set point (*max_stcpr_stpt*) = 2.5 in. w.g.

High duct static pressure AIRCx adjustable parameters include the following:

- High duct (static pressure) zone damper threshold (*hdzone_damper_threshold*) = 30%
- Minimum duct static pressure set point (*min_stcpr_stpt*) = 0.2 in. w.g.

No duct static pressure set point reset AIRCx adjustable parameters include the following:

- Static pressure reset threshold (*stcpr_reset_threshold*) = 0.25 in. w.g.

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

The following array conventions will be used in subsequent sections:

- The first element of an array is accessed by using "0" as the index surrounded by brackets. The last element of an array is access by using "-1" as the index surrounded by brackets.
  - Example: consider an array, ***example_array*** = [1.5, 2.0, 5.3, 10.2], then,

example_array[0] =1.5

example_array[-1] = 10.2

example_array[-1] – ***example_array***[0] = 10.2 – 1.5 = 8.7

- An empty array will be evaluated to false when used with an "If" conditional.
  - Example: consider the arrays, ***another_example*** = [], and ***example_array*** = [1.5, 2.0, 5.3, 10.2], then,
    - If ***another_example***,
      - This if conditional evaluates to false.
    - If not ***another_example***,
      - This conditional evaluates to true.
    - If ***example_array***,
      - This conditional evaluates to true.
    - If not ***example_array***,
      - This condition evaluates to false.

The AIRCx main process handles the diagnostics prerequisites (i.e., prerequisites that apply to all of the air-side diagnostics) and data management (passing thresholds values and data for the AHU and zone terminal box controllers to the diagnostics) for all seven diagnostics sub-processes (Figure 2.1). The

BACnet data interface queries data off the local controller or BAS at a constant (user configurable) rate, which should not exceed five minutes to ensure accurate diagnostic results. The data are then supplied to the algorithm. The execution of the diagnostic is identical for metered data provided via CSV text file except no auto-correction can be applied.

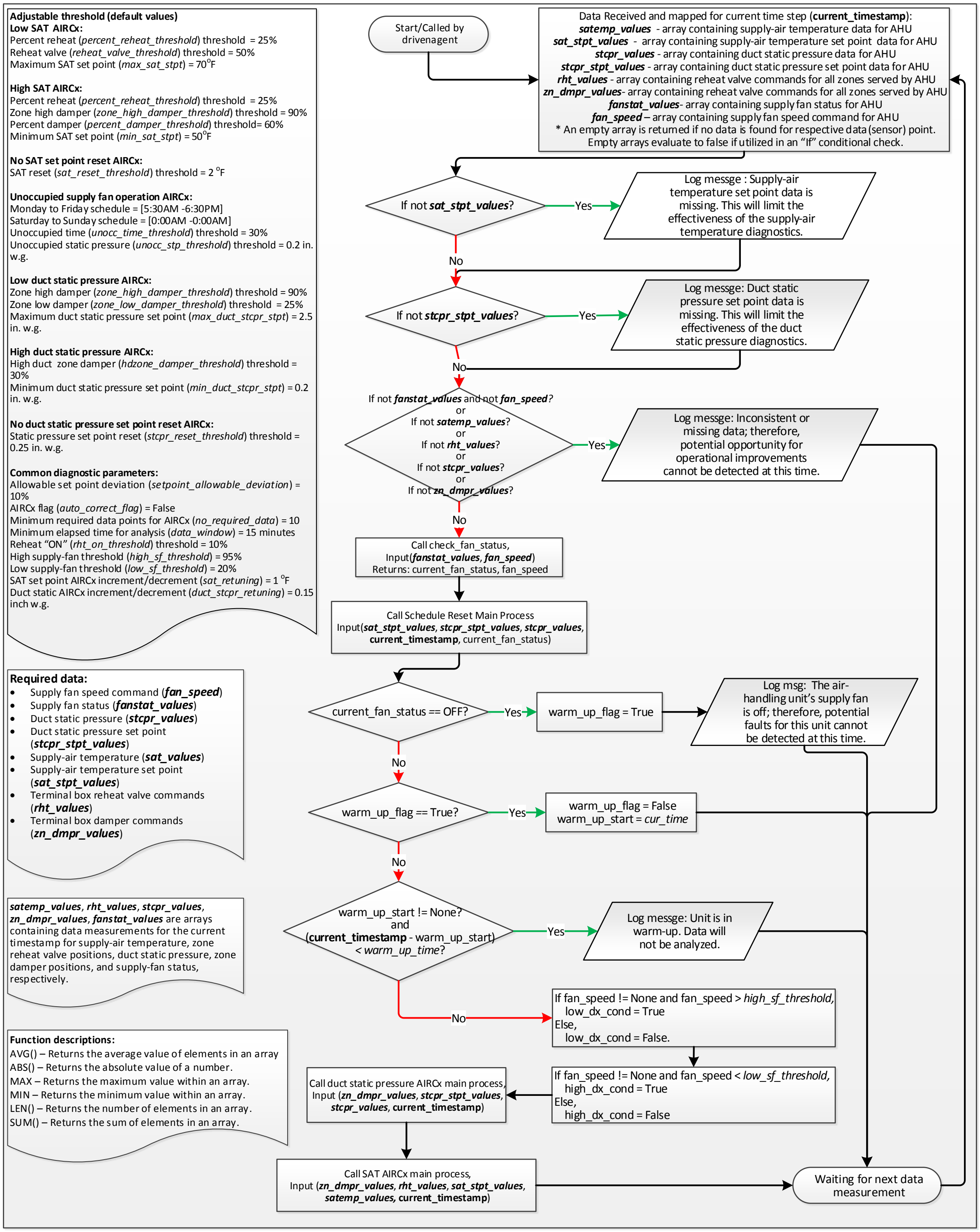

Figure 2.1. Flow Chart for the Air-side AIRCx Main Process

Figure 2.2, Figure 2.3, and Figure 2.4 contain three diagnostic functions called within the main Air-side AIRCx process. These functions verify whether any faults exist in the set point of the supply-air temperature, the set point of the static pressure, and operation of the fan, respectively.

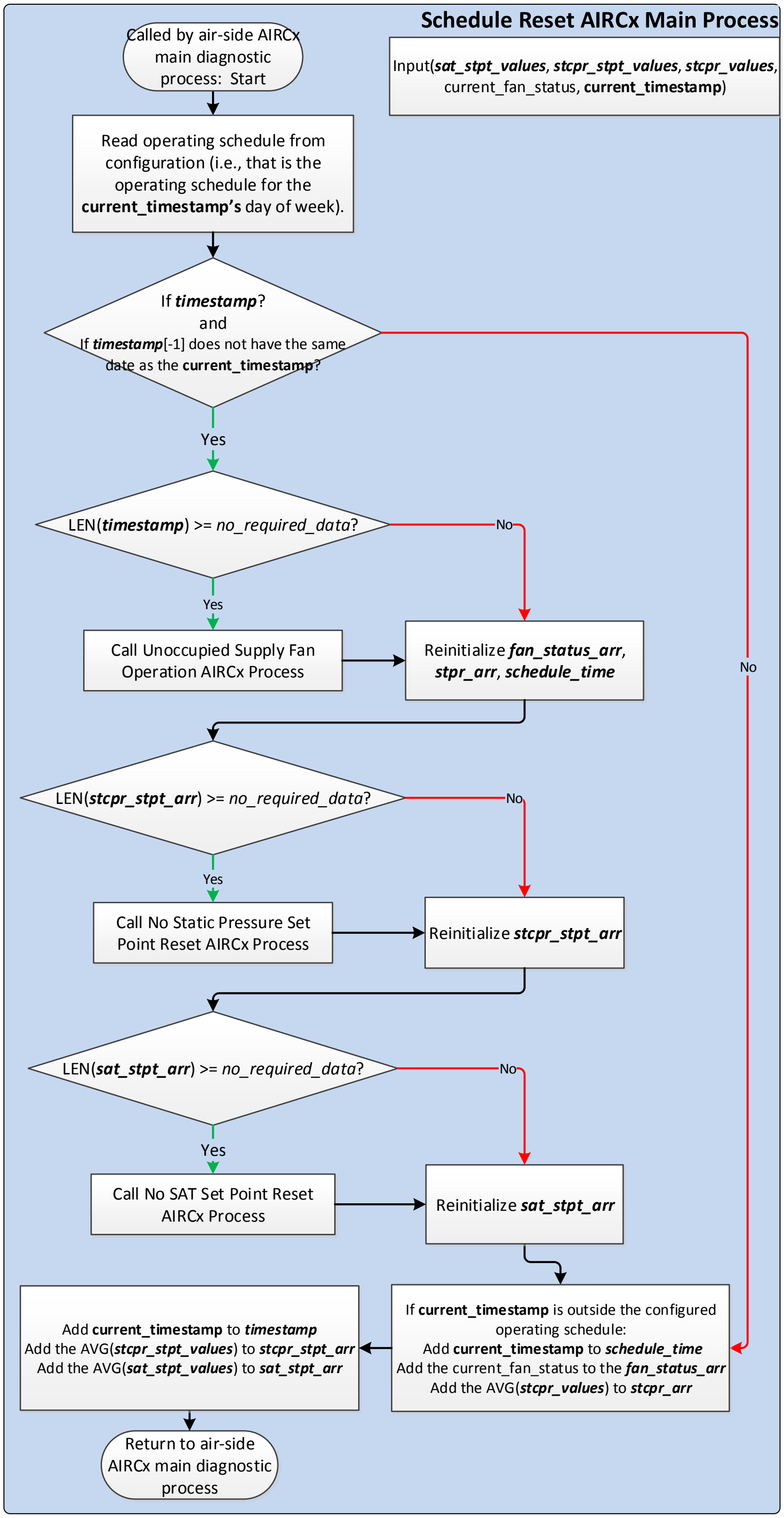

Figure 2.2. Flow Chart for the Schedule Reset AIRCx Main Process

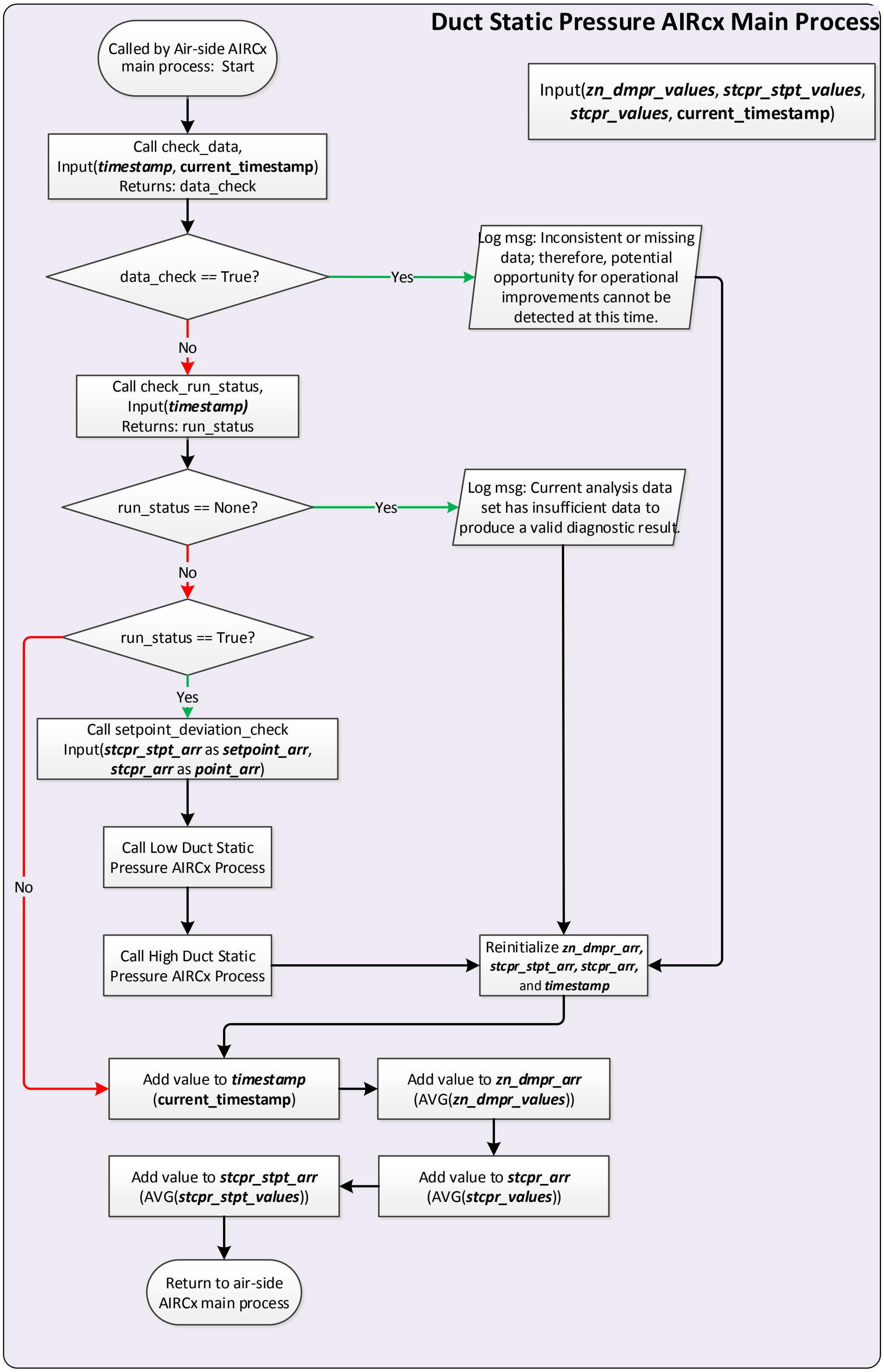

Figure 2.3. Flow Chart for the Duct Static Pressure AIRCx Main Process

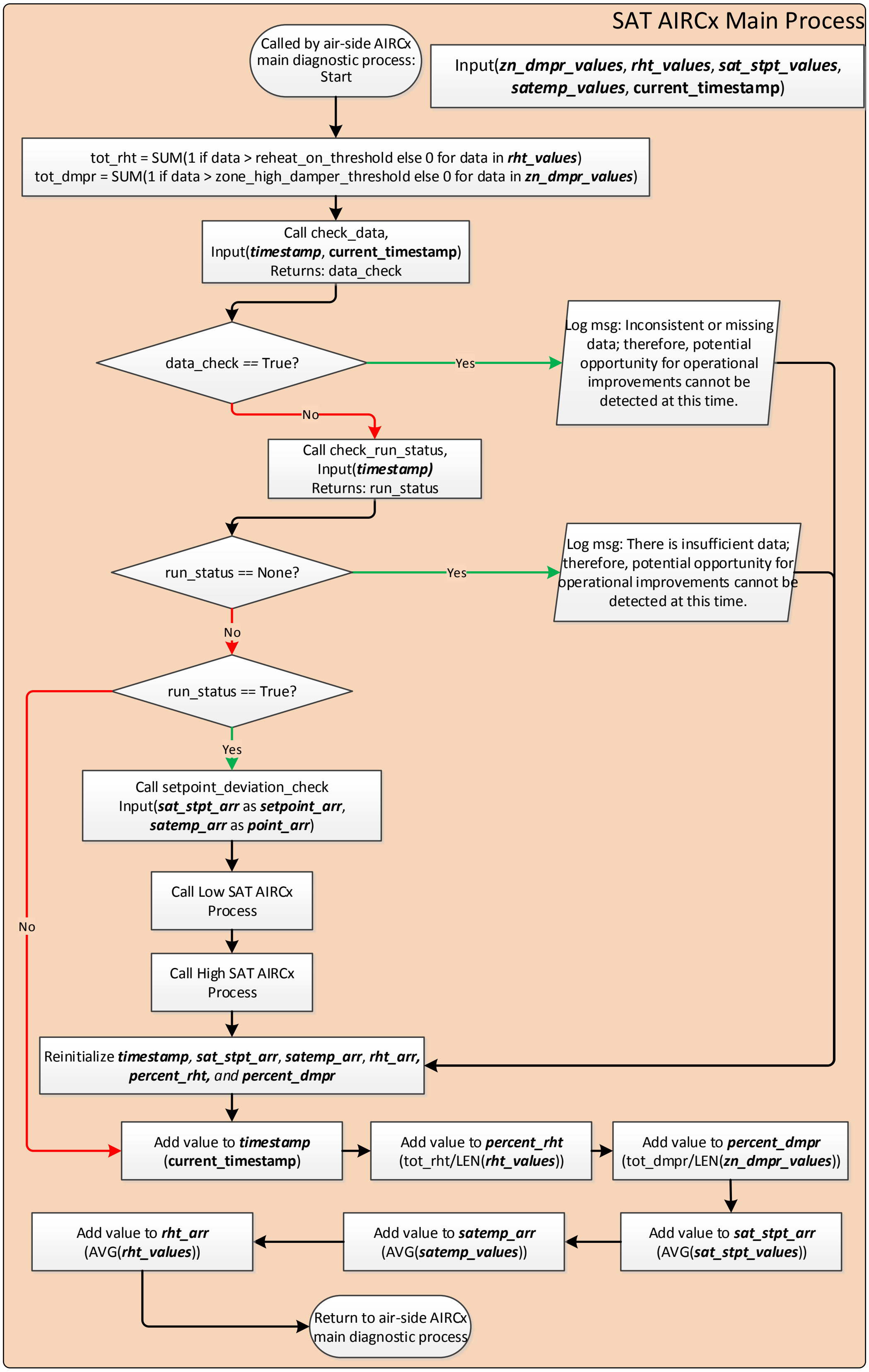

Figure 2.4. Flow Chart for the SAT AIRCx Main Process

Besides the functions shown in Figure 2.2, Figure 2.3, and Figure 2.4, there are also three "check" functions for determining whether the received data are appropriate for analysis:

- Check set point deviation function (Figure 2.5). It determines whether the control variable is significantly deviating from the set point.
- Check data function (Figure 2.6). It verifies that there are no large missing data gaps.
- Check run status function (Figure 2.7). It determines whether there are sufficient data for analysis.
- Check fan status function (Figure 2.8). It determines the current supply fan status and the current supply fan speed command.

