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1.0 Introduction

Several subcontractors under the PIER-funded *Energy Efficient & Affordable Small Commercial and Residential Buildings Program* (PIER Contract # 400-99-011) developed and tested methods to diagnose problems with HVAC system performance. This project will integrate the following methods into a suite of web-accessible applications:

- NIST's air-handling unit diagnostics (APAR); and
- Diagnostics for chillers, cooling towers, and associated equipment, developed under prior PIER sponsored research (Project 2.5, Pattern Recognition Based FDD) based on the ENFORMA[®] HVAC Diagnostics Analyzer.

This document describes the initial investigation, testing, and modifications required to implement NIST's APAR rule set.

2.0 APAR background

The concepts behind and development of NIST's Air Handler Performance Assessment Rules (APAR) have been well documented in existing reports. These reports are listed in the references section. An extract of one of the source documents that describes APAR is as follows.

Adapted from House et al. (2002):

The Air Handling Unit Performance Assessment Ruleset (APAR) consists of 28 rules. House et al. (2001) provide a description of the rules and the reasoning behind them. For this reason, the rules are simply listed in Table 2-1 without detailed explanation. Table 2-1 groups the rules according to mode of operation. As indicated in the column heading for the rule expression, a true expression is indicative of a fault. Nomenclature for the rule set is provided as an appendix to this section. Table 2-2 presents the rules as related groups and indicates the sensors and control signals used to evaluate each rule. The first group of rules treats the relationship of temperatures in the coil subsystem of the AHU. For these four rules, only the relational operator in the rules change from one mode to another. A typical rule from this subgroup requires the supply air temperature to be lower than the sum of the mixed air temperature and the temperature rise across the supply fan in the mechanical cooling modes. There are also groups of rules treating the mixing box subsystem, the zone subsystem, economizer operation, comfort requirements, and controller logic/tuning. Hence, although there are 28 rules, in reality only a small number of temperature and control signal relationships are used to define the rules.

The modes are shown graphically in Figure 2-1. Modes are determined solely by the condition of control signals to the heating and cooling coil valves and the outdoor air damper. Depending on the status of these three control signals, one of the four displayed modes is selected. In addition, there are two other modes: not operating, when the system is off, and unknown, when the combination of control signals does not correspond with any of the normal modes of operation.

Table 2-1. Original APAR Rule Set (House, et al.)

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

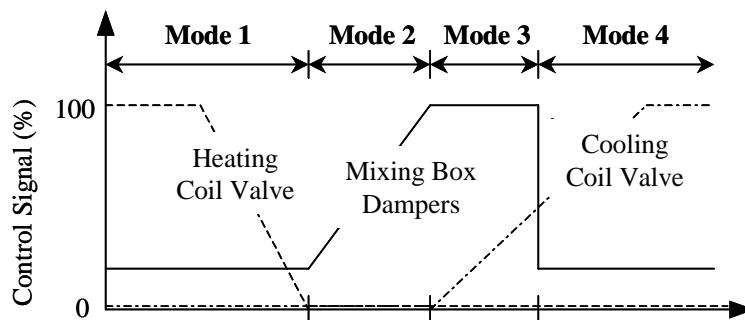


Figure 2-1. Typical operating modes of an air-handling unit. (House, 2001)

Table 2-2. Summary of rule relationships (reference?)

Rule	Mode *	Sensors and Control Signals											Relationship Between Grouped Rules	
		T _{sa}	T _{ra}	T _{ma}	T _{oa}	T _{sa,s}	ΔT _{sf}	ΔT _{rf}	T _{co}	U _{cc}	U _{hc}	U _d		
1	1	■		■			■							Coil Subsystem: The relational sign (<, >, etc.) changes based on the mode of operation.
7	2	■		■			■							
11	3	■		■			■							
16	4	■		■			■							
2	1		■	■	■									Mixing Box Subsystem: Rules are related through calculation of outdoor air fraction. If Rule 26 or 27 is satisfied, the outdoor air fraction will be negative or greater than unity.
18	4		■	■	■									
26	1, 2, 3, 4		■	■	■									
27	1, 2, 3, 4		■	■	■									
25	1, 2, 3, 4	■				■								Comfort Requirements: The first four rules indicate comfort is sacrificed (with Rules 3, 13, and 19 indicating the system is out of control), whereas the latter three rules indicate comfort could soon be sacrificed (system is out of control).
3	1	■				■						■		
13	3	■				■						■		
19	4	■				■						■		
4	1												■	
14	3												■	
20	4												■	
5	2				■	■	■							The relational sign (<, >, etc.) changes based on the mode of operation.
8	3				■	■	■							
6	2	■	■					■						Zone Subsystem: Rules are identical.
12	3	■	■					■						
17	4	■	■					■						
9	3				■					■				Economizer: The relational sign (<, >, etc.) changes based on the mode of operation.
15	4				■					■				
10	3			■	■									Controller Logic/Tuning: Rules are related and identify periods of operation associated with controller problems, such as simultaneous heating and cooling, and excessive mode changes.
21	-									■	■	■		
22	-									■	■	■		
23	-									■	■	■		
24	-									■	■	■		
28	-									■	■	■		

* The dash symbol indicates either an unknown mode or multiple modes of operation.

To reduce the potential for false positives related to transients in the system, the APAR developers employed two techniques. The first was to evaluate the rules using an exponentially weighted moving average (EWMA) to dampen the input variables. EWMA's are widely used for noise removal in signal processing, and are evaluated as follows:

$$XAvg_N = \lambda \times X + (1 - \lambda) \times XAvg_{N-1}$$

Where:

$XAvg_N$ is the current weighted average of X

λ is a weighting factor to determine how damped the moving average is

$XAvg_{N-1}$ is the previous value of the weighted average of X

The second technique that the developers used to reduce false positives was to evaluate the ruleset only after the system had operated in a mode for 60 minutes. After one hour, it is likely that the system is relatively stable and that temperatures have reached a steady state condition. The advantage of this approach is that transients during mode switches will not be evaluated. The disadvantage is that if a system undergoes multiple mode switches during a day, less time will be available for actually performing the fault detection.

Finally, a rule must be triggered constantly for one hour before it is reported as a detected fault. If the rule is not triggered during a timestep, the timer is reset. By requiring the rule to be violated for at least an hour before reporting it as a fault will reduce the number of false positives.

3.0 APAR Implementation Approach

The web-enabled version of APAR is based on a version of the APAR rules called APAR_standalone.m. This version was developed by NIST and is a more streamlined version than those used during initial testing; much of the features associated with test inputs and outputs have been removed. Because it was written for the MATLAB environment, we continued to perform our review and initial testing within MATLAB.

The steps we used to implement APAR are as follows:

- Test APAR with datasets collected during previous field tests.
- Modify the code as necessary based on testing.
- Translate the Matlab version to java.

Each of these steps are described in the following sections

4.0 Development of APAR outputs

The APAR fault detection engine generates an output record for each input record. In other words, if five-minute data are inputted into the engine, five-minute results are generated. This output is useful for testing the engine, but is less useful for quickly determining the performance of an air handler, and so a more compact output has been developed. This more compact output consists of hourly and daily summaries, as described below. These summaries can also be displayed in a graphical form for easy scanning.

The summaries present data only when rules are violated. This avoids cluttering the summaries with periods of normal operation.

4.1 Hourly summary

The hourly summary indicates the steady-state system modes that occurred during each hour, and the rules that were violated (what faults were detected) during that hour. The hourly mode summary lists the percentage of time that the system operated at steady state in each mode. In a similar fashion, the hourly rule violation summary is presented as a percentage of the time that the system operated in the applicable mode. An example is presented below.

