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# Enhancing operational performance of AHUs through an advanced fault detection and diagnosis process based on temporal association and decision rules

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## Abstract

The pervasive monitoring of HVAC systems through Building Energy Management Systems (BEMSs) is enabling the full exploitation of data-driven based methodologies for performing advanced energy management strategies. In this context, the implementation of Automated Fault Detection and Diagnosis (AFDD) based on collected operational data of Air Handling Units (AHUs) proved to be particularly effective to prevent anomalous running modes which can lead to significant energy waste over time and discomfort conditions in the built environment. The present work proposes a novel methodology for performing AFDD, based on both unsupervised and supervised data-driven methods tailored according to the operation of an AHU during transient and non-transient periods. The whole process is developed and tested on a sample of real data gathered from monitoring campaigns on two identical AHUs in the framework of the Research Project ASHRAE RP-1312. During the start-up period of operation, the methodology exploits Temporal Association Rules Mining (TARM) algorithm for an early detection of faults, while during non-transient period a number of classification models are developed for the identification of the deviation from the normal operation. The proposed methodology, conceived for real-time implementation, proved to be capable of robustly and promptly identifying the presence of typical faults in AHUs.

25 **Keywords:** HVAC systems; Air Handling Units; Fault Detection and Diagnosis; Temporal  
26 Association Rules Mining; Intelligent energy management

## 27 **Highlights**

- 28 • A fault detection and diagnosis process is applied on AHU monitoring data;
- 29 • A novel methodology tailored on transient and non-transient operation is proposed;
- 30 • Faults in the transient period are detected with multivariate association rules;
- 31 • Temporal associations are exploited during the start-up period of the system;
- 32 • Decision rules are extracted for fault diagnosis in non-transient regime of AHU;

## 33 **1 Introduction**

34 Recent years have seen an increasing interest of the scientific community in exploring solutions to  
35 improve energy efficiency in buildings by implementing advanced data-analytics based energy  
36 management strategies. The application of these strategies is supported by the increasing penetration  
37 of ICT (Information and Communication Technologies) and EMSs (Energy Management System) in  
38 buildings, which may enable the adoption of data analytics based procedures for the exploitation of  
39 collected energy-related data and the extraction of hidden knowledge in an automatic way [1].  
40 Building Energy Management System (BEMS) are mainly used for tracking and managing the  
41 operation and energy performance over time of Heating Ventilation and Air Conditioning (HVAC)  
42 systems. The optimal management of HVAC systems, which accounts in the developed countries for  
43 10-20% of the total energy share in buildings [2], is a crucial task, considering that such systems  
44 account for 50% of the energy demand in commercial buildings [3].  
45 However, due to lack of proper maintenance, failure of components or incorrect installation, Air  
46 Handling Units (AHUs) are often run in inappropriate operational conditions. A study conducted on

47 more than 55.000 AHUs, showed that a fraction of 90% of them runs with one or multiple faults [4],  
48 where a fault is intended as an abnormal system state, an unpermitted deviation of at least one  
49 characteristic property of the system from the acceptable, usual, standard conditions. The  
50 identification and diagnosis of faults, in the case of HVAC systems, can lead to potential savings of  
51 about 30% [5]. This process is also known as Fault Detection and Diagnosis (FDD) where *fault*  
52 *detection* consists in the recognition of a fault occurrence, and *fault diagnosis* corresponds to the  
53 identification of the causes and the location of the fault [6]. Advanced methods of *fault detection* are  
54 based on mathematical models and on methods of system and process modelling to generate fault  
55 *symptoms* (e.g. residuals). *Fault diagnosis* methods use causal fault-symptom-relationships by  
56 applying techniques from statistical decision, artificial intelligence and soft computing [6].  
57 Although currently underutilized, FDD is a powerful tool for ensuring high efficiency in building  
58 operation and FDD products represent a very fast-growing market in the context of building analytics  
59 technologies [7]. According to [8], over 30 FDD products are available in U.S. that may be delivered  
60 through different implementation models [7]. The algorithms behind FDD tools may be integrated  
61 into server-based software, desktop software, or software directly embedded in equipment controllers.  
62 FDD algorithms are based on historical data that can be gathered from different sources such as  
63 Building Automation Systems (BAS), equipment controllers, external sensors and meters, or mixed  
64 sources. Despite the existing differences in the way tools are implemented and integrated with the  
65 monitoring system, the main tool classification can be performed according to the approach employed  
66 for conducting the FDD analysis.

67 The methods used for performing an FDD analysis can be classified in quantitative model-based,  
68 qualitative model-based and data driven-based, as done in [9].

69 The quantitative model-based approach includes all the methods involving engineering models with  
70 different levels of detail in the physical description of the system (e.g. white box models). The  
71 qualitative model-based methods exploit the system knowledge derived from domain expertise (e.g.  
72 rule-based, qualitative models). The last category includes data-driven methodologies exploiting

73 collected operational data of the system under investigation (e.g. Artificial Neural Networks,  
74 Association Rules Mining, grey box models). While rule-based methodologies (qualitative approach)  
75 are largely used, vendors are beginning to use data driven methodologies for addressing FDD tasks  
76 [7].

77 The next section provides an overview of the use of data-driven approach for FDD, with a specific  
78 focus to AHU systems.

### 79 1.1 Data-driven approach for FDD analysis in AHUs

80 In the last few years, the data-driven approach for the FDD analysis gained more and more interest,  
81 thanks to its applicability even in the case engineering models of the building and systems are  
82 inadequate or difficult to be developed, or the physics-based knowledge is not wide enough [9]. In  
83 this context, particularly promising appears the implementation of machine-learning techniques,  
84 which include both supervised and unsupervised algorithms. As pointed out in [10], the main  
85 advantages of the artificial intelligence-based data-driven approach, in comparison to traditional  
86 approaches, rely on the opportunity to:

- 87 • Learn automatically patterns from system operational data without the use of physical models.  
88 The data-driven approach does not require an a-priori understanding of the relationships that  
89 exist among faults and their symptoms.
- 90 • Achieve higher fault-detection and fault-diagnosis accuracy than qualitative methods (rules  
91 based on expert knowledge), also for faults of low severity levels.
- 92 • Perform FDD analysis exploiting a limited number of variables. It means that approach can  
93 enable an optimisation of sensor installation and then significantly reduce the number of  
94 required sensors.

95 More in detail, the supervised approach uses the domain expertise to develop useful prediction tool,  
96 since monitored data include variables for both input and output of the model (i.e. regression or

97 classification methods). On the other hand, the unsupervised methods (e.g., cluster analysis,  
98 association-rule mining) are capable to extract hidden knowledge without a pre-defined target (i.e.  
99 data used do not have any output values) and are particularly effective in case of poor-information  
100 systems or when the objective of the analysis is not a-priori constrained [11].

101 The methods involving the construction of supervised estimation models mainly consider the  
102 implementation of a residual analysis in order to perform an FDD process. The residual in that context  
103 is the difference between the estimated and the measured value of a specific target variable: the  
104 estimation is performed by means of a fault-free supervised model, while actual data may be related  
105 to faulty conditions. Therefore, the residual analysis is used as a way for assessing the severity of the  
106 deviation from the fault-free conditions during operation [12].

107 Many applications of supervised and unsupervised techniques for Automated Fault Detection and  
108 Diagnosis (AFDD) are reported in literature, particularly for detecting faults during the non-transient  
109 operation of AHUs [13].

110 Even though each component of an AHU can be potentially corrupted by a fault, the most common  
111 faults can affect sensors (e.g. offset in the measurement), controlled devices (e.g. blockage or leakage  
112 of air damper or coil valves), equipment (e.g. coil fouling or reduced capacity, duct leakage, fan  
113 complete failure or deviation in the pressure drop or belt slippage) and controllers (e.g. unstable or  
114 frozen control signal for dampers, coils or fan) [14]. In [15] was proposed a methodology to identify  
115 faults related to the fans and the air dampers of an AHU. The methodology uses a Multi-Class Support  
116 Vector Machine (MC-SVM), for the identification of both pre-labelled faults and new ones. In [16]  
117 and [17], a Bayesian Network (BN) was adopted for the diagnosis of faults related to air dampers,  
118 cooling coil valve stuck and return fan failure. The BN exploited in input the residuals obtained from  
119 a set of limit-checking rules and statistical models, capable of estimating air temperature, water flow  
120 rate, air flow rate and fan power consumption. Mulumba et al. proposed in [18] a methodology to  
121 diagnose the presence of several faults affecting air dampers, cooling coil valve and return fan by  
122 using a SVM in combination with an autoregressive model with exogenous inputs. Yan et al. proposed

123 in [19] a combination of two supervised techniques to diagnose the blockage of air dampers and coil  
124 valve, the duct leakage and the return fan failure. In [19] a Classification Tree (CT) was developed,  
125 which used in input both monitored data (i.e. air temperature and flow rate, fan speed and power, and  
126 cooling coil valve position) and residuals obtained from a regression model of the fan speed, while  
127 in output the labels of different faults were considered. The methodology developed in [19] made it  
128 possible to accurately perform fault diagnosis, but without taking into account transient periods of  
129 operation. Different classification models for fault detection were also compared in the work of  
130 McHugh et al. [20] and the Classification (decision) Tree model was selected as the best choice for  
131 the detection of steam or chilled water leakage.

132 The unsupervised methods proved to be particularly flexible for their nature in exploring data set  
133 without any *a priori* constraint, as opposed to the supervised models [11].

134 Yu et al. proposed in [21] an unsupervised methodology to identify energy wastes and faults of a fan  
135 in an AHU, by exploiting Association Rules Mining (ARM). This type of algorithm requires a strong  
136 expertise by the analyst for the interpretation of the results, considering that the rule set extracted  
137 could include also not-interesting information for the identification of anomalous operation of the air  
138 conditioning system [21]. Many studies make use of ARM for the identification of faults in different  
139 types of HVAC systems (e.g. district heating substation, AHU, chillers)[10]. ARM has been adopted  
140 also for the analysis of a district heating substation in order to identify inefficient operation and sensor  
141 faults by searching anomalous correlation expressed by association rules [22]. In order to help the  
142 domain expert in the interpretation of the results, in [23] a methodology was proposed to reduce the  
143 number of rules to be analysed and to effectively group them for distinguishing the faulty from the  
144 normal operation. Furthermore, the temporal relation among the energy consumption of different  
145 HVAC components was studied in [24] and [25] to determine the presence of faults and prevent a  
146 reduction of energy performance over time.

147 A combination of a supervised and unsupervised methods (e.g., decision tree and clustering analysis)  
148 was proposed in [26] and [27] for the detection of anomalous energy consumption in a group of smart

office buildings. Furthermore, Dey et al. achieved in [28] high values of accuracy in the automatic FDD on fan coil units operation by combining MC-SVM and cluster analysis.

Du et al. in [29] proposed a methodology to identify faults of temperature, flow rate and pressure sensors in a VAV system by implementing Artificial Neural Networks (ANNs) in combination with a signal decomposition technique (i.e. Wavelet analysis). In [30], an ANN was combined with clustering analysis to diagnose faults related to cooling coil valve, air damper and temperature sensors in an AHU. In the first step, the ANN was used for the estimation of supply air and water temperature to perform a residual analysis, then the methodology leveraged on clustering analysis for the fault diagnosis stage. Guo et al. used a Hidden Markov Model (HMM) for the fault detection phase and a cluster analysis for the identification of various types of faults such as the blockage of dampers, frozen fan or unstable cooling coil valve control signal [31]. In [32] and [33], an unsupervised data-driven approach was used to identify the presence of cooling coil valve blockage, heating coil valve leakage and air damper blockage, by analysing the error generated from the reduction of variables by means of Wavelet Transform and Principal Component Analysis. Successively, the fault diagnosis was performed by analysing the trend of each variable during faulty conditions, in order to identify the variable mostly influenced by the fault source.

Liang et al. in [34] proposed a methodology to diagnose the stuck of the recirculation damper and of the cooling coil valve in an AHU, as well as the decreasing of the supply fan speed. In that work, an SVM was used in combination with a white box model, exploiting the residuals obtained by comparing actual and simulated fault-free values of supply and mixed air temperature, and cooling coil outlet water temperature. Wu et al. in [35] combined a quantitative model-based method with an unsupervised data-driven method to diagnose sensor faults, air damper blockage or frozen fan. In that work, first the variables considered were reduced (i.e., by means of Principal Component Analysis), then the presence of faults was investigated comparing actual monitored data with the estimation of airflow rate and energy calculated by using simplified balance equations for energy and pressure-flow. In other works, a qualitative-based approach was used to perform automatic FDD in



175 combination with the data-driven approach. In [36], the detection of faults occurring in an AHU was  
176 performed by exploiting “IF-THEN” expert rules related to the residuals of mixed air temperature,  
177 return air flow rate, supply air static pressure and cooling coil valve control signal, generated with  
178 different General Regression Neural Networks. In [37] the integration of expert rules with Bayesian  
179 Networks was pursued, in order to better isolate faults in AHU. Such approach made it possible to  
180 exploit the violation of expert rules, to better detect the co-occurrence of multiple faults at the same  
181 time.

182 The above reported literature review demonstrated how much the scientific research has been active  
183 in the field of artificial intelligence for FDD in AHU and HVAC systems. However, the opportunity  
184 to approach this well-known task (i.e., FDD) from this innovative point of view was mainly due to  
185 the growing availability of huge amount of monitored data, related to the actual performance of  
186 buildings and energy systems. In this context some projects, supported by the American Society of  
187 Heating, Refrigerating and Air- Conditioning Engineers (ASHRAE) made very comprehensive field  
188 surveys, laboratory tests and performance evaluations on the performance of HVAC systems also in  
189 faulty conditions. The outcomes of such projects (e.g., ASHRAE Project 1312-RP and 1043-RP)  
190 enabled a great spread of FDD methodologies which exploit experimental data.

191 Among the reviewed papers, several published studies focused on the ASHRAE RP-1312 data set for  
192 developing and testing FDD methodologies for AHUs [16,17,38–43]. Despite those papers discuss  
193 the results of FDD methodologies on the same data set, not always the assumptions behind the  
194 analysis are the same. The main differences are related to the operation mode considered (cooling,  
195 heating, spring), the number and the type of faults analysed, the regime of operation considered  
196 (transient, non-transient). However, from the analysis of these works, some general considerations  
197 can be made:

- 198 • In most of the cases the analysis is performed for the summer period achieving high values of  
199 accuracy in diagnosing faults (over 90% of accuracy),

- The analysis is performed for data collected with sampling frequency of 1-min (original granularity of the dataset),
- Data-driven models used for characterizing the normal behaviour of the AHU lack of interpretability (SVM, ANN)
- In most of the cases, the fault diagnosis is performed through interpretable classifiers (decision trees, Bayesian networks).

In this context, the present paper aims at introducing an FDD methodology for AHU systems (based on data of ASHRAE RP-1312) that is data-driven, fully interpretable and rule-based. Indeed, the rule-based approach can satisfy the user need of simplicity and interpretability while the data-driven nature of the methodology can enable the automatic learning of system operational patterns. Another objective is also to reduce the granularity of the dataset while maintaining good performance in fault diagnosis. In fact, analyse data with a high sampling frequency could expose the FDD tool to instabilities when deployed for operating in real time (presence of punctual anomalies, missing values, sensor network latency).

In the approach proposed in this paper two rule-extraction methods (association rule mining, decision tree) were employed for conducting FDD analysis in AHU system, by exploiting the reduction and transformation of multiple time series related to the operation variables of the system. In the next section a discussion is provided about the automatic extraction of rules in multiple time series (Section 2.10) and the work novelty is explained (Section 2.1); the case study analysed in the paper is presented in Section 3; a focus on data analysis methods exploited in the analysis is provided in Section 4 and a description of the proposed methodology is provided in Section 5. In Section 6, the results obtained from the application of the methodology are presented. Eventually in Section 7 the discussion of results and concluding remarks are provided.

## **2 Rule extraction in multiple time series for FDD in AHUs**

The analysis reported in section 1.1 on the most relevant works published in the last few years, showed how FDD strategies in AHUs can widely benefit from the implementation of data mining and machine learning techniques, especially when they are supported by a robust expertise in building physics for an effective exploitation and interpretation of the extracted knowledge. However, the complexity of an AHU with multiple operational parameters and the temporal interactions among them makes the effective characterisation of its behaviour challenging.

The operation of an AHU system is characterized by two major time-regimes, namely transient and non-transient. The transient operation typically occurs when the AHU is started-up and is approaching the steady state conditions, or when it is shutdown or disturbed from its non-transient regime. The disturbances could be caused by either variation of thermal loads or by feedback controls. During transient periods some variables can exhibit strong variation in short time and a significant temporally lagged response with respect to the control signals. In addition, the behaviour of an AHU system varies as its mode of operation changes during the day and the year i.e., off mode, heating mode, free cooling mode, and cooling mode. Therefore, a robust data-driven-based FDD tool should be able to automatically determine the mode of operation of the system, to prevent false alarms from being generated. For example, normal behaviour during summer season may be faulty if the system is operating in heating mode (winter season). In order to avoid that condition, FDD tools in AHU systems are characterized by a hierarchical architecture that makes it possible to exploit only the portion of knowledge that is consistent with the specific operation mode considered. In this perspective, when using data-driven based FDD tools it is necessary for the training data to be exhaustive as possible for each operation mode.

However, given their complexity, data-driven-based FDD tools often lack in interpretability. In this context, the use of rule-based data-driven methods for FDD can satisfy the user need of simplicity in terms of understanding the FDD tool, using, commissioning and integrating it with existing BAS, and updating it. For this reason, great attention has been paid in this study to the application of advanced

supervised and unsupervised rule extraction methods (i.e., decision trees, association rule mining) with reference to multivariate problems. The operation of an AHU is a perfect case that can be effectively described through the analysis of multiple time series (defined as series data points indexed in time order) associated to each operational variable of the system. However, the large number of time series with high sampling frequency could significantly increase the complexity and computational cost of the analysis, often making necessary a proper reduction (aggregation in the time domain) and discretization (quantization of the signal value) of data. This is a challenging task, considering that each variable has its own behaviour and distribution and, as a consequence, the optimal time aggregation and value discretization of the signal need to be identified with the aim of minimizing the information loss and of maximizing the mining performance. Such preparation of the time series is an essential step in FDD methodologies based on rule extraction techniques (e.g., based on association-rule mining algorithms or decision trees) that, in the literature, have been used for effectively mining co-occurrences or implications between discrete values and events in the time domain during HVAC operation [19,24,44].

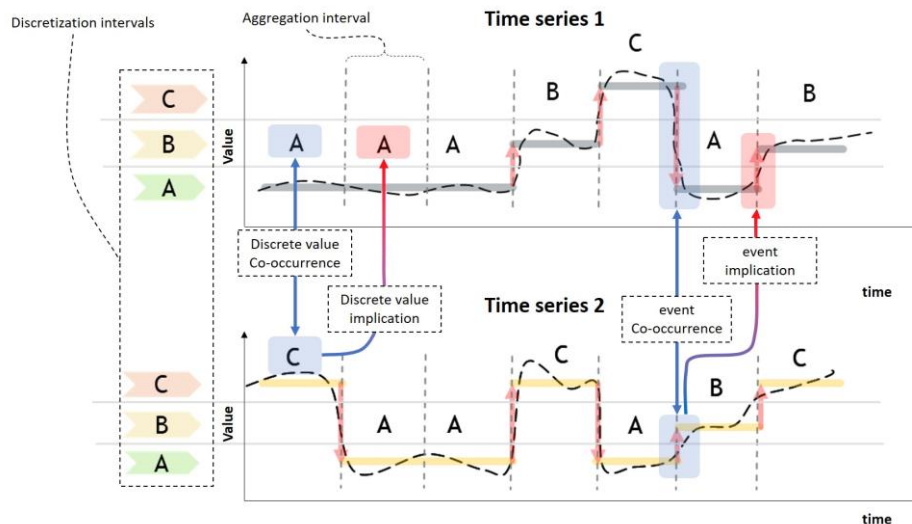


Figure 1. Graphical representation of co-occurrence and implication between discrete values and events among multiple time series.

Figure 1 depicts in graphical form the concepts, of discrete value, event (change of discrete value between two contiguous aggregation intervals), co-occurrence and implication of discrete values and

268 events with reference to two time series encoded in symbols by means of Symbolic Aggregate  
269 approXimation (SAX) [45].

270 When multiple time series are considered, rule extraction techniques can be categorized in intra-  
271 transactional and inter-transactional respectively. The first type of extraction aims at discovering co-  
272 occurrences between discrete values and events that frequently happen at the same time among  
273 different time series (Figure 1). The second type of rule extraction is more complex, considering that  
274 the occurrences of discrete values and events among different time series, in that case, are searched  
275 taking into account the existence of a time lag (Figure 1). During transient periods of AHUs operation,  
276 the latter approach is particularly favourable in describing phenomena that are characterized by  
277 temporal dependences among variables representative of the system operation (e.g., change of status  
278 in a fan speed and the corresponding effect on supply air temperature).

279 In order to develop an FDD process capable to be flexible in relation to different conditions of  
280 operation in AHUs, the present study proposes the application of two rule extraction methodologies  
281 tailored for both transient and non-transient periods.

282 The developed framework aims at preventing anomalous running modes of AHUs, which could lead  
283 to significant energy waste over time and/or discomfort conditions in the built environment.

284 The analysis relies on temporal abstraction as a pre-processing stage. Temporal abstraction is aimed  
285 at reducing and transforming time series in discrete-time and discrete-value signals through  
286 aggregation on the time axis and discretization of the value in order to perform the extraction of  
287 interesting co-occurrences and implications. In this study, an adaptive process based on a Symbolic  
288 SAX is employed for conducting the temporal abstraction.

289 Furthermore, strong relations between events (i.e., change of discrete value between contiguous  
290 aggregation intervals) are automatically mined by means of temporal IF-THEN association rules in  
291 the transient period of AHU operation (i.e., start-up phase), considering an intra-transactional  
292 approach for characterizing the fault-free behaviour of the system. Similarly, during the non-transient  
293 period of operation, a set of classification trees are developed for extracting reference patterns in the

294 form of decision rules. Potential faulty conditions are then detected when the discovered association  
295 and decision rules are violated over time. Successively, the identified anomalous patterns (during the  
296 non-transient period) are exploited for performing a diagnosis of the most probable faults associated  
297 to a specific kind of rule violation by means of a classification algorithm.

## 298 2.1 Novelty of the paper

299 The present work introduces an automatic methodology for performing an FDD analysis in AHUs by  
300 using experimental data obtained in the framework of the ASHRAE project RP-1312. The entire  
301 process relies on the application of data mining-based algorithms in order to develop a tool capable  
302 to detect and diagnose operational faults in AHUs which can determine energy waste over time and  
303 the occurrence of discomfort conditions in the built environment.

304 Based on the FDD literature review presented in section 1.1, the main innovative aspects introduced  
305 by the present paper are the following:

- 306 • An adaptive process of data reduction and transformation is employed to develop a robust  
307 FDD methodology. In complex systems as AHUs, the number of monitored variables and  
308 their sampling frequencies could be very high. Extracting only key information from large  
309 data set is essential for reducing redundancy, complexity and computational cost. In this study,  
310 the methodology makes it possible to achieve good performance in FDD (comparable to other  
311 studies focused on the same dataset [16,17,38–43]) leveraging only on the analysis of  
312 significant discrete intervals of the operational variables over time.
- 313 • The start-up period of AHU operation is isolated and treated separately by developing a  
314 tailored analytics module (instead of being filtered out as happened in other studies focused  
315 on the same dataset [16,17,38–43]). During transient period of operation time lags occur for  
316 example between a change of status in the fan speed and the corresponding effect on supply

air temperature. For this reason, temporal association rules are extracted, following an intra-transactional approach, for discovering associations between events during transient periods, across multiple time series, that frequently occurs within a time lag.

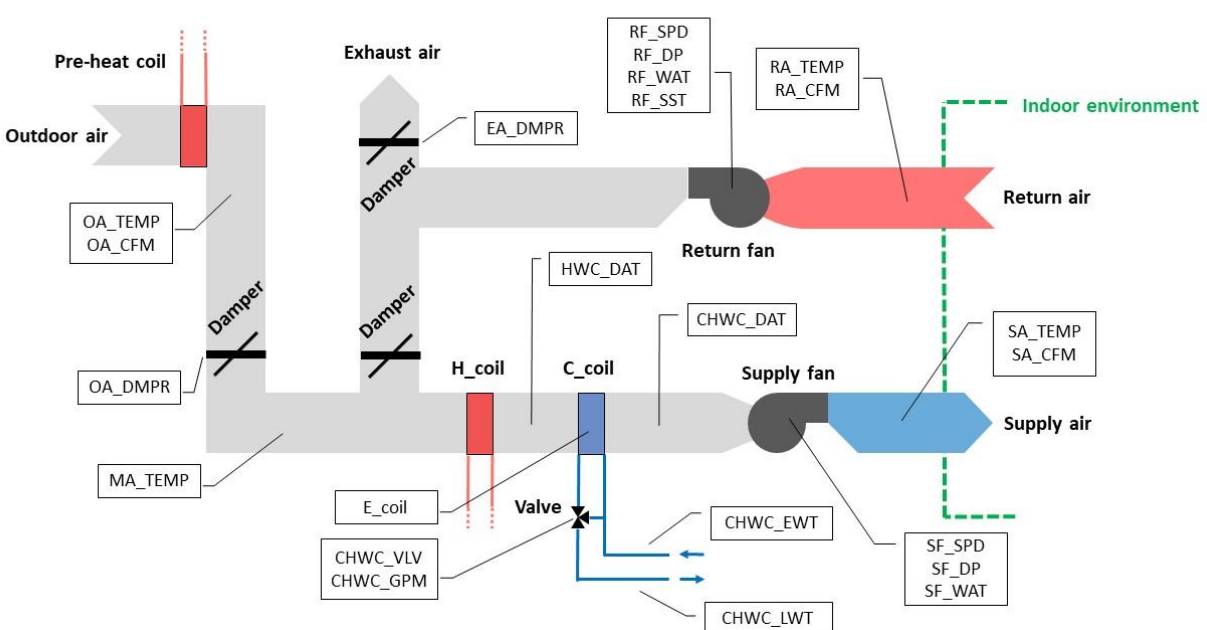
- The characterization of normal behaviour during the non-transient period is completely automated and performed by using a set of estimation models based on decision trees. In comparison to other studies focused on the same dataset [16,17,38–43], the reference behaviour of the AHU is evaluated estimating the most probable discrete value of each influencing operational variable in relation to all the others monitored. In that way, all the existing relations between variables are exploited through several estimation models, for detecting potential faulty conditions. Such approach exhibits high flexibility and generalizability in the formulation of the FDD problem.
- A fault diagnosis during non-transient period of AHU operation is performed by employing a decision tree, capable to extract rules for the classification of typical faults. The diagnosis process exploits the residuals evaluated by means of a set of estimation models as input attributes for the classification of the most probable faults.

In that perspective, this study was aimed at conceiving, developing and testing a methodological framework that introduces the aforementioned novelties in automatic FDD, in as robust a way as possible. As previously stated in the literature review, several studies considered the RP-1312 data set in the analysis, achieving an accuracy in fault diagnosing over 90%. As a consequence, the main objective of this study is not to improve the (already high) FDD performance achieved on the RP-1312 dataset, but rather to demonstrate the opportunity to achieve high performance as well through a fully interpretable and simplified data-driven approach, based on rule extraction techniques.

### **3 Case study**

In order to test the validity and the effectiveness of the proposed methodology, operational data related to two AHUs collected in the framework of the Research Project ASHRAE RP-1312 [14]

342 were analysed. The system investigated is a Variable Air Volume (VAV) AHU. A VAV system is  
 343 able to modulate the air flow rate according to the variation of the building load and it is typically  
 344 made up of 4 subsystem controllers, acting on supply air temperature, dampers and valves, supply air  
 345 static pressure and return air flow rate. Specifically, the control logic maintains the supply air  
 346 temperature set-point acting on damper and valve positions, according to the mode of operation (i.e.  
 347 heating, cooling with partial mixing of outdoor air, cooling with 100% of outdoor air, cooling with  
 348 minimum outdoor air).  
 349 Furthermore, also the static pressure of the supplied air and the difference between the supply and  
 350 return air flow rate is controlled. The return air flow rate is modulated acting on the mixing dampers  
 351 and the return fan speed, while the system maintains the static pressure set point for the supply air.  
 352 As a result, the difference between the supply and return air flow rate is kept constant [12].  
 353 The dataset used in this paper is particularly interesting as it includes several running conditions for  
 354 two AHUs in faulty and fault-free operation. The faulty operation was obtained by artificially  
 355 implementing a number of different faults. The site, where the monitoring data have been collected,  
 356 is a test facility simulating a typical schedule of occupancy in commercial building.



357  
 358 *Figure 2. Scheme of the AHU analysed (refer to Table 2 for variable encoding).*



359 The monitoring data were gathered from two AHUs of the facility (AHU-A and B), which are  
360 perfectly identical from technical and operational points of view and serve specular zones. The zones  
361 served by AHU-A and B face east and west orientation, respectively, in order to be comparable also  
362 under the aspect of the thermal loads. The AHUs are characterised by a mixing chamber, to mix return  
363 air with outdoor air by means of dampers. Each AHU is equipped with heating and cooling coils and  
364 VAV devices to locally adjust the supply air temperature. However, the control volume considered  
365 in this work excludes the local VAV devices.

366 Figure 2 shows a schematic configuration of the system with the indication of the monitored variables  
367 (a description of the variables is provided in Table 2).

368 In the context of the ASHARE project, a number of different faults were implemented one per time,  
369 each for a whole day, only in the AHU-A, in order to analyse independently the effects of each fault.

370 The AHU-B was always run in fault-free conditions to have a reference of the normal operation. The  
371 data collection was conducted over three seasons and only the monitoring data of the summer season  
372 were considered in this study.

373 *Table 1. Tags and descriptions of faults.*

| <b>Fault Tag</b> | <b>Description</b>                    | <b>Number of days</b> |
|------------------|---------------------------------------|-----------------------|
| CCVS15           | Cooling coil valve stuck at 15%       | 1                     |
| CCVS65           | Cooling coil valve stuck at 65%       | 1                     |
| CCVSFC           | Cooling coil valve stuck fully closed | 1                     |
| CCVSFO           | Cooling coil valve stuck open         | 1                     |
| EASFC            | Exhaust air damper stuck fully closed | 1                     |
| EASFO            | Exhaust air damper stuck fully open   | 1                     |
| Normal           | Normal operation                      | 22                    |
| OAS45            | Outdoor air damper stuck 45%          | 1                     |
| OAS55            | Outdoor air damper stuck 55%          | 1                     |
| OASFC            | Outdoor air damper stuck fully closed | 1                     |
| RFCF             | Return fan complete failure           | 1                     |
| RFF30            | Return fan at fixed speed (30%)       | 1                     |

374

375 The dataset consists of multiple time series (one for each monitored variable) with a length of 33 days  
376 and a sampling time of 1 minute. In particular, 22 out of 33 days are tagged as fault-free days while  
377 the remaining 11 days correspond to different faulty conditions. Table 1 summarizes the number of

378 fault-free and faulty days, the description of each fault and the tags used for labelling each day  
379 included in the monitoring campaign.

380 A feature selection was preliminarily performed on the basis of expert considerations to focus the  
381 analysis only on relevant variables.

382 As a result, the variables considered for the implementation of the FDD methodology are: the  
383 electrical load, the pressure drop and speed of fans, the flow rate and temperature of the air measured  
384 in different parts of the system, the damper position, the valve position, the water flow rate and energy  
385 transferred in the cooling coil.

386 Table 2 reports the list of the 23 variables considered for the analysis, together with the specification  
387 of labels, description, ID number and unit of measurement for each variable.

388 *Table 2. List of variables considered in the analysis.*

| Variable | Description                           | ID<br>n° | Unit              |
|----------|---------------------------------------|----------|-------------------|
| SF_WAT   | Supply fan power                      | 1        | W                 |
| RF_WAT   | Return fan power                      | 2        | W                 |
| SA_CFM   | Supply air flow rate                  | 3        | m <sup>3</sup> /h |
| RA_CFM   | Return air flow rate                  | 4        | m <sup>3</sup> /h |
| OA_CFM   | Outdoor air flow rate                 | 5        | m <sup>3</sup> /h |
| SA_TEMP  | Supply air temperature                | 6        | °C                |
| MA_TEMP  | Mixed air temperature                 | 7        | °C                |
| RA_TEMP  | Return air temperature                | 8        | °C                |
| HWC_DAT  | Heating coil air temperature          | 9        | °C                |
| CHWC_DAT | Cooling coil air temperature          | 10       | °C                |
| SF_DP    | Supply fan pressure drop              | 11       | Pa                |
| RF_DP    | Return fan pressure drop              | 12       | Pa                |
| SF_SPD   | Supply fan speed                      | 13       | %                 |
| RF_SPD   | Return fan speed                      | 14       | %                 |
| OA_TEMP  | Outdoor air temperature               | 15       | °C                |
| CHWC_EWT | Cooling coil input water temperature  | 16       | °C                |
| CHWC_LWT | Cooling coil output water temperature | 17       | °C                |
| CHWC_GPM | Cooling coil water flow rate          | 18       | m <sup>3</sup> /h |
| E_ccoil  | Cooling coil power                    | 19       | kW                |
| CHWC_VLV | Cooling coil valve position           | 20       | %                 |
| EA_DMPR  | Exhaust air damper position           | 21       | %                 |
| OA_DMPR  | Outdoor air damper position           | 22       | %                 |
| RF_SST   | Return fan start/stop signal          | 23       | -                 |

389

390 For the application of the proposed methodology, the data sample was split into two datasets. The  
391 first one was used for the characterization of the normal operating condition of the system, while the  
392 latter was used for the fault detection and diagnosis. The first dataset is composed of 20 days tagged  
393 as “Normal” (training dataset), while the second by the rest of the days including 2 “Normal” days  
394 and 11 “Faulty” days (testing dataset).

## 395 **4 Description of the data analysis methods**

396 In this section, the overview is presented of the techniques used for the proposed FDD methodology,  
397 describing their main features in relation to the FDD problem under investigation.

### 398 **4.1 Adaptive symbolic aggregate approximation**

399 The Symbolic Aggregate approXimation (SAX) is a temporal abstraction technique capable to reduce  
400 the dimension of a time series of length  $n$  in a time series of length  $m$  with  $m < n$ , and to transform it  
401 in a symbolic string. The reduction of the time series is performed through a Piecewise Aggregate  
402 Approximation (PAA), which segments the time axis in equally sized non-overlapping time windows  
403 (i.e., aggregation intervals). The PAA approximates the original time series replacing the values  
404 within the same aggregation interval with their mean value.

405 The transformation of the time series is then performed by substituting the values of the PAA with  
406 symbols. To this purpose, the y-axis is discretized in a pre-defined number of regions and a symbol  
407 is associated to each of them. Lin et al. in [46] proposed a simple procedure to perform the SAX,  
408 employing a Z-score transformation ( i.e.,  $Z(t) = \frac{x(t) - \mu}{\sigma}$  where  $\mu$  is the mean value of the sample  
409 and  $\sigma$  the standard deviation) before the data reduction and identifying the desired range of each  
410 symbol assuming a-priori a Gaussian distribution of data.

411 A variation of SAX technique, called adaptive Symbolic Aggregate approXimation (aSAX), was  
412 proposed in the literature [45] in order to improve the quality of the discretization in the case of non-  
413 normal distribution of data. The adaptive symbolic aggregate approximation introduced by Pham et

414 al. [45] is based on the original SAX method, but an adaptive process is used for the identification of  
415 breakpoints (i.e. the position of boundaries of each symbol range). The position of the adaptive  
416 breakpoints is evaluated through a univariate clustering procedure, that minimises the total  
417 representation error after the SAX transformation.

418 In this paper, the aSAX algorithm has been employed to improve the results of the automated and  
419 unsupervised discretization process, which represents the most important analysis for ensuring the  
420 robustness of the “event” extraction from time series.

## 421 4.2 Temporal Association Rules Mining

422 Association Rule Mining (ARM) is an unsupervised data mining method for identifying all  
423 associations and correlations between attribute values in a set of categorical/discretized data [47]. The  
424 output is a set of association rules that are used to represent patterns of attributes that are frequently  
425 associated together (i.e., frequent patterns).

426 Let  $I = \{i_1, i_2, \dots, i_d\}$  be the set of all items in a dataset and  $D = \{d_1, d_2, \dots, d_d\}$  be the set of all  
427 transactions. Each transaction  $d_i$  contains a subset of items chosen from  $I$ . In association analysis, a  
428 collection of items is named *itemset* and the transaction width is defined as the number of items  
429 present in a transaction. A transaction  $d_j$  contains an itemset  $X$  if  $X$  is a subset of  $d_j$ . An important  
430 property of an itemset is its support count, that corresponds to the number of transactions that contain  
431 a specific itemset. The support count,  $\sigma(X)$ , for an itemset  $X$  can be expressed as follows [47] (eq.1)

$$432 \quad \sigma(X) = |\{d_i | X \subseteq d_i, d_i \in D\}| \quad (1)$$

433 Association rules are usually represented in the form  $X \rightarrow Y$ , where  $X$  (also called antecedent) and  
434  $Y$  (also called consequent) are disjoint item sets (i.e.,  $X \cap Y = \emptyset$ ). Rule quality is usually measured  
435 through rule support and confidence. Rule support is the fraction of the total number of transactions  
436 in which both the item sets  $X$  and  $Y$  occur while confidence determines how frequently items in  $Y$

437 appear in transactions that contain X. According to [47], Support  $s(X \rightarrow Y)$  and Confidence  $c(X \rightarrow Y)$   
438 can be calculated with the following equations (eq. 2 and 3):

$$439 \quad \text{Support, } s(X \rightarrow Y) = \frac{\sigma(X \cup Y)}{N} \quad (2)$$

$$440 \quad \text{Confidence, } c(X \rightarrow Y) = \frac{\sigma(X \cup Y)}{\sigma(X)} \quad (3)$$

441 where N is the total number of transactions. Therefore, given a dataset D, the generic record of which  
442 is a set of items, an ARM process discovers all association rules with support and confidence greater  
443 than, or equal to, minimum thresholds defined a-priori by the analyst (i.e, MinSup and MinConf).

444 In the context of discrete-value-transactions, association rules can be used as an efficient method for  
445 mining co-occurrences or implications also between events in the time domain (Temporal Association  
446 Rule Mining (TARM)). TARM is an extension of sequential pattern mining, which is an important  
447 data mining method with broad applications, capable to extract frequent itemset sequences while  
448 maintaining their order. Many sequential pattern mining algorithms, such as GSP [48], PrefixSpan  
449 [49,50], SPADE [51], and SPAM [52], have been proposed. However, those sequential pattern mining  
450 algorithms consider only the itemset occurrence order, but do not consider the time intervals between  
451 successive item sets (temporal constraint of event association). To that purpose, in the literature  
452 several sequential pattern mining algorithms were proposed, to deal with the extraction of sequential  
453 patterns considering the existence of interval between item sets (in terms of item gap and time  
454 interval) [53–56]. Such algorithms extract rules, satisfying not only user-specified minimum support  
455 constraints, but also user-specified gap constraints. The minimum and maximum gap values should  
456 be defined as constraints by the user. For those rules, the search space in the time domain is  
457 represented by a sliding window, the length of which is set in advance by the analyst. In detail, this  
458 kind of rules can be represented in the following form:  $X \xrightarrow{t} Y$ . Therefore, the occurrence of the  
459 antecedent itemset X implies the occurrence of the consequent itemset Y within a time  $t$ .

460 In this paper, the extraction of temporal association rules is performed by means of the cSpade,  
 461 algorithm based on [51]. The algorithm was implemented in R [69], including the rule extraction  
 462 phase which was performed by using the “cSpade” function of the “arules” package [70].  
 463 That algorithm extracts sequential rules, considering some constraints defined by the user according  
 464 to his/her needs. The constraints may drive the mining of frequent patterns from the database of  
 465 transactions, for instance by setting the length of the sliding window, or a minimum time gap between  
 466 antecedent and consequent of the rules.

467 However, since the database of transactions considered in the present study is generated by using a  
 468 sample-by-sample sliding window approach, the number of the transactions  $N$  results to be very high  
 469 with items mostly overlapped. For this reason, the calculation of rule support  $s(X \rightarrow Y)$  cannot be  
 470 performed with the canonical formulation. In fact, the value of support  $s(X \rightarrow Y)$  calculated according  
 471 to eq. 2 can be affected by the high value of the denominator (i.e., the total number of transactions),  
 472 suggesting the use of a formulation less sensitive to the sample size [57].

473 In this study, according to [58], the support of an association rule is defined as the ratio between the  
 474 number of transactions that include both antecedent and consequent, and the number of transactions  
 475 that include at least the consequent itemset (eq. 4).

$$476 \quad \text{Support, } s(X \rightarrow Y) = \frac{\sigma(X \cup Y)}{\sigma(Y)} \quad (4)$$

477 The support calculated with eq. 4 has the denominator dramatically lowered in comparison to the one  
 478 in eq. 2 and makes it possible to have high values of support also for large transaction datasets,  
 479 obtained through a sliding window. The support calculated through Eq. (4) assesses the frequency of  
 480  $X \cup Y$  on a smaller portion of the total number of transactions (i.e., only the transactions that include  
 481 the consequent itemset  $Y$ ). The support is in the range (0-1) and allows an easier extraction of rules  
 482 to be assumed as reference patterns (i.e., with high support) of the occurrence of a specific condition  
 483 over time (i.e., consequent itemset  $Y$ ). However, the confidence can be still calculated according to

Eq. (3) only if the consequent itemset  $Y$  occurs in a transaction not violating the chronological order respect to the antecedent itemset  $X$ .

In general, the mining of association rules can be summed up as a two-step's procedure. In a first phase, the frequent itemset with a support greater than the MinSup are extracted, then the confidence is considered for filtering out rules that consist in weak implications [59]. In this paper, the same two-steps procedure is followed but additional metrics are also considered in the rule filtering phase (as discussed in section 5.3).

### 4.3 Classification And Regression Tree

Decision trees are machine-learning algorithms that are used to develop descriptive and/or predictive models from a collection of records. Each record can be expressed as a tuple  $(\mathbf{x}, y)$ , where  $\mathbf{x}$  represents the explanatory attribute set while  $y$  is the target attribute. The type of target attribute is the key factor that distinguishes classification from regression trees (i.e. discrete attribute in the first case and continuous attribute in the second one) [47]. In this work, the Classification And Regression Tree (CART) algorithm, based on recursive partitioning algorithm [60], has been selected to conduct a predictive modelling task, as it is able to easily handle categorical attributes as both explanatory and target attributes. The CART is a specific machine learning technique that is based on a recursive binary splitting of the whole feature space into finite disjoint sets, and its output can be translated into a hierarchical tree structure composed by nodes and directed edges (i.e., branches). The leaves (i.e., final nodes) represent the predicted class labels of the target attribute, while the branches represent the conjunctions of the explanatory attributes that lead to the class labels

The development of a classification tree unfolds over two steps: training and testing of the model.

Each decision tree developed has been pruned following a cost-complexity approach and validated through a k-fold cross validation process as explained in [61]. The development of a classification tree unfolds over two steps: *training* and *testing* of the model. Firstly, all the records are grouped in

508 the root node and the CT algorithm iteratively evaluates the best partitioning of the dataset, using the  
509 explanatory attribute that minimises the average impurity measure (e.g., Gini index, Entropy) of the  
510 child nodes after each split. If no stopping rules are set by the analyst, the classification tree grows  
511 continuously until the impurity in the leaf nodes of the target variable is zero. In order to avoid this  
512 condition of model overfitting, various types of appropriate early stopping criteria can be set in  
513 advance by the analyst (e.g., minimum number of cases in parent and child nodes, maximum tree  
514 depth, minimum reduction in node impurity after splitting). Even when the early stop criteria have  
515 been satisfied, the tree may continue to be quite large and/or complex completely losing its  
516 interpretability. For this purpose, it is possible to define a cost-complexity parameter ( $cp$ ) during the  
517 model validation phase, for optimising the trade-off between the cost of misclassification and the tree  
518 complexity. Therefore, the  $cp$  allows the analyst to set the right tree size by pruning branches and leaf  
519 nodes that do not significantly increase the model performance.

520 Starting from the fully grown tree, the cost-complexity pruning procedure is repeated iteratively, and  
521 smaller and smaller subtrees are found until the root node is reached. At the end of the iterations, the  
522 final pruned tree can be evaluated by plotting the relative errors of the subtrees versus their  $cp$  values.  
523 This kind of plot usually shows an initial sharp drop, followed by a relatively flat region. When the  
524 decision tree is subject to a validation procedure (e.g., k-fold cross-validation), it is also possible to  
525 compute a standard error for each relative error of the sub-tree. The choice of the best subtree starts  
526 from the flat region of the subtree errors that includes the minimum cross validated error that has  
527 been achieved. In fact, the values falling within one standard error of the achieved minimum risk (i.e.,  
528 1-SE rule) identify statistically equivalent sub-trees [60]. The simplest model (with the minimum  
529 number of final nodes) of all the identified sub-trees in the flat region is then chosen.

530 K-fold cross-validation has been used in this paper. For this kind of method, the original sample  
531 of data with  $M$  objects is divided into  $k$  equal sized subsamples. A single subsample is selected for  
532 the evaluated  $k$  subsamples as a validation dataset for testing the model, and the remaining  $(k-1)$



533 subsamples are used for the training. This process is then repeated  $k$  times, using a subsample at a  
534 time for the testing

535 In this paper, all the classification trees developed for extracting decision rules have been subjected  
536 to the previously described procedure of validation and pruning (as discussed in section 5.4).

## 537 **5 Methodological framework of analysis**

538 The methodology relies on the application of both supervised and unsupervised algorithms to perform  
539 robust fault detection and diagnosis in AHUs.

540 The framework unfolds over different stages as shown in Figure 3. Two different analytics modules  
541 are proposed for developing an FDD tool tailored for both transient and non-transient conditions of  
542 the AHUs operation. For that purpose, in the methodological framework, a data segmentation phase  
543 is preliminarily carried out in order to split the data according to the regime of operation they belong  
544 to (i.e. transient or non-transient). In the following sections the pre-processing analysis, applied to the  
545 entire dataset, and the two analytics modules, tailored for transient and non-transient periods,  
546 respectively, are then described.

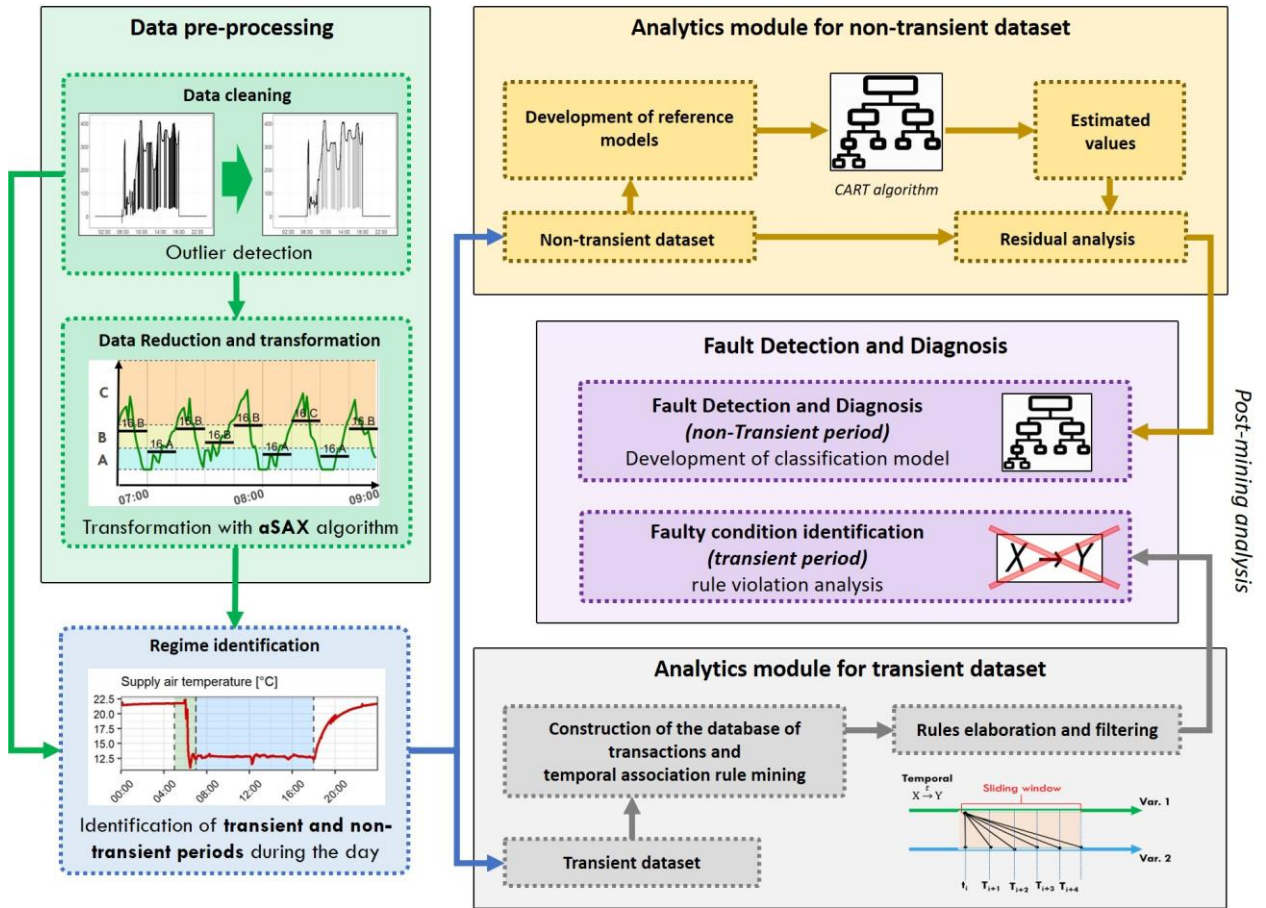


Figure 3. General framework of the analysis.

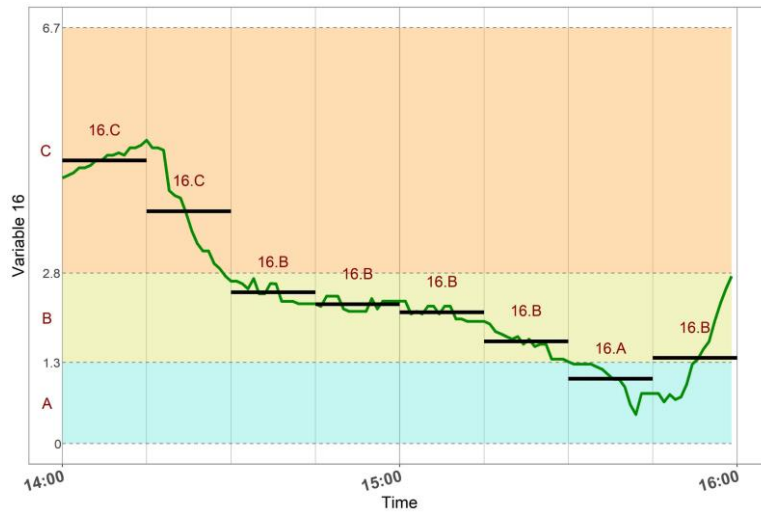
## 5.1 Data pre-processing stage

The pre-processing stage consists of three main tasks i.e., cleaning, reduction and transformation, typically accomplished for preparing the data sets. In detail, outlier detection and replacement are firstly performed (for each time series) by using the Hampel filter method [62]. For each data point in the time series, the algorithm computes the median of a window that includes the considered data point and its  $k$  surrounding samples. If a data point differs from the median by more than a standard deviation, it is tagged as a statistical outlier and replaced with the median.

The monitoring data were available in time-series with a sampling time of 1-minute, which would make the analysis onerous to be performed. For this reason, in a successive step a data reduction and transformation process is performed by means of the adaptive Symbolic Aggregate Approximation (aSAX) method [45]. This algorithm is employed for reducing the time series through a piecewise

560 technique aggregating data with a fixed length window from 1 minute to 15 minutes and then for  
561 transforming it into a symbolic string. The objective is to maximise data compression and minimise  
562 the complexity of the time series while preserving important information. The symbolic  
563 representation of time series is always subjected to information loss due to the piecewise aggregate  
564 approximation (especially information about the slope). However, when the segments are encoded in  
565 symbols it is possible to preserve qualitative information about global trends of the time series, and  
566 to easily detect important changes of patterns over time.

567 Figure 4 reports an example of data reduction and transformation through aSAX algorithm for a  
568 portion of the time series related to the variable encoded with the ID n° 16 according to Table 2 (i.e.,  
569 *cooling coil input water temperature* (CHWC\_EWT)). The figure shows the time series after the  
570 application of the Hampel filter (green curve) and the time series in form of constant approximated  
571 piecewise (black lines). Furthermore, Figure 4 also shows the result of the aSAX transformation of  
572 the time series into a symbolic string. The variable can assume three discrete values encoded with the  
573 symbols 16.A, 16.B or 16.C according to the region the piecewise segments of 15-min fall in.



574  
575 *Figure 4. Example of aSAX transformation for a numerical variable.*

576 The obtained symbol sequence is 16.C-16.C-16.B-16.B-16.B-16.B-16.A-16.B from which it is  
577 possible to infer that the original time series is characterized by changes in the pattern at times 14:30,  
578 15:30, 15:45, that in this work are intended as events.

579 As a result, time series are transformed in discrete-time discrete-value sequences of equidistant  
580 symbols making it possible to extract events from them.

581 **5.2 Regime identification**

582 At this stage, a regime identification is performed on a daily scale, to detect when transient and non-  
583 transient conditions typically occur during the AHU operation.

584 To that purpose, an automatic regime detector is used to identify the transient period and separate it  
585 from the non-transient one. The details of the detector used are the same as that reported in [16][63].

586 The transient identification is performed on data with sampling time of 1 minute, specifically  
587 analysing the *cooling coil valve position* (CHWC\_VLV), the *supply air temperature* (SA\_TEMP),  
588 *supply fan speed* (SF\_SPD) and the supply air static pressure. Then, the frequency of transient data  
589 points during the day is evaluated for each 15-min aggregation interval, derived from the data  
590 reduction phase (Figure 5). Thanks to that analysis, it is possible to establish during which  
591 aggregation interval, out of the reduced (15-min-long) daily time series, a transient condition has the  
592 highest frequency of occurrence.

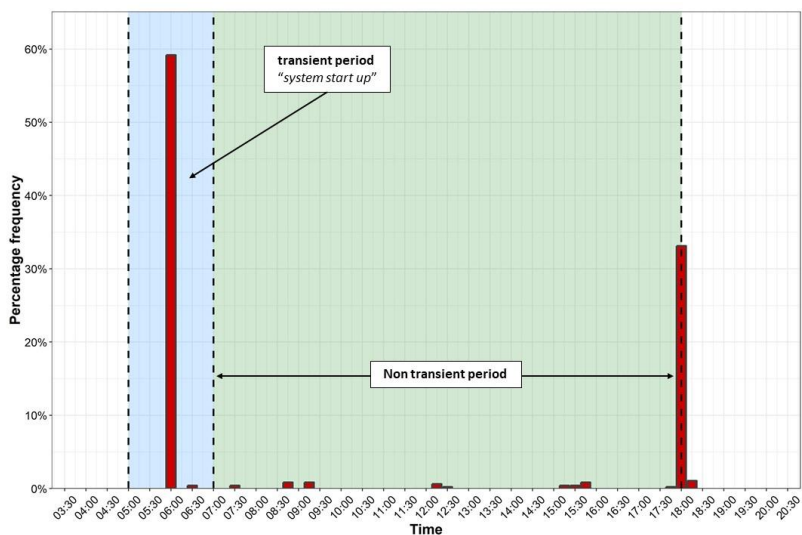


Figure 5. Identification of the transient period.

595 Starting from such aggregation interval of 15 min, the transient period is evaluated considering a time  
596 window of two hours (i.e., blue area of the plot) that includes one hour before and later the aggregation  
597 interval considered (Figure 5).

598 As can be noticed from Figure 5, transients occur at the start-up and the shut-down of the AHU.  
599 Among the two transient periods, only the start-up transient is investigated in this paper because  
600 during that period the system dynamics affects the successive operation, while in the other case the  
601 system is thereafter turned off.

602 As a result, the non-transient period is supposed to start at the end of the start-up time interval and to  
603 end when the system is turned off.

604 Therefore, excluding the night hours, during which the AHU is certainly not operated, the dataset is  
605 segmented as follows:

- 606 • From 05:00 to 07:00: transient period labelled as “*system start-up*”;
- 607 • From 07:00 to 18:00: non-transient period.

608 In the following sections a tailored FDD methodology for each operation regime of the systems under  
609 analysis (i.e., transient, non-transient) is presented.

### 610 5.3 FDD methodology for the transient period

611 The main flow of FDD research reported in literature has been carried out in a steady-state approach  
612 [14,17,19,64,65], because the operating characteristics during this operation is relatively more  
613 credible and reproducible than in a transient state [64].

614 Transient data are characterised by great variation in the time domain and require specific data  
615 analytics algorithms to be employed to properly reflect the system dynamics. The herein proposed  
616 methodology provides, as a main added value to what was already present in literature papers, a  
617 tailored approach for such condition of operation.

618 An overall procedure is developed to obtain temporal association rules that are representative of  
619 frequent relationships between events in multiple time series, using a time window and a time lag.  
620 As discussed in Section 4.2 temporal association rules are an interesting extension of association rules  
621 that include a temporal constraint, which leads to different forms of IF-THEN implication over time.  
622 When an event leads to the occurrence of another event, there may be causal relationship or certain  
623 correlation between them. The corresponding mining purpose is to find out the reference fault-free  
624 association rules between events and time in a temporal transaction dataset, whose violation can  
625 suggest the presence of faulty conditions during the start-up period of the AHU system. The extraction  
626 makes it possible to find those sequences of events that appear many times among monitored fault-  
627 free days and have a high rate of occurrence (i.e., reference rules).  
628 The reference association rules have been searched in the 20 days tagged as fault-free (training  
629 dataset) while the remaining 2 fault-free days and 11 faulty days (testing dataset) were used in the  
630 successive fault detection phase.

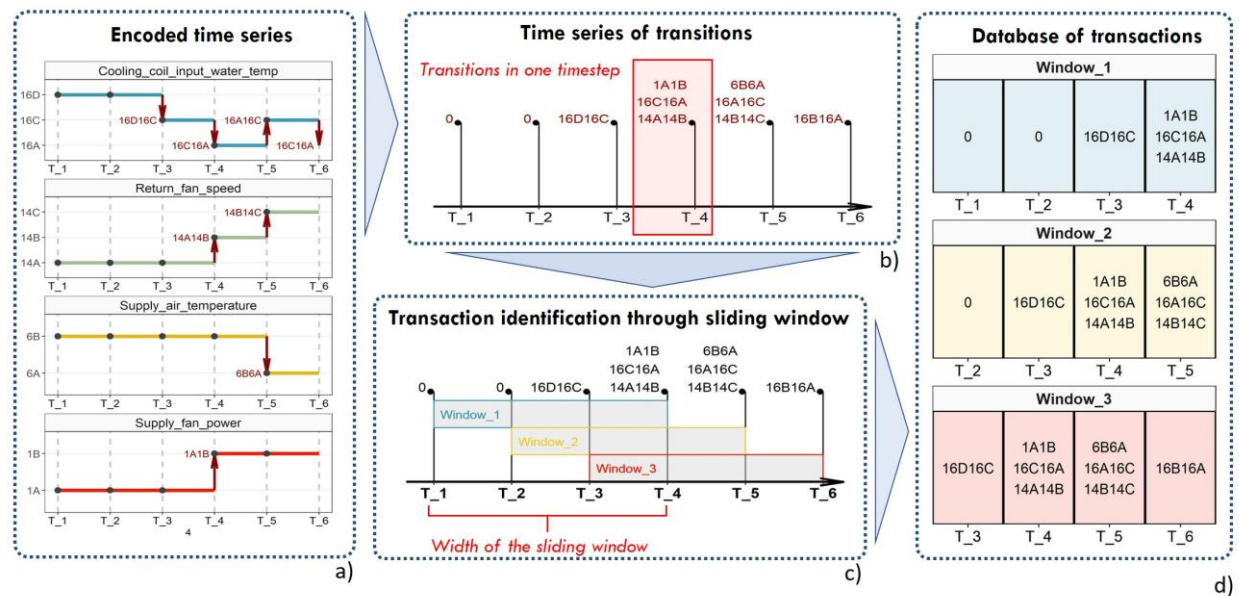


Figure 6. Procedure for the construction of the database of transactions.

633 Before extracting reference temporal association rules from data, it is necessary to create the database  
634 of transactions T following the framework shown in Figure 6.

635 The first step consists of putting together all the transitions that occur in each time series into a unique  
636 multivariate time series of transitions.

637 In particular, according to the symbolic transformation performed during the pre-processing stage a  
638 transition in a time series is a kind of event that corresponds to the change of symbol (i.e., encoded  
639 discrete values of the variable) in a specific timestep across two consecutive aggregation intervals.

640 As an example, Figure 6 (a) shows six timesteps of four time series (i.e., *cooling coil input water*  
641 *temperature* (CHWC\_EWT), *return fan speed* (RF\_SPD), *supply air temperature* (SA\_TEMP), *supply*  
642 *fan power* (SF\_WAT)). The time series *supply fan power* (SF\_WAT) corresponds to the operation  
643 variable of the AHU encoded with the ID n° 1 and assumes only two discrete values (encoded with  
644 the symbols 1A and 1B) along the six timesteps considered. In the same way the time series *return*  
645 *fan speed* that corresponds to the operation variable of the AHU encoded with the ID n° 14, assumes  
646 three discrete values (encoded with the symbols 14A, 14B and 14C) among the six timesteps. If two  
647 consecutive aggregation intervals are encoded with the same symbol, no transition (i.e., event) is  
648 detected. Otherwise, during a specific timestep, a transition (i.e., event) is encoded reporting the ID  
649 n° of the variable and the two symbols included in the change of discrete value. For example,  
650 according to Figure 6 (a), at the first timestep T\_1 for any time series, a transition does not occur and  
651 then 0 is stored in the time series of transitions (Figure 5 (b)). On the contrary, at the fourth timestep  
652 T\_4, a transition occurs for the time series 1, 14 and 16. In particular, for time series 1 and 14, occurs  
653 a change from symbol “A” to symbol “B” (events encoded as “1A1B” and “14A14B” respectively)  
654 while for time series 16 the variable changes symbol from “C” to “A” (event encoded as “16C16A”).

655 Once the encoded events are stored in the multivariate time series of transitions (Figure 6b), the  
656 database of transactions is constructed by chunking this time series considering a fixed-length sliding  
657 time window (Figure 6 (c)). Figure 6 (d) shows how the encoded transitions for each timestep are  
658 stored in the database of transactions. For example, assuming a sliding window that includes four  
659 timesteps, the database T can be represented by a  $4 \times n$  transition matrix where n corresponds to the  
660 maximum number of sliding windows which can be contained in the time series of transitions.



661 Considering that the time windows are sliding a timestep by time, two consecutive rows in the  
662 database T (Figure 6 (d)) differ only for a single item. As a reference considering a time series of  
663 transitions with 6 timesteps and a sliding window that includes 4 timesteps, the database of  
664 transactions is a  $4 \times 3$  transition matrix given that the maximum number of complete time windows  
665 is equal to 3 (Figure 6 (d)). After the construction of the database T, the temporal association rules  
666 are searched among transactions.

667 The cSpade algorithm [51] has been selected for the extraction of the rules from the inter-transactional  
668 database, setting in advance three fundamental parameters: minimum confidence, minimum support,  
669 and maximum time lag between antecedent and consequent item sets (equal to the sliding window  
670 length).

671 According to the proposed methodology, the first two parameters (i.e., confidence and support)  
672 should be as high as possible, to ensure that the extracted rules are much frequent as possible and  
673 then representative of the normal behaviour of the system.

674 Once the reference rule set has been identified, it is used for detecting the presence of potential faults  
675 in a testing dataset.

676 In particular, a temporal association rule is expressed as a logical IF-THEN implication where the  
677 presence of an event (i.e., antecedent) implies the occurrence of another event (i.e., consequent)  
678 within a certain time lag. According to this formulation, three potential violations can occur when  
679 such rules are applied on a testing set of data:

- 680 i) absence of the antecedent itemset,
- 681 ii) absence of consequent itemset,
- 682 iii) absence of antecedent and consequent item sets.

683 In that perspective, the violation analysis helps physical interpretation of rules making it possible to  
684 assess their sensitivity to the presence of specific faults or group of them.



685 In section 6.2, the results of the transient methodology herein described are presented and discussed  
686 providing further details about the setting of the input parameters and the post-processing of the  
687 extracted association rules.

## 688 5.4 FDD methodology for the non-transient period

689 The methodology employed for performing the FDD analysis during non-transient period relies on  
690 three fundamental phases that can be generalized as follows:

- 691 • Development of reference models through classification trees, representative of the normal  
692 behaviour (fault-free condition) of the system under analysis;
- 693 • Comparison between the estimated behaviour of the system and the actual one (i.e., evaluation  
694 of model residuals) for detecting potential faulty conditions;
- 695 • Analysis of the model residuals for diagnosing the most probable cause associated to a specific  
696 fault (fault diagnosis).

697 The first step of the process consists of a robust characterization of the fault free operation of the  
698 AHU during the non-transient period (i.e., from 07:00 to 18:00). To this purpose, several estimation  
699 models (i.e., classification trees) have been developed on a portion of the available non-transient  
700 dataset. In detail 20 days tagged as fault-free were considered at this stage (training dataset) while the  
701 remaining 2 fault-free days and 11 faulty days (testing dataset) were used in the successive diagnostic  
702 phase.

703 For the development of the estimation models (i.e., classification trees), all the variables related to  
704 the operation of the AHU (e.g., *supply fan power* (SF\_WAT), *return fan power* (RF\_WAT), *supply*  
705 *air flow rate* (SA\_CFM)) have been selected once at a time as target attribute while the remaining  
706 ones have been used as input attributes. However, features related to external forcing variables to the  
707 AHU system (i.e., *cooling coil input water temperature* (CHWC\_EWT), *outdoor air temperature*  
708 (OA\_TEMP)) have been used only as input attributes.

709 In that way, 21 classification trees are developed for providing a robust benchmark of the fault-free  
710 operation. To that purpose, a CART algorithm is employed as a supervised classifier in the study.  
711 The developed classification trees estimate for each target variable and for each 15-min aggregation  
712 interval included in the non-transient period the most probable discrete value (encoded as symbol)  
713 according to the relationship that exists between all the input variables and the dependent attribute.  
714 Successively all the classification trees developed are put together in the same estimation layer as  
715 shown in Figure 7. At this stage, the estimation process can be summarized as follow<sup>s</sup>:

- 716 • At each aggregation interval (i.e., 15 min.) the monitored variables are encoded into symbols  
717 through the aSAX method (i.e., pre-processing stage);
- 718 • The set of encoded variables goes through the estimation layer (that consists of 21  
719 classification trees) providing an estimation of each target variable for the considered  
720 aggregation interval;
- 721 • The actual symbols are compared with the estimated ones.

722 The latter step consists in the evaluation of the model residuals.

723 In this study, the difference between two equal symbols is assumed to be zero, while the residual  
724 differs from zero if the symbols are at least one alphabet apart. For example, if the estimated and  
725 actual symbol for a variable is equal to “A” and “B” respectively, the residual between those symbolic  
726 discrete-values is equal to 1 (Figure 7).

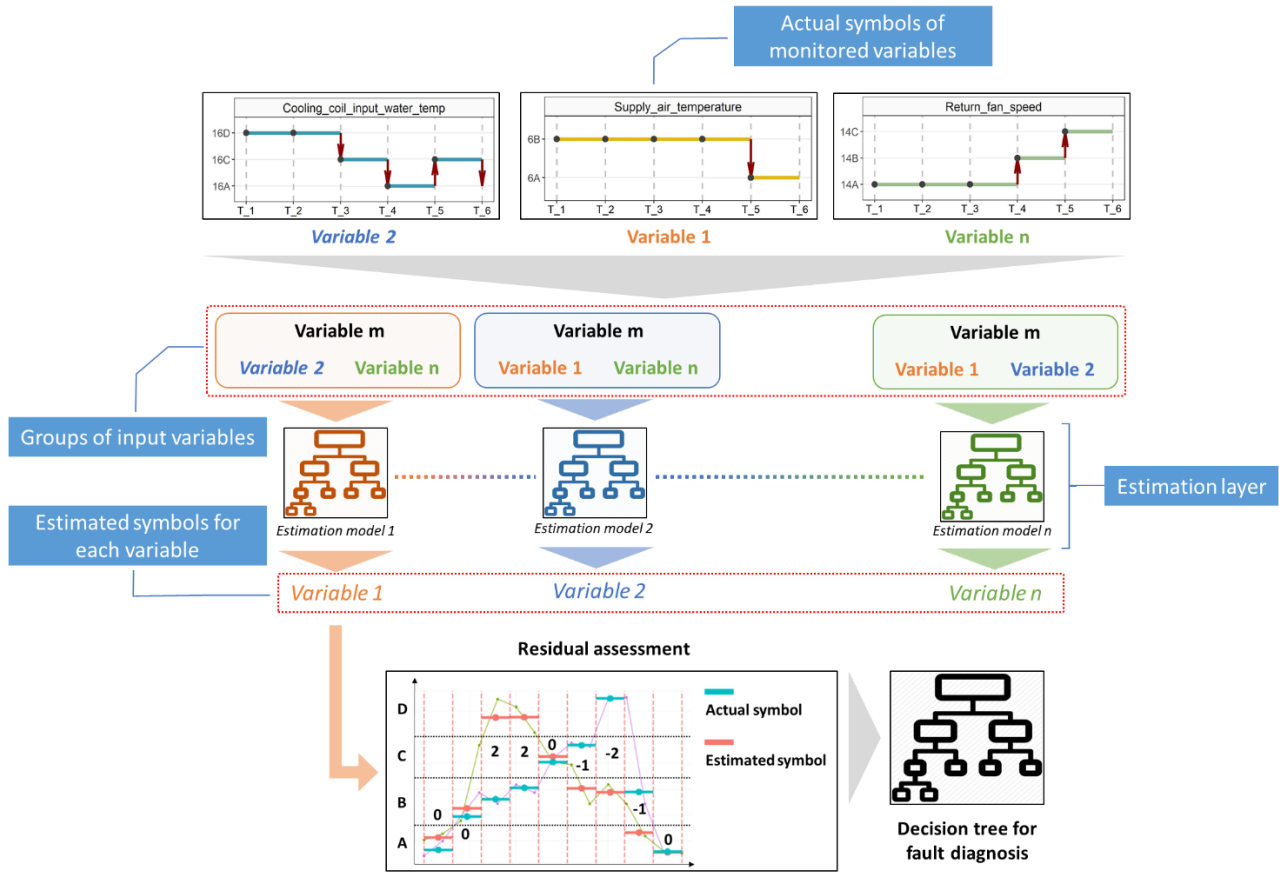


Figure 7. Analytics module for the non-transient period.

Considering that the estimation models are trained on fault-free data, at the end of the estimation process it is possible to assess how much the input data differ from the reference fault-free behaviour of the AHU through the analysis of residuals. Understanding which variables are out of range and assessing the severity of those deviations enables the detection of possible faulty conditions. In order to test this FDD procedure, all the days excluded from the training set of the reference models (i.e., 2 fault-free days and 11 faulty days) have been considered. In particular, each day included in the testing dataset is labelled as “Normal” or with the tag of one of the faults reported in Table 1.

The time series of the 13 days are pre-processed (aggregated in intervals of 15-min and encoded in symbols) and put through the estimation layer (i.e., 21 classification trees) generating a dataset of residuals as shown in Figure 8. At this stage, a further classification tree has been developed to predict the label of each faulty or normal condition (Figure 8) for performing the fault diagnosis. This classification tree estimates the most probable label (e.g., CCVSFC, EASFC, RFCF or Normal) according to the residuals evaluated for each variable as an outcome of the estimation layer.

| Aggregation interval | Day | Variable 1 Residual | Variable n Residual | Variable 21 Residual | Fault label |
|----------------------|-----|---------------------|---------------------|----------------------|-------------|
| 15:00 – 15:15        | 1   | 0                   | ...                 | 0                    | Normal      |
| 15:15 – 15:30        | 1   | 0                   | ...                 | 0                    | Normal      |
| 15:30 – 15:45        | 1   | 0                   | ...                 | 0                    | Normal      |
| ...                  | ... | ...                 | ...                 | ...                  | ...         |
| 15:00 – 15:15        | 5   | 1                   | ...                 | 3                    | CCVSFC      |
| 15:15 – 15:30        | 5   | 0                   | ...                 | -1                   | CCVSFC      |
| 15:30 – 15:45        | 5   | -2                  | ...                 | 0                    | CCVSFC      |
| ...                  | ... | ...                 | ...                 | ...                  | ...         |
| 15:00 – 15:15        | 10  | 2                   | ...                 | 1                    | EASFC       |
| 15:15 – 15:30        | 10  | 1                   | ...                 | 0                    | EASFC       |
| 15:30 – 15:45        | 10  | 0                   | ...                 | -2                   | EASFC       |
| ...                  | ... | ...                 | ...                 | ...                  | ...         |
| 15:00 – 15:15        | 13  | -3                  | ...                 | 1                    | RFCF        |
| 15:15 – 15:30        | 13  | 1                   | ...                 | -2                   | RFCF        |

Set of input variables of the classification tree
Target variable of the classification tree

Figure 8. Structure of the database used for developing the classification tree of fault diagnosis

In the dataset reported in Figure 8 the target variable is the fault tag, and the same tag is assigned to all of the 44 aggregation intervals of 15-min that belong to the same day (included in the 11 hours of “non transient” operation of the AHU from 7:00 to 18:00), generating a total amount of 572 instances on which develop the classifier. The present methodology exploits the CART algorithm for developing the decision trees since it proved to be a good choice for fault diagnosis [19][66].

As already mentioned above, in this paper the developed FDD tool is trained and tested on real data of an AHU operated in non-transient cooling mode for 33 non-consecutive days during the summer season (22 “normal” days and 11 “faulty” days). Note that the decision and association rules extracted through the proposed supervised and unsupervised approaches can be considered valid only for the operation mode under consideration. In this perspective, rule-based tools can be easily integrated in FDD process with hierarchical architecture capable to exploit only the useful knowledge during specific conditions. For instance, the use of automatic detector makes it possible to call specific sets of rules depending on the operating mode of the AHU: off mode, heating mode, free cooling mode, and mechanical cooling mode [67].

In Section 6.3, the results of the non-transient methodology herein described are presented and discussed providing further details about the performance, reliability and generalizability of the entire process.

## 6 Results

### 6.1 Pre-processing stage

According to the methodological framework introduced in Section 5, a data preparation stage was preliminarily implemented. Firstly, outliers were filtered out by implementing the Hampel filter on the 1-minute time series. For each data sample of the time series, the filter computes the standard deviation and the median of a window composed of the current sample and  $\frac{Len-1}{2}$  adjacent samples on each side of the current sample. *Len* is the window length and in this study is set equal to 31 minutes. A window with a length of 31 minutes could be not too much sensitive to the presence of outliers considering that the sample on which the standard deviation is computed is quite large. However, such window length proved to be suitable for identifying extremal values that certainly are related to problems of the sensing system. In the performed analysis, the filter does not take into account the first and the last  $(Len-1)/2$  data points of each daily time series. Such data points are always related to measurements during the hours when the AHU system is turned off (time intervals from 00:00 to 00:14 and from 23:45 to 23:59) and do not affect the results in any ways.

After data pre-processing (i.e., cleaning and replacement of outliers) a data reduction was performed by means of a PAA process with the aim of approximating the time series of each considered variable to the mean value calculated in non-overlapped time intervals with a fixed length of 15 min. The time interval length of 15 minutes was chosen as the best trade-off between approximation accuracy and data size reduction. Successively, the encoding of the reduced variables in symbols was carried out by implementing the aSAX algorithm [45].

The algorithm was initialised for each variable by identifying the number of symbols (i.e., discretization intervals) and the initial positions of the breakpoints (i.e., borders of the discretization intervals) with a hierarchical cluster analysis using the Ward linkage method [47]. Through the clustering algorithm, it was possible to obtain the optimal number of discretization intervals (i.e.,

number of symbols) by computing several cluster validation metrics. This process was completely automated and performed through Nbclust package [68] available in the statistical software R. The number of discretization intervals was constrained from 2 to 4 considering only data referred to the period of operation of the system (i.e., ON-hours of the system).

When the optimal positions of the adaptive breakpoints were found and each variable was encoded in symbols, the operation conditions of the AHU were considered fully characterised. Then, the data related to OFF-hours of the system operation were analysed to find possible additional intervals. In particular, if during OFF-hours a variable typically assumes values that are out of the identified ranges of discretization, a new lower or upper half-open interval was appended to the previous ones.

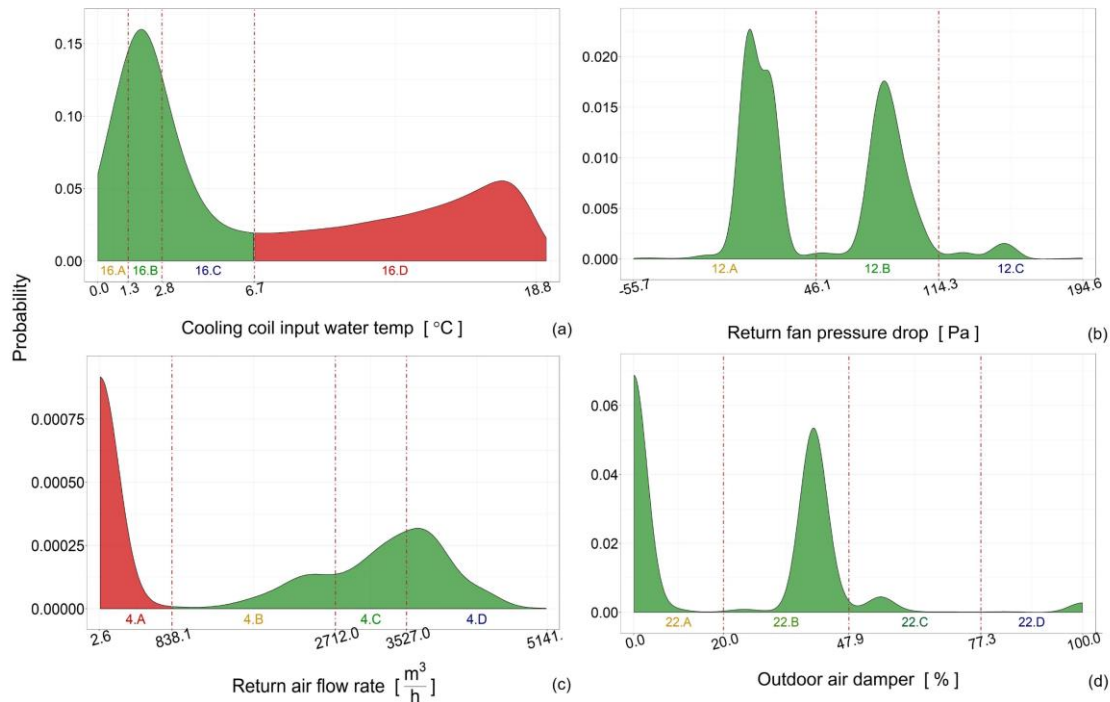


Figure 9. Distributions and breakpoint identification for some variables.

Figure 9 shows the encoding process performed for 4 variables (i.e., *cooling coil input water temperature* (CHWC\_EWT), *return fan pressure drop* (RF\_DP), *return air flow rate* (RA\_CFM), *outdoor air damper position* (OA\_DMPP)) randomly selected from the set of inputs. It can be observed that for two variables an additional OFF-hours discretization interval (i.e., red area of the distributions in Figure 9 (a) and (c)) was added to the other ranges of values for the symbol encoding (i.e., ID  $n^{\circ} = 16$ , symbol = D and ID  $n^{\circ} = 4$ , symbol = A).

802 As a reference, Table A in Appendix A summarizes the transformation results obtained, with the  
803 specification of the numerical range corresponding to each symbol for all the analysed operational  
804 variables.

805 At this stage, according to the procedure described in Section 5.2, transient and non-transient periods  
806 were identified and the data set was consequently segmented. In particular, the time interval between  
807 5:00 and 7:00 was labelled as transient start-up period, while the period from 7:00 to 18:00 was  
808 considered as non-transient period. The results obtained from the application of the methodological  
809 framework are in the following presented and discussed separately for transient and non-transient  
810 periods.

## 811 6.2 Fault detection analysis for the transient period (system start-up)

812 According to the methodological process introduced in section 5, the encoded time series were  
813 analysed for extracting temporal association rules in the start-up period of system operation. In detail,  
814 the transitions of the variables (i.e., change from a symbolic discrete-value to another one) were  
815 preliminarily encoded and the inter-transactional database was created considering a sliding window  
816 of 60 minutes. The width of the sliding window was chosen to be large enough to include any effect  
817 of the system dynamics, but tight enough to ensure that the occurrence of a consequent itemset was  
818 related to a physics-based implication with its antecedent itemset.

819 Considering that the fault detection methodology was conceived for extracting reference association  
820 rules of normal operation, the inter-transactional database was created from the fault-free dataset, by  
821 selecting rules with high values of support and confidence.

822 Typically, the main issue related to association rules mining consists in handling and filtering the  
823 large number of rules extracted and eventually identify those that are of interest [20]. To tackle this  
824 problem and facilitate the mining of useful knowledge from extracted rules, a post-mining phase was  
825 performed.

826 The post-mining phase was aimed at solving various practical issues, such as interestingness,  
827 redundancy, generalization, visualization and interpretability of association rules.  
828 To this purpose, additional quality metrics were introduced: the daily support of the rule (i.e.  
829 SUPP.DAY) calculated for both fault-free (SUPP.DAY<sub>NORMAL</sub>) and the faulty days  
830 (SUPP.DAY<sub>FAULTY</sub>) and the actual time lag between the antecedent and consequent of a rule  
831 (ACTUAL TIME LAG). In more detail, the SUPP.DAY<sub>NORMAL</sub> is defined as the percentage of fault-  
832 free days during which a single association rule ( $R_i$ ) occurred, while SUPP.DAY<sub>FAULTY</sub> is calculated  
833 for the faulty days (Eq. (5) and Eq. (6), respectively).

834

$$835 \quad SUPP.DAY_{NORMAL}, R_i = \frac{\text{N}^\circ \text{ of Free-fault days with of the occurrence of the rule } R_i}{\text{Tot. N}^\circ \text{ of Free-fault days}} \quad (5)$$

836

$$837 \quad SUPP.DAY_{FAULTY}, R_i = \frac{\text{N}^\circ \text{ of Faulty days with of the occurrence of the rule } R_i}{\text{Tot. N}^\circ \text{ of Faulty days}} \quad (6)$$

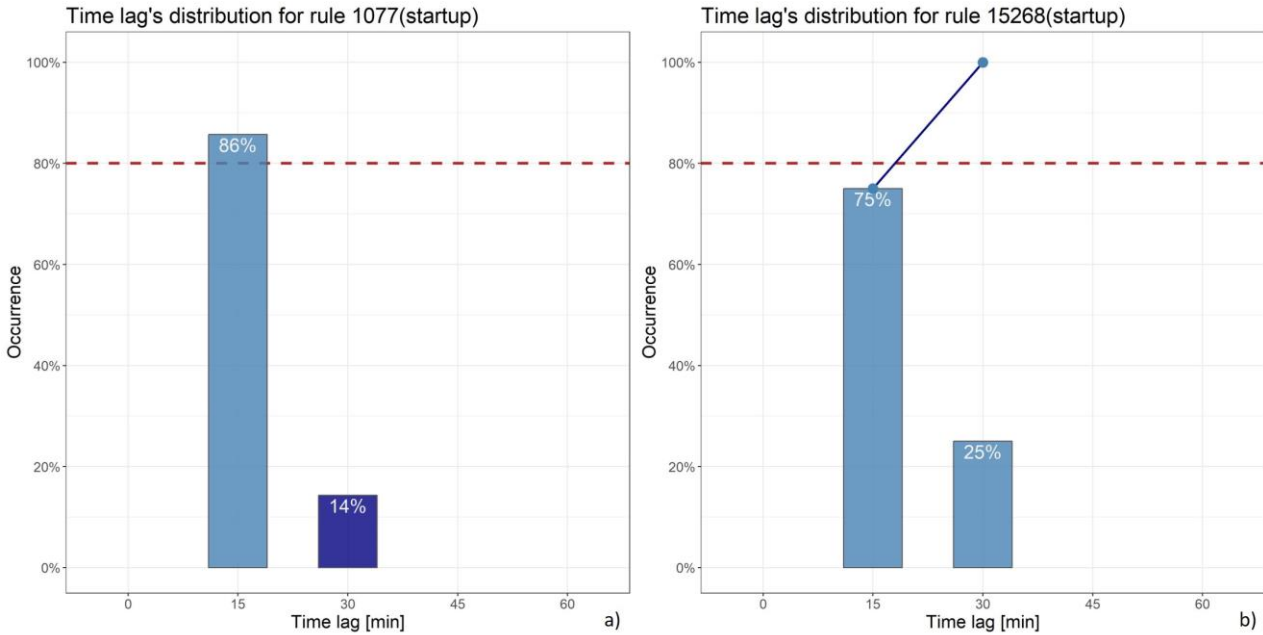
838 However, according to ASHRAE project RP-1312, during the faulty day tagged as CCVSFO (i.e.,  
839 cooling coil valve stuck open), the blockage of the cooling valve in fully open position was  
840 implemented from 8:00 to 18:00 and hence out of the start-up period of the system. For this reason,  
841 the day tagged as CCVSFO has been not considered in the calculation of SUPP.DAY<sub>FAULTY</sub>.

842 The ACTUAL TIME LAG was introduced to evaluate the most frequent temporal distance between  
843 the first occurrence of an antecedent and the last occurrence of the corresponding consequent of a  
844 specific rule. Consequently, even though the rules are searched with a sliding window of 60 minutes,  
845 the user can have a feedback about the most frequent time interval within a consequent occurs given  
846 the presence of its antecedent.

847 The ACTUAL TIME LAG was calculated for each rule by computing the cumulative frequency of  
848 occurrences of the temporal distance between antecedent and consequent. For each rule a cumulated  
849 frequency threshold of 80% was considered in order to evaluate this metric.



850 Figure 10 shows the frequency distribution of the ACTUAL TIME LAG for two rules. The rule on  
851 the left (i.e., rule 1077) occurs for more than the 80% of the time with an actual time lag between the  
852 antecedent itemset and consequent itemset of 15 minutes, while for the rule on the right (i.e., rule  
853 15268) the 80% of occurrences has a characteristic time lag lower or equal to 30 minutes.  
854



855  
856 *Figure 10. Distribution of the time lags for rule 1077 (a) and rule 15268 (b) – (refer to Table B in Appendix A for the*  
857 *description of the rules).*

858 At this stage, more than 15,000 rules were extracted from the start-up dataset of fault-free days (in  
859 more or less 10 min.), assuming minimum support and minimum confidence equal to 0.7 and not  
860 including drivers of system's operation as potential consequent events (i.e. *outdoor air temperature*  
861 (*OA\_TEMP*) and *cooling coil input water temperature* (*CHWC\_EWT*)).

862 After the rule extraction, the values of support and confidence were recalculated considering only the  
863 occurrences of each rule within the evaluated ACTUAL TIME LAG (instead of the window of 60-  
864 min), reducing the set of rules to 7,419 rules.

865 Since the rules extracted should be representative of the fault-free operation of the system, only the  
866 rules, which in the testing dataset frequently occur in normal days and rarely in the faulty ones, are  
867 of interest for the problem under investigation. To this purpose, after the application of the 7,419

temporal association rules to the testing dataset, only the rules with a  $SUPP.DAY_{NORMAL}$  equal to 1 (i.e., the rule occurring for each day labelled as “normal” included in the testing dataset) and a maximum value of  $SUPP.DAY_{FAULTY}$  equal to 0.3 were considered with the final result of obtaining 465 reference rules ( $SUPP.DAY$  values are set by the user).

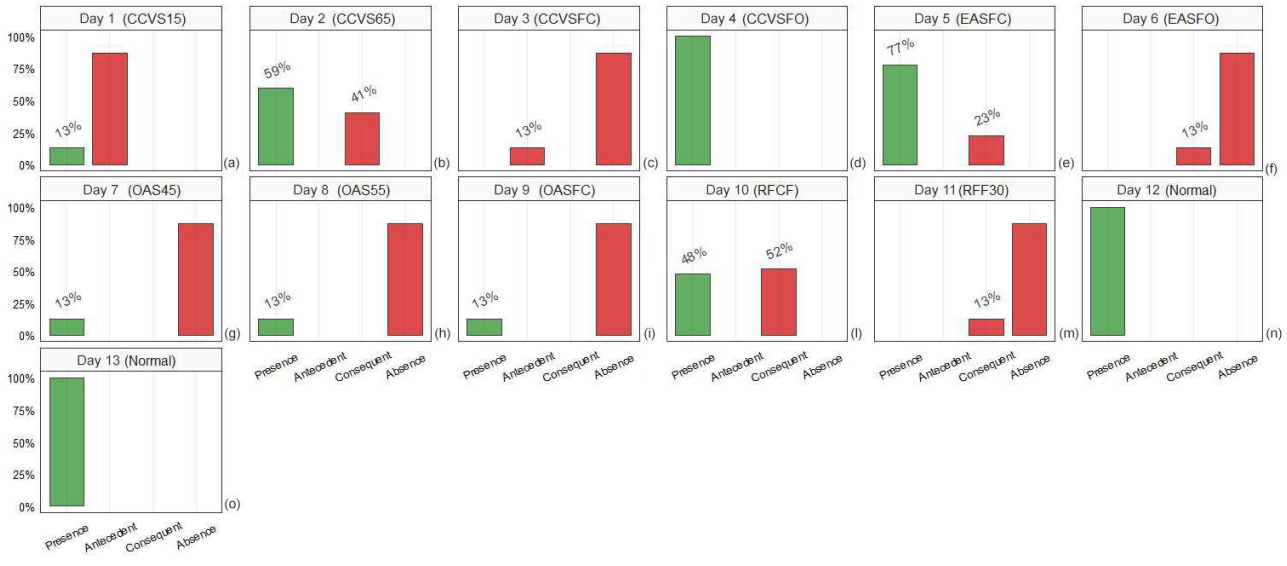
As a general approach, the parameters were set in order to obtain a limited number of interesting rules, which respect the following conditions i) each rule occurs during fault-free condition with high support and confidence, ii) each rule has high probability to be violated during faulty conditions regardless from the fault type.

In this perspective, general rules that are sensitive to more fault types at the same time were preferred to those violated only for specific faults.

The introduced metrics allow an enhanced comprehension of the rule set, making it possible to discriminate rules with high support and confidence occurring during both fault-free and faulty days, from the rules, robust as well, occurring only during the normal operation of the system.

Figure 11 shows for each day in the testing dataset (composed by 11 different faulty days and 2 Normal days) the percentage of rules (out of the 465 considered) which occurred and/or have been violated, with specification of the kind of violation detected. In particular, the label “*presence*” indicates that the rule occurred with its antecedent and consequent while the labels “*antecedent*”, “*consequent*” and “*absence*” indicate three different types of violation. In detail, the label “*antecedent*” denotes that a rule was violated because of the only presence of the antecedent; the label “*consequent*” indicates that a rule was violated because of the only presence of the consequent; the label “*absence*” indicates the complete violation of a rule because of the absence of both antecedent and consequent. The characterisation of the rules in terms of type of violation helps the interpretation of the path which determines a specific fault. In fact, the presence of the only antecedent, the only consequent, rather than the absence of both item sets, correspond to different behaviours of the system in relation to the presence of the considered faults.

893 The results obtained can be described according to the severity of rule violation for each day  
 894 representative of a specific fault implementation or normal operation. To this purpose four different  
 895 groups of days were identified and in the following described.



896  
 897 *Figure 11. Characterization of the presence or the violation of the extracted rules for the testing days (refer to Table 1*  
 898 *for the encoding of faults).*

899 The first group includes days characterized by the presence of the 100% of the 465 rules tested. This  
 900 is the case of days in Figure 11 (d), (n) and (o) tagged as Normal and the faulty day tagged as  
 901 CCVSFO. Such condition suggests, as expected, that during the faulty day CCVSFO the start-up of  
 902 the system can be considered normal.

903 The second group instead, includes the days in Figure 11 (a), (c), (f), (g), (h), (i) and (m) that are  
 904 characterized by a net prevalence of rule violations (more than 70%). Moreover, for those days, the  
 905 presence of a fault is also associated to a specific kind of violation of the rules. As a reference, in case  
 906 of CCVSFC, EASFO, OAS45, OAS55, OASFC and RFF30 the rules are violated mainly due to the  
 907 absence of both antecedents and consequents, while only in the in case of CCVS15 the rule was  
 908 violated for the absence of consequent.

909 The third group includes the day in Figure 11 (e) for which, during the start-up period, the percentage  
 910 of violations is lower than the percentage of valid occurrences of the rules. Such condition suggests  
 911 that during this day the behaviour of the system is similar to the normal one limiting the number of

912 violations occurred. The main reason is that such fault does not strongly affect the system operation  
913 making the detection process less sensible to its presence. This result agreed with the findings of the  
914 ASHRAE-RP 1312 project, during which the analysed dataset was generated [14].

915 The last group includes days in Figure 11 (b) and (l) that are characterized by a similar amount of  
916 violated and not violated rules (violation rate between 40% and 60%). These two faults seem to affect  
917 the performance of the system differently from other faults respect to which hypothetically should  
918 exhibit high similarity (i.e., CCVS15 and RFF30). Regarding the fault CCVS65 (Figure 11 (b)), the  
919 cooling coil valve is stuck open at 65% and therefore the supply air flow is overcooled. In this case,  
920 the system reacts by opening the heating coil valve and operating in fully recirculation mode for  
921 increasing the *supply air temperature* (SA\_TEMP). Consequently, the failure of the cooling coil valve  
922 does not affect the capability of the system in reaching the supply set-point temperature, but the  
923 operation of the other components is different from the normal condition.

924 On the opposite, during the day (Figure 11 (a)) tagged as CCVS15 (included in group 2) the cooling  
925 coil valve is almost closed limiting the heat transfer with the supply air flow that does not reach the  
926 set point temperature. Such case is representative of the complete failure of the system in maintaining  
927 the desired conditions of the indoor environment, as a matter of fact, justifying a higher rule violation  
928 rate for CCVS15 respect to CCVS65.

929 Regarding the fault RFCF (Figure 11 (l)), the system is operated implementing the complete failure  
930 of the return fan despite its speed control signal is correctly elaborated. Instead, during the day in  
931 Figure 11 (m) tagged as RFF30 (included in group 2), the return fan is not corrupted, but it is subjected  
932 to a faulty control signal. In this case the high number of rules violated for RFF30 suggests a higher  
933 sensitivity of the extracted rules to frequent transitions of the fan speed discrete values rather than fan  
934 power ones.

935 Some key figures related to the 465 extracted rules are described below. The rules are characterized  
936 by an ACTUAL TIME LAG that lies between 15 and 30 minutes. The evaluation of the ACTUAL  
937 TIME LAG can be considered as an essential step for reducing the intrinsic latency of the FDD

process during real implementation. Indeed, the ACTUAL TIME LAG gives the opportunity to check the occurrence of a rule within a time interval smaller than the width of the sliding window used for the rule extraction (in this case study, equal to 60 min.).

The transitions in the antecedent and consequent item sets are reported in Table 3 with the corresponding occurrence frequency. In particular, the number of different consequent item sets is 13, resulting from a combination of 4 different events, while the antecedent item sets are 99, resulting from the combination of 12 different events.

Table 3. Occurrence frequency of each event included in the antecedent and consequent item sets

| Itemset    | Variable                              | Event          | Frequency |
|------------|---------------------------------------|----------------|-----------|
| Antecedent | Return Fan Speed                      | RF_SPD [A-B]   | 87%       |
|            | Cooling coil input water temperature  | CHWC_EWT [D-C] | 31%       |
|            | Return fan power                      | RF_WAT [A-B]   | 24%       |
|            | Exhaust air damper position           | EA_DMPR [A-B]  | 23%       |
|            | Cooling coil output water temperature | CHWC_LWT [C-B] | 22%       |
|            | Supply fan speed                      | SF_SPD [A-B]   | 22%       |
|            | Cooling coil input water temperature  | CHWC_EWT [C-A] | 21%       |
|            | Supply fan power                      | SF_WAT [A-B]   | 21%       |
|            | Return fan start/stop signal          | RF_SST [A-B]   | 18%       |
|            | Return air flow rate                  | RA_CFM [A-B]   | 16%       |
|            | Return fan pressure drop              | RF_DP [A-B]    | 12%       |
|            | Return fan pressure drop              | SF_DP [A-B]    | 9%        |
| Consequent | Return Fan Speed                      | RF_SPD [B-C]   | 87%       |
|            | Supply Air Temperature                | SA_TEMP [B-A]  | 49%       |
|            | Cooling coil output water temperature | CHWC_LWT [B-A] | 46%       |
|            | Cooling coil air temperature          | CHWC_DAT [B-A] | 36%       |

The obtained rule set, including the most representative rules, is reported in Table B in Appendix A. The rules extracted are meaningful since they can be interpreted as chains of events that characterise the normal operation of the AHU in reaching the set-point conditions during the start-up period. Indeed, extracted rules can be expressed as IF-THEN implications to be verified within a specific time interval. As a reference, the rule n° 8661 (included in Table B in Appendix A) can be written and interpreted as follow: IF (RF\_SPD [A-B] and CHWC\_LWT [C-B] and EA\_DMPR [A-B]) occur THEN (CHWC\_DAT [B-A] and RF\_SPD [B-C]) will occur within 30 minutes with the 100% of confidence during a normal day.

955 In detail, the antecedent itemset includes transitions related to the return fan speed (RF\_SPD), the  
956 *cooling coil output water temperature* (CHWC\_LWT) and the *exhaust air damper position*  
957 (EA\_DMPPR) that imply the occurrence of consequent transitions related to *cooling coil output water*  
958 *temperature* (CHWC\_LWT) and *return fan speed* (RF\_SPD).

959 In order to further improve the interpretability of the rules a novel visualization was proposed in this  
960 work. An example of this visualization is showed in Figure 12, where the profiles of the variables  
961 involved in rule n°1253 (see Table B in Appendix A).

962 Figure 12 shows the trend of the variables in terms of real profile (i.e. green curve) and PAA (i.e.  
963 black segments). Regardless of the approximation introduced by the PAA, the behaviour of the  
964 variables during the transient period is preserved, as can be seen by looking at the *supply air*  
965 *temperature* trend (SA\_TEMP). In fact, during the start-up period the *supply fan speed* (SF\_SPD)  
966 initially ramps up and then it is reduced to a constant level. The transitions of the antecedent itemset  
967 are reported in red, while the consequent itemset in blue. The PAA is represented in a window of 60  
968 minutes, while with a darker shade of grey the length of the ACTUAL TIME LAG (i.e., 15 minutes)  
969 is reported. On the y-axis are shown the values used for the discretization of each variable.

970 The rule in Figure 12 shows a typical behaviour of the system at the start-up period, in terms of the  
971 variation of *supply fan speed* (SF\_SPD), *exhaust air damper* (EA\_DMPPR), *return fan power*  
972 (RF\_WAT), and *supply air temperature* (SA\_TEMP).

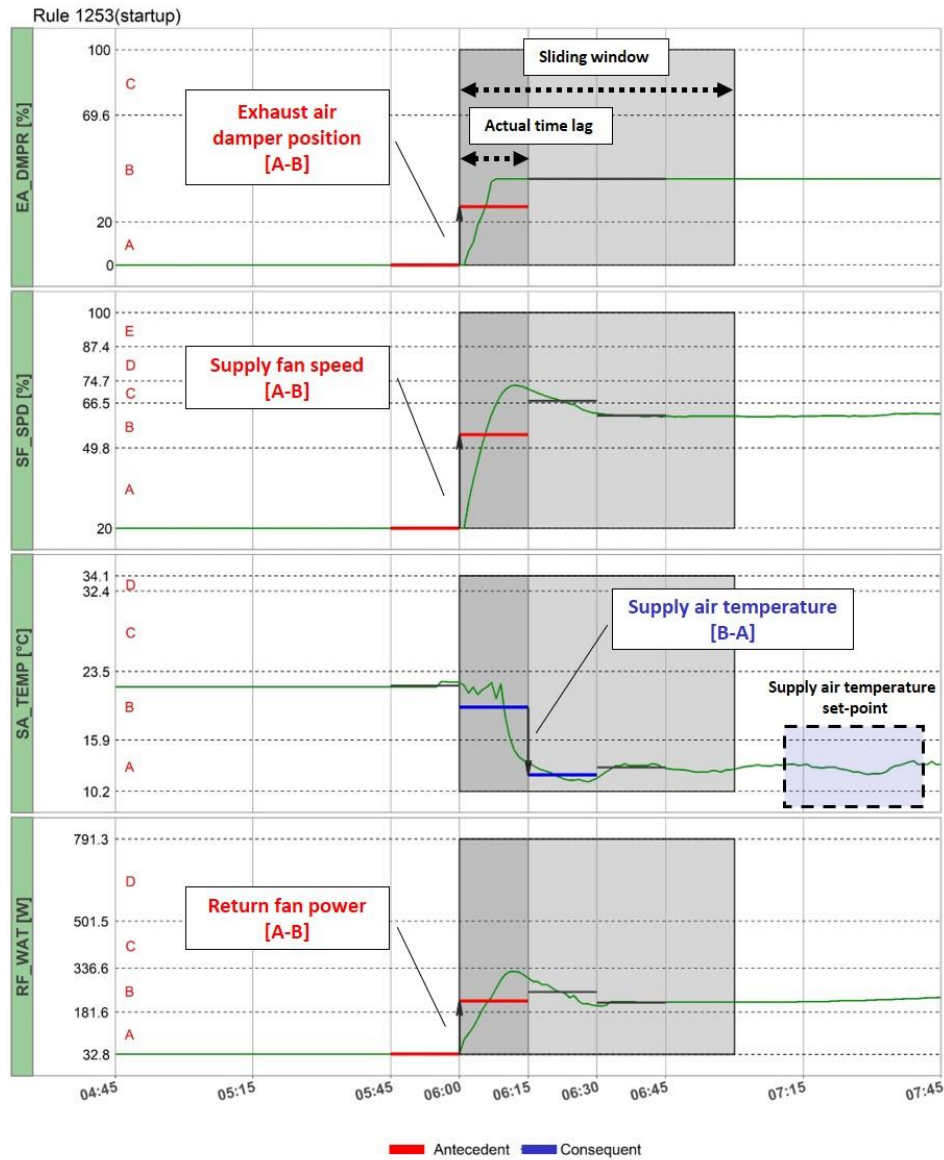
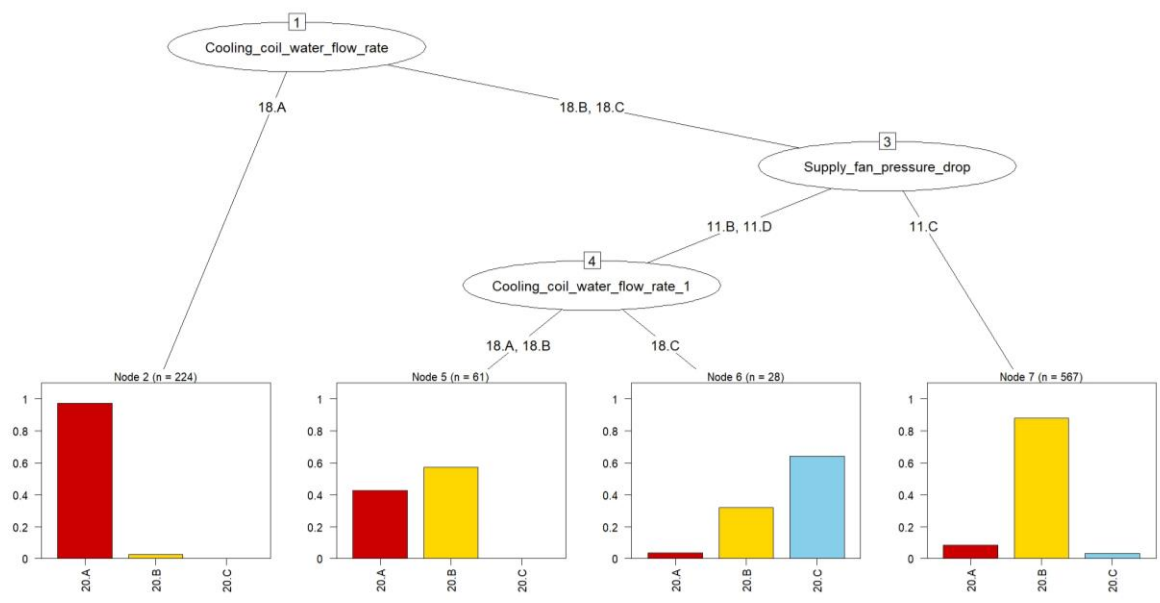


Figure 12. Visualization of an extracted temporal association rule (refer to Table 2 for variable encoding).

According to this rule, usually at the time scheduled for the start-up (i.e. 6:00 a.m.), the supply fan receives the start signal contemporary to the opening of the exhaust air damper while the *return fan power* (RF\_WAT) increases (change from A to B). After 15 minutes from the occurrence of the first antecedent transition in the event chain, according to the rule, the *supply air temperature* (SA\_TEMP) decreases from symbolic discrete-value B to A until the reaching of the desired set-point. This proved that the chain of events related to each association rule provides information about the expected behaviour in terms of discrete-value changes among influencing variables of the AHU during normal operation.

983 6.3 Fault detection and diagnosis during non-transient period

984 In this section, the results obtained for the application of the methodology during non-transient period  
985 described in section 5 are presented. The first step is aimed at developing a CT reference model for  
986 each variable to predict the normal operation of the system. For the development of these reference  
987 estimation models, all the variables related to the operation of the AHU have been selected once at a  
988 time as target attribute while the remaining ones have been used as input attributes. However, features  
989 related to external forcing variables to the AHU system (i.e., *cooling coil input water temperature*  
990 (*CHWC\_EWT*), *outdoor air temperature* (*OA\_TEMP*)) have been used only as input attributes. As a  
991 result, 21 reference models were built for providing a robust benchmark of fault-free operation.  
992 Moreover, the variables used as input were also considered with a maximum backward lag of four  
993 time steps (i.e. 60 minutes). Indeed, the decision trees are able to predict the discrete values (i.e.,  
994 symbol) of a target variable considering the discrete values of the input variables both in the same  
995 and previous aggregation intervals.



996  
997 Figure 13. Classification tree for the estimation of the symbolic discrete-values of the cooling coil valve position  
998 (CHWC\_VLV).

999 Figure 13 reports as an example the CT model developed for predicting the discrete values (i.e.,  
1000 symbol) of the variable *cooling coil water valve position* (i.e., variable tagged as CHWC\_VLV with



ID n° = 20), with an overall accuracy of 88% evaluated as the fraction of correct predictions with respect to the total number of predictions. The algorithm selected as input variables the *cooling coil water flow rate* (i.e., variable tagged as CHWC\_GPM with ID n° = 18) and the *pressure drop of the supply fan* (i.e., variable tagged as SF\_DP with ID n° = 11). From this CT, it is possible to extract useful decision rules for straightforwardly characterizing all the implications between discrete values (i.e., symbols) that typically occur during the fault-free operation of the AHU. Table 4 reports all the IF-THEN decision rules extracted from the CT shown in Figure 13 with the evidence of the accuracy achieved in each leaf node. The accuracy refers to each single leaf node assuming that the predicted label of the node corresponds to the label of the majority of the objects.

For example, according to rule 4, the value of the response variable *cooling coil valve position* is equal to 20\_B (i.e. CHWC\_VLV lies in the interval 41 – 75 [%]) if the *cooling coil water flow rate* is equal to 18\_B or 18\_C (i.e. CHWC\_GPM lies in the interval 0,89 – 2.7 [m<sup>3</sup>/h]) and the *supply fan pressure drop* is equal to 11\_C (i.e. SF\_DP lies in the interval 562 – 770 [Pa]).

Table 4. Decision rules for the estimation of the symbolic discrete-value of cooling coil valve position (CHWC\_VLV).

| Rule number | Decision rules   | CHWC_VLV discrete-value | N° of objects | Leaf node accuracy |
|-------------|--|-------------------------|---------------|--------------------|
| 1)          | IF CHWC_GPM = 18_A   | 20_A                    | 224           | 95%                |
| 2)          | IF CHWC_GPM = 18_B or 18_C AND SF_DP = 11_B or 11_D AND CHWC_GPM (lag -1) = 18_A or 18_B | 20_B                    | 61            | 55%                |
| 3)          | IF CHWC_GPM = 18_B or 18_C AND SF_DP = 11_B or 11_D AND CHWC_GPM (lag -1) = 18_C         | 20_C                    | 28            | 65%                |
| 4)          | IF CHWC_GPM = 18_B or 18_C AND SF_DP = 11_C  | 20_B                    | 567           | 85%                |

Once all the estimation models were trained and validated, the residual analysis was performed by using a testing dataset including both faulty and fault-free data (i.e., 2 fault-free and 11 faulty days). Therefore, the difference between the actual status of a variable and that estimated by the CT during a aggregation interval determines the detection or not of a potential faulty condition, since the predicted status should be considered as the reference condition (fault-free). The values of the

residuals can be equal to zero in case of absence of deviation from the normal conditions, positive if the actual value is higher than expected, while negative if the actual value is lower than expected. Eventually, in order to perform fault diagnosis, an additional CT model was developed, which uses in input the residuals obtained from the estimation performed through the previously described reference models and as output the tags related to the various faults analysed in this study. Figure 14 shows the classification model obtained, which can classify the faults considered with a set of intuitive rules, reaching an overall accuracy of the 90%.

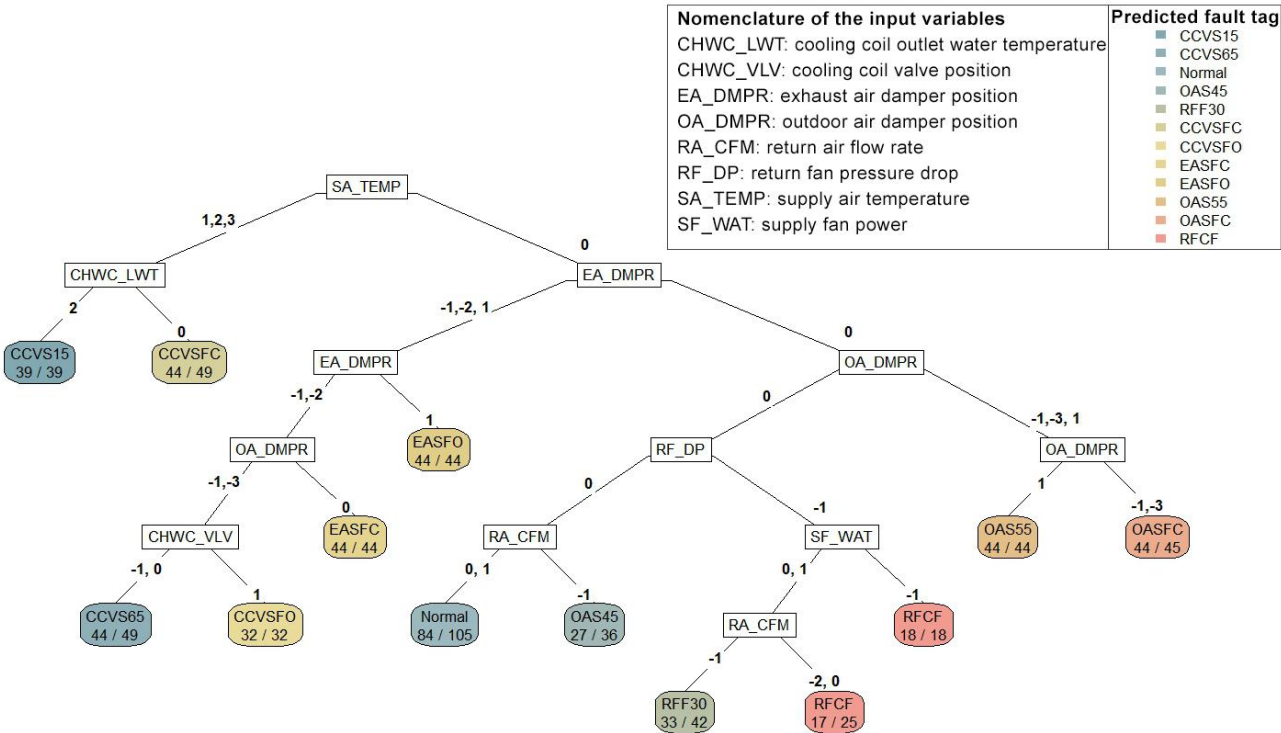


Figure 14. Classification tree for the fault diagnosis during the non-transient period.

The variables involved in input for the classification are the *supply air temperature* (SA\_TEMP), the *outdoor air damper position* (OA\_DMPR), the *exhaust air damper position* (EA\_DMPR), the *cooling coil outlet water temperature* (CHWC\_LWT), the *cooling coil valve position* (CHWC\_VLV), the *supply fan power* (SF\_WAT), the *return fan pressure drop* (RF\_DP) and the *return air flow rate* (RA\_CFM). The CT developed can diagnose 11 different faults and the normal condition as well. The latter is predicted by following the path of the CT (Figure 14) that includes all zeros (i.e. residual equal to zero) in the splits for the variables SA\_TEMP, EA\_DMPR, OA\_DMPR, RF\_DP and RA\_CFM. With reference to Figure 14, some other rules are described in the following.

1037 The first split made by the CT algorithm is driven by the *supply air temperature* (SA\_TEMP), which  
1038 identifies the faults due to a blockage of the cooling coil valve at 0% (CCSFC) or at 15% (CCVS15)  
1039 if the air temperature presents higher values than normal (i.e., SA\_TEMP residuals = 1, 2, 3).

1040 In some cases, the faults can be diagnosed by analysing the variables directly related to the corrupted  
1041 component, such as the blockage of the exhaust and outdoor air dampers at 0%, 55% or 100% (i.e.  
1042 OASFC, OAS55, EASFC, and EASFO). In other cases, a series of deviation from the normal  
1043 condition for different variables are considered as symptoms for a specific fault. That is the case, for  
1044 example, of anomalous energy transfer in the cooling coil due to blockage of the cooling coil valve  
1045 at 65% (CCVS65) or 100% (CCVSFO). These faults are diagnosed in the case both the air dampers  
1046 are completely closed (i.e. negative values of residuals), but the *supply air temperature* (SA\_TEMP)  
1047 does not present a deviation from the normal condition. In this case, the system tries to counterbalance  
1048 the excessive decrease of the temperature of the air by operating in fully recirculation mode.

1049 The effect of a fault related to the return fan (Figure 14) can be easily identified, since the pressure  
1050 drop at the return fan is reduced, with the absence of deviation, from normal condition, for *supply air*  
1051 *temperature* (SA\_TEMP) and air dampers.

1052 The discrimination between the *return fan complete failure* (RFCF) and the case when the speed is  
1053 fixed at 30% (RFF30) can be performed by evaluating the severity of the reduction of the *return air*  
1054 *flow rate* (RA\_CFM) rather than the reduction of the *supply fan power* (SF\_WAT).

1055 The introduced FDD tool is a multiclass classifier and when in operation sorts data into either fault-  
1056 free (i.e., normal) or faulty classes.

1057 All the evaluation metrics for a multiclass classification model can be understood in the context of a  
1058 binary classification model (where the classes are “positive” and “negative”). These metrics are  
1059 derived from the following categories:

- 1060 • True Positives (TP): Objects labelled as positive and predicted to be positive.
- 1061 • False Positives (FP): Objects labelled as negative and predicted to be positive.
- 1062 • True Negatives (TN): Objects labelled as negative and predicted to be negative.

- False Negatives (FN): Objects labelled as positive and predicted to be negative.

The multiclass classification problem can be seen as a set of many binary classification problems and its performance can be assessed labelling as “positive” each class once at time. In the context of the presented multiclass FDD classifiers some metrics have been calculated:

- Accuracy (A): Objects of items correctly identified as either truly positive or truly negative out of the total number of items i.e.,  $(TP + TN)/(TP + TN + FP + FN)$ .
- Recall (R): Number of objects correctly identified as positive out of the total actual positives i.e.,  $TP/(TP + FN)$ . The recall is calculated for each class and then averaged among classes for a global performance assessment of the CT.
- Precision (P): Number of objects correctly identified as positive out of the total items predicted as positive i.e.,  $TP/(TP + FP)$ . The precision is calculated for each class and then averaged among classes for a global performance assessment of the CT.
- False Positive Rate (FPR), Type I error: Number of objects wrongly identified as faulty out of the total actual fault-free data i.e.,  $FP/(FP + TN)$ . In FDD processes, this error means that data belonging to fault-free class (negative) are incorrectly labelled as faulty (positives) generating false alarms.
- False Negative Rate (FNR), Type II error : Number of objects wrongly predicted as fault-free out of the total actual faulty data i.e.,  $FN/(FN + TP)$ . In FDD processes, this error means that data belonging to one of the fault classes (positives) are incorrectly labelled as fault-free (negative) generating missing detection opportunities.

The developed CT exhibits the following performances  $A = 90\%$ ,  $R = 89\%$ ,  $P = 91\%$ ,  $FNR = 4\%$ ,  $FPR = 4\%$ . The performance of the CT can be also assessed with the detail of each class considered. To this purpose, in Table 5 is reported the Confusion Matrix (CM) of the CT. The CM, in form of table (actual class vs predicted class), allows an effective analysis of the performance of the CT algorithm making it possible to identify confusion between all the considered classes (i.e., mislabelling of objects belonging to a class and classified into another one).

1089 In particular, rows of the table correspond to the actual classes while columns to the predicted ones.  
 1090 At this stage it is possible to evaluate in each class the proportion of prediction actually correct (i.e.,  
 1091 Precision) and the proportion of actual values predicted correctly (i.e., Recall).

1092 *Table 5. Precision and recall for classification tree of fault diagnosis during non-transient period.*

|                  | CCVS15    | CCVS65    | Normal    | OAS45     | RFF30     | CCVSFC    | CCVSFO    | EASFC     | EASFO     | OAS55     | OASFC     | RFCF      | Total              | Recall             |
|------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|--------------------|--------------------|
| CCVS15           | <b>39</b> | 0         | 0         | 0         | 0         | 5         | 0         | 0         | 0         | 0         | 0         | 0         | 44                 | 89%                |
| CCVS65           | 0         | <b>44</b> | 0         | 0         | 0         | 0         | 0         | 0         | 0         | 0         | 0         | 0         | 44                 | 100%               |
| Normal           | 0         | 0         | <b>84</b> | 3         | 0         | 0         | 0         | 0         | 0         | 0         | 1         | 0         | 88                 | 96%                |
| OAS45            | 0         | 0         | 17        | <b>27</b> | 0         | 0         | 0         | 0         | 0         | 0         | 0         | 0         | 44                 | 61%                |
| RFF30            | 0         | 0         | 2         | 1         | <b>33</b> | 0         | 0         | 0         | 0         | 0         | 0         | 8         | 44                 | 75%                |
| CCVSFC           | 0         | 0         | 0         | 0         | 0         | <b>44</b> | 0         | 0         | 0         | 0         | 0         | 0         | 44                 | 100%               |
| CCVSFO           | 0         | 5         | 2         | 5         | 0         | 0         | <b>32</b> | 0         | 0         | 0         | 0         | 0         | 44                 | 73%                |
| EASFC            | 0         | 0         | 0         | 0         | 0         | 0         | 0         | <b>44</b> | 0         | 0         | 0         | 0         | 44                 | 100%               |
| EASFO            | 0         | 0         | 0         | 0         | 0         | 0         | 0         | 0         | <b>44</b> | 0         | 0         | 0         | 44                 | 100%               |
| OAS55            | 0         | 0         | 0         | 0         | 0         | 0         | 0         | 0         | 0         | <b>44</b> | 0         | 0         | 44                 | 100%               |
| OASFC            | 0         | 0         | 0         | 0         | 0         | 0         | 0         | 0         | 0         | 0         | <b>44</b> | 0         | 44                 | 100%               |
| RFCF             | 0         | 0         | 0         | 0         | 9         | 0         | 0         | 0         | 0         | 0         | 0         | <b>35</b> | 44                 | 80%                |
| <b>Total</b>     | 39        | 49        | 105       | 36        | 42        | 49        | 32        | 44        | 44        | 44        | 45        | 43        | 572                | <b>Average 89%</b> |
| <b>Precision</b> | 100%      | 90%       | 80%       | 75%       | 79%       | 90%       | 100%      | 100%      | 100%      | 100%      | 98%       | 81%       | <b>Average 91%</b> |                    |

1093  
 1094 Thanks to the methodology introduced in the present paper the faults in the dataset were diagnosed  
 1095 with both high precision and recall, as can be seen in Table 5. The lowest values of precision and  
 1096 recall are related to the fault *outdoor air damper stuck at 45%* (OAS45), for which part of the records  
 1097 have been mislabelled as “Normal” (i.e., 17 out of 44 objects, that correspond to the 39% of data  
 1098 labelled as OAS45 and to the 89% of the total amount of False Negatives). This condition is due to  
 1099 the fact that the outdoor air damper stuck open at 45% does not invalidate the operation of the system  
 1100 which is similar to the fault-free one during the non-transient period. It is worth nothing that all the  
 1101 assumptions taken, and results obtained are related to a specific operative condition of the system  
 1102 (i.e., cooling mode). The set of rules extracted can be then considered a valid FDD solution if only  
 1103 applied on data consistent with the initial hypotheses. Despite this, even though the analysis is related  
 1104 to a portion of the possible operative conditions of an AHU, the performance achieved suggests good  
 1105 perspectives in applicability and generalizability of the proposed methodology.

## 7 Discussion and concluding remarks

The paper introduces a data-driven based methodology to perform an AFDD in AHUs. Two different analytics modules were proposed for transient and non-transient conditions of the AHU operation and consequently to enhance the energy performance of the ventilation and air-conditioning process. The dataset used for testing the methodology includes several faulty and fault-free running conditions related to the cooling operative mode of AHUs. Data were gathered from monitoring campaign on two identical AHUs in the framework of the Research Project ASHRAE RP-1312.

The fault detection during the start-up period was performed with an innovative approach by searching frequent and non-anomalous relationships between events in a temporal transaction set using temporal association rules. A temporal association rule is expressed as a logical IF-THEN implication where the presence of an event (i.e., antecedent) implies the occurrence of another event (i.e., consequent) within a certain time lag. According to this approach, in the analysed case study the violation of a rule or group of rules may suggest the occurrence of abnormal conditions during system operation. Three potential rule violations have been considered for detecting faults during the start-up period: i) absence of the antecedent, ii) absence of consequent, iii) absence of antecedent and consequent.

The used rules are extracted by expert knowledge from a large set of possible rules and are representative of the normal operation of the AHU and are characterised by high physical interpretability. The introduction of innovative parameters (e.g. SUPP.DAY in faulty and normal conditions, support and confidence in the ACTUAL TIME LAG) allowed a robust selection of the most interesting association rules, minimising the effort required in the post-processing stage. Furthermore, an effective visualization of the temporal association rules was introduced with the aim of supporting energy managers in the interpretation of the temporal associations between operational variables in real-time.

The AFDD during non-transient period was performed by training and testing 21 CT models for providing a robust benchmark of the fault-free operation. The CT models are able to predict the

1132 discrete values of a target operational variable considering the values of the input variables both in  
1133 the same and previous aggregation interval. The CTs showed high performance (i.e., high accuracy,  
1134 precision and recall) in modeling all the variable relations that are characteristic of the operative  
1135 condition of interest (i.e., 20 days of AHU operated in cooling mode).

1136 Eventually, an additional CT was developed in order to perform fault diagnosis. The model showed  
1137 an overall accuracy of 90% and consists of a set of intuitive rules easy to be implemented for detecting  
1138 up to 11 typical faults in AHUs. However, the set of rules extracted can be then considered as a valid  
1139 FDD solution only if applied on data consistent with the initial hypotheses (i.e., AHU operated in  
1140 cooling mode).

1141 Overall, the results obtained are characterised by robustness and high interpretability proving the  
1142 effectiveness of the proposed methodology for ensuring a correct energy and operational management  
1143 of the ventilation and air-conditioning process.

1144 Even though the rule set and the classification models are tailored for the case study analysed, the  
1145 outcomes of the process can be considered flexible and generalizable. The methodologies were  
1146 conceived for being automatic and for effectively managing the redundancy, interpretability and  
1147 physical meaningfulness of the association and classification rules. Moreover, the proposed AFDD  
1148 process is conceived for quasi real-time implementation, also minimising the user contribution and  
1149 paying attention to the optimisation of computational cost. To this purpose, the preliminary  
1150 discretisation of the variables, performed through the aSAