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# Deliverable 1.03

# Open library of standardized DBN models for the most common components & sensors, models and controls in HVAC installations

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# SUMMARY

In the B4B project, DBNs (Diagnostic Bayesian Networks) are developed for fault detection and diagnosis (FDD) purposes based on the 4S3F (four symptoms and 3 faults) architecture developed by Taal [1]. However, the DBN models in [1] are specific to the research. In this report, a start is made for setup a library with standardised HVAC DBN models. In particular, 4S3F DBN models, developed in [1] and DBNs from B4B case studies

An HVAC system consists of subsystems, which could also contain subsystems. This document proposes four system levels in which component and control faults could be isolated.

- Level A: partly or whole HVAC system
- Level B: HVAC subsystems
- Level C: components
- Level D: subcomponents inside components

FDD DBNs at Levels A to C were discussed in this document. These DBN models can be set up in several ways. This report's proposed DBN models at level B were based on the HVAC hydronic and air handling unit modules presented in ISSO publications 31, 44 and 47, Dutch guidelines for HVAC systems. A generic hydronic DBN can be developed for a generator, distribution and user module. A specific hydronic module can be adapted by leaving out some nodes.

The discussed component DBNs at level C were extracted from these modules and the DBNs at level A can be setup by combinations of DBNs at level B.

The Level A and B DBN models can contain embedded lower level DBNs as well as subsystem or component nodes. Considerations and recommendations for choices were presented. Examples of DBNs in case studies (presented in Appendix C) supported the choices. So-called 'Help' nodes could support setting up DBNs when many symptoms are linked to a fault node or to rule out faults in an HVAC mode.

Although the purpose of this document is not to discuss the rules and set probabilities for symptom detection, consideration has been given to possible symptom rules for an air handling unit to help narrow down options for symptoms.

The main recommendation of this document is that the DBN library be modular, meaning that parts of generic DBNs can be replaced by others and that the DBN can be easily modified and extended without changing the DBN structure. For example, energy-related input and output sensors are placed outside a standardized module or component DBN to be linked to multiple modules and component fault nodes and DBNs. In addition, generic hydronic modules should be developed to reduce the number of DBNs in a library. This could also be done for air distribution and user modules. It was recommended to realize this for a sensor-rich (in accordance with ISSO 31) and a sensor-poor environment (in accordance with ASHRAE).

Next to this, it was recommended that in addition to hydronic HVAC and air handling unit modules, modules should also be developed for air distribution and user modules, and non-HVAC modules as electrical systems, solar collectors, cogeneration systems.

Furthermore, research should be done into multiple symptoms linked to one fault, setting probabilities in DBN nodes and the application of so-called Help nodes.

# TABLE OF CONTENTS

# 1 INTRODUCTION

In the B4B project DBNs are applied for the 4S3F method based on DBNs developed by Taal [1]. However, these models are specific to the research being conducted. In this report, a start is made for standardised HVAC DBN models. In particular, the structure of 4S3F DBN models is discussed but also DBNs from B4B case studies. This document does not consider the symptom detection rules, and the set values for the prior and conditional probabilities in the DBN nodes are not considered in this document.

An HVAC system consists of subsystems, which could also contain subsystems. In [1], four system levels are proposed:

- Level A: partly or whole HVAC system (for instance, an HVAC system which supplies heat and cold)
- Level B: aggregated systems (for instance, an air handling unit (AHU) or a heat generator module), which could be present in the system at level A.
- Level C: components (for instance, an AHU fan) that could be present in the systems of level B.
- Level D: subcomponents inside components (for instance, the transmission belt of a fan) in the components at level C.

Next to components, control systems are embedded in these levels.

In the 4S3F method, levels A to C are considered. Level D is ignored because it is assumed that suppliers or manufacturers of components will isolate faults in components.

This report presents the structure of DBN models based on the HVAC components and systems in ISSO 31, a Dutch guideline for sensor placement in HVAC systems.

First, in section 2, the structure of 4S3F DBNs is explained. Section 3 discusses the HVAC modules presented in ISSO 31 (and 44 and 47), which could be applied to set up DBNs at levels A, B and C. In sections 4 to 7, the proposed 4S3F DBNs for HVAC systems are presented. First at level C in section 4, level B in sections 5 and 6 and finally, level A in section 7. Section 8 discusses the application of so-called Help nodes. In addition, section 9 discusses multiple symptom rules and the probability tables of faults and symptoms. Finally, conclusions from this delivery and recommendations are discussed in section 10.

# 2 4S3F DBN ARCHITECTURE

## 2.1 Introduction

DBNs in the 4S3F FDD consist of 3 types of faults and 4 types of symptoms. See Figure 2.1.

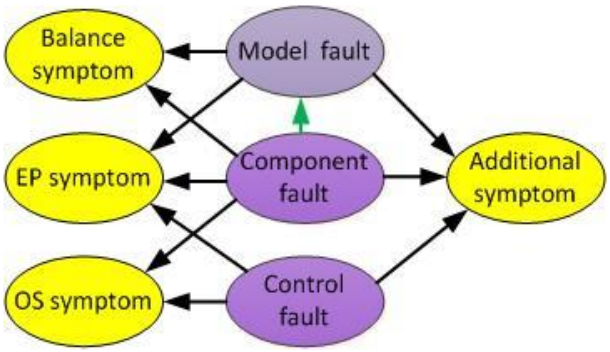



*Figure 2.1 Four symptoms and three faults (ref. TAA).*

The symptoms are coloured yellow, and the faults purple.

### Faults

- Component faults: malfunctioning or designed physical HVAC components or systems. Because sensor values could be faulty, for instance, biased, sensors can also be considered component faults.
- Control faults: incorrect setpoint of controllers, incorrect regulation of actuators, broken connections to and from the controller, and incorrect control strategies.
- Model fault: assumption faults in soft sensors or models to estimate symptoms.

### Symptoms

- Balance symptoms: mass, energy and pressure balances. These symptoms help to find sensor faults and are important because sensor values are used to estimate performance and for control purposes.
- EP (energy performance) symptoms: COPs, efficiencies and capacities (to estimate expected energy flow is realised).
- OS (operational state) symptoms: unexpected behaviour of the mechanical component (on-off, rotation speed), supplied and return temperatures, pressures and flow rates.
- Additional symptoms: HVAC modes, alerts, information from building users or facility management, and maintenance.

Symptoms are estimated as present or absent by rules which use measurements from sensor signals and control signals from the controllers to actuators.

The most common sensors are temperature, flow rate, pressure and humidity sensors. The applied control signals are on-off, 0-100% and set values in the controller.

Sections 2.1 to 2.4 discuss DBNs based on the four types of symptoms.

## 2.2 Balance symptoms

This section discusses symptoms based on energy, mass and pressure balances. Flow sensors can be applied on mass balance symptoms, for thermal energy balances temperature and flow sensors and for pressure balances, pressure sensors.

As an example of a DBN with a balance symptom, the thermal energy balance of a heat exchanger is considered. First, this energy balance is set up. Figure 2.2 shows a block schematic with input and output process variables pressure p, temperature T and mass m for the fluids which exchange thermal energy (see Appendix A).

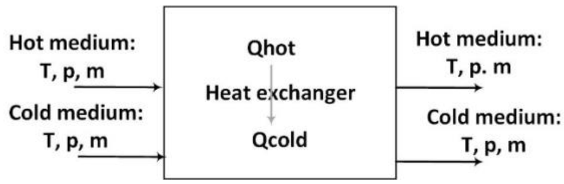



*Figure 2.2 Block schematic for a heat exchanger.*

The exchanged heat $Q_{hot}$ from the hot medium and $Q_{cold}$ to the cold medium during a period must be the same if heat losses are ignored, which leads to the next reasonable equation:

$$Q_{hot} = Q_{cold}$$

with

$$Q_{hot} = H_{hot,in} - H_{hot,out} = m_{hot}.c_{hot}.(T_{hot,in} - T_{hot,out})$$

and

$$Q_{cold} = H_{cold,out} - H_{cold,in} = m_{cold}.c_{cold}.(T_{cold,out} - T_{cold,in})$$

As can be seen, to estimate the (thermal) energy balance, the next temperature sensors are needed: $T_{hot,in}$, $T_{hot,out}$, $T_{cold,in}$, $T_{cold,out}$. The mass through the heat exchanger can be calculated from: $m = \emptyset_V.\Delta t$ wherein $\Delta t$= considered period. Therefore, two flow sensors are needed. Pressures are not present in the heat equations. Thus, 6 sensors are needed to set up an energy balance.

Figure 2.3 presents a corresponding DBN applied in [TAA]. In this figure qV stands for the flow rate $\emptyset_V$.

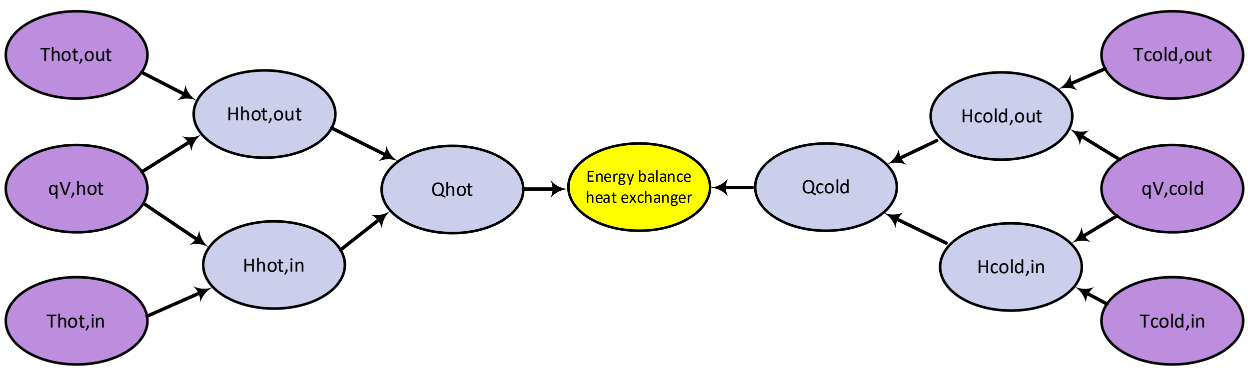



*Figure 2.3 DBN model for an energy balance symptom of a heat exchanger.*

A present energy balance symptom indicates in this way that one or more of the six sensors are faulty. In [1] dummy nodes for H and Q (blue depicted) are present to have a clear DBN in case more symptoms are present. It delimits arcs which cross each other.

An issue is that energy amounts are needed for symptom detection, which requires all six sensors, which is usually not common.

However, input and output temperatures could be the same if no heat is exchanged (for instance, when the heat generators are off). These temperatures could be compared when a flow is present or, if not, when the sensors are located close together in the same ambient environment. See an example of the corresponding DBN in Figure 2.4 for which a temperature balance symptom could be formulated as:

If Thot,out is not equal to Thot,in and heat is not exchanged during x minutes, then the symptom is present.

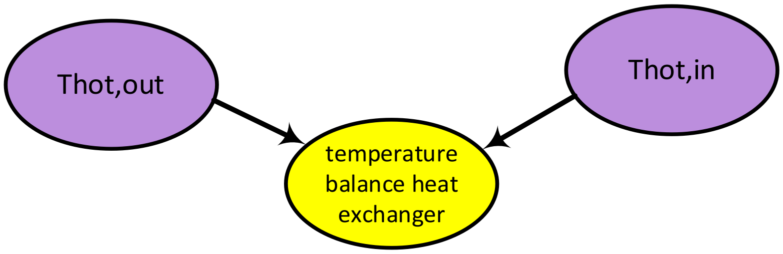



*Figure 2.4 A temperature symptom node: DBN for a temperature balance symptom.*

## 2.3 Operational state symptoms

Operational state symptoms could be distinguished in

- Difference between measured and expected values.
- Incorrect measurements: unrealistic or missing values.
- Deviating setpoint values.
- Incorrect HVAC mode (e.g. on-off mode of a component).

### Difference between measured and expected values

A controller sets some state values. For instance, a supply temperature. As an example, a controlled supply temperature is considered. An OS symptom estimates whether the expected supply temperature is derived or not. The corresponding DBN is presented in Figure 2.5. The most common fault is a controller fault. However, the measured temperature could also be faulty. Not shown in Figure 2.5, this symptom could also be present by too low component capacity, for instance.

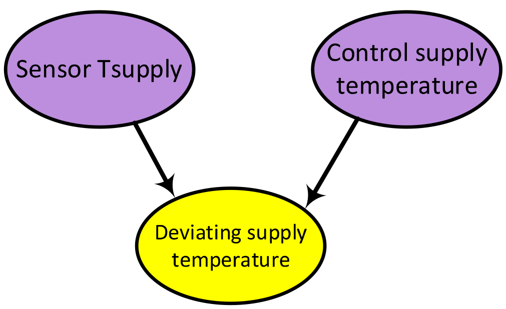



*Figure 2.5 DBN for a temperature OS symptom.*

Based on design rules, some uncontrolled state values could be expected. For instance, the return water temperature from a distribution system.

### Incorrect measurements

Some measurements could be unrealistic. For instance, an outlier for a temperature higher than physically possible. This is caused by a sensor fault, which could be temporary. See Figure 2.6. Also, missing values could be present caused by a faulty sensor or building measurement system (BMS). See Figure 2.7. This values could be corrected by preprocessing the corresponding data before FDD when the symptoms are present temporary.

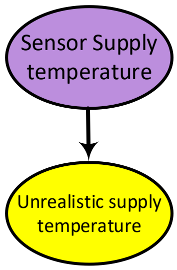



*Figure 2.6 DBN unrealistic supply temperature*

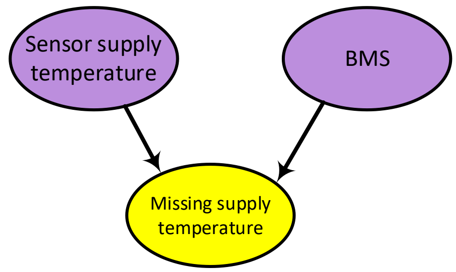



*Figure 2.7 DBN missing supply temperature*

## 2.4 Energy performance symptoms

First, we consider COP symptoms. Then, there are efficiency symptoms and capacity symptoms.

### COP symptom

The COP is formulated as the usable energy divided by the generated energy input. As an example, the heat pump is considered. See Figure 2.8, where a block schematic is presented for the heat pump.

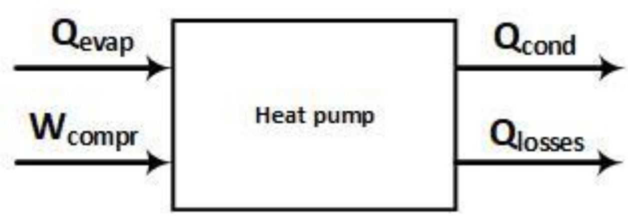



*Figure 2.8 Block schematic of a heat pump.*

The COP of the heat pump is

$$COP = \frac{Q_{cond}}{W_{compr}}$$

with

$$Q_{cond} = m_{cond} \cdot c_w \cdot (T_{cond,out} - T_{cond,in})$$

As in Figure 2.3, sensor faults (including $W_{compr}$) could be present. Next to these, control faults for the supplied temperature of the condenser and evaporator could cause a lower COP. The corresponding DBN for the COP symptom is then:

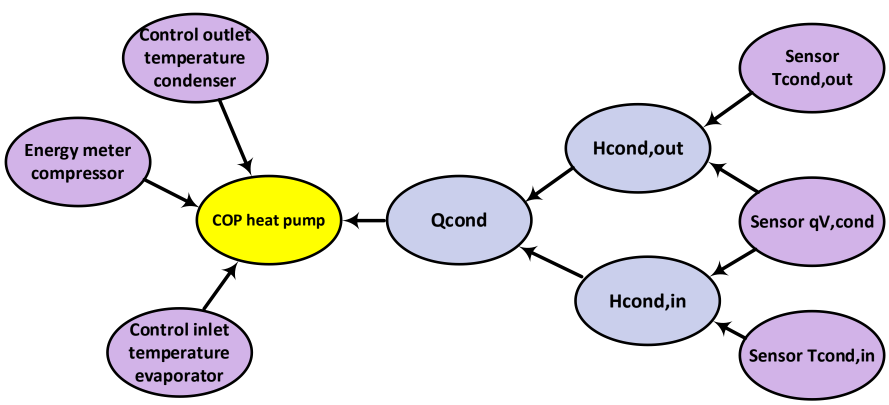



*Figure 2.9 DBN model for a heat pump COP symptom.*

### Efficiency symptom

Next to COP symptoms, efficiency symptoms are proposed for hydronic and air systems. As an example, we consider the heat exchanger efficiency. See Figure 2.10.

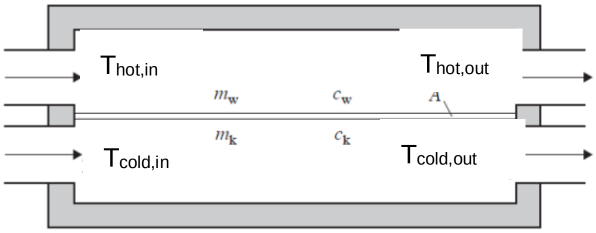



*Figure 2.10 Schematic of a heat exchanger.*

The temperature efficiency for the cold medium is defined as:

$$\eta_{cold} = \frac{T_{cold,out} - T_{cold,in}}{T_{hot,in} - T_{cold,in}}$$

And for the hot medium as

$$\eta_{hot} = \frac{T_{hot,out} - T_{hot,in}}{T_{cold,in} - T_{hot,in}}$$

The DBN becomes then:

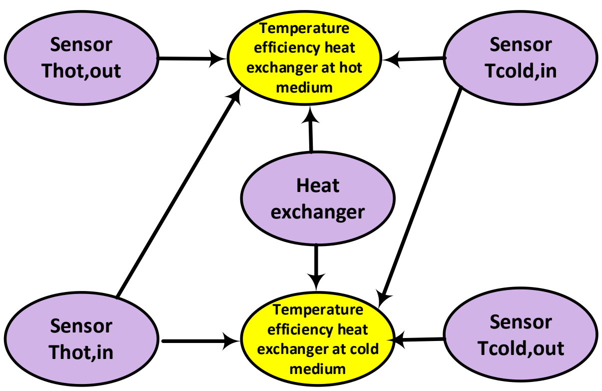



*Figure 2.11 DBN model for the heat exchanger efficiency symptoms.*

A too-low efficiency can be caused by a too-low small heat exchanger (small UA value) or polluted heat exchanger. Still, the symptom could also be detected by incorrect temperature sensors.

### Capacity symptom

A capacity symptom could also estimate a component too low in capacity. The estimated energy flow is calculated and compared with the expected (e.g. designed) one.

Figure 2.12 shows the corresponding DBN.

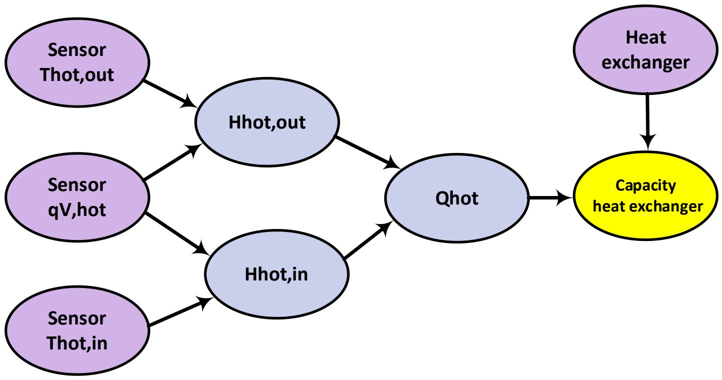



*Figure 2.12 DBN model for the heat exchanger capacity symptoms.*

This DBN can be extended with a fault node for the controlled inlet temperatures and flow rates.

## 2.5 Additional symptoms

The additional symptoms can be connected to faults to estimate the presence or absence of them with very high posterior probability. Figure 2.13 presents the structure of a DBN with an fan alert symptom node. It is common use that BMSs presents malfunctioning of the most mechanical components. The same DBN structure could be present for HVAC modes, information from building users or facility management, and maintenance.

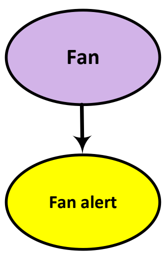



*Figure 2.13 DBN with an alert.*

## 2.6 Soft sensors

In the above DBNs, it is assumed that temperature and flow sensors are all physic present. In practice some hard sensors could be absent. They could be replaced by soft sensors, which are assumed values by models. In Figure 2.1, this is shown in light purple.

## 2.7 Submodel DBNs

Nodes can be aggregated to a DBN sub model for readability and reuse. See Figure 2.14 in which temperature and flow sensor nodes are aggregated to an enthalpy and a heat sub DBN model.

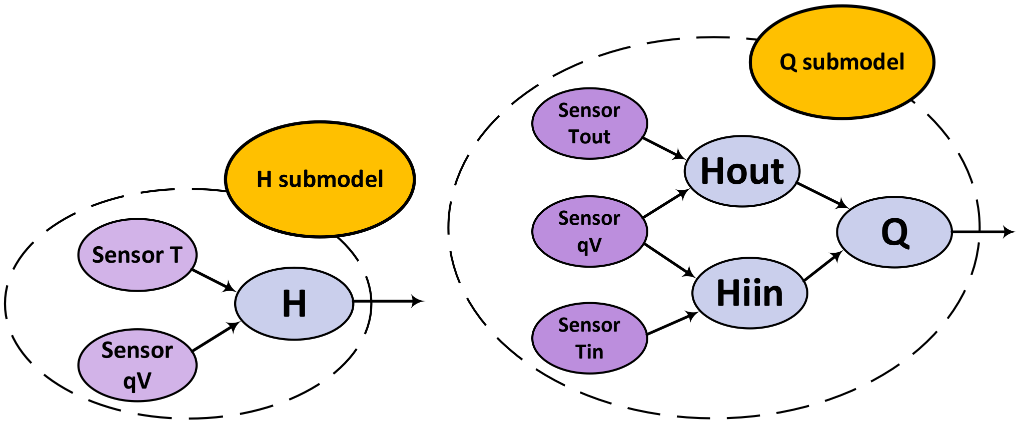



*Figure 2.14 Nested DBN models for enthalpy H and heat Q.*

# 3 HVAC COMPONENTS AND SYSTEMS

## 3.1 Introduction

In this section, a description of HVAC systems is presented, which can be used to set up a DBNs. It is examined whether a generic approach is possible for similar HVAC systems.

The overview is based on the Dutch guidelines ISSO 44 and 47 [2 and 3], which describe hydronic HVAC systems for heating and cooling. These guidelines can be used to estimate components in HVAC systems and define HVAC systems at level B. In addition to ISSO 44 and 47, ISSO 31 [4] describes the proposed sensors for the next purposes:

- Control of the HVAC system. For instance, the control of the supplied air temperature of an AHU.
- Security of the HVAC system. For instance, to prevent hot water freezing at low outdoor temperatures.
- Monitoring for analysis purposes. For instance, to analyse the misfunctioning of a heating system.

In ISSO 31, also the HVAC modules, shown in ISSO 44 and 47, are discussed, classified in

- Generator modules
- Distribution modules
- User-modules
- Air handling units

These systems could be part of an HVAC system at level A and consist of components at level C. Appendix B1 presents an overview of these modules.

The generator modules are thermal hydronic modules divided in 9 heat and 11 cold generator modules. They contain thermal energy generators such as heat pumps, gas boilers and chillers, linked pumps, pipes and control systems.

The (thermal) distribution modules contain pipes, pumps and possible control systems. 4 hot water distribution modules and 3 cold water distribution modules are discussed.

The hydronic user modules consist of pipes, pumps, end-user components and their control. One or more heat exchanger systems are present in the user groups, which is not discussed in ISSO 31. 8 heat user modules are distinguished and 8 cold user modules.

Next to the thermal energy modules, 4 air-handling unit modules are discussed.

The modules can be considered as aggregated systems at level B, consisting of components and controls at level C.

## 3.2 Thermal hydronic modules

Here, we discuss the thermal hydronic modules which supply heat, based on ISSO 31 and 44. The same approach is possible for modules for cooling purposes.

A hydronic HVAC system can build up from heat generator modules (section 3.2.1), distribution modules (section 3.2.2) and user modules (section 3.2.3).

### Heat generator modules

Nine heat generator modules are discussed in ISSO 31 and are applicable for gas boilers, heat exchangers, CHP (combined heat and power) systems, heat pumps, and heat nets. As an example, Figure 3.1 presents the module OW06 in which a constant flow rate (measured by the flow sensor FP1) is present over the heat generator (WO). In contrast, the flow rate $q_{V3}$ is variable to the distribution system and the supply water temperature (TP1) is controlled (by three-way valve RA1) based on the outdoor temperature measured by TPe.

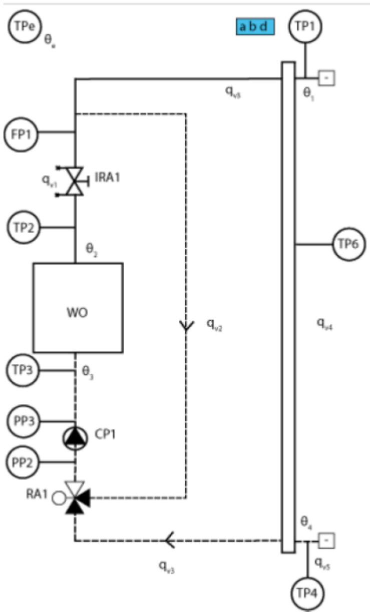



*Figure 3.1 P&ID of heat generator module OW06 (ref. ISSO 31) (CP=pump, WO=heat generator, TP=temperature sensor, FP=flow sensor, PP=pressure sensor, RA=control valve, IRA=balancing valve)*

In Table 3.1 the modules (code WO) are presented with characteristic features. See ISSO 31 for the module codes and description. Next to the possible heat generator, the main components, pump, valves, and buffers, are shown in this table. Furthermore, controls are next to the heat generator control (not shown in the table). It is depicted that the module is passive (P) or active (A). Active means that the supply pressure after the module can deliver water flow to the distribution module. Otherwise, the module is passive, meaning it must contain a distribution pump.

Several correct solutions for the heat generator modules are possible. The choice of the user module(s) affects the solution. Other reasons could also influence the choices made. For instance, OW04 could be applied to ensure a (partly) working heat generation when one of the heat generators is stuck. ISSO guideline 44 presents the selection procedures.