The majority of the rules are evaluated only for specific modes. For example, rules 1 through 4 are applicable to mode 1 (Heating). If rule 1 was violated for 30 minutes and the system operated in Mode 1 under steady state conditions for 40 minutes during the hour, the hourly result would be as follows:

- Mode 1: 66 percent
- Rule 1: 75 percent

By expressing the results this way, it becomes clear which rules are violated most often during its applicable mode.

4.2 Daily summary

The daily summaries are calculated in a manner similar to the hourly summaries, but are based on operation for an entire day.

5.0 APAR Modifications

The modes included in the original APAR are shown in Figure 5-1. Mode 1 provides heating, and Modes 2 through 4 provide cooling. In mode 2, the outside air dampers modulate to maintain the mixed and supply air temperature at the supply temperature setpoint. Mode 3 begins when the ambient temperature is no longer below the supply air temperature, and mechanical cooling, provided by chilled water, is required to cool the airstream. Mode 4 begins when the ambient temperature is greater than the return temperature, and the outside air damper is closed to its minimum value. These modes are based on supply air temperature setpoint maintenance.

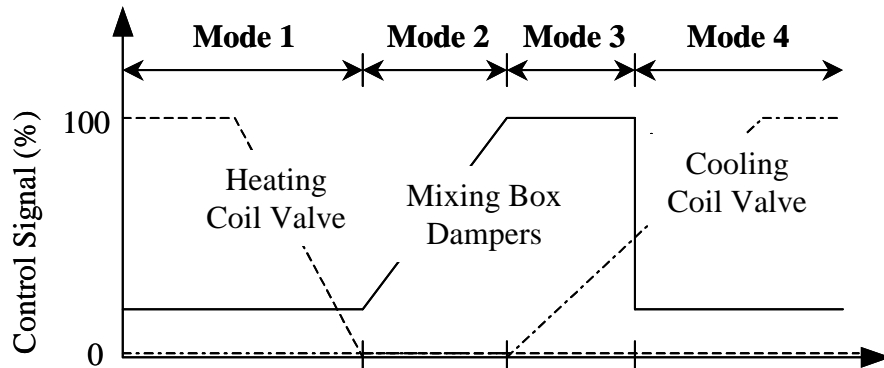


Figure 5-1. Typical operating modes of an air-handling unit. (House, 2001)

We have observed other modes in buildings. For example, it is not uncommon for a building to operate with 100 percent outside air without running a chiller, even when ambient temperature is above supply air setpoint, especially if zone setpoints are satisfied. In Figure 5-1, this mode would exist between modes 2 and 3.

Another common mode, especially on single-zone units, is circulation-only. In this mode, no heating or cooling is provided to the zone, only minimum outside air. This mode would be represented between modes 1 and 2 in Figure 5-1.

To expand the capability of APAR, these modes have been added, along with appropriate rules. These new modes and their respective rules are shown in Table 5-1.

Table 5-1. Expanded modes and rules

Mode	Rule	Rule Expression (true implies existence of a fault)	Description
Mode 1: Heating	1	$T_{sa} < T_{ma} + \Delta T_{sf} - \epsilon_t$	Supply Air Temp should be greater than mixed air temp
	2	For $ T_{ra} - T_{oa} \geq \Delta T_{min}$: $ Q_{oa}/Q_{sa} - (Q_{oa}/Q_{sa})_{min} > \epsilon_f$ OR, $(abs((T_{ma}_{av} - Tra_{av})/(Toa_{av} - Tra_{av}) - Qoa_{frac_min}) > \epsilon_f)$	OA fraction too low or too high
	3	$ u_{hc} - I \leq \epsilon_{hc}$ and $T_{sa,s} - T_{sa} \geq \epsilon_t$	Htg coil is saturated and persistent supply air temp error exists
	4	$ u_{hc} - I \leq \epsilon_{hc}$	Warning: htg coil is saturated if htg load increases supply air temp error will increase
Mode 2: Cooling with Outdoor Air	5	$T_{oa} > T_{sa,s} - \Delta T_{sf} + \epsilon_t$	Outdoor temperature is too high for cooling with OA
	6	$T_{sa} > T_{ra} - \Delta T_{rf} + \epsilon_t$	Supply Air Temp should be less than Return Air Temp
	7	$ T_{sa} - \Delta T_{sf} - T_{ma} > \epsilon_t$	Supply Air Temp should be equal to Mixed Air Temp
Mode 3: Mechanical Cooling with 100% Outdoor Air	8	$T_{oa} < T_{sa,s} - \Delta T_{sf} - \epsilon_t$	Outdoor temperature is too low for mechanical cooling
	9	$T_{oa} > T_{co} + \epsilon_t$ (or $Toa > Tra + \epsilon_t$)	Outdoor enthalpy is too high for 100 % outdoor air
	10	$ T_{oa} - T_{ma} > \epsilon_t$	Outside Temp should be equal to Mixed Air Temp
	11	$T_{sa} > T_{ma} + \Delta T_{sf} + \epsilon_t$	Supply Air Temp should be less than Mixed Air Temp
	12	$T_{sa} > T_{ra} - \Delta T_{rf} + \epsilon_t$	Supply Air Temp should be less than Return Air Temp
	13	$ u_{cc} - I \leq \epsilon_{cc}$ and $T_{sa} - T_{sa,s} \geq \epsilon_t$	Clg coil is saturated and persistent supply air temp error exists
Mode 4: Mechanical Cooling with Minimum Outdoor Air	14	$ u_{cc} - I \leq \epsilon_{cc}$	Warning: clg coil is saturated if clg load increases supply air temp error will increase
	15	$T_{oa} < T_{co} - \epsilon_t$ or $(Toa < Tra - \epsilon_t)$	Outdoor enthalpy is too low for minimum outdoor air
	16	$T_{sa} > T_{ma} + \Delta T_{sf} + \epsilon_t$	Supply Air Temp should be less than Mixed Air Temp
	17	$T_{sa} > T_{ra} - \Delta T_{rf} + \epsilon_t$	Supply Air Temp should be less than Return Air Temp
	18	If $ T_{ra} - T_{oa} \geq \Delta T_{min}$: $abs((T_{ma} - Tra)/(Toa - Tra) - Qoa_{frac}) > \epsilon_f$	OA fraction too low or too high
	19	$ u_{cc} - I \leq \epsilon_{cc}$ and $T_{sa} - T_{sa,s} \geq \epsilon_t$	Clg coil is saturated and persistent supply air temp error exists
New Mode 5: Cooling with 100% Outdoor air ONLY	20	$ u_{cc} - I \leq \epsilon_{cc}$	Warning: clg coil is saturated if clg load increases supply air temp error will increase
	29	$T_{sa} > T_{ra} - \Delta T_{rf} + \epsilon_t$	Supply Air Temp should be less than Return Air Temp
	30	$ T_{sa} - \Delta T_{sf} - T_{ma} > \epsilon_t$	Supply Air Temp should be equal to Mixed Air Temp
Mode 6: Ventilation with Minimum Outdoor Air	31	$ T_{oa} - T_{ma} > \epsilon_t$	Outside Temp should be equal to Mixed Air Temp
	32	$ T_{sa} - \Delta T_{sf} - T_{ma} > \epsilon_t$	Supply Air Temp should be equal to Mixed Air Temp
	33	$T_{sa} > T_{ma} + \Delta T_{sf} + \epsilon_t$	Supply Air Temp should be less than Mixed Air Temp
	34	$T_{sa} > T_{ra} - \Delta T_{rf} + \epsilon_t$	Supply Air Temp should be less than Return Air Temp
	35	For $ T_{ra} - T_{oa} \geq \Delta T_{min}$: $ Q_{oa}/Q_{sa} - (Q_{oa}/Q_{sa})_{min} > \epsilon_f$ OR, $(abs((T_{ma}_{av} - Tra_{av})/(Toa_{av} - Tra_{av}) - Qoa_{frac_min}) > \epsilon_f)$	OA fraction too low or too high
Mode 7: Unknown Occupied Mode	21	$u_{cc} > \epsilon_{cc}$ and $u_{hc} > \epsilon_{hc}$ and $\epsilon_d < u_d < 1 - \epsilon_d$	Htg coil valve, clg coil valve, and mixing box dampers are all modulating simultaneously
	22	$u_{hc} > \epsilon_{hc}$ and $u_{cc} > \epsilon_{cc}$	Htg coil valve and clg coil valve are modulating simultaneously
	23	$u_{hc} > \epsilon_{hc}$ and $u_d > \epsilon_d$	Htg coil valve and mixing box dampers are modulating simultaneously
	24	$\epsilon_d < u_d < 1 - \epsilon_d$ and $u_{cc} > \epsilon_{cc}$	Clg coil valve and mixing box dampers are modulating simultaneously
	36	$u_d > (1 - \epsilon_d)$ and $(Toa > Tra + \epsilon_t)$	Economizer control indicates fully open when it should
	37	$u_d < \epsilon_d$ and $(Toa < Tra - \epsilon_t)$ and $Toa > (T_{sa,s} - DT_{sf} + \epsilon_t)$	Economizer control indicates minimum position when it should
	38	$(u_d \geq \epsilon_d) \& (u_d < (1 - \epsilon_d))$ and $(Toa < Tra - \epsilon_t)$ and $Toa > (T_{sa,s} - DT_{sf} + \epsilon_t)$	Economizer control indicates intermediate position when it should
	39	$(u_d \geq \epsilon_d) \& (u_d < (1 - \epsilon_d))$ and $(Toa > Tra + \epsilon_t)$	Economizer control indicates intermediate position when it should
	40	$u_d > (1 - \epsilon_d)$ and $(Toa < (T_{sa,s} - DT_{sf} + \epsilon_t))$	Economizer control indicates fully open when it should
	41	$u_d < \epsilon_d$ and $(Toa < (T_{sa,s} - DT_{sf} + \epsilon_t))$	Economizer control indicates minimum position when it should
All occupied modes	42	$ Toa - T_{ma} > \epsilon_t$ and $u_d > (1 - \epsilon_d)$	Economizer control indicates fully open although it is
	25	$ T_{sa} - T_{sa,s} > \epsilon_t$	Persistent supply air temp error exists
	26	$T_{ma} < \min(T_{ra}, T_{oa}) - \epsilon_t$	Mixed Air Temp should be between Return Air Temp and Outside Temp
	27	$T_{ma} > \max(T_{ra}, T_{oa}) + \epsilon_t$	Mixed Air Temp should be between Return Air Temp and Outside Temp
	28	$Number\ of\ mode\ transitions\ per\ hour > MT_{max}$	Too many mode switches

