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by

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Background of this technical report

This document aims to be a working document regarding FDD methodology classifications, definitions, and concepts for systems within buildings. With the immense body of literature on the topic of FDD, the authors have aimed to make an open-source document in a working draft to be updated when new and relevant literature occurs.

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Concepts and Definitions

This section describes the different concepts and definitions of the nomenclature in FDD.

There exist numerous definitions of the various FDD concepts. However, this section aims to provide suggestions for a uniform FDD definition. With the growing availability of data, the use of machine learning in the FDD purposes in buildings has become increasingly popular. Although numerous datasets are available in the literature, it is essential to note that the quality and consistency of these datasets can vary. Therefore, enhancing these datasets through a standardized glossary could potentially improve their quality and usefulness in FDD research.

To this end, the authors propose a concept and corresponding definition as follows shown in Figure 1.

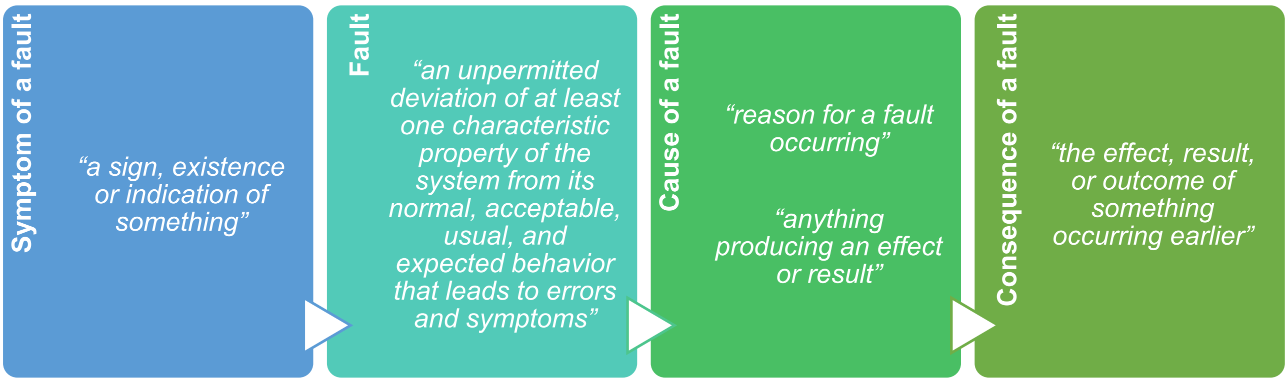

Figure 1: Proposed concepts and corresponding definitions for symptom of a fault, fault, causes of a fault and consequence of a fault.

What is a symptom of a fault?

"a sign, existence or indication of something"

Modified definition from Collins Dictionary [1]

What is a fault?

"an unpermitted deviation of at least one characteristic property of the system from its normal, acceptable, usual, and expected behavior that leads to errors and symptoms."

[2]

Other annotations of faults can be *outlier*, *error*, *abnormal*, *anomaly*, *deviation*.

What is a cause?

"reason for a fault occurring"

"anything producing an effect or result"

What is a consequence?

"the effect, result, or outcome of the fault occurring earlier"

[3]

Figure 2 shows examples of how to use the framework to define the faults for different HVAC systems, HVAC components, buildings zones and more. The symptom of the fault includes what is a visible consequence of the fault, the fault is what has gone wrong, the cause of the fault is why it has gone wrong and the consequence of the fault is what is impacted by the fault. It should be noted that some of these 4 parts can overlap, and for example a symptom can also be a consequence.