*Table 3.1 Characteristic features of the heat generation modules in ISSO 31.*

| Heat generation module WO | Serial connection to heat generation number | Additional components | | | | | Heat generator | | | | | | Active or passive module | Control | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | pumps | Modulating control valves | Open-close control valves | Balancing valves | buffers | Gas boiler | Heat pump (condenser side) | Heat exchanger water-water | Heat exchanger heat net | Heat exchanger CHP system | Number of generators | | Supply temperature control | Supply pressure control | Buffer temperature control | Control return water temperature to generator |
| 01 | - | 0 | 0 | 0 | 0 | 0 | V | | | V | | 1 | P | V | - | - | - |
| 04 | 4,6,8,9,10, 11 | 2 | 0 | 2 | 2 | 0 | V | V | | | V | 2 | P | V | - | - | - |
| 06 | 4,6,8,9,10, 11 | 1 | 1 | 0 | 1 | 0 | V | V | | | V | 1 | P | V | - | - | V |
| 08 | 4,6,8,9,10, 11 | 1 | 0 | 0 | 1 | 1 | V | V | | | V | 1 | P | V | - | V | - |

| Heat generation module WO | Serial connection to heat generation number | Additional components | | | | | Heat generator | | | | | | Active or passive module | Control | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | pumps | Modulating control valves | Open-close control valves | Balancing valves | buffers | Gas boiler | Heat pump (condenser side) | Heat exchanger water-water | Heat exchanger heat net | Heat exchanger CHP system | Number of generators | | Supply temperature control | Supply pressure control | Buffer temperature control | Control return water temperature to generator |
| 09 | 4,6,8,9,10, 11 | 1 | 1 | 0 | 1 | 1 | V | V | | | V | 1 | P | V | - | V | - |
| 10 | 4,6,8,9,10, 11 | 1 | 2 | 0 | 1 | 1 | V | V | | | V | 1 | P | V | - | V | V |
| 11 | 4,6,8,9,10, 11 | 1 | 1 | 0 | 1 | 1 | V | V | | | V | 1 | P | V | - | V | V |
| 13 | - | 2 | 0 | 2 | 2 | 0 | V | | V | V | | 2 | A | V | - | - | - |
| 15 | - | 0 | 1 | 0 | 0 | 0 | | | | V | | - | A/ P | - | V | - | - |

### Heat distribution modules

Four heat distribution modules are discussed in ISSO 31 and are applicable to link generators to user systems. As an example, Figure 3.2 presents the module DM2 in which a pump transports water from the heat generator system to the user system(s).

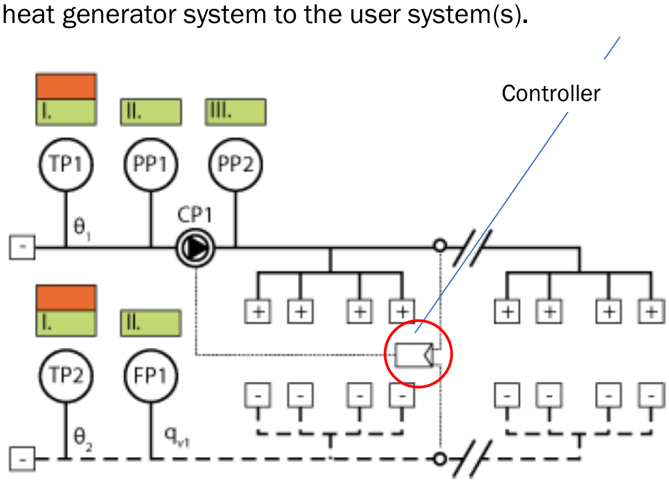



*Figure 3.2 P&ID of the heat distribution module DM2 (ref. ISSO 31) (CP=pump, TP=temperature sensor, FP=flow sensor, PP=pressure sensor) red= security purposes, green = monitoring purposes*

In Table 3.2 the 4 heat distribution modules (code DM) are presented with characteristic. See ISSO 31 for the module codes and description. This table shows whether a pump is present and whether the module can be connected to active and passive generator systems. The regulation of the flow rate is also displayed.

*Table 3.2 Characteristic features of the heat distribution modules in ISSO 31. (0=present, 1=absent)*

| Heat distribution module DM | pump | Supply flow control | Heat generator system | |
|---|---|---|---|---|
| | | | A | P |
| 1 | 0 | 0 | P | A |
| 2 | 1 | 1 | - | P |
| 3 | 1 | 1 | P | - |
| 4 | 0 | 0 | A | - |

## Heat user modules

Eight heat user modules are discussed as applicable for modules containing radiators, convectors, radiation panels, climate ceilings, heaters in an AHU, floor and wall heating systems, heat exchangers and hot water boilers. As an example, Figure 3.3 presents the module WGM4 in which the flow rate (measured by FP5) only depends of the flow rate in the distribution module. The flow rate, and thus the exchanged heat, over the users is controlled by the three-way valve RA1.

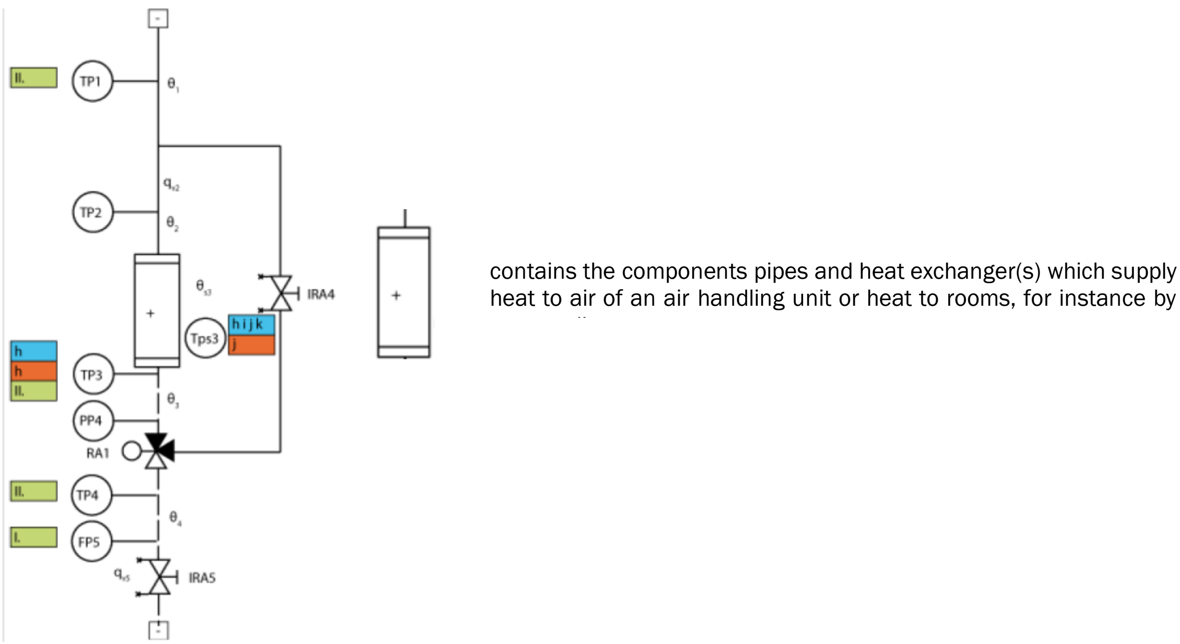



*Figure 3.3 P&ID of heat user module WGM4 (ref. ISSO 31) (TP=temperature sensor, FP=flow sensor, PP=pressure sensor, RA control valve, IRA=balancing valve) red = security purposes, green = monitoring purposes, blue = control purposes.*

In Table 3.3 the eight user modules are presented with characteristic features. See ISSO 31 for the module codes and description.

*Table 3.3 Characteristic features of the heat user modules in ISSO 31.*

| Heat user module WGM | Serial connection to other user modules | Additional components | | | Heat end users | | | | | | | | | | Active or passive module | Control | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | pumps | Control valves | Balancing valves | Radiators | Convectors | Radiation panels | Climate ceilings | AHU preheater | AHU reheater | Floor heating systems | Wall heating systems | Heat exchangers to secondary | Hot water boilers | | Control supply temperature | Control return temperature | Control room temperature | Control supply air temperature | Control boiler temperature or | On-off control summer-winter |
| 1 | 1,2, 3,4 | 1 | 1 | 2 | V | V | V | V | V | | | | | | P | V | | V | V | | V |
| 2 | 1,2, 3,4 | 1 | 1 | 2 | V | V | V | V | V | V | V | V | | | P | V | | V | V | | V |
| 3 | 1,2, 3,4 | 0 | 0 | 1 | V | | | | | | | | V | | P | | | | | | |
| 4 | 1,2, 3,4 | 0 | 1 | 1 | | | | | V | V | | | V | V | P | | | V | V | V | V |
| 5 | 3 | 1 | 1 | 2 | V | | V | V | V | | V | V | | | P | V | | V | V | | V |
| 6 | 3 | 0 | 1 | 1 | | | | | V | V | | | V | V | P | | | V | V | V | V |
| 7 | 3 | 1 | 1 | 1 | V | | V | V | V | | | | | | A | V | | V | V | | V |
| 8 | 3 | 1 | 1 | 2 | V | | V | V | | | V | V | | | A | V | V | V | | | V |

In this table, next to the possible heat user which could be present in the module, additionally, the main components, pumps and valves are shown. Furthermore, controls which are present next to the heat user control (not shown in the table). Whether the module is passive (P) or active (A) is depicted. Active means that the pressure after the module can deliver water flow to the distribution module. Otherwise, the module is passive, meaning the distribution or generator module must contain a distribution pump.

As can be seen, several correct solutions for the heat user modules are possible. The choice of the generator and distribution module(s) affects the solution. ISSO guideline 44 presents the selection procedures and more characteristics of these modules.

## 3.3 Air handling unit modules

ISSO 31 presents 4 types of air handling units (AHUs). All contain the next components

- Inlet damper
- Inlet filter
- Heating coils
- Cooling coils
- Humidifier
- Supply fan
- Outlet filter
- Return fan
- Outlet damper

In addition, temperature, flow, pressure, or humidity sensors are present.

The difference between the modules is the heat recovery:

- L13: by mixing return air with fresh air
- L14: by a heat recovery wheel
- L15: by a heat exchanger
- L16: by a twin coil system

Figure 3.4 presents the P&ID of module AHU L14.

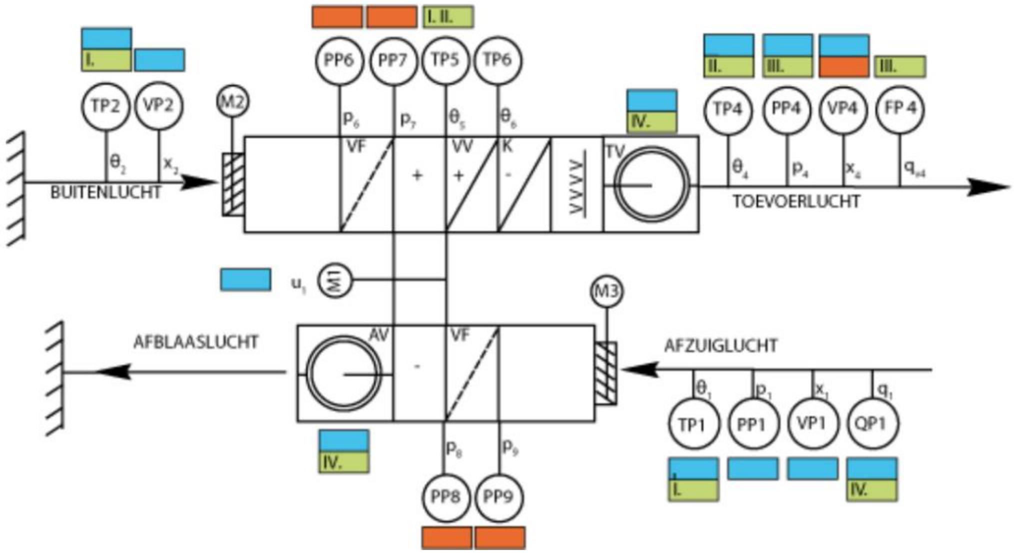



*Figure 3.4 P&ID of the AHU module L14 (ref. ISSO 31). red = security purposes, green = monitoring purposes, blue = control purposes.*

## 3.4 Conclusions and recommendations

The ISSO publications 31, 44 and 47 present HVAC modules for hydronic systems and air handling units. As well components (sensors are included) as controls are described. Therefore, these modules can be the starting point for setting up HVAC DBN models. Tables 3.1 to 3.3 show that it is possible to set up generic hydronic modules DBNs. A DBN could be made specific by removing or adding nodes depending on the presence of components and controls.

Unfortunately, guidelines ISSO 31, 44 and 47 do not discuss modules for air distribution and user modules. Furthermore, electric facilities are missing. Such as lighting systems and electricity generation (including cogeneration with thermal energy). In addition, solar collectors and chemical systems (e.g. hydrogen storage for fuel cells) are missing. It is recommended to prepare module descriptions for these systems.

# 4 DBNS FOR HVAC SYSTEMS AT LEVEL C

## 4.1 Introduction

In this section, DBN models at level C are discussed. Level C components are present in HVAC systems at level B, such as generators, valves, and pumps. In addition, the actuators, controllers, and sensor control systems inside the module are at level C. To each DBN node of a component at level C, symptom nodes classified in the 4S3F method as OS, EP, balance and additional symptoms can be linked. Table 4.1 presents an overview of the components presented in ISSO 31 with possible symptoms. Not listed, the symptoms are stated conditionally, and there may be multiple. For instance, the symptom '*Flow rate deviates strongly from expected one*' could be multiple OS symptoms as '*the flow rate is 0 while the HVAC system is on and supply temperature is lower than the set value*', '*the flow rate is high while the supply temperature is too high'* or '*flow rate is present at non-working hours*'.

We see in Table 4.1, based on [1, 5 and 6], that one or more operational state systems can always be linked to components and controls. Next to this, balance symptoms are linked to sensors.

*Table 4.1 HVAC Faults with possible corresponding symptoms.*

| Faults | | Symptoms |
|---|---|---|
| Component faults | Kind of faults | |
| Pump | Stuck, capacity | Low flow rate, low pressure, on at non-working hours, off at working hours. |
| Fan | Stuck, capacity | Low flow rate, too low pressure, on at non-working hours, off at working hours. |
| Valve | Stuck, frozen, leakage | Temperature after deviates strongly from expected one.<br>Flow rate deviates strongly from expected one. |
| Damper | Stuck, frozen, leakage | Flow rate deviates strongly from expected one. |
| Buffer | capacity | Temperature deviates strongly from expected one. |
| Generator | Stuck, capacity | on at non-working hours, low COP, low supply temperature. |
| Sensor | Stuck, frozen | No signal in BMS, balance is incorrect, values remains long time the same, unrealistic values. |
| Heat exchanger | capacity | Temperatures deviate strongly from expected one, low efficiency. |
| Humidifier | Stuck, capacity | Humidity deviates strongly from expected one. |
| Energy recovery wheel | Stuck, frozen, capacity, leakage | Temperatures deviate strongly from expected one, low efficiency. |
| Filter | Polluted, leakage | High pressure drop. |
| Control faults | Kind of faults | |
| Supply temperature | Incorrect setpoint | Temperature deviates strongly from expected one. |
| Supply flow | Incorrect setpoint | Flow rate deviates strongly from expected one while pump or fan is on. |
| Supply pressure | Incorrect setpoint | Pressure deviates strongly from expected one while fan or pump is on. |
| Buffer temperature | Incorrect setpoint | Temperature deviates strongly from expected one. |
| Room temperature | Incorrect setpoint | Temperature deviates strongly from expected one while HVAC system is on or off. |
| Return temperature | Incorrect setpoint | Temperature deviates strongly from expected one. |
| State generator | Incorrect mode | State deviates strongly from expected one, high energy consumption, unexpected supply temperature. |

| Faults | | Symptoms |
|---|---|---|
| Component faults | Kind of faults | |
| State pump | Incorrect mode | State deviates strongly from expected one, high energy consumption, unexpected flow rate or pressure. |
| State fan | Incorrect mode | State deviates strongly from expected one, high energy consumption unexpected flow rate or pressure. |
| State valve | Incorrect mode | State deviates strongly from expected one, unexpected temperature or flow rate. |
| State damper | Incorrect mode | State deviates strongly from expected one, unexpected flow rate. |
| State humidifier | Incorrect mode | State deviates strongly from expected one, unexpected humidity. |
| State heat recovery wheel | Incorrect mode | State deviates strongly from expected one, unexpected temperatures. |

Examples of DBN models for components in hydronic nodules are discussed in section 4.1 and DBN models for components in air handling units in Section 4.2.

## 4.2 DBN models for components in hydronic modules.

As an example, a three-way valve is considered. In a three-way valve, two flows are mixed to one flow. See the three-way valve RA1 in Figure 4.1, depicting the sensors with corresponding codes. Figure 4.1 shows, as an example, a DBN for a three-way control valve RA, which could be present in a generator or user module.

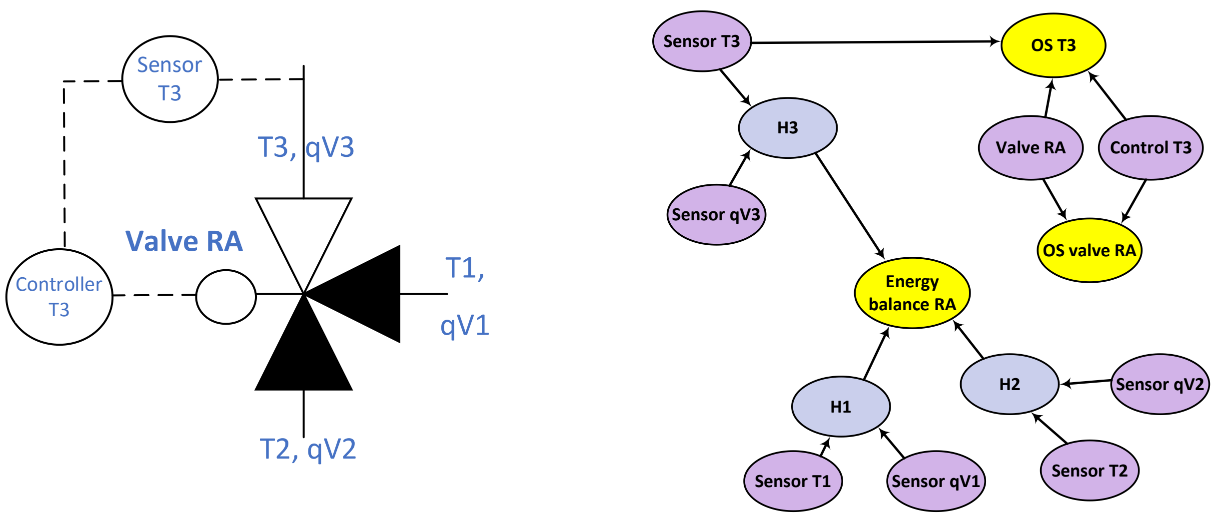



*Figure 4.1 DBN for a three-way valve RA.*

As can be seen, three symptoms (balance and 2x OS) are present. The operational state symptom *OS T3* depicts an unexpectedly supply temperature, The symptom *OS valve RA* stands for an unexpected opened or closed valve position and the Balance symptom *Energy balance RA* for an incorrect energy balance. In practice, multiple *OS valve RA* nodes could be present. See Appendix C1 which presents a case study with two OS symptoms for a heating coil valve. These symptoms are data driven using historical data.

The sensors present in Figure 4.1 are hard sensors. However, some sensors are mostly absent in practice. Soft sensors could replace them. For instance, two balances could be used if one of the temperatures or flows is not measured:

$$\emptyset_{V,3} = \emptyset_{V,1} + \emptyset_{V,2}$$

and

$$\emptyset_{V,3} \cdot T_3 = \emptyset_{V,1} \cdot T_1 + \emptyset_{V,2} \cdot T_2$$

And instead by a flow sensor, the flow rate could be calculated from a set pump flow rate.

## 4.3 DBN models for components in air handling unit modules.

In this section DBN models for components in air handling units (AHUs) modules are discussed.

AHU faults considered in this section are component (including sensor) and control faults (model fault are not considered). In Table 4.2, faults derived from Figure 3.4 are presented. As can be seen, multiple types of component and control faults can be present.

*Table 4.2 Faults present in air handling units.*

| Component and control faults | Fault types |
|---|---|
| Supply filter | Fouled<br>Filter by-pass leakage<br>Stuck filter |
| Energy recovery wheel (ERW) | Too low capacity (affects efficiency)<br>Fouled (leads to lower efficiency)<br>Stuck electric motor (no rotation)<br>Stuck mechanical parts<br>Too high by-pass leakage |
| Control ERW | Incorrect rotation speed control (e.g., set PID values in controller)<br>Incorrect on-off control |
| Heating coils | Too low capacity<br>Fouled heat exchanger |
| Cooling coils | Too low capacity<br>Fouled |
| Humidifier | Too low capacity<br>Fouled |
| Control humidifier | Incorrect setpoint |
| Supply fan | Too low capacity (flow rate, pressure)<br>Too low efficiency<br>Stuck electric motor<br>Broken belt<br>Misfunctioning fan bearing<br>Stuck fan blades |
| Control supply fan | Incorrect rotation speed control (e.g., set PID values in controller).<br>Incorrect on-off control |
| Return filter | Fouled<br>Filter by-pass leakage<br>Stuck filter |
| Return fan | Too low capacity (flow rate, pressure)<br>Too low efficiency<br>Stuck electric motor<br>Broken belt<br>Misfunctioning bearing<br>Stuck blades |
| Control return fan | Incorrect rotation speed control (e.g., set PID values in controller). |

| Component and control faults | Fault types |
|---|---|
| | Incorrect on-off control. |
| Inlet temperature sensor | Outlier<br>Positive biased<br>Negative biased<br>Stuck |
| Preheated temperature sensor | Outlier<br>Positive biased<br>Negative biased<br>Stuck |
| Heated temperature sensor | Outlier<br>Positive biased<br>Negative biased<br>Stuck |
| Supply temperature sensor | Outlier<br>Positive biased<br>Negative biased<br>Stuck |
| Return temperature sensor | Outlier<br>Positive biased<br>Negative biased<br>Stuck |
| Supply pressure sensor | Outlier<br>Positive biased<br>Negative biased<br>Stuck |
| Return pressure sensor | Outlier<br>Positive biased<br>Negative biased<br>Stuck |
| Supply flow rate | Outlier<br>Positive biased<br>Negative biased<br>Stuck |
| Return flow rate | Outlier<br>Positive biased<br>Negative biased<br>Stuck |
| Inlet humidity | Outlier<br>Positive biased<br>Negative biased<br>Stuck |
| Supply humidity | Outlier<br>Positive biased<br>Negative biased<br>Stuck |
| Return humidity | Outlier<br>Positive biased |

| Component and control faults | Fault types |
| --- | --- |
| | Negative biased<br>Stuck |
| Supply difference pressure sensor<br>PP6-PP7 | Outlier<br>Biased<br>Stuck<br>Missing signal |
| Return difference pressure sensor<br>PP9-PP8 | Outlier<br>Positive biased<br>Negative biased<br>Stuck |
| Building management system (BMS) | Failed communication to BMS |
| Control supply temperature by setpoint | Positive incorrect setpoint<br>Negative incorrect setpoint<br>Incorrect sequence control (combination ERW, HCV and CCV) |
| Control supply pressure by setpoint | Positive incorrect setpoint<br>Negative incorrect setpoint |
| Control return pressure by setpoint | Positive incorrect setpoint<br>Negative incorrect setpoint |
| Inlet damper | Closed frozen<br>Opened frozen |
| Outlet damper | Closed frozen<br>Opened frozen |

### Symptoms related to AHU components

The next types of symptoms could be considered.

1. Failure of components (Additional symptoms)
2. Incorrect setpoints (Additional symptoms)
3. Incorrect HVAC mode (OS symptoms)
4. Incorrect operational temperature states (OS symptoms)
5. Incorrect operational pressure states (OS symptoms)
6. Incorrect operational flow rate states (OS symptoms)
7. Incorrect operational humidity states (OS symptoms)
8. Unrealistic state values (OS symptoms)
9. Missing state values (OS symptoms)
10. Incorrect energy performance (EP symptoms)
11. Incorrect energy balances (Balance symptoms)
12. Incorrect mass balances (Balance symptoms)
13. Incorrect pressure balances (Balance symptoms)
14. incorrect temperature deviations (Balance symptoms)

Figure 4.2 presents a DBN model for a fan with EP, OS and additional symptoms. The OS symptom is shaded because multiple symptoms can be present depending on for instance, HVAC modes and symptoms for negative or positive deviations.

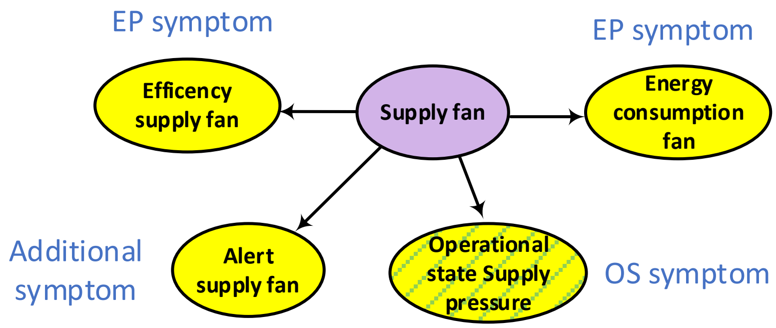



*Figure 4.2 Block schematic and thermodynamic formulas of a damper.*

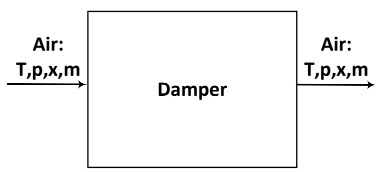
### Balance symptoms

Balance symptoms are based on thermodynamic laws. State data is needed to setup balances. Below, they are discussed for AHU components.

Assumptions made to formulate balance sheet equations are
- Temperature increase by friction is neglected.
- No heat losses in the AHU.
- Energy consumption for regulation of the dampers and HRW is neglected.
- Energy consumption for humidification (steam generation) is neglected.
- Humidifier: water spraying (then the enthalpy increase ΔH=0). It is common use, that the absolute humidity x has the unity g water/ kg air.

### Damper

Only the pressure will change when an air flow is present which results in a pressure drop.



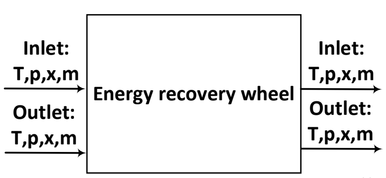

$$H_{out} = H_{in}$$
$$T_{out} \approx T_{in}$$[1]
$$x_{out} = x_{in}$$
$$m_{out} = m_{in}$$
$$p_{out} = p_{in} - \Delta p_{damper}$$

*Figure 4.3 Block schematic and thermodynamic formulas of a damper.*

### Energy recovery wheel

The energy recovery wheel is a particular form of a heat exchanger in which also moisture is exchanged. This leads to changes in the supply's temperature and humidity (x in g/kg) and return air. The temperature and moisture efficiencies ($\eta_T$ and $\eta_x$) depend on the flow rates.

$$H_{in,outlet} - H_{out,outlet} = H_{out,inlet} - H_{in,inlet}$$

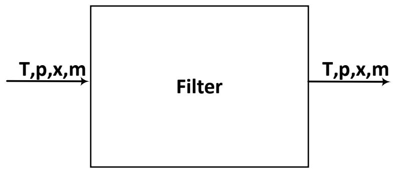



$$T_{out,inlet} \approx T_{in,inlet} + \eta_{T\_hrw,inlet} \cdot (T_{in,outlet} - T_{in,inlet})$$
$$T_{out,outlet} \approx T_{in,outlet} + \eta_{T\_hrw,outlet} \cdot (T_{in,inlet} - T_{in,outlet})$$
$$x_{out,inlet} \approx x_{in,inlet} + \eta_{x\_hrw,inlet} \cdot (x_{in,outlet} - x_{in,inlet})$$
$$x_{out,outlet} \approx x_{in,outlet} + \eta_{x\_hrw,outlet} \cdot (x_{in,inlet} - x_{in,outlet})$$
$$m_{out} = m_{in}$$
$$p_{out} = p_{in} - \Delta p_{hrw}$$

*Figure 4.4 Block schematic and thermodynamic formulas of an (thermal) energy recovery wheel.*

[1] The temperature will actually increase by friction. However, the increase is supposed to be neglectable.