6.0 APAR testing

Several datasets have been developed using data collected with MicroDataLogger™ data acquisition equipment during field diagnostic monitoring on a variety of projects. Three samples that are provided with the ENFORMA HVAC Analyzer software have been used for the majority of the testing. Because these datasets were developed without any EMS data, certain values that are normally provided by the EMS were estimated based on expected and observed operation of the HVAC system. These values are used to determine the operating mode of the air handler and are critical to performing the fault detection, and are listed in Table 6-1.

Table 6-1. Mode indicators

Variable	Variable Description	Method used to estimate correct value for variable
UCC	Cooling coil valve position	If chiller is on, then UCC = 0.99, else UCC=0
UHC	Heating coil valve position	UHC = 0 in all cases. (All air handlers were assumed to not have any heat provided by the main air handler.)
UD	Economizer damper position	Return and outdoor air temperatures were evaluated to determine the optimal economizer position, as follows: OAT>SAT setpoint, and RAT>OAT: UD=maximum RAT<OAT: UD=minimum OAT

Other inputs not available for these tests include setpoints and schedules. For testing, these were estimated, and were only used to observe the response of the ruleset, not to identify actual faults within the datasets.

A description of each dataset is as follows:

6.1 Sample1

Sample 1 is a large VAV system with a chiller and single-speed cooling tower located in Virginia.

Results for this sample are shown in Table 6-2.

Table 6-2. Sample 1 complete fault detection results

Day	Mode	Percent of Day in Mode	Rule Violated	Percent of time rule violated	Rule Description
1	3	31%	10	88%	MAT is not equal to OAT. In this mode (100% OA), they should be equal.
2	3	23%	10	65%	MAT is not equal to OAT.
3	3	15%	10	94%	MAT is not equal to OAT.
3	3	15%	25	46%	SAT does not equal SAT set point
3	7	19%	24	95%	CC valve and economizer are both modulating incorrectly
3	7	19%	25	46%	SAT does not equal SAT set point
4	2	34%	25	95%	SAT does not equal SAT set point
4	7	6%	24	84%	CC valve and economizer are both modulating incorrectly
4	7	6%	25	95%	SAT does not equal SAT set point
5	2	63%	25	97%	SAT does not equal SAT set point
6	2	67%	25	99%	SAT does not equal SAT set point
7	2	66%	25	99%	SAT does not equal SAT set point
8	2	64%	25	99%	SAT does not equal SAT set point
9	2	61%	25	97%	SAT does not equal SAT set point
10	2	48%	25	98%	SAT does not equal SAT set point

11	2	34%	25	80%	SAT does not equal SAT set point
11	7	7%	24	86%	CC valve and economizer are both modulating incorrectly
11	7	7%	25	80%	SAT does not equal SAT set point
12	2	18%	25	95%	SAT does not equal SAT set point
12	3	37%	10	97%	MAT is not equal to OAT.
12	3	37%	25	95%	SAT does not equal SAT set point
12	7	1%	25	95%	SAT does not equal SAT set point
13	3	41%	10	93%	MAT is not equal to OAT.
13	3	41%	25	2%	SAT does not equal SAT set point
13	7	2%	24	50%	CC valve and economizer are both modulating incorrectly
13	7	2%	25	2%	SAT does not equal SAT set point
14	2	27%	25	45%	SAT does not equal SAT set point
14	7	30%	24	97%	CC valve and economizer are both modulating incorrectly
14	7	30%	25	45%	SAT does not equal SAT set point
15	2	46%	6	14%	SAT is greater than RAT.
15	2	46%	25	59%	SAT does not equal SAT set point
15	7	29%	24	97%	CC valve and economizer are both modulating incorrectly
15	7	29%	25	59%	SAT does not equal SAT set point
16	2	81%	6	14%	SAT is greater than RAT.
16	2	81%	25	100%	SAT does not equal SAT set point
17	2	41%	25	98%	SAT does not equal SAT set point
18	2	28%	25	77%	SAT does not equal SAT set point
18	3	5%	10	81%	MAT is not equal to OAT.
18	3	5%	25	77%	SAT does not equal SAT set point
18	7	2%	24	53%	CC valve and economizer are both modulating incorrectly
18	7	2%	25	77%	SAT does not equal SAT set point

As was discussed earlier, the rules associated with the supply air temperature setpoint maintenance (rule 25) are not applicable since the actual setpoint was not included in the input data file. A reduced list of detected faults, eliminating rule 25, is shown in Table 6-3

Table 6-3. Sample 1 fault detection result extraction

Day	Mode	Percent of Day in Mode	Rule Violated	Percent of time rule violated	Rule Description
1	3	31%	10	88%	MAT is not equal to OAT. In this mode (100% OA), they should be equal.
2	3	23%	10	65%	MAT is not equal to OAT.
3	3	15%	10	94%	MAT is not equal to OAT.
3	7	19%	24	95%	CC valve and economizer are both modulating incorrectly
4	7	6%	24	84%	CC valve and economizer are both modulating incorrectly
11	7	7%	24	86%	CC valve and economizer are both modulating

					incorrectly
12	3	37%	10	97%	MAT is not equal to OAT.
13	3	41%	10	93%	MAT is not equal to OAT.
13	7	2%	24	50%	CC valve and economizer are both modulating incorrectly
14	7	30%	24	97%	CC valve and economizer are both modulating incorrectly
15	2	46%	6	14%	SAT is greater than RAT.
15	7	29%	24	97%	CC valve and economizer are both modulating incorrectly
16	2	81%	6	14%	SAT is greater than RAT.
18	3	5%	10	81%	MAT is not equal to OAT.
18	7	2%	24	53%	CC valve and economizer are both modulating incorrectly

The system operated in three modes, as follows:

- Mode 2: Cooling with outside air,
- Mode 3: Cooling with outside air and mechanical cooling, and
- Mode 7: Unknown mode.

