Research note

Project	TRECO Office/ WP 4.4	**Date**	21 Dec. 2017
Subject	Rule-based FDD approach for AHU's	**Status**	Draft
Author	J.I. Torrens (TUE)	**Co-reader**	Kees Wisse (DWA)

This Research note describes the application of APAR Fault Detection and Diagnosis (FDD) to the TRECO project Air Handling Unit (AHU). The APAR rule-based FDD approach has been adapted for the specific characteristics of the TRECO AHU (no mixing chamber, enthalpy wheel heat recovery).

- ***Air handling unit performance assessment rules (APAR) – FDD approach***

Air handling unit performance assessment rules (APAR) is a fault detection tool that uses a set of expert rules derived from mass and energy balances to detect faults in air handling units (AHUs) [1]. This FD method was developed for application to single duct variable or constant volume AHUs, which covers the majority of AHUs in operation. The rules that are used for FDD focus on temperature control in an AHU. APAR uses control signals and occupancy information to identify the mode of operation of the AHU. Every mode will have a subset of rules associated to it that specify temperature relationships that are applicable. The original operation modes [1] were adapted to suit the TRECO AHU, resulting in the following ones:

  - Mode 11: ***Heating*** (Heat recovery ON + Heating Coil ON)
  - Mode 21: ***Heat Recovery*** (HR)
  - Mode 22: ***Free Cooling*** (HR OFF, Heating and Cooling coils OFF)
  - Mode 32: ***Mechanical cooling*** (HR ON, Cooling Coil ON)
  - Mode 99: ***unknown*** (used as transition period between the above modes)

APAR does not search for the existence of a specific set of faults. Rather, any fault that causes a rule to be satisfied would be detected and additional effort would be necessary to isolate the source of the problem. In general, the rule set can identify the following faults:

- Stuck or leaking mixing box dampers, heating coil valves, and cooling coil valves;
- Temperature sensor faults;
- Design faults such as undersized coils;
- Controller programming errors related to tuning, setpoints, and sequencing logic;
- Inappropriate operator intervention.

- ***TRECO-office Air Handling Unit description***

The schematic of an existing AHU from the project case-study is shown in Figure 1. The AHU consists of heating and cooling coils, humidification and heat recovery (through an enthalpy/heat recovery wheel).

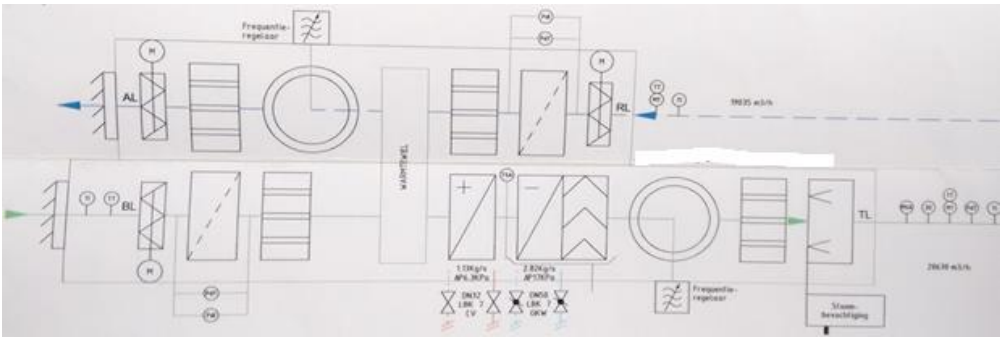

Figure 1. Schematic of the Air-Handling unit from the TRECO-office case-study building

Temperatures, Control signal of fans, dampers valves (heating and cooling coils and humidification) and thermal wheel motor are monitored with a frequency of 1h.