## Filter

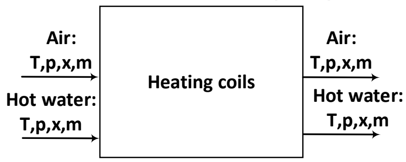



$$H_{out} = H_{in}$$
$$T_{out} \approx T_{in}$$ [1]
$$x_{out} = x_{in}$$
$$m_{out} = m_{in}$$
$$p_{out} = p_{in} - \Delta p_{filter}$$

*Figure 4.5 Block schematic and thermodynamic formulas of an air filter.*

## Heating coils

The heating coils are heat exchangers. The system boundaries are placed around the heat-exchanging surface. Thus, a valve or a pump in the warm water circuit and their control are not considered.

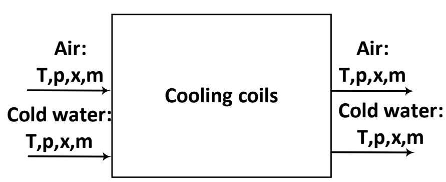



$$H_{out} = H_{in} + Q_{heat}$$
with $Q_{heat} = m_{hw} c_{hw} (T_{hw,in} - T_{hw,out})$
$$T_{out} = T_{in} + \frac{Q_{heat}}{m_{air} c_{air}}$$
$$x_{out} = x_{in}$$
$$m_{out} = m_{in}$$
$$p_{out} = p_{in} - \Delta p_{hc}$$

*Figure 4.6 Block schematic and thermodynamic formulas of the heating coils in an AHU.*

## Cooling coils

The cooling coils are a heat exchanger. The system boundaries are placed around the heat-exchanging surface. Thus, a valve or a pump in the cold water circuit and their control are not considered. Two types of cooling are distinguished. The first one is dry cooling whereby no condensation of water vapor occurs. At the second one, a part of the water vapor condenses because the coil temperature is below the dew point of the air. Below, the equations for dry cooling is presented. Those for the wet cooling is not shown because they are depending on the implementation of the cooling coil system.




$$p_{out} = p_{in} - \Delta p_{cc}$$
$$m_{out} \approx m_{in}$$

**Dry cooling**

$$H_{out} = H_{in} - Q_{cold}$$
with $Q_{cold} = m_{cw} c_{cw} (T_{cw,out} - T_{cw,in})$
$$T_{out} = T_{in} - \frac{Q_{cold}}{m_{air} c_{air}}$$
$$x_{out} = x_{in}$$

*Figure 4.7 Block schematic and thermodynamic formulas of the cooling coils in an AHU.*

## Humidifier

In the humidifier water is supplied. In the most common types, liquid water or steam is supplied. In the first case the temperature of the air increases because water is vaporized. The supplied enthalpy by the liquid water could be neglected (small amount) as a result of which the process is assumed adiabatic wherein liquid water is evaporated. The specific vaporization heat is rounded to 2491 kJ/kg and the specific heat of steam 1.926 kJ/kgK.

However, in the second case, the air enthalpy increases by the supplied steam. The air temperature increases a little bit (<0,5 K) at steam of 100°C. Therefore temperature change could be ignored in most cases.


**Liquid water spraying**

$$H_{out} \approx H_{in}$$
$$T_{out} \approx T_{in} - 2491 \cdot m_{steam}$$

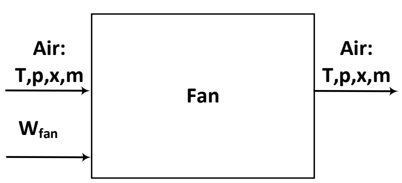
**Steam humification**

$$H_{out} = H_{in} + (2491 + 1.926 \cdot T_{steam}) \cdot m_{steam}$$
$$T_{out} \approx T_{in}$$
$$m_{out} \approx m_{in}$$
$$x_{out} = x_{in} + x_{supply}$$
$$p_{out} = p_{in} - \Delta p_{hum}$$

*Figure 4.8 Block schematic and thermodynamic formulas of a humidifier in an AHU.*

### Fan

A part of the supplied electric energy ($W_{fan,nt}$) causes an increase in the enthalpy. This depends on the fan efficiency.




$$H_{out} = H_{in} + W_{fan,nt}$$
$$T_{out} = T_{in} + \Delta T_{fan}$$
$$x_{out} = x_{in}$$
$$m_{out} = m_{in}$$
$$p_{out} = p_{in} + \Delta p_{fan}$$

*Figure 4.9 Block schematic and thermodynamic formulas of a fan in an AHU.*

A P&ID and DBN for a heating coil AHU component is presented in Figure 4.10. In the DBN, an EP symptom for the energy efficiency of the heating coil is present next to a balance, OS and another EP (capacity) symptom. The fault nodes are six sensor faults and one fault for the heating coils. This DBN could be extended with temperature symptom nodes as shown in Figure 2.4 to estimate sensor faults.

Note: In the above example, only the heating coils are considered. In practice, one could consider the **heating coils system,** which also often contains a control of the supplied heat, a pump and a valve (actuator). This heating coil system is a hydronic user module discussed in section 3.2.

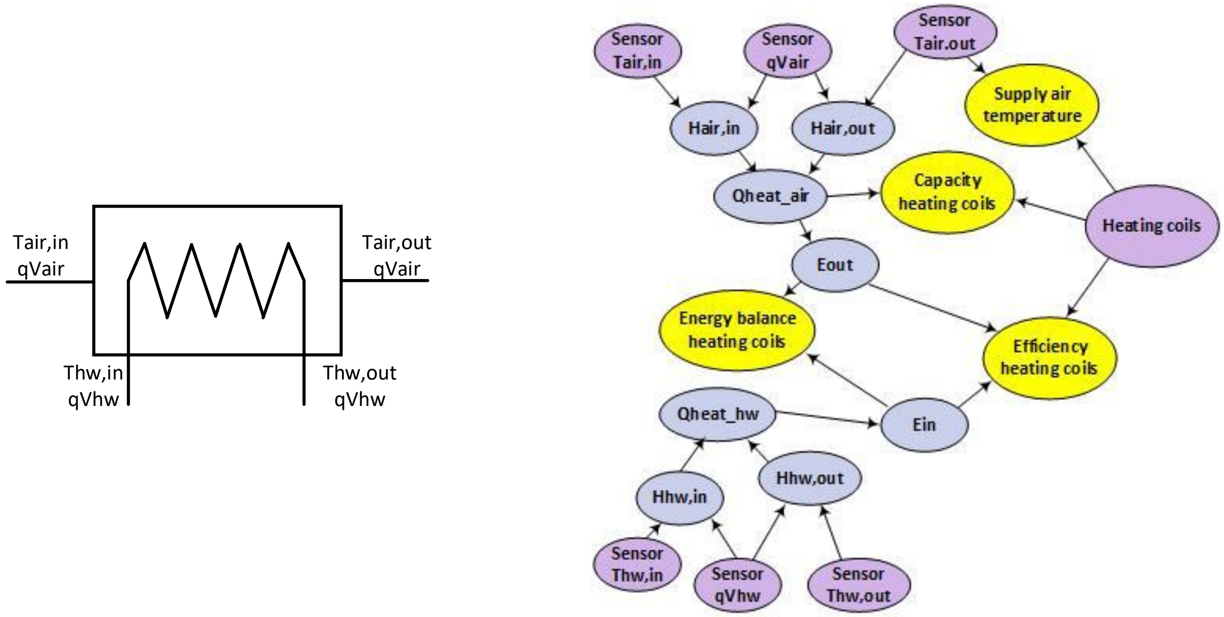



*Figure 4.10 Schematic and DBN for an AHU heating coils component (hw= hot water, qV=flow rate, E=energy).*

## 4.4 Conclusions and recommendations

This section shows that DBNs at level C can be setup for component faults from the HVAC module description in ISSO publication 31. The main components can be derived from these modules. Model faults are not discussed in this section. For instance, incorrect models for soft sensors. Next to this, only a few DBNs are presented in this section. Therefore, a library with components and soft sensors with its symptoms should be setup. This could be done for a sensor poor and rich environment.

# 5 DBNS FOR AIR HANDLING UNITS AT LEVEL B

## 5.1 Introduction

In this section, AHU DBN models at level B are discussed. Level B means that the system consists of components at level C. These aggregated systems could be modules as described in ISSO 31. A DBN at level B can be set up in three ways:

- As a DBN with all fault nodes at level C. See Section 5.2.
- As a DBN consisting of nested DBNs. See Section 5.3.
- As a DBN with only fault nodes at level B. This will be discussed in Section 5.4.

## 5.2 DBN model for an AHU module with fault nodes at level C.

This section discusses a flat DBN model in which all component and control faults are present. This is done at the hand of air handling unit L14 shown in ISSO 31. Figure 1.1 presents the P&ID of this AHU. In this figure, control signals (u), alerts (A) and sensors (PP,TT, VP, FP) are depicted.

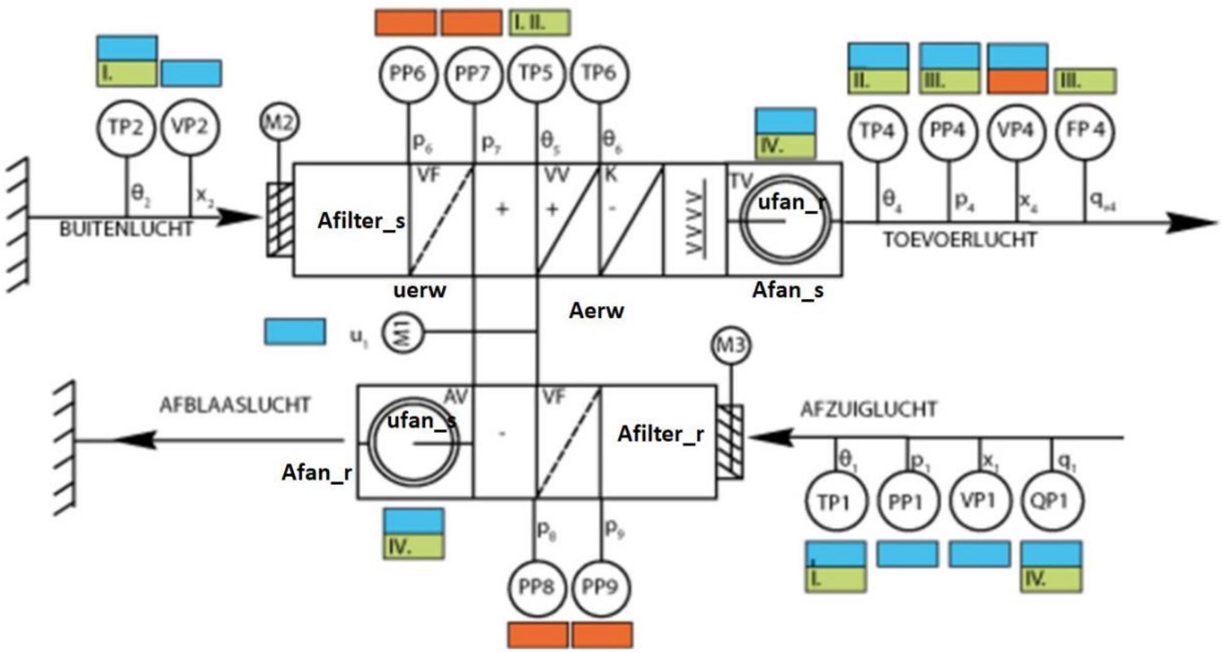



*Figure 5.1 BMS dialogic window with variables for sensors, setpoints, states and control signals (green=on).*

Information from the hot and cold water systems is needed for diagnosis purposes. These heating and cooling coils systems include valves, pumps and their controls next to the heat exchangers. See Appendix C2 for a P&ID of an existing AHU with these systems. Figure 5.2 shows a block schematic with the main AHU components present in AHU L14.

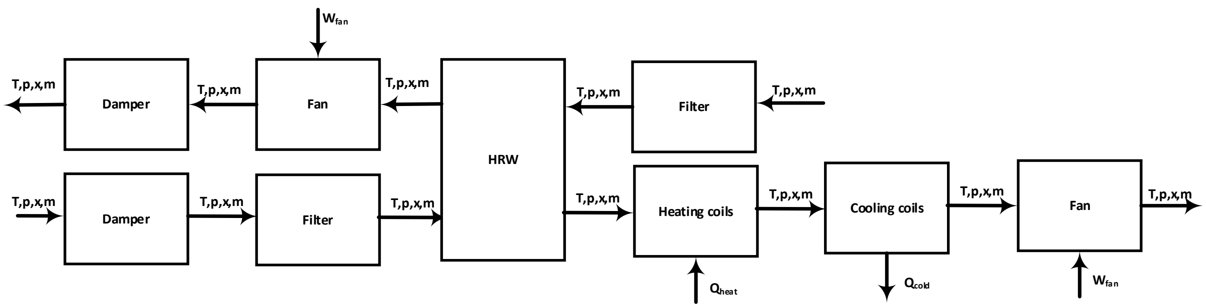



*Figure 5.2 AHU schematic with component (T=temperature, p=pressure, x=absolute humidity, m=mass)*

In section 5.1.1 possible AHU faults are discussed and in section 5.1.2 possible symptoms. Section 5.1.3 presents the resulting DBN with and without sensor faults.

## AHU faults

AHU faults considered in this section are component (including sensor) and control faults (model fault are not taken into account in this example). For simplicity purposes, humidity and flow rate control and sensors are not taken into account. In addition, night ventilation is ignored. Then, from Figure 5.1, 24 Fault nodes can be distinguished. In Table 5.1 these faults are presented. As can be seen, multiple types of component and control faults can be present. Heating and cooling coils systems are presented in this table despite they are part of hydronic user modules as defined in ISSO 31. This is depicted in yellow. Thus, next to an AHU module, heat and cold user modules are considered (as black boxes) in this section!

*Table 5.1. Faults present in AHU L14 of ISSO 31.*

*Yellow: belongs to hydronic user module (see ISSO31)*

| | Component and control faults |
|---|---|
| F1 | Supply filter |
| F2 | Energy recovery wheel (ERW) |
| F3 | Control ERW |
| F4 | Heating coils (HC) user module |
| F5 | Cooling coils (CC) user module |
| F6 | Supply fan (FAN_s) |
| F7 | Control supply fan |
| F8 | Return filter |
| F9 | Return fan (FAN_r) |
| F10 | Control return fan |
| F11 | Inlet temperature sensor (TP2) |
| F12 | Preheated temperature sensor (TP5) |
| F13 | Heated temperature sensor (TP6) |
| F14 | Supply temperature sensor(TP4) |
| F15 | Return temperature sensor (TP1) |
| F16 | Supply pressure sensor (PP4) |
| F17 | Return pressure sensor (PP1) |
| F18 | Supply difference pressure sensor PP6-PP7 |
| F19 | Return difference pressure sensor PP9-PP8 |
| F20 | BMS |
| F21 | Control supply temperature by setpoint Tset |
| F22 | Control supply pressure by setpoint ps_set |
| F23 | Control return pressure by setpoint pr_set |
| F24 | Inlet damper |

## AHU Symptoms

In this section, examples of symptoms linked to the faults are discussed to show the architecture of an AHU DBN at level B.

The symptoms applied, depend on the presence of sensors. See Table 5.2 which is presented by Lu at a B4B consortium meeting. This complicates the setup of standardized DBNs. In this section, the sensor rich environment, discussed in ISSO 31, is taken as starting point.

*Table 5.2 Sensors present in 18 AHU systems (A=recommended by ASHRAE and I=recommended by ISSO 31).*

| **Sensor** | **A** | **I** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Outdoor air temperature | ✓ | ✓ | ✓ | | | | ✓ | | | ✓ | | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ |
| Outdoor air relative humidity | | ✓ | | | | | | | | | | | | | | | ✓ | ✓ | ✓ | ✓ |
| Preheated air temperature | ✓ | ✓ | | | ✓ | | | | | | | | | ✓ | | | ✓ | ✓ | ✓ | |
| Preheated air relative humidity | | ✓ | | | | | | | | | | | | ✓ | | | | | | |
| Supply air temperature | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Supply air relative humidity | | ✓ | | | ✓ | | ✓ | | ✓ | ✓ | | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| Return air relative humidity | | ✓ | | | ✓ | | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ |
| Exhaust air temperature | ✓ | ✓ | | | | ✓ | ✓ | | | | | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ |
| Exhaust air relative humidity | | ✓ | | | | | | | | | | | | ✓ | | | ✓ | ✓ | | |
| Supply water temperature | ✓ | ✓ | | | | | | | | | | | | ✓ | ✓ | | ✓ | | | |
| Return water temperature | ✓ | ✓ | | | | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ |
| Pressure difference at supply air filter | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Pressure difference at return air filter | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Pressure difference at supply air on fan | | ✓ | | | ✓ | | | | | | | ✓ | | | | | ✓ | | | |
| Pressure difference at return air on fan | | ✓ | | | | | | | | | | ✓ | | | | | | | | |
| Supply air flow rate | ✓ | ✓ | | ✓ | | | | | | | | | | | | | ✓ | | | |
| Return air flow rate | ✓ | ✓ | | | | | | | | | | | | | | | | | | |
| Coil valve openness | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Supply fan state | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Return fan state | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Supply damper state | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Return damper state | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Air quality sensor | | ✓ | | | | ✓ | | ✓ | | ✓ | | | | | ✓ | | | | | |
| Temperature sensor after coil | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Coil water flow | | ✓ | | | | | | | | ✓ | | ✓ | | | | | | | | |
| Fit ASHRAE recommendation | - | - | | | | | | | | | | | | Yes | | | Yes | Yes | Yes | |

Table 5.3 presents an overview of symptoms applied in this section (see Section 4, which discusses these symptoms). The symptoms shown are worked out in Appendix D. As can be seen many symptoms can be distinguished.

*Table 5.3 Symptoms considered*

| Symptoms | | | 4S type |
|---|---|---|---|
| Failure of components | | S1a to S1e | additional |
| Incorrect HVAC mode | | S2a to S2g | OS |
| Operational temperature states | Preheated temperature TP5 | S3a to S3f | OS |
| | Supply temperature TP4 | S3g to S3k | |
| | Heated temperature TP6 | S3l to S3n | |
| Operational pressure states | Pressure drop filters PP9-PP8 and PP6-PP7 | S4a and S4b | OS |
| | Supply pressure PP4 | S4c to S4e | |
| | Return pressure PP1 | S4f to S4h | |
| | Inlet pressure PP6 | S4i | |
| Energy performance | Energy recovery wheel | S5a and S5b | EP |
| | Heating coils capacity | S5c | |
| | Cooling coils capacity | S5d | |
| | Supply fan efficiency | S5e | |
| | Return fan efficiency | S5f | |
| | Energy consumption supply fan | S5g | |
| | Energy consumption return fan | S5h | |
| | Energy consumption heating coils | S5i | |
| | Energy consumption cooling coils | S5j | |
| Balances | Temperature balances | S6a to S6c, S6h and S6i | Balance |
| | Pressure balances | S6d to S6g | |
| Setpoints | Supply temperate | S7a and S7b | additional |
| | Supply pressure | S7c and S7d | |
| | Return pressure | S7e and S7f | |
| Unrealistic state values | Temperatures | S8a to S8e | OS |

| | | | |
|---|---|---|---|
| | Pressures | S8f to S8i | |
| Missing state values | Temperatures | S9a to S9e | OS |
| | Pressures | S9f to S9i | |
| | Component | S9j to S9l | |

## AHU DBN model

Table 5.4 presents the fault-symptom relationship of the considered air handling unit L14. Based on this table a DBN is set up. See Figure 5.4. Some operational state symptoms are presented as a merged OS node (yellow shaded) for readability

*Table 5.4 Fault-symptom relations.*

| | Component and control fault | OS symptom | EP symptom | Balance symptom | Additional symptom |
|---|---|---|---|---|---|
| F1 | Supply filter | S4a | | | S1d |
| F2 | ERW | S3a,d | S5a, i, j | | S1a |
| F3 | Control ERW | S2a S3b,c,e,f,k,m | S5b, i, j | | |
| F4 | Heating coil system | S2b,g S3g,i,l,n | S5c | | |
| F5 | Cooling coil system | S2g S3h,j | S5d | | |
| F6 | Supply fan | S4d | S5e, g | | |
| F7 | Control supply fan | S2c,d S4c,e | S5g | | S1b |
| F8 | Return filter | S4b | | | S1e |
| F9 | Return fan | S4g | S5f, h | | S1c |
| F10 | Control return fan | S2e,f S4f,h | S5h | | |
| F11 | Inlet temperature sensor (TP2) | S8a S9a | | S6h, i | |
| F12 | Preheated temperature sensor (TP5) | S8b S9b | | S6a, c, h | |
| F13 | Heated temperature sensor (TP6) | S8e S9e | | S6b, c | |
| F14 | Supply temperature sensor(TP4) | S8c S9c | | S6a, b, i | |
| F15 | Return temperature sensor (TP1) | S8d S9d | | | |
| F16 | Supply pressure sensor (PP4) | S8f S9f | | S6d | |
| F17 | Return pressure sensor (PP1) | S8g S9g | | S6e | |
| F18 | Supply difference pressure sensor PP6-PP7 | S8h S9h | | S6f | |
| F19 | Return difference pressure sensor | S8i S9i | | S6g | |
| F20 | BMS PP8-PP9 | S9a to S9l | | | |
| F21 | Control supply temperature Tset | | | | S7a, b |
| F22 | Control supply pressure (ps_set) | | | | S7c, d |
| F23 | Control return pressure (pr_set) | | | | S7e, f |
| F24 | Inlet damper | S4i | | | |

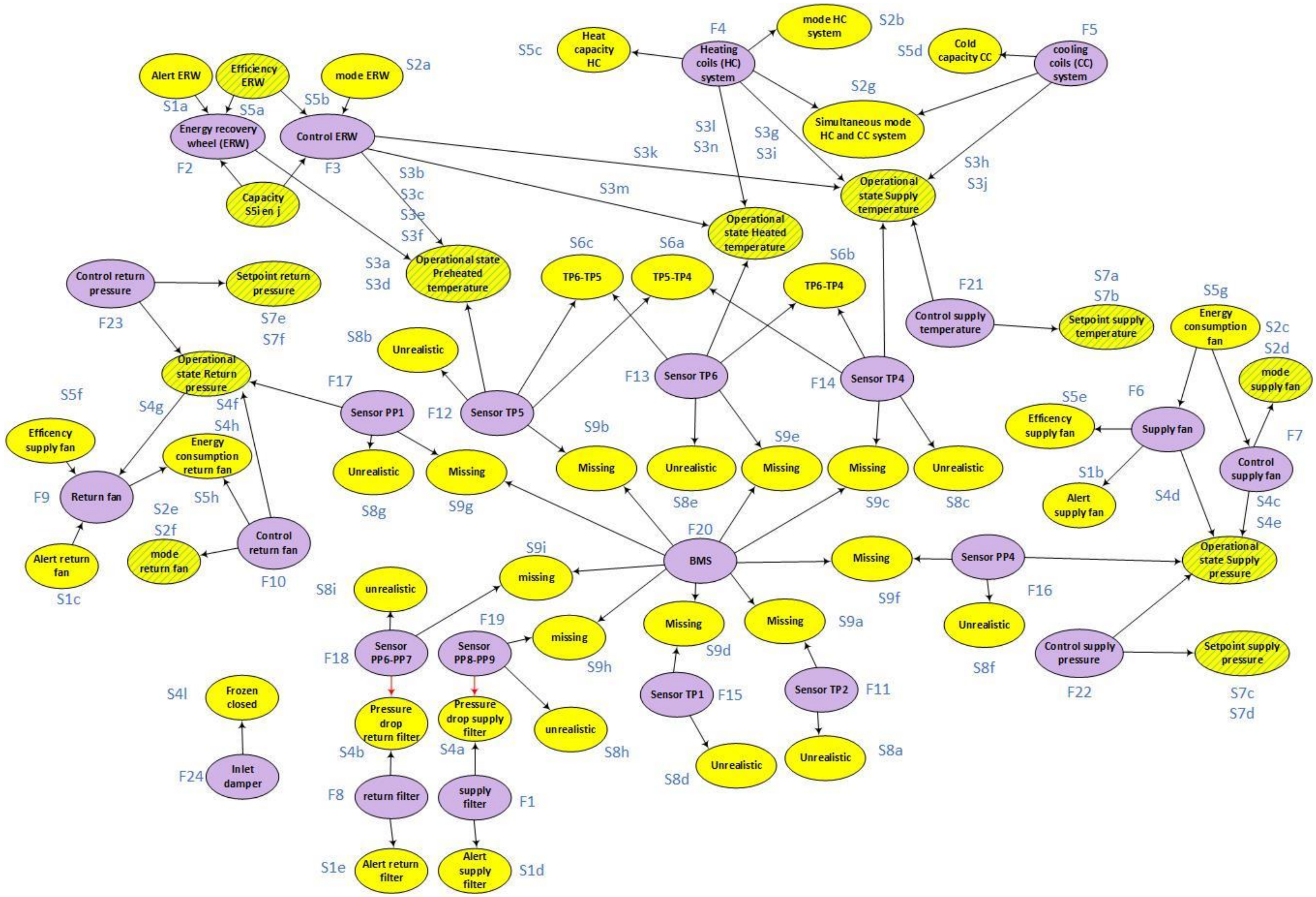



*Figure 5.3 AHU at level B with nodes for all AHU components and controls.*

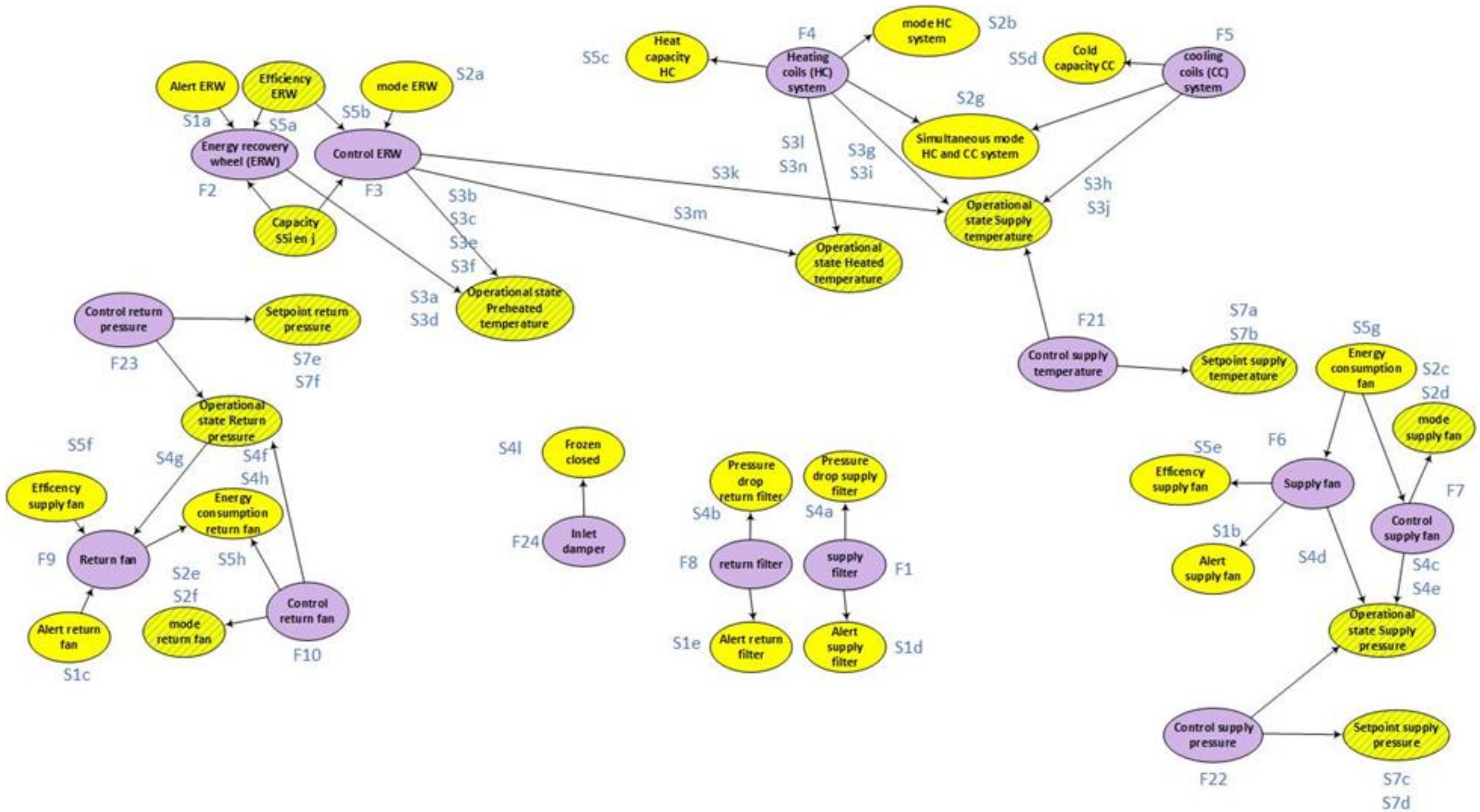



*Figure 5.4 AHU at level B with nodes for all AHU components and controls without sensor fault.*

Despite that, a selection is made for the possible faults (for instance, flow and humidity faults are ignored), this DBN becomes large. In case sensor faults could be ignored, for instance, by commissioning, the DBN of Figure 5.3 could be simplified. See Figure 5.4.

## 5.3 One DBN model for a HVAC module with DBN subsystems for components, controls and systems

The DBN of section 5.1 is specific for an AHU module. In addition the DBN could be very large and therefore unreadable when also energy balances, and faults and symptoms for humidity and flow rates are taken into account. Furthermore, this approach is not modular which complicates reuse of DBN modules. The solution is to create DBN subsystems for one or multiple faults with symptoms which are only linked to these faults. See section 2.7. Figure 5.5 presents such a subsystem (in orange) derived from Figure 5.3.

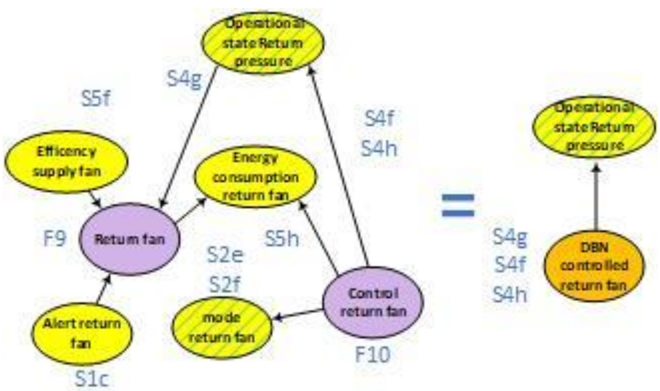



Figure 5.5 DBN model for a controlled return fan.

Figure 5.6 shows the adapted DBN of figure 5.3 with DBN submodels. In this way, a library with DBN submodels can be set up. A submodel can be selected based on the sensors present in an AHU. Thus, symptoms can be added or removed as listed in Section 5.1.2. Warning: make sure that the direction of arcs is from a fault DBN to the symptoms.

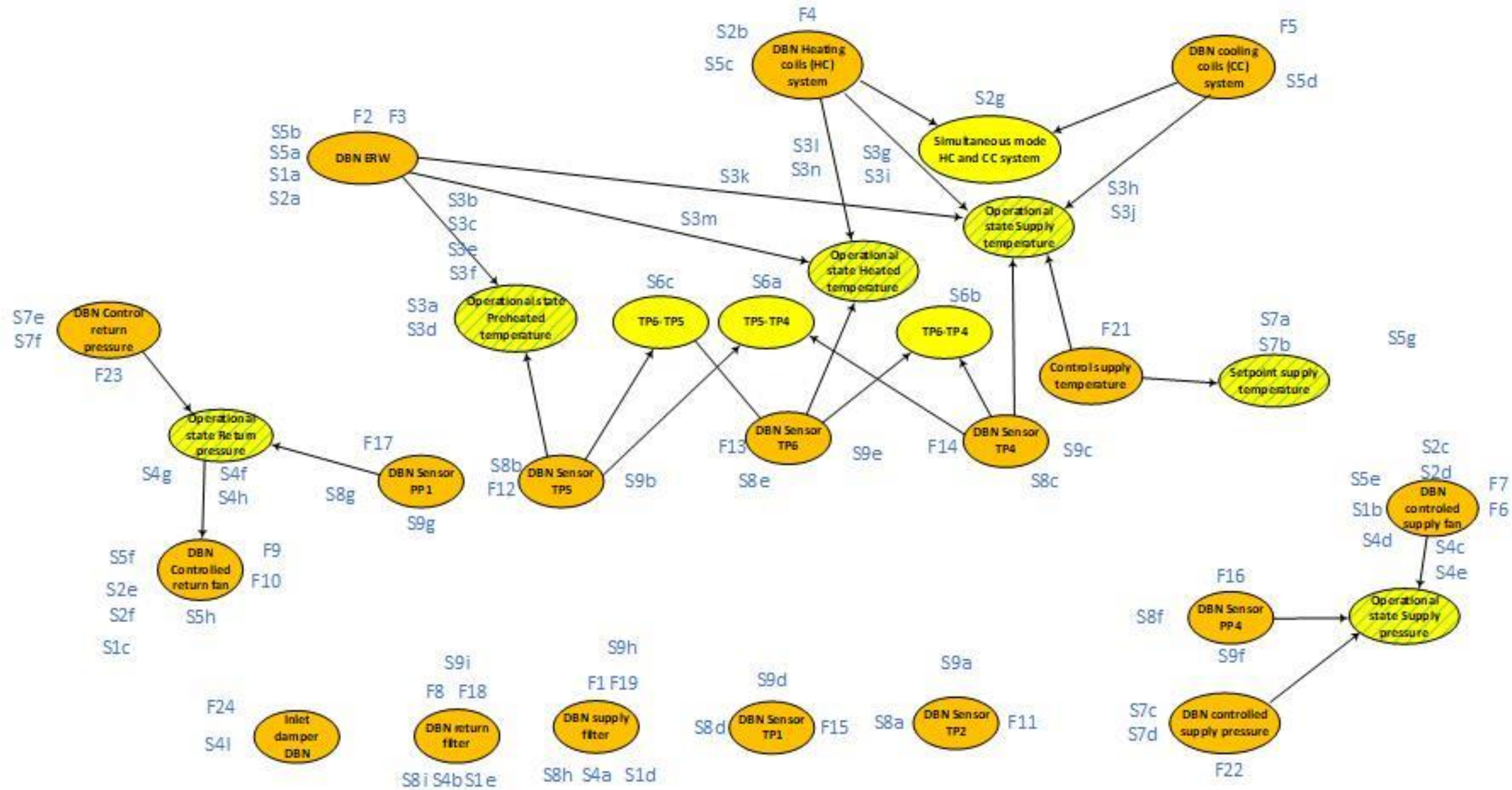



*Figure 5.6 An AHU DBN at level B with nested component DBNs.*

Appendix C2 discusses a DBN for the AHU of Building 28 of TUDelft. This DBN is successfully applied for FDD research at winter HVAC mode (cooling is not considered). See [8]. In contrast to the DBN of Figure 5.3, faults in the heating coils systems are considered: heating coil, heating coil valve and pump. It can be seen that the symptom types discussed in section 5.1.2 were applied.

## 5.4 Single AHU DBN fault node

In section 5.3, DBN nodes are realised for one component fault. However, aggregation is possible for multiple component faults depending on the presence and absence of sensors. For instance, for an aggregated thermal energy AHU system if measurements after ERW and heating coils are missing. See Figure 5.7.

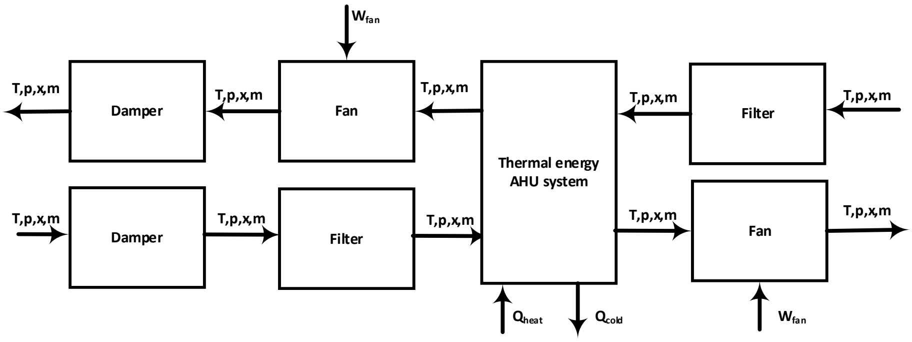



*Figure 5.7 AHU schematic with an aggregated thermal energy component.*

In the DBN submodels of Figure 5.6, only one component fault is present (as seen in Figure 5.5). It is possible to setup DBNs containing multiple component faults. In this way a single DBN can be setup for an AHU. As example, see Figure 5.8. Most symptoms shown in Figure 5.3 are enclosed in this DBN. Here, three symptoms fall outside the scope of the DBN, as they may also be applied to other DBN subsystems, such as room-level DBNs. This AHU DBN can be customized by moving symptoms outward for coupling with the cold and heat hydronic systems (not shown). Furthermore, faults and symptoms concerning supplied air flow rate and humidity could be added inside and outside the DBN.

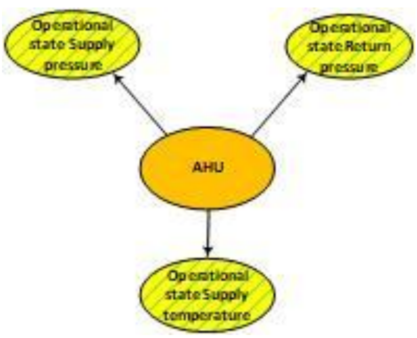



*Figure 5.8 DBN with an AHU DBN fault node.*

## 5.5 Single AHU fault node

It is also possible that the 'DBN AHU 'is replaced by one single AHU fault node. See Figure 5.9. This is a black box approach in which only faults could be diagnosed without estimating the individual component, control and model faults.

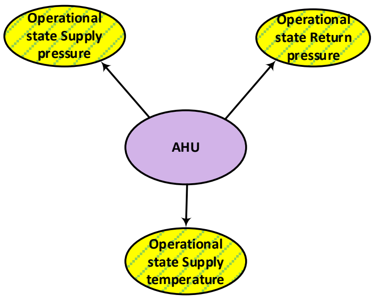



*Figure 5.9 DBN with an AHU fault node.*

## 5.6 Conclusions and recommendations

Air handling unit DBNs at level B can be set up based on the air handling unit module description in ISSO publication 31.

The DBNs at level B can be setup as a flat DBN in which all component faults are present as nodes. This could be adapted by combining the single fault nodes with their control and symptoms to DBNs. The second approach is to combine multiple fault nodes to a DBN node. This could result in a single AHU DBN node. The AHU could also be considered as a black box. An AHU node then replaces the AHU DBN node.

Symptom examples are presented in this section based on the sensors present in ISSO 31. However, often sensors are missing in existing air handling units. Therefore, a library with AHU symptoms and DBNs for sensor poor and rich environments could be setup. ISSO 31 could be applied for a sensor rich environment and ASHRAE for a sensor poor environment. DBN models present in this library could be adapted for specific HVAC systems.

As can be seen in this section, multiple symptoms can be linked to a fault node. For instance, the 'control energy recovery wheel' fault could be coupled to 10 symptom nodes. In case the symptom states are as well Present and Absent, the presence of a few symptoms will lead to incorrect diagnosis because most symptoms are Absent. It is recommended to conduct research at merged symptoms to one single symptom rule. For instance, the separate symptoms S3b,S3c,S3e,S3f,3k and S3m could be merged by the rule that 'S3b or S3c or S3e or S3f or 3k or S3m' is Absent or Present. See for instance symptom S22 in Appendix C2. Furthermore, research at different conditional probabilities in the symptoms, in such way that strong relationships can dominate (see [8]).

# 6 DBNS FOR HYDRONIC MODULES AT LEVEL B

DBNs for hydronic modules at level B can be setup for AHU DBNs as discussed in Section 5. In this section, an example of a DBN with separate fault and symptom nodes is discussed.

Figure 6.1 shows a generic block schematic for modules applicable to all types of thermal generators, distribution and user modules. From the science of thermodynamics it is known that work (W) and heat (Q) can be exchanged over the system boundaries. In addition thermal (coupled to the pressure p) and work (coupled to the temperature T) related energy can be exchanged by a fluid that flows over the system boundaries (because of open system). Here, we left kinetic, potential and chemical energy is disregarded.

In Figure 6.2 this is worked out for a heat pump system. The work W consist of $W_{aux}$ and $W_{compr}$. $W_{aux}$ stands for auxiliary work performed by pumps and fans and $W_{compr}$ for compressor work. Furthermore the term $Q_{losses}$ stands for thermal energy losses. The index pr stands for primary circuit (the heating circuit) and sec for the secondary circuit (the heat source circuit).

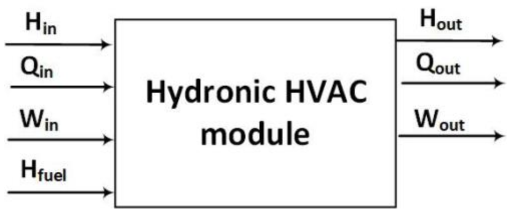



*Figure 6.1 Generic block schematic thermal energy module.*

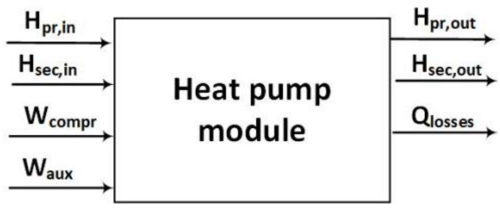



*Figure 6.2 Block schematic heat pump.*

Figure 6.3 shows an example of the DBN structure for an energy generator system. In this model only one component fault is present: the **generator**. Next to a faulty generator, the next faults are distinguished (in purple depicted):

- Component faults: hard sensor faults (measured temperatures and energy)
- Control fault: the control or regulation of the heat generator system.
- Control fault: the outlet temperature control of the supplied heat.
- Model fault: model for the energy balance equation.

For simplicity purposes, valves and pumps are not considered.

In light blue, nodes for readability purposes are depicted.

Soft sensors could replace some hard sensors (a model is plied to estimate a state value). These sensors could be depicted by the light purple colour (see Figure 2.1). For instance, when flow meters are not present, assumptions could be made for the flow rate.

Symptoms to be applied:

- Energy balance
- COP
- Capacity
- Temperature supply hot water

Figure 6.3 is applicable for all generators shown in Table 6.1 based on ISSO 31. For specific generators, some energy nodes are absent (see Table 6.2). Therefore, the DBN has to be adapted by deleting nodes.

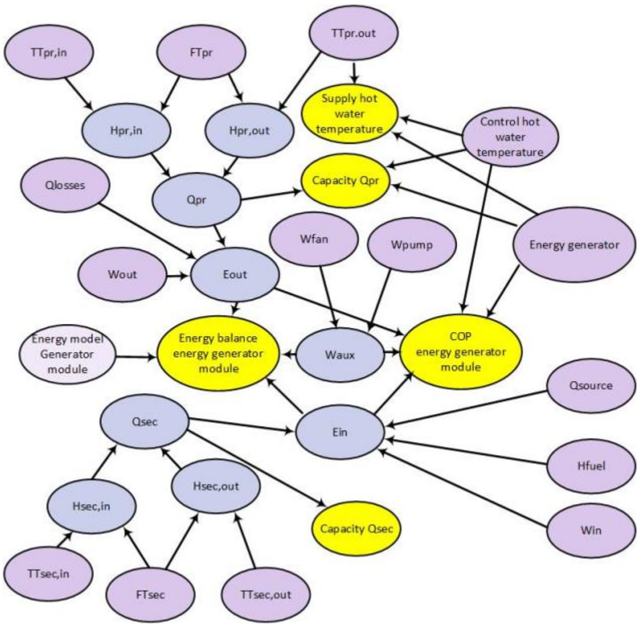



*Figure 6.3 Generic DBN model for an energy generator module.*

*Table 6.1 Overview of energy forms present in heat generators.*

| | | | Generic Heat generator | Gas boiler | Heat pump | CHP system | Heat exchanger | Heat net |
|---|---|---|---|---|---|---|---|---|
| $E_{in}$ | $H_{fuel}$ | | V | V | | V | | |
| | $Q_{source}$ | | V | | | | | |
| | $W_{in}$ | | V | | V | | | |
| | $W_{aux}$ | $W_{pump}$ | V | V | V | V | | V |
| | | $W_{fan}$ | V | V | V | | | |
| | $H_{sec,in}$ | | V | | V | | V | V |
| | $H_{sec,out}$ | | V | | V | | V | V |
| $E_{out}$ | $H_{pr,out}$ | | V | V | V | V | V | V |
| | $H_{pr,in}$ | | V | V | V | V | V | V |
| | $W_{out}$ | | V | | | V | | |

Hydronic DBNs at level B can be setup from the hydronic module description in ISSO publications 31 . Symptom examples are presented based on the sensors present in ISSO 31. However, often sensors are missing in existing air handling units. Therefore, a library with hydronic symptoms and DBNs for sensor poor and rich environments could be setup.

# 7 DBNS FOR HVAC SYSTEMS AT LEVEL A

As with level B, a DBN at level A can be composed of DBN submodels. As example, see Figure 7.1.

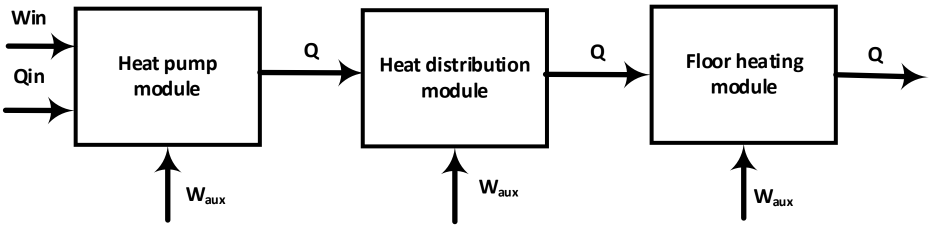



*Figure 7.1 Schematic for heat supply by a heat pump and by floor heating.*

All kind of combinations of modules can be present which can be part of or an entire HVAC system. See Appendices C3.3 (eight hydronic modules) and C4 in which two generator modules, three combined distribution and user modules, two air handling units and three zone systems are present. Next to modules present in ISSO 31, modules could be present at level A, for instance concerning electric systems (solar panels and batteries), cogeneration systems (fuel cells) and solar collectors.

Multiple solutions are possible to set up a DBN with nested DBNs because modules at level B can also be aggregated to a combined DBN model (in appendix C4 the hydronic distribution and user modules are merged). In addition, multiple fault and symptom nodes could be present inside a DBN at level B or outside at level A.

Section C3.3.1 of Appendix C3 presents a DBN which is applied for energy performance (see [1]). Nodes concerning energy are present in the hydronic modules. And in Section C3.3.2, a DBN for sensor FDD is discussed. In this DBN, sensor faults are present in the DBN of the hydronic modules. The approaches in these sections conflict with the 4S3F method's premise that all arrows in the DBN go from faults to symptoms. This could complicate extension with other modules and thus modularity.

This paragraph proposes a DBN at level A with DBN nodes for HVAC modules with symptoms which are linked to multiple modules are present at level A. As example, see the DBN in Figure 7.2, which presents a hydronic HVAC system at level A. In this DBN three module DBNs at level B with three symptoms are present.

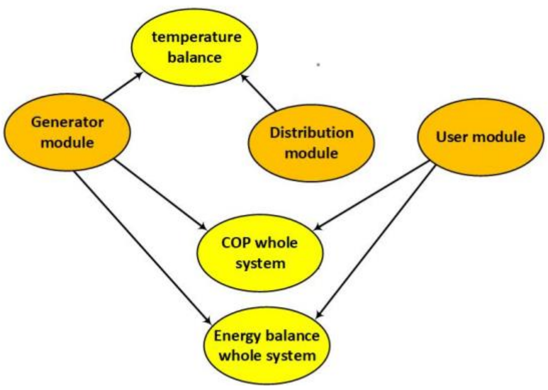



*Figure 7.2 Example DBN model at level A with embedded DBN models.*

Figure 7.3 presents the heat generator module present in this figure.

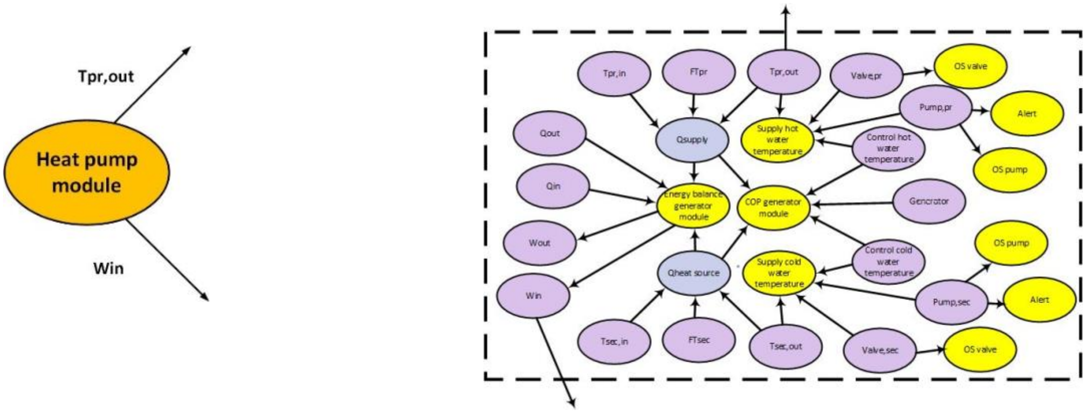



*Figure 7.3 Nested DBN for a heat pump module.*
*(pr=primary circuit, sec=secondary circuit, E=electricity, Q=heat, TT=temperature sensor, FT=flow sensor).*

Instead of DBN nodes, normal nodes could be applied. See Figure 7.4.

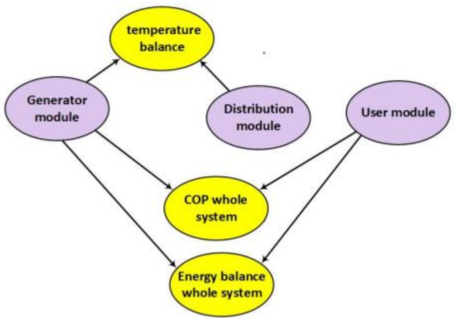



*Figure 7.4 Example of a DBN model at level A with fault nodes.*

In this DBN at level A, all sensors are present in the embedded DBNs because this leads to a clear figure. However, an issue is that some energy related nodes are needed in multiple hydronic modules. Therefore, a solution is that energy related sensors, applied for multiple nested systems in the DBN, and linked symptoms, are present at level A. Elaboration of this for a heat pump module leads to Figure 7.5.

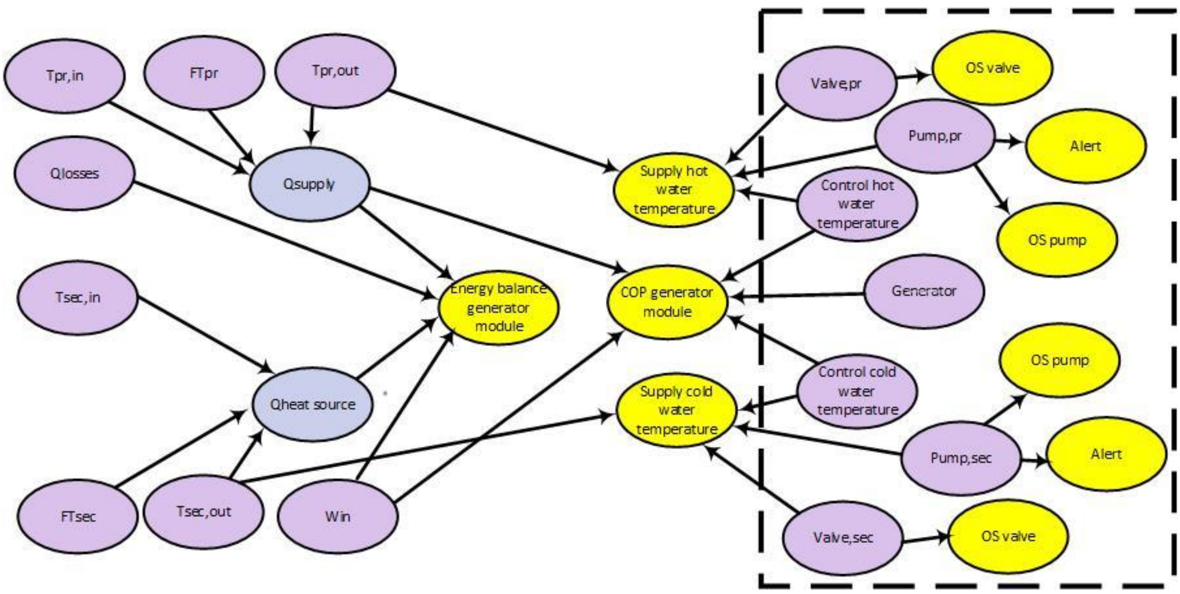



*Figure 7.5 Nested DBN for a heat pump module with energy related nodes outside the DBN at level B.*

In addition, the energy related nodes could be embedded in an energy module node. See Figure 7.6.

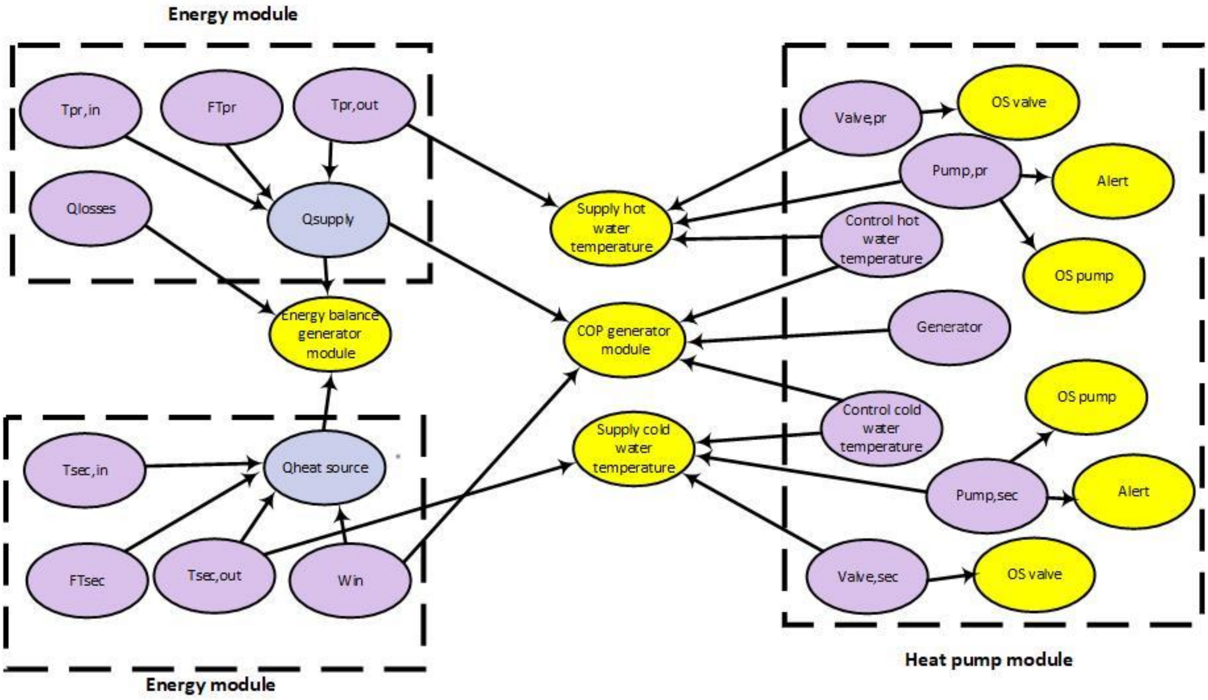



*Figure 7.6 Nested DBN for a heat pump module and for energy related nodes.*

Figure 7.7 shows this DBN with a heat pump module DBN node and two energy module DBN nodes.

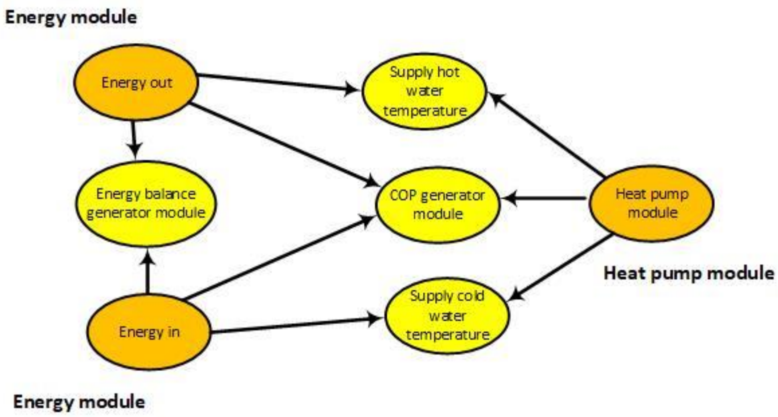



*Figure 7.7 A heat pump DBN node connected to two energy DBN nodes.*

In this way, as example (more symptoms could be added), the adapted Figure 7.2 could be become as shown in Figure 7.8.

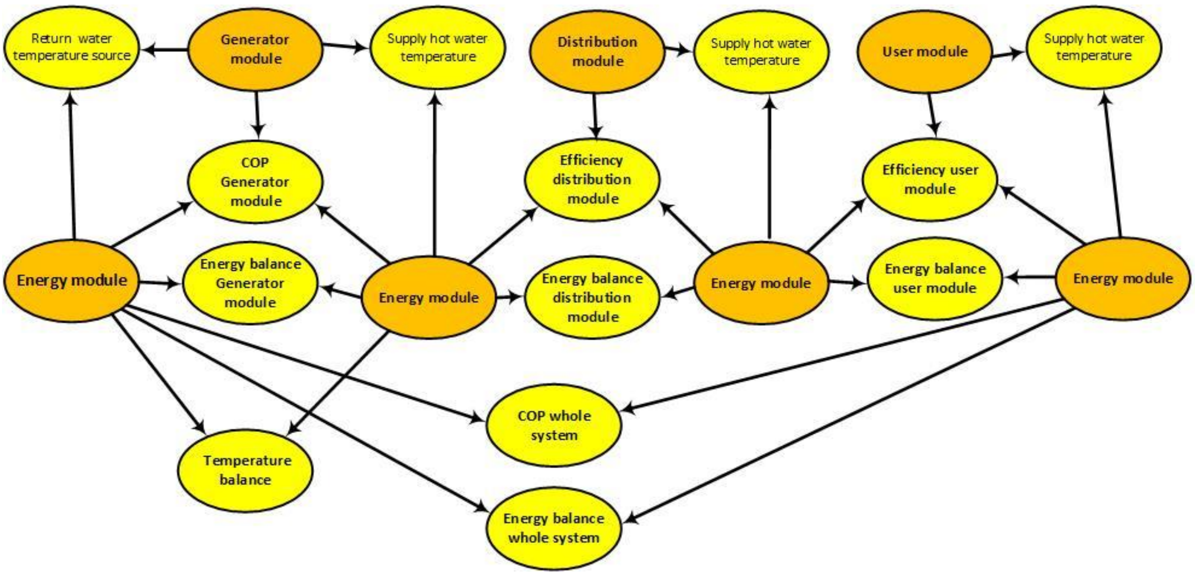



*Figure 7.8 A DBN at level A with three hydronic module DBNs and four Energy module DBNs.*

Fault nodes can replace the hydronic module DBNs in Figure 7.8. The DBN could then be adjusted by moving some more symptoms from the DBN modules to level A. For example, alerts. This has not been worked out.

## Conclusions

This section shows that DBNs at level A can be setup with module nodes or DBNs applying ISSO publications 31. It is possible to setup generic DBNs. A DBN at level A can be setup in a modular way by leaving out energy related sensors outside the hydronic modules. Furthermore, symptoms related to multiple hydronic modules have to be present at level A. An important rule is that arcs are directed from faults to symptoms. A DBN at level A becomes then modular which can be extended with other modules.

## Recommendations

It is recommended for a specific HVAC system, to start with the setup of a block schematic with the modules of the HVAC system at level A. Then, setup a DBN with HVAC modules as fault nodes. Faults which affect multiple modules should be placed outside these module nodes. For instance, HVAC mode controls and sensors. In addition, symptoms at level A can be placed. Start with OS symptoms for which examples are shown in this section. Depending on the number of energy related sensors, few or many balance and energy performance symptoms could be placed. Often, temperature balances can be applied.

In a later stage, the module nodes could be replaced by DBN module nodes at level B.

Only one DBN at level A is presented in this section. Therefore, a library with systems at level A with symptoms at level A should be setup. Modules which should be considered are hydronic heat and cold modules, air handling units, room modules and electric modules. This could be done for a sensor poor and rich environment as recommended for DBNs at Level B and C shown in sections 4 to 6.

# 8 HELP NODES IN DBNS

In this section, the application of additional symptom nodes are discussed which helps the diagnosis, modularity and readability of DBN models.

## 8.1 Missing sensors

In specific heat generator modules, some nodes are absent. This can be done in two ways:

- Adapting of an existing DBN.
- By adding ABS (absent) nodes. See Figure 8.1, where a DBN is presented, and three sensors are coupled to an ABS node. If these sensors are not present, the ABS is set to Present once at setting up the DBN.

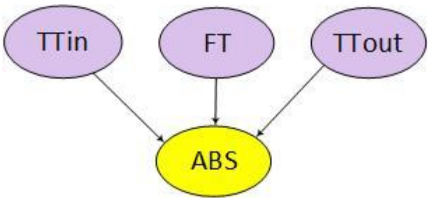



*Figure 8.1 Application of ABS nodes.*

The sensors TTin, FT and TTout have to set to *Absent* when ABS is *Present* and set to their probabilities when ABS is *Absent*.

Table 8.1 presents the corresponding conditional probabilities table (CPT) for the symptom node ABS.

*Table 8.1 Conditional probabilities for an ABS node.*

| Parent | TTin | FT | TTout | LEAK |
|---|---|---|---|---|
| State | *Present* | *Present* | *Present* | |
| *Absent* | 1 | 1 | 1 | 0.999 |
| *Present* | 0 | 0 | 0 | 0.001 |

How to read? The state of ABS is always *Absent* when TTin and/or FT and/or TTout is *Present*. Thus ABS can only be *Present* when TTin, FT and TTout are all *Absent*. This can be set by the *Present* LEAK value of 0.001 which is tested in [1].

This could help the setup of a library. For instance, one DBN for all kind energy generator modules could be developed. As an example, the DBN of Figure 5.3 becomes then Figure 8.2.

The ABS nodes must set **once** for a specific DBN. For instance, Table 6.1 is applied to setup Table 8.2 which presents the presence of sensor nodes for the 5 heat generators in ISSO 31.

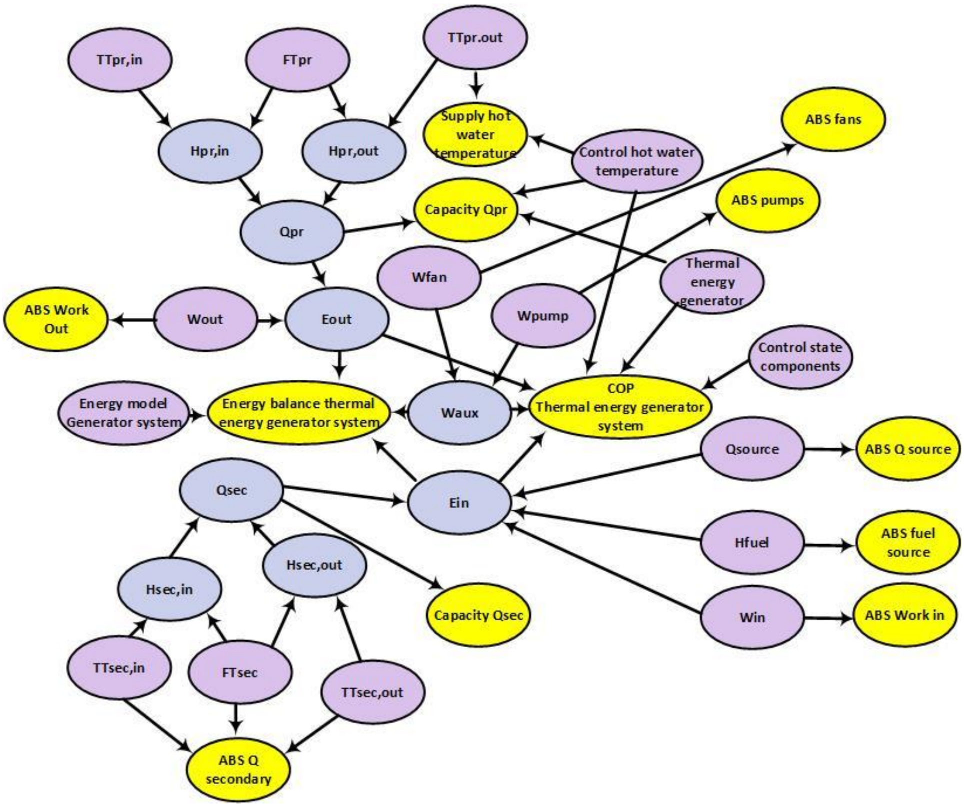



*Figure 8.2 DBN energy generator module with ABS nodes.*

*Table 8.2 Presence of ABS for several heat generators.*

| | Presence of ABS nodes | | | | |
|---|---|---|---|---|---|
| | Gas boiler system | Heat pump system | CHP system | Heat exchanger system | Heat net system |
| $H_{fuel}$ | | 1 | | 1 | 1 |
| $Q_{source}$ | 1 | 1 | 1 | 1 | 1 |
| $W_{in}$ | 1 | 1 | 1 | 1 | 1 |
| $TT_{sec,in}$ | 1 | | 1 | | |
| $TT_{sec,out}$ | 1 | | 1 | | |
| $FT_{sec}$ | 1 | | 1 | | |
| $W_{pump}$ | | | | 1 | 1 |
| $W_{fan}$ | | 0/1 | 1 | 1 | 1 |
| $W_{out}$ | 1 | 1 | | 1 | 1 |

## 8.2 Negligible nodes

The DBN of a whole HVAC system could be complex by a large number of faults. To avoid false faults, negligible energy (NE) nodes can be implemented in the DBN model, which indicate the presence of small energy amounts in the systems and set the faults in the sensor and model nodes in the fault layer of these systems to *Absent*. Figure 8.3 shows an example in which NE01 is a negligible energy node.

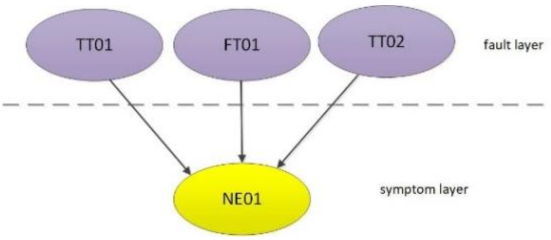
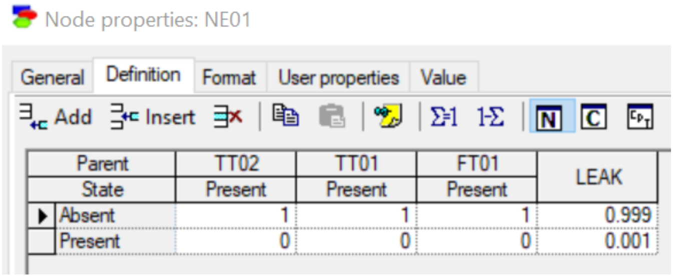



*Figure 8.3 Example of a DBN Negligible Energy (NE) node.*

The fault nodes are set to *Present* when the linked negligible energy symptom is *Present* and *Absent* if *Absent* in the same way as at the ABS nodes. Figure 8.4 presents an example of the CPT of the NE symptom node (from [1]). When the symptom node NE01 is set to Present, thus the exchanged energy amount is small, all sensor faults are set to Absent.


Node properties: NE01

General | Definition | Format | User properties | Value

Add | Insert

| Parent | TT02 | TT01 | FT01 | LEAK |
|---|---|---|---|---|
| State | Present | Present | Present | |
| Absent | 1 | 1 | 1 | 0.999 |
| Present | 0 | 0 | 0 | 0.001 |

*Figure 8.4. Example of a DBN NE node (from [1]).*

## 8.3 In-between nodes

As stated in Section 2.2, DBNs can be made more readable by application of enthalpy ()H) and heat (Q) (fault) nodes. See, as examples, Figures 2.3 and 7.5. In this way uncertainties and inaccuracies in the estimation of H and Q could be incorporated. See as example the CPT of an H node in Table 8.3.

*Table 8.3 Conditional probability table for an enthalpy node.*

| Parent | TT | FT | LEAK |
|---|---|---|---|
| State | Present | Present | |
| Present | 0.999 | 0.999 | 0.001 |
| Absent | 0.001 | 0.001 | 0.999 |

To be read: The node H is set to *Present* with high probability when TT or/and FT is *Present* and sent to *Absent* with high probability when both TT and FT are *Absent*.

## 8.4 Results from other FDD methods

Some components contain their own FDD method from which an alert could be derived. As additional information for sensor TT01, the symptom node FDD TT01 could be present in the DBN. See Figure 8.4.

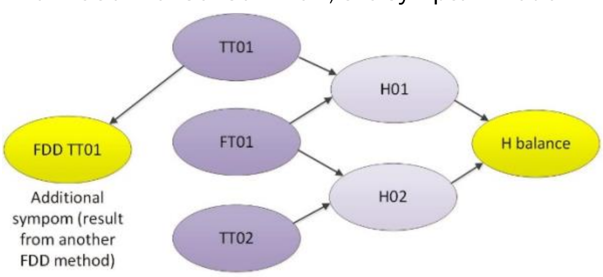



*Figure 8.4 Example of adding an FDD node..*

The corresponding CPT is shown in Table 8.4.

*Table 8.4 Conditional probability table for an FDD node.*

| Parent | TT01 | |
|---|---|---|
| State | Present | Absent |
| Present | 1 | 0 |
| Absent | 0 | 1 |

The posterior outcomes for TT01, FT01, and TT02 depend on the state of FDD TT01 when symptom *Hbalance* is set to Present. [1] showed that all sensors have almost the same Present probability (34-35%) when the evidence of FDD TT01 is unknown. When FDD TT01 is Present then TT01 is set correctly to Present and set to Absent when FDD TT01 is Absent.

## 8.5 Conclusions and recommendations

This section discussed ABS, NE, energy and FDD symptoms that appear to be promising. However, these symptoms were partially tested in case studies. In particular, the determined probabilities shown can be a problem when combined with multiple symptom nodes on one fault node. It is recommended to conduct research into this.

# 9 STATES OF FAULTS AND SYMPTOMS

## 9.1 Introduction

In this section, the states of faults and symptoms is considered. In the case studies presented in the appendices C2 to C5 only two states were distinguished in the fault and symptom nodes: Present or Absent. Multiple fault states could help to estimate the type of fault. For instance, a broken, a positive or a negative biased sensor. In the same way, multiple states of symptoms could be applied. For instance, a small or large deviation, negative or positive deviation or unknown state of a symptom.

All symptom nodes contain a CPT (conditional probability table). The values inside the table could be adapted depending on the process states as mode of mechanical components. Some additional conditions in the rules could be removed, making the rules easier. However, software is needed to set the conditional probabilities for the symptoms. In addition, check of the rules is more difficult.

Many symptoms linked to a fault could lead to incorrect diagnosis. It is proposed to set the current conditional Present probability (i.e. symptom present) very high for some symptoms, such as warnings and unrealistic sensor values.

## 9.2 Conclusions

Several solutions are suggested to avoid issues related to too many symptoms linked to a fault. The first is merging symptoms. Furthermore, setting different prior and conditional probabilities could help. And maybe, ignoring symptoms by adding an unknown state. Next to this, multiple fault and symptom states could help isolate the fault type, which helps the correction phase.

## 9.3 Recommendations

Research has to be conducted to make proposals for the issue that multiple symptoms are linked to one fault. For instance, the number of symptoms which could be linked to a fault for which one Present symptom leads to a correct isolation of the fault. Furthermore, which symptoms could be merged?

For fault correction purposes, research is desired to set multiple states in the symptom and fault nodes. Next to this, can a correct diagnosis been conducted when some symptom states are unknown?

And finally, which prior and conditional values must be set in the fault and symptom nodes?

# 10 CONCLUSIONS AND RECOMMENDATIONS

## 10.1 Conclusions

In this report, a start is made for the standardisation of HVAC DBN models at levels A, B and C. Level A means complete or partly HVAC systems, level B subsystems and level C HVAC components.

The DBN models at level B are defined by the hydronic and AHU modules, described in ISSO 31. Examples showed how a DBN can be set up with operational state, balance, energy performance and additional symptoms. Rules for symptoms were presented for an AHU module. A generic hydronic module DBN could be setup for all kind of generator, distribution and user modules. By removing nodes, this DBN could be made generic.

Several solutions are possible to set up DBNs at levels A and B. See table 10.1 in which advantages and disadvantages are presented for three options. An example of option I for a module shows Figure 5.4. Figure 7.3 presents an example of option III at level A. The DBN submodels are orange coloured there. Replacing these orange DBN nodes by DBN nodes gives option II (see section 5.3).

*Table 10.1 Options for the structure of dBNs at level A and B.*

| | Option I: Flat DBN | Option II | Option III |
|---|---|---|---|
| | One DBN, consisting of all fault nodes for the considered system in a single DBN. | One DBN, containing several nodes for components or modules of a lower level. | DBN contains several nested DBNs for components or modules at a lower level. |
| advantages | All faults, symptoms and arcs are present in one DBN figure. | It is most easy to set up a DBN at level A when a complex HVAC system contains many hydronic systems and AHUs. | Faults at level A, B and C could be isolated simultaneously. |
| | | It is most easy to set up a DBN at level B when a complex HVAC module contains many components. | |
| | Applicable for a sensor poor environment (few symptoms) | Applicable for a sensor poor HVAC system. | Applicable for a sensor rich HVAC system. |
| | | High modularity | Very high modularity. |
| | | Very good readability | Good readability |
| | | Adaption of the DBN is possible by replacing the fault nodes by fault DBNs → Change to option III. | |
| disadvantages | DBN could be very large and unreadable because arcs cross each other. | Faults within the considered component/system cannot be isolated. Only faults at the corresponding DBN level. | Software needed which can setup nested DBNs. |
| | Low modularity | | |

All three approaches are presented for hydronic and AHU modules. The DBN examples showed component, control and model faults, and balance, EP and OS symptoms.

Preference is given to option III because of the very high modularity of the DBNs.

## 10.2 Recommendations

### Library

All three DBN approaches are useable because each has advantages and disadvantages. It is recommended that these approaches be applied depending on the presence and absence of sensors.

In this note, ISSO 31 is taken as a starting point. As an example, DBNs for ISSO 31 modules have been set up. An issue is that the DBNs become very large, partly due to possible sensor faults.

So-called 'Help' nodes could support setting up DBNs when many symptoms are linked to a fault node or to rule out faults in an HVAC mode.

Although no symptom detection rules have been developed and probabilities have been determined in this document, attention has been paid to symptom rules for an air handling unit.

The main recommendation is that the DBN library be modular, meaning that parts of generic DBNs can be replaced by others and that the DBN can be easily modified and extended without changing the DBN structure. For example, energy-related input and output sensors are placed outside a standardized module or component DBN so that they can be linked to multiple modules and component fault nodes and DBNs. It was recommended to realize this for a sensor-rich (in accordance with ISSO 31) and a sensor-poor environment (in accordance with ASHRAE).

Next to this, it was recommended that in addition to hydronic HVAC and air handling unit modules, modules should also be developed for air distribution and user modules, and non-HVAC modules as electrical systems, solar collectors, cogeneration systems.

The 4 types of symptoms and 3 types of faults in the 4S3F method should be applied to build up a DBN library. A sensor-rich environment (application of ISSO 31) and a sensor-poor environment (application of proposed sensors by ASHRAE) need to be developed. It is recommended to set up an overview of components and controls with the symptoms which could be applied. A consideration is to set up a separate sub-library without sensor faults because these could be unconsidered by periodic commissioning. In addition, for DBNs without energy balance symptoms.

### Further research

Generic hydronic module DBNs should be researched for all types of generator, distribution and user modules. The DBNs could be more or less generic. The two extreme solutions are one DBN for a hydronic module or DBNs for all hydronic modules in ISSO 31, 44 and 47. Attention has to be paid to user modules with room devices.

To address the problem to diagnose sensor faults, which result in large DBNs and possible incorrect diagnoses, sensor commissioning could be applied. In addition, data-driven symptoms could be applied (e.g. pattern recognition of abnormal measurements). This can also be done for components as shown in Appendix C1.

Research should be conducted on elaborating model faults at which no attention is paid in this document.

Furthermore, research should be done into multiple symptoms linked to one fault, setting probabilities in DBN nodes and the application of so-called Help nodes.

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[9] Mosteiro-Romero, M., Lu, C. J., Wang, Z., & Itard, L. C. M. (2024). Whole-Building HVAC Fault Detection and Diagnosis with the 4S3F Method: Towards Integrating Systems and Occupant Feedback. Paper presented at The 5th Asia Conference of International Building Performance Simulation Association 2024, Osaka, Japan.

# APPENDIX A. EQUATIONS FOR HVAC SYSTEMS.

In the 4S3F method, energy is used for EP detection as well for balance detection. In this section, the system approach is used to set up EP and balance symptoms.

Figure A.1 shows a block schematic for an HVAC system.

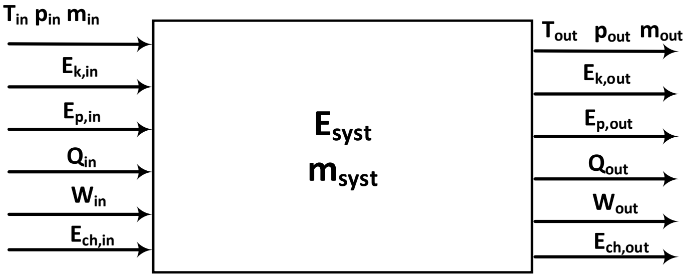



*Figure A.1 Generic block schematic energy system.*

In case that the system is thermodynamically an open system, mass will flow over de system boundaries. Next to chemical energy ($E_{ch}$), kinetic energy related to velocity ($E_k$) and potential energy related to height ($E_p$), thermal energy is coupled to mass by its temperature and mechanical energy coupled to the pressure p. Q and W are thermal energy and technical work which is not coupled to exchanged mass. In section A.1, the energy balance equation is discussed, followed by the mass and pressure equations in section A.2 and A.3.

## A.1 Generic energy balance equation

The formula for an energy system can be formulated by the equation:

$$E_{in} - E_{out} = \Delta E_{syst}$$

with $E_{in}$ = energy input to the system [J]

$E_{out}$ = energy output of the system [J]

$E_{syst}$= energy storage in the system [J]

Energy E is built up from energy forms:

$$E = H + E_k + E_p + Q + W_t + E_{ch}$$

with H = enthalpy [J]

$E_k$ = kinetic energy [J]

$E_p$ = potential energy [J]

$E_{ch}$= chemical energy [J]

Q = supplied heat [J]

$W_t$ = delivered (technical) work [J]

The enthalpy H consists of a thermal and a mechanical term:

$$H = U + pV = m.c_V T + \frac{m}{\rho}.p$$

with U = internal energy [J]

p = pressure [Pa]

V = volume [m3]

$c_V$= specific heat capacity at constant volume [J/kg.K]
ρ = density [kg/m3]

## A.2 Generic mass balance equation

$$m_{in} - m_{out} + m_{prod} = \Delta m_{syst}$$

with $m_{in}$ = mass input to the system [kg]
$m_{out}$ = mass output of the system [kg]
$m_{prod}$ = mass production in the system [kg]
$m_{syst}$= mass storage in the system [kg]

In the mass balance equation, a production term by a chemical reaction is present. The mass balance can set up for each component when material which contains multiple components.

## A.3 Generic pressure balance equation

$$p_{in} - p_{out} + \Delta p_{prod} = \Delta p_{syst}$$

with $p_{in}$ = input pressure to the system [pa]
$p_{out}$ = output pressure of the system [pa]
$\Delta p_{prod}$= pressure rise in the system [pa]
$p_{syst}$= pressure in the system [pa]

In the pressure balance equation, a part of the production term is negative by friction within the system.

# APPENDIX B. ISSO 31

Table B.1 presents the HVAC modules presented in ISSO 31.

