Automated Proactive Techniques for Commissioning Air-Handling Units

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Lack of or improper commissioning, the inability of the building operators to grasp the complexity controls, and lack of proper maintenance lead to inefficient operations and reduced lifetimes of equipment. If regularly scheduled manual maintenance or re-commissioning practices are adopted, they can be expensive and time consuming. Automated proactive commissioning and diagnostic technologies applied to parts of the commissioning process address two of the main barriers to commissioning: cost and schedules. Automated proactive commissioning and diagnostic tools can reduce both the cost and time associated with commissioning, as well as enhance the persistence of commissioning fixes. In the long run, automation even offers the potential for automatically correcting problems by reconfiguring controls or changing control algorithms dynamically. This paper discusses procedures and processes that can be used to automate and continuously commission the economizer operation and outdoor-air ventilation systems of an air-handling unit. [DOI: 10.1115/1.1591800]

1 Introduction

Many buildings today use sophisticated building automation systems (BASs) to manage a wide and varied range of building systems. Although the capabilities of BASs have increased over time, many buildings still are not properly commissioned, operated or maintained. Lack of commissioning, improper operating practices and lack of proper maintenance lead to inefficient operation, excess expenditures on energy, poor indoor conditions, and reduced lifetimes for equipment. A study of 60 commercial buildings [1] found that more than half of them suffered from control problems. In addition, 40% had problems with the heating, ventilation, and air conditioning (HVAC) equipment, and one-third had sensors that were not operating properly.

Effective maintenance and re-commissioning extends equipment life, maintains comfort, improves equipment availability, and results in fewer complaints from building occupants. Unfortunately, the time required and expense of manual maintenance or re-commissioning often lead to their reduction or elimination in times of budgetary pressure, exacerbating the problems.

Automated commissioning and diagnostic technologies potentially address these two significant barriers to good maintenance and commissioning. Automated proactive commissioning tools can reduce both the cost and time associated with commissioning, as well as enhance the persistence of fixes implemented during commissioning. In the long run, automation even offers the potential for automatically correcting problems by reconfiguring controls or changing control algorithms dynamically.

In this paper, we describe methodologies for automated proactive commissioning for air-handling units (AHUs). Some basic concepts are introduced in Section 2. The automated proactive commissioning process is then described in Section 3. Examples of proactive commissioning for air-handler components are provided in Section 4, and the importance and impacts of thresholds and tolerances are discussed in Section 5, followed by conclusions and recommendations in Section 6 and a list of references.

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2 Concepts and Terminology

2.1 Continuous Commissioning[1] Versus Automated Proactive Commissioning. *Commissioning* is a systematic process by which proper installation and operation of building systems and equipment are checked and when necessary, adjusted to improve performance. Well-done commissioning begins during design, continues through construction (remodeling or retrofit), and includes establishment of a good preventative maintenance program [1,2]. It applies equally to new construction and existing buildings, and when applied to existing buildings, is often referred to as *retro-commissioning*.

Continuous commissioning, like commissioning, is a systematic process to identify and correct building system problems and optimize system performance in existing buildings, the primary distinction being that it incorporates performance monitoring and periodic maintenance based on measured performance. Without maintenance, the performance of well-commissioned systems will deteriorate over time. Ensuring the persistence of the performance improvements from commissioning is the key difference between continuous commissioning and start-up or retro-commissioning.

Continuous commissioning addresses these problems and their re-occurrence. As practiced today, however, it involves periodic review of monitored results and manual diagnosis of anomalous behavior [3]. This process can require additional labor and special expertise, increasing the costs of a process that is already difficult to sell to building owners and developers.

Automation may provide a means by which to reduce these costs while at the same time improving the process. By transferring menial activities from humans to computers, embedding knowledge in computer software, and having these tools monitor, evaluate, and when needed diagnose building operation, commissioning may be made less costly, yet more effective. Fully *automated proactive commissioning* would entail essentially conducting the entire process at the push of a button (or automatically without even pushing a button). Semi-automated proactive commissioning would be slightly less automated, involving automa-

[1]Continuous Commission is as service mark of Energy Systems Laboratory, Texas A&M University.

tion of parts of the commissioning process while still requiring human intervention and involvement for activities requiring human judgment or for which automation is too difficult to be cost effective. For a more detailed comparison of the manual commissioning and automated proactive commissioning see Katipamula et al. [4].

Although automated proactive commissioning will ensure persistence of optimal operation, it is not a substitute for some of the start-up commissioning activities that should be performed during the installation of building systems. Many functional tests, however, that are routinely performed as part of start-up commissioning can be automated and frequently performed to maintain optimal operation. These actives include ensuring proper sequence of operations, checking energy-saving control strategies (e.g., proper economizer operation), maintaining proper set points (e.g., for temperature and pressure), ensuring that heating and cooling do not occur simultaneously, ensuring proper ventilation is provided at all occupied times, and ensuring that sensors are calibrated and installed properly. All these represent potential targets for automation.

2.2 AFDD as an Enabler for Automated Proactive Commissioning. *Automated fault detection and diagnosis (AFDD)* is an automatic process by which faulty operation, degraded performance, and broken components are detected and understood. For example, the temperature of the supply air provided by an air-handling unit might be observed to be chronically high during hot weather. This conclusion can be drawn by visually inspecting a time series plot of the supply-air temperature. Alternatively, a computer algorithm could process this data on a continuous basis, reach this same conclusion, and report the condition to the operator.

Automated diagnostics generally goes a step further than simply detecting for ''out-of-bounds'' problems. In this air-handler example, an AFDD system that constantly monitors the temperature and humidity of the outside air, return air, mixed air, and supply air, as well as the status of the supply fan, hot-water valve, and chilled-water valve of the air handler, might conclude that the outside-air damper is stuck fully open. As a result, during hot weather, too much hot and humid outdoor air is brought in, increasing the mechanical cooling required and at many times, exceeding the capacity of the mechanical cooling system. As a result, the supply-air temperature is chronically high. This is an example of how AFDD might work, but we have yet to integrate it into a commissioning process.

Commissioning (new buildings) and retro-commissioning (existing buildings) generally involve functional tests conducted to determine whether equipment and systems are operating properly. Continuing the air-handler example, a test during commissioning would likely reveal that the outdoor-air damper is stuck fully open. These tests generally are only performed during the discrete activity of commissioning, at the start-up of a new building or during retro-commissioning of an existing building. To pass the commissioning process, the stuck damper (and other problems) must be repaired and proper operation verified by observation or repeating the functional test. This process, however, does not ensure that the equipment continues to function properly in the future. A damper may stop working properly at any time for any of a variety of reasons (e.g., a piece of wood is blown into the damper during high winds and gets lodged in the blades, the fix of the damper was only temporary and failed, someone introduced an error into the control code for this damper while trying to correct some other operational problem, a corroded wire broke, or the damper actuator wore out). Only by continuously monitoring the status of equipment and its performance can proper operation be ensured on a continuous basis. An AFDD system monitoring this damper would detect a new operation problem when it occurs and report that failure and its cause to the building operation team.