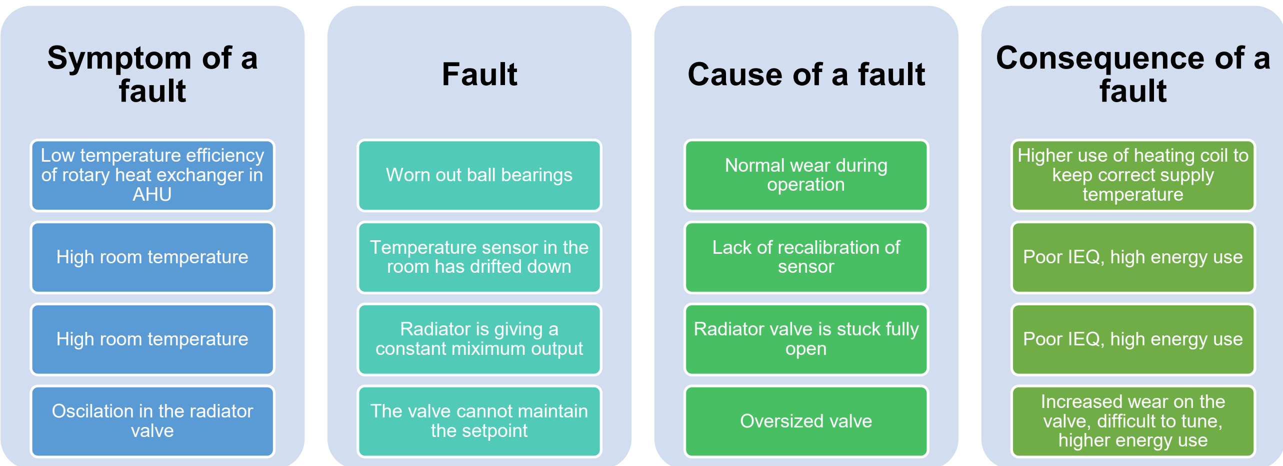

Figure 2: Examples of the fault definitions in different HVAC systems and zones.

Type of faults / fault categories

This section will be updated in version number 2 with definitions and examples of soft- and hard faults. Mechanical- and controller faults, and human behavior will be further outlined.

The FDD process

The FDD process consists of up to four different high-level processes, the first is the act of detecting the fault, in which it is determined if the system is faulty. If it is faulty, the next step can occur. This step is the diagnosis of the fault, where the cause of the fault is isolated and identified, thus provicing information on what is causing the fault. The following step is the evaluation of the fault impact, where the cost of the fault is evaluated. Once one or more of these steps have been performed, the process of handling the fault commences. This process can either be driven by an algorithm or left to the operational personnel to handle. The graphical illustration of this process can be seen in Figure 2, and a more detailed explanation is found in [4].

Figure 2 describes the framework for the data flow of the FDD process in the built environment.

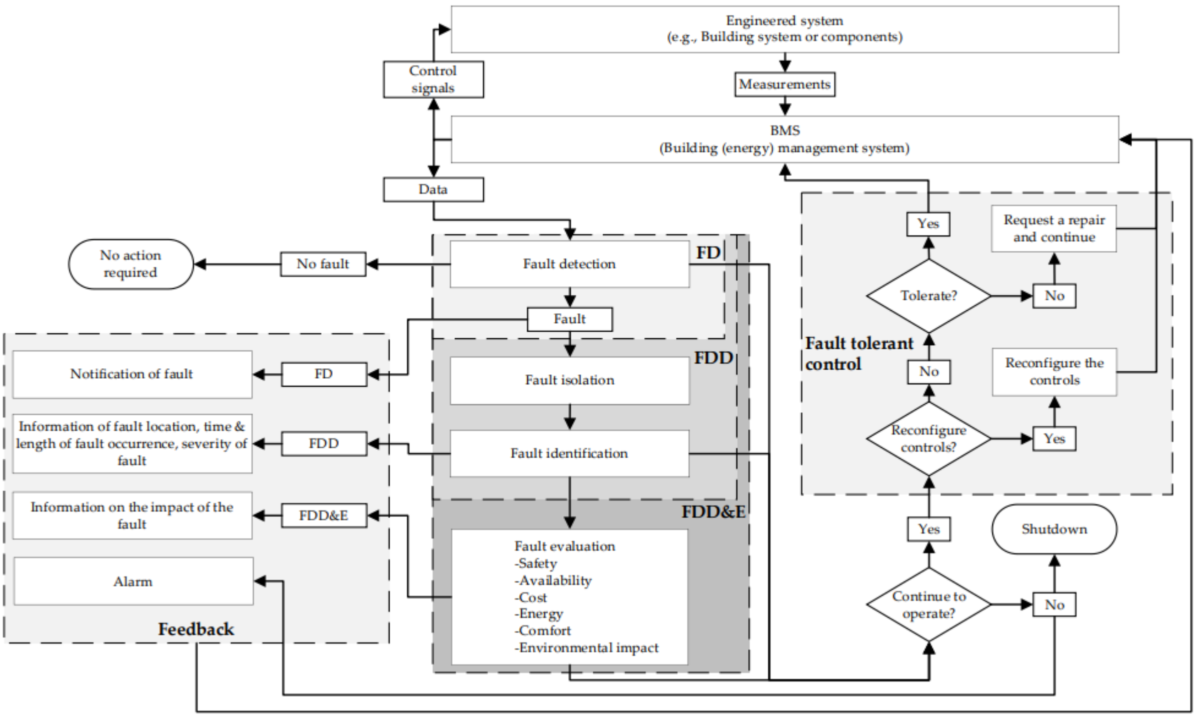

Figure 3: Framework for the FDD process [4], modified from the original [5].