*B.1 Structure and codes*

| | | Code |
|---|---|---|
| Heating | User module | Warmtegebruikermodule 1 (WGM1) |
| | | Warmtegebruikermodule 2 (WGM2) |
| | | Warmtegebruikermodule 3 (WGM3) |
| | | Warmtegebruikermodule 4 (WGM4) |
| | | Warmtegebruikermodule 5 (WGM5) |
| | | Warmtegebruikermodule (WGM6) |
| | | Warmtegebruikermodule (WGM7) |
| | | Warmtegebruikermodule 8 (WGM8) |
| | Distribution module | Distributiemodule 1 (DM1) |
| | | Distributiemodule 2 (DM2) |
| | | Distributiemodule 3 (DM3) |
| | | Distributiemodule 4 (DM4) |
| | Generation module | Verwarming opwekkermodule 1 (OW01) |
| | | Verwarming opwekkermodule 4 (OW04) |
| | | Verwarming opwekkermodule 6 (OW06) |
| | | Verwarming opwekkermodule 8 (OW08) |
| | | Verwarming opwekkermodule 9 (OW09) |
| | | Verwarming opwekkermodule 10 (OW10) |
| | | Verwarming opwekkermodule 11 (OW11) |
| | | Verwarming opwekkermodule 13 (OW13) |
| | | Verwarming opwekkermodule 15 (OW15) |
| Cooling | User module | Koudegebruikersmodule 1 (KGM01) |
| | | Koudegebruikersmodule 2 (KGM02) |
| | | Koudegebruikersmodule 3 (KGM03) |
| | | Koudegebruikersmodule 4 (KGM04) |
| | | Koudegebruikersmodule 5 (KGM05) |
| | | Koudegebruikersmodule 6 (KGM06) |
| | | Koudegebruikersmodule 7 (KGM07) |
| | | Koudegebruikersmodule 8 (KGM08) |
| | Reversing module | Omkeermodule 1 (OKM01) |
| | | Omkeermodule 2 (OKM02) |
| | | Omkeermodule 3 (OKM03) |
| | Generation module | Koeling opwekkermodule 1 (KOM01) |
| | | Koeling opwekkermodule 4 (KOM04) |

| | | Code |
|---|---|---|
| | | Koeling opwekkermodule 6 (KOM06) |
| | | Koeling opwekkermodule 9 (KOM09) |
| | | Koeling opwekkermodule 10 (KOM10) |
| | | Koeling opwekkermodule 11 (KOM11) |
| | | Koeling opwekkermodule 12 (KOM12) |
| | | Koeling opwekkermodule 13 (KOM13) |
| | | Koeling opwekkermodule 14 (KOM14) |
| | | Koeling opwekkermodule 15 (KOM15) |
| | | Koeling opwekkermodule 17 (KOM17) |
| Air handling | Air handling module | Luchtmodule 13 (L13) |
| | | Luchtmodule 14 (L14) |
| | | Luchtmodule 15 (L15) |
| | | Luchtmodule 16 (L16) |

B2. Example from ISSO 31

Figure B2.1 presents a description of a heat user module in ISSO 31 in Dutsch.

# 3 Meetpunten en meetmethoden hydraulische schakelingen voor verwarming

In dit hoofdstuk worden per hydraulische module (conform ISSO-publicatie 44 opgedeeld naar gebruikersmodulen, distributiemodulen en opwekkermodulen) de benodigde meetpunten per doel gepresenteerd.

Hierbij worden de volgende drie meetdoelen aangehouden:
1. Regelen/Besturen;
2. Beveiligen;
3. Monitoren.

Daarnaast wordt de beschrijving van de gangbare toepassingen van de module en de beschrijving van de functie van de inregelafsluiters weergegeven. Deze omschrijvingen sluiten aan op ISSO-publicatie 44.

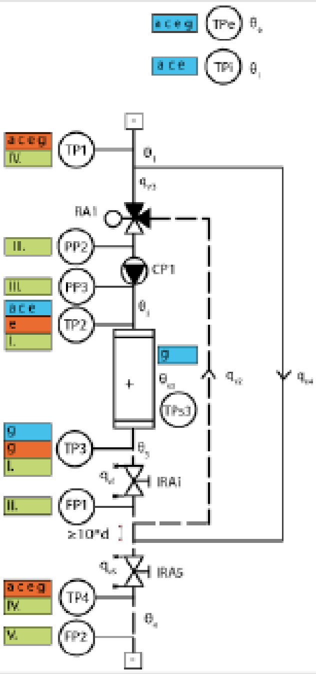
De beschrijving van deze functies en inregelafsluiters draagt bij aan de begripsvorming over mogelijke regelingen. Daarnaast hebben inregelafsluiters een functie binnen de diverse bepalingsmethoden voor monitoring.

Verdere informatie over hydraulisch gedrag van de modules onder belasting is niet opgenomen aangezien deze uitvoerig in de publicatie ISSO-publicatie 44 is beschreven. Selectie van de modules zal dan ook op basis van ISSO-publicatie 44 moeten plaatsvinden. Vanuit de selectie, gemaakt met behulp van ISSO-publicatie 44, kan deze publicatie gebruikt worden om de juiste meetpunten, meetapparatuur en meetmethoden te selecteren.

De beschrijving van de meetpunten wordt gerelateerd aan de voorkeurstoepassing (functie) van de module.

## 3.1 Gebruikersmodulen voor verwarming

### 3.1.1 Warmtegebruikermodule 1 (WGM1)




Toepassing(en)
a. Radiatoren/convectoren
c. Stralingspanelen
e. Klimaatplafond
g. Voorverwarmer LBK

Inregelafsluiters
Vollast volumestroom qv1,100 met IRA1.
Vollast volumestroom qv5,100 = qv1,100 met IRA5.

Opmerkingen
Bij meerdere afgiftelichamen met (thermostatische) regelventielen een toerengeregelde pomp toepassen en volumestroom voor monitoring alleen te bepalen via FP2 bepalingsmethode 7.3.2.
Zodanig inregelen dat qv5 > qv1 (circa 5%) om invloeden uit het distributienet te minimaliseren.

*Figure B2.1 heat user module WGM1 (copy from ISSO 31 [4]).*

# APPENDIX C. DBN EXAMPLES

## C1 DBN for a part of the air handling unit of the Kropman building in Breda

Wang et al. [6] researched FDD at the heat recovery wheel (HRW) and the valve of a heating coils system (HCV) of the AHU of the Kropman building in Breda. In Figure C1.1, a P&ID of the AHU is shown with these components depicted.

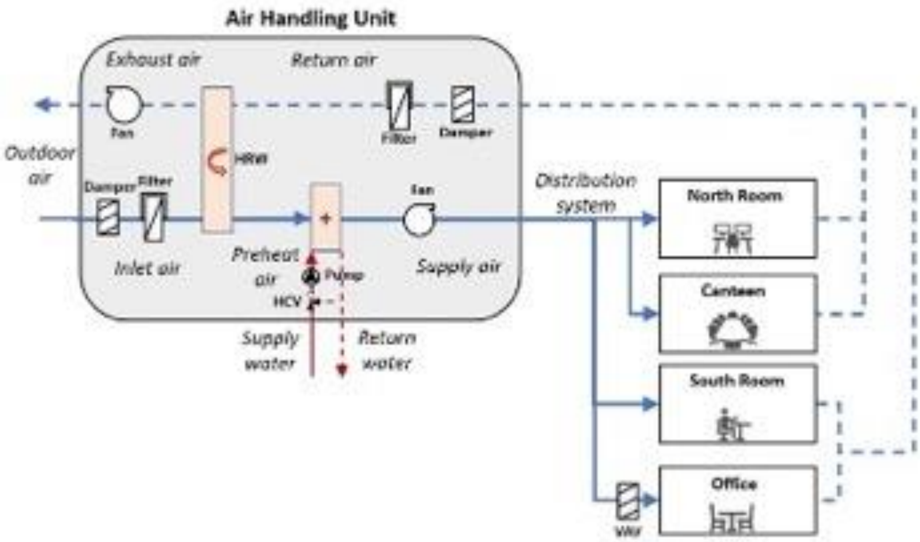



*Figure C1.1 P&ID of the air handling in the Kropman building in Breda (from [7]).*

The DBN is shown in Figure C1.2.

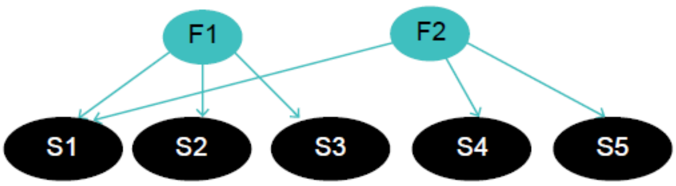



*Figure C1.2 DBN for heating coil valve and heat recovery wheel faults.*

F1 stands for heating coil valve and F2 for the heat recovery wheel. The fault F1 and F2, and symptoms S1 to S5 are shown in Table C1.2. The symptoms S1 and S3 were data-driven and S2, S4 and S5 knowledge based.

*Table C1.2 Systems present in the DBN of Figure C1.2.*

| Fault | 3F type | Symptom | 4S type |
|---|---|---|---|
| F1 Energy recovery wheel (HRW) | component | S1 Difference of HCV position prediction | OS |
| F2 Heating coil valve HCV | component | S2 Difference of setpoint and supply temperature | OS |
| | | S3 HCV openness frozen | OS |
| | | S4 HRW efficiency | EP |
| | | S5 Difference between temperature before and after HRW | balance |

## C2 DBN FOR AN AIR HANDLING UNIT OF THE BUILDING 28

An FDD case study was applied on one of the air handling units of building 28 of the Technical university of Delft [8] . Figure C2.1 presents the P&ID, present in the BMS.

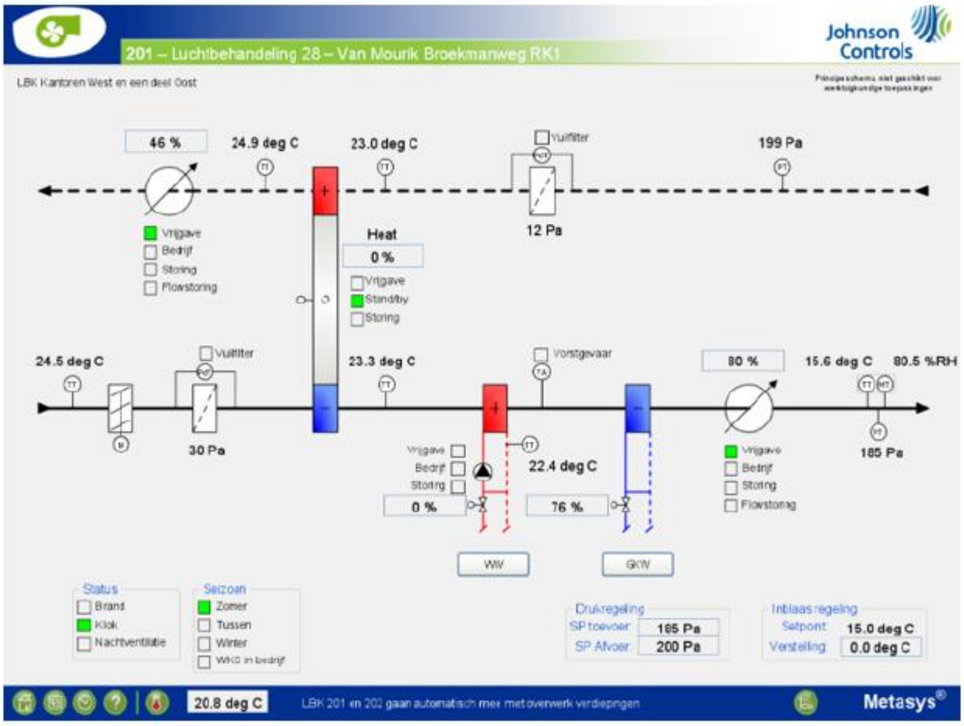



*Figure C2.1 P&ID of AHU101 of Building 28 TU Delft (source BMS).*

The main thermal energy exchange systems are the energy recovery wheel (ERW), the heat coil (HC) system and the cold coil (CC) system. Next to this, we see an inlet damper, fans and filters, and sensors. Less sensors are present than indicated in ISSO 31. In P&ID sensors are present. As can be seen a temperature sensor after the energy recovery wheel is missing. And also flow rate sensors are not present.

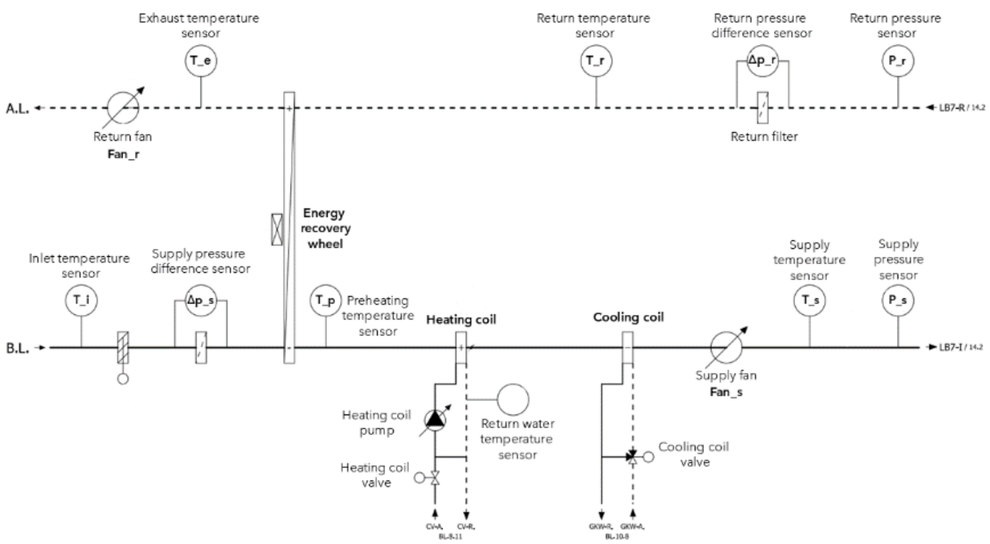
Research was conducted on this AHU based on the 4S3F method. The considered faults and symptoms are shown in Table C2.1.

*Table C2.1 Faults and symptom present in the AHU case study.*

| Fault | | 3F type | Symptom | 4S type |
|---|---|---|---|---|
| F1 Supply fan | | component | S1 Temperature deviation Ti and To | Balance |
| F2 Return fan | | component | S2 Supply fan alert is present | Additional |
| F3 Supply filter | leakage | component | S3 Difference ps and ps,set at $0<Us,fan<100$ | OS |
| | fouling | | | |
| F4 Return filter | leakage | component | S4 Difference ps and ps,set | OS |
| | fouling | | | |
| F5 Energy recovery wheel ERW | | component | S5 Return fan alert is present | Additional |
| F6 Supply damper | | component | S6 Difference pr and pr,set at $0<Ur,fan<100$ | OS |
| F7 Supply pressure sensor ps | | component | S7 Difference pr and pr,set | OS |
| F8 Return pressure sensor pr | | component | S8 Comparison ps,set with design value | OS |
| F9 Inlet temperature Ti (before ERW) | | component | S9 Comparison pr,set with design value | OS |
| F10 Preheated temperature Tp (after ERW) | | component | S10 High Δps | OS |
| F11 Supply temperature sensor Ts | | component | S11 Supply filter alert present | Additional |
| F12 Return temperature sensor Tr (before ERW) | | component | S12 High Δpr | OS |
| F13 Exhaust temperature sensor Te (after ERW) | | component | S13 Return filter alert present | Additional |
| F14 Supply temperature setpoint Tset | | component | S14 Low Δps | OS |
| F15 Supply pressure setpoint ps,set | | control | S15 Low Δpr | OS |
| F16 Return pressure setpoint pr,set | | control | S16A Temperature deviation Ti and To<br>B Ti outlier or missing data | Balance<br>OS |
| F17 ERW control | | control | S17A Temperature deviation Tp and Ti at ERW off<br>B Tp outlier or missing data | Balance<br>OS |
| F18 Heating coil valve control (HCV) | | control | S18A Temperature deviation Ts and Tp at HCV & CCV closed<br>B Ts outlier or missing data | Balance |
| F19 Supply fan control | | control | S19 Tr outlier or missing data | OS |
| F20 Return fan control | | control | S20 Te outlier or missing data | OS |
| F21 Heating coil (leakage) | | control | S21 Temperature deviation Te and Tr at ERW off | Balance |
| F22 Heating coil pump (HC failure) | | component | S22A Difference Ts and Tset at $0<Uhcv<100\%$<br>B $Uhcv<100\%$ and $Uerw<100\%$<br>C Uhcv outlier | OS<br>OS<br>OS |
| F23 Supply filter pressure difference sensor | | component | S23 Difference Ts and Tset | OS |
| F24 Return filter pressure difference sensor | | component | S24 Heating coil system pump alert | Additional |
| | | | S25 Low heating coil efficiency | EP |
| | | | S26 Temperature deviation Ts and Tp at HCV closed | Balance |

| Fault | 3F type | Symptom | 4S type |
|---|---|---|---|
| | | S27A Ts<Tset at Tr>To and Uerw<100%<br>B Uerw>0% at Tr<To<br>C Ts>Tset at Uerw>0%<br>D Uerw<100% and Uhcv>0%<br>E Uerw outlier | OS<br>OS<br>OS<br>OS<br>OS |
| | | S28 Low ERW efficiency | EP |
| | | S29 ERW alert present | Additional |
| | | S30 ps outlier or missing data | OS |
| | | S31 pr outlier or missing data | OS |
| | | S32 Δps outlier or missing data | OS |
| | | S33 Δpr outlier or missing data | OS |
| | | S34 High or low Tset | OS |
| | | S35 | |

The sensor variables are depicted in Figure 2.2. Us,fan stands for the rotation speed (0..100%) of the supply fan and Ur,fan for the return fan. ps,set is the setpoint of the supply pressure and pr,set is the setpoint of the return pressure. Tset is the setpoint of the supply temperature. Next to this, To stands for the measured outdoor temperature.




| Variable | Description |
|---|---|
| Ti | Inlet temperature |
| Tp | Preheated temperature after ERW |
| Ts | Supply temperature |
| Tr | Return air temperature |
| Te | Exhaust temperature after ERW |
| ps | Supply pressure |
| pr | Return pressure |
| Δps | Pressure drop over inlet filter |
| Δpr | Pressure drop over return filter |

*Figure C2.2 P&ID of AHU101 in Building 28 of TU Delft.*

The filter faults have been split into two types of faults: leakage over the filter and fouling.

The additional symptoms S2, S5, S11, S13, S24 and S29 are alerts derived from the BMS. They are linked with high relationship to a component.

Some OS symptoms indicate unrealistic values: S19, S20 and S30 to S33. The (temperature) balance symptoms S1, S16 to S18, S21 and S26 indicate unexpected deviations between two temperatures which should be the same at some on-off conditions of the thermal energy components. These symptoms help to estimate sensor faults.

The symptoms S3, S4, S7, S22, S23 and S27 compare a controlled state with the setpoint. The pressure setpoints present in the BMS are compared with those in documents by symptoms S8 and S9. Next to this, S34 indicates low or high supply temperature setpoints.

In addition, OS symptom are present for low or high pressure drops over the filters: S10, S12, S14 and S15.

Furthermore, two EP symptoms (S25 and S28) for heating coil and ERW efficiencies are present.

Strong and weak links between faults and symptoms are distinguished (90 and 30% probabilties).

The corresponding DBN is shown in Figure C2.2.

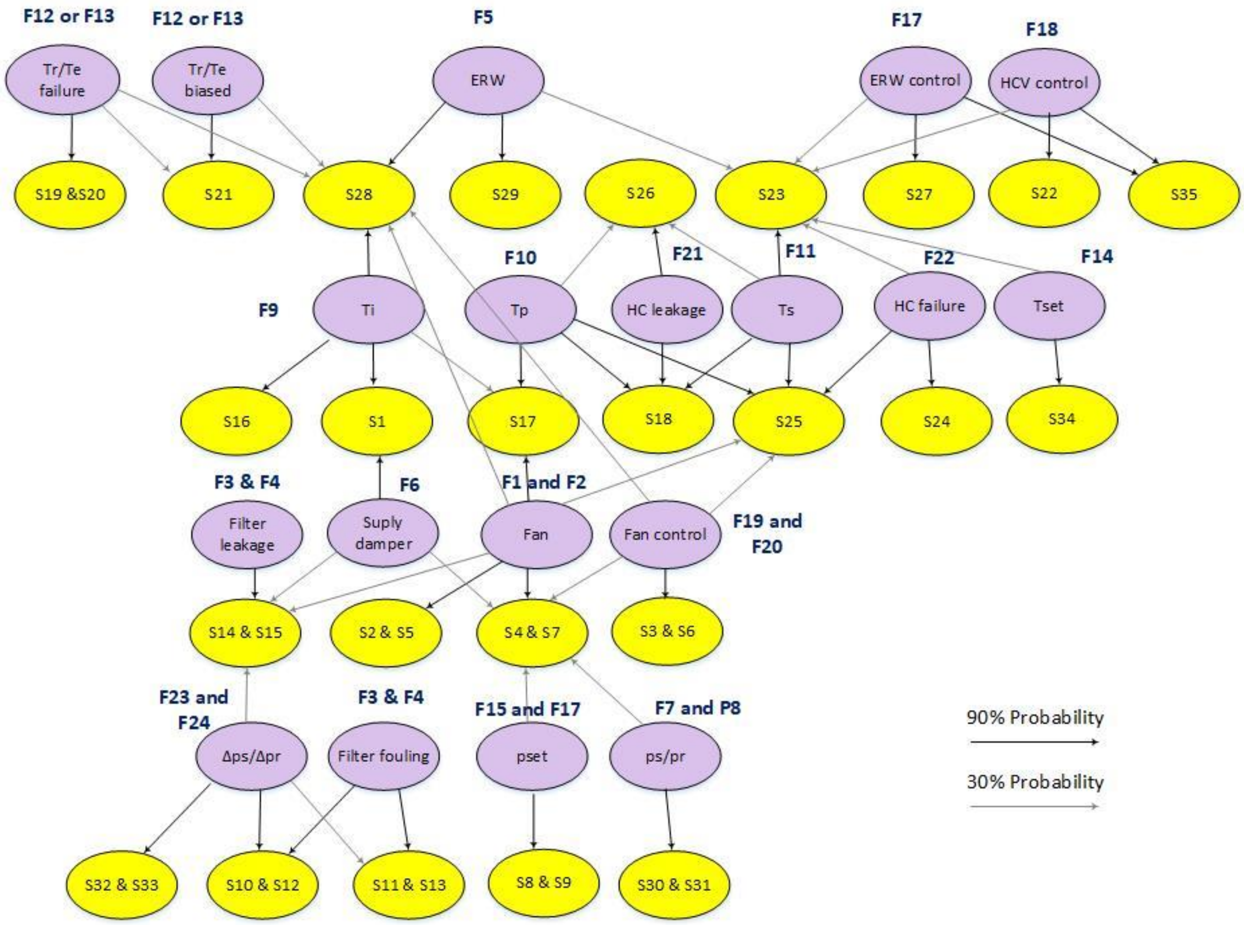



*Figure C2.2 DBN AHU 201 Building 28.*

35 symptoms were distinguished. See Table C2.1, which shows the 4S type for each symptom.

# C3 DBNS FOR THE HYDRONIC THERMAL SYSTEM OF THE BUILDING OF THE HAGUE UNIVERSITY IN DELFT

In this appendix DBN models realized and tested (see [1]) for the hydronic HVAC system of the building of The Hague University of Applied Sciences (THUAS) in Delft are shown. The symptoms in these DBNs are all knowledge based.

## C3.1 DBN at Level C

Figure C3.1 presents a P&ID for a heat pump.

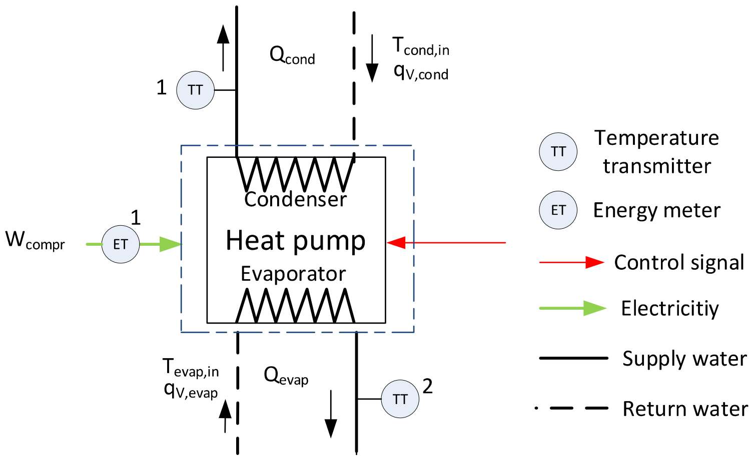



*Figure C3.1 A P&ID of a heat pump.*

Faults and symptoms which could be distinguished in this P&ID are shown in Table C3.1.

*Table C3.1. Faults and Symptoms present in Figure C3.1.*

| Fault | 3F type | Symptom | 4S type |
|---|---|---|---|
| F1 Heat pump | component | S1 Capacity heat pump: nominal power of the heat pump | EP |
| F2 Energy sensor ET1 | component | | |
| F3 Temperature sensor TT1 | component | S2 Energy balance heat pump | balance |
| F4 Temperature sensor TT2 | component | S3 COPheat_pump | EP |
| F5 Model return temperature condenser | model | | |
| F6 Model flow rate condenser | model | | |
| F7 Energy model heat pump | model | | |
| F8 Model flow rate evaporator | model | | |
| F9 Model return temperature evaporator | model | | |

The corresponding DBN is shown in Figure C3.2. Note that the sensors are placed at different location than at the heat pump system!

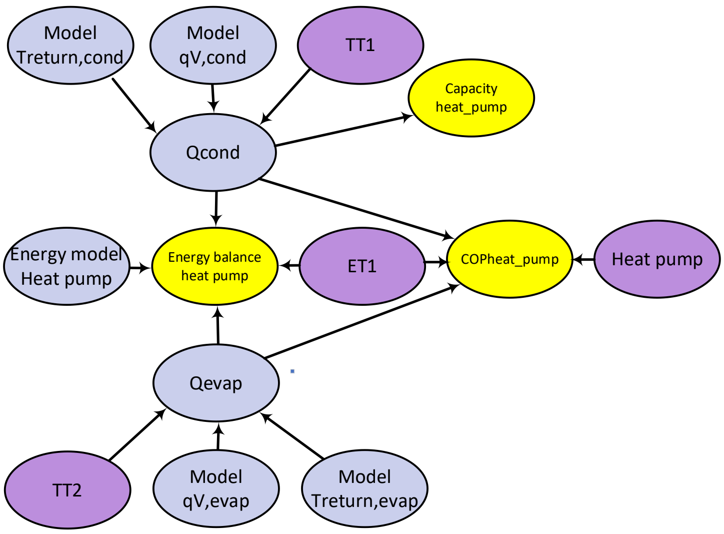



*Figure C3.2. DBN model for a heat pump.*

## C3.2 DBNs at Level B

### C3.2.1 Heat pump system vs 1

Figure C3.3 presents as example a P&ID of a heat pump system. Here, it is assumed that all needed temperature and flow sensors are installed.