Mode 2 is identified by no mechanical cooling (UCC=0), no heating (UHC=0), and an outside air fraction between greater than minimum and up to 100 percent (min<UD<1). Mode 3 is identified by mechanical cooling and an OAF equal to 100 percent. Mode 7 is identified when the control signals do not correspond to any known mode. The faults in each mode are discussed below.

6.1.1 Mode 2 detected faults

The system operated in Mode-2 46 percent of the time on day 15 and 81 percent on day 16. Rule 6 (SAT is greater than RAT) was violated 14 percent of the time during this period. Although this is a relatively short period, it can be investigated further. Table 6-4 lists the hourly faults for mode 2. The fault began during the last hour of day 15, and continued until the third hour of day 16. The problem that caused the rule to be violated is clear in Figure 6-1, which shows a temperature history of the supply, mixed, and return temperatures when the system operated in Mode 2. For the hours listed in Table 6-4, the return air temperature dropped from its 75°F to 80°F to the 60 degree range. In addition, the supply air temperature increased to the 70-75°F range, in essence, in the heating mode. This uncovers a weakness in the data set which was discussed earlier: actual control signals to the valves and dampers were inferred based on the operation of the chiller and the relationship between the ambient and expected supply temperature setpoint. In reality, the AHU was in the heating mode.

Table 6-4. Sample 1 Mode 2 Hourly Faults

Day	Hour	Mode	Percent of Hour in Mode	Rule Violated	Percent of time rule violated	Rule Description
15	23	2	1	6	0.586	SAT is greater than RAT
16	0	2	1	6	1	SAT is greater than RAT
16	1	2	1	6	1	SAT is greater than RAT
16	2	2	1	6	1	SAT is greater than RAT
16	3	2	1	6	0.7	SAT is greater than RAT

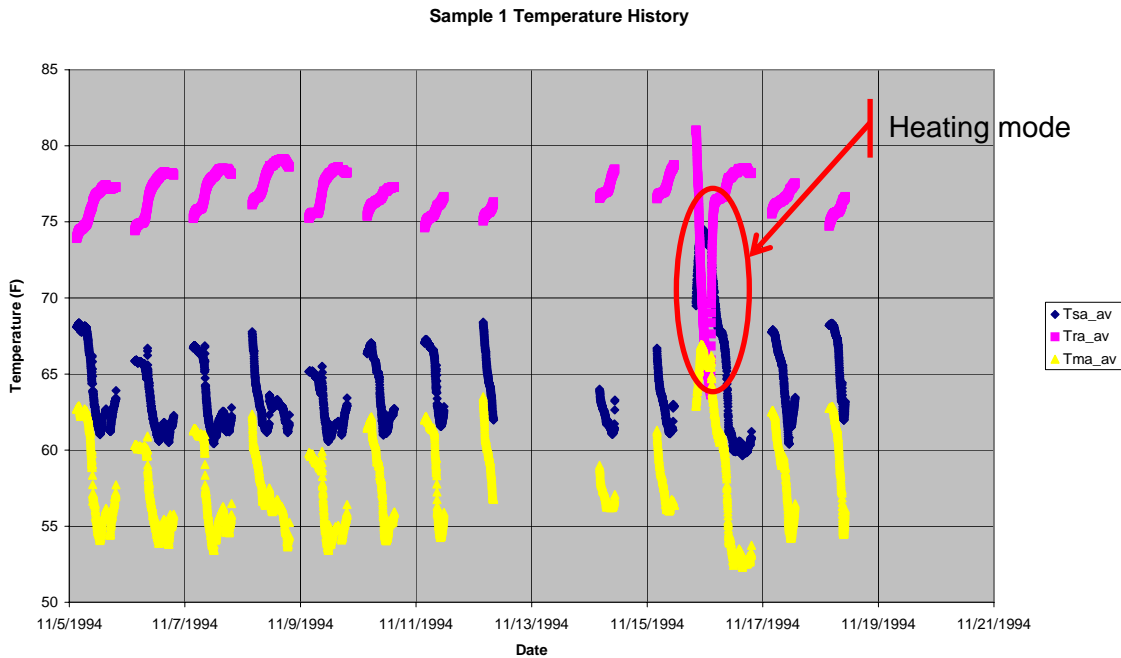


Figure 6-1. Sample 1 Mode 2 temperature history

6.1.2 Mode 3 detected faults

In mode 3 (cooling with 100% outside air and mechanical cooling)), the AHU should be operating with 100 percent outside air.

Rule 10 (mixed air temperature not equal to outside air temperature) was almost always triggered when in mode 3, which indicates that the controller was calling for 100 percent outside air, but the economizer was not providing 100% outside air. To illustrate the problem, a plot showing the economizer performance is shown in Figure 6-2 below. This figure plots the difference between MAT and RAT on the Y-axis and the difference between OAT and RAT on the X-axis. The slope of the line indicates the outside air fraction (OAF). Lines indicating 100 and 50 percent OAF are shown in the figure. In mode 3, the mixed and ambient temperatures should be equal. To meet this condition, the data shown in Figure 6-2 should follow the lower 100 percent OAF line. The data is between the 100 and 50 percent OAF lines at lower temperatures, and even above the 50 percent line at higher temperatures.

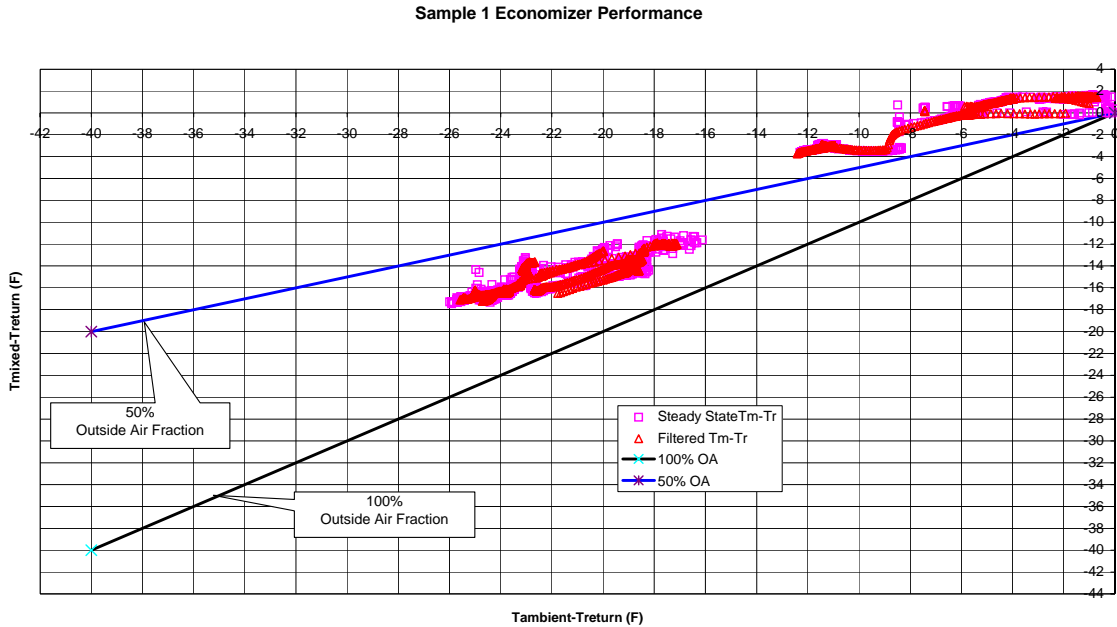


Figure 6-2. Sample 1 Mode 3 economizer performance

APAR has listed the potential causes for this fault as the following:

- MAT Sensor Error
- OAT Sensor Error
- Leaking Mixing Box Dampers
- Stuck Mixing Box Dampers

When faced with this detected fault, a building operator should investigate these potential errors. Since Mode 2 (cooling with outdoor air) determined that the difference between the supply and mixed temperatures was within tolerances, it is likely that sensor error is not the problem, at least for the mixed air sensor. Therefore, when determining the cause for this fault, the building operator should focus on the mixing box dampers to determine why the mixed air temperature was not equal to the outside air temperature.

6.1.3 Mode 7 detected faults

Mode 7 occurs when the relationship between the heating and cooling valves and the outside air dampers are inconsistent with the defined modes. The existence of this mode is indicative of a fault. Since the position of the heating coil valve was assumed to be closed for all of the Sample 1 data set, mode 7 occurred because of improper modulation of the cooling coil valve and the economizer. Rule 24 has identified this fault.

Figure 6-3 shows the position of the economizer and the cooling coil valve. A value of 1 indicates fully open. Notice that the cooling coil valve (UCC) is fully open, even though the ambient temperature is below 52°F. During mode 7, the economizer controller modulated the outside air damper between 0.6 and 0.9, attempting to maintain the mixed air temperature at the desired 55°F supply air setpoint. The problem here is that the chilled water valve was open when it should have been closed. The system operator should investigate this fault to determine why it was open.

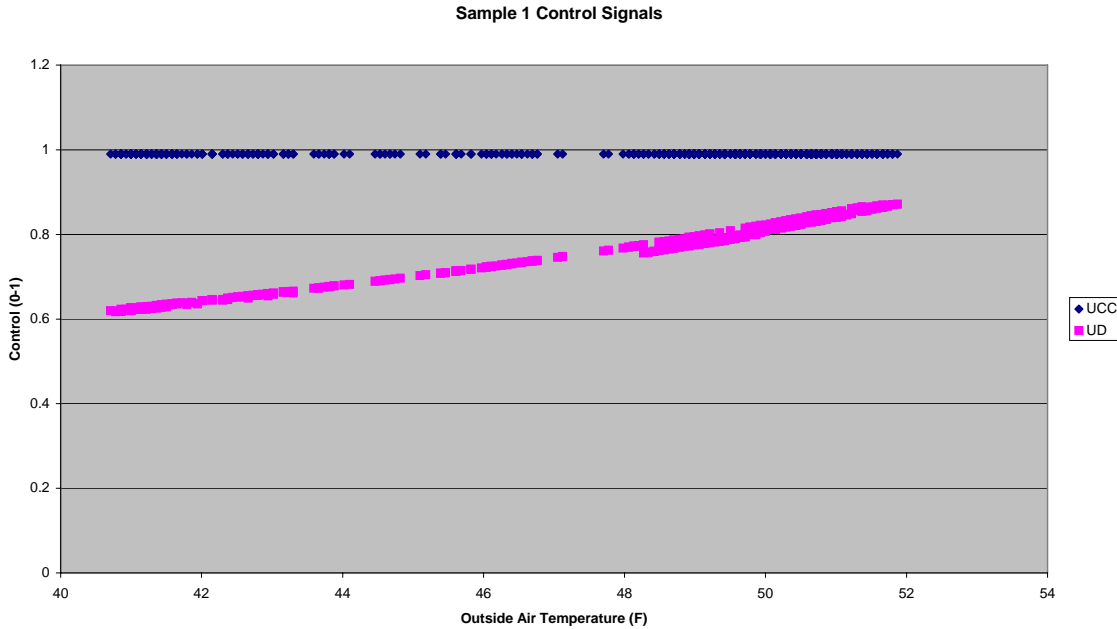


Figure 6-3. Sample 1 Mode 7 Control Signals

6.2 Sample2

Sample 2 is a smaller VAV system with chiller and cooling tower. The building that was used to generate this data set has an economizer with ideal performance characteristics. The economizer performance is shown in Figure 6-4. This plot is similar to the economizer plot for Sample 1 shown in Figure 6-2, with lines of 0, 50, and 100 percent outside air fraction. Notice that the economizer, for the most part, operates at 100 percent outside air fraction at low temperatures, and at minimum outside air fraction when the return air temperature is lower than the outside air temperature.

Figure 6-4 also shows a comparison between the raw input data and the filtered steady-state data for rule evaluation for Sample 2. Notice that the scatter in the data has in general been tightened up.

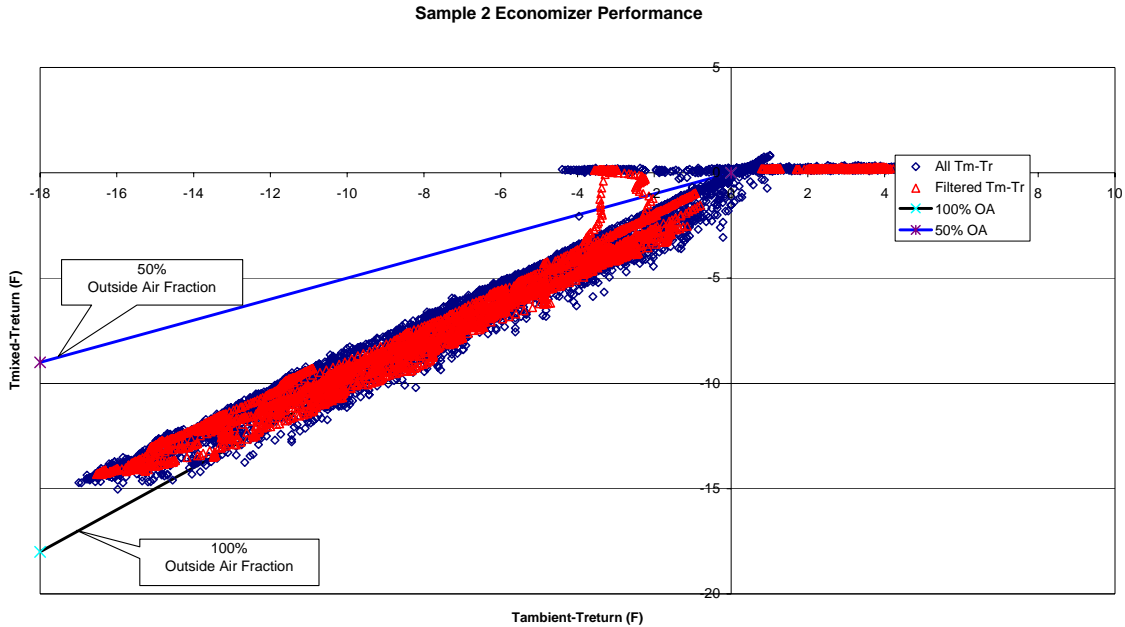


Figure 6-4. Sample 2 economizer performance

The faults detected in Sample 2 consist solely of differences between the supply air temperature and the supply air temperature setpoint. As was discussed in the previous section, this fault has been caused by assumptions when developing the data sets. The actual supply air temperature setpoint was not known, and so the fact that a difference was detected between the assumed setpoint and the actual supply air temperature is not indicative of a problem with the air handler.

Table 6-5. Sample 2 hourly fault detection results

Day	Hour	Mode	Percent of Hour in Mode	Rule Violated	Percent of time rule violated	Rule Description
9	11	3	1	25	0.379	SAT does not equal SAT set point
9	12	3	1	25	0.7	SAT does not equal SAT set point
10	10	3	1	25	0.806	SAT does not equal SAT set point
10	11	3	1	25	1	SAT does not equal SAT set point
10	12	3	1	25	1	SAT does not equal SAT set point
10	13	3	1	25	0.677	SAT does not equal SAT set point

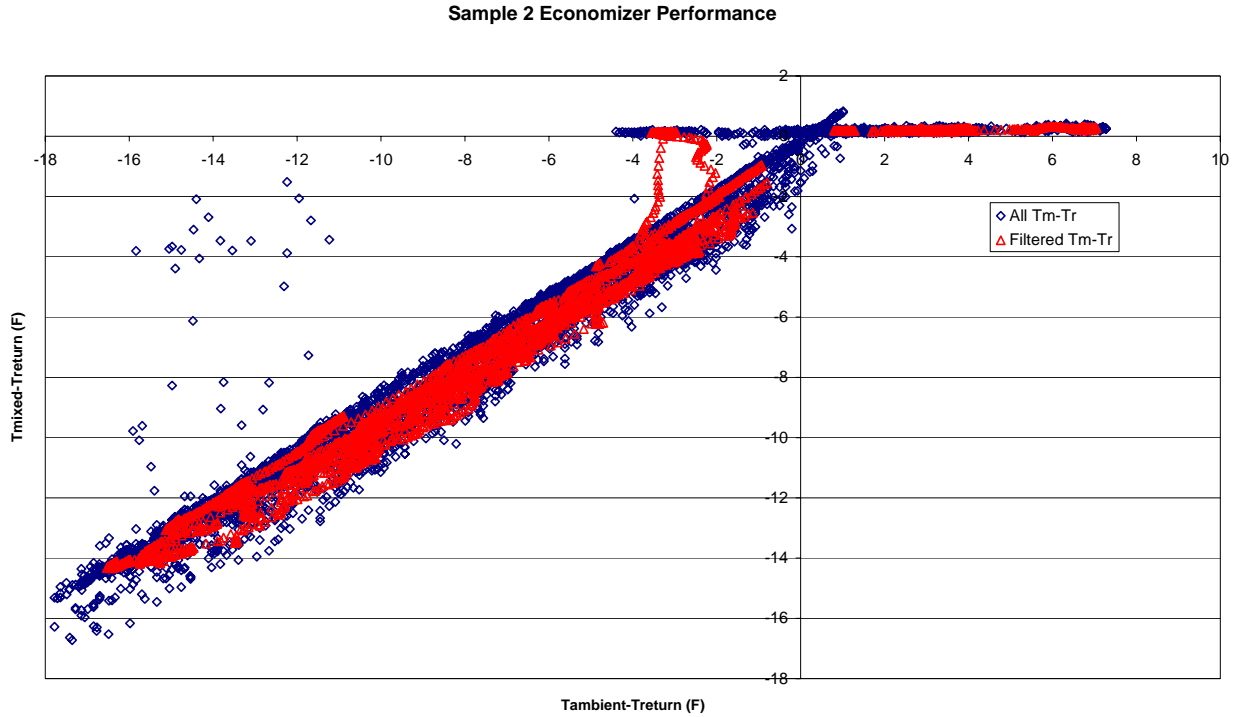


Figure 6-5. Sample 2 Economizer performance: Raw and Filtered data

6.3 Sample3

Sample 3 contains data for a medium sized packaged VAV rooftop unit. There are two faults included in this data: the first is that the static pressure drops at high flow. The other fault is that whenever mechanical cooling is called, the economizer outside air damper goes to a minimum position. Since the current version of APAR does not consider faults associated with static pressure, this problem will not be considered. However, the economizer problem will be considered.

The hourly fault detection is shown in Table 6-6. Faults were detected in modes 3 (Mechanical cooling with 100% outside air) and mode 5 (Cooling with 100% Outdoor air: no mechanical cooling). Note that Mode 5 is a new mode to account for cases when cooling is possible when the outdoor temperature is below the return temperature, but not below the normal supply air temperature setpoint. Rule 10 and 31 were violated. These rules are functionally similar, indicating that the mixed and ambient temperatures are not equal.

Table 6-6. Sample 3 hourly fault detection results

Day	Hour	Mode	Percent of Hour in Mode	Rule Violated	Percent of time rule violated	Rule Description
2	0	3	0.633	10	0.842	MAT is not equal to OAT. In this mode (100% OA), they should be equal.
3	22	3	0.645	10	0.75	MAT is not equal to OAT.

4	20	3	0.724	10	0.667	MAT is not equal to OAT.
4	21	3	0.667	10	1	MAT is not equal to OAT.
5	8	3	0.483	10	0.5	MAT is not equal to OAT.
5	9	3	0.567	10	0.412	MAT is not equal to OAT.
5	20	3	0.517	10	0.533	MAT is not equal to OAT.
5	20	3	0.517	10	0.533	MAT is not equal to OAT.
5	21	3	0.167	10	1	MAT is not equal to OAT.
5	23	3	0.586	10	0.588	MAT is not equal to OAT.
6	0	3	0.067	10	1	MAT is not equal to OAT.
6	21	3	0.433	10	0.923	MAT is not equal to OAT.
6	23	3	0.69	10	0.65	MAT is not equal to OAT.
7	1	3	0.548	10	0.588	MAT is not equal to OAT.
7	2	3	0.069	10	1	MAT is not equal to OAT.
7	4	3	0.29	10	0.889	MAT is not equal to OAT.
9	9	3	0.467	10	0.5	MAT is not equal to OAT.
9	10	3	1	10	1	MAT is not equal to OAT.
9	11	3	1	10	0.414	MAT is not equal to OAT.
9	16	3	0.548	10	0.588	MAT is not equal to OAT.
9	17	3	1	10	1	MAT is not equal to OAT.
9	18	3	0.967	10	1	MAT is not equal to OAT.
9	21	3	0.467	10	0.857	MAT is not equal to OAT.
10	7	5	0.581	31	0.333	MAT is not equal to OAT.
10	8	5	0.345	31	1	MAT is not equal to OAT.
10	9	3	0.633	10	0.263	MAT is not equal to OAT.
10	10	3	1	10	0.935	MAT is not equal to OAT.
10	11	3	0.207	10	0.833	MAT is not equal to OAT.
10	18	3	1	10	0.167	MAT is not equal to OAT.
10	19	3	0.452	10	1	MAT is not equal to OAT.
10	21	3	0.5	10	0.867	MAT is not equal to OAT.
11	8	5	0.552	31	0.875	MAT is not equal to OAT.
11	22	3	0.387	10	0.417	MAT is not equal to OAT.
11	23	3	0.276	10	1	MAT is not equal to OAT.
12	21	3	0.633	10	0.632	MAT is not equal to OAT.
13	18	3	0.967	10	0.241	MAT is not equal to OAT.
14	9	3	0.967	10	0.759	MAT is not equal to OAT.
14	10	3	1	10	0.613	MAT is not equal to OAT.

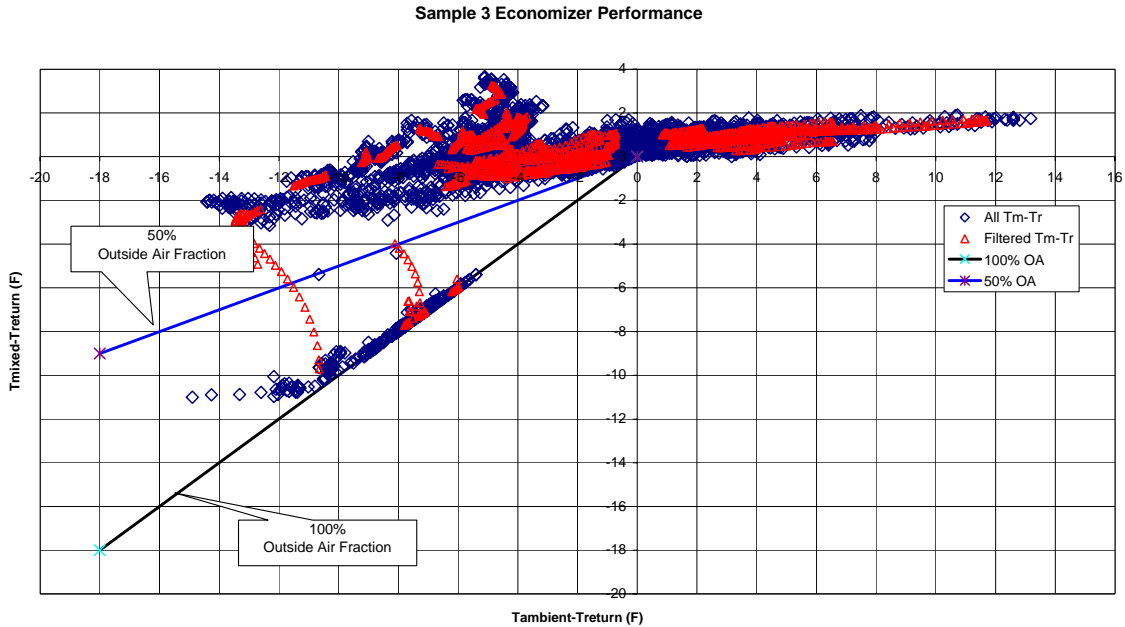


Figure 6-6. Sample 3 economizer performance

Faults were detected during Mode 5 operation, which occurred only twice during the two-week data collection period: between hours 8-9 on day 10, and during hour 8 on day 11. These periods are shown in Figure 6-7. The rule was violated because the data was not following the lower 100% OAF line. In other words, the economizer was closed when it should have been open.

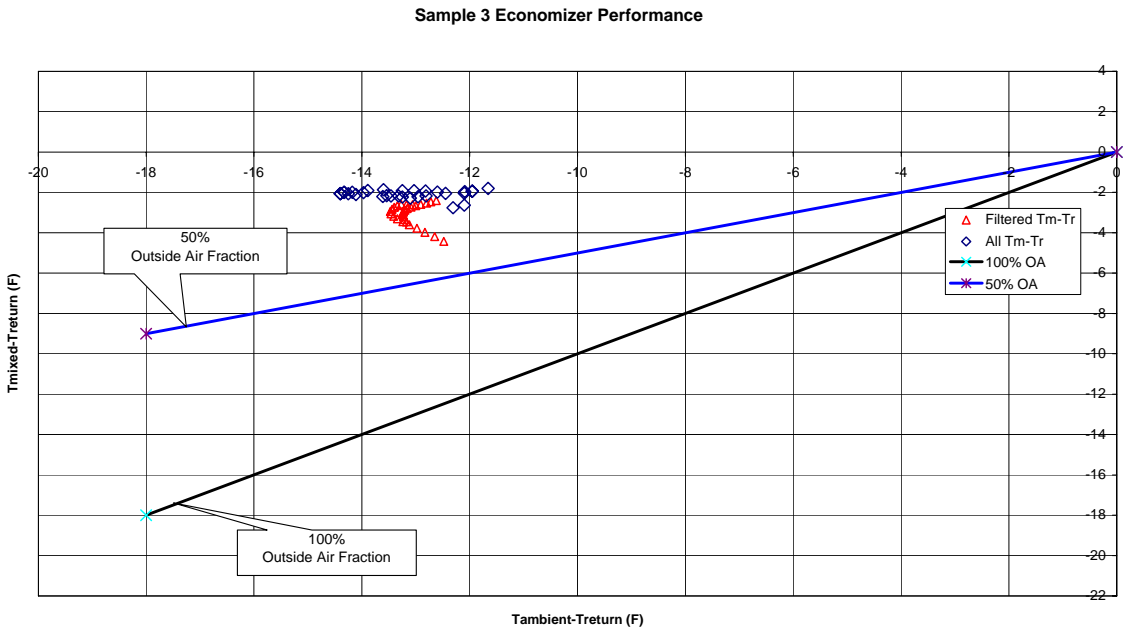


Figure 6-7. Sample 3 economizer performance: Mode 5 Rule 31 violated

Figure 6-8 shows the periods when rule 10 was violated during mode 3. Similar to the situation discussed in the previous figure, the data should be following the lower 100% OAF line.

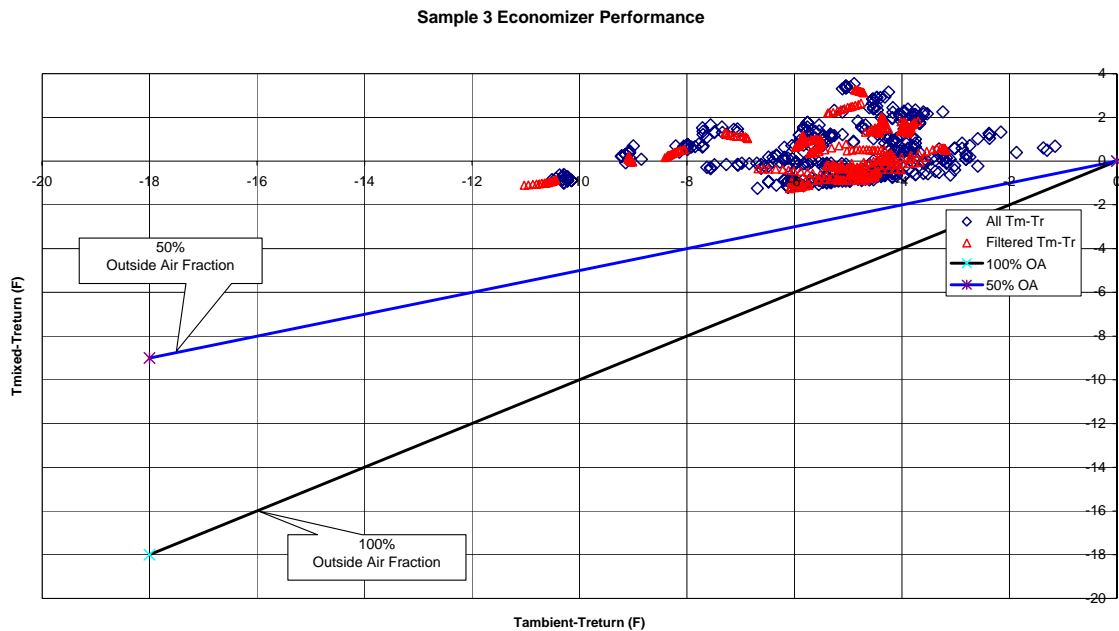


Figure 6-8. Sample 3 economizer performance: Mode 3 Rule 10 violated

It is clear from Figure 6-6 that the economizer can and does operate at 100 percent outside air fraction. However, it is also clear that it modulates to a minimum position, particularly in Mode 3 when the system is providing cooling using mechanical cooling. When presented with this fault, the building operator should investigate why the economizer operates at minimum position whenever mechanical cooling is being used.

The actual cause of this behavior was related to a non-integrated economizer. Recall that sample 3 is based on a packaged system with DX cooling. In this system, the economizer goes to a minimum position whenever one or more of the compressors is energized. This fault would not exist in a system with a properly operating integrated economizer control.