Table 1 and Table 2 describes the different abbreviations used in FDD. Table 1 is the high level processes combining the subprocesses from Table 2. The table is modified and inspired by the following references, with permission from the authors: [4], [2] and [6].

Table 1: High level processes used in FDD.

Abbreviation	Full name	Synonym	Definition
FDD&E	Fault Detection and Diagnosis & Evaluation	Automated Fault Detection and Diagnostics / Automated Fault Detection and Diagnosis	It consists of Fault Detection, Fault Isolation, Fault Identification, Fault Evaluation
FDD	Fault Detection and Diagnosis	Fault Detection and Diagnostics	Consists of Fault Detection, Fault Isolation, and Fault Identification (with the last two commonly known collectively as Fault Diagnosis)
FD	Fault Detection	Fault Indicator	This step is about monitoring the physical system or device and detecting any abnormal conditions (problems)

Table 2: Subprocesses used in FDD.

Abbreviation	Full name	Synonym	Definition
FI	Fault Isolation	Fault Analysis	This process involves isolating the specific fault that occurred, including determining the kind of fault, the location of the fault, and the time of detection
FI	Fault Identification		This process includes determining the size and time-variant behavior of a fault (in terms of scale/severity and how long the fault has occurred)
FDI	Fault Detection & Isolation	-	Fault Detection and Fault Isolation (Includes the processes fault detection and fault isolation)
FDI	Fault Detection & Identification	-	Fault Detection and Fault Identification (Includes the processes fault detection and fault identification)
FE	Fault Evaluation	Fault Impact Analysis (FIA)	Fault Evaluation assesses the size and significance of the impact on system performance (in terms of energy use, cost, availability, or effects on other performance indicators)

Fault-tolerant control

A strongly related field of FDD is fault-tolerant control. More information on this topic will be presented later. One of several literature recommendations in this field is the following: [2].

Existing FDD Frameworks and Overviews

This section describes the existing review overviews of FDD methodology classifications in building systems. Table 3 describes the existing reviews and method characterizations defined in the corresponding review.

Table 3: Categorization of methods according to existing literature.

References	Method categorizations
Katipamula et al. [5]	- Qualitative model-based - Quantitative model-based - Process history based
Zhao et al. [7]	- Data-driven methods - Knowledge-driven methods
Mirnaghi et al. [8]	- Statistical methods - Data-mining methods
Matetic et al. [9]	- Knowledge-discovery approach - Data-driven approach - Physics-based approach
Ahmad et al [10]	- Prediction - Optimization - Control and diagnosis
Melgaard et al [4]	- Data-based methods - Model-based methods

Figures 4, 5, 6, 7 and 8 describes the different method classifications from the above mentioned reviews in Table 3.