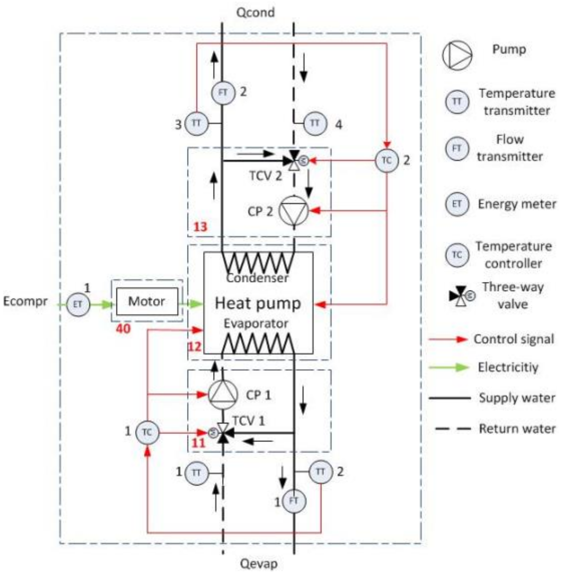



*Figure C3.3 P&ID of a heat pump system.*

Table C3.2 presents possible fault and symptoms in this generator module.

*Table C3.2. Symptoms present in Figure C3.3.*

| Fault | 3F type | Symptom | 4S type |
|---|---|---|---|
| F1 Heat pump | component | S1 Supply hot water temperature | OS |
| F2 Control hot water temperature | control | S2 Energy balance heat pump | Balance |
| F3 Control hot water temperature | control | S3 COPheat_pump | EP |
| F4 Temperature sensor TT1 | component | S4 Supply cold water temperature | OS |
| F5 Temperature sensor TT2 | component | | |

| Fault | 3F type | Symptom | 4S type |
|---|---|---|---|
| F6 Temperature sensor TT3 | component | | |
| F7 Temperature sensor TT4 | component | | |
| F8 Flow sensor FT1 | component | | |
| F9 Flow sensor FT2 | component | | |
| F10 Electricity meter ET1 | component | | |

In the control fault nodes, faults of controllers and actuators (valves) are included. Sensors are handled as separate component faults. Table C3.3 presents the Faults-relation table for this heat pump system.

*Table C3.3 Faults-relation table for a heat pump system.*

| Faults | Heat pump | Control outlet water temperature of the evaporator | Control outlet water temperature of the condenser | Sensor TT1 | Sensor TT2 | Sensor TT3 | Sensor TT4 | Sensor FT1 | Sensor FT2 | Meter ET1 |
|---|---|---|---|---|---|---|---|---|---|---|
| Symptoms | | | | | | | | | | |
| Energy balance | | | | | | | | | | |
| COP heat pump in heating mode | | | | | | | | | | |
| Outlet water temperature evaporator | | | | | | | | | | |
| Outlet water temperature condenser | | | | | | | | | | |

The corresponding 4S3F DBN model is shown in Figure C3.4. In this DBN model three model fault nodes (blue) are added for calculation of Qcond and Qevap and for the energy model of the heat pump in which Qlosses is incorporated.

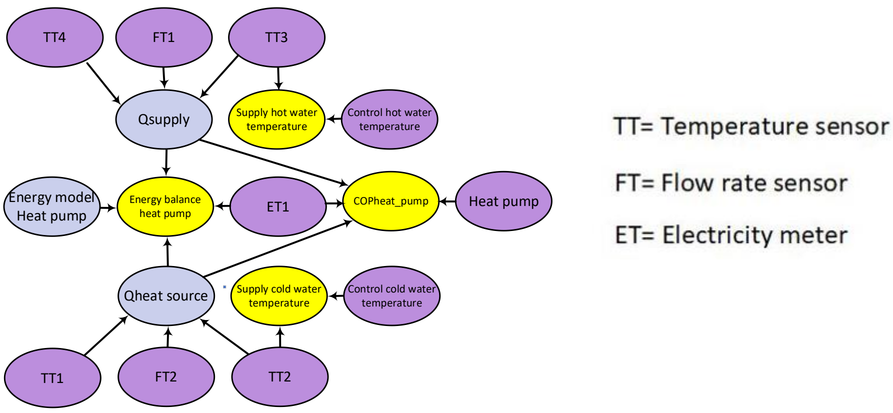



*Figure C3.4 4S3F DBN model for a heat pump system.*

### C3.2.2 Heat pump system vs 2.

Figure C3.5 shows another DBN for a heat pump system. In addition to the DBN of Figure C3.4, enthalpy nodes are present. Model fault nodes are colored light purple. Table 3.4 presents the faults and symptoms present in this DBN.

*Table C3.3. Faults and symptoms present in Figure C3.3.*

| Fault | 3F type | Symptom | 4S type |
|---|---|---|---|
| F1 Model COP heat pump | model | S1 Qbalance_heatpump: heat balance heat pump | balance |
| F2 Model EER heat pump | model | S2 Qbalance system C: heat balance heat pump system | balance |
| F3 Model heat pump system C | model | S3 Qbalance condenser module: heat balance condenser heat pump | balance |
| F4 State pump in BMS CP04_01 | control | S4 Qbalance evaporator module: heat balance evaporator heat pump | balance |
| F5 State pump in BMS CP04_02 | control | S5 COP heat pump | EP |
| F6 Temperature sensor TT04_01 | component | S6 EER heat pump | EP |
| F7 Temperature sensor TT04_02 | component | S7 TT04-TT05: temperature difference TT04 and TT05 at Sunday night | balance |
| F8 Temperature sensor TT04_03 | component | S8 TT04-TT06: temperature difference TT04 and TT06 at Sunday night | balance |
| F9 Temperature sensor TT04-04 | component | S9 NEcond: ignoring faults at condenser side of heat pump | additional |
| F10 Temperature sensor TT04-05 | component | S10 NEevap: ignoring faults at condenser side of heat pump | additional |
| F11 Temperature sensor TT04-06 | component | | |
| F12 Electricity meter Whp | component | | |
| F13 Flow sensor FT04_01 | component | | |
| F14 Flow sensor FT04_02 | component | | |

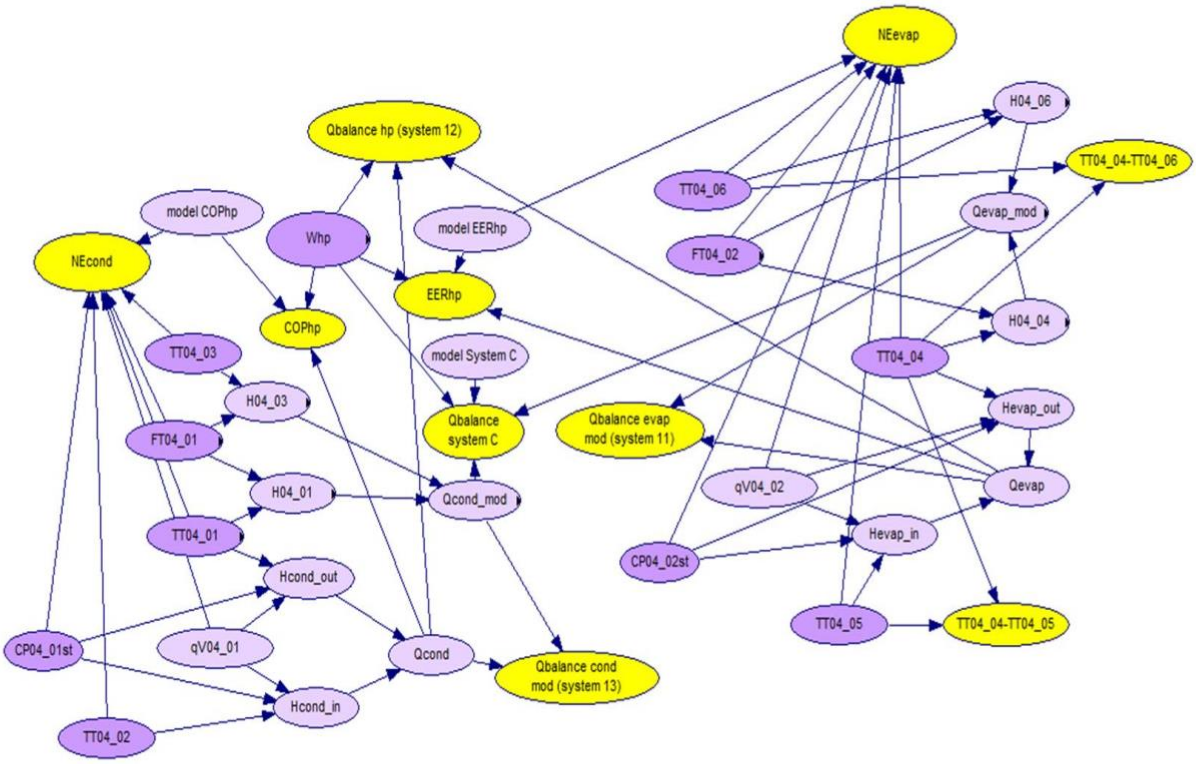



*Figure C3.5. Example specific heat pump system DBN model. At level B.*

### C3.2.3 ATES system

Figure C3.6 presents a P&ID for the thermal energy system of the THUAS building in which a heat pump, a gas boiler and an ATES system are present.
Table C3.6 presents the faults and symptoms which could be present.

*Table C3.6. Symptoms present in Figure C3.6.*

| Fault | 3F type | Symptom | 4S type |
|---|---|---|---|
| F1 Sensor inlet temperature primary circuit | component | S1 Supply primary water temperature | balance |
| F2 Sensor outlet temperature primary circuit | component | S2 Energy balance heat exchanger ATES system (TSA) | balance |
| F3 Sensor water flow primary circuit | component | | |
| F4 Sensor inlet temperature well ATES system | component | | |
| F5 Sensor outlet temperature well ATES system | component | | |
| F6 Sensor water flow ATES system | component | | |
| F7 State well pumps (load or unload ATES) | model | | |
| F8 Control inlet temperature well ATES system | control | | |

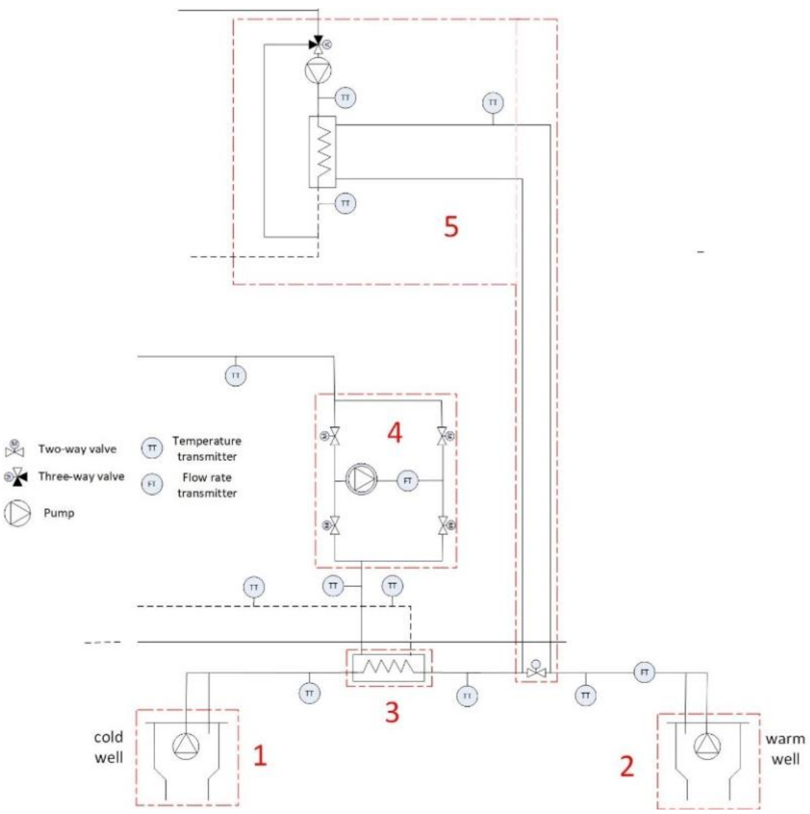



*Figure C3.6 A P&ID of the ATES system.*

The corresponding DBN for the system containing numbers 1 to 3, is shown in Figure C3.7.

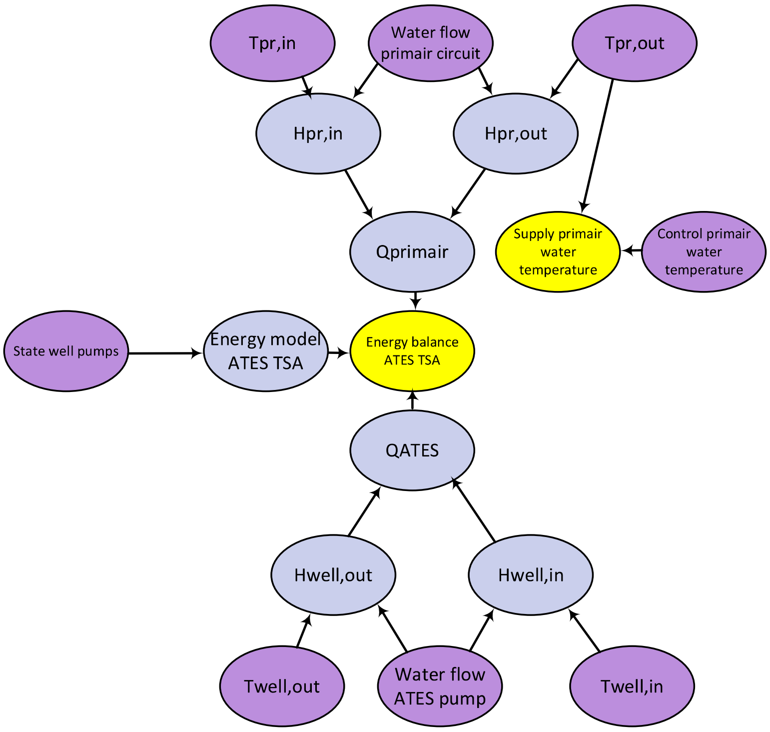



*Figure C3.7. A DBN for the ATES system of the THUAS building.*

## C3.3 DBN at Level A

### C3.3.1 Whole hydronic HVAC system for energy performance purposes

Figure C3.8 shows a DBN applied for energy performances diagnosis of the thermal energy system of the building of the Hague University of Applied Sciences in Delft.

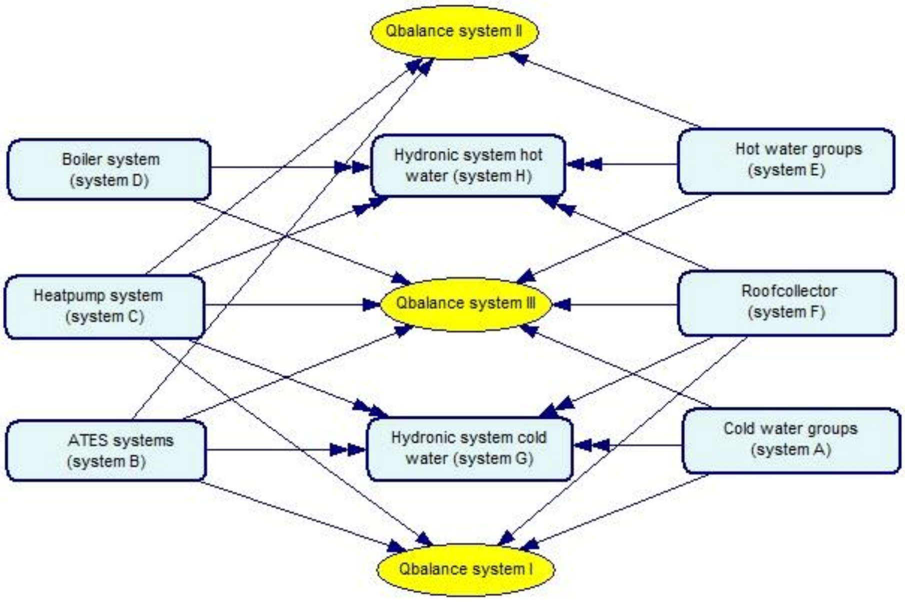



*Figure C3.8. Example specific DBN model at level A with balance symptoms.*

The hydronic thermal system consists of DBNs for heat and cold generation modules with a heat pump, a gas boiler and an ATES system. In addition, DBNs for hot and cold water distribution modules and furthermore, DBNs for heat and cold user modules.

In this figure, three balance symptoms are present which are shown in Table C3.7.

*Table C3.7 Nodes present in the DBN of Figure C3.8.*

| Fault | 3F type | Symptom | 4S type |
|---|---|---|---|
| F1 Boiler system | component | S1 Qbalance I: energy balance cold water system | Balance |
| F2 Heat pump system | component | S2 Qbalance II: energy balance hot water system | Balance |
| F3 ATES system | component | S3 Qbalance III: energy balance thermal energy system | Balance |
| F4 Hydronic system hot water | component | | |
| F5 Hydronic system cold water | component | | |
| F6 Hot water groups | component | | |
| F7 Cold water groups | component | | |
| F8 Roof collector system | component | | |

Additional faults and symptoms are present inside the DBNs of the 8 hydronic modules. For instance, the DBN of the heat pump module is shown in Figure C3.9. In this research, temperature sensor faults are not taken into account because these faults are corrected by preprocessing (therefore, also the 4S3F method is applied! See Section C3.3.4).

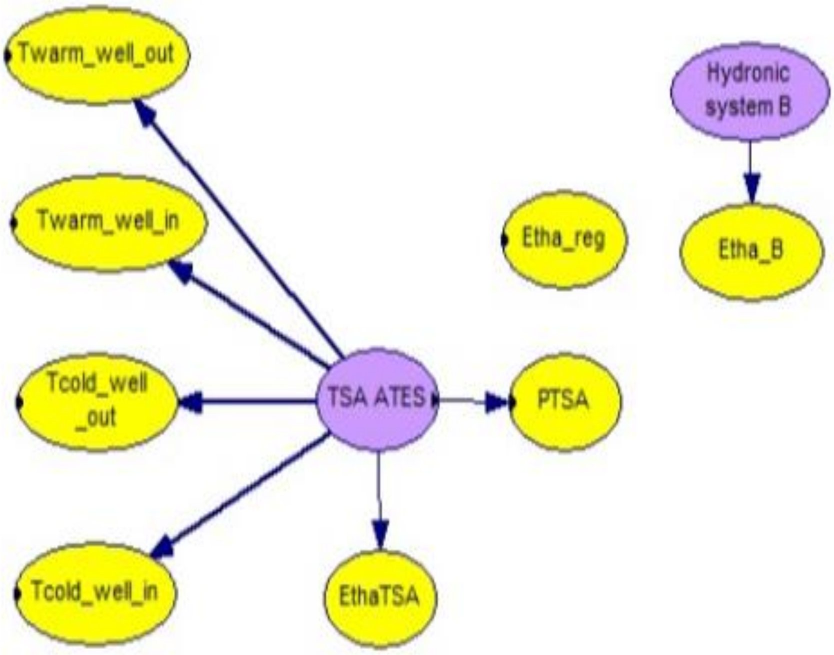



*Figure C3.9 DBN model of the heat pump system (system C) node in Figure C3.8.*

As help to set up the whole DBN with sub DBNs, a table with cross links between the faults and the symptoms is created. See Table C3.8.

*Table C3.8 Fault-symptom relationships for energy performance of the THUAS building in Delft.*

| Component and control faults at level B (aggregated systems A to H) | *Control supply temperature hw* | *Hydronic system hw E* | *Control supply temperature cw* | *Hydronic system cw A* | *Heat pump system C* | | | | *Boiler system D* | | *Control roof system F* | *Roof system F* | *Control ATES system* | *ATES system B* | | *Control regeneration* | *Hydronic system HW H* | *Hydronic system HW G* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Component and control faults at Level C (components 1 to 40) | | | | | *Control outlet temperature condenser* | *Control outlet temperature evaporator* | *Heat pump 12* | *Hydronic system C* | *Boiler 33* | *Hydronic system D* | | *TSA roof 39* | | *TSA_ATES 8* | *Hydronic system B* | | | |
| **Symptoms** | | | | | | | | | | | | | | | | | | |
| $\eta_{systB}$ | | | | | | | | | | | | | | | ■ | | | |
| $\eta_{systC}$ | | | | | | | | ■ | | | | | | | | | | |
| $\eta_{systD}$ | | | | | | | | | | ■ | | | | | | | | |
| $\eta_{systG}$ | | | | | | | | | | | | | | | | | | ■ |
| $\eta_{systH}$ | | | | | | | | | | | | | | | | | ■ | |
| $\eta_{reg}$ | | | | | | | | | | | | | | | | ■ | | |
| $\eta_{TSA}$ | | | | | | | | | | | | | | ■ | | | | |
| *SCOPhw* | ■ | | | | ■ | | ■ | | ■ | | | | | | | | | |
| *SEERcw* | | | ■ | | | ■ | | | | | | | ■ | ■ | | | | ■ |
| *SCOProof* | | | | | | | | | | | ■ | ■ | | | | | | |
| *SCOPreg* | | | | | | | | | | | | ■ | | | | ■ | | |
| *SCOPhp* | | | | | ■ | | ■ | | | | | | | | | | | |
| *SEERhp* | | | | | ■ | | ■ | | | | | | | | | | | |
| *Phw* | ■ | | | | ■ | | ■ | | ■ | | | | | | | | | |
| *Pcw* | | | ■ | | | | | | | | | | ■ | ■ | | | | |
| *Php* | | | | | ■ | | ■ | | | | | | | | | | | |
| *Proof* | | | | | | | | | | | ■ | ■ | | | | | | |
| *Preg* | | | | | | | | | | | | ■ | | | | ■ | | |
| *PTSA* | | | | | | ■ | | | | | | | ■ | ■ | | | | |
| *Pboiler* | | | | | | | | | ■ | | | | | | | | | |
| *Thw_supply* | ■ | | | | ■ | | | | | | | | | | | | | |
| *Tcw_supply* | | | ■ | | | ■ | | | | | ■ | | ■ | ■ | | | | |
| *Tcond_out* | | | | | ■ | | ■ | | | | | | | | | | | |
| *Tevap_out* | | | | | | ■ | ■ | | | | ■ | | | | | | | |
| *Tin, cold well* | | | | | | ■ | | | | | ■ | | ■ | ■ | | | | |
| *Tin,warm well* | | | ■ | | | | | | | | | | ■ | ■ | ■ | | | |
| *Thw_return* | ■ | ■ | | | ■ | | | | | | | | | | | | | |
| *Tcw_return* | | | ■ | ■ | | | | | | | | | ■ | ■ | | | | |
| *Tevap_in* | | | | | | | | | | | | | ■ | | | | | |
| *Tout, cold well* | | | | | | ■ | | | | | | | ■ | ■ | | | | |
| *Tout,warm well* | | | ■ | | | | | | | | | | ■ | ■ | ■ | | | |

## C3.3.4 Whole hydronic HVAC system for sensor fault purposes

Figure C3.10 shows the DBN for sensor fault diagnosis applied in [1]. In this figure, the eight hydronic modules are present as DBN nodes as in Section C3.3.3. These DBN submodels contain sensor faults as nodes. See Section C3.2.2 in which the DBN of the heat pump module is discussed.

Table C3.9 shows the present faults and symptoms in Figure C3.10.

*Table C3.9 Faults and symptoms present in Figure C3.10.*

| Fault | 3F type | Symptom | 4S type |
|---|---|---|---|
| F1 Boiler system | component | S1 Phw: nominal power of the heat generation system | EP |
| F2 Heat pump system | component | S2 SCOPhw: Seasonable COP of the heat supply to the hot water system | EP |
| F3 ATES system | component | S3 SEERcw: Seasonable COP of the cold supply to the cold water system | EP |
| F4 Hydronic system hot water | component | S4 SCOProof: Seasonable COP of the heat supply to the roof | EP |
| F5 Hydronic system cold water | component | S5 Preg: nominal power of the regeneration of the ATES system | EP |
| F6 Hot water groups | component | S6 Pcw: nominal power of the cold generation system | EP |
| F7 Cold water groups | component | S7 SCOPreg: Seasonable COP of regeneration of the ATES system | EP |
| F8 Roofcollector system | component | | |

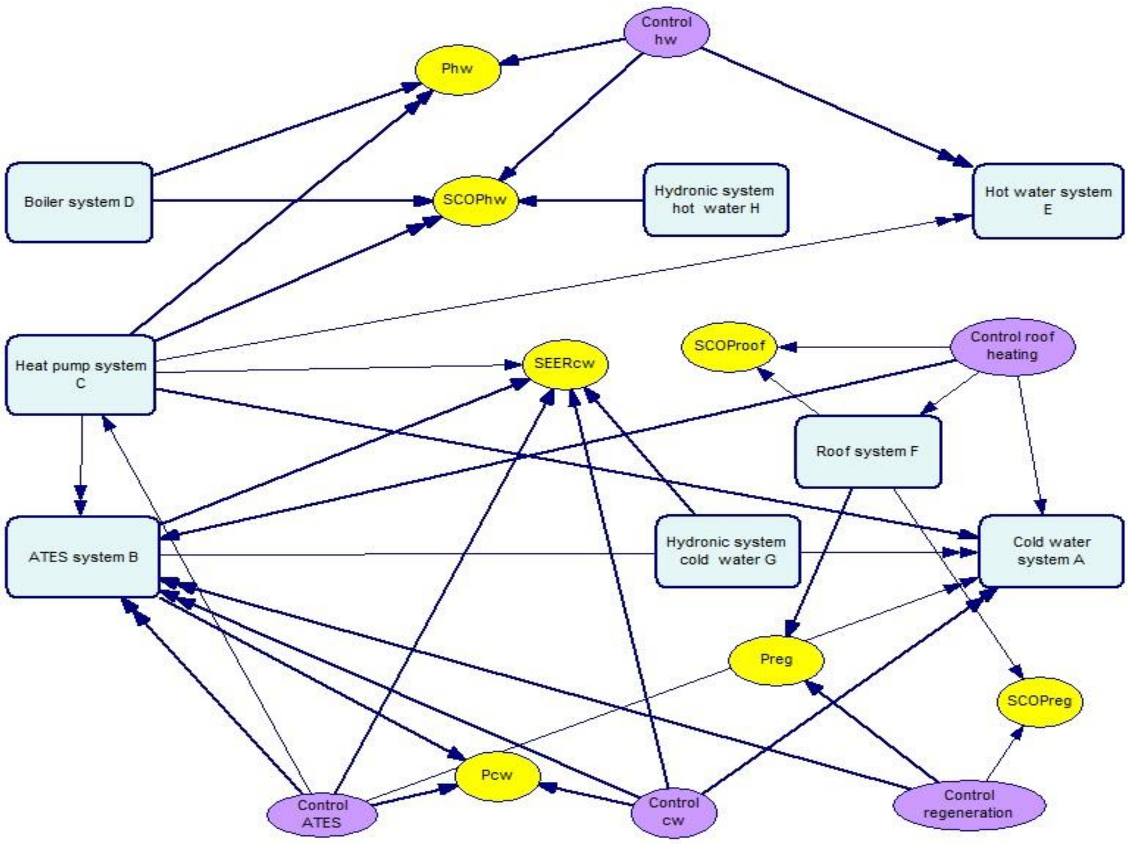



*Figure C3.10 Example specific DBN model at level A with energy performance and operational state symptoms (derived from [1])*

C4 DBNS FOR THE THERMAL SYSTEM OF BUILDING 28 OF TUDELFT

In this appendix the DBN model at level A is shown, realized for the HVAC system of building 28 in Delft. Figure C4.1 presents a schematic of this HVAC system.