- ***Measured data and initial assumptions***

Two sets of measured data were used in the application of the APAR FDD approach. The complete months of December (characteristic of winter operation) and August (characteristic of summer operation) were recorded with an hourly frequency.
The temperature after the enthalpy wheel, was computed based on the temperatures of the return air and the outside air and assuming that its thermal efficiency follows a performance curve represented by:

$$eff = eff_{max} * (1 - \exp(-0.08x))$$

Where:
eff= heat exchange efficiency [0,1] of the enthalpy wheel (maximum efficiency assumed to be 70%)
x = control signal [0,1] of wheel speed

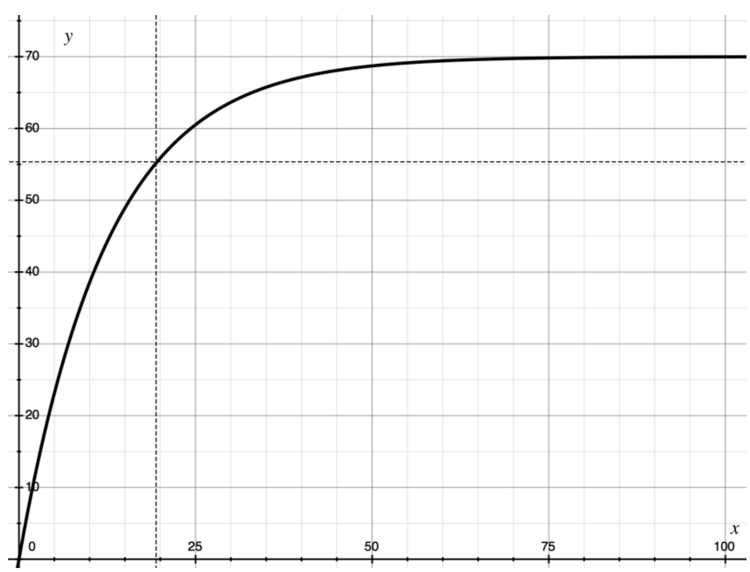

Figure 2. Performance Curve assumed for the operation of the enthalpy wheel

- ***FDD applied to the TRECO AHU***

The outside air temperature and the demand on the building side, and the return temperature dictate the most suitable operation mode and the operation objective they try to accomplish (Figure 3).