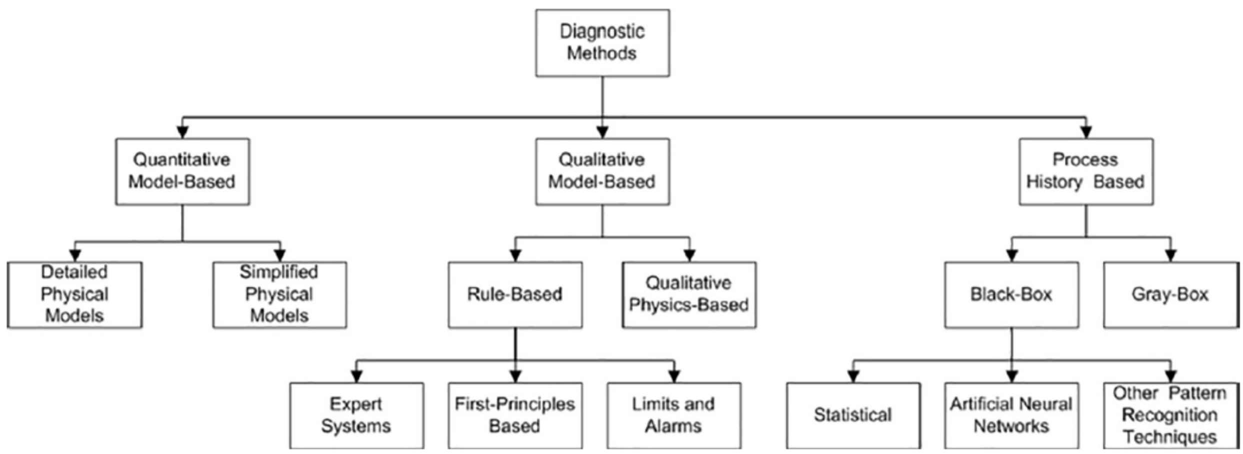

Figure 4: Classification of fault detection and diagnosis methods according to [5].

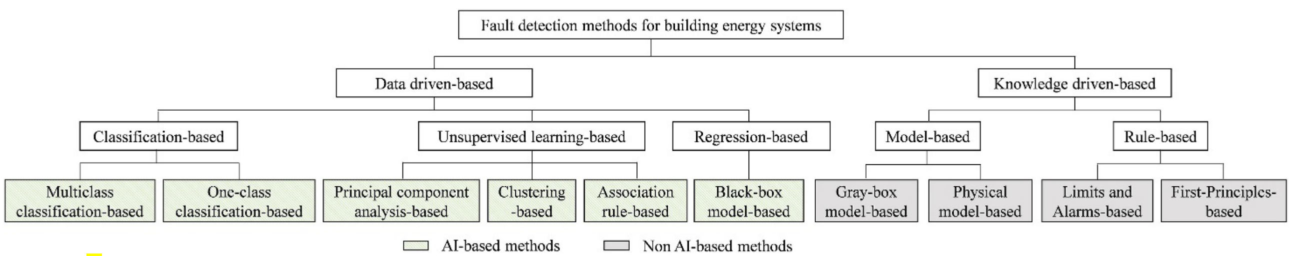

Figure 5: Classification of fault detection and diagnosis methods according to [7].

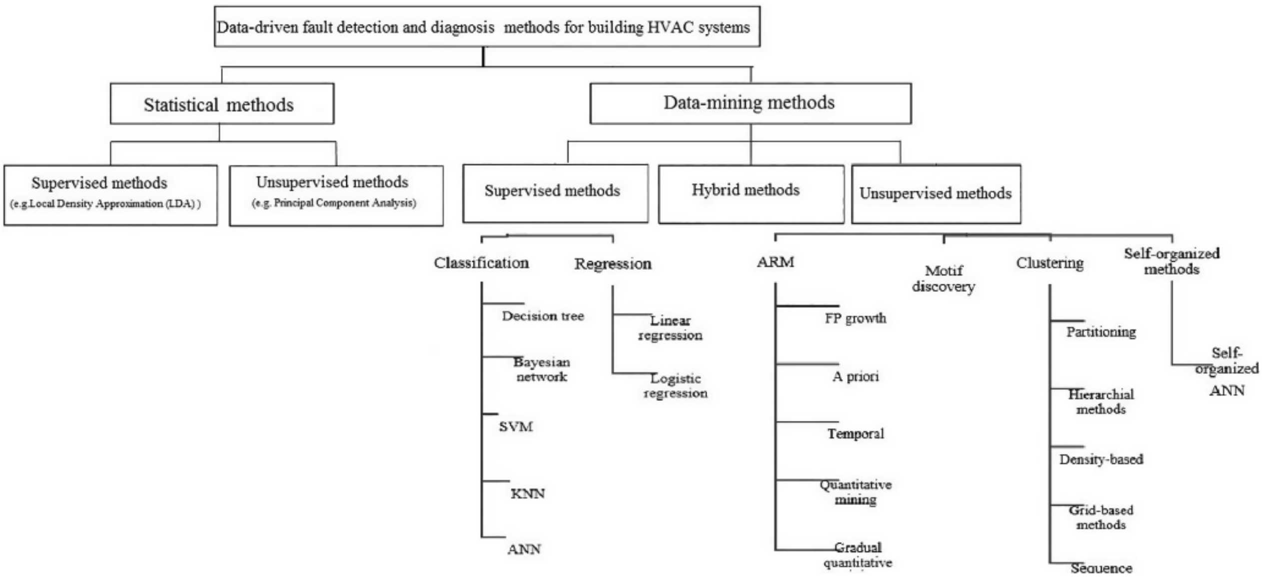

Figure 6: Classification of fault detection and diagnosis methods according to [8].