7.0 Potential Causes

Determining the single cause that resulted in an air handler fault is difficult because of the wide range of ways that an air handler can cause a particular fault. For example, during a free cooling mode when the outside air and the mixed air temperatures should be roughly equal. If the data show that these temperatures are not equal, it could be due to sensor error, a mechanical problem with the dampers or actuators, electrical or pneumatic problems, or control algorithm problems. Without more data, it is impractical to attempt to determine which potential cause was the actual cause of the fault. However, over time, when the system has been exercised through enough modes, it could be possible to narrow the number of potential causes, but during normal operation, this may take a period of several months. However, the goal of any fault detection system should be to announce that a fault has occurred to the operator so that action can be taken to resolve the problem. Waiting several months to allow the system to determine the actual cause will result in months of sub-optimal operation.

Therefore, it is more expedient to provide a list of potential causes to the system operator rather than to attempt to reduce the list of causes. A table of potential causes for each rule violation is shown in Table 7-1.

Table 7-1. Potential Causes Matrix

Mode	Rule	Rule Expression (true implies existence of a fault)	SAT Sensor Error	RAT Sensor Error	MAT Sensor Error	OAT Sensor Error	Leaking CC Valve	Stuck CC Valve	Undersized CC	Fouled CC	CHWST too high	CHW circ pump fault	CHW not available	Leaking HC Valve	Stuck HC Valve	Undersized HC	
Mode 1: Heating	1	$T_{sa} < T_{ma} + \Delta T_{sf} - \epsilon_t$	*														
	2	For $ T_{ra} - T_{oa} \geq \Delta T_{min}$: $ Q_{oa}/Q_{sa} - (Q_{oa}/Q_{sa})_{min} > \epsilon_f$ OR, $(abs((T_{ma}_{av} - T_{ra}_{av}))(Toa_{av} - T_{ra}_{av}) - Q_{oa_frac_min}) > \epsilon_f$		*													
	3	$ u_{hc} - l \leq \epsilon_{hc}$ and $T_{sa,s} - T_{sa} \geq \epsilon_t$	*														
	4	$ u_{hc} - l \leq \epsilon_{hc}$	*														
Mode 2: Cooling with Outdoor Air	5	$T_{oa} > T_{sa,s} - \Delta T_{sf} + \epsilon_t$	*														
	6	$T_{sa} > T_{ra} - \Delta T_{rf} + \epsilon_t$	*	*													
	7	$ T_{sa} - \Delta T_{sf} - T_{ma} > \epsilon_t$	*														
Mode 3: Mechanical Cooling with 100%Outdoor Air	8	$T_{oa} < T_{sa,s} - \Delta T_{sf} - \epsilon_t$	*														
	9	$T_{oa} > T_{co} + \epsilon_t$ (or $Toa > Tra + \epsilon_t$)															
	10	$ T_{oa} - T_{ma} > \epsilon_t$															
	11	$T_{sa} > T_{ma} + \Delta T_{sf} + \epsilon_t$	*														
	12	$T_{sa} > T_{ra} - \Delta T_{rf} + \epsilon_t$	*	*													
	13	$ u_{cc} - l \leq \epsilon_{cc}$ and $T_{sa} - T_{sa,s} \geq \epsilon_t$	*														
Mode 4: Mechanical Cooling with Minimum Outdoor Air	14	$ u_{cc} - l \leq \epsilon_{cc}$	*														
	15	$T_{oa} < T_{co} - \epsilon_t$ or $(Toa < Tra - \epsilon_t)$															
	16	$T_{sa} > T_{ma} + \Delta T_{sf} + \epsilon_t$	*														
	17	$T_{sa} > T_{ra} - \Delta T_{rf} + \epsilon_t$	*	*													
	18	If $ T_{ra} - T_{oa} \geq \Delta T_{min}$: $abs(T_{ma} - T_{ra}) / (Toa - T_{ra}) - Q_{oa_frac} > \epsilon_f$		*													
	19	$ u_{cc} - l \leq \epsilon_{cc}$ and $T_{sa} - T_{sa,s} \geq \epsilon_t$	*														
New Mode 5: Cooling with 100% Outdoor air ONLY	20	$ u_{cc} - l \leq \epsilon_{cc}$	*														
	29	$T_{sa} > T_{ra} - \Delta T_{rf} + \epsilon_t$															
	30	$ T_{sa} - \Delta T_{sf} - T_{ma} > \epsilon_t$															
	31	$ T_{oa} - T_{ma} > \epsilon_t$															
Mode 6: Ventilation with Minimum Outdoor Air	32	$ T_{sa} - \Delta T_{sf} - T_{ma} > \epsilon_t$															
	33	$T_{sa} > T_{ma} + \Delta T_{sf} + \epsilon_t$															
	34	$T_{sa} > T_{ra} - \Delta T_{rf} + \epsilon_t$															
Mode 7: Unknown Occupied Mode	35	For $ T_{ra} - T_{oa} \geq \Delta T_{min}$: $ Q_{oa}/Q_{sa} - (Q_{oa}/Q_{sa})_{min} > \epsilon_f$ OR, $(abs((T_{ma}_{av} - T_{ra}_{av}))(Toa_{av} - T_{ra}_{av}) - Q_{oa_frac_min}) > \epsilon_f$															
	21	$u_{cc} > \epsilon_{cc}$ and $u_{hc} > \epsilon_{hc}$ and $\epsilon_d < u_d < 1 - \epsilon_d$															
	22	$u_{hc} > \epsilon_{hc}$ and $u_{cc} > \epsilon_{cc}$															
	23	$u_{hc} > \epsilon_{hc}$ and $u_d > \epsilon_d$															
	24	$\epsilon_d < u_d < 1 - \epsilon_d$ and $u_{cc} > \epsilon_{cc}$															
	36	$u_d > (1 - \epsilon_d)$ and $(Toa > Tra + \epsilon_t)$															
	37	$u_d < \epsilon_d$ and $(Toa < Tra - \epsilon_t)$ and $Toa > (T_{sa,s} - DT_{sf} + \epsilon_t)$															
	38	$(u_d > \epsilon_d) \& (u_d < (1 - \epsilon_d))$ and $(Toa < Tra - \epsilon_t)$ and $Toa > (T_{sa,s} - DT_{sf} + \epsilon_t)$															
	39	$(u_d > \epsilon_d) \& (u_d < (1 - \epsilon_d))$ and $(Toa > Tra + \epsilon_t)$															
	40	$u_d > (1 - \epsilon_d)$ and $(Toa < (T_{sa,s} - DT_{sf} - \epsilon_t))$															
All occupied modes	41	$u_d < \epsilon_d$ and $(Toa < (T_{sa,s} - DT_{sf} - \epsilon_t))$															
	42	$ Toa - T_{ma} > \epsilon_t$ and $u_d > (1 - \epsilon_d)$															
	25	$ T_{sa} - T_{sa,s} > \epsilon_t$															
	26	$T_{ma} < \min(T_{ra}, T_{oa}) - \epsilon_t$															
	27	$T_{ma} > \max(T_{ra}, T_{oa}) + \epsilon_t$		*													
	28	Number of mode transitions per hour $> MT_{max}$		*													

8.0 Conclusions

The results from these three data sets show that APAR can successfully identify faults in air handlers. In addition, well operating systems do not generate false positives, which is perhaps just as important to ensure that the system is used and trusted.

9.0 References

[1] Bushby, S.T., Castro, N.S., Schein, J, House, J.M., 2001, "Testing AHU rule-based diagnostic tool & VAV diagnostic tool using the VCBT", Energy Efficient and Affordable Small Commercial and Residential Buildings Research Program Task Report

[2] House, J.M., Vaezi-Nejad, H., and Whitcomb, J.M., 2001, "An Expert Rule Set for Fault Detection in Air-Handling Units," *ASHRAE Transactions*, Vol. 107, Pt. 1.