As with discrete commissioning, repair usually requires intervention by humans. So, with the stuck damper, in response to the information from the AFDD system, a repair person inspects the damper, verifies the actual cause of the problem, and fixes it. The AFDD system can then automatically verify that the problem was fixed without an operator or service technician manually performing the test for verification. The AFDD system is central to this proactive commissioning process by constantly watching the equipment and identifying if, when, and how it degrades in performance or fails. The human operator and repair person remain critical to completing the commissioning cycle, but without the automated system monitoring continuously, these sorts of problems can go undetected for days, week, months, or even years.

2.3 Passive Versus Proactive Fault Detection and Diagnosis. Functional tests performed during commissioning are generally proactive procedures aimed at determining whether equipment and systems are installed and operating properly [2]. These tests generally involve observing changes in equipment as it operates or collecting data after instigating changes in parameters in control code (e.g., artificially overriding the value of a temperature measurement with one designed to instigate a behavior to be tested) and then analyzing the resulting data to determine whether equipment performance meets specifications and expectations.

Most AFDD applications developed to date use data collected by passively monitoring operation. They do not initiate tests automatically to cause operational excursions. As a result, the system must wait weeks or months, even changes in season, before the diagnostic system experiences a full range of operating conditions. *Proactive diagnostics* involve automatically initiating changes to cause or to simulate operating conditions that may not occur for some time, thus producing results that might not be available for months otherwise. Such tests could be automated to cover a complete range of conditions or to deepen diagnosis beyond what might be possible without this capability. Methods for such proactive diagnostics for air handlers are presented later in this paper

3 Generic Automated Proactive Commissioning Process

In this section, a generic automated proactive commissioning process is described that not only can detect and diagnose problems automatically, but can also proactively correct problems that are detected by reconfiguring controls when possible. This process is referred to as *automated proactive commissioning (APC)*.

Over the past decade fault detection and diagnostics (FDD) has been an active area of research among the buildings and the HVAC research communities [5]. As mentioned previously, automated FDD is central to automated proactive commissioning be-

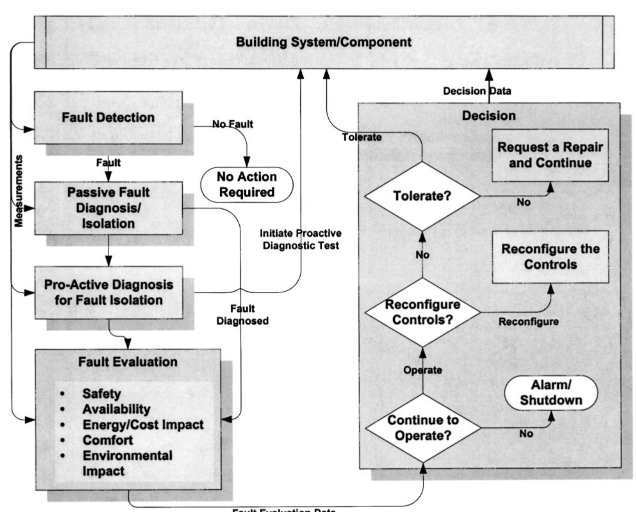

Fig. 1 Generic automated proactive commissioning process

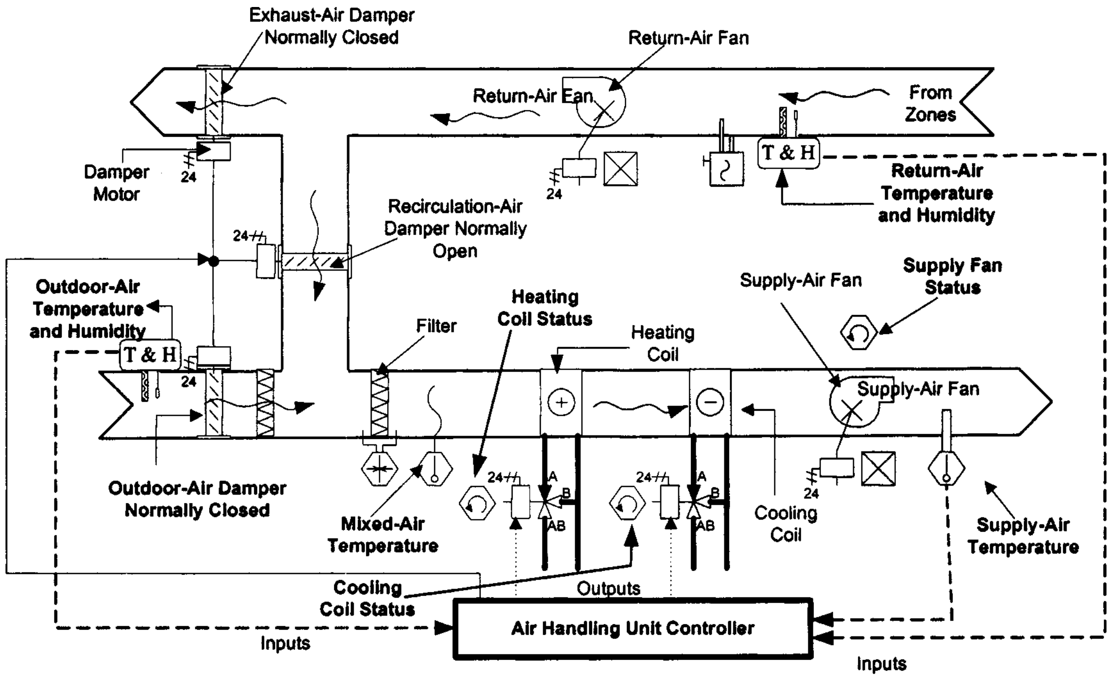

Fig. 2 Schematic of a typical air-handling unit with sensors and controllers

cause commissioning requires monitoring of building systems to detect abnormal conditions. As a result, automated FDD (AFDD) systems can be used to build automated proactive commissioning tools.

The primary objective of an FDD system is early detection of faults and diagnosis of their causes (and correction of them) before significant performance degradation or a catastrophic failure occurs. Fault detection is accomplished by continuously monitoring the operation of a system or a process to detect and diagnose abnormal conditions. In addition to fault detection and diagnosis, an automated proactive commissioning system requires a process to evaluate the severity of the fault and a process to respond to the faults associated with abnormal conditions.

With only a few exceptions, most FDD systems for building applications existing today lack the evaluation process [5], and none of them yet implement processes for responding automatically to faults.

An automated proactive commissioning process or an AFDD system can be viewed as four distinct but interconnected functional processes, as shown in Fig. 1. The first functional step is to monitor the building systems and detect abnormal (fault or problem) conditions. This step is generally referred to as the *fault detection* phase. If an abnormal condition is detected, then the *fault diagnosis* process identifies the cause of the abnormal condition. If the fault cannot be diagnosed using passive diagnostic techniques, proactive diagnostics techniques may be required to isolate the fault. The proactive diagnostic approach to isolate faults is described in more detail later in the paper. Following diagnosis, *fault evaluation* assesses the impact (energy, cost, and availability) on system performance. Finally, a *decision* is made on how to react to the fault. In most cases, detection of faults is easier than diagnosing the cause of the fault or evaluating the impact arising from the fault. Detailed descriptions of the four processes are provided in Katipamula et al. [4,5].