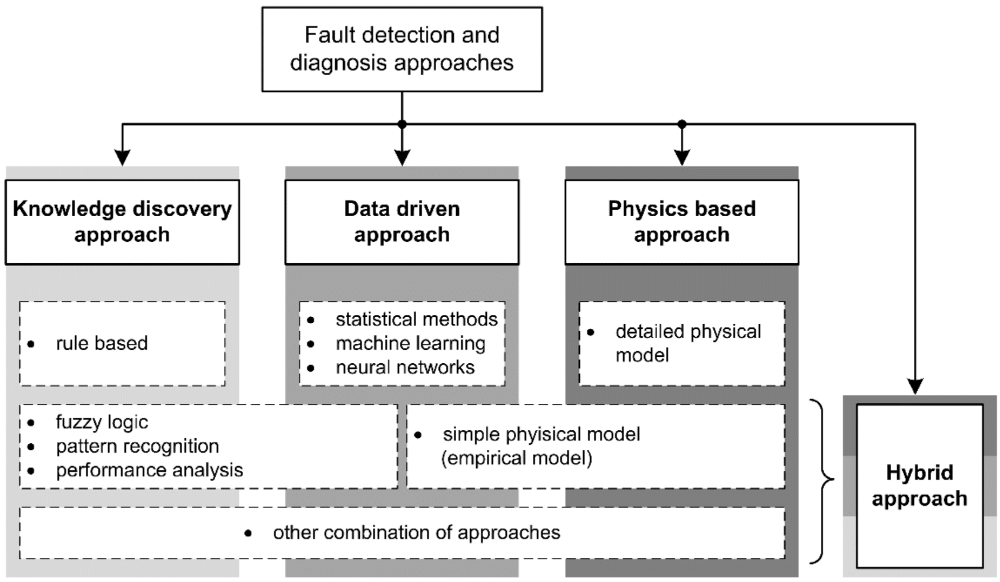

Figure 7: Classification of fault detection and diagnosis methods according to [9].