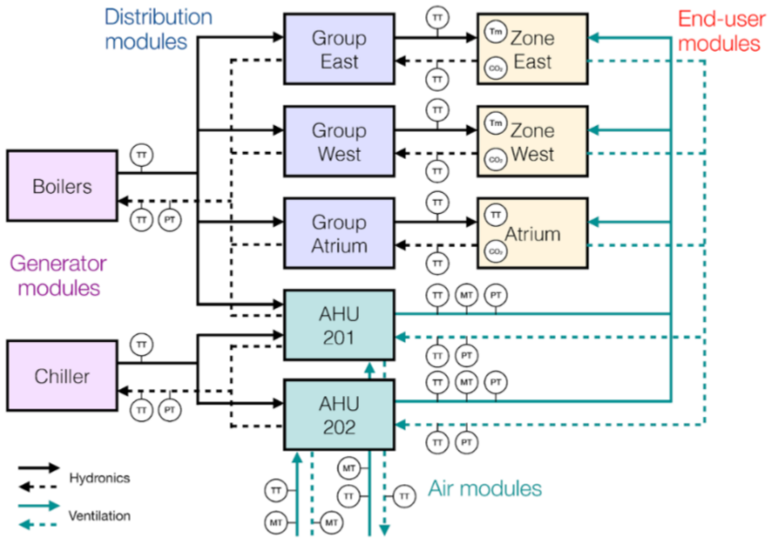



*Figure C4.1 Schematic of the HVAC system of building 28 in Delft.*

The whole system consists of two generator systems (boilers and chiller), two air handling units (AHU201 and AHU202), three groups containing distribution and user systems (Group East, West and Atrium) and three end-user groups at room level (Zone East, Zone West and Atrium). The faults assumed are the groups and their controls. See faults F1 to F20 in Table C4.1. Next to this faults multiple sensor faults are present (F21 to Fxx): 12 sensors in the hydronic system, 16 sensors at the supply and return air of the air handling units and multiple air sensors (temperature and $CO_2$) in the rooms. In this Table, the symptoms considered are shown.

Figure C4.1 presents the corresponding DBN. The component faults F1 to F10 are present as nodes (thus not as DBN node). As can be seen, many n to n-relationships are present between faults and symptoms. For instance, a bad mean indoor temperature (depicted as $T_{i,mean}$) could be effected by malfunctioning of one of the thermal energy groups, the user groups or one of the air handlings units (F1 to F20).

*Table C4.1 Faults and symptoms in experiment whole HVAC system Building 28 of TU Delft (n=1 or 2, i=1 to 3).*

| Fault | 3F type | Symptom | 4S type |
|---|---|---|---|
| F1 Boilergroup | component | S1 $T_{b,sup}$ boiler supply temperature | OS |
| F2 Chiller group | component | S2 $T_{b,set}$ boiler setpoint temperature | OS |
| F3 Hydronic group 1 (East) | component | S3 $T_{b,ret}$ boiler return temperature | OS |
| F4 Hydronic group 2 (West) | component | S4 $P_{b,ret}$ boiler return pressure | OS |
| F5 Hydronic group 3 (Atrium) | component | S5 $T_{c,sup}$ chiller supply temperature | OS |
| F6 Air handling unit AHU 201 | component | S6 $T_{c,ret}$ chiller return temperature | OS |
| F7 Air handling unit AHU 202 | component | S7 $\Delta T_c$ chiller sensor bias at chiller off | balance |
| F8 Air group 1 (Zone East) | component | S8 $P_{c,ret}$ chiller return pressure | OS |
| F9 Air group 2 (Zone West) | component | S9 $T_{dist,i,sup}$ hydronic group i supply temperature | OS |
| F10 Air group 3 (Zone Atrium) | component | S10 $T_{dist,i,ret}$ hydronic group i return temperature | OS |
| F11 Boilers control | control | S11 $T_{n,sup}$ AHU n supply temperature | OS |
| F12 Control Chiller group | control | S12 $T_{n,set}$ AHU n setpoint temperature | OS |
| F13 Control Hydronic group 1 (East) | control | S13 $T_{n,ret}$ AHU n return temperature | OS |
| F14 Control Hydronic group 2 (West) | control | S14 $P_{n,sup/set}$ AHU n supply/return pressure | OS |
| F15 Control Hydronic group 3 (Atrium) | control | S15 $T_{i,min}$ zone i minimum temperature | OS |
| F16 Control Air handling unit AHU 201 | control | S16 $T_i$ zone i temperature comfort range | EP |
| F17 Control Air handling unit AHU 202 | control | $\overline{S17\ CO2_i}$ zone i CO2 sensor bias | balance |
| F18 Control Air group 1 (Zone East) | control | S18 $CO2_{i,max}$ zone i maximum room CO2 | OS |
| F19 Control Air group 2 (Zone West) | control | S19 $RH_{n,sup}$ AHU n relative humidity | EP |
| F20 Control Air group 3 (Zone Atrium) | control | | |
| F21 Sensor outdoor temperature | component | | |
| F22 to Fxx Other sensors | component | | |

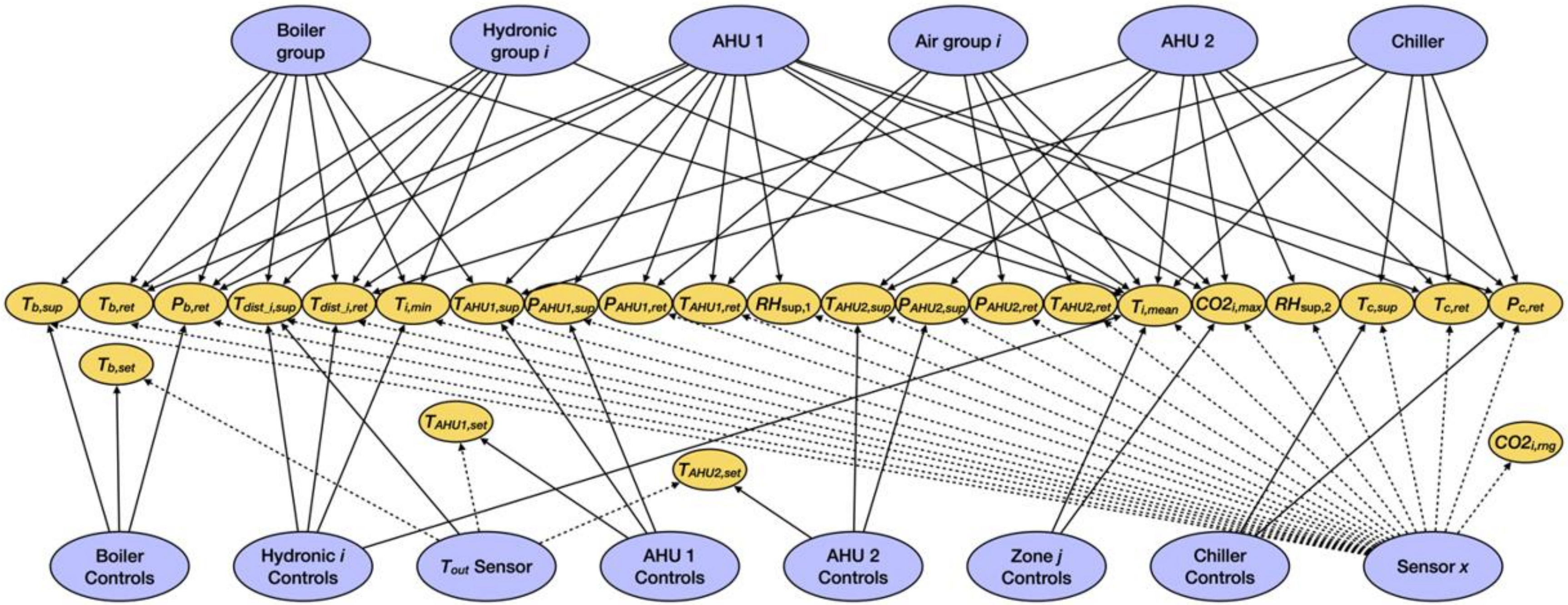
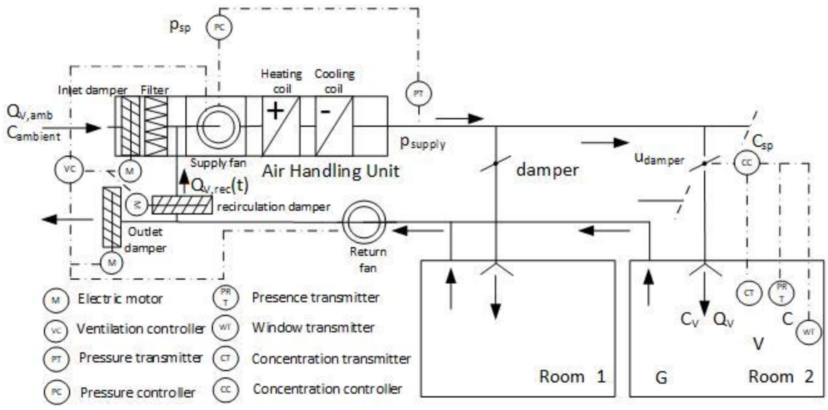



*Figure C4.2 DBN of the HVAC system of Building 28.*

# C5 DBN OF THE DCV SYSTEM OF THE THUAS BUILDING IN DELFT

Figure C5.1 shows the P&ID based on the demand controlled ventilation system of the THUAS building in Delft.




G=$CO_2$ production in the room [kg/s].

C=$CO_2$ concentration in the room [ppm].

$C_{sp}$=setpoint of the maximum $CO_2$ concentration in the room [ppm].

$p_{sp}$=setpoint of static pressure of the supply air [Pa].

$p_{supply}$= Static pressure of the supply air [Pa].

$C_v$=$CO_2$ concentration of the supply air [ppm].

$C_{ambient}$=$CO_2$ concentration of ambient air [ppm].

$Q_{v,ambient}$=ambient air rate flow [$m^3$/s].

$Q_v$=supply air rate flow to the room [$m^3$/s].

$Q_{v,rec}$=recirculated air flow rate [$m^3$/s].

$u_{damper}$= damper position [0..100 %].

V=room air volume [$m^3$].

*Figure C5.1 P&ID for a demand controlled ventilation (DCV) system (from [1]).*

Table C5.1 shows the faults and symptoms considered.

*Table C5.1 Faults and symptom considered in the DCV FDD.*

| Nr | Fault | Type | Nr | Symptom | Type |
|---|---|---|---|---|---|
| F1 | Occupancy | Control | S1 | High CO2 and high qV | OS |
| F2 | CO2 sensor | Component | S2<br>S3<br>S4 | CO2 unrealistic<br>CO2 missing<br>ΔCO2 neighbours | OS<br>OS<br>Balance |
| F3 | AHU | Component | S5<br>S6<br>S7 | qV_AHU=0<br>qV=0<br>High CO2 and qV=0 | OS<br>OS<br>OS |
| F4 | PIR sensor | Component | S8<br>S9 | ΔCO2 and PIR=0<br>Presence outside working hours | Balance<br>OS |
| F5 | Damper | Component | S10<br>S11<br>S12<br>S13 | High CO2 and qV=0<br>High CO2 and low qV<br>Low CO2 and qV>0<br>qV=0 | OS<br>OS<br>OS<br>OS |
| F6 | qV sensor | Component | S14<br>S15 | qV unrealistic<br>qV missing | OS<br>OS |
| F7 | BMS | Component | S16<br>S17 | qV missing<br>CO2 missing | OS<br>OS |
| F8 | Window control | Control | S18 | High CO2 and qV=0 | OS |
| F9 | CO2 control | Control | S19 | High CO2 and low qV | OS |

In [1] a DBN is setup for DCV FFD which is presented in Figure C5.2.

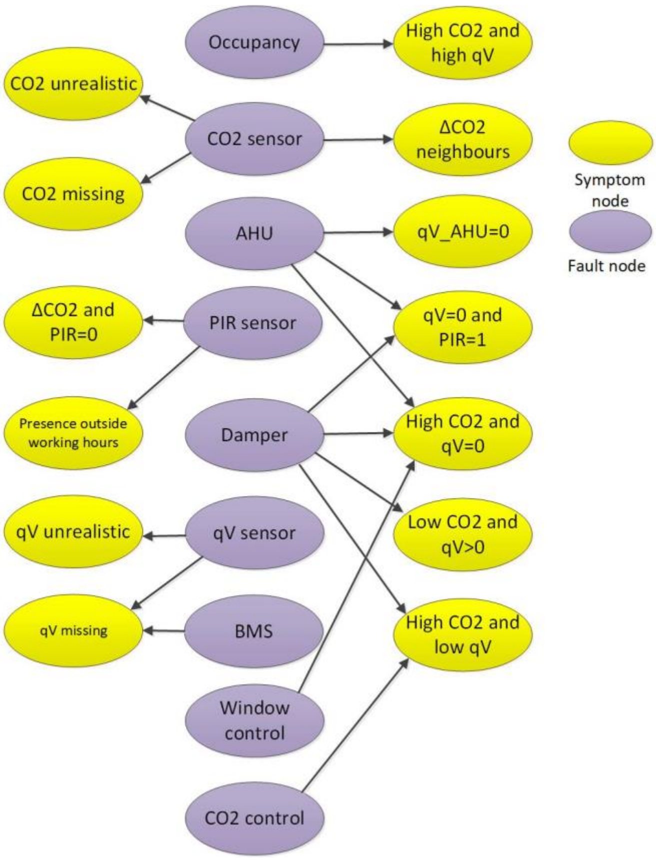



*Figure C5.2 DBN for the DCV FDD THUAS.*

In this DBN, a fault node is present for the air handling unit (AHU). Furthermore, one fault node for the building management system (BMS) and fault nodes at room level, as well component (three sensors and a room damper) and control (by occupant, $CO_2$ control and window openness control).

# APPENDIX D. SYMPTOMS FOR AN AIR HANDLING UNIT

In this appendix, symptoms with their rules which are applied for the DBNs at level B for an air handling unit (see Section 5) are presented.

## Failure of components

Most BMSs present alerts when a component failures:

*S1a : Rule: Aerw=on.* *Fault: ERW*

*S1b : Rule: Afan_s=on.* *Fault: supply fan*

*S1c: Rule: Afan_r=on.* *Fault: return fan*

*S1d: The pressure drop exceeds the maximum value. Rule: Afilter_s=on.* *Fault: supply filter*

*S1e: The pressure drop exceeds the maximum value. Rule: Afilter_r=on.* *Fault: return filter*

## Incorrect HVAC mode

These symptoms are related to incorrect on-off control at working and non-working hours.

### Switch condition

*S2a : The ERW is on during non-working hours. Rule: u_erw>0% while clock=off.* *Fault: ERW control*

*S2b : The HC system is on during non-working hours. Rule: TP6>TP5 while clock=off.* *Fault: HC system*

*S2c : The supply fan is on during non-working hours. Rule: ufan_s>0% while clock=off.* *Fault: control supply fan*

*S2d : The supply fan is off during working hours. Rule: ufan_s=0% while clock=on.* *Fault: control supply fan*

*S2e : The return fan is on during non-working hours. Rule: ufan_r>0% while clock=off.* *Fault: control return fan*

*S2f : The return fan is off during working hours. Rule: ufan_r=0% while clock=on.* *Fault: control return fan*

### Incorrectly combined conditions

*S2g: heat and cold is supplied simultaneously. Rule: TP6>TP5 and TP6>TP4.* *Fault: HC or CC system*

## Operational temperature states

### Preheated temperature TP5

The ERW tries to reach the set point.

**Preheated temperature TP5 after ERW is lower than expected**

*S3a: The preheated temperature is not derived with maximum rotation speed of ERW.*

*Rule:* $TP5 < min\,(TP2 + \eta_{expected,max}(TP1 - TP2), Tset)$ *with TP1>TP2, clock=on, ufan_s>0% and u_erw=100%. Fault:ERW or TP5*

*S3b: The preheated temperature is not derived while rotation speed is not maximum.*

*Rule:* $TP5 < min\,(TP2 + \eta_{expected,max}(TP1 - TP2), Tset)$ *with TP1>TP2, clock=on, ufan_s>0% and u_erw<100%. Fault: ERW control or TP5*

*S3c: The preheated temperature is not derived at summer condition.*

*Rule:* $TP5 < \min\,(TP2, Tset)$ *with TP1<TP2, clock=on, ufan_s>0% and u_erw>0%. Fault: ERW control or TP5*

**Preheated temperature TP5 after ERW is higher than expected**

*S3d: The preheated temperature is higher than Tset at summer condition*

*Rule:* $TP5 > min\,(TP2 + \eta_{expected}(TP1 - TP2), Tset)$ *with TP1<TP2, clock=on, ufan_s>0% and u_erw=100%. Fault:ERW or TP5*

*S3e: The preheated temperature is not derived while rotation speed is not maximum.*

*Rule:* $TP5 > min\,(TP2 + \eta_{expected,max}(TP1 - TP2), Tset)$ *with TP1<TP2, clock=on, ufan_s>0% and u_erw<100%. Fault: ERW control or TP5*

*S3f: The preheated temperature is too high at winter condition.*

*Rule:* $TP5 > min\,(TP2 + \eta_{expected}(TP1 - TP2), Tset)$ *with TP1>TP2, clock=on, ufan_s>0% and u_erw>0%. Fault: ERW control or TP5*

### Supply temperature TP4

TP4 is controlled by the setpoint at clock time.

**Supply temperature TP4 is lower than the setpoint Tset.**

*S3g: Supply temperature is not derived*

*Rule: TP4<Tset at TP6=TP5, clock=on, ufan_s>0%, uerw>0%* *Fault: HC system or TP4*

*S3h: Supply temperature is too low by cold supply.*
*Rule: TP4<Tset atTP4>TP6, clock=on, ufan_s>0%.* *Fault: CC system or TP4*

**Supply temperature TP4 is higher than the setpoint Tset.**

*S3i: Supply temperature is too high because heat is supplied by HC system.*
*Rule: TP4>Tset, TP6>TP5, clock=on, ufan_s>0%.* *Fault: HC system or TP4*
*S3j: Supply temperature is not derived at summer conditions because too little cold is supplied.*
*Rule: TP4>Tset, TP6=TP5, clock=on, ufan_s>0%.* *Fault: CC system or TP4*
*S3k: Supply temperature is not derived because rotation speed ERW lower than maximum.*
*Rule: TP4>Tset, clock=on, ufan_s>0%, TP2<TP1 and u_erw<100%* *Fault: ERW control or TP4*

Heated temperature TP6

TP6 is controlled by the setpoint at clock time.

**Heated temperature TP6 is lower than the setpoint Tset.**

*S3l: Desired heated temperature is not derived at full load ERW.*
*Rule: TP6<Tset, clock=on, ufan_s>0%, TP1>TP2 and u_erw=100%.* *Fault: HC system or TP6*
*S3m: Heated temperature is not derived with partial load of ERW.*
*Rule: TP6<Tset, clock=on, ufan_s>0%, TP1>TP2 and u_erw<100%* *Fault: ERW control or TP6*

**Heated temperature TP6 is higher than the setpoint Tset.**

*S3n: Supply temperature is too high.*
*Rule: TP6>Tset, TP6>TP5, clock=on, ufan_s>0%.* *Fault: HC system or TP6*

### Operational pressure states

Pressure drop filters

*S4a: The pressure drop of the supply filter is lower than the expected value. Rule:PP6-PP7≠ 0 Fault: supply filter*
*S4b: The pressure drop of the return filter is lower than the expected value. Rule:PP9-PP8 ≠ 0Fault: return filter*

Supply pressure

*S4c: The supply pressure is lower than the expected one at low fan speed.*
*Rule: PP4<ps_set while 0<ufan_s<100%* *Fault: control supply fan*
*S4d: The supply pressure is lower than the expected one at full fan speed.*
*Rule: PP4<ps_set while ufan_s=100%* *Fault: supply fan*
*S4e: The supply pressure is higher than the expected one.*
*Rule: PP4>ps_set while ufan_s>0%* *Fault: control supply fan*

Return pressure

*S4f: The return pressure is higher than the expected one at low fan speed.*
*Rule: PP1>pr_set while 0<ufan_r<100%* *Fault: control return fan*
*S4g: The return pressure is higher than the expected one at full fan speed.*
*Rule: PP1>pr_set while ufan_r=100%* *Fault: return fan*
*S4h: The return pressure is lower than the expected one.*
*Rule: PP1<pr_set while ufan_r>0%* *Fault: control return fan*

Inlet pressure

*S4i: The inlet damper is frozen closed*
*Rule: PP6<t while 0<ufan_r<100%* *Fault: inlet damper*

### Energy performance

*S5a: Temperature efficiency ERW at supply air side too low while ERW at maximum speed*
*Rule:* $\frac{TP5-TP2}{TP1-TP2} < \eta_{expected}$ *with u_erw=100%* *Fault: ERW*
*S5b: Temperature efficiency ERW at supply air side too low while ERW at low speed*
*Rule:* $\frac{TP5-TP2}{TP1-TP2} < \eta_{expected}$ *with u_erw<100%* *Fault: ERW control*
*S5c: Heating coil capacity lower than expected*
*Rule:* $max\ (\emptyset_V \rho c(TP6 - TP5)) < P_{HC,nom}$ *Fault: heating coils system*
*S5d: Cooling coil capacity lower than expected*

*Rule:* $|min\ (\emptyset_V \rho c(TP4 - TP6))| < P_{CC,nom}$ *Fault: cooling coils system*

*S5e: Supply fan efficiency lower than expected*

*Rule:* $\frac{FP4.(PP4-PP6)}{P_{fan\_s}} < \eta_{expected}\ during\ \Delta t$ *Fault: supply fan*

*S5f: Return fan efficiency lower than expected*

*Rule:* $\frac{FP1.(Pomg-PP8)}{P_{fan\_r}} < \eta_{expected}\ during\ \Delta t$ *Fault: return fan*

*S5g:Energy consumption of supply fan higher than expected*

*Rule:* $\Sigma P_{fan\_s} \Delta t > W_{fan,expected}$ *Fault: control supply fan or supply fan*

*S5h:Energy consumption of return fan higher than expected*

*Rule:* $\Sigma P_{fan\_r} \Delta t > W_{fan,expected}$ *Fault: control return fan or return fan*

*S5i: Supplied heat is higher than expected*

*Rule:* $\Sigma \phi_V \rho c(TP6 - TP5)\Delta t > Q_{heating\ coil,exp}$ *with TP5<Tset* *Fault: ERW or ERW control*

*S5j: Supplied cold is higher than expected*

*Rule:* $\Sigma \phi_V \rho c(TP4 - TP6)\Delta t > Q_{cooling\ coil,exp}$ *with TP5>Tset* *Fault: ERW or ERW control*

## Balances

*S6a: Preheated temperature has to be the same as the supply temperature with AHU is off.*

*Rule: TP5≠TP4 when clock=off* *Fault: TP5 or TP4*

*S6b: Heated temperature has to be the same as the supply temperature with AHU is off.*

*Rule: TP6≠TP4 when clock=off* *Fault: TP6 or TP4*

*S6c: Heated temperature has to be the same as the preheated temperature with AHU is off.*

*Rule: TP6≠TP5 when clock=off* *Fault: TP6 or TP5*

*S6d: Supply pressure has to be very low with ufan_s=0%.*

*Rule: PP4>5?pa when clock=off* *Fault: PP4*

*S6e: Return pressure has to be very low with ufan_r=0%.*

*Rule: PP1>5?pa when clock=off* *Fault: PP1*

*S6f: Pressure drop over supply filter has to be very low with ufan_s=0%.*

*Rule: PP6-PP7>10?pa when clock=off* *Fault: PP6-PP7*

*S6g: Pressure drop over return filter has to be very low with ufan_r=0%.*

*Rule: PP8-PP9>10?pa when clock=off* *Fault: PP8-PP9*

*S6h: Preheated temperature has to be the same as the inlet temperature with ERW is off.*

*Rule: TP5≠TP2when u_erw=0.* *Fault: TP5 or TP2*

*S6i: Supply temperature has to be the same as the inlet temperature with ERW is off and u_hcv=0 and u_ccv=0.*

*Rule: TP4≠TP2 when u_erw=0, u_hcv=0 and u_ccv=0.* *Fault: TP4 or TP2*

## Setpoints

*S7a Setpoint supply temperature is higher than the designed one. Rule: Tset>Tdesign* *Fault: Tset*

*S7b: Setpoint supply temperature is lower than the designed one. Rule: Tset<Tdesign* *Fault: Tset*

*S7c: Setpoint supply pressure is higher than the designed one. Rule: ps_set>ps_design* *Fault: ps_set*

*S7d: Setpoint supply pressure is lower than the designed one. Rule: ps_set<ps_design* *Fault: ps_set*

*S7e: Setpoint return pressure is higher than the designed one. Rule: pr_set>pr_design* *Fault: pr_set*

*S7f: Setpoint return pressure is lower than the designed one. Rule: pr_set<pr_design* *Fault: pr_set*

## Unrealistic state values

Temperature state is unrealistic

*S8a: Rule: TP2= unrealistic* *Fault: TP2*

*S8b: Rule: TP5= unrealistic* *Fault: TP5*

*S8c: Rule: TP4= unrealistic* *Fault: TP4*

*S8d: Rule: TP1= unrealistic* *Fault: TP1*

*S8e: Rule: TP6= unrealistic* *Fault: TP6*

Pressure state is unrealistic

*S8f: Rule: PP4= unrealistic* *Fault: PP4*

*S8g: Rule: PP6-PP7= unrealistic* *Fault: PP6-PP7*

*S8h: Rule: PP1= unrealistic* *Fault: PP1*

*S8i: Rule: PP8-PP9= unrealistic* *Fault: PP8-PP9*

### Missing state values

Temperature state is NaN

*S9a: Rule: TP2= NaN* *Fault: TP2 or BMS*

*S9b: Rule: TP5= NaN* *Fault: TP5 or BMS*

*S9c: Rule: TP4= NaN* *Fault: TP4 or BMS*

*S9d: Rule: TP1= NaN* *Fault: TP1 or BMS*

*S9e: Rule: TP6= NaN* *Fault: TP6 or BMS*

Pressure state is NaN

*S9f: Rule: PP4= NaN* *Fault: PP4 or BMS*

*S9g: Rule: PP1= NaN* *Fault: PP1 or BMS*

*S9h: Rule: PP6-PP7= NaN* *Fault: PP6-PP7 or BMS*

*S9i: Rule: PP9-PP8= NaN* *Fault: PP9-PP8 or BMS*

Component state is NaN

*S9j: Rule: u_erw= NaN* *Fault: BMS*

*S9k: Rule: u_fan_s= NaN* *Fault: BMS*

*S9l: Rule: u_fan_r= NaN* *Fault: BMS*