4 Automated Proactive Commissioning for Air-Handling Units

4.1 Basic Operating Sequence of an AHU. An AHU typically has two main controllers: 1) to control the outdoor-air intake, and 2) to control the supply-air temperature (in some cases mixed-air temperature is controlled rather than supply-air temperature). The basic operation of the AHU is to draw in outdoor air and mix it with return air from the zones and, when necessary, condition it before supplying the air back to the zones, as shown in Fig. 2.

An AHU typically has four primary modes of operation (Fig. 3) for maintaining ventilation (fresh air intake) and comfort (the supply-air temperature at its set point) when the building is occupied. The operating sequence determines the mode of operation based on ventilation requirements, the internal and external thermal loads, and indoor and outdoor conditions (for details on the basic operation refer to Katipamula et al. [4]).

For AHUs without economizers, there are two basic modes of operation (heating and mechanical cooling). For economizers that are not integrated with the mechanical cooling (i.e., they cannot economize and provide mechanical cooling simultaneously), there are three basic modes of operation (heating, economizing, and mechanical cooling).

4.2 Method for Automated Proactive Commissioning for Air-Handling Units. Application of the generic, automated,

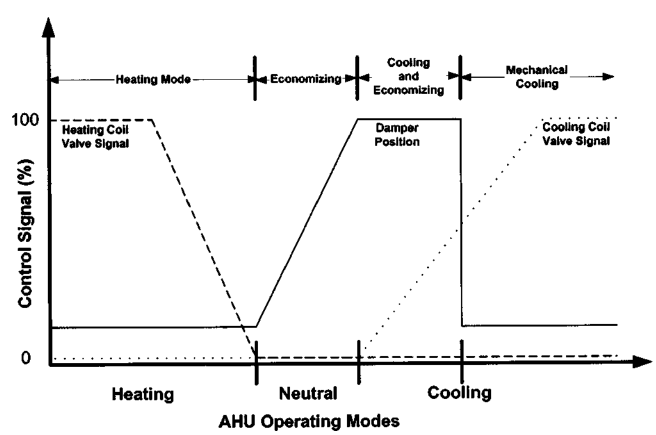

Fig. 3 Basic operating sequence of an air-handling unit

proactive commissioning process described in Section 3 requires development of methods (and ultimately software modules) for each of the four fundamental processes it comprises:

- fault detection and diagnosis based on passive observations (measurements)
- proactive fault detection and diagnostics
- fault evaluation
- decisions regarding if and what corrective actions to take, including automatically implementing some of the selected actions

This section covers these four components of APC for air-handling units. It covers the air-side functions of an AHU and detection of simultaneous heating and cooling, but it does not cover other water-side failures (such as failed heating and cooling valves or coils).

A method for the first step in the APC process for detecting and diagnosing problems based on passive observations is documented by the authors elsewhere (see [4–6]). The air-side fault detection has been automated in a software tool known as the Outdoor-Air/Economizer (OAE) diagnostic module of the Whole Building Diagnostician (WBD) [6–8]. The OAE tool detects and diagnoses faults based on data collected during routine operation of AHUs, but it does not perform proactive diagnostics.

For systems without economizers, the OAE diagnostician detects only ventilation and simultaneous heating and cooling problems. For systems with economizers, it detects problems with ventilation, economizer operations, and latent faults such as simultaneous heating and cooling (faults that do not result in discomfort, but lead to excessive use of energy). The OAE continuously monitors the performance of AHUs and can detect over 20 different basic operation problems or faults. It, however, does not detect problems on the water-side of the AHU.

The flow chart in Fig. 4 shows the basic structure of the logical process used by the OAE, as well as the faulty and the fault-free states it detects. These states become the starting points for the proactive processes described in the remainder of this section.

Automated FDD processes generally rely on analytical or physical redundancies to isolate a fault during diagnosis. Most HVAC systems in commercial buildings lack physical redundancy, because HVAC systems are considered non-critical (i.e., failures do not represent an immediate risk to the health and safety of the occupants). An AFDD process can use proactive diagnostic processes to create analytical redundancy to help isolate the causes of faults. The proactive diagnostic process is similar to functional testing that is performed during manual commissioning of systems. These functional tests generally involve collecting data after instigating changes in parameters or conditions in control code, and then analyzing the resulting data to determine whether equipment performance meets specifications and expectations.

Likewise, proactive diagnostics involve automatically initiating changes to cause or to simulate operating conditions that may not occur for some time, thus producing results that might not be available for months. Such tests can be automated to cover a complete range of operating conditions or to deepen a diagnosis beyond what might be possible without this capability.

Although proactive diagnostics help in isolating faults and deepening diagnosis, they are by nature intrusive. Some building owners and operators may consider this disruptive to normal operation of building systems. They may not, however, if such proactive tests can be conducted quickly enough so that acceptable control of the building systems is maintained. Entirely proactive commissioning procedures could provide "continuous" commissioning if they were periodically triggered (e.g., once a day, week, or perhaps month). These procedures might be scheduled to occur during unoccupied hours to reduce their intrusion on normal operations.

Two examples of proactive diagnostics are provided in the sections that follow: 1) isolation of a faulty outdoor-, return-, or mixed-air temperature sensor and 2) diagnosis of a faulty outdoor-air damper. Proactive diagnostics for many other AHU faults are provided in Katipamula et al. [4].

4.3 Isolation of Outdoor-, Return-, and Mixed-Air Temperature Sensor Problems. The process described in this section follows identification of a problem with the outdoor-, return-, or mixed-air temperature sensor using the process based on passive observations shown in Fig. 4 (with the fault identified as *Problem: Bad air temperature sensor*). One of these sensors is faulty but which specific one is not known.

In an AHU, the return- and outdoor-air streams are mixed and the resulting air stream is called the mixed-air stream (as shown in Fig. 2). Therefore, the fundamental equations for sensible energy balance along with positioning of the return-air and the outdoor-air dampers can be used to isolate the fault. Placing the dampers at specific positions in this case provides analytical redundancy, which provides additional information.

As shown in Fig. 5, the first step in the proactive diagnostic process is to close the outdoor-air damper completely and wait for the conditions to reach steady-state, which usually occurs within a few minutes. While keeping the outdoor-air damper fully closed, the return-air and mixed-air temperatures are sampled for a few minutes. With 100% of the return-air recirculated, the average mixed-air temperature should nearly equal the return-air temperature. If this is found, then the return-air and mixed-air temperature sensors are consistent with one another and, because one of the three sensors has failed, the outdoor-air temperature sensor must be faulty.

If the return-air and the mixed-air temperatures are *not* approximately equal, command the outdoor-air dampers to open fully and wait until steady-state conditions are achieved. When the outdoor-air damper is fully open, no return air recirculates and the average mixed-air temperature should approximately equal the average outdoor-air temperature during the sampling period. If this condition is found, then the outdoor-air and mixed-air temperature sensors are consistent with one another, and the return-air temperature sensor is faulty. If the measured mixed-air temperature does not equal the measured outdoor-air temperature, then the mixed-air temperature sensor is faulty (because earlier the return-air temperature sensor was found fault-free).