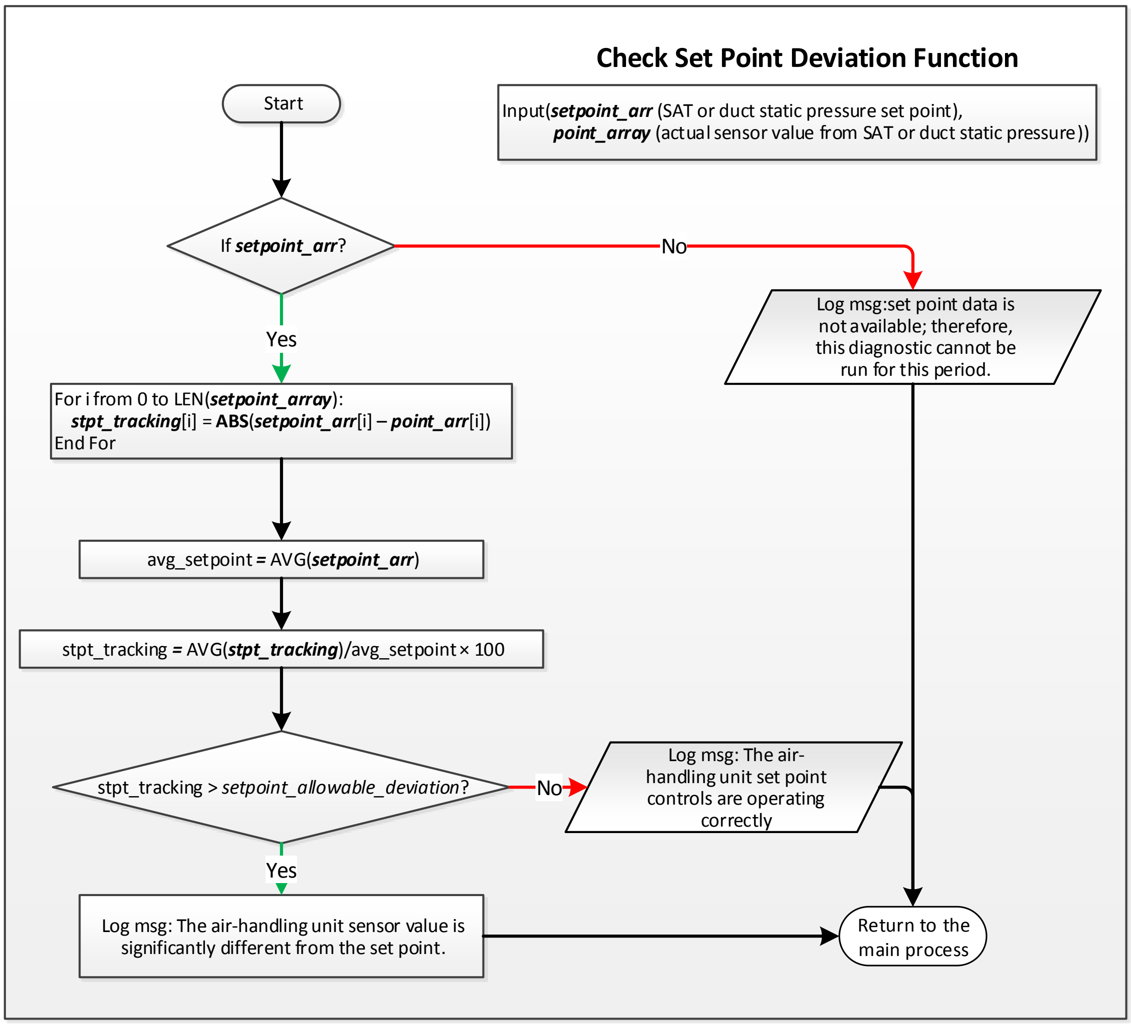

Figure 2.5. Flow Chart for the Check Set Point Deviation Function

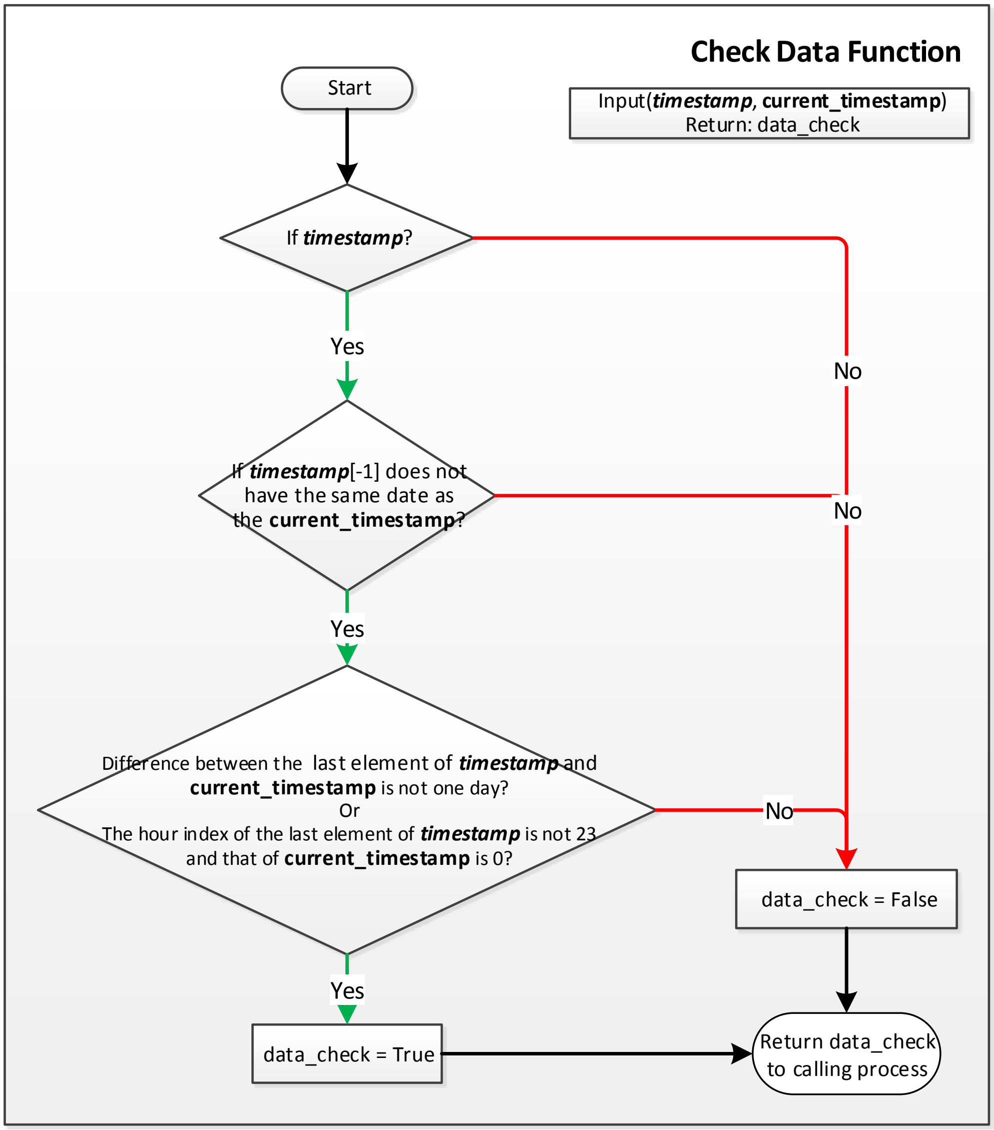

Figure 2.6. Flow Chart for the Check Data Function

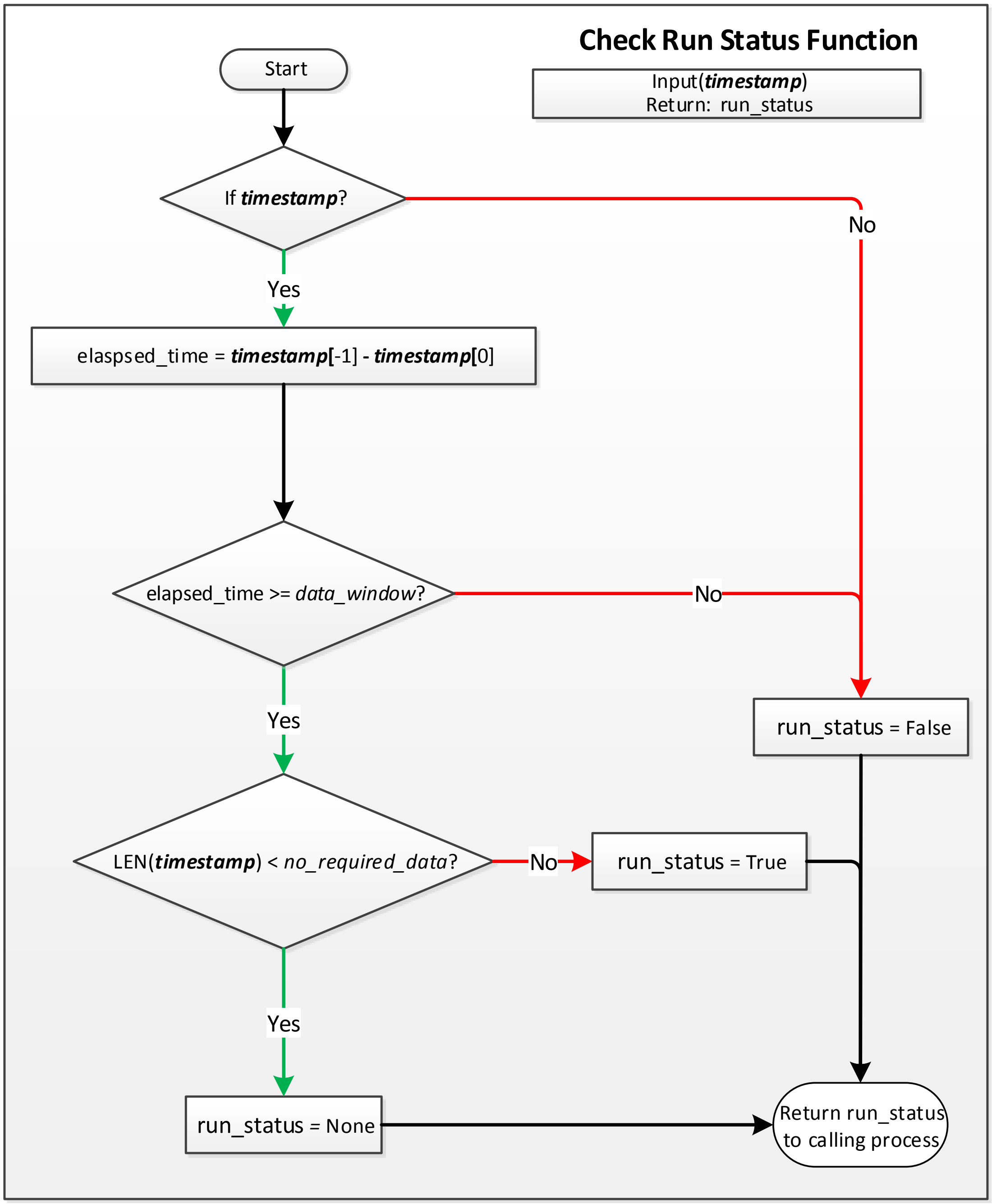

Figure 2.7. Flow Chart for the Check Run Status Function

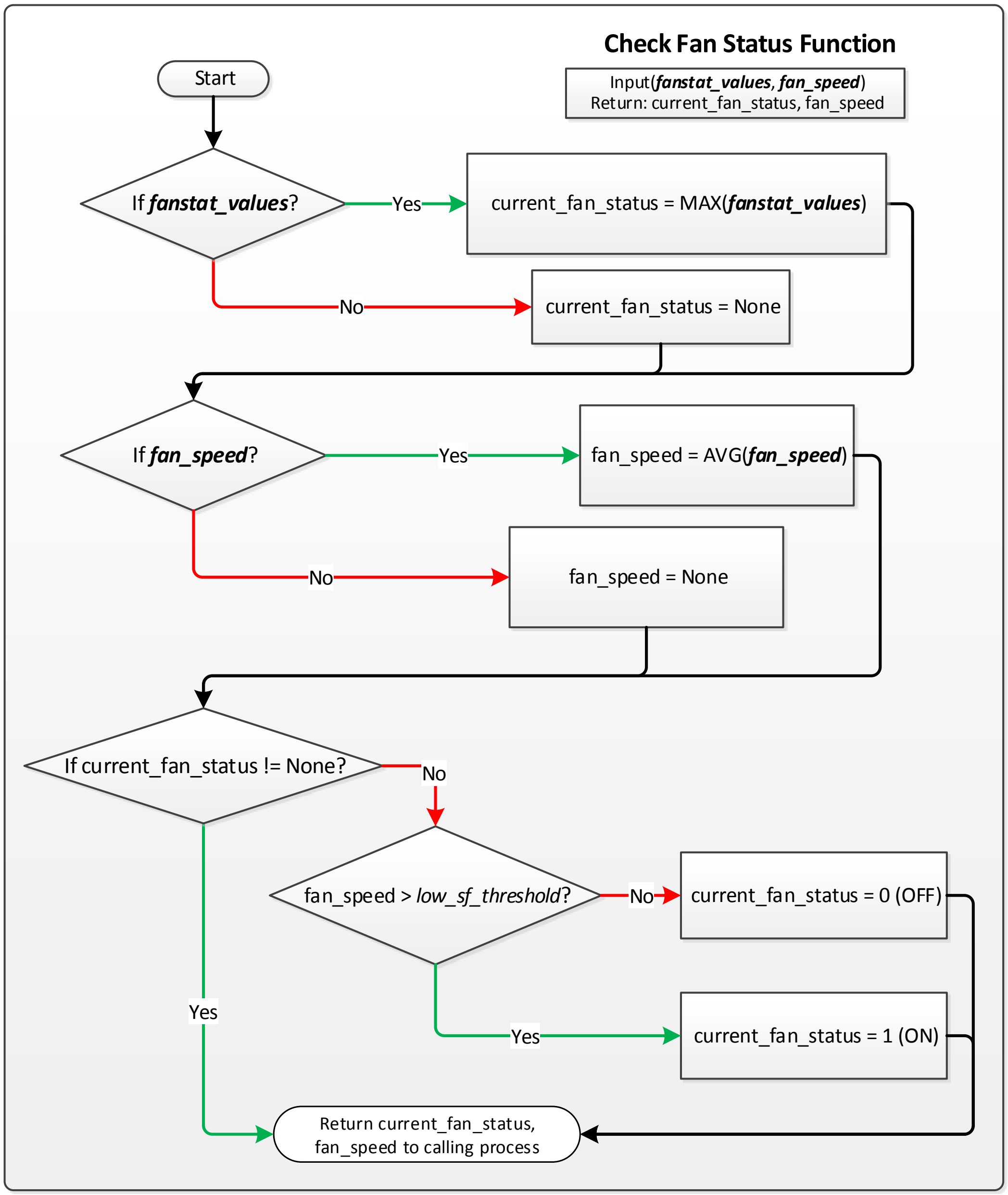

Figure 2.8. Flow Chart for the Check Fan Status Function

2.2 Low Supply-Air Temperature AIRCx Process

The purpose of the low SAT AIRCx process is to identify the re-tuning opportunities within the SAT control strategy. This AIRCx process can be implemented on single-duct VAV AHUs that do 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 an AHU's supply fan is ON, the zone reheat valve positions can be used to determine whether 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 cooling energy consumption but may increase the humidity ratio in the supply air. A high humidity ratio in 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 either run this diagnostic without auto-correction enabled (*auto_correct_flag* = True), 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 AIRCx Action for Low SAT

When the user has configured the *auto_correct_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 *auto_correct_flag* = False, then no automatic action(s) will occur. Automatic actions are based upon the following assumptions.

- There are no overrides pertaining to the SAT set point.
- There are no overrides pertaining to related equipment (cooling coil commands, etc.).

A maximum SAT set point (*max_sat_stpt*) 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, *max_sat_stpt*, 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 the 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°F for VAV systems with terminal box reheat.

The low SAT AIRCx process 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 can be adjusted by the user. This diagnostic should be run once every 15 minutes (this can be adjusted by modifying the parameter called *data_window*).

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

2.2.2 Monitored Data for Low SAT AIRCx

This section describes the required input data for the low SAT AIRCx process. The following data points are required for the execution of this diagnostic (data management for the low SAT AIRCx process is performed by the SAT AIRCx main process).

Input data from BACnet driver interface or text CSV:

- All reheat valve commands from the terminal box controllers (or BAS) served by the AHU (***rht_values***).

- SAT set point at each time step of the analysis dataset (***sat_stpt_arr***).
- SAT at each time step of the analysis dataset (***sat_arr***).
- Timestamp at each time step of the analysis dataset (***timestamp***).

Calculated values:

- The average of all reheat valve commands from the terminal box controllers served by the AHU at each time step of the analysis dataset (***rht_arr***).
- The percent of zones served by the AHU that are reheating at each time step of the analysis dataset (***percent_rht***).
  - Ratio of number zones where the terminal box reheat command is greater than or equal to the *rht_on_threshold* to the total number of zones.

2.2.3 Low SAT AIRCx Diagnostic Process

This section provides the AIRCx steps for the low SAT process including a detailed flow chart (Figure 2.9).

The following steps are used to detect the re-tuning opportunity (Step 1 and Step 2 occur in the SAT AIRCx main process but are included here to add clarity to the AIRCx process):

1. Calculate the elapsed time (elapsed_time) in the analysis dataset:
   - elapse_time = ***timestamp***[-1] – ***timestamp***[0]
2. If elapsed_time >= *data_window*,
   - If LEN(***timestamp***) > *no_required_data*,
     - The required elapsed time for the AIRCx process has elapsed and there is sufficient data to perform the AIRCx process.
     - Proceed to Step 3.
   - Else,
     - The required elapsed time for the AIRCx process has elapsed but there is insufficient data to perform the AIRCx process.
     - Generate diagnostic message: There is insufficient data; therefore, potential opportunity for operational improvements cannot be detected at this time.
     - Proceed to Step 8.

   Else,

   - The required elapsed time for the AIRCx process has not elapsed.
   - Proceed to Step 9.
3. Calculate avg_zones_rht (average percent of zones over the analysis period for which the terminal box reheat valve command is greater than *reheat_on_threshold*):
   - avg_zones_rht = AVG(***percent_rht***) × 100.
4. Calculate rht_avg (average zone reheat valve command over the analysis period):

- rht_avg = AVG(***rht_arr***).

5. Check zone conditions (i.e., the terminal box reheat valve command parameters calculated in Step 3 and Step 4) to detect operational problems:

   - If avg_zones_rht > *percent_reheat_threshold* and rht_avg > *reheat_valve_threshold*,
     - Proceed to Step 6.
   - Else,
     - Generate diagnostic message: The air-handler supply-air temperature is not low for this period.
     - Proceed to Step 8.

6. Check the availability of ***sat_stpt_arr***:

   - If ***sat_stpt_arr***,
     - Proceed to Step 7.
   - Else
     - Generate diagnostic message: The air-handler supply-air temperature is low, but supply-air temperature set point data is not available (cannot auto-correct).
     - Proceed to Step 8.

7. If *auto_correct_flag* == True,

   - Ensure that auto-correction will not increase the SAT set point above the maximum configured SAT set point (*max_sat_stpt*). Calculate the intended auto-corrected SAT set point (autocorrect_sat_stpt):
   - autocorrect_sat_stpt = AVG(***sat_stpt_arr***) + *sat_retuning*
     - If autocorrect_sat_stpt > *max_sat_stpt*,
       - Generate diagnostic message: The air-hander supply-air temperature is low, while it is at the maximum set point value.
       - sat_stpt = *max_sat_stpt.*
     - Else,
       - Generate diagnostic message: The air-handler supply-air temperature is low; this could result in zone over cooling or excess reheat (with auto-correction enabled).
       - sat_stpt = autocorrect_sat_stpt.
   - Proceed to Step 8.

   Else,

   - Generate diagnostic message: The air-handler supply-air temperature is low; this could result in zone over cooling or excess reheat (with auto-correction disabled).
   - Proceed to Step 8.

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

9. Return to the SAT AIRCx main process, and wait for the next available data.

The adjustable thresholds and parameters for this diagnostic are as follows:

- Minimum elapsed time for analysis (*data_window*) = 15 minutes
- Number of required data points for AIRCx (*no_required_data*) = 5
- Maximum SAT set point (*max_sat_stpt*) = 70°F
- Percent reheat threshold (*percent_reheat_threshold*) = 25%
- Reheat "ON" threshold (*reheat_on_threshold*) = 10%
- Reheat valve threshold (*reheat_valve_threshold*) = 50%
- SAT set point AIRCx increment/decrement (*sat_retuning*) = 1°F.

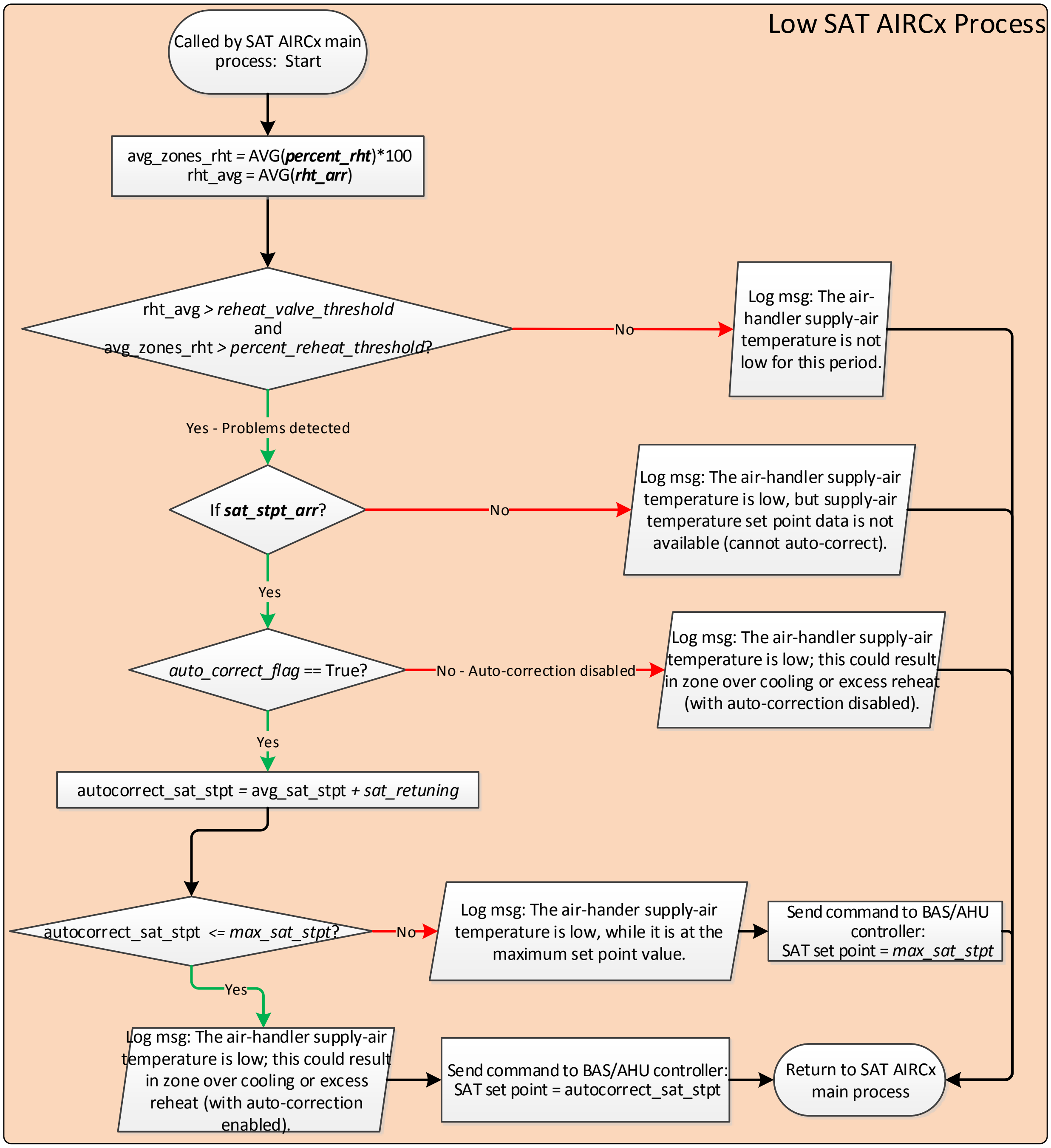

Figure 2.9. Flow Chart for the Low SAT AIRCx Process

2.3 High Supply-Air Temperature AIRCx Process

The purpose of the high SAT AIRCx process is to identify re-tuning opportunities with the SAT control strategy. This AIRCx process is intended for use on single-duct VAV AHUs that do 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 whether 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 using reheating. Zone reheating is used to heat air supplied by the AHU that is too cold for the space (common zone reheating methods include hot-water reheating and electric resistance reheating). If more than 25% (adjustable threshold) of zones are using reheating, 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 also increase the load on the chiller plant.

2.3.1 Proposed AIRCx Action for High SAT

When the user has configured the *auto_correct_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 *auto_correct_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.).

A minimum SAT set point (*min_sat_stpt*) is required as an input by the software user. The *min_sat_stpt* sets a limit on the AIRCx 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 *min_sat_stpt* will be reduced further. Exercise caution to ensure that safety components (e.g., low-temperature thermostats) are not tripped inadvertently or that excessively cold air is not allowed into the AHU during cold weather as a result of improper SAT set points.

The high SAT AIRCx process 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, and it can be adjusted by modifying parameter called *data_window*).

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

2.3.2 Monitored Data for High SAT AIRCx

This section describes the required input data for the high SAT AIRCx process. The following data points are required for the execution of this diagnostic (data management for the high SAT AIRCx process is performed by the SAT AIRCx main process).

Input data from BACnet driver interface or text CSV:

- All reheat valve commands from the terminal box controllers (or BAS) served by the AHU (***rht_values***).
- All damper commands from the terminal box controllers (or BAS) served by the AHU (***zn_dmpr_values***).
- SAT set point at each time step of the analysis dataset (***sat_stpt_arr***).
- SAT at each time step of the analysis dataset (***sat_arr***).
- Timestamp at each time step of the analysis dataset (***timestamp***).

Calculated values:

- The average of all reheat valve commands from the terminal box controllers served by the AHU at each time step of the analysis dataset (***rht_arr***).
- The percent of zones served by the AHU that are reheating at each time step of the analysis dataset (***percent_rht***).
  - Ratio of number zones where the terminal box reheat command is greater than *rht_on_threshold* to the total number of zones.
- The percent of zones served by the AHU where the terminal box damper command is greater than the zone high damper threshold (*zone_high_damper_threshold*) at each time step of the analysis dataset (***percent_dmpr***).
  - Ratio of number zones where the terminal box damper command is greater than *zone_high_damper_threshold* to the total number of zones.

2.3.3 High SAT AIRCx Diagnostic Process

This section provides the AIRCx steps for the high SAT process including a detailed flow chart (Figure 2.10).

The following steps are used to detect the re-tuning opportunity (Steps 1 and Step 2 occur in the SAT AIRCx main process but are included here to add clarity to the AIRCx process):

1. Calculate the elapsed time (elapsed_time) in the analysis dataset:
   - elapse_time = ***timestamp***[-1] – ***timestamp***[0].
2. If elapsed_time >= *data_window*,
   - If LEN(***timestamp***) > *no_required_data*,
     - The required elapsed time for the AIRCx process has elapsed and there is sufficient data to perform the AIRCx process.
     - Proceed to Step 3.

- Else,
  - The required elapsed time for the AIRCx process has elapsed but there is insufficient data to perform the AIRCx process.
  - Generate diagnostic message: There is insufficient data; therefore, potential opportunity for operational improvements cannot be detected at this time.
  - Proceed to Step 8.

Else,

- The required elapsed time for the AIRCx process has not elapsed.
- Proceed to Step 9.

3. Calculate avg_zones_rht (the average percent of zones over the analysis period for which the terminal box reheat valve command is greater than the *reheat_on_threshold*):
   - avg_zones_rht = AVG(***percent_rht*****).**
4. Calculate avg_zone_dmpr_data (the average percent of zones over the analysis period for which the terminal box damper command is greater than the *zone_high_damper_threshold*):
   - avg_zones_dmpr = AVG(***percent_dmpr***).
5. Check the zone conditions (i.e., the terminal box reheat valve command parameter calculated in in Step 3 and terminal box damper command parameter calculated in Step 4) to detect operational problems:
   - If avg_zones_dmpr > *percent_ damper_threshold* and avg_zones_rht < *percent_ reheat_threshold*,
     - Proceed to Step 6.
   - Else,
     - Generate diagnostic message: The air-handler supply-air temperature is not high for this period.
     - Proceed to Step 8.
6. Check the availability of ***sat_stpt_arr***:
   - If ***sat_stpt_arr***,
     - Proceed to Step 7.
   - Else,
     - Generate diagnostic message: The air-handler supply-air temperature is high, but the supply-air temperature set point data is not available (cannot auto-correct).
     - Proceed to Step 8.
7. If *auto_correct_flag* == True,
   - Ensure that auto-correction will not reduce the SAT set point below the minimum configured SAT set point (*min_sat_stpt*). Calculate the intended auto-corrected SAT set point (autocorrect_sat_stpt):
   - autocorrect_sat_stpt = AVG(***sat_stpt_arr***) - *sat_retuning*

    - If autocorrect_sat_stpt ≥ *min_sat_stpt*,
        - Generate diagnostic message: The SAT was detected to be too high. The SAT set point has been increased to *autocorrect_sat_stpt.*
        - sat_stpt = autocorrect_sat_stpt.
    - Else,
        - Generate diagnostic message: The air-hander supply-air temperature is high, while it is at the minimum set point value.
        - sat_stpt = *min_sat_stpt*.
- Proceed to Step 8.

Else,

- Generate diagnostic message: The air-handler supply-air temperature is high; this could result in zone over heating (with auto-correction disabled).
- Proceed to Step 8.

8. Send the command to the BAS or AHU controller, set the SAT set point to sat_stpt (if a re-tuning opportunity was detected and auto-correction is enabled), and make diagnostic message(s) available to the operator.
9. Return to the SAT AIRCx main process, and wait for the next available data.

The adjustable thresholds and parameters for this diagnostic are as follows:

- Minimum elapsed time for analysis (*data_window*) = 15 minutes
- Number of required data points for AIRCx (*no_required_data*) = 5
- Reheat "ON" threshold (*reheat_on_threshold*) = 10%
- Minimum SAT set point (*min_sat_stpt*) = 50°F
- Percent damper threshold (*percent_damper_threshold*) = 60%
- Zone high damper threshold (*zone_high_damper_threshold*) = 90%
- Percent reheat threshold (*percent_ reheat_threshold*) = 25%
- SAT set point AIRCx increment/decrement (*sat_retuning*) = 1°F.

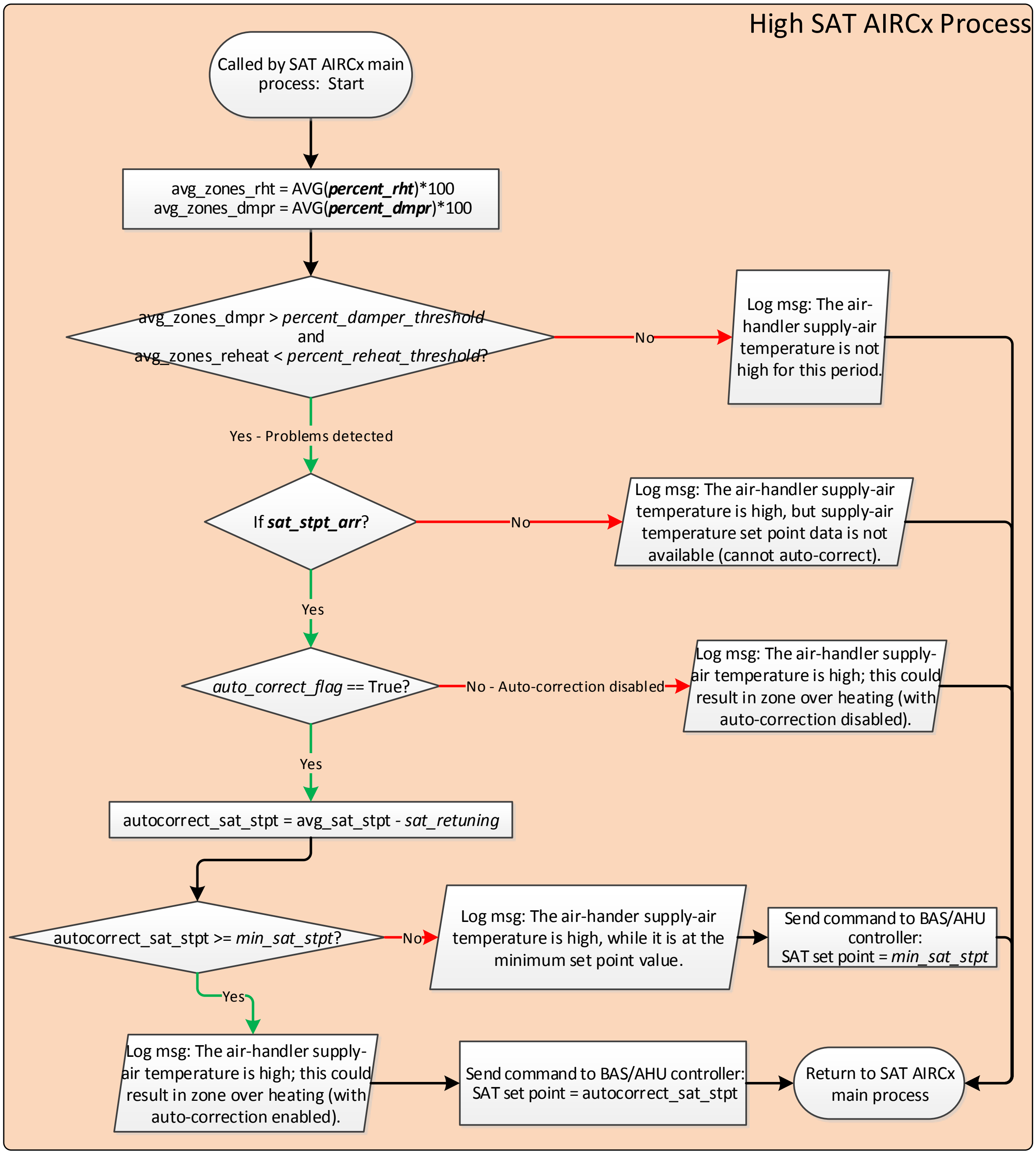

Figure 2.10. Flow Chart for the High SAT AIRCx Process

2.4 No Supply-Air Temperature Set Point Reset AIRCx Process

The purpose of the no SAT set point reset AIRCx process is to identify opportunities with the SAT control strategy associated with SAT set point reset. 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 plant 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 used. 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 2.11 shows an example of good operation during which 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 outside-air temperature (OAT), reheat valve commands, or a set schedule.

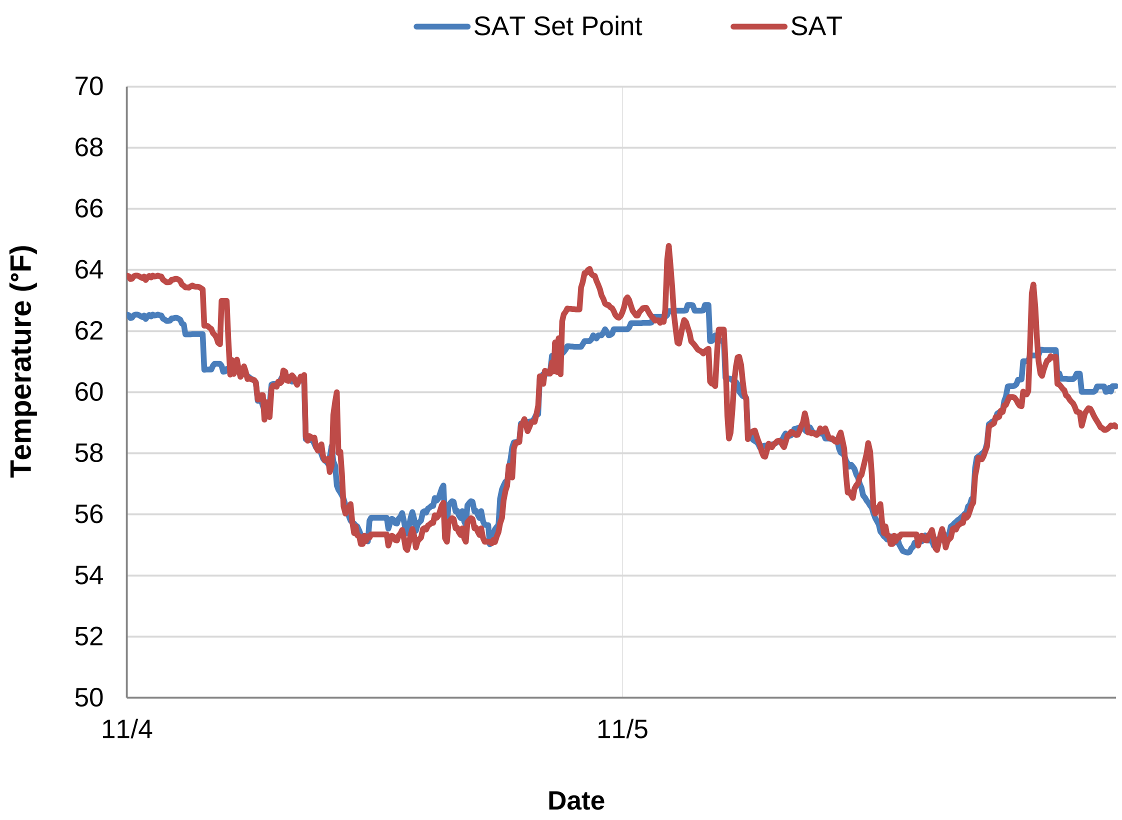

Figure 2.11. Example of Good Operation, SAT Set Point Shows Variation

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 AIRCx

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

Input data from BACnet driver interface or text CSV:

- SAT set point at each time step of the analysis dataset (***sat_stpt_arr***).

2.4.2 No SAT Set Point Reset AIRCx Diagnostic Process

This section provides the steps for the no SAT set point reset AIRCx process including a detailed flow chart (Figure 2.12). 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 schedule reset AIRCx main process but is included here to add clarity to the AIRCx process):

1. Upon the completion of day (i.e., midnight),
   - If LEN(***sat_stpt_ar***) > *no_required_data*,
     - Proceed to Step 2.
   - Else,
     - Generate diagnostic message: There is insufficient data; therefore, potential opportunity for operational improvements cannot be detected at this time.
     - Proceed to Step 3.
2. Check if the supply air temperature set point varies throughout the day,
   - If MAX(***sat_stpt_arr***) **-** MIN(***sat_stpt_arr***) <= *sat_reset_threshold*,
     - Generate diagnostic message: No air-handler supply-air temperature reset is detected for this time period; this may result in excess energy consumption. Supply-air temperature reset can save significant energy.
     - Proceed to Step 3.
   - Else,
     - Generate diagnostic message: The air-handler supply-air temperature is being reset for this time period.
     - Proceed to Step 3.
3. Make diagnostic message(s) available to the operator.
4. Return to schedule reset AIRCx main process, and wait for the next available data.

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

- SAT reset threshold (*sat_reset_threshold*) = 2°F.
- Number of required data points for AIRCx (*no_req_data*) = 10.

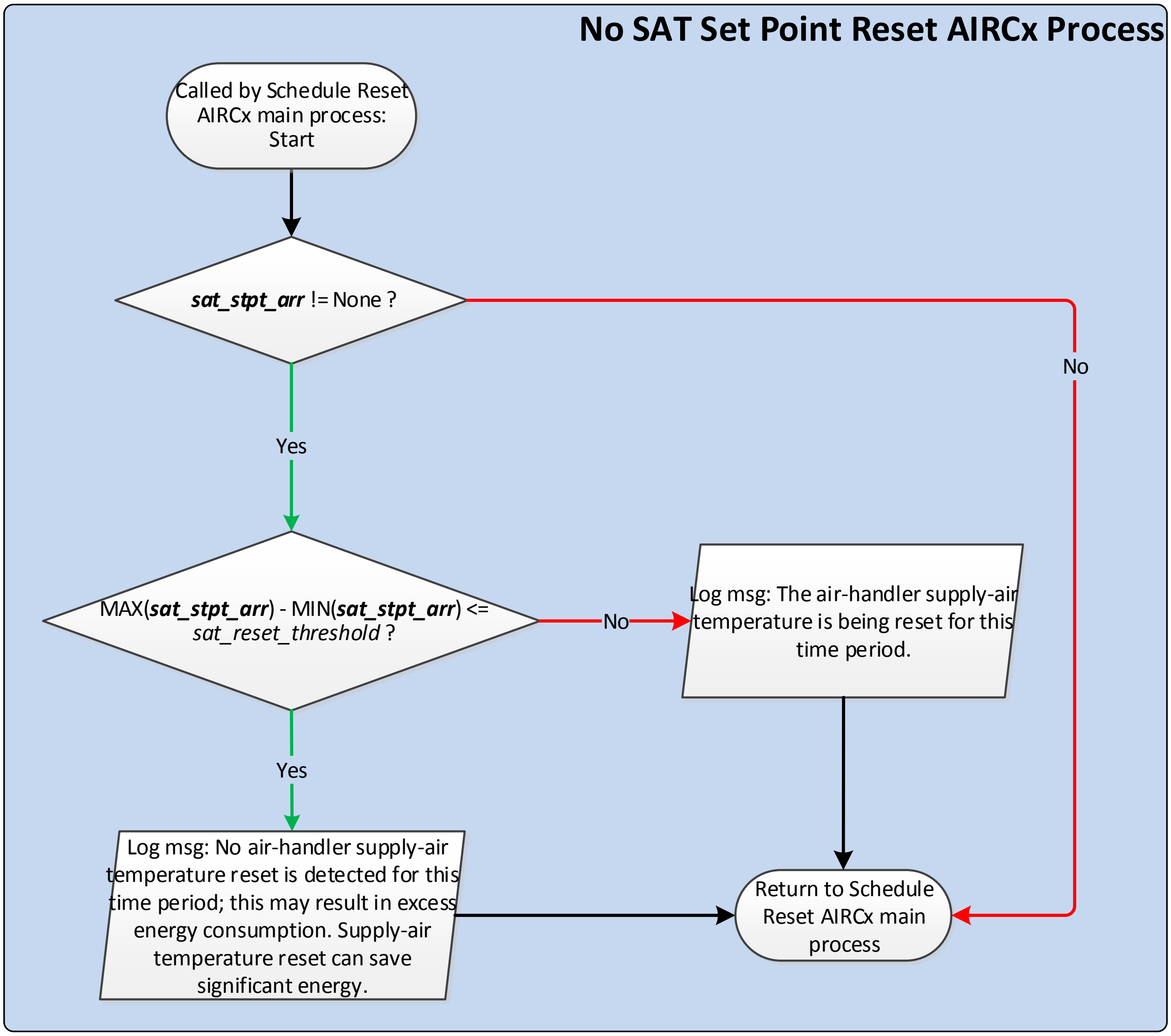

Figure 2.12. Flow Chart for the No SAT Set Point Reset AIRCx Process

2.5 Unoccupied Supply-Fan Operation AIRCx

The purpose of the unoccupied supply-fan operation AIRCx process it 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 both fan energy savings and potential cooling and heating energy savings.

The supply fan should be turned off when the building is not occupied. There may be circumstances when the supply fan will 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 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 and 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 subject to change weekly, this diagnostic will need to be reviewed on a regular basis to mitigate false alarms.

2.5.1 Monitored Data for Unoccupied Supply-Fan Operation AIRCx

This section describes the required input data for the unoccupied supply-fan operation AIRCx process. The following data points are required for the execution of this diagnostic (data management for the unoccupied supply-fan operation AIRCx process is performed by the schedule reset AIRCx main process).

Input data from BACnet driver interface or text CSV:

- AHU supply-fan status (***fanstat_values***) or AHU supply-fan speed (**fan_speed**).
- Duct static pressure at each time step of the analysis dataset (***stcpr_arr***).

2.5.2 Unoccupied Supply-Fan Operation AIRCx Diagnostic Process

This section provides the steps for the unoccupied supply-fan operation AIRCx process including a detailed flow chart (Figure 2.13). 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 schedule reset AIRCx main process but is included here to add clarity to the process):

1. Upon the completion of day (i.e., midnight),
    - If LEN(***timestamp***) > *no_required_data*,
        – The required elapsed time for the AIRCx process has elapsed and there is sufficient data to perform the AIRCx process.
        – Proceed to Step 2.
    - Else,
        – Generate diagnostic message: There is insufficient data; therefore, potential opportunity for operational improvements cannot be detected at this time.
        – Proceed to Step 8.
2. Iterate over ***fan_status_arr*** and create an array with the hour for each entry in ***fan_status_arr*** (***fan_status***) and an array with hour entry for each entry in ***fan_status_arr*** where the supply fan is ON (***fan_status_on***) (Note: The hour operator (.hour) will return the return the hour of a timestamp as an integer from 0 to 23):
    - For i from 0 to LEN(***fan_status_arr***),

  - ***fan_status***[i] = ***sched_time***[i].hour
  - If ***fan_status_arr***[i] == 1,
    - ***fan_status_on***[i] = ***sched_time***[i].hour
- End For

3. Iterate over each hour (from 0 to 23) and create an array (***hourly_counter***) where each entry is the hourly percentage of operation time where the supply fan is ON during the unoccupied period:
   - For i from 0 to 23,
     - ***fan_on_count*** = [1 for item in ***fan_status_on*** if item == i]
     - ***fan_count*** = [1 for item in ***fan_status*** if item == i]
     - ***hourly_counter***[i] = LEN(***fan_on_count***)/LEN(***fan_count)*** × 100
   - End For
4. Calculate the percent of unoccupied time the supply fan was in operation:
   - percent_on = LEN(***fan_status_on***)/LEN(***fan_status_arr***) × 100
5. Check if supply fan is ON for a significant amount of time during the unoccupied period:
   - If percent_on > *unocc_time_threshold* (supply-fan unoccupied schedule threshold),
     - Generate diagnostic message: The system is ON for a significant amount of time during the unoccupied period.
     - Proceed to Step 7.
   - Else,
     - Proceed to Step 6.
6. Check whether the average duct static pressure during the unoccupied period exceeds a threshold:
   - If AVG(***stcpr_arr***) < *unocc_stcpr_threshold* (duct static pressure unoccupied schedule threshold),
     - Generate diagnostic message: No schedule problems is detected for this period.
     - Proceed to Step 8.
   - Else
     - Generate diagnostic message: The system status shows the unit is OFF but the static pressure reading is high.
     - Proceed to Step 8.
7. Use ***hourly_counter*** to log each hour where the supply fan operated a significant amount of time in the unoccupied period.
8. Make diagnostic message(s) available for the operator.
9. Return to schedule reset main AIRCx process, and wait for the next available data.

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

- Default Building Schedule:

- *monday_sch* = [5:30 AM – 6:30 PM]
- *tuesday_sch* = [5:30 AM – 6:30 PM]
- *wednesday_sch* = [5:30 AM – 6:30 PM]
- *thursday_sch* = [5:30 AM – 6:30 PM]
- *friday_sch* = [5:30 AM – 6:30 PM]
- *saturday_sch* = [0:00 AM – 0:00 AM] (unoccupied all day)
- *sunday_sch* = [0:00 AM – 0:00 AM] (unoccupied all day)
  - *unocc_time_threshold* = 30%
  - *unocc_stcpr_threshold* = 0.2 in. w.g.
  - *no_req_data* = 10.

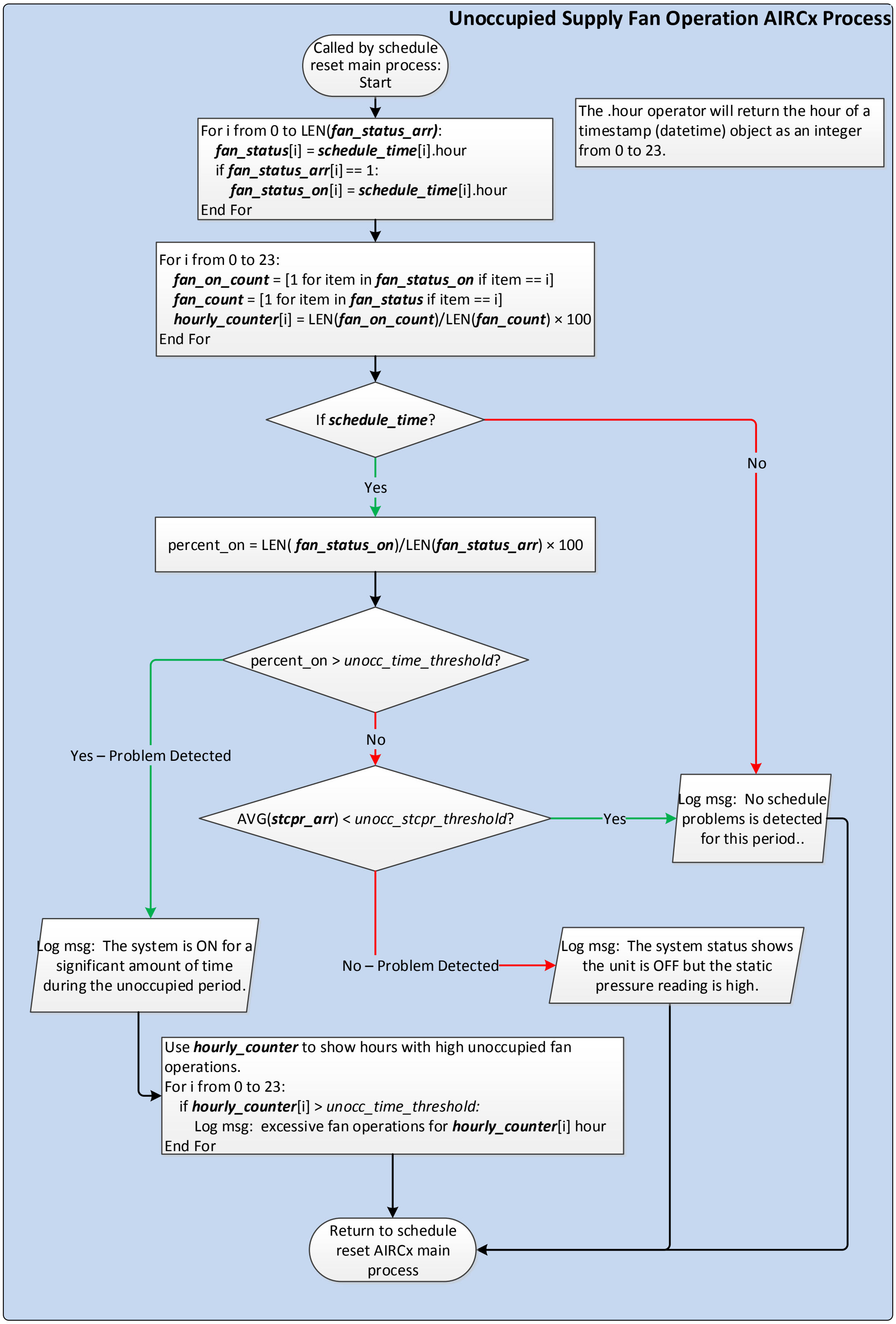

Figure 2.13. Flow Chart for the Unoccupied Supply-Fan Operation AIRCx Process

2.6 Low Duct Static Pressure AIRCx Process

The purpose of the low duct static pressure AIRCx 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 corrected, may 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 the 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 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 duct static pressure is fixed.

If duct static pressure is too low and the supply fan VFD is running at less than 100% speed, the result could be that the fan is providing less air flow than required at individual zone terminal boxes. This mismatch can cascade into other areas that affect equipment performance and occupant comfort. Building operator actions (e.g., set point overrides) 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 duct static pressure set point). Figure 2.14 shows an example of poor operations. Nearly all of 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 run). Figure 2.15 shows an example of good operations. Most of the zone dampers are between 50% and 75% open.

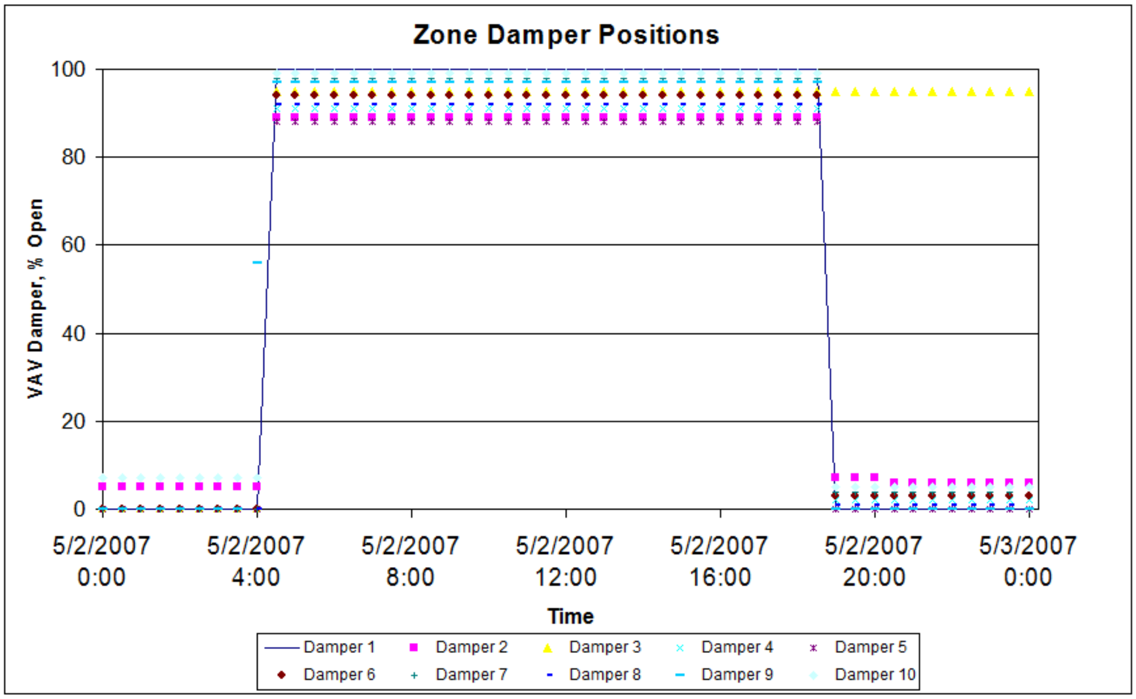

Figure 2.14. Example of Bad Operation – All Zone Dampers Are Nearly 100% Open

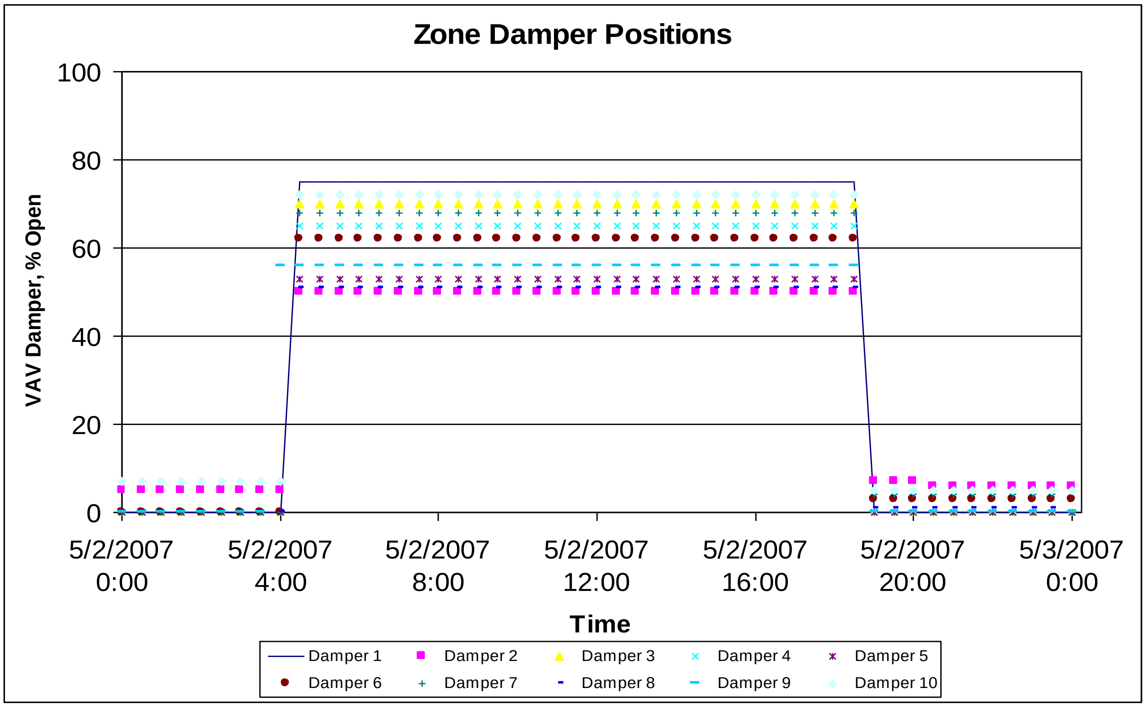

Figure 2.15. Example of Good Operations – Most Zone Dampers Are Open Between 50% and 75%

2.6.1 Proposed AIRCx Action for Low Duct Static Pressure

When the user has configured the *auto_correct_flag* = True, and the diagnostic process has detected a re-tuning opportunity, the existing duct static pressure set point will be adjusted to a higher value. If the *auto_correct_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.).

This diagnostic process 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 2.5 in. w.g. should be configured as the maximum allowable duct static pressure set point to ensure equipment protection.

The low duct static pressure AIRCx process 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 (this can be adjusted by modifying the parameter called *data_window*).

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 Duct Static Pressure AIRCx

This section describes the required input data for the low duct static pressure AIRCx process. The following data points are required for the execution of this diagnostic (data management for the low duct static pressure AIRCx process is performed by the duct static pressure AIRCx main process).

Input data from BACnet driver interface or text CSV:

- Duct static pressure set point at each time step of the analysis dataset (***stcpr_stpt_arr***).
- Duct static pressure at each time step of the analysis dataset (***stcpr_arr***).

Calculated values:

- The average of all damper commands from the terminal box controllers served by the AHU at each time step of the analysis dataset (***zn_dmpr_arr***).
  - 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) are needed for an accurate diagnostic result.

2.6.3 Low Duct Static Pressure AIRCx Diagnostic Process

This section provides the steps for the low duct static pressure AIRCx process including a detailed flow chart (Figure 2.16). The following steps are used to detect the re-tuning opportunity (Step 1 in this diagnostic occurs in the duct static pressure AIRCx main diagnostic process but is included here to add clarity to the AIRCx process):

1. Calculate the elapsed time (elapsed_time) in the analysis dataset:
   - elapse_time = ***timestamp***[-1] – ***timestamp***[0].
2. If elapsed_time >= *data_window*,
   - If LEN(***timestamp***) > *no_required_data*,
     - The required elapsed time for the AIRCx process has elapsed and there is sufficient data to perform the AIRCx process.
     - Proceed to Step 3.
   - Else,
     - The required elapsed time for the AIRCx process has elapsed but there is insufficient data to perform the AIRCx process.
     - Generate diagnostic message: There is insufficient data; therefore, potential opportunity for operational improvements cannot be detected at this time.
     - Proceed to Step 7.

   Else,

   - The required elapsed time for the AIRCx process has not elapsed.
   - Proceed to Step 8.
3. Sort the values in ***zn_dmpr_arr*** from largest to smallest. Use the largest 50% of the zone terminal box damper commands to calculate an average zone terminal box damper command

(zn_dmpr_high_avg). Use the smallest 50% of the zone terminal box damper commands to calculate an average zone terminal box damper command (zn_dmpr_low_avg).

4. If zn_dmpr_high_avg > *zone_high_damper_threshold* and zn_dmpr_low_avg > *zone_low_damper_threshold*,

   - Proceed to Step 5.

   Else,

   - Generate diagnostic message: The air-handler duct static pressure is not low for this period.
   - Proceed to Step 8.

5. Check the availability of ***stcpr_stpt_arr***.

   - If ***stcpr_stpt_arr***,
     – Proceed to Step 6.
   - Else,
     – Generate diagnostic message: The air-handler duct static pressure is low, but duct static pressure set point data is not available (cannot auto-correct).
     – Proceed to Step 7.

6. If *auto_correct_flag* == True,

   - Ensure that auto-correction will not increase the duct static pressure set point above the maximum configured static pressure set point (*max_stcpr_stpt*). Calculate the intended auto-corrected static pressure set point (auto_correct_stcpr_stpt):
   - auto_correct_stcpr_stpt = AVG(***stcpr_stpt_arr***) + *stcpr_retuning*
     – If auto_correct_stcpr_stpt > *max_stcpr_stpt*,
       – Generate diagnostic message: The air-hander duct static pressure is unable to meet the zone airflow requirements, while at the maximum set point value.
       – stcpr_stpt = *max_stcpr_stpt*.
     – Else,
       – Generate diagnostic message: The air-handler duct static pressure is low; therefore, it may not be able to meet the zone airflow requirements (with auto-correction enabled).
       – stcpr_stpt = auto_correct_stcpr_stpt.
   - Proceed to Step 7.

   Else,

   - Generate diagnostic message: The air-handler duct static pressure is low; therefore, it may not be able to meet the zone airflow requirements (with auto-correction disabled).
   - Proceed to Step 7.

7. Send the command to the BAS or AHU controller, set the duct static pressure set point to stcpr_stpt (if a re-tuning opportunity was detected and auto-correction was enabled), and make diagnostic message(s) available for the operator.

8. Return to the duct static pressure AIRCx main process, and wait for the next available data.

The default but adjustable thresholds and parameters for this diagnostic are as follows:

- Minimum elapsed time for analysis (*data_window*) = 15 minutes
- Number of required data points for AIRCx (*no_required_data*) = 5
- Zone low damper threshold (*zone_low_damper_threshold*) = 25%
- Zone high damper threshold (*zone_high_damper_threshold*) = 90%
- Maximum duct static pressure set point (*max_stcpr_stpt*) = 2.5 in. w.g.

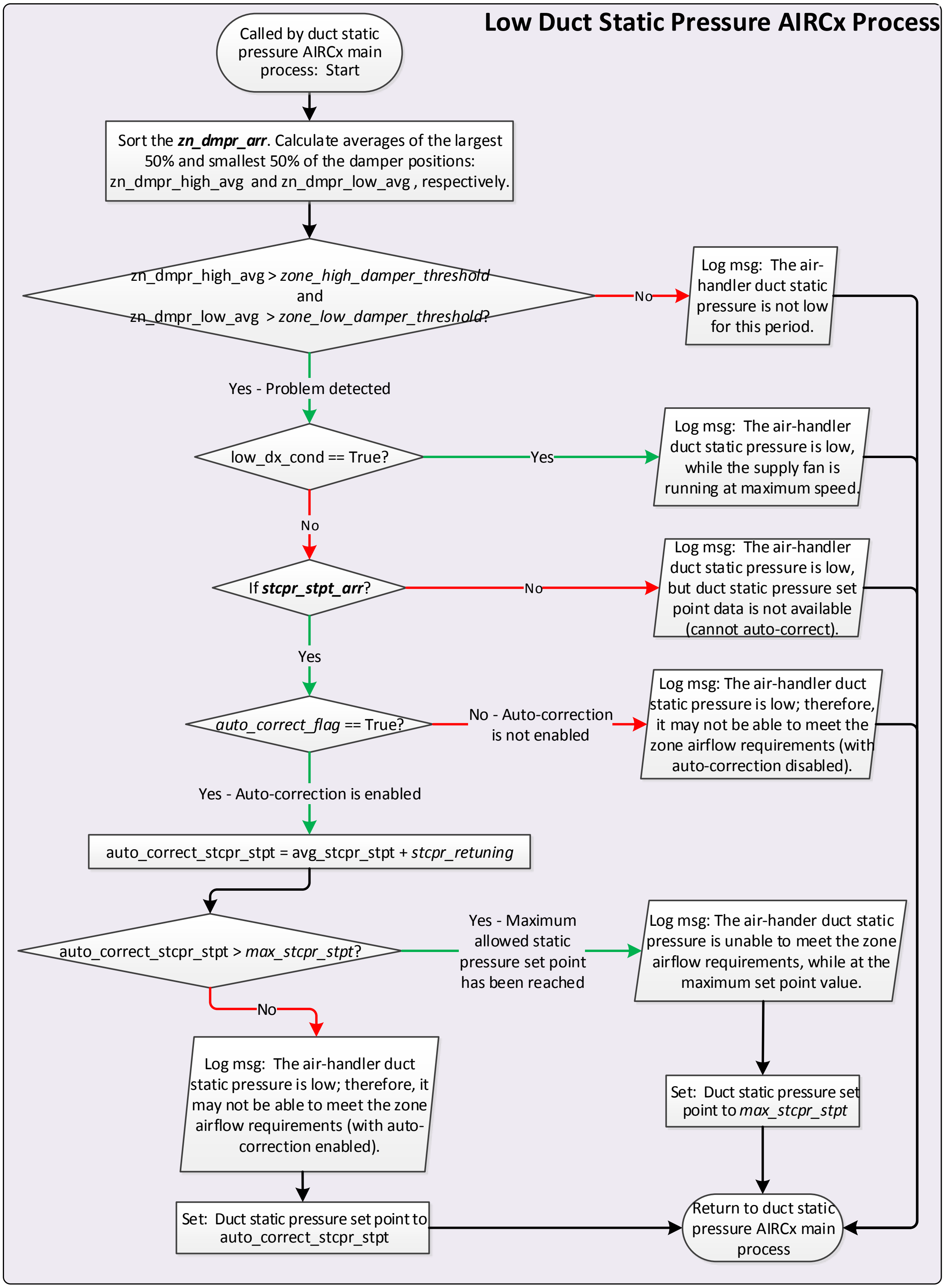

Figure 2.16. Flow Chart for the Low Duct Static Pressure AIRCx Process

2.7 High Duct Static Pressure AIRCx Process

The purpose of the high duct static pressure AIRCx process is to identify conditions under which 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 VFD speed or inlet vanes are modulated 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 duct static 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 affect equipment performance and energy efficiency. Building operator actions (e.g., set point overrides) can have an adverse impact on the supply-fan system.

Zone information is critical in detecting whether the duct 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 2.17 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 duct static pressure set point that is too high.

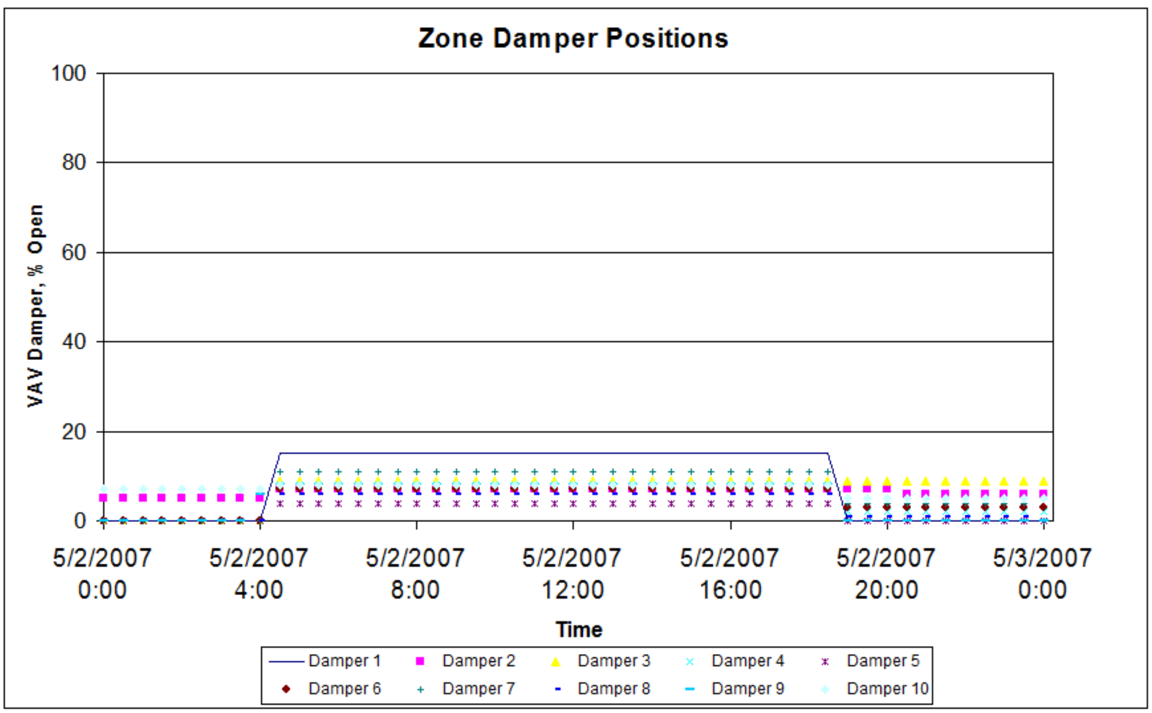

Figure 2.17. Example of Bad Operation – All Zone Dampers Are Nearly Closed

Figure 2.18 shows an example of good operations. Most of the zone dampers are between 50% and 75% open. This indicates that that the duct static pressure set point is not too high; zones are not experiencing excessive air flow.

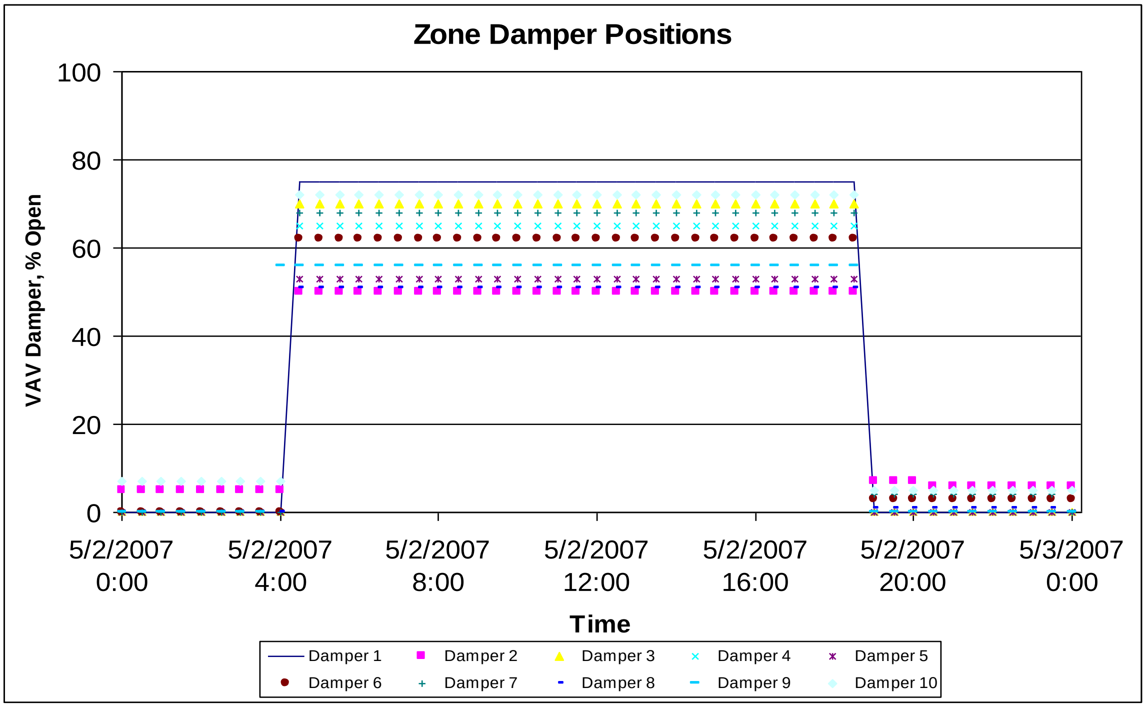

Figure 2.18. Example of Good Operations – Most Zone Dampers Are Open Between 50% and 75%

2.7.1 Proposed AIRCx Action for High Duct Static Pressure

When the user has configured the *auto_correct_flag* = True, and the diagnostic process has detected a re-tuning opportunity, the existing duct static pressure set point will be adjusted to a lower value. If the *auto_correct_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.).

This diagnostic process includes a minimum low limit value for the duct static pressure set point that the auto-corrected value can never drop below. For instance, a minimum value of 0.2 in. w.g. should be configured as the minimum allowable duct static pressure set point to ensure occupant comfort and ventilation requirements.

The high duct static pressure AIRCx process 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 (this can be adjusted by modifying the parameter called *data_window*).

This continuous diagnostic will automatically apply the re-tuning measures, decreasing 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 minimum duct static pressure set point is reached.

2.7.2 Monitored Data for High Duct Static Pressure AIRCx

This section describes the required input data for the high duct static pressure AIRCx process. The following data points are required for the execution of this diagnostic (data management for the high duct static pressure AIRCx process is performed by the duct static pressure AIRCx main process).

Input data from BACnet driver interface or text CSV:

- Duct static pressure set point at each time step of the analysis dataset (***stcpr_stpt_arr***).
- Duct static pressure at each time step of the analysis dataset (***stcpr_arr***).

Calculated values:

- The average of all damper commands from the terminal box controllers served by the AHU at each time step of the analysis dataset (***zn_dmpr_arr***).
  - 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) are needed for an accurate diagnostic result.

2.7.3 High Duct Static Pressure AIRCx Diagnostic Process

This section provides the steps for the steps for the high duct static pressure AIRCx process including a detailed flow chart (Figure 2.19).

The following steps are used to detect the re-tuning opportunity (Step 1 in this diagnostic occurs in the duct static pressure AIRCx main diagnostic process but is included here to add clarity to the AIRCx process):

1. Calculate the elapsed time (elapsed_time) in the analysis dataset:
   - elapse_time = ***timestamp***[-1] – ***timestamp***[0].
2. If elapsed_time >= *data_window*,
   - If LEN(***timestamp***) > *no_required_data*,
     - The required elapsed time for the AIRCx process has elapsed and there is sufficient data to perform the AIRCx process.
     - Proceed to Step 3.
   - Else,
     - The required elapsed time for the AIRCx process has elapsed but there is insufficient data to perform the AIRCx process.
     - Generate diagnostic message: There is insufficient data; therefore, potential opportunity for operational improvements cannot be detected at this time.
     - Proceed to Step 7.

   Else,

   - The required elapsed time for the AIRCx process has not elapsed.
   - Proceed to Step 8.

3. Sort the values in ***zn_dmpr_arr*** from largest to smallest. Use the largest 50% of the zone terminal box damper commands to calculate an average zone terminal box damper command (zn_dmpr_high_avg).

4. If zn_dmpr_high_avg <= *hdzone_damper_threshold* (zone high damper threshold),

   - Proceed to Step 5.

   Else,

   - Generate diagnostic message: The air-handler duct static pressure is not high for this period.
   - Proceed to Step 7.

5. Check the availability of ***stcpr_stpt_arr***:

   - If ***stcpr_stpt_arr,***
     – Proceed to Step 6.
   - Else,
     – Generate diagnostic message: The air-handler duct static pressure is high, but duct static pressure set point data is not available (cannot autocorrect).
     – Proceed to Step 7.

6. If *auto_correct_flag* == True,

   - Ensure that auto-correction will not decrease the duct static pressure set point below the minimum configured static pressure set point (*min_stcpr_stpt*). Calculate the intended auto-corrected static pressure set point (auto_correct_stcpr_stpt).
   - auto_correct_stcpr_stpt = AVG(***stcpr_stpt_arr***) - *stcpr_retuning*
     – If auto_correct_stcpr_stpt < *min_stcpr_stpt*,
       – Generate diagnostic message: The air-hander duct static pressure is, while the set point value is at the minimum.
       – stcpr_stpt = *min_stcpr_stpt*.
     – Else,
       – Generate diagnostic message: The air-handler duct static pressure is high; this could lead to higher supply fan energy consumption and additional zone reheat (with auto-correction enabled).
       – stcpr_stpt = auto_correct_stcpr_stpt.
   - Proceed to Step 6.

   Else,

   - Generate diagnostic message: The air-handler duct static pressure is high; this could lead to higher supply fan energy consumption and additional zone reheat (with auto-correction disabled).
   - Proceed to Step 7.

7. Send the command to the BAS or AHU controller, set the duct static pressure set point to stcpr_stpt (if a re-tuning opportunity was detected and auto-correction was enabled) and make diagnostic message(s) available for the operator.
8. Return to duct static AIRCx main diagnostic process, and wait for the next available data.

The default but adjustable thresholds and parameters for this diagnostic are as follows:

- Minimum elapsed time for analysis (*data_window*) = 15 minutes
- Number of required data points for AIRCx (*no_required_data*) = 5
- High duct zone damper (*hdzone_damper_threshold*) threshold = 30%
- Minimum duct static pressure set point (*min_stcpr_stpt*) = 0.3 in. w.g.
- Static pressure set point auto-correct decrement (*stcpr_retuning*) = 0.15 in. w.g.

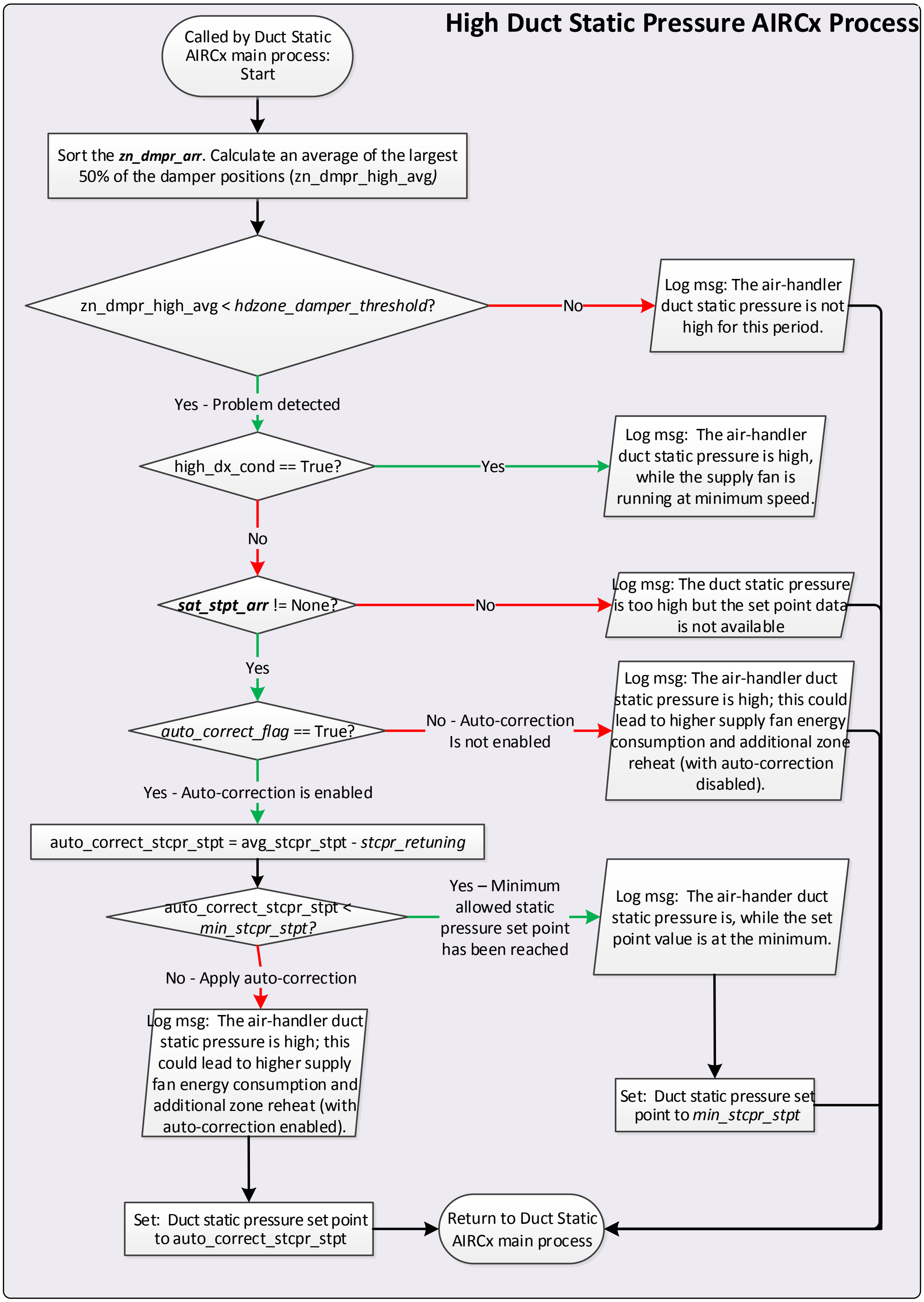

Figure 2.19. Flow Chart for the High Duct Static Pressure AIRCx Process

2.8 No Duct Static Pressure Set Point Reset AIRCx Process

The purpose of the no duct static pressure set point reset AIRCx process is to identify conditions under which 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 used. 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 2.20 shows an example of good operation. The duct static pressure set point varies and 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.

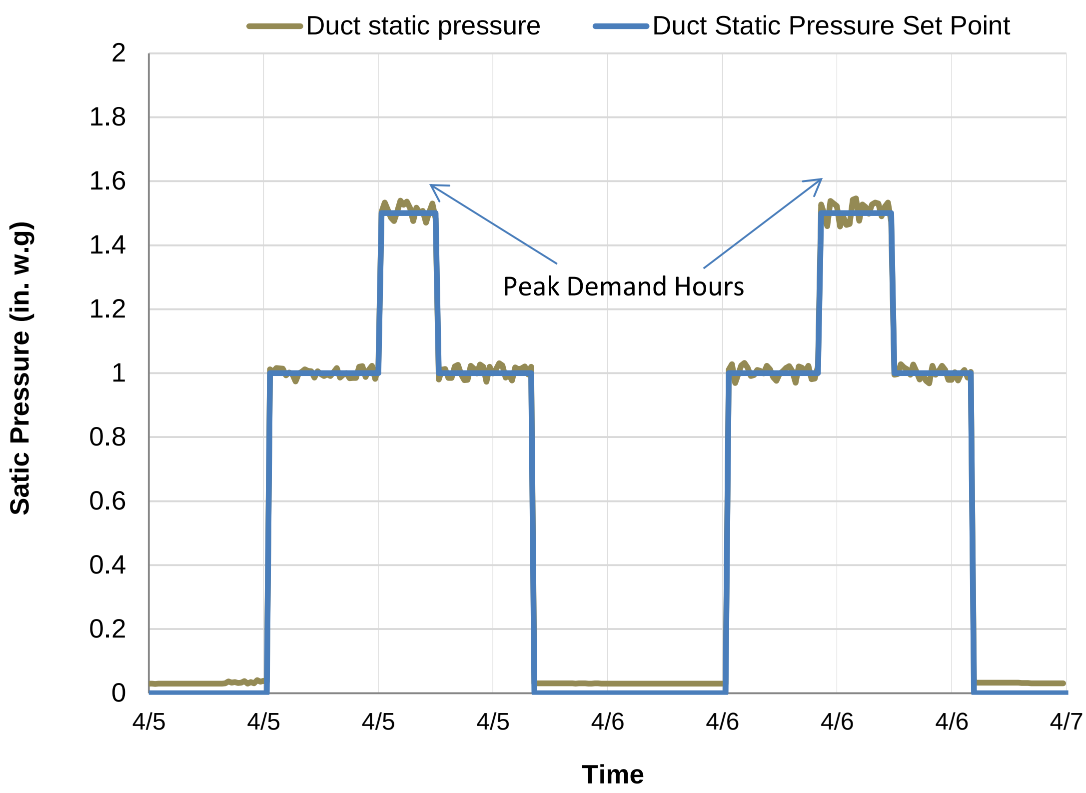

Figure 2.20. Example of Good Operations - The Duct Static Pressure Set Point Varies

2.8.1 Monitored Data for No Duct Static Pressure Reset AIRCx

This section describes the required input data for the no duct static pressure reset AIRCx process. The following data points are required for the execution of this diagnostic (data management for the no duct static pressure reset AIRCx process is performed by the duct static pressure AIRCx main process).

Input data from BACnet driver interface or text CSV:

- Duct static pressure set point at each time step of the analysis dataset (***stcpr_stpt_values***).

2.8.2 No Duct Static Pressure Set Point Reset AIRCx Diagnostic Process

This section provides the steps for the no duct static pressure set point reset AIRCx process including a detailed flow chart (Figure 2.21). 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 Schedule Reset Diagnostics main process but is included here to add clarity to the AIRCx process):

1. Upon the completion of day (i.e., midnight),
   - If LEN(***stcpr_stpt_arr***) >= *no_required_data*,
     – Proceed to Step 2.
   - Else,
     – Generate diagnostic message: There is insufficient data; therefore, potential opportunity for operational improvements cannot be detected at this time.
     – Proceed to Step 3.
2. Check if the duct static pressure set point varies throughout a day,
   - If MAX(***stcpr_stpt_arr***) - MIN(***stcpr_stpt_arr***) < *stcpr_reset_threshold* (duct static pressure set point reset threshold),
     – Generate diagnostic message: No air-handler static pressure reset is detected for this time period; this may result in excess energy consumption. Static pressure reset can save significant energy.
     – Proceed to Step 3.
   - Else,
     – Generate diagnostic message: The air-handler static pressure is being reset for this time period.
     – Proceed to Step 3.
3. Make diagnostic message(s) available to the building operator.
4. Return to the schedule reset AIRCx main process, and wait for the next available data.

The default but adjustable thresholds and parameters for this diagnostic are as follows:

- *stcpr_reset_threshold* = 0.25 in. w.g.
- *no_req_data* = 5.

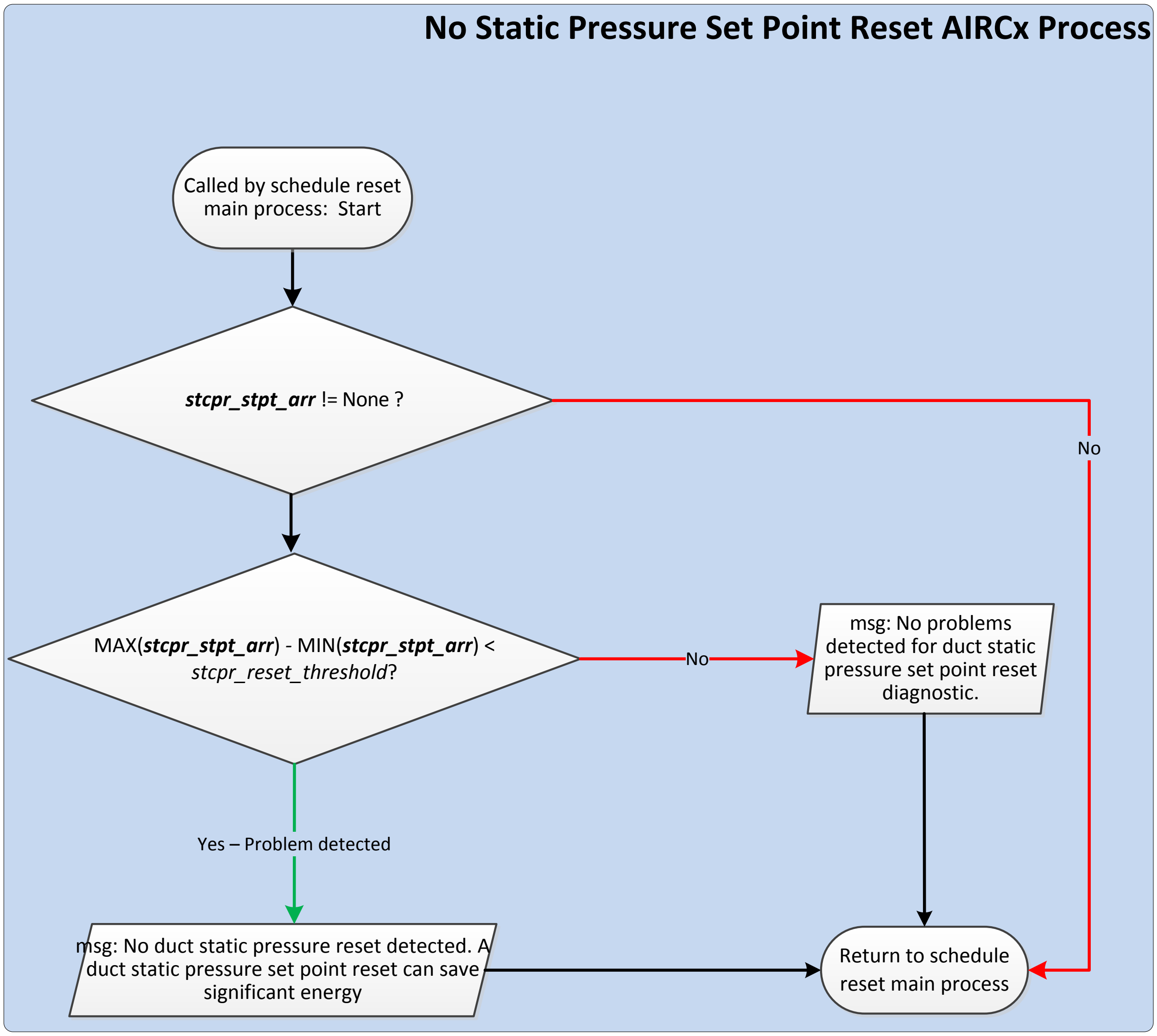

Figure 2.21. Flow Chart for the No Static Pressure Set Point Reset AIRCx Process

3.0 Economizer Controls AIRCx Algorithms

The economizer controls AIRCx processes use 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-air temperatures (MATs), return-air temperatures (RATs), outdoor-air temperatures (OATs), 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, and chiller rated energy efficiency ratio, as well as other parameters. The measured data can be trended at any interval (e.g., 1-minute, 5-minute, half-hourly, or hourly), but the AIRCx process will produce more accurate results if the data is trended at a rate of 5-minutes or smaller.

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 AIRCx 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 cooling 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 AIRCx algorithms will work with the following economizer types—high-limit dry-bulb or DDB. 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 do not result in comfort problems and are 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 AIRCx algorithms are designed to monitor conditions of the system not normally experienced by occupants and to alert the building operator when there is evidence of a fault as well as indicate 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 are related to conditions when the economizer should be ON (favorable for economizing) but it is OFF as well as 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 whether 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 use rules derived from engineering principles of proper and improper AHU operations. The five algorithms include the following.

- Detect AHU sensor faults (outdoor-air, mixed-air, and return-air temperature sensors).

- Detect if the AHU is not economizing when it should.
- Detect if the AHU is economizing when it should not.
- Detect if the AHU is using excess outdoor air.
- 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 sensors) and status signals (including fan, chilled-water valve command, and outdoor-air damper). The 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).

3.1 Economizer Control AIRCx Main Diagnostic Process

For the AIRCx 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 fan status (**fan_status**), cooling valve position **(cooling_valve)**, the outdoor-air temperature (**oatemp**), the return-air temperature (**ratemp**), the mixed-air temperature (**matemp**), the outdoor-air damper signal (**damper_signal**), and the fan speed (**fan_sp**) are available**.**
- The **oatemp** and the **ratemp** are not too close to each other:

ABS(**oatemp- ratemp**) >= *oaf_temp_threshold*

A cooling status flag (cooling_call) and an economizer status flag (econ_condition) are generated at each time step and made available for the five economizer diagnostics.

The cooling status flag is generated as follows:

- If **cooling_valve** > *cooling_enabled_threshold* (cooling enabled threshold),
  - cooling_call = True.
- Else,
  - cooling_call = False.

The AHU economizer status flag is generated as follows:

- If the economizer_type == DDB,
  - econ_condition = (**ratemp - oatemp** > *temp_deadband*) as a Boolean.

- Else,
  - econ_condition = (*econ_hl_temp* **- oatemp** > *temp_deadband*) as a Boolean.

The configuration parameters with default values for the economizer diagnostics are as follows:

- Low OAT threshold (*oat_low_threshold*) = 30°F
- High OAT threshold (*oat_high_threshold*) = 100°F
- Low MAT threshold (*mat_low_threshold*) = 50°F
- High MAT threshold (*mat_high_threshold*) = 90°F
- Low RAT threshold (*rat_low_threshold*) = 50°F
- High RAT threshold (*rat_high_threshold*) = 90°F
- Temperature dead band (*temp_deadband*) = 1°F
- Economizer temperature threshold (*oaf_temp_threshold*) = 4°F
- Temperature difference threshold (*temp_diff_threshold*) = 4°F
- OAT and MAT consistency threshold (*oat_mat_check*)= 5°F
- Chilled-water valve cooling enabled threshold (*cooling_enabled_threshold*) = 5%
- Rated Energy Efficiency Ratio (*eer*) = 10.0 (used to estimate the energy impact)
- Economizing damper threshold *(open_damper_threshold)* = 80%.
- Economizer oaf threshold (*oaf_economizing_threshold*) = 60%
- Economizer type (*economizer_type*) = DDB
- High-limit temperature (*econ_hl_temp*) = 65°F (Only needed if the economizer type is HL)
- Minimum elapsed time for analysis (*data_window*) = 30 minutes
- Maximum elapsed time for analysis *(max_dx_time)* = 60 minutes
- Number of required data points for analysis (*no_required_data*) = 10 measurements
- Estimated Rated cubic feet per minute (CFM) when supply fan is at full speed (*cfm*) = 6000 (site and unit specific)
- Excess damper threshold (*excess_damper_threshold*) = 30%
- Minimum damper position set point (*min_damper_sp*) = 20%
- Excess outdoor-air fraction (OAF) threshold (*excess_oaf_threshold*) = 30%
- Insufficient OAF threshold (*ventilation_oaf_threshold*) = 15%
- Desired OAF when outdoor-air damper (OAD) is at minimum position (*desired_oaf*) = 10%.

The main process handles the global prerequisites (i.e., prerequisites apply to all five of the economizer diagnostics), the temperature sensors high and low limit checks, and data management (passing thresholds values and data for the AHU to the diagnostics) (Figure 3.1). The BACnet driver interface queries data off the local controller or BAS at a constant (user configurable) rate. The data are then supplied to the algorithm. The execution of the diagnostic is identical for metered data provided via CSV text file except no auto-correction can be applied.