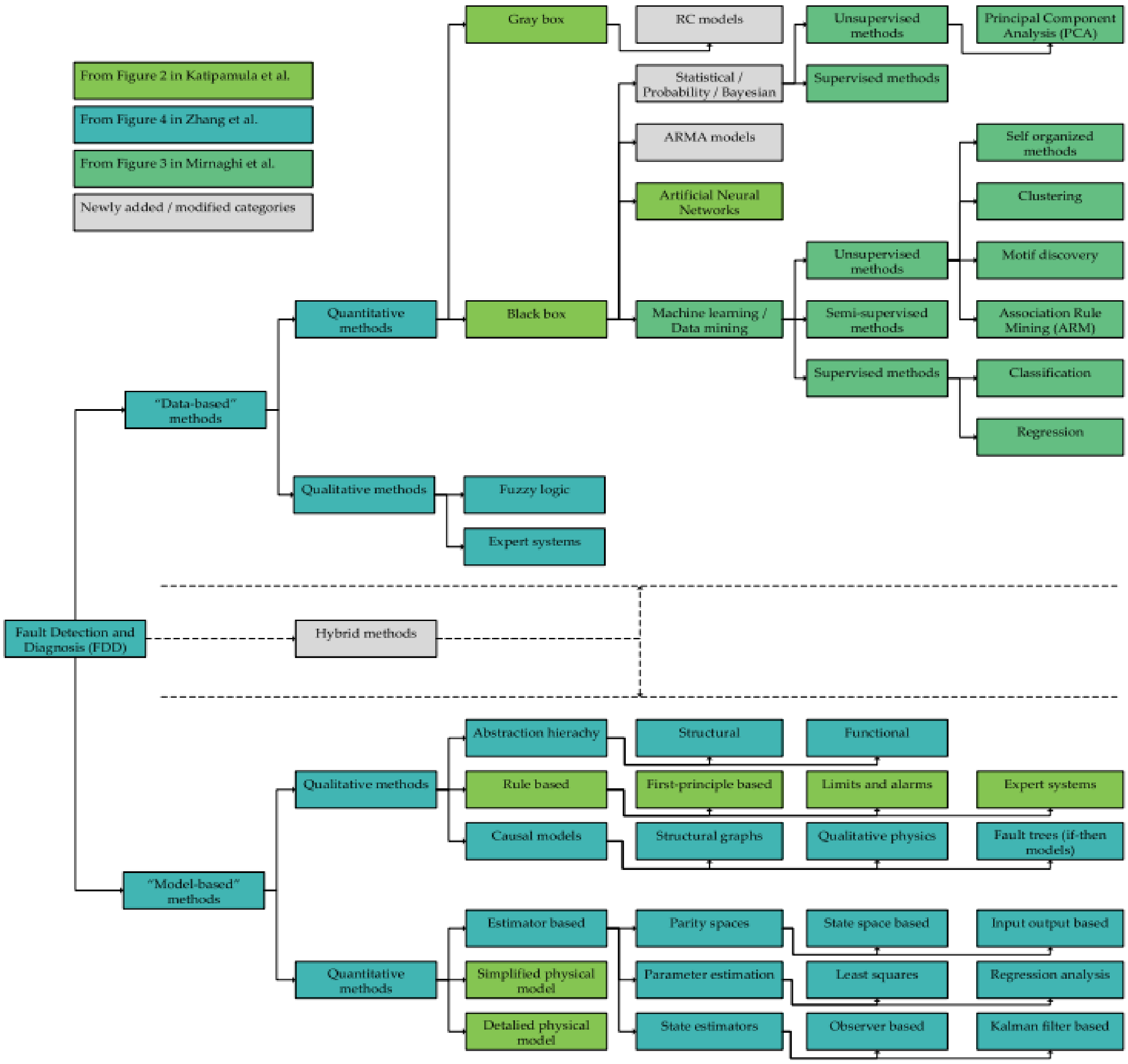

Figure 8: Classification of fault detection and diagnosis methods according to [4]. Zhang et al. can be found here: [11] and Mirnaghi et al. can be found here [8].

Typical Faults Occurring in Building Systems

This section accounts for studies and examples focusing on typical faults occurring in building systems. This section will get more focus in version 2.

[12] presented typical faults occurring in demand-controlled ventilation in the following framework: faults, symptom of faults, causes of faults and symptoms and consequences presented in Table 4. Table 5 describes the various symptoms and consequences of possible faults that can occur in a district heating (DH) system according to [13].

Table 4: Faults, symptom of faults, causes of faults and symptoms and consequences from the study of [12].

Fault no.	Symptom of fault	Faults	Causes of faults and symptoms	Consequences
1	Doors are hard to open or close	Ventilation unbalance	- DCV-damper (either supply or exhaust) are mounted after rehabilitation, no balanced ventilation or commissioning is provided - Rooms with large deviations increased the pressure - Wear and tear of the system - Not sufficient or satisfactory commissioning (commissioned with noticeable over- or under pressure) - Load testing of the ventilation system improper or neglected - Complex ventilation system - Cracks or punctures in duct system (airtightness test not performed)	Overpressure or under pressure have occurred, ventilation airflows not balanced), fan needs to work at a higher level – increasing the energy consumption, lower or higher supply of air which can make the occupants feel draft, too warm and will decrease performance
2	Poor IEQ	Incorrect, unsuitable placement or nonworking CO2, pressure and/or temperature sensor	- No calibration of the sensors in DCV-damper and the room - Defective component or controller failure - Improper installation - Room structure not optimal for sensor placement - Wrong component connection (no insulation/airtightness in the cables so CO2 concentration sensor measures outdoor concentration)	Deviating supply air temperature and supply airflow, higher CO2 concentration, unsatisfied occupants, draft may also occur if the combined sensor shows higher temperature and CO2 concentration than actual room temperature
3	Noticeable noise from the ventilation system		- Sound silencer/insulation not mounted with DCV-damper (forgotten or neglected) - Wear and tear of fan bearings - Wrong placement of DCV-damper which provides incorrect actuator point	Noise will be noticeable and bothersome, unsatisfied occupants
4	No access to DCV-damper		- Low ceiling, DCV-damper does not fit properly - Design of DCV-damper - No cleaning hatch for removing dust and dirt from the	Deviating supply- and exhaust airflow if measuring cross is dusted, higher CO2 concentration