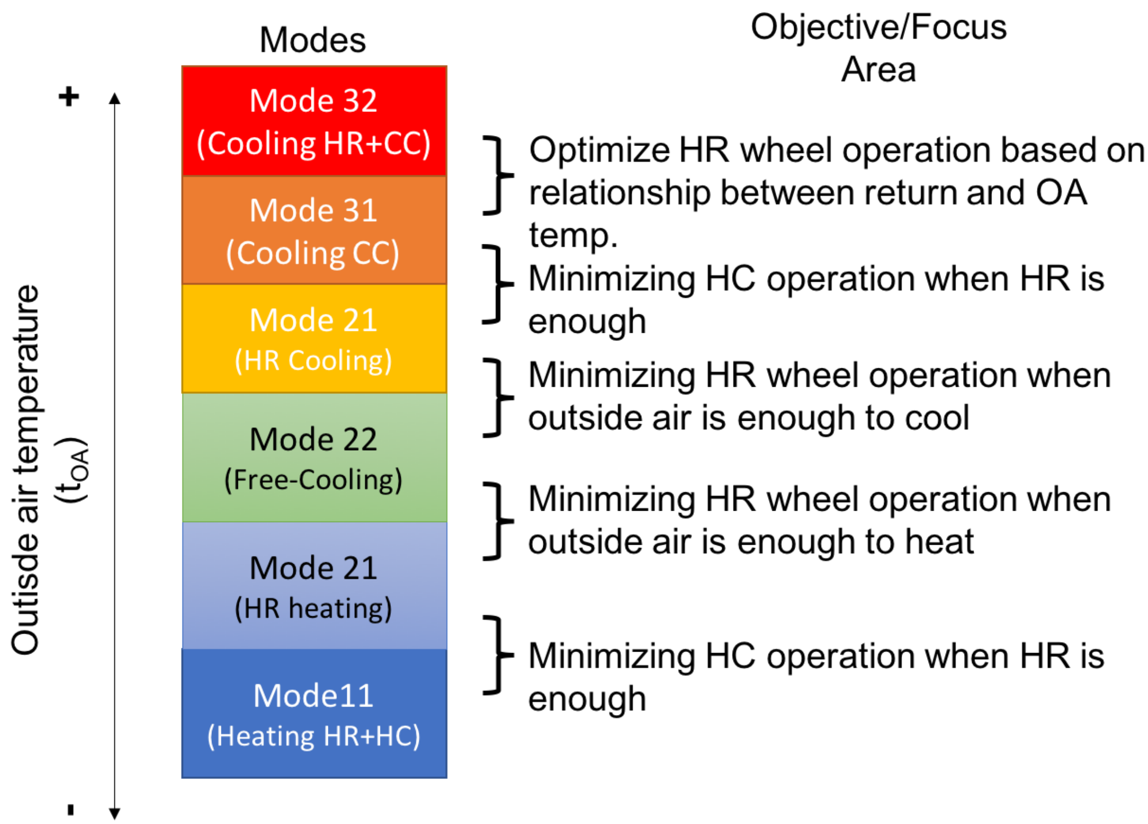

Figure 3. AHU Operation modes and objectives

An APAR AHU FDD program is implemented in Matlab to identify faults directly related to the specified modes of operation based on temperature readings and control signals. The complete list of faults considered can be observed in Table 1.

Table 1. Rule-set

RULE 1: inconsistency between the supply and heat recovery temperatures
RULE 2: the fraction of outdoor air entering the AHU is either too high or too low
RULE 4: warning: the system is out of control
RULE 5: outdoor temperature is too high for the free-cooling mode

RULE 6: inconsistency between the supply and return air temperatures
RULE 7: inconsistency between the supply and heat recovery air
RULE 8: outdoor temperature air is too low for the mode of mechanical cooling with 100% outdoor air
RULE 9: outdoor temperature is too high for mechanical cooling with 100% outdoor air
RULE 10: inconsistency between outdoor and heat recovery air temperatures
RULE 11: inconsistency between supply and heat recovery air temperatures
RULE 12: inconsistency between supply and return air temperatures
RULE 13: cooling coil valve is saturated
RULE 14: warning: the system is out of control
RULE 15: outdoor air temperature is too low for mode of mechanical cooling with minimum outdoor air
RULE 16: inconsistency between supply and heat recovery air temperatures
RULE 17: inconsistency between supply and returned air temperatures
RULE 19: cooling coil valve is saturated
RULE 20: warning: the system is out of control
RULE 21: cooling coil valve, heating coil valve and heat recovery wheel are modulating simultaneously
RULE 22: at least two of the devices: CC valve, HC valve and HR wheel are modulating simultaneously
RULE 23: at least two of the devices: CC valve, HC valve and HR wheel are modulating simultaneously
RULE 24: at least two of the devices: CC valve, HC valve and HR wheel are modulating simultaneously
RULE 25: Supply air temperature set point is not being satisfied
RULE 26: inconsistency in mixed, return or outdoor temperature measurements
RULE 27: inconsistency in mixed, return or outdoor temperature measurements
RULE 28: mode changes too quickly

After running the FDD approach in the measure data-sets, we can observe, at first glance, the distribution of operation modes in the time evaluated. As can be seen in Figure 4.