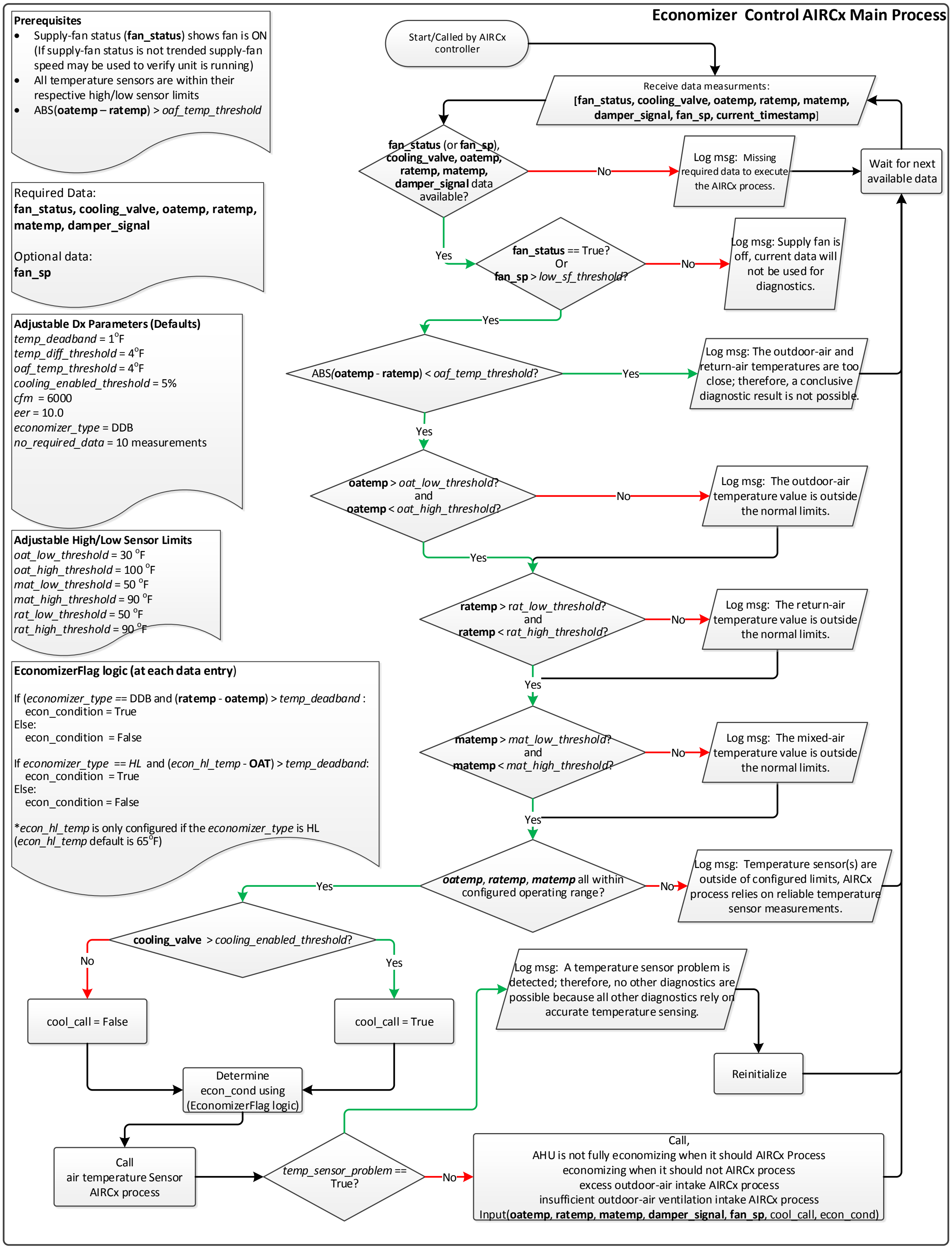

Figure 3.1. Flow Chart for the Economizer Control AIRCx Main Process

3.2 Air Temperature Sensor Fault AIRCx Process

The air temperature sensor fault AIRCx process determines whether 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 (e.g., OAT), 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 (e.g., day of year), 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 are 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.

3.2.1 Monitored Data for Air Temperature Sensor Fault AIRCx

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

- **matemp**
- **ratemp**
- **oatemp**
- **damper_signal**.

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

3.2.2 Temperature Sensor Fault AIRCx Diagnostic Process

This section provides the steps for the temperature sensor fault AIRCx process including a detailed flow chart (Figure 3.2). The airside temperature sensor fault AIRCx process calls an additional AIRCx process, the OAT and MAT consistency AIRCx process (Figure 3.3), which checks for consistency between the outdoor-air temperature (**oatemp**) and mixed-air temperature (**matemp**) when the outdoor-air damper (**damper_signal**) is fully open (**damper_signal** > *temp_damper_threshold*). The global economizer prerequisites (checked in the economizer control AIRCx main process discussed previously) must be satisfied in order for the temperature sensor diagnostic to run.

The following steps are used for this diagnostic process.

1. On the initial call from the economizer control AIRCx main diagnostic process, initialize the analysis dataset (i.e., ***oat_values***, ***rat_values***, ***mat_values***, and ***timestamp*** arrays).
2. Add data measurements for current time step (**current_timestamp**) to the analysis dataset:
   - Add **oatemp** to ***oatemp_values*** array.
   - Add **ratemp** to ***ratemp_values*** array.

- Add **matemp** to ***matemp_values*** array.
- Add **current_timestamp** to ***timestamp*** array.

3. Calculate the elapsed time (elapsed_time) in the analysis dataset:
   - elapse_time = ***timestamp***[**-**1] – ***timestamp***[0].
4. If elapsed_time >= *data_window*,
   - If LEN(***timestamp***) >= *no_required_data*,
     - The required elapsed time for the AIRCx process has elapsed and there is sufficient data to perform the AIRCx process.
     - Proceed to Step 5.
   - Else,
     - The required elapsed time for the AIRCx process has elapsed but there is insufficient data to perform the AIRCx process.
     - Generate diagnostic message: There is insufficient data; therefore, potential problems with temperature sensors cannot be identified at this time.
     - Proceed to Step 8.

   Else,
   - The required elapsed time for the AIRCx process has not elapsed.
   - Proceed to Step 8.
5. If elapsed_time > *max_dx_time,*
   - Generate diagnostic message: Inconsistent or missing data; therefore, potential problems with temperature sensors cannot be identified at this time.
   - Proceed to step 9.

   Else,
   - Proceed to Step 6.
6. Calculate the average value of the difference between each temperature sensors' readings contained within the analysis dataset (avg_oa_ma, avg_ra_ma, avg_ma_oa, and avg_ma_ra, respectively).
7. If avg_oa_ma > *temp_diff_threshold* and avg_ra_ma > *temp_diff_threshold* ,
   - Generate diagnostic message: The mixed-air temperature value is less than both the outdoor-air and return-air temperatures; therefore, there is a temperature sensor problem.
   - temp_sensor_problem = True.

   Else, if avg_ma_oa > *temp_diff_threshold* and avg_ma_ra > *temp_diff_threshold*,
   - Generate diagnostic message: The mixed-air temperature value is greater than both the outdoor-air and return-air temperatures; therefore, there is a temperature sensor problem.
   - temp_sensor_problem = True.

   Else,

- Generate diagnostic message: No temperature problem with temperature sensors is detected.

8. Call OAT and MAT consistency AIRCx process (steps 8a. – 8f.).
   a. On initial call from air temperature sensor fault AIRCx process initialize ***open_oat*** and ***open_mat*** arrays.
   b. If **damper_signal** > *temp_damper_threshold*,
      - If not econ_steady_state,
        – econ_steady_state = **current_timestamp**
        – Return to air temperature sensor fault AIRCx process, proceed to step 9.

      Else,
      - If **current_timestamp** – econ_steady_state >= *econ_check_time*,
        – Add **oatemp** to ***open_oat*** array.
        – Add **matemp** to ***open_mat*** array.
        – Proceed to Step 8c.
      - Else,
        – Return to air temperature sensor fault AIRCx process, proceed to step 9.
   c. Calculate mat_oat_diff:
      - For i from 0 to LEN(***open_oat***):
        – ***mat_oat_arr***[i] = ABS(***open_oat***[i] – ***open_mat***[i])
      - End For
      - mat_oat_diff = AVG(***mat_oat_arr***)
      - Proceed to step 8d.
   d. If mat_oat_diff > *oat_mat_check*,
      - Generate diagnostic message: The outdoor-air and mixed-air temperature sensor readings are not consistent when the outdoor-air damper is fully open.
      - Proceed to Step 8e.

      Else,
      - Generate diagnostic message: The outdoor-air and mixed-air temperature sensor readings are consistent when the outdoor-air damper is fully open.
      - Proceed to Step 8e.
   e. Reinitialize the ***open_oat*** array, ***open_mat*** array, and econ_steady_state = False.
   f. Return to air temperature sensor fault AIRCx process, proceed to step 9.
9. Make the diagnostic message(s) available to the operator.
10. Reinitialize the analysis dataset (i.e., ***oat_values***, ***rat_values***, ***mat_values***, and ***timestamp*** arrays).
11. Return to economizer control AIRCx main process, and wait for the next data.

The default but adjustable thresholds and parameters for this diagnostic are as follows:

- *temp_diff_threshold* = 4°F
- *oat_mat_check* = 5°F
- *data_window* = 30 minutes
- *no_required_data* = 20
- *open_damper_threshold* = 90%
- *max_dx_time* = 60 min
- Time to state conditions once the outside-air damper (OAD) is fully open (*open_damper_time*) = 5 minutes.

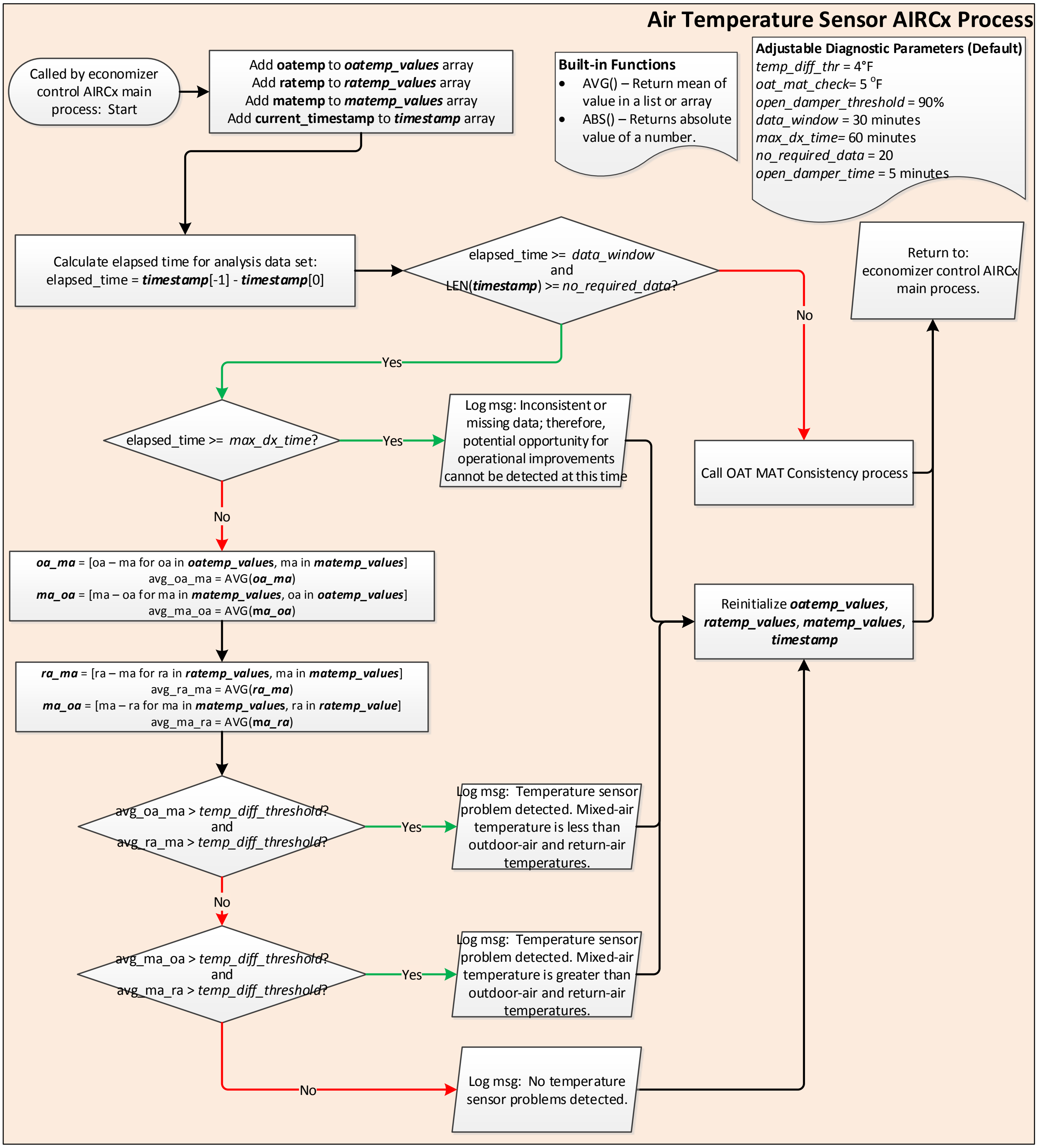

Figure 3.2. Flow Chart for the Air Temperature Sensor Fault AIRCx Process

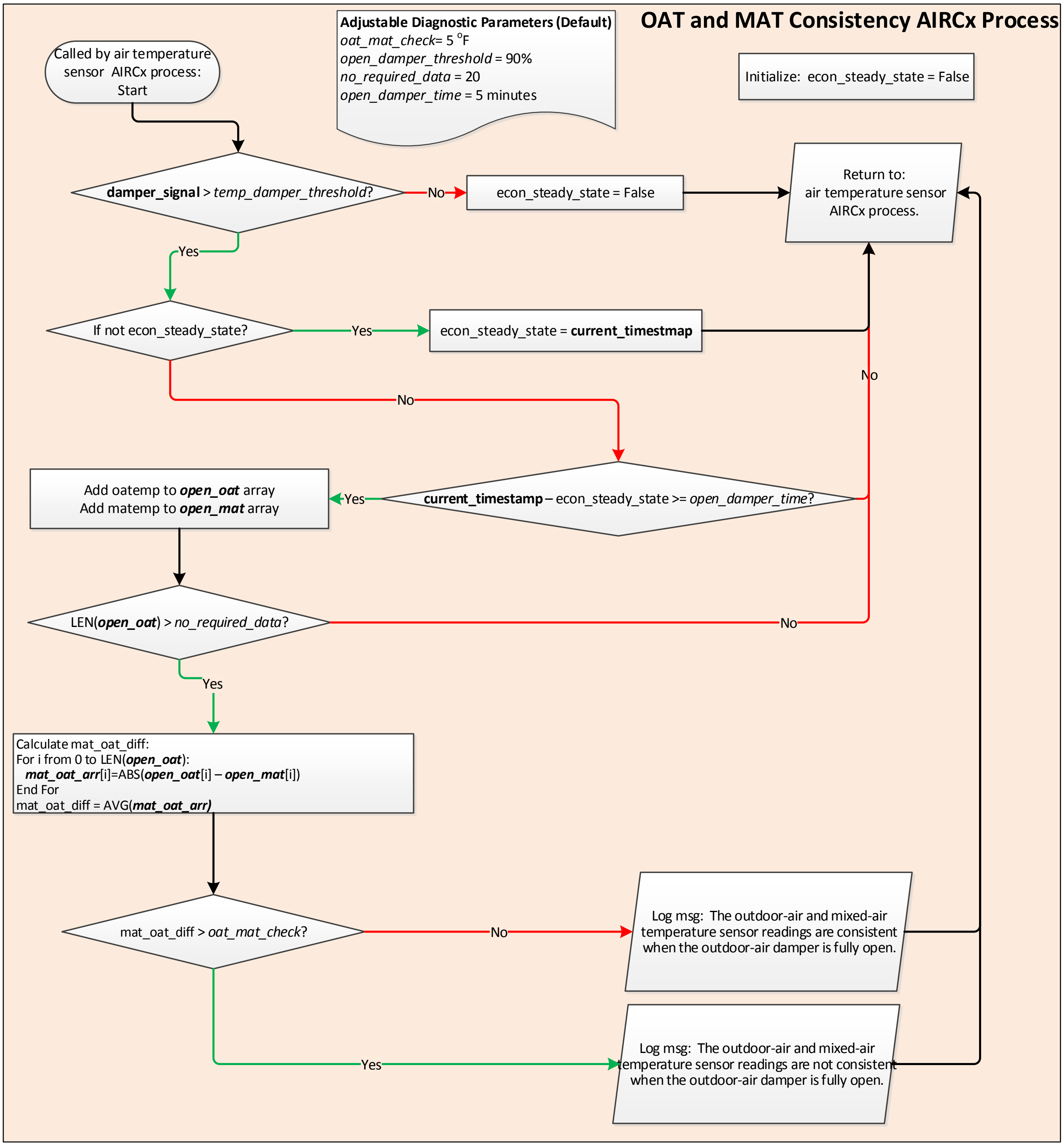

Figure 3.3. Flow Chart for the OAT and MAT Consistency AIRCx Process

3.3 AHU is not Fully Economizing When It Should AIRCx Process

The AHU is not fully economizing when it should AIRCx process determines whether the economizer is ON and working properly when conditions are favorable for economizing. There are two configurations for the type of economizer: (1) DDB 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 the DDB economizer only.

When the AHU is actively cooling and the OAT is less than the RAT, 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, energy is being wasted. In many cases, outdoor air is cool enough to satisfy all of 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 whether the unit is bringing in nearly 100% outdoor air or at least greater than a threshold value (default 60% 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, as well as to discover 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 MAT and RAT and the difference between OAT and RAT as shown in the equation below:

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

The OAF calculation 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 OAT and RAT (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 use 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).

3.3.1 Monitored Data for AHU is not Economizing When It Should AIRCx

This section describes the required input data for the AHU is not economizing when it should AIRCx. The following data points are required for the execution of this diagnostic:

- **matemp**
- **ratemp**
- **oatemp**
- **fan_sp**

- **damper_signal**.

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

3.3.2 AHU is not Economizing When It Should AIRCx Diagnostic Process

This section provides the steps for the AHU is not economizing when it should AIRCx process including a detailed flow chart (Figure 3.4). The following prerequisite must be met (in addition to the global prerequisites that are checked in the economizer control AIRCx main process discussed previously):

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

If the prerequisite conditions are not satisfied, the current data measurements will not be used for this economizer AIRCx process. The following steps are used to for the diagnostic process:

1. On the initial call from the economizer control AIRCx main process, initialize the analysis dataset (i.e., ***oad_values***, ***oat_values***, ***rat_values***, ***mat_values***, ***fan_speed_values***, and ***timestamp*** arrays).
2. Check if all prerequisites are met:
    - If all of the prerequisites are met,
        - Add **damper_signal** to the ***oad_values*** array.
        - Add **oatemp** to ***oatemp_values*** array.
        - Add **ratemp** to ***ratemp_values*** array.
        - Add **matemp** to ***matemp_values*** array.
        - Add **fan_speed** to ***fan_speed_values*** array.
        - Add **current_timestamp** to ***timestamp*** array.
    - If all of the prerequisites are not met, do not add data measurements to the current analysis dataset.
3. Calculate the elapsed time (elapsed_time) in the analysis dataset:
    - elapse_time = ***timestamp***[-1] – ***timestamp***[0].
4. If elapsed_time >= *data_window*,
    - If LEN(***timestamp***) >= *no_required_data,*
        - The required elapsed time for the AIRCx process has elapsed and there is sufficient data to perform the AIRCx process.
        - Proceed to Step 5.
    - Else,
        - The required elapsed time for the AIRCx process has elapsed but there is insufficient data to perform the AIRCx process.
        - Generate diagnostic message: There is insufficient data; therefore, potential opportunity for operational improvements cannot be detected at this time.

   - Proceed to Step 11.

   Else,

   - The required elapsed time for the AIRCx process has not elapsed.
   - Proceed to Step 13.

5. If elapsed_time > *max_dx_time*,

   - Generate diagnostic message: Inconsistent or missing data; therefore, potential opportunity for operational improvements cannot be detected at this time
   - Proceed to step 11

   Else,

   - Proceed to Step 6.

6. Calculate average OAF (avg_oaf) as follows:

   - For i from 0 to LEN(***timestamp***):
     - ***oaf***[i] = (***mat_values***[i] – ***rat_values***[i])/(***oat_values***[i] – ***rat_values***[i])
   - End For
   - avg_oaf = AVG(***oaf***) × 100.
   - Proceed to Step 7.

7. Calculate the average outdoor-air damper signal for the analysis dataset (avg_damper_signal).

   - avg_damper_signal = AVG(***oad_values***).

8. If avg_damper_signal < *open_damper_threshold* (economizing damper threshold),

   - Generate diagnostic message: The conditions are favorable for economizing but the outdoor-air damper is not fully open and the mechanical cooling is active.
   - Proceed to Step 10.

   Else,

   - Proceed to Step 9.

9. If avg_oaf < *oaf_economizing_threshold* (economizing OAF threshold),

   - Generate diagnostic message: The outdoor-air damper is commanded to be fully open; however, the outdoor-air fraction is significantly lower than 100%.
   - Proceed to Step 10.

   Else,

   - Generate diagnostic message: The economizer is functioning as expected.
   - Proceed to Step 11.

10. If a problem was detected for this economizer AIRCx process,

    - Calculate the estimated energy impact associated with the problem(s) (see Figure 3.4 for details).

- Proceed to Step 11.

11. Make the diagnostic message(s) available to the operator.
12. Reinitialize the analysis dataset (i.e., ***oad_values***, ***oat_values***, ***rat_values***, ***mat_values***, ***fan_speed_values***, and ***timestamp*** arrays).
13. Return to the economizer control AIRCx main process, and wait for the next data.

The default but adjustable thresholds and parameters for this diagnostic are as follows:

- *open_damper_threshold* = 80%
- *oaf_economizing_threshold* = 60%
- *data_window* = 30 minutes
- *max_dx_time* = 60 min
- *no_required_data* = 10.

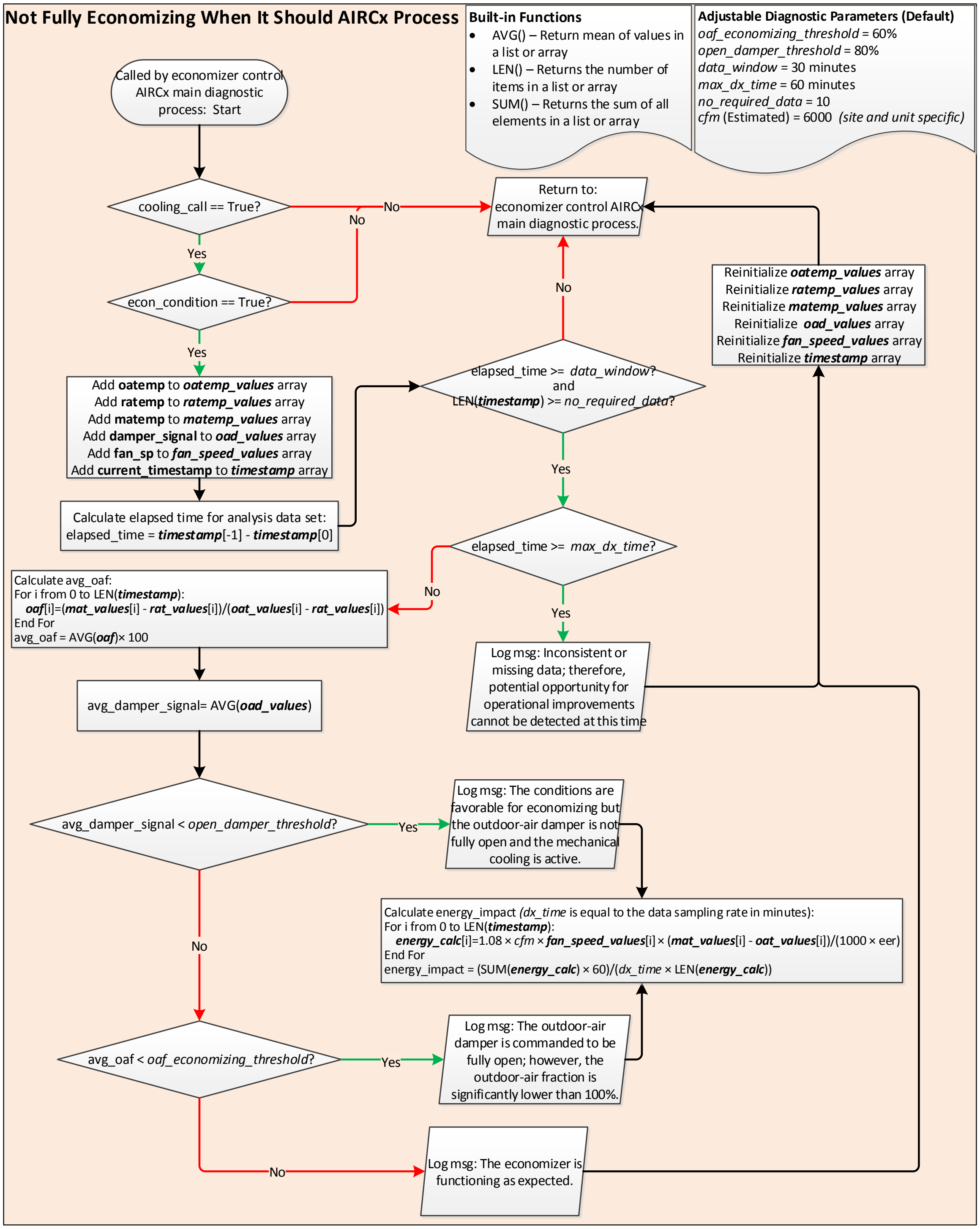

Figure 3.4. Flow Chart for the Not Fully Economizing When It Should AIRCx Process

3.4 Economizing When It Should Not AIRCx Processs

The economizing when it should not AIRCx process determines whether 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 OAF exceed their minimum threshold values. Even though economizing has the 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 whether 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, at least the following three conditions should be evaluated for this fault condition:

- When there is no call for cooling or heating, the damper command should be at the minimum position.
- When there is a call for heating, the damper command should be at the minimum position.
- When there is a call for cooling and the conditions are not favorable for economizing (e.g., the 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 RAT, the system is in unoccupied cooling mode, and the fan is running. The same is 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.

3.4.1 Monitored Data for AHU is Economizing When it Should Not AIRCx Process

The following data points are required for the execution of the AHU is economizing when it should not AIRCx process. The following data points are required for the execution of this diagnostic:

- **fan_sp**
- **damper_signal**.

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

3.4.2 AHU is Economizing When it Should Not AIRCx Diagnostic Process

This section provides the steps for the AHU is economizing when it should not AIRCx process including a detailed flow chart (Figure 3.5). The following prerequisite must be met before the process is initiated:

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

If the prerequisite conditions are not satisfied, the current data measurements will not be used for this economizer AIRCx process. The following steps are used to for the diagnostic process:

1. On the initial call from the economizer control AIRCx main process, initialize the analysis dataset (i.e., ***oad_values***, ***fan_speed_values***, and ***timestamp*** arrays).
2. Check if all prerequisites are met:
    - If all of the prerequisites are met,

    - Add **damper_signal** to the ***oad_values*** array.
    - Add **fan_speed** to ***fan_speed_values*** array.
    - Add **current_timestamp** to ***timestamp*** array.
  - If all of the prerequisites are not met, do not add data measurements to the current analysis dataset.

3. Calculate the elapsed time (elapsed_time) in the analysis dataset:
   - elapse_time = ***timestamp***[-1] – ***timestamp***[0].
4. If elapsed_time >= *data_window*,
   - If LEN(***timestamp***) >= *no_required_data*,
     - The required elapsed time for the AIRCx process has elapsed and there is sufficient data to perform the AIRCx process.
     - Proceed to Step 5.
   - Else,
     - The required elapsed time for the AIRCx process has elapsed but there is insufficient data to perform the AIRCx process.
     - Generate diagnostic message: There is insufficient data; therefore, potential opportunity for operational improvements cannot be detected at this time.
     - Proceed to Step 8.

   Else,
   - The required elapsed time for the AIRCx process has not elapsed.
   - Proceed to Step 10.
5. If elapsed_time > *max_dx_time*,
   - Generate diagnostic message: Inconsistent or missing data; therefore, potential opportunity for operational improvements cannot be detected at this time
   - Proceed to Step 8

   Else,
   - Proceed to Step 6.
6. Calculate the average outdoor-air damper signal for the analysis dataset (avg_damper_signal).
   - avg_damper_signal = AVG(***oad_values***).
7. If avg_damper_signal > *excess_damper_threshold* (excess damper threshold).
   - Generate diagnostic message: The outdoor-air damper should be at the minimum position to meet the ventilation requirement, but it is significantly above that value.
   - Calculate the estimated energy impact associated with the problem(s) (see Figure 3.5 for details).
   - Proceed to Step 8.

   Else,

- Generate diagnostic message: The economizer is functioning as expected.
- Proceed to Step 8.

8. Make diagnostic message(s) and energy impact available to the operator.
9. Reinitialize the analysis dataset (i.e., ***oad_values***, ***fan_speed_values***, and ***timestamp*** arrays).
10. Return to the economizer control AIRCx main process, and wait for the next data.

The default but adjustable thresholds and parameters for this diagnostic are as follows:

- *min_damper_s*p = 20%
- *excess_damper_threshold* = *min_damper_sp* × 1.5 = 30%
- *data_window* = 30 minutes
- *no_required_data* = 10.

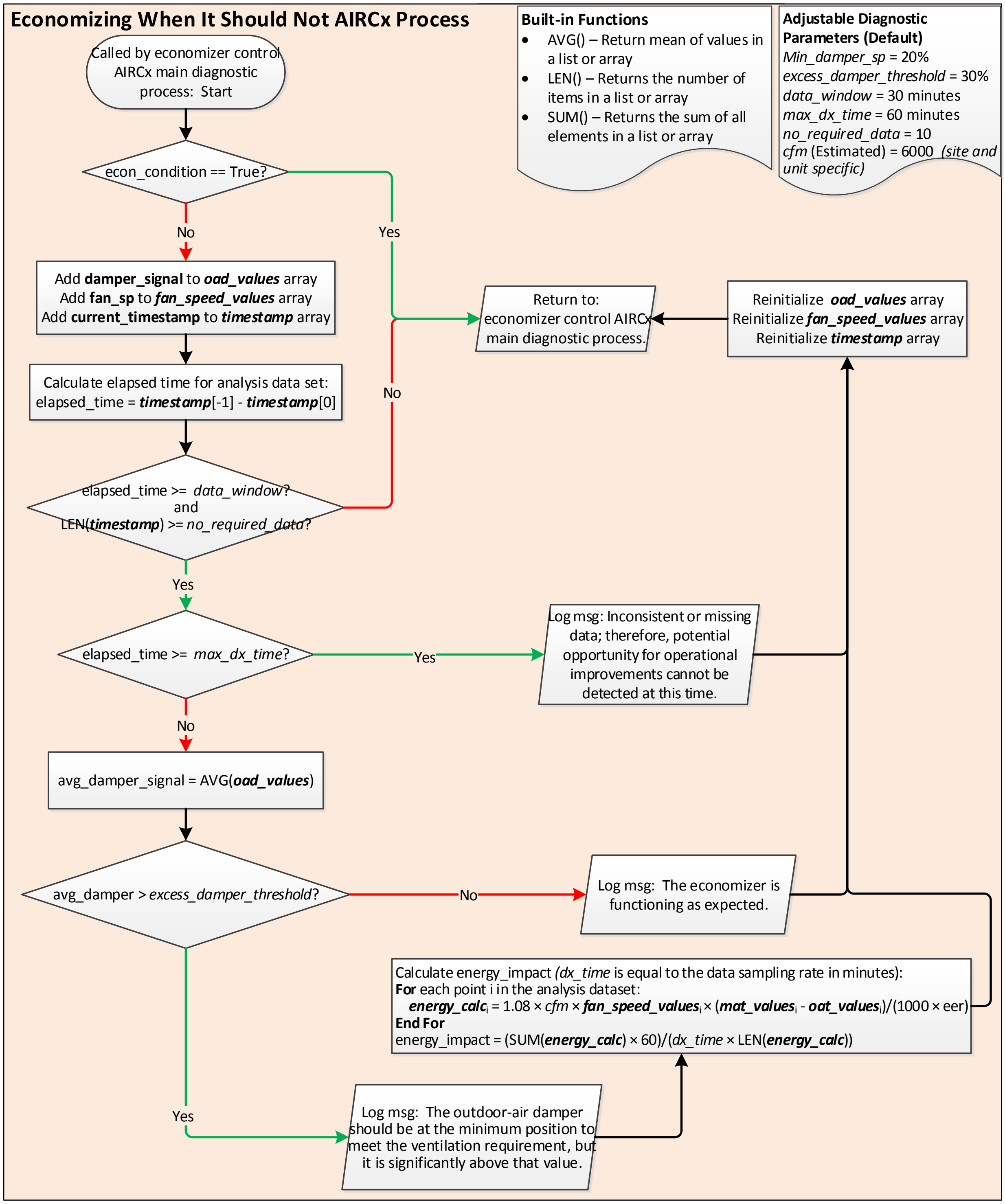

Figure 3.5. Flow Chart for the Economizing When It Should Not AIRCx Process

3.5 Excess Outdoor-air Intake AIRCx Process

The excess outdoor-air intake AIRCx process determines whether 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 OAF will be used to determine whether the AHU/rooftop unit is providing too much outdoor air. The OAF can be calculated as a ratio of the difference between the mixed-air temperature and RAT and the difference between OAT and RAT, 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 OAT is close to the RAT. Therefore, a conclusive diagnostic will only be returned when there is a significant difference between the OAT and RAT—a difference of at least 4 to 5°F. The calculated OAF is compared to an OAF threshold (adjustable) to determine whether excess outdoor air is being introduced into the space. If the calculated OAF exceeds a threshold, a fault is indicated.

3.5.1 Monitored Data for Excess Outdoor-air Intake AIRCx Process

This section describes the required input data for the excess outdoor-air intake AIRCx process. The following data points are required for the execution of this diagnostic. The following data points are required for the execution of this diagnostic:

- **matemp**
- **ratemp**
- **oatemp**
- **fan_sp**
- **damper_signal**.

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

3.5.2 Excess Outdoor-air Intake AIRCx Diagnostic Process

This section provides the steps for the excess outdoor-air intake AIRCx process including a detailed flow chart (Figure 3.6). The following prerequisite must be met.

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

If the prerequisite conditions are not satisfied, the current data measurements are used for this economizer AIRCx process. The following steps are used for the diagnostic process.

1. On the initial call from the economizer control AIRCx main diagnostic process, initialize the analysis dataset (***oad_values***, ***oat_values***, ***rat_values***, ***mat_values***, ***fan_speed_values***, and ***timestamp*** arrays).
2. Check if all prerequisites are met.
    - If all of the prerequisites are met,
        – Add **damper_signal** to the ***oad_values*** array.

    - Add **oatemp** to ***oatemp_values*** array.
    - Add **ratemp** to ***ratemp_values*** array.
    - Add **matemp** to ***matemp_values*** array.
    - Add **fan_speed** to ***fan_speed_values*** array.
    - Add **current_timestamp** to ***timestamp*** array.
  - If all of the prerequisites are not met, do not add data measurements to the current analysis dataset.
3. Calculate the elapsed time (elapsed_time) in the analysis dataset:
  - elapse_time = ***timestamp***[**-**1] – ***timestamp***[0].
4. If elapsed_time >= *data_window*,
  - If LEN(***timestamp***) > *no_required_data*,
    - The required elapsed time for the AIRCx process has elapsed and there is sufficient data to perform the AIRCx process.
    - Proceed to Step 5.
  - Else,
    - The required elapsed time for the AIRCx process has elapsed but there is insufficient data to perform the AIRCx process.
    - Generate diagnostic message: There is insufficient data; therefore, potential opportunity for operational improvements cannot be detected at this time.
    - Proceed to Step 12.

   Else,
  - The required elapsed time for the AIRCx process has not elapsed.
  - Proceed to Step 14.
5. If elapsed_time > *max_dx_time,*
  - Generate diagnostic message: Inconsistent or missing data; therefore, potential opportunity for operational improvements cannot be detected at this time
  - Proceed to step 12

   Else,
  - Proceed to Step 6.
6. Calculate average OAF (avg_oaf) as follows:
  - For i from 0 to LEN(***timestamp***):
    - ***oaf***[i] = (***mat_values***[i] – ***rat_values***[i])/(***oat_values***[i] – ***rat_values***[i])
  - End For
  - avg_oaf = AVG(***oaf***) × 100.
  - Proceed to Step 7.

7. Calculate the average outdoor-air damper signal for the analysis dataset (avg_damper_signal).
   - avg_damper_signal = AVG(***oad_values***).
8. Is the avg_oaf within acceptable limits?
   - If 0 < avg_oaf < 125,
     – Proceed to Step 9.
   - Else,
     – Generate diagnostic message: No conclusions can be drawn because outdoor-air fraction calculation is not reliable during this time period.
     – Proceed to Step 12.
9. If avg_damper > *excess_damper_threshold* (excess damper threshold),
   - Set oad_fault = True.
   - Proceed to Step 10.
10. If avg_oaf – *desired_oaf* > *excess_oaf_threshold* (excess OAF threshold),
    - If oad_fault == True*:*
      – Generate diagnostic message: The outdoor-air damper should be at the minimum position to meet the ventilation needs, but it is significantly above that value. The air-handling/rooftop unit is bringing in excess outdoor air; this will increase heating/cooling costs.
      – Proceed to step 11.
    - Else,
      – Generate diagnostic message: The air-handling/rooftop unit is bringing in excess outdoor air; this will increase heating/cooling costs.
      – Proceed to step 11.

    Else, if oad_fault == True,
    - Generate diagnostic message: The outdoor-air damper should be at the minimum position to meet the ventilation needs, but it is significantly above that value.
    - Proceed to step 11.

    Else,
    - Generate diagnostic message: The air-handling/rooftop unit is operating as expected.
    - Proceed to step 12.
11. Calculate the estimated energy impact associated with the problem(s) (see Figure 3.6 for details).
12. Make the diagnostic message(s) and energy impact available to the operator.
13. Reinitialize the analysis dataset (i.e., ***oad_values***, ***oat_values***, ***rat_values***, ***mat_values***, ***fan_speed_values***, and ***timestamp*** arrays).
14. Return to the economizer control AIRCx main process, and wait for the next data.

The default but adjustable thresholds and parameters for this diagnostic are as follows:

- *min_damper_sp* = 20%
- *desired_oaf* = 10% (when OAD is at minimum position)
- excess_damper_threshold = min_damper_sp × 1.5 = 30%
- *excess_oaf_threshold* = min_damper_sp + 10 = 30%
- *data_window* = 30 minutes
- *no_required_data* = 10.

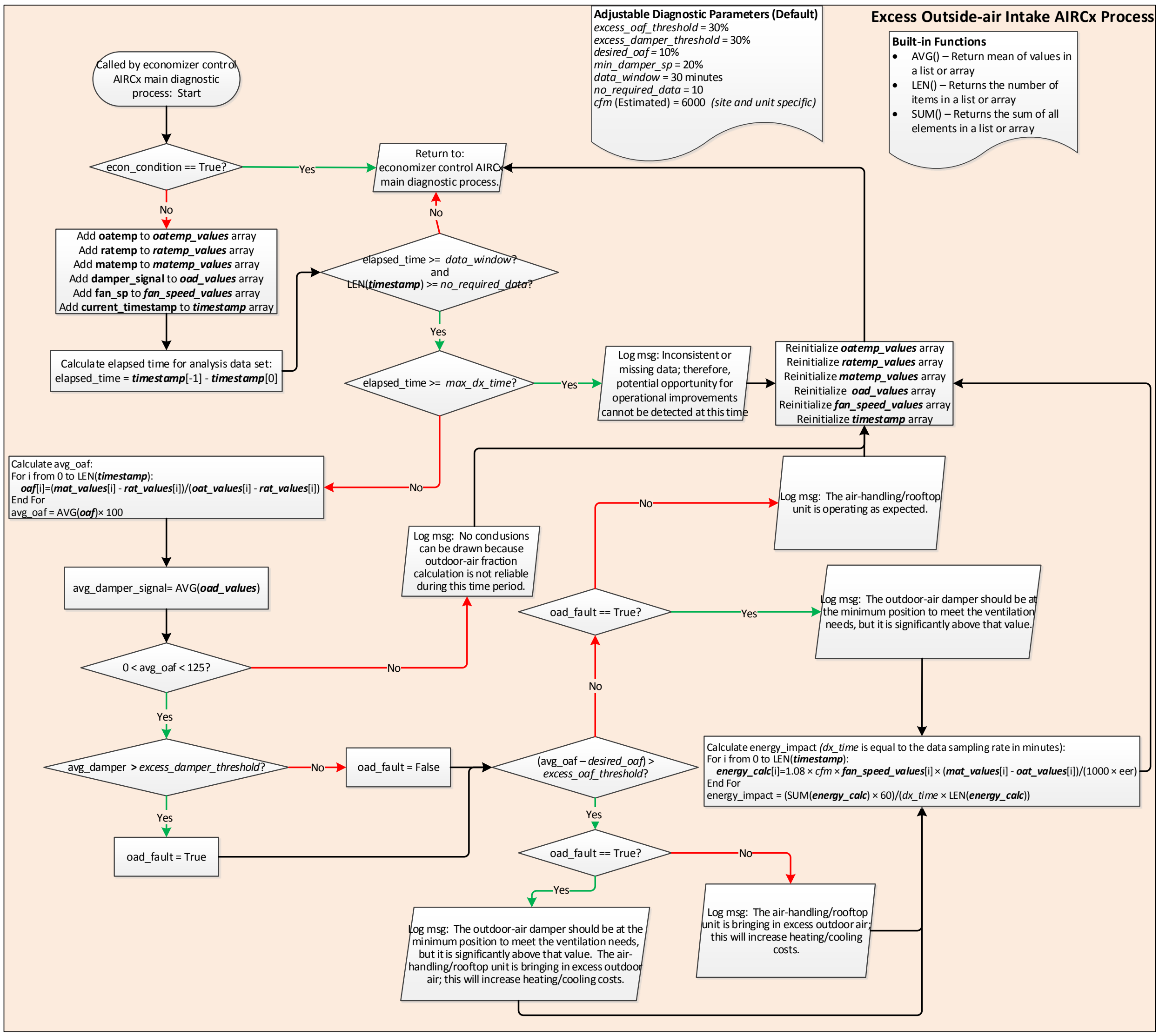

Figure 3.6. Flow Chart for the Excess Outdoor-air Intake AIRCx Process

3.6 Insufficient Outdoor-air Ventilation Intake AIRCx Process

This diagnostic determines whether 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 carbon dioxide gases and could lead to potentially negative building pressurization problems, which can contribute to infiltration of unwanted dust, moisture, pollens, and 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 they are 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 whether 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 RAT and the difference between OAT and RAT, 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 OAT and RAT (e.g., a difference of at least 4 to 5°F).

The calculated average OAF (AvgOAF) is compared to the minimum OAF, to determine whether 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.

3.6.1 Monitored Data for Insufficient Outdoor-air Intake AIRCx

This section describes the required input data for the insufficient outdoor-air ventilation intake AIRCx process. The following data points are required for the execution of this diagnostic:

- **matemp**
- **ratemp**
- **oatemp.**

3.6.2 Insufficient Outdoor-air Intake AIRCx Diagnostic Process

This section provides the steps for the insufficient outdoor-air intake AIRCx process including a detailed flow chart (Figure 3.7).

The following steps are used to for the diagnostic process:

1. On the initial call from the economizer control AIRCx main diagnostic process, initialize the analysis dataset (***oat_values***, ***rat_values***, ***mat_values***, and ***timestamp*** arrays).
2. Check if all prerequisites are met:

- If all of the prerequisites are met,
  - Add **oatemp** to ***oatemp_values*** array.
  - Add **ratemp** to ***ratemp_values*** array.
  - Add **matemp** to ***matemp_values*** array.
  - Add **current_timestamp** to ***timestamp*** array.
- If all of the prerequisites are not met, do not add data measurements to the current analysis dataset.

3. Calculate the elapsed time (elapsed_time) in the analysis dataset:
   - elapse_time = ***timestamp***[**-**1] – ***timestamp***[0].
4. If elapsed_time >= *data_window*,
   - If LEN(***timestamp***) >= *no_required_data*,
     - The required elapsed time for the AIRCx process has elapsed and there is sufficient data to perform the AIRCx process.
     - Proceed to Step 5.
   - Else,
     - The required elapsed time for the AIRCx process has elapsed but there is insufficient data to perform the AIRCx process.
     - Generate diagnostic message: There is insufficient data; therefore, potential opportunity for operational improvements cannot be detected at this time.
     - Proceed to Step 9.

   Else,
   - The required elapsed time for the AIRCx process has not elapsed.
   - Proceed to Step 11.
5. If elapsed_time > *max_dx_time,*
   - Generate diagnostic message: Inconsistent or missing data; therefore, potential opportunity for operational improvements cannot be detected at this time
   - Proceed to Step 9.

   Else,
   - Proceed to Step 6.
6. Calculate average OAF (avg_oaf) as follows:
   - For i from 0 to LEN(***timestamp***):
     - ***oaf***[i] = (***mat_values***[i] – ***rat_values***[i])/(***oat_values***[i] – ***rat_values***[i])
   - End For
   - avg_oaf = AVG(***oaf***) × 100.
   - Proceed to Step 7.

7. Is the avg_oaf within acceptable limits?
   - If 0 < avg_oaf < 125,
     – Proceed to Step 8.
   - Else,
     – Generate diagnostic message: No conclusions can be drawn because outdoor-air fraction calculation is not reliable during this time period.
     – Proceed to Step 9.
8. If (*desired_oaf* – avg_oaf) > *ventilation_oaf_threshold* (insufficient OAF threshold),
   - Generate diagnostic message: The air-handling/rooftop unit is not providing adequate ventilation air based on the outdoor-air fraction.
   - Proceed to step 9.

   Else,
   - Generate diagnostic message: The air-handling unit/rooftop unit is operating as expected.
   - Proceed to step 9.
9. Make the diagnostic message(s) available to the operator.
10. Reinitialize the analysis dataset (i.e., ***oat_values***, ***rat_values***, ***mat_values***, and ***timestamp***).
11. Return to the economizer control AIRCx main process, and wait for the next data.

The default but adjustable thresholds and parameters for this diagnostic are as follows:

- *desired_oaf* = 10%
- *ventilation_oaf_threshold* = *desired_oaf* × 0.5 = 5%
- *data_window* = 30 minutes
- *no_required_data* = 10.

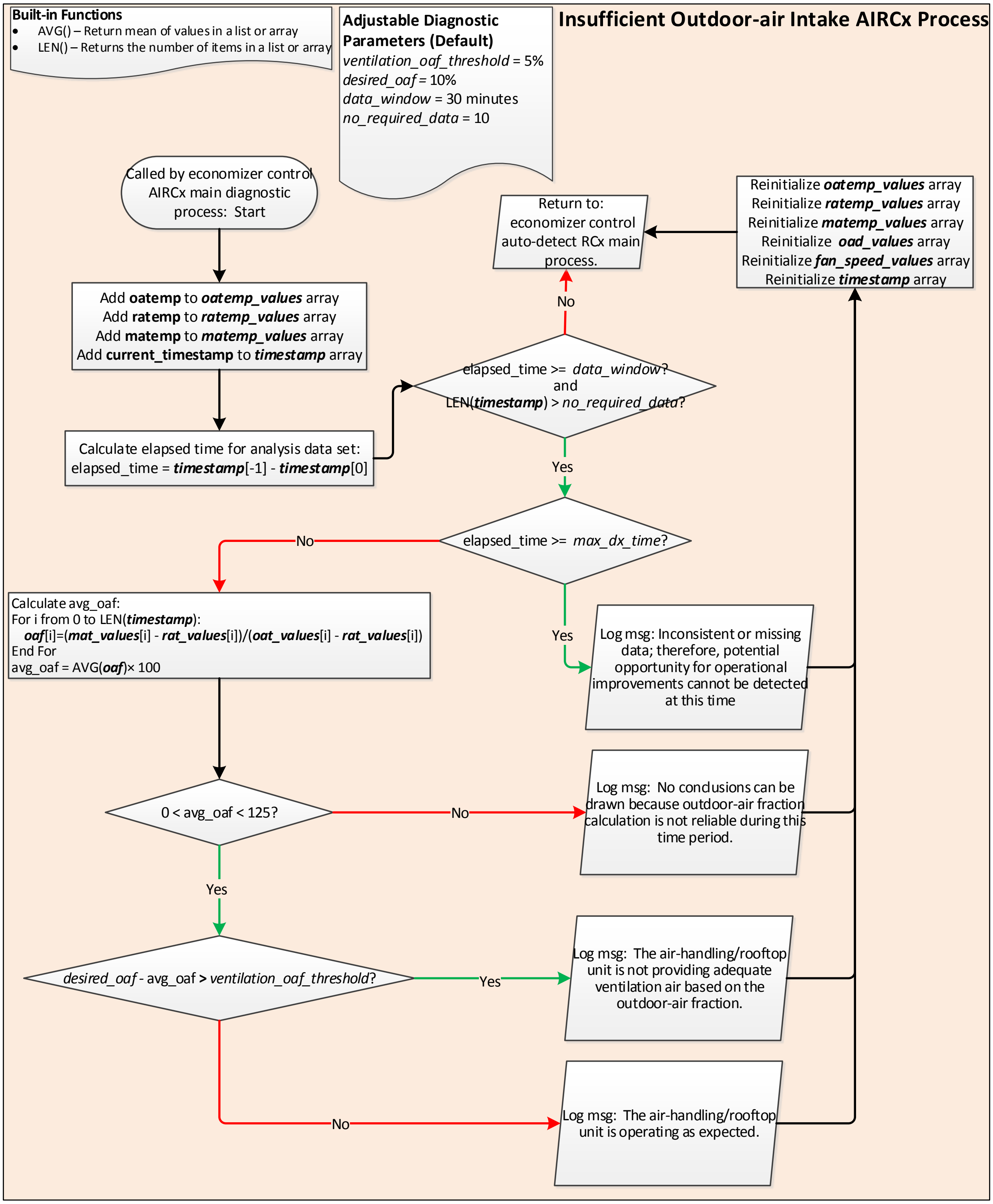

Figure 3.7. Flow Chart for the Insufficient Outdoor-air Intake AIRCx Process

4.0 Hot-Water Distribution System AIRCx Algorithms

The hot-water (HW) distribution system AIRCx processes use a decision-tree structure to detect and diagnose problems associated with HW system operations.

The faults detected can be grouped into five categories: (1) high HW loop differential pressure (DP) set point, (2) no reset for the HW DP set point, (3) high HW loop supply temperature, (4) no reset for HW loop supply temperature set point, and (5) low delta-T for HW loop.

The algorithms use rules derived from engineering principles of proper and improper HW system operations. The five algorithms include the following.

- Detect whether the DP for the HW loop is too high.
- Detect whether the DP set point for the HW loop is not reset.
- Detect whether the supply water temperature for the HW loop is too high.
- Detect whether the supply water temperature set point for the HW loop is not reset.
- Detect whether the temperature difference between supply and return water for the HW loop is too low.

The intent of these algorithms is to provide actionable information to building owners and operations staff while minimizing false alarms. 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 algorithms.

4.1 HW Distribution System Diagnostic Main Process

The HW distribution system main process (Figure 4.1) algorithm handles the diagnostics prerequisites (i.e., prerequisites that apply to all of the HW diagnostics), sensors high and low limit checks, and provides data management (passing thresholds values and data for the hot water distribution system to the diagnostics).

The following prerequisites have to be met for the diagnostics to be initiated.

- At least one boiler is operational and ON (the boiler status data (***boiler_status_values***) for at least one boiler in the HW loop indicates the boiler is ON).
- HW loop differential pressure (HWLoopDP) is greater than a minimum threshold (*MinDP*) and less than a maximum threshold (*MaxDP*).
  - $MinDP < \text{HWLoopDP} < MaxDP$.
- HW supply temperature (HWST) is within the configured operating range.
  - $MinHWST < \text{HWST} < MaxHWST$.
- HW return temperature (HWRT) is within the configured operating range.
  - $MinHWRT < \text{HWRT} < MaxHWRT$.

The configuration parameters required for the HW distribution system AIRCx process include the following:

- Minimum differential pressure (*MinDP*) = 2.5 psi
- Maximum differential pressure (*MaxDP*) = 25.0 psi
- Minimum HW supply temperature (*MinHWST*) = 125°F
- Maximum HW supply temperature (*MaxHWST*) = 190°F
- Minimum HW return temperature (*MinHWRT*) = 115°F
- Maximum HW return temperature (*MaxHWRT*) = 180°F
- Allowable deviation from set point (*allowable_deviation*) = 10%
- Minimum elapsed time for analysis (*data_window*) = 120 minutes
- Number of required data points for AIRCx (*no_required_data*) = 20.

High HW loop DP AIRCx adjustable parameters include the following:

- Pump differential pressure threshold (*pump_dp_threshold*) = 45%
- High DP outdoor-air temperature threshold (*hw_oat_threshold*) = 60°F.

No HW loop differential pressure set point reset AIRCx adjustable parameter includes the following:

- Differential pressure set point difference threshold (*dp_reset_threshold*) = 2.5 psi.

High HW supply temperature AIRCx process parameters include the following:

- HW supply temperature threshold (*high_hwst_threshold*) = 130°F
- HW pump VFD threshold (*hwst_pump_threshold*) = 35%.

No HW supply temperature set point reset AIRCx adjustable parameter includes the following:

- HW supply temperature set point reset threshold (*hwst_reset_threshold*) = 10°F.

Low HW loop delta-T AIRCx adjustable parameters include the following:

- Desired delta-T (*desired_delta_t*) = 20°F
- Delta-T threshold (*delta_t_threshold*) = 10°F.

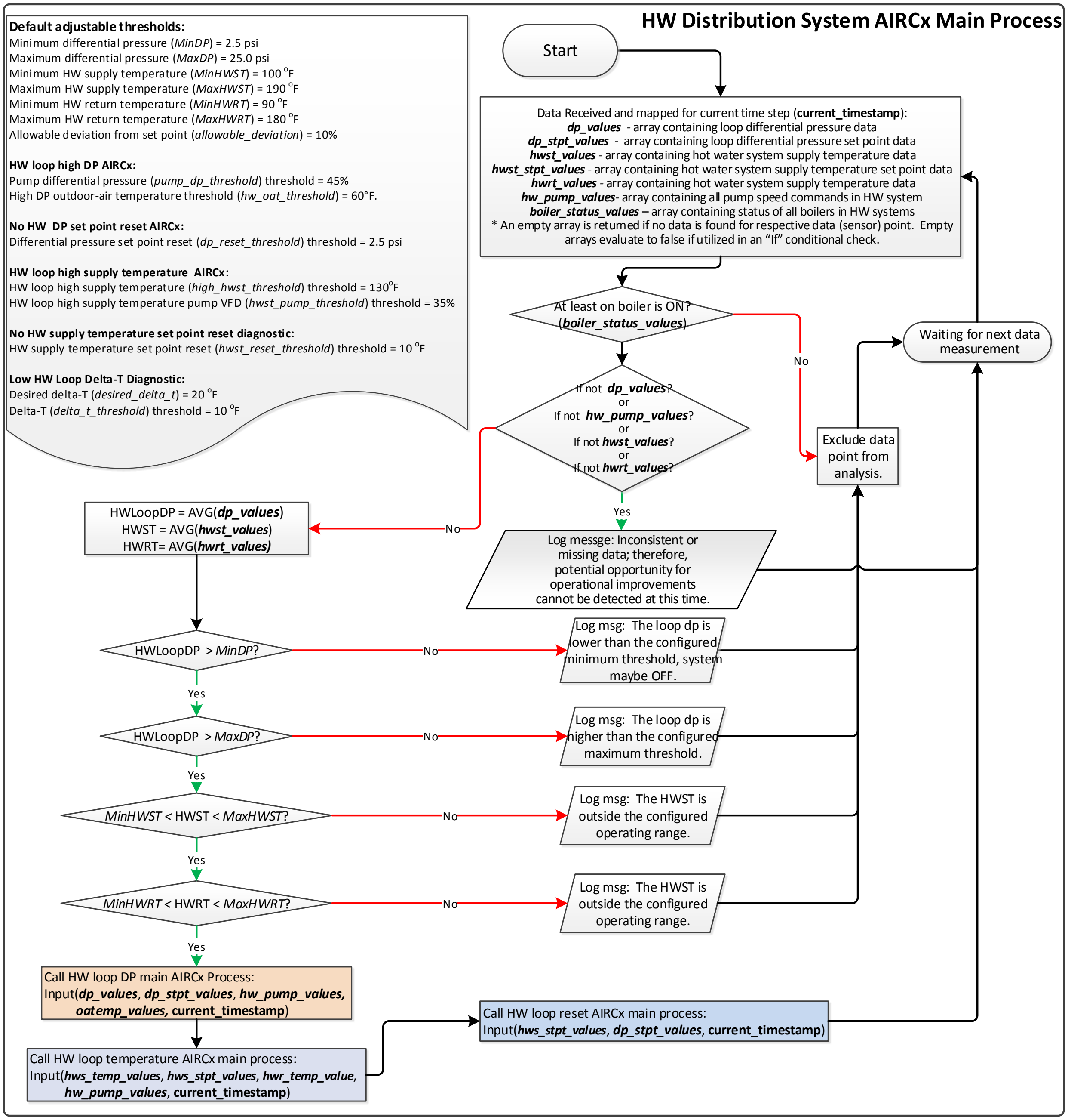

Figure 4.1. Flow Chart for the HW Distribution System AIRCx Main Process

Figure 4.2, Figure 4.3, and Figure 4.4 contain three diagnostic processes from within the HW distribution system AIRCx main process. These functions verify whether any faults exist in the set point of the HW loop DP or the set point of the HW distribution system supply water temperature, and whether a HW supply temperature set point reset and HW DP set point reset are being utilized, respectively.

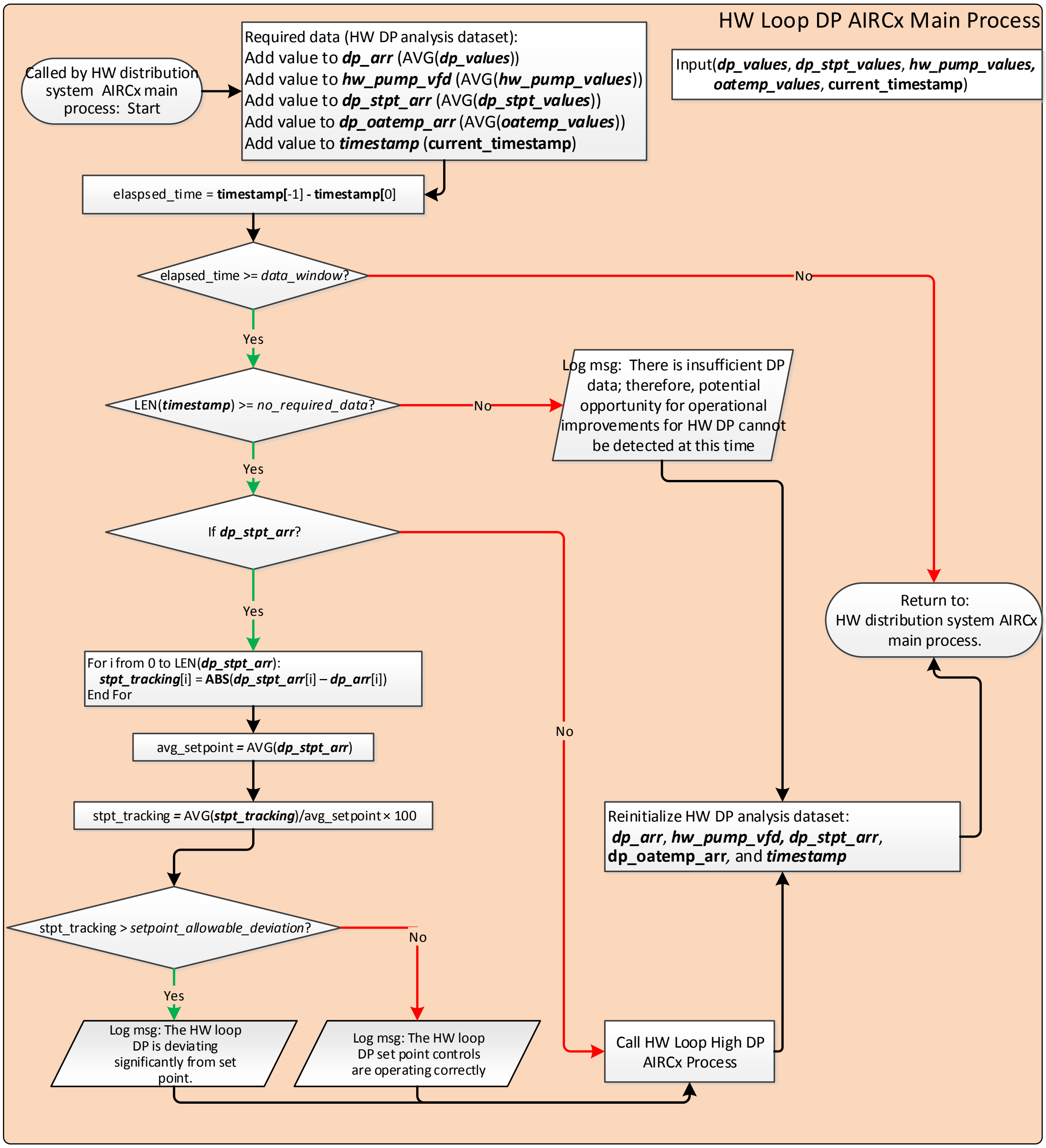

Figure 4.2. Flow Chart for HW Loop DP AIRCx Main Process

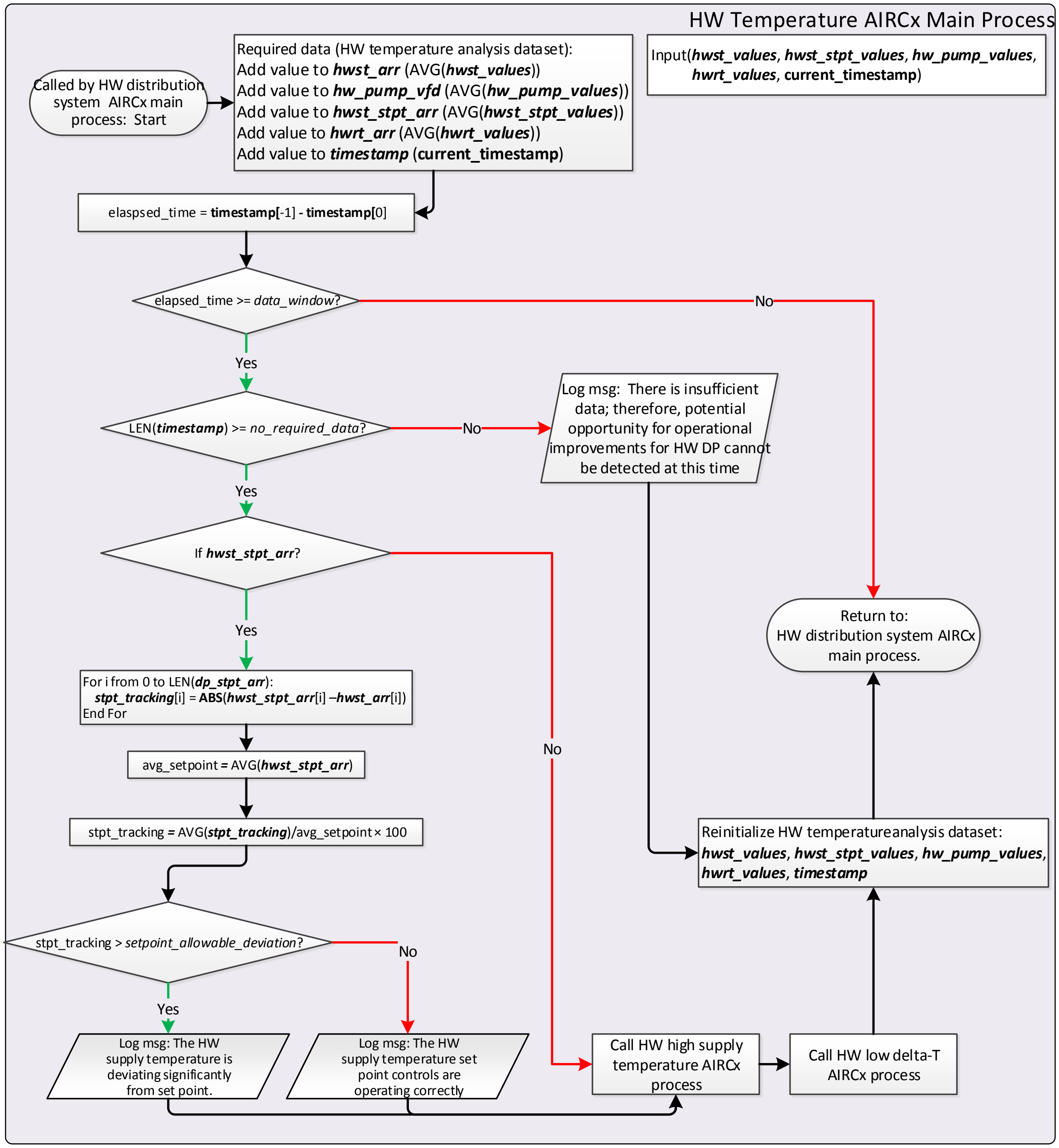

Figure 4.3. Flow Chart for HW Temperature AIRCx Main Process

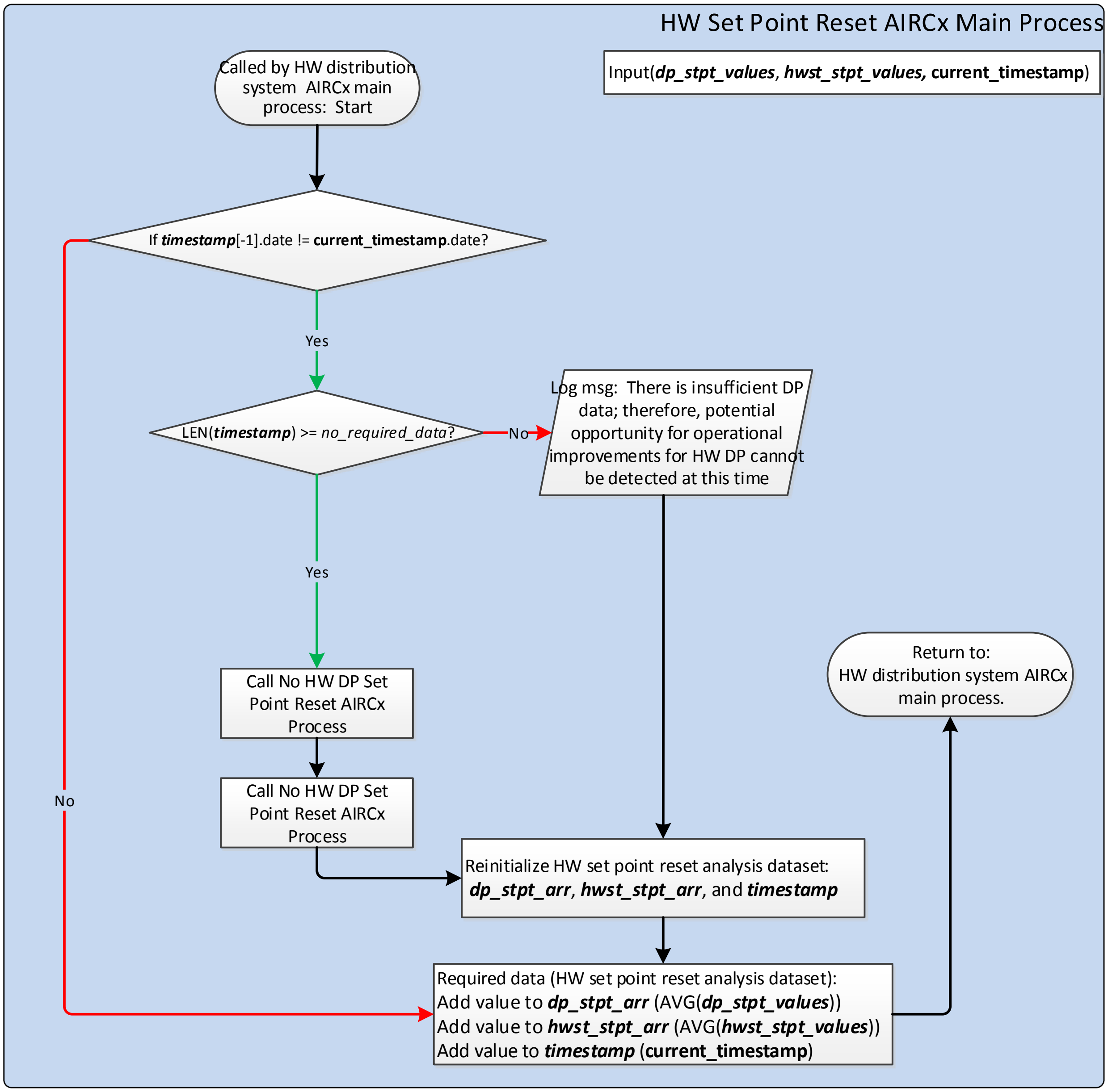

Figure 4.4. Flow Chart for HW Set Point Reset AIRCx Main Process

4.2 HW Loop High Differential Pressure AIRCx Process

The purpose of the high HW loop DP diagnostic is to identify conditions when the HW system loop DP is too high. The loop DP for a HW system is the primary feedback for HW pump VFD control. When demand for heating, typically terminal box reheat for commercial buildings, and/or demand for HW provided by the boiler is low, it is not necessary to maintain the loop DP at the design (maximum) setting. Often, the loop DP is not reset to match building loads, outdoor conditions, or some other parameter that indicates the HW needs of the building. Sometimes, if a DP reset is implemented, it is not aggressive, and there is still room to further lower the loop DP while meeting the heating needs of the building.

When a HW system is running, the pump VFD command coupled with the outdoor-air temperature can be used to validate whether the HW loop DP is too high. When the average value for the pump VFD command is greater than a given threshold value and the outdoor-air temperature is greater than a given threshold, the diagnostic will alert the building operator/user that a re-tuning opportunity exists.

4.2.1 Monitored Data for HW Loop High Differential Pressure AIRCx

This section describes the required input data for the HW loop high differential pressure AIRCx process. The following data points are required for the execution of this diagnostic.

Input data from BACnet driver interface or text CSV:

- All HW distribution system pump VFD speed commands from the VFD controllers (or BAS) (***hw_pump_values***).
- Outdoor-air temperature at each time step of the analysis data set (***dp_oatemp_arr***).
- Timestamp at each time step of the analysis dataset (***timestamp***).

Calculated values:

- The average of all HW distribution system pump VFD speed commands at each time step of the analysis dataset (***hw_pump_vfd***).

4.2.2 HW Loop High Differential Pressure AIRCx Diagnostic Process

This section provides the steps for the HW loop high differential pressure AIRCx process including a detailed flow chart (Figure 4.5).

The following steps are used to detect the re-tuning opportunity (Step 1 and Step 2 in this diagnostic occurs in the HW loop DP AIRCx main process but is included here to add clarity to the AIRCx process).

1. Calculate the elapsed time (elapsed_time) in the analysis dataset:
    - elapse_time = ***timestamp***[-1] – ***timestamp***[0]
2. If elapsed_time >= *data_window*,
    - If LEN(***timestamp***) > *no_required_data*,
        - The required elapsed time for the AIRCx process has elapsed and there is sufficient data to perform the AIRCx process.
        - Proceed to Step 3.
    - Else,
        - The required elapsed time for the AIRCx process has elapsed but there is insufficient data to perform the AIRCx process.
        - Generate diagnostic message: There is insufficient data; therefore, potential opportunity for operational improvements cannot be detected at this time.
        - Proceed to Step 7.

    Else,

    - The required elapsed time for the AIRCx process has not elapsed.

- Proceed to Step 8.

3. Calculate the average HW loop pump VFD commands in the current HW DP analysis dataset (avg_pump_vfd):

   - avg_pump_vfd = AVG(***hw_pump_vfd***).

4. If avg_pump_vfd > *pump_dp_threshold*,

   - Proceed to Step 5.

   Else,

   - Generate diagnostic message: The differential pressure for the hot water distribution system is not high.
   - Proceed to Step 7.

5. Calculate the average outdoor-air temperature for the analysis data set:

   - avg_oatemp = AVG(***dp_oatemp_arr***)

6. If avg_oatemp > *hw_oat_threshold*,

   - Generate diagnostic message: The HW loop DP has been detected to be too high.
   - Proceed to Step 7.

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

8. Return to the HW loop DP AIRCx main process.

The default but adjustable thresholds and parameters for this diagnostic are as follows:

- *pump_dp_threshold* = 45%
- *hw_oat_threshold* = 60°F
- *data_window* = 60 minutes
- *no_required_data* = 20.

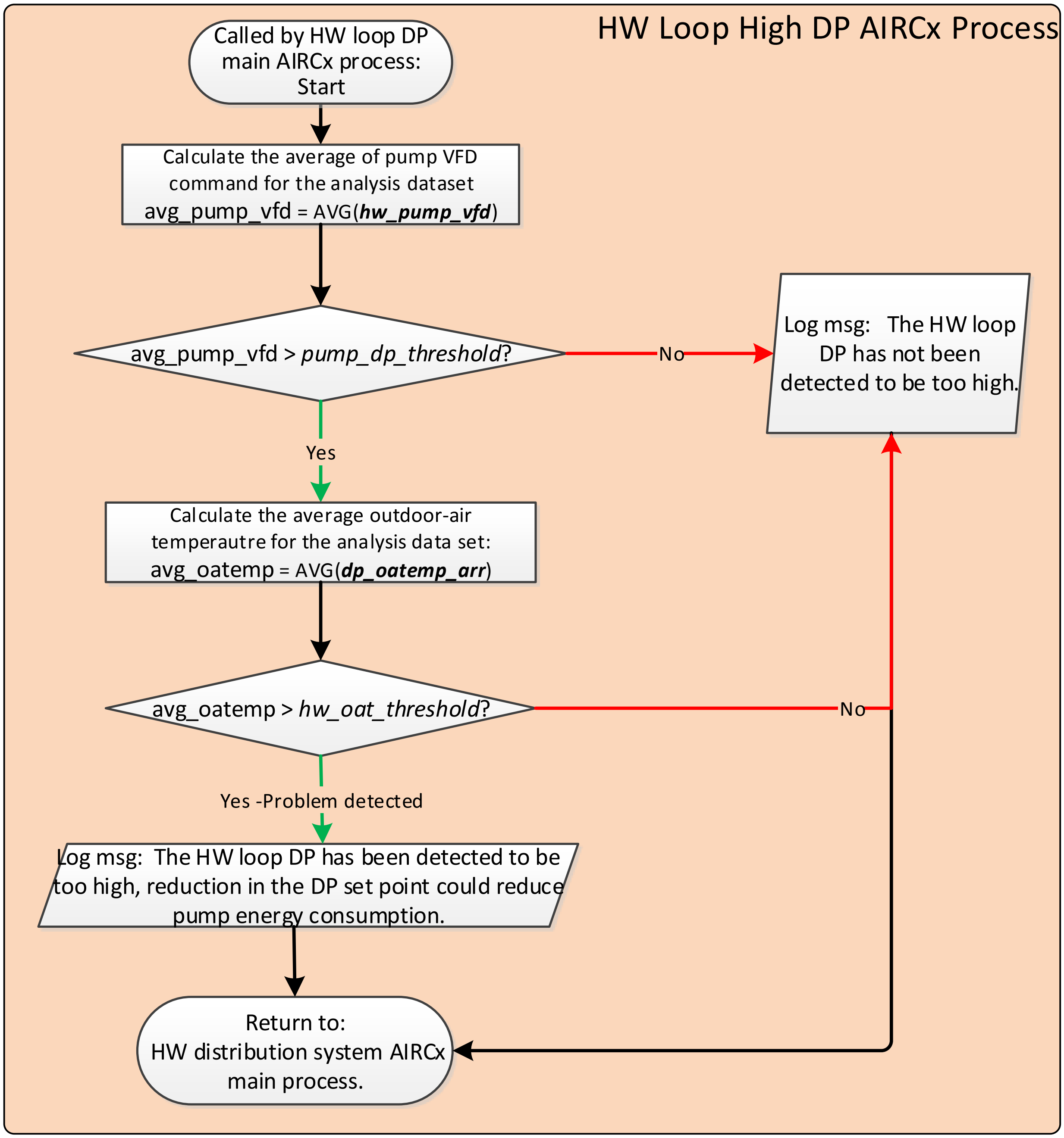

Figure 4.5. Flow Chart for the HW Loop High Differential Pressure AIRCx Process

4.3 No HW DP Set Point Reset AIRCx Process

The purpose of the HW DP set point reset AIRCx process is to identify conditions under which the HW loop DP is constant even when the heating loads on the building change. If the HW loop DP set point does not change over time—to match some condition indicative of the HW needs of the building (e.g., outdoor-air temperature, zone reheat valve)—then opportunities to save energy will be lost and the building equipment will incur increased wear.

When the HW system is ON, if the loop DP set point is not resetting to match the systems loads, the pumps are usually running at higher speeds and consuming more energy than would otherwise be required.

4.3.1 Monitored Data for No HW DP Set Point Reset AIRCx

This section describes the required input data for the no HW loop high DP set point reset AIRCx process. The following data points are required for the execution of this diagnostic.

Input data from BACnet driver interface or text CSV:

- HW loop DP set point (***dp_stpt_arr***) for each time step of the analysis data set.
- Timestamp at each time step of the analysis dataset (***timestamp***).

4.3.2 No HW DP Set Point Reset AIRCx Diagnostic Process

This section provides the steps for the no HW loop DP set point reset AIRCx process including a detailed flow chart (Figure 4.6). This diagnostic is executed daily, at midnight, to ensure accurate results and allow sufficient time for variation in the HW loop DP set point to occur.

The following steps are used to detect the opportunity (Step 1 occurs in the HW set point reset AIRCx main process but is included here to add clarity to the AIRCx process).

1. Upon the completion of day (i.e., midnight):
   - If LEN(***timestamp***) > no_required_data,
     - Proceed to Step 2.
   - Else,
     - Generate diagnostic message: There is insufficient data; therefore, potential opportunity for operational improvements cannot be detected at this time.
     - Proceed to Step 3.
2. Check if the HW loop DP set point varies throughout a day.
   - If MAX(***dp_stpt_arr***) – MIN(***dp_stpt_arr***) < *dp_reset_threshold*,
     - Generate diagnostic message: No HW DP reset is detected for this time period; this may result in excess energy consumption.
     - Proceed to Step 3.
   - Else,
     - Generate diagnostic message: The HW loop DP is being reset for this period.
     - Proceed to Step 3.
3. Make the diagnostic message(s) available to the operator.
4. Return to the HW set point reset AIRCx main process.

The default but adjustable thresholds and parameters for this diagnostic are as follows:

- *dp_reset_threshold* = 2.5 psi

- *no_required_data* = 20.

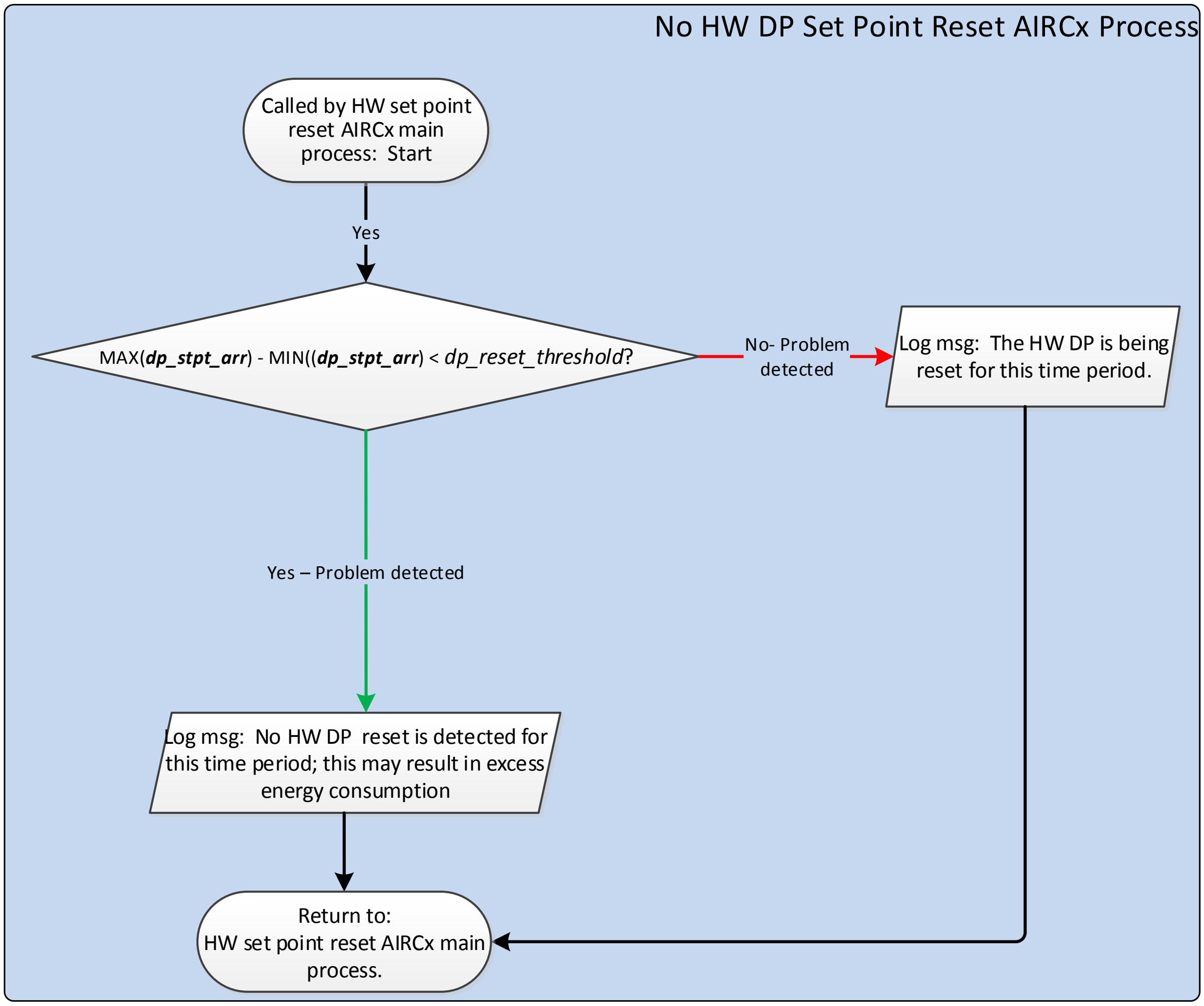

Figure 4.6. Flow Chart for the HW Loop Differential Pressure Set Point Reset AIRCx Process

4.4 HW High Supply Temperature AIRCx Process

The purpose of the high HW supply temperature diagnostic is to identify conditions when the HW supply temperature is higher than needed to satisfy the heating load for the building. When this is the case, there is an opportunity to lower the HW supply temperature set point and improve the efficiency of the system. Often, this opportunity can be diagnosed by monitoring the HW pump VFD signal(s). If these pumps are operating at low speeds, this often indicates excess heating capacity.

When the average value for the HW pump VFD signal is less than a minimum threshold and the HW supply temperature is greater than a minimum value, the diagnostic will alert the building operator/user to lower the HW supply temperature set point to improve the operational efficiency of the building.

4.4.1 Monitored Data for HW High Supply Temperature AIRCx

This section describes the required input data for the HW high supply temperature AIRCx process. The following data points are required for the execution of this diagnostic.

Input data from BACnet driver interface or text CSV:

- All HW distribution system pump VFD speed commands from the VFD controllers (or BAS) (***hw_pump_values***).
- HW loop supply temperature (***hwst _arr***) at each time step of the analysis data set.
- Timestamp at each time step of the analysis dataset (***timestamp***).

Calculated values:

- The average of all HW distribution system pump VFD speed commands at each time step of the analysis dataset (***hw_pump_vfd***).

4.4.2 HW High Supply Temperature AIRCx Diagnostic Process

This section provides the steps for the HW high supply temperature AIRCx process including a detailed flow chart (Figure 4.7).

The following steps are used to detect the re-tuning (Step 1 and Step 2 in this diagnostic occurs in the HW temperature AIRCx main process but is included here to add clarity to the AIRCx process).

1. Calculate the elapsed time (elapsed_time) in the analysis dataset:
   - elapse_time = ***timestamp***[-1] – ***timestamp***[0].
2. If elapsed_time >= *data_window*,
   - If LEN(***timestamp***) > *no_required_data*,
     - The required elapsed time for the AIRCx process has elapsed and there is sufficient data to perform the AIRCx process.
     - Proceed to Step 3.
   - Else,
     - The required elapsed time for the AIRCx process has elapsed but there is insufficient data to perform the AIRCx process.
     - Generate diagnostic message: There is insufficient data; therefore, potential opportunity for operational improvements cannot be detected at this time.
     - Proceed to Step 5.

   Else,

   - The required elapsed time for the AIRCx process has not elapsed.
   - Proceed to Step 6.
3. Calculate the average HW pump VFD command (avg_pump_speed) for the current HW temperature analysis dataset:

- avg_pump_speed = AVG(***hw_pump_vfd***).

4. Calculate the average HW supply temperature (avg_hwst) for the current HW supply temperature analysis dataset:

   - If avg_pump_speed < *hwst_pump_threshold* and avg_hwst > *high_hwst_threshold*,
     - Generate diagnostic message: The HW loop supply temperature has been detected to be too high.
     - Proceed to Step 5.
   - Else,
     - Generate diagnostic message: The HW distribution system supply water temperature is not high, no problem detected for the HW high supply temperature AIRCx process.
     - Proceed to Step 5.

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

6. Return to the HW temperature AIRCx main process.

The default but adjustable thresholds and parameters for this diagnostic are as follows:

- *high_hwst_threshold* = 130°F
- *hwst_pump_threshold* = 35%
- *data_window* = 60 minutes
- *no_required_data* = 20.

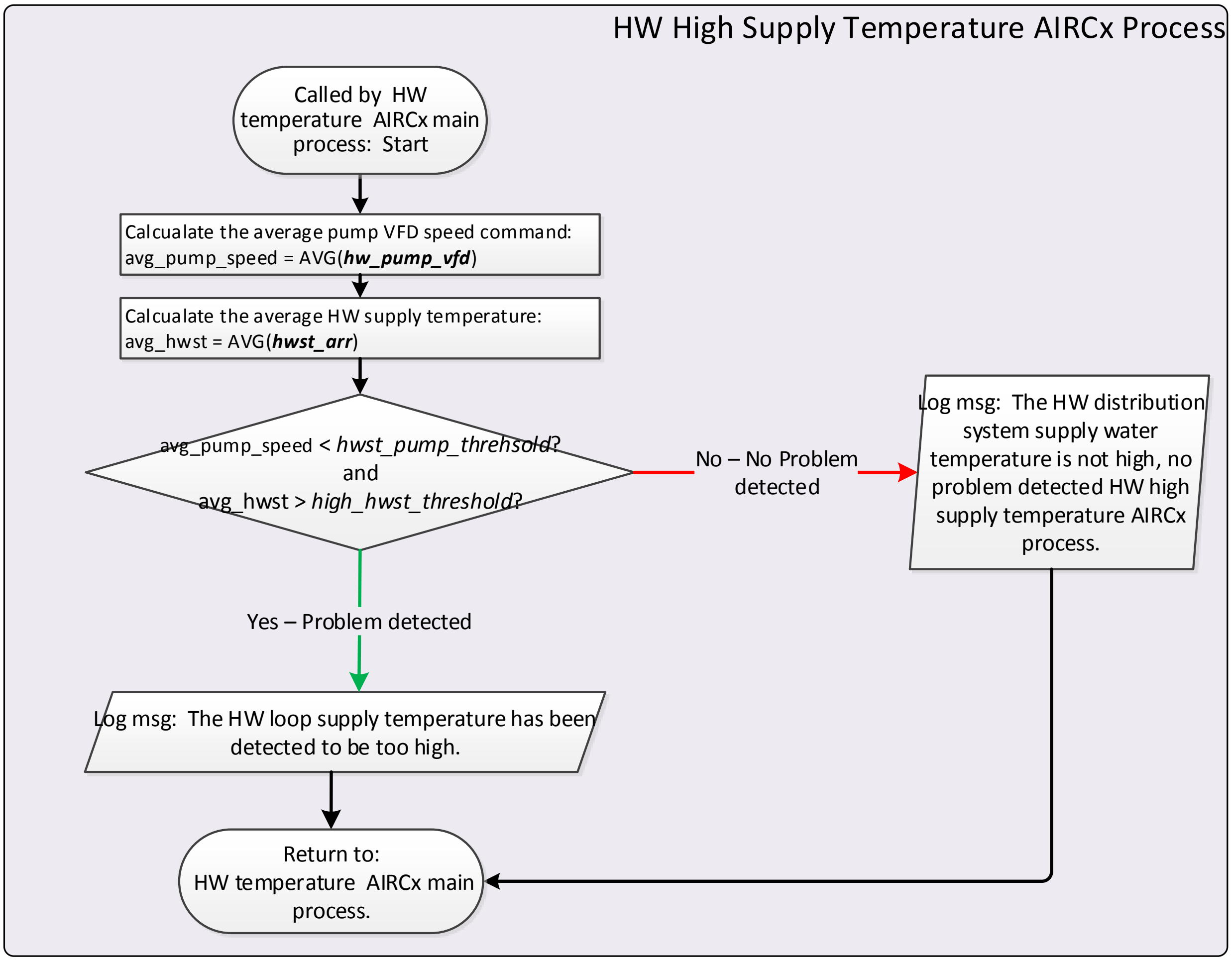

Figure 4.7. Flow Chart for the HW High Supply Temperature AIRCx Process

4.5 No HW Supply Temperature Set Point Reset AIRCx Process

The purpose of the no HW loop temperature reset AIRCx process is to identify conditions under which the boiler supply temperature set point does not appear to be reset (or is constant). Care should be taken when employing a HW supply temperature reset on non-condensing boilers due to possible damage to boilers from condensation in the flue stacks that are corrosive.

When a HW system is ON, the boiler's supply temperature set point value should automatically adjust to internal/external conditions that will allow the boiler to operate more efficiently. The HW supply temperature set point is reset based on some measureable condition that is indicative of the HW needs of the building. When the HW supply set point value is consistently constant (at the same values) for a specified period of time and during low load conditions, which otherwise would be advantageous for lower HW supply temperature set points, the diagnostic will alert the building operator/user that a re-tuning opportunity exists.

Enabling the HW supply temperature reset or creating one will increase energy efficiency and possible occupant comfort. Failure to investigate or correct or mitigate, in all likelihood, will lead to increased energy consumption and excess equipment wear and tear. Figure 4.8 shows an example of conditions that indicate no HW supply temperature reset. The HW supply temperature set point is constant regardless of the outdoor-air conditions.

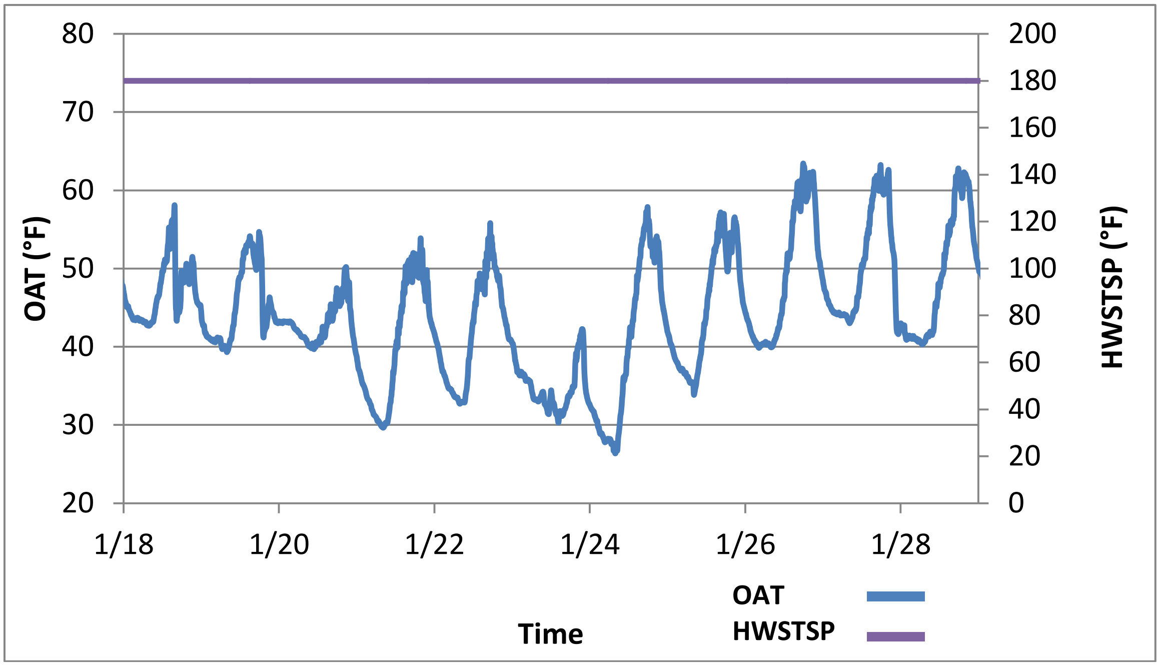

Figure 4.8. Example of Bad Operation – HW Supply Temperature Set Point is Constant at 180°F when the Outdoor-air Temperature Varies from 25°F to 65°F

Figure 4.9 shows an example of good operations. The HW supply temperature is reset based on the outdoor-air temperature.

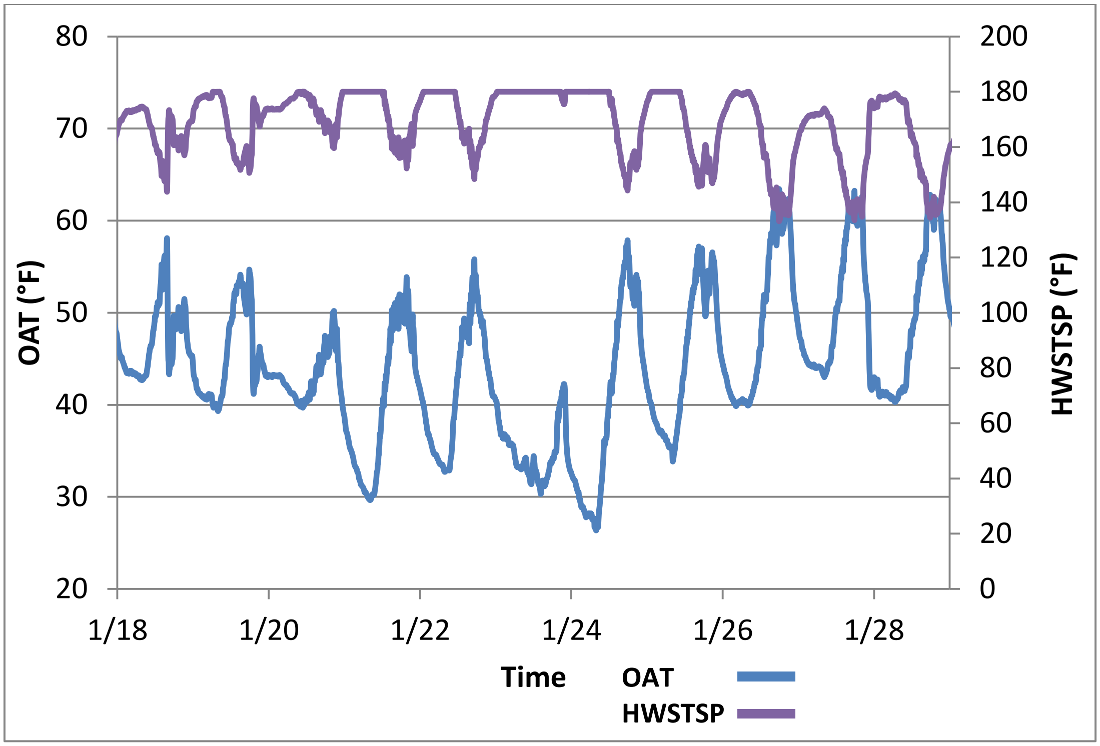

Figure 4.9. Example of Good Operations – The HW Supply Temperature Set Point Is Reset Based on Outdoor-air Temperature

4.5.1 Monitored Data for No HW Loop Supply Temperature Reset AIRCx Process

This section describes the required input data for the no HW loop supply temperature reset AIRCx process. The following data point is required for the execution of this diagnostic.

Input data from the BACnet driver interface or text CSV:

- HW loop supply temperature set point (***hwst_stpt_arr***) each time step of the analysis data set.
- Timestamp at each time step of the analysis dataset (***timestamp***).

4.5.2 No HW Loop Supply Temperature Set Point Reset AIRCx Process

This section provides the steps for the no HW loop supply temperature set point reset AIRCx process including a detailed flow chart (Figure 4.10). This diagnostic is executed daily, at midnight, to ensure accurate results and allow sufficient time for variation in the HW loop supply temperature set point to occur.

The following steps are used to detect the opportunity (Step 1 occurs in the HW set point reset AIRCx main process but is included here to add clarity to the AIRCx process).

1. Upon the completion of day (i.e., midnight):
   - If LEN(***timestamp***) > *no_required_data*,
     – Proceed to Step 2.

- Else,
  - Generate diagnostic message: There is insufficient data; therefore, potential opportunity for operational improvements cannot be detected at this time.
  - Proceed to Step 3.

2. Check if the HW loop DP set point varies throughout a day,
   - If MAX(***hwst_stpt_arr***) – MIN(***hwst_stpt_arr***) < *hwst_reset_threshold*,
     - Generate diagnostic message: No HW supply temperature set point reset is detected for this time period; this may result in excess energy consumption.
     - Proceed to Step 3.
   - Else,
     - Generate diagnostic message: The HW supply temperature set point is being reset for this period.
     - Proceed to Step 3
3. Make the diagnostic message(s) available to the operator.
4. Return to the HW set point reset AIRCx main process.

The default but adjustable thresholds and parameters for this diagnostic are as follows:

- *hwst_reset_threshold* = 10°F
- *data_window* = 60 minutes
- *no_required_data* = 20.

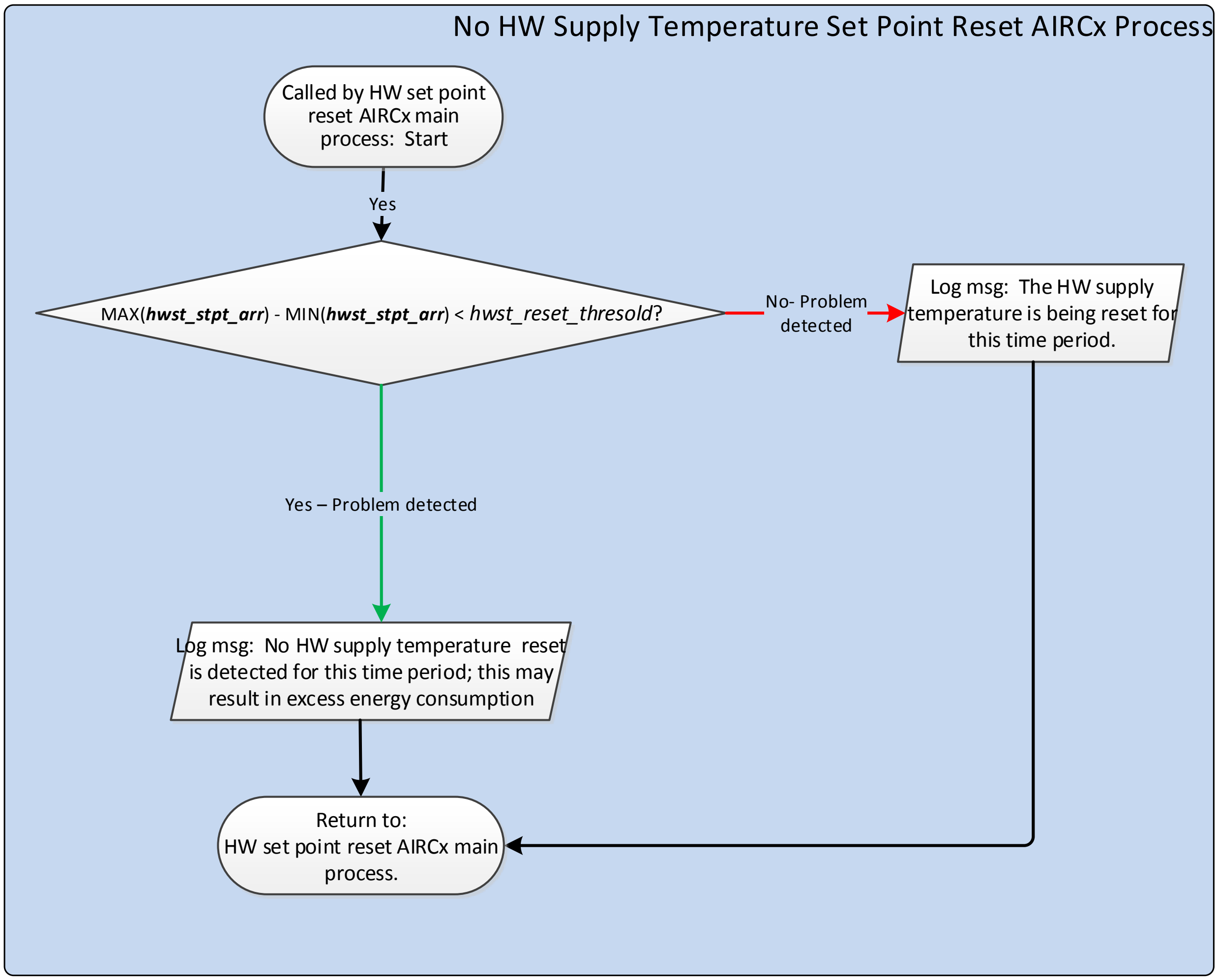

Figure 4.10. Flow Chart for the No HW Supply Temperature Set Point Reset AIRCx Process

4.6 Low HW Loop Delta-T AIRCx Process

The purpose of the low HW loop delta-T diagnostic is to identify conditions under which the difference between the HW supply and return temperatures is lower than expected.

When a HW system is ON, delta-T values can be used to determine the overall effectiveness of the building HW system. When the delta-T values are consistently below expected values, indicative of inefficient operations, the diagnostic algorithm will alert the building operator/user that the delta-T values for the HW loop are below the “optimal” operational value.

When the average difference between the building HW supply and return temperatures has reduced below a threshold value, this diagnostic will alert the building operator/user that a re-tuning opportunity exists. Figure 4.11 shows an example of poor operations with respect to the HW loop delta-T. The difference between the HW supply temperature and the HW return temperature is less than 10°F.

If the difference between the HW supply and return temperature is low (less than 10°F), this could indicate that the HW supply temperature set point is too high or demand for HW is low (i.e., partial load conditions). If the HW loop high supply temperature AIRCx process, described in Section 4.4 of this report, finds that the hot-water loop supply temperature is too high, then lowering the HWST set point should mitigate these operational issues and increase the efficiency of the HW system.

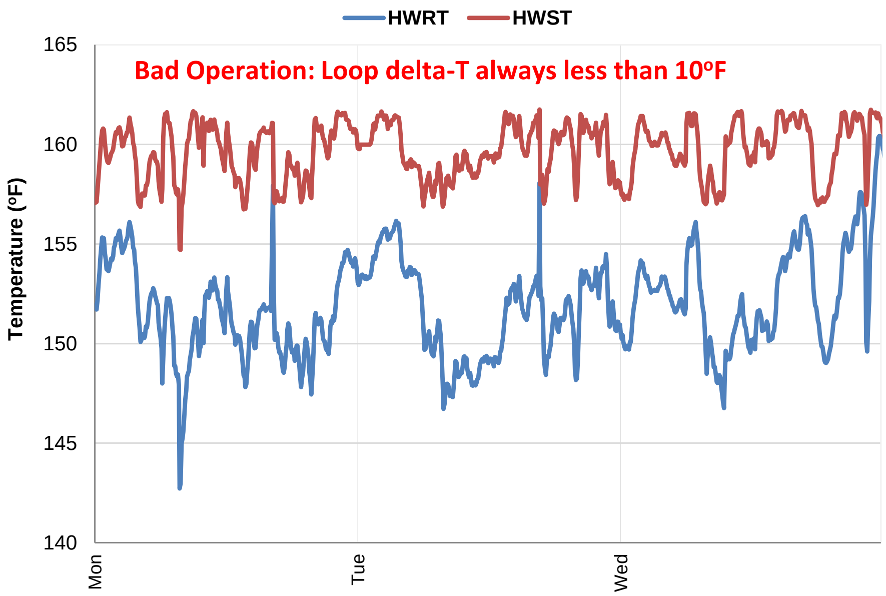

Figure 4.11. Example of Bad Operations of HW System with Respect to Low Delta-T

Figure 4.12 shows an example of good operations with respect to the HW loop delta-T. The difference between the HW supply and HW return temperature is approximately 20°F.

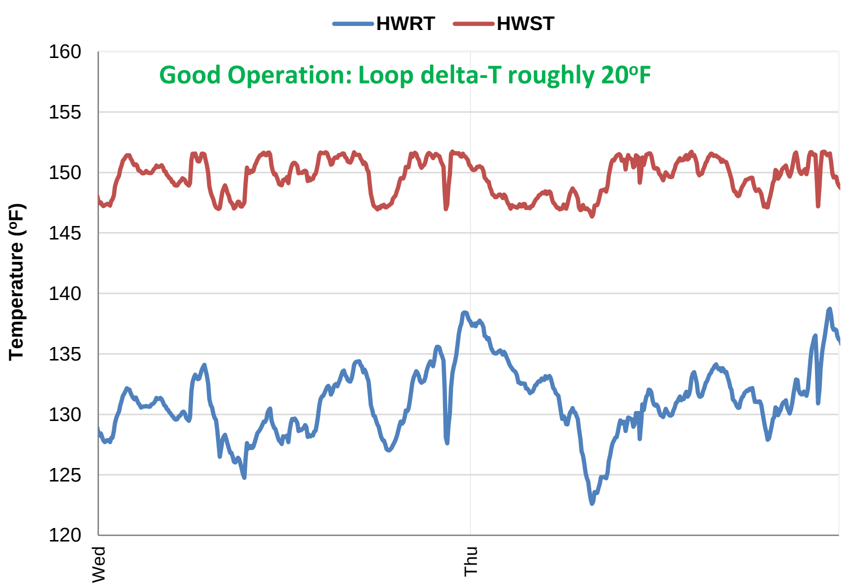

Figure 4.12. Example of Good Operations of HW System with Respect to Low Delta-T

4.6.1 Monitored Data for Low HW Loop Delta-T Diagnostic

This section describes the required input data for the low HW loop delta-T AIRCx process.

Input data from the BACnet driver interface or text CSV:

- HW loop supply temperature (***hwst_arr***) at each time step of the analysis data set.
- HW loop return temperature (***hwsr_arr***) at each time step of the analysis data set.
- Timestamp at each time step of the analysis dataset (***timestamp***).

4.6.2 Re-tuning Diagnostic Low HW Loop Delta-T AIRCx Diagnostic Process

This section provides the steps for the low HW loop delta-T AIRCx process including a detailed flow chart (Figure 4.13).

The following steps are used to detect the re-tuning (Step 1 and Step 2 in this diagnostic occurs in the HW temperature AIRCx main process but is included here to add clarity to the AIRCx process).

1. Calculate the elapsed time (elapsed_time) in the analysis dataset:
   - elapse_time = ***timestamp***[-1] – ***timestamp***[0].
2. If elapsed_time >= *data_window*,
   - If LEN(***timestamp***) > *no_required_data*,
     - The required elapsed time for the AIRCx process has elapsed and there is sufficient data to perform the AIRCx process.
     - Proceed to Step 3.
   - Else,
     - The required elapsed time for the AIRCx process has elapsed but there is insufficient data to perform the AIRCx process.
     - Generate diagnostic message: There is insufficient data; therefore, potential opportunity for operational improvements cannot be detected at this time.
     - Proceed to Step 5.

   Else,
   - The required elapsed time for the AIRCx process has not elapsed.
   - Proceed to Step 6.
3. Calculate the average of difference between the HWST and the HWRT (avg_delta_t):
   - For i from 0 to LEN(***timestamp***):
     - ***delta_t***[i] = ***hwst_arr***[i] – ***hwrt_arr***[i]
   - End For
   - avg_delta_t = AVG(***delta_t***)
   - Proceed to Step 4.
4. If *desired_delta_t* – avg_delta_t > *delta_t_threshold*,
   - Generate diagnostic message: The HW loop delta-T is detected to be too low.
   - Proceed to Step 5.

Else,

- Generate diagnostic message: The HW loop delta-T is not low. No problem detected for HW loop low delta-T AIRCx process.
- Proceed to Step 5.

5. Make the diagnostic message(s) available to the operator.
6. Return to the HW temperature AIRCx main process.

The default but adjustable thresholds and parameters for this diagnostic are as follows:

- *desired_delta_t* = 20°F
- *delta_t_threshold* = 10°F
- *data_window* = 60 minutes
- *no_required_data* = 20.

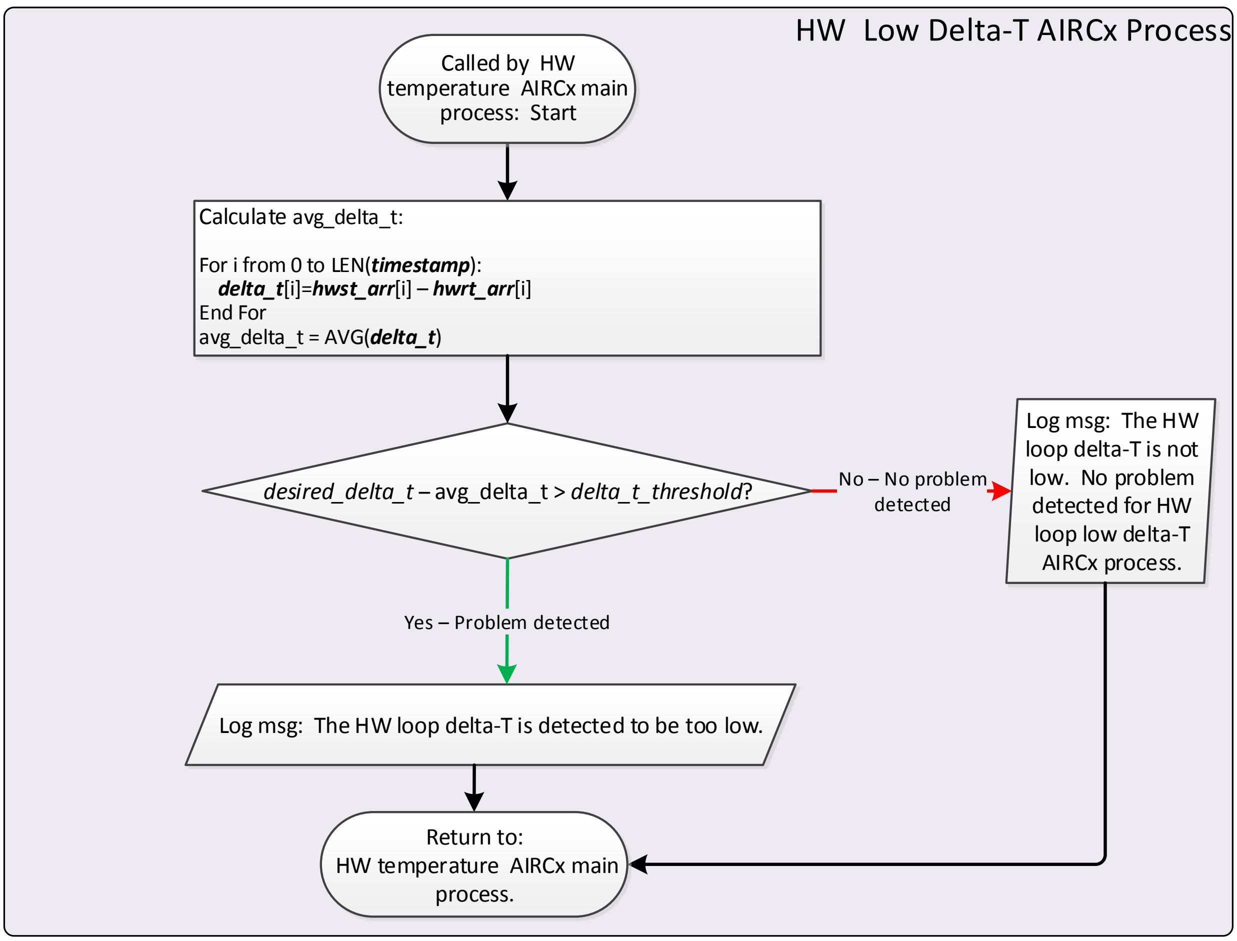

Figure 4.13. Flow Chart for the HW Loop Low Delta-T AIRCx Process

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