			- measuring cross. - The ceiling is hard to remove/require demolition	due to dust and dirt on measuring cross, unsatisfied occupants due to the aforementioned reasons
5	Poor IEQ	Lower or higher airflow than designed supplied to a room	- Electrical error or component error which makes the fire valve close - Frozen DCV-damper sensor - Low fan speed - Clogged, damaged or dirty coils - Wrong choice of duct dimensions	Deviating supply- and exhaust airflow from designed value, higher CO2 concentration, unsatisfied occupants
6	Users complain about a too cold or too warm environment		- Wrongly designed airflow rate - Non-strategically placement of room sensors contributing to the wrong reading to damper or not connected to BMS at all - Sensors have not been calibrated providing the wrong temperatures - DCV-dampers is placed to close after bend which provides a wrongly measured airflow rate - Not optimal design of air intake (placed in the sun or exposed to wind) - No ventilation cooling is installed - Broken heating- or cooling coil - Components wrongly connected during commissioning or inspection - Higher occupancy load than designed - Malfunction/fouling in the control valve of the heating and cooling coil - Wrong duct size which provides low-pressure differences	Deviating supply air temperature, unsatisfied occupants increased energy use because of increased ventilation cooling or heating, deviating supplyand exhaust airflow from the designed value
7	Higher energy consumption than designed		- - Not designed Vmin and Vmax (AHU operates as a constant volume ventilation strategy) - Lights are left on 24/7 (light sensor or schedule might not be working) - Cooling and heating coils operate on/off from wrong installation or wear and tear - Abnormal user-behavior - The heating system in the room is set to max (heating 24/7) - Windows are frequently opened	Additional energy cost may increase, the building may not reach energy goal if part of an energy/sustainability scheme
8	High pressure drop across filters	Blocked filters	- No cleaning or change of filters - No access to the DCV-damper	Deviating supply- and exhaust airflow, air feels heavy due

				to lower supply of air
9	faults found due to unsatisfactory / not finished commissioning	Improper commissioning	- No ventilation documentation provided or missing/nonexisting FDV-documentation - Improper installation - PID coefficients in DCV-damper not calibrated - DCV-damper pressure control frozen, or poor/wrong system operating setpoints	Deviating supply air temperature and supply airflow, unbalance, fouling components in the HVAC system, increased energy use
10		Building Management System (BMS) does not show necessary parameters for efficient building operation	- Not optimal BMS - Wrong choice of BMS for building operation	Deviating supply air temperature and supply airflow, unbalance, fouling HVAC system

Table 5: Faults, symptom of faults, causes of faults and symptoms and consequences from the study of [14] regarding the DH systems in the customer side (buildings).

Fault no.	Symptom of fault	Faults	Causes of faults and symptoms	Consequences
1	Heat load patterns do not follow expected pattern for the building type (Unsuitable heat load pattern)	Faulty settings in a building's control systems	Wrong settings in the building's control system caused by incorrect occupancy behaviour.	- Decreased heating efficiency to the DH grid - Increased energy consumption - High operation costs
2	Low average annual temperature difference	Several possible faults in the heating installation	Widespread set of causes, e.g. defective components, high heating settings, etc. As a result, low average annual temperature differences cannot be attributed to systematic faults associated with a specific fault but rather have unique explanations for each substation/customer.	
3	Irregular oscillations and bad correlation between heating and outdoor temperature (Poor substation control)	Several possible faults in the heating installation	The poor substation control is not a fault in itself but rather an indication of underlying faults that may be due to physical components or human wrong utilization. This issue can occur in both the substations and the secondary systems. Nevertheless, there is minimal correlation between low average annual temperature differences and this symptom.	

As one can see in the table above, the existing FD framework still lacks a proper explanation between the possible faults in the end-user side and the observed symptoms in the measured data from the smart heating meters (SHM). This lack is due to an inexistent ground truth generated by DH companies and technicians. To tackle this problem, [15], developed a taxonomy for labelling faults occurring in the heating installations in the customer side. This taxonomy is involving five-labelling steps and are based on the experience and feedback provided by different Swedish DH companies [16]. In Table 6, it is observed the definition of the five-steps taxonomy proposed by [15].