After isolating the faulty sensor, further diagnosis can identify the underlying cause or nature of the problem. In contrast to relative humidity, air flow, fluid flow, and pressure sensors, temperature sensors are more reliable, but they do exhibit erratic behavior occasionally. In addition to random noise, temperature sensors commonly acquire drift over time and bias. A process for detecting and estimating bias in temperature measurements is described in the next section. The ability to detect the drift over time does not require proactive testing; it can be detected using passive methods (see [4]).

Some notes of caution are appropriate for users of the process described here because tolerances of mechanical components can vary widely and change over time. All dampers possess seals to prevent leakage when they are fully closed. Some leakage, however, occurs around the seals, and as the AHU ages, the seals deteriorate, increasing the leakage. Under these conditions, when the return-air dampers are closed, the mixed air consists mostly of outdoor air but mixed with some leaked return air. As a result, the mixed-air temperature may not equal the outdoor-air temperature precisely. Therefore, in addition to allowing for measurement inaccuracies of the sensors, the equality tests in Fig. 5 should also account for damper leakage. Compensation for these sources of uncertainty can be accomplished by relaxing the tolerances on the equality tests (i.e., increasing them). This may sometimes lead to incorrect identification of a faulty mixed-air sensor even when the outdoor-air or the return-air temperature sensor is slightly biased (because it is the least resistive path on the flow chart in Fig. 5).

These sorts of tradeoffs between sensitivity of diagnosis to detect problems and the potential for false alarms or false diagnoses are best determined through field tests and experience. This topic is discussed later in the paper.

Stratification of air in the mixing box leads to another potential source of error. The measured mixed-air temperature may vary significantly across the duct cross-section. The mixed-air temperature measured at a single point may differ significantly from the average mixed-air temperature and lead to misleading diagnoses. To prevent this, the mixed-air temperature should always be measured across the duct and averaged using an averaging sensor.

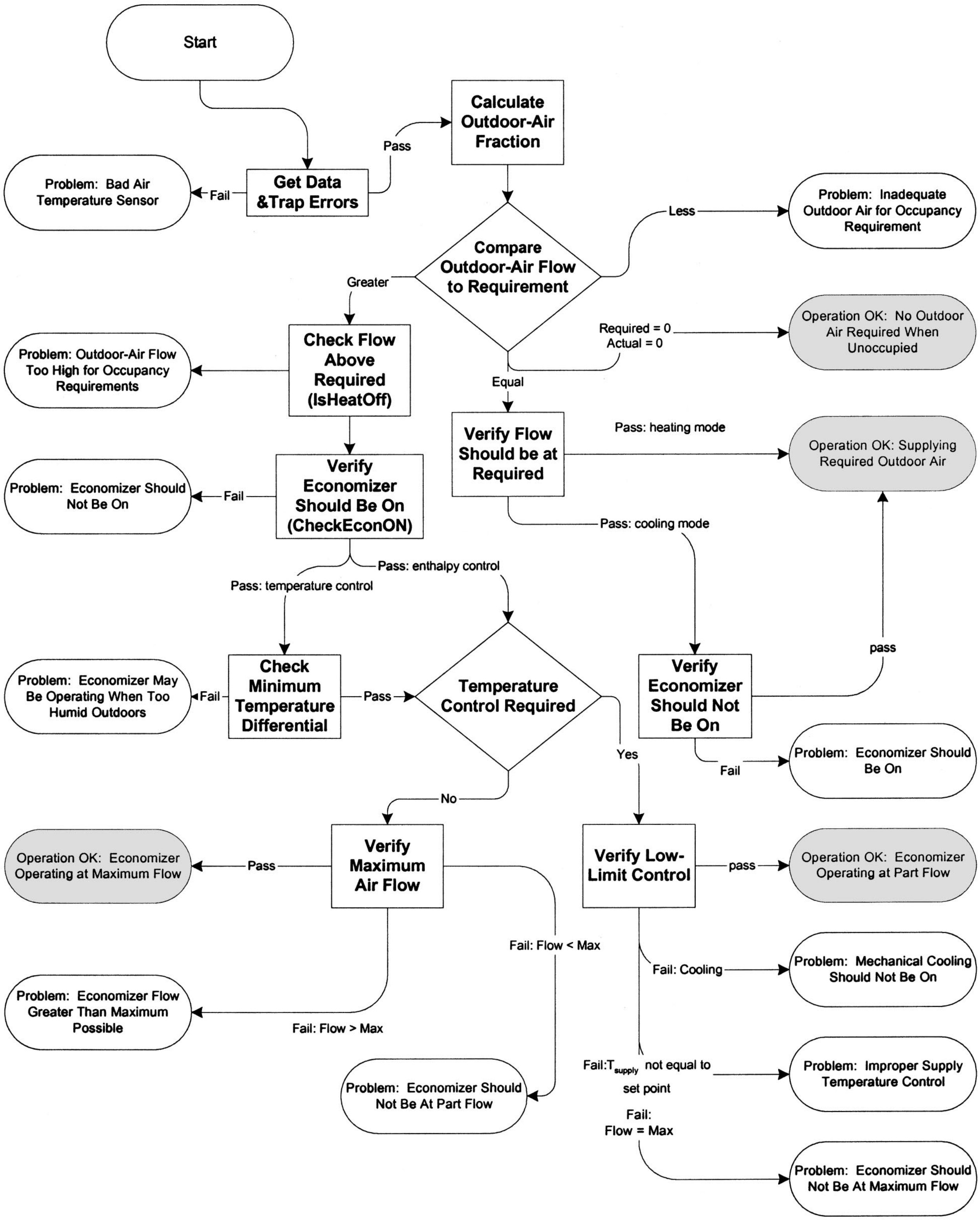

Fig. 4 Overview of the passive part of the automated proactive commissioning process for an AHU (including economizer and ventilation operations)

4.4 Diagnosing the Bias in an Outdoor-Air Temperature Sensor. In this section, we present an approach for classifying the nature of the fault found in an outdoor-air temperature sensor as an example of a method that can be applied to other temperature sensors (see [4] for detailed schemes for other sensors).

Once the outdoor-air temperature sensor has been identified as the faulty sensor using the process described in Section 4.3, further classification of the fault is possible. For a biased outdoor-air temperature sensor, the process to estimate the bias and reconfigure the controls is described in this section.

The first step in this proactive diagnostic process (Fig. 6) is to fully open the outdoor-air damper and wait for conditions to reach steady-state. In this case, values of the mixed-air temperature can be used to identify when steady-state conditions are attained, because at this point in the diagnostic process, we know that the mixed-air temperature sensor is good. One form of steady-state filter is based on the rate of change of the mixed-air temperature. If the rate of change is zero or below a predefined threshold, steady-state conditions have been achieved. After steady-state conditions are achieved, compute the difference between the outdoor-air and the mixed-air temperatures and store the result for further analysis.

The frequency of sampling and the duration of the proactive test depend on field conditions. A sampling rate of a minute or less and total test duration of 15 min should be sufficient in most cases. In some cases, the test may have to be performed at different times of the day to ensure that the bias is consistent at all hours of the day. In some cases, something as simple as positioning of the sensor may affect its readings. For example, an outdoor-air temperature sensor positioned so it is exposed to sunlight part of the day may read a few degrees high for a few hours of the day, the amount depending on the position of the sun, but may otherwise read normal. This type of bias or problem is difficult to detect, unless the proactive test is repeated several times at different hours of the day and then correlated with other observations, such as solar position. An outdoor-air temperature sensor showing bias during certain hours of the day each day for many days in a row (but not at other hours) would indicate such a problem. As with uncertainty mentioned earlier, field tests are required to better understand these issues.

After the difference between the outdoor-air and the mixed-air temperatures is computed for the duration of the test at a desired sampling rate, the next step is the analysis of the stored data to confirm whether the difference is nearly constant over the entire test period. Commonly used statistical tests such as the mean and the standard deviation of the sample are recommended. The mean provides the central tendency of the sampled data (the estimate of the bias), while the standard deviation provides the dispersion (how tightly the data are clustered around the mean).

In order for the test to be true (i.e., the difference nearly equal over the test period), the mean must be greater than the tolerance or the accuracy of the temperature sensors and the standard devia-

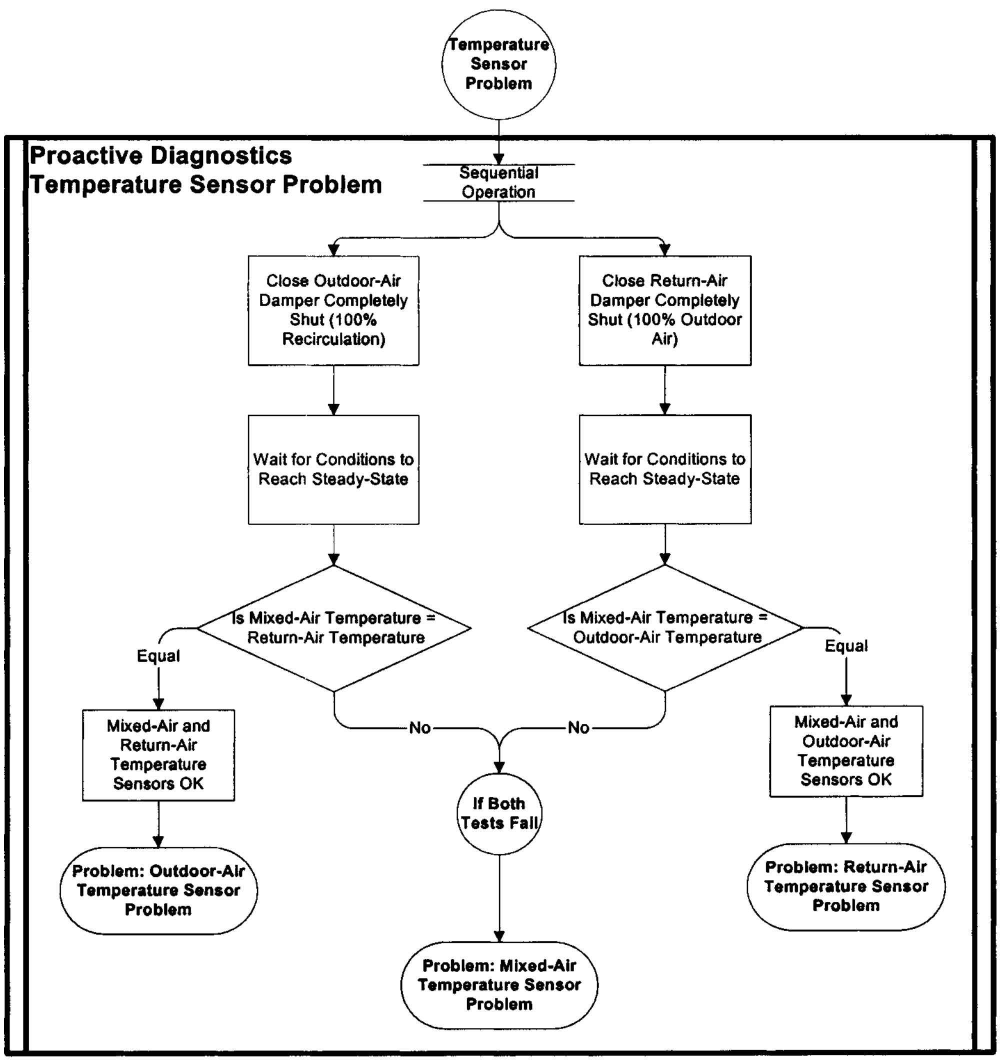

Fig. 5 Decision tree to isolate the faulty temperature sensor

tion should be reasonable. Another statistical metric called the coefficient of variation can be used to check whether the standard deviation is reasonable compared to the sample mean and the sensor tolerance. The coefficient of variation measures the relative scatter in data with respect to the mean; it is computed as the ratio of standard deviation to the mean. A threshold for the coefficient of variation must be selected. Below this threshold, the standard deviation would be acceptable and the bias considered constant. Previous studies that used field data to develop empirical models have concluded that a coefficient of variation of about 15% is reasonable.

4.5 Reconfiguration of Controls. The final step in the APC process involves reconfiguring the control algorithms to account for a constant bias in the outdoor-air temperature sensor. If the previous test concludes that the temperature difference (bias) is not constant, then the controls can be reconfigured to use another properly functioning outdoor-air temperature sensor, because buildings often have several outdoor-air temperature sensors. Any time controls have been reconfigured as the result of a proactive test, a report should be generated to notify the building manager or the building operator of this change. Then, when the sensor is repaired or replaced, this report will alert the manager or operator that the outdoor-air sensor used for control can be re-configured.

Proactive procedures similar to the one presented in this section can be developed for return-air, mixed-air, and supply-air temperatures [4].

4.6 Detection and Diagnosis of Malfunctioning Dampers. Identification of malfunctioning dampers in an AHU is difficult without monitoring system conditions closely. Even drastically malfunctioning dampers often do not affect the comfort of occupants and can go undetected for long periods of time. Mechanical cooling (or heating) generally compensates for the load from excess hot (or cold) outdoor air brought in because an outdoor-air damper is stuck wide open. The damper failure has little or no impact on comfort.

The passive methods discussed in Section 3.2.1 can detect extreme damper failures, but generally not the details of a failure (e.g., the position of a stuck damper). Bushby et al. [8] found that the relationships between air-flow rates, outdoor-air fraction (OAF), damper position, and fan-power consumption varies non-linearly and across system types and configurations. In this section, we present an approach for detecting malfunctioning dampers that better accounts for these non-linearities and can be applied in a variety of HVAC applications. Still, because dampers fail from broken linkages, failed actuators, improper control sequences, and broken motors, distinguishing among these causes is a level deeper than the diagnosis provided by this method. Generally, these methods will identify occurrence of a fault, localize it to some degree, and then require that a technician investigate further and take corrective action. As such, however, they provide a critical capability for automating proactive commissioning of AHUs.

The passive methodology described in Section 3.2.1 uses sensors commonly found in AHUs. This alternative proactive diagnostic method requires additional sensors to measure pressure drop across the outdoor-air damper and the power consumption of the fan. Because sensors for these measurements are not commonly found in air handlers, this method requires their installation.

The damper pressure drop and fan power measurements are compared to a reference model for normal operation to detect whether a fault exists and then to model for various kinds of faulty behavior to isolate the fault. The increase in fan power consumption and the change in the pressure drop across the damper caused by improper operation depend on the specific configuration and condition of the AHU. Therefore, to automate this proactive commissioning process, the behavior of the damper and the fan under normal and faulty operations must be characterized separately. The characterizations can be done off-line as separate processes or they can be done on-line in an automated way as a part of the automated proactive process.

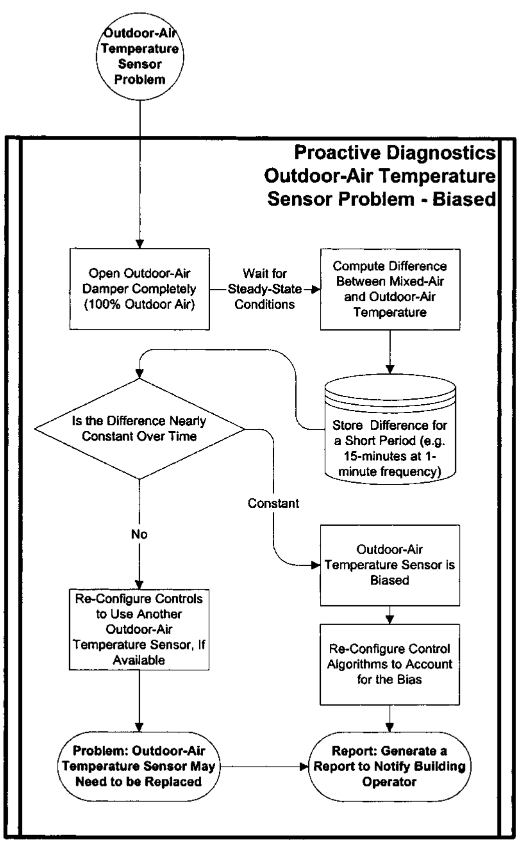

Fig. 6 Decision tree to check if the outdoor-air temperature sensor is biased and implement a temporary correction

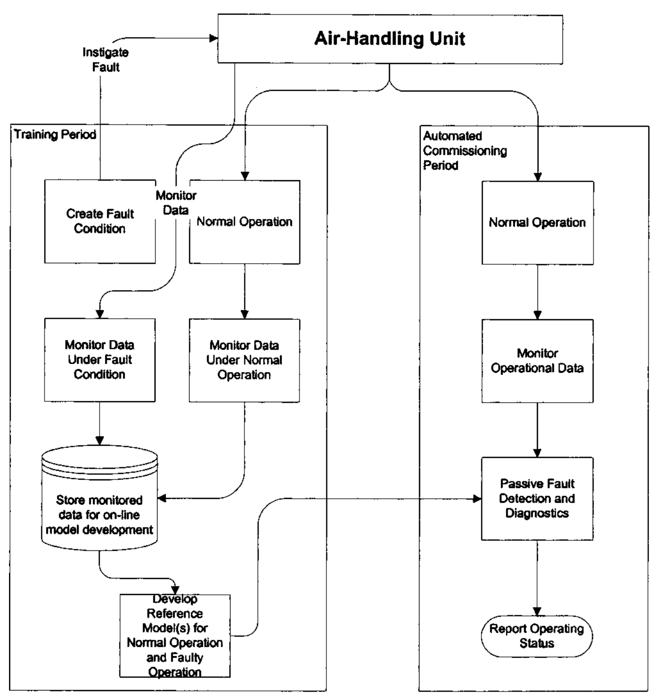

Fig. 7 Overview of an online training and proactive commissioning process

The online training and automated proactive commissioning process is shown schematically in Fig. 7. Before the automated proactive commissioning process is initiated, the online training process is used to characterize the damper operation under normal and faulty conditions. To characterize the outdoor-air damper operation, the pressure drop, the fan power consumption, and the OAF are monitored and used to develop a reference model. The process involved in developing the reference model is illustrated in more detail in Fig. 8. The reference model provides the basis for identifying faulty and malfunctioning dampers.

As an example, we present the process for detecting and diagnosing faulty outdoor-air dampers. The methodology can be extended for return- and exhaust-air dampers, as well as other dampers.

The first step in characterizing normal behavior of the outdoor-air damper requires fully closing it, then commanding the return-air and exhaust-air dampers to positions that correspond to the fully closed outdoor-air damper position (Fig. 9). After the conditions reach steady-state, monitor the pressure drop, power consumption and the OAF (which can be calculated from the outdoor-air, return-air and mixed-air temperatures), and store the data. Then command the outdoor-air damper to open 10% and command the return-air and the exhaust-air dampers to positions corresponding to the new outdoor-air damper position. Wait for the conditions to reach steady-state and store the monitored data. Change the outdoor-air damper position to 20% open, and command the return-air and exhaust-air damper positions again to positions corresponding to the new outdoor-air damper position and continue the process in incremental increases in outdoor-air damper position of 10% until the outdoor-air damper is fully open. This procedure can be repeated for the outdoor-air damper stuck in other positions to provide an ability to distinguish between the various fault conditions.

After the data for normal outdoor-air damper operation are collected, a reference model of normal operation can be developed. The reference model can be empirically developed using regression analysis or simply a lookup table based on the measured data. Because the stored data covers the entire range of normal operations (fully open to fully closed), a lookup table is likely easier to implement in software.

The procedure to build a reference model to characterize faulty behavior is similar to that described for normal operation. The process for an outdoor-air damper stuck fully closed is illustrated in Fig. 10. Throughout this test, the outdoor-air damper must be forced to remain in the fully-closed position irrespective of its control signal. Command the return-air and the exhaust-air dampers to positions that correspond to the fully closed outdoor-air damper position (Fig. 9). After steady-state conditions are reached, monitor the pressure drop, power consumption and OAF, and store the data. Next, command the return-air and exhaust-air dampers to positions that correspond to 10% open outdoor-air damper, while actually keeping the outdoor-air dampers fully closed. Wait for the conditions to reach steady-state and record the monitored data. Reposition the return-air and the exhaust-air dampers again, this time to correspond to 20% open outdoor-air damper. Continue the process increasing the positions of the return-air and exhaust-air dampers in increments corresponding to 10% increases in the outdoor-air damper position until the corre-

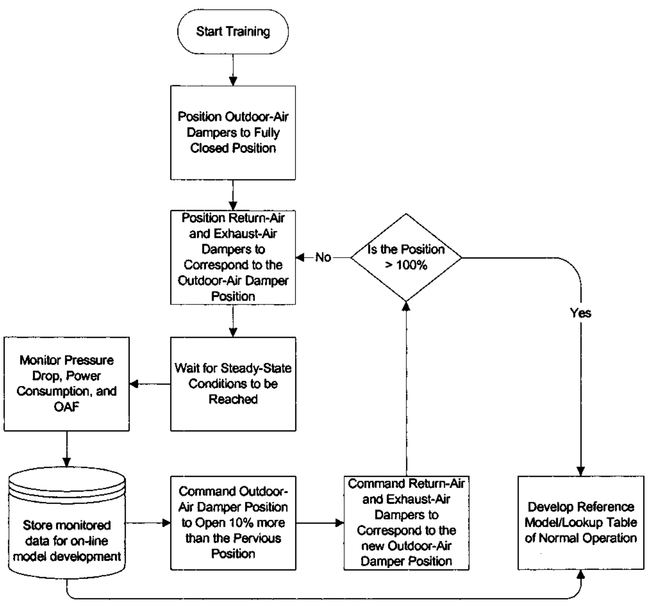

Fig. 8 Overview of the process to develop a reference model to characterize the normal operation of an outdoor-air damper

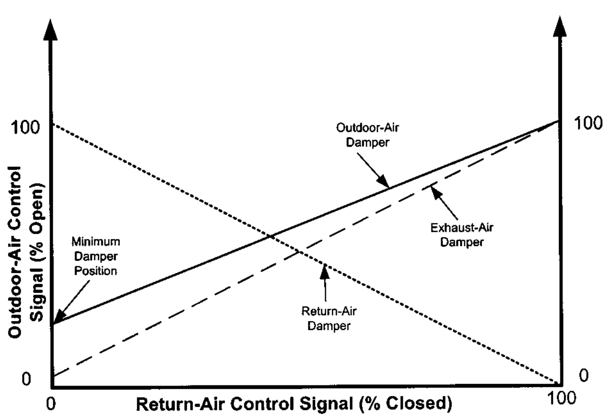

Fig. 9 Relationship of the damper positions during normal operations

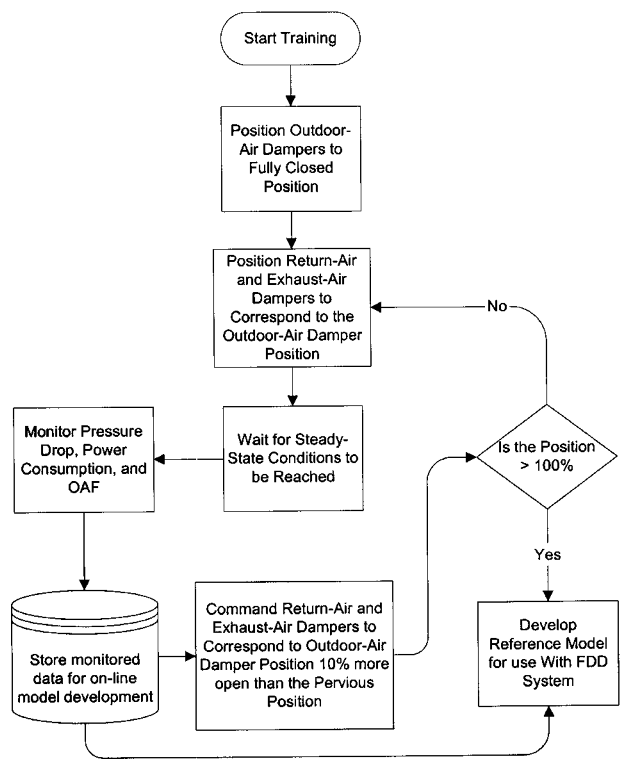

Fig. 10 Overview of the process to develop a reference model to characterize the outdoor-air damper stuck fully closed

Table 1 A simple lookup table for normal and faulty outdoor-air damper operation

Outdoor-Air Damper Signal (% Open)	Normal Operation		Outdoor-Air Damper Stuck Fully Closed		Outdoor-Air Damper Stuck Fully Open	
	Outdoor-Air Fraction	Supply Fan Power Consumption (kW)	Outdoor-Air Fraction	Supply Fan Power Consumption (kW)	Outdoor-Air Fraction	Supply Fan Power Consumption (kW)
10	0.15	1.55	0.05	1.56	0.15	1.54
20	0.25	1.52	0.08	1.55	0.25	1.52
30	0.40	1.51	0.15	1.60	0.40	1.50
50	0.60	1.50	0.20	1.65	0.60	1.48
70	0.75	1.48	0.40	1.70	0.75	1.46
100	1.00	1.45	0.70	1.80	1.00	1.45

sponding outdoor-air damper position is 100% (fully open), while keeping the actual outdoor-air damper fully closed. Using the data recorded, develop a lookup table for faulty operation of the outdoor-air damper.

4.7 Outdoor-Air Damper Fault Detection and Diagnostics. Once the normal and faulty operation of the outdoor-air damper system has been characterized, the automated proactive commissioning mode can be activated (Fig. 7). The decision tree for detecting and diagnosing faulty operation is shown in Fig. 11. Although the automated proactive commissioning process will identify improper operation, it may not be able to reconfigure the controls to compensate for the fault. Therefore, most problems will require some type of human intervention to repair or replace the faulty parts.

The first step in the automated proactive commissioning process is to validate all sensor measurements (see Sections 4.3 and 4.4). If the sensor measurements are good, then estimate the signal value that controls the damper system using the operating mode of the AHU (heating or cooling) and the indoor and outdoor conditions (by calculating outdoor air fraction), and compare it to the actual value measured for the signal. If the measured signal value is incorrect, then a problem exists either with the controller or with the control algorithm. If the measured control signal matches the estimated control signal, verify that the measured power consumption of the supply fan and the pressure drop across the outdoor-air damper system match the values in the lookup table (or provided by another model) for normal operation. If they do, the outdoor-air dampers are operating normally. If not, conclude that the outdoor-air damper is operating improperly.

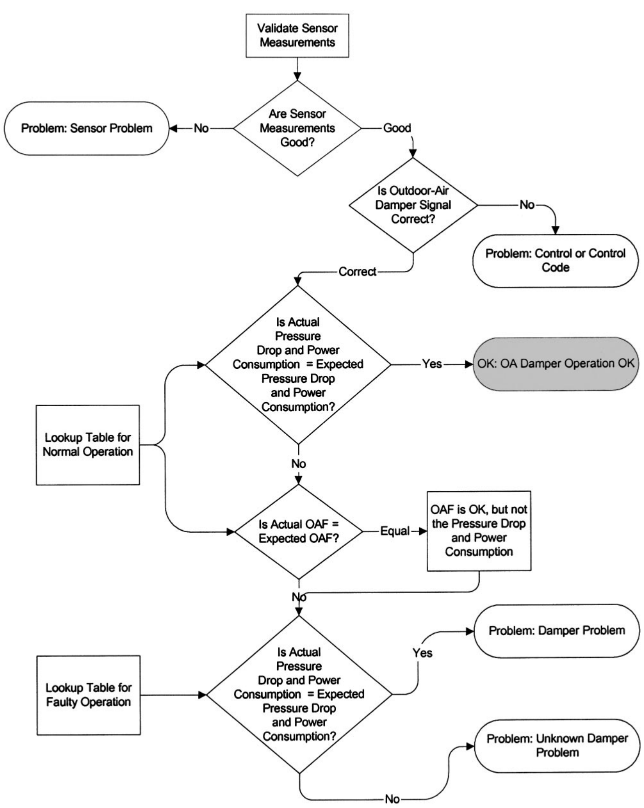

Fig. 11 Decision tree to detect and diagnose outdoor-air damper faults

The next step is to then diagnose the cause of the fault by comparing the measured values for the power consumption and pressure drop to the values in the lookup table for faulty operations. The problem corresponding to the pattern of variables that best matches the measurements is identified as the fault. If no pattern of values matches, conclude that an unknown damper problem exists. There are several techniques that can be used to match the measured and expected values of power and pressure drop. One efficient technique is fuzzy-logic-based rules.

As noted earlier, the automated proactive commissioning process can also be implemented with measurements for supply-fan power consumption only. This process is illustrated here as an example. Following the process in Fig. 11, the first step is to build a lookup table (Table 1) to characterize normal operations followed by building a lookup table (Table 1) to characterize faulty behavior using a process similar to the one for characterizing normal operation. The characterization of outdoor-air damper behavior when it is stuck in a fully closed position is illustrated in Fig. 10. This process can be adapted to empirically characterize behavior for the outdoor-air damper stuck in other positions. Table 1 provides values for the damper stuck fully open and fully closed only These particular values are for illustrative purposes only and do not correspond to measurements on a specific AHU.

After the normal and faulty behaviors are characterized, detection and diagnosis of outdoor-air damper problems can be automated. The first step in the detection process is to estimate the expected damper position signal and compare that to the actual damper signal (Fig. 11). If the expected and the actual damper position signals match, then compare the actual measured power consumption to the value that corresponds to the damper signal in the lookup table (Table 1). For example, if the expected damper signal is 50% open and the measured supply-fan power consumption approximately equals 1.5 kW, then conclude that the outdoor-air damper is properly functioning. Suppose instead that the expected damper signal is 50% open and the supply fan power consumption is about 1.64 kW, which is greater than 1.5 kW, then, we conclude that the damper operation is faulty. We then attempt to match the measured power consumption with the power consumption for fully closed and fully open operations in Table 1. Because the measured power consumption of 1.64 kW approximately equals 1.65 kW corresponding to the fully closed failure position in Table 1, we conclude that the outdoor-air damper is stuck fully closed. When both the power consumption and pressure drop are available, the lookup function is a bit more complex, but it can be automated easily using a fuzzy-logic-based algorithm.

5 Thresholds and Tolerances

The rule-based methodologies presented in this paper rely on comparisons of the values of variables to traverse through decision trees. These comparison tests must account for both random noise and measurement uncertainty. In addition, measured data from the field may also have systematic bias (i.e., be consistently high or low relative to the true value of the variable). The comparison methodology must account for these uncertainties in measured values to ensure reasonable levels of confidence in the results.

The tolerances assigned to each variable should, at a minimum, account for the measurement uncertainty (or accuracy) specified by the sensor manufacturer. For example, a typical commercial grade temperature sensor is accurate to within about $\pm 0.5°C$ or $\pm 1°F$. By specifying tolerances and propagating them through the comparisons in the decision tree, the level of sensitivity for fault detection and the occurrence of false alarms can be controlled; however, there will always be a trade-off between increased detection sensitivity and increased occurrence of false alarms.

Although in this paper comparison tests in the decision trees are shown as simple definitive comparisons, actual implementation in software for automation requires inclusion of tolerances in each comparison. For example, to test whether the outdoor-air temperature is equal to the mixed-air temperature, assuming that tolerances of $\pm 0.5°F$ have been assigned to both measurements, the outdoor-air temperature is equal to the mixed-air temperature if the following condition is true:

$$|(T_{out}-T_{mix})| \leq 0.5-(-0.5)=1.0$$

Similarly, less than and greater than tests also can be constructed using the assigned tolerances.

A better way to handle this issue is to introduce tolerances for each measured and static input variable to account for the uncertainty in the measured values. The tolerances are propagated through all calculations and tests. For example, to test if the outdoor-air temperature is greater than the return-air temperature, not only should the value of the outdoor-air temperature exceed the return-air temperature, it should be greater than the return-air temperature plus the uncertainty of the difference between the two measured values to minimize the probability that the true outdoor-air temperature is less than or equal to the return-air temperature. The uncertainty of the differences between two measured variables is equal to the sum of the tolerances for each of the two variables. Similarly, the uncertainty associated with other algebraic combinations of measured variables and tests can be evaluated using standard formulas for the propagation of errors in calculations (see, e.g., Croarken and Tobias [9]).

6 Conclusions

We have presented logic for a generic process for APC and selected example applications to AHU components. A more comprehensive treatment is provided in Katipamula et al. [4]. Automation of a portion of this logic has been implemented. Future work should address fully automating these procedures and testing them in the laboratory and field to verify their performance and to empirically investigate the setting of tolerances and its influence on detection sensitivity and the rate of false alarms.

Integration into the APC process requires collaboration with operation staff who are committed to using this new approach and closing the APC loop by taking actions to correct faults detected using these automated procedures. These operators will be critical to the long-term development of APC and its promise to lower commissioning costs and improve its impacts.

Acknowledgments

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References

[1] Portland Energy Conservation Inc. (PECI), 1997, Commissioning for Better Buildings In Oregon, Oregon Office of Energy, Salem, OR.

[2] U.S. Department of Energy/PECI. 1998, Model Commissioning Plan and Guide Commissioning Specifications, Version 2.05, PECI, Portland, OR.

[3] Claridge, D.E., Culp, C.H., Liu, M., Deng, S., Turner, W.D., and Haberl, J.S. 2000, ''Campus-Wide Continuous Commissioning^{SM} of University Buildings,'' *Proc. of ACEEE 2000 Summer Study on Energy Efficiency in Buildings*, Pacific Grove, CA, Aug. 20-25, pp. 3.101–3.112.

[4] Katipamula, S., Pratt, R.G., and Brambley, M.R., 2003, ''Methods for Automated and Continuous Commissioning of Building Systems,'' in publication, PNWD-32-72, Pacific Northwest National Laboratory, Richland, Washington.

[5] Katipamula, S., Pratt, R.G., and Braun, J., 2000, Building Systems Diagnostics and Predictive Maintenance, *CRC Handbook of Heating Ventilation, and Air Conditioning*, Jan F. Kreider (ed.), CRC Press, New York, NY.

[6] Katipamula, S., Pratt, R.G., Chassin, D.P., Taylor, Z.T., Gowri, K., and Brambley, M.R., 1999, ''Automated Fault Detection and Diagnostics for Outdoor-Air Ventilation Systems and Economizers: Methodology and Results from Field Testing,'' ASHRAE Trans., **105**(1), pp. 555–567.

[7] Brambley, M.R., Pratt, R.G., Chassin, D.P., and Katipamula, S., 1998, ''Automated Diagnostics for Outdoor Air Ventilation and Economizers,'' ASHRAE J., **40**(10), pp. 49–55.

[8] Bushby, S.T, Castro, N.S., Schein, J., and House, J., 2002, Using the Virtual Cybernetic Building Testbed and FDD Test Shell for FDD Tool Development, NISTIR 6818. National Institute of Standards and Technology, Gaithersburg, MD.

[9] Croarkin, C., and Tobias, P., (ed.), 2003, *Engineering Statistics Handbook*, Section 2.5.5, National Institute of Standards and Technology and SEMATECH, Available at http://www.itl.nist.gov/div898/handbook/.