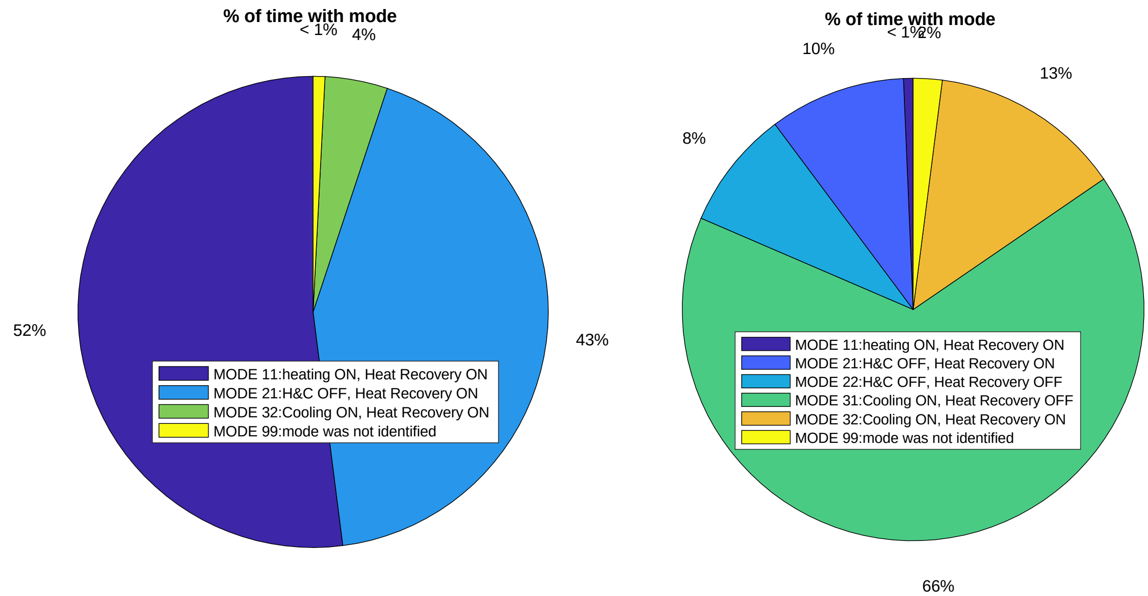

Figure 4. Time spent in AHU operation modes for December (left) and August (right)

In December, as expected the heat recovery wheel is in operation for the whole time (>99%). Heating (95% of the time) occurs with the operation of the Heating coil but for 43% of the time, the supply set-point temperature is satisfied through the use of heat recovery. In August, Cooling without heat recovery is active for two thirds of the time, but we can see a greater diversity of modes operation occurring, likely due to a variation of the outside air temperature that goes above and below the supply air temperature set point prescribed.

Faults triggered the December data-set

The total number of faults identified by the FDD program can be observed in Figure 5. Discarding the faults triggered by Mode 99 (unidentified), rule no. 1 and rule no. 7 are frequently triggered. The description, impact and actions recommended associated with the fault are presented as follows:

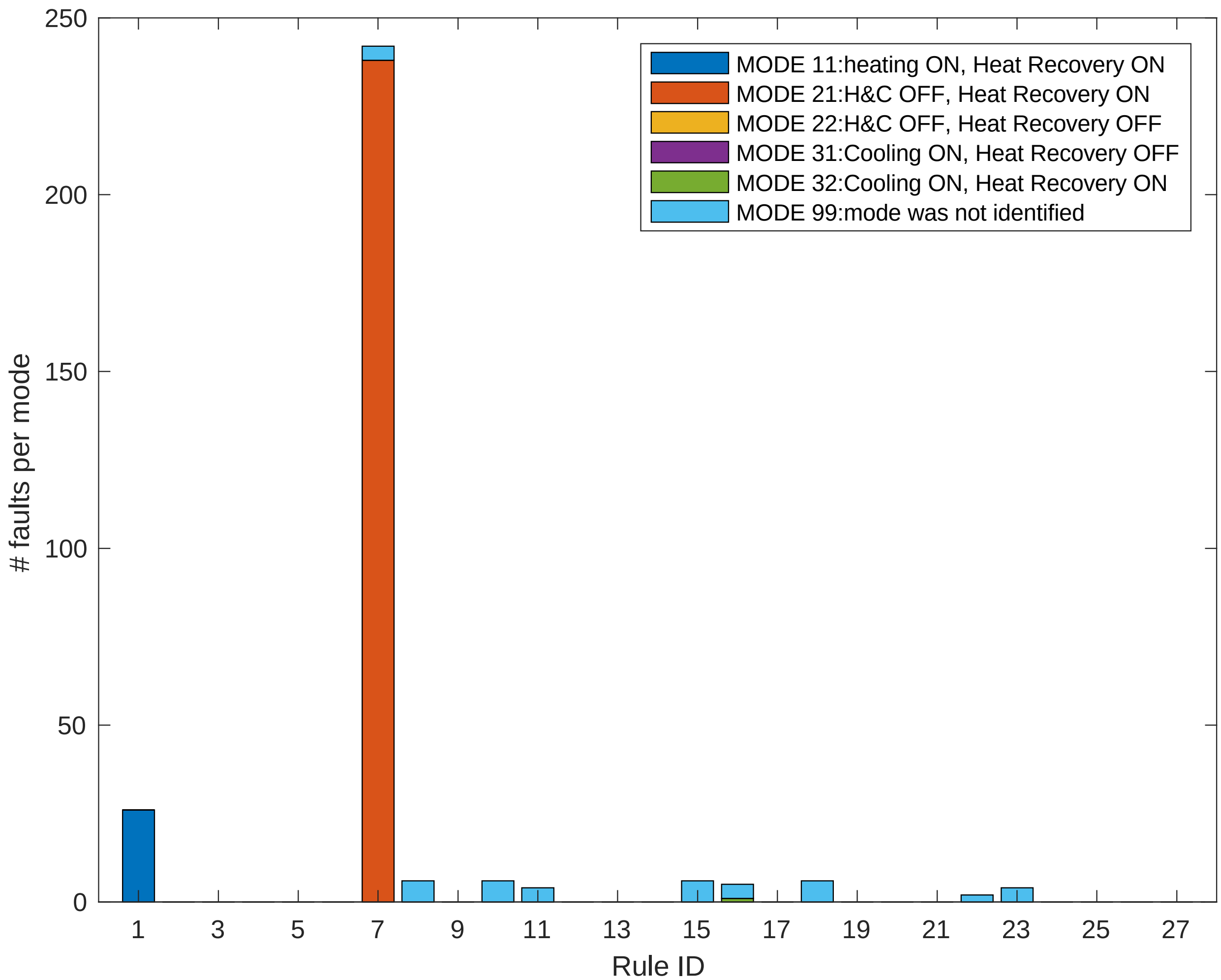

Figure 5. Faults triggered based on rule ID and AHU operation mode for December

Rule 1: inconsistency between the supply and heat recovery temperatures

- ***Impact***: Comfort and Energy
  - ***Action*** Check Heating and Cooling valve/signals and sensors (sensor malfunction / leaking valves)

Rule 7: inconsistency between the supply and heat recovery air

- ***Impact***: Energy
  - ***Action*** Check Heating and Cooling valve/signals and sensors (sensor malfunction / leaking valves)
- Review estimation of Thr (temperature after the enthalpy wheel). Validate it measuring Thr

Faults triggered the August data-set

The total number of faults identified by the FDD program can be observed in Figure 6. Discarding the faults triggered by Mode 99 (unidentified), a number of rules are triggered. The description, impact and actions recommended associated with these faults are presented as follows:

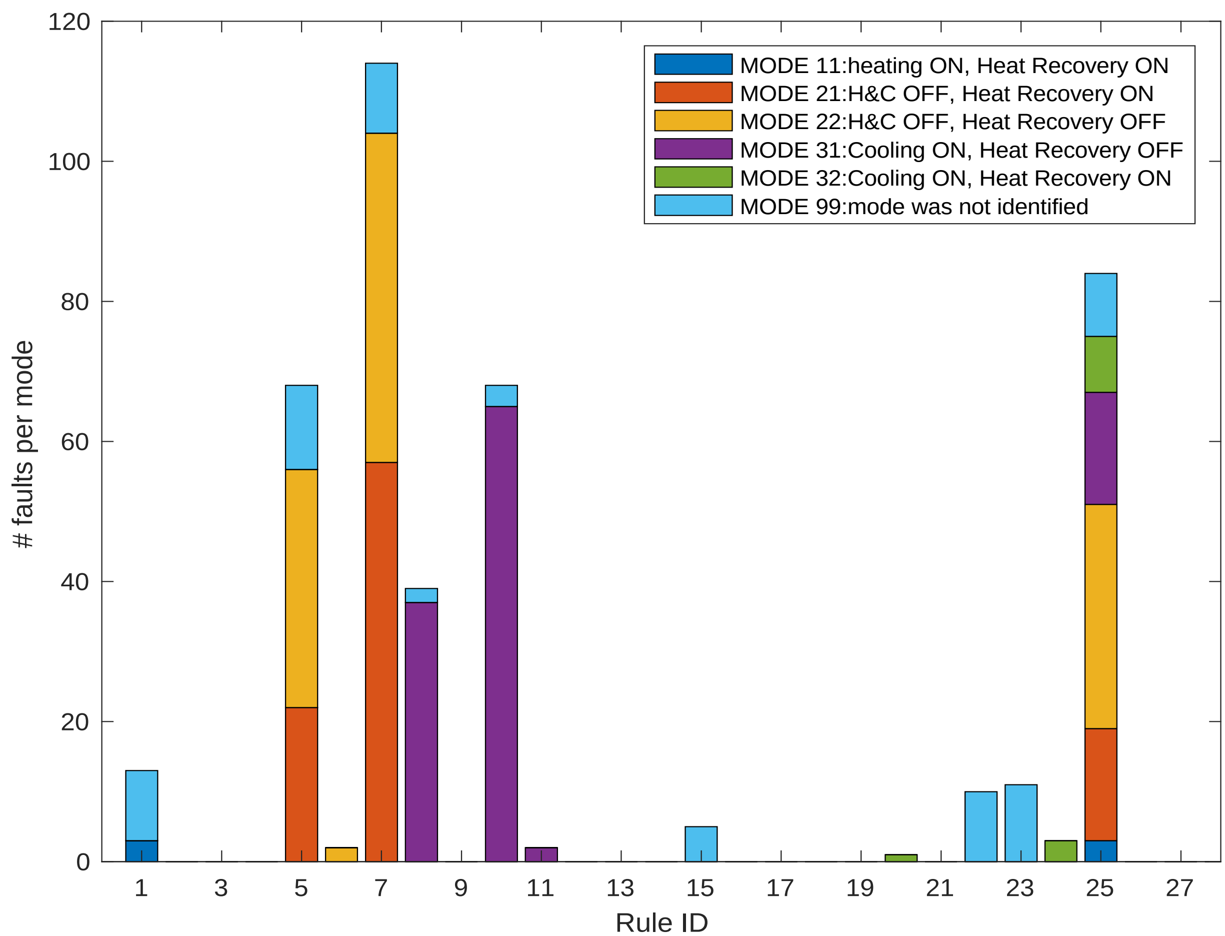

Figure 6. Faults triggered based on rule ID and AHU operation mode for August

Rule 1: inconsistency between the supply and heat recovery temperatures

- ***Impact***: Comfort and Energy
    - ***Action*** Check Heating and Cooling valve/signals and sensors (sensor malfunction / leaking valves)

Rule 5: outdoor temperature is too high for the free-cooling mode

- ***Impact***: Energy
- The control should transition to Cooling Modes (31 or 32) since Outdoor temp. is too high
    - ***Action*** Check OA temperature and supply air sensors (sensor malfunction / leaking valves)

Rule 7: inconsistency between the supply and heat recovery air

- ***Impact***: Energy
    - ***Action*** Check Heating and Cooling valve/signals and sensors (sensor malfunction / leaking valves)
- Review estimation of Thr (temperature after the enthalpy wheel), validate it measuring Thr

Rule 8: outdoor temperature air is too low for the mode of mechanical cooling with no HR

- ***Impact***: Energy
- The control should transition to HR or free cooling modes (21 or 22) since Outdoor temp. is too low for the CC to be ON. Possible passing/stuck heating/cooling valves.
    - ***Action*** Check Heating and Cooling valve/signals and sensors

Rule 10: inconsistency between outdoor and heat recovery air temperatures

- ***Impact***: Energy
- Significant difference between OA air temp and HR temp with HR OFF
    - ***Action*** Check OA and HR temp. sensors and air leakage in the Enthalpy wheel

Rule 25: Supply air temperature set point is not being satisfied

- ***Impact***: Energy
- Supply air temperature not satisfied
    - ***Action*** Check Control strategy/tuning

Future work

Based on the requisites of the approach, and looking at the measured data available from the AHU case-study, several actions could be taken to further enhance the APAR FDD approach:

1. Increased frequency of monitored data. As opposed to hydronic systems, an AHU can have a rapid response to input control signals and demands from the conditioned space. Therefore, the data (temperatures, control signals) required as input for this approach, is recommended to be of at least 15min frequency.
2. For the presented results, the air temperature after heating recovery was estimated based on a characteristic Performance curve of enthalpy wheels and a maximum thermal efficiency of 70%. A further study to validate this assumption would be beneficial to eliminate false positives from the faults detected.
3. The operation of the humidifier was only taken into account in post-processing to assess the faults detected, the integration of this humidifier as sub-component in the program, as well as the integration of relative humidity across the AHU for FD is recommended for further investigation.

References

[1] J. Schein, S. T. Bushby, N. S. Castro, and J. M. House, "A rule-based fault detection method for air handling units," *Energy Build.*, vol. 38, no. 12, pp. 1485–1492, Dec. 2006.