Table 6: Summary of the taxonomy for labelling deviations in the DH customers proposed by [15].

Level	Level designation	Definition
1	Cause of deviation	Outlines the underlying reasons for deviations in DH customer data based on the system or subsystem to which the components contribute their function. Four categories are proposed: "Fault in Primary System District Heating", "Fault in District Heating Metering", "Fault in Heating System", and "Fault in Hot Water System".
2	Component	This level provides a comprehensive collection of a possible faulty component that falls under one of the categories selected previously to be selected.
3	Fault description	The technician will specify the issue with the selected component above. As the user enters the input at this stage, the system will offer several suggestions for the fault description based on earlier inputs.
4	Action	In this level, it is provided information regarding the actions taken to rectify the identified fault.
5	Status	At this level, the current status of the cause of deviation is outlined, which includes information regarding the effectiveness of the measures taken to rectify the fault, i.e., whether they have been fully or partially successful or have been ineffective.

The final taxonomy structure also incorporates two additional categories, namely "Fault in Distribution System" and "Changed Energy Use". The "Fault in Distribution System" pertain to issues in the DH distribution system outside the building and its heating installation however impacting the recorded data. The "Changed Energy Use" refers to the customer's installation, but it does not necessarily indicate a fault. This category can result from various reasons, such as new occupants moving into the building. Such instances can cause variations in energy usage, leading to deviations in data that differ significantly from the previous normal operation of the installation. However, the change in energy use is not a fault but a normal change in behavior that requires some form of labeling or identification.

Existing labeled dataset with ground truth for FDD

This section lists the different dataset repositories available for the built environment, including HVAC systems, components, full building and more. The full list can be seen in Table 6. Some of the datasets are publicly available for free, while others are not open. Some of the repositories also include the code used by their authors to perform their method of FDD.

Table 7: Repositories containing datasets for different parts of the built environment such as chillers, AHUs, full buildings, etc. The table is expanded from [4].

Building system	Description	Reference	Type of data/code	Open source?
Dataset repositories				
Chiller	Tools and data for FDD methods applied to chillers: ASHRAE RP-1043	[17]	Experimental data	No
Air handling units	Tools for evaluating fault detection and diagnostic methods for air-handling units: ASHRAE RP-1312	[18]	Simulation data	No
Real building	Demonstration of fault detection and diagnostic methods in a real building: ASHRAE RP-1020	[19]	Implementation	No
Vapor compression equipment	Development and comparison of one-lone model training techniques for model-based FDD methods applied to vapor-compression equipment: ASHRAE RP-1139	[20]	Simulation / numerical data	No
Chiller	Electric factory dataset	[21]	Experimental data	No
Heat pump	Validation of the self-diagnosis efficiency system	[22]	Experimental / Simulation data	No
Air handling unit and rooftop unit	Labeled data for FDD	[23]	Experimental and simulation data	Yes
Air handling unit	Air Handling Fault Test Data	[24]	Experimental data	No
Chiller and boiler plant	Automated Diagnostic Algorithms for Chillers, Boilers, Cooling Towers, and Chilled Water Distribution	[25]	Simulation data	No
Air handling unit	Versatile AHU fault detection – Design, field validation and practical application	[26]	Case data	Yes
Air handling unit	Data Sets for Evaluation of Building Fault Detection and Diagnostics Algorithms	[27]	Simulation data	Yes
Central heating station	Dataset for assessing the reliability of central heating station-based units of buildings	[28]	Case study	Yes
Open code and data repositories				
Air handling unit	Development of Fault Models for Hybrid Fault Detection and Diagnostics Algorithm	[29], [30]	Code and data	Yes
Air handling unit	Fault Detection and Diagnosis in Air Handling Unit using Dymola Data	[31]	Code and data	Yes
Building energy use data	Methods to analyze the available data set of historic building energy fault data	[32]	Code and data	Yes
Heat pump and air conditioner	LabView codes, and associated codes, for doing a rule-based-chart method of fault detection and diagnosis	[33]	Code and data	Yes

Planned in the next version of this technical report

- Fault types and categorizations
- An outline of the fault tolerant control
- An update of the typical faults occurring in building systems
- An update on the existing datasets of labeled dataset with ground truth for FDD
- Suggestion for labeled data set with faulty ground truth
- Metrics for evaluating FDD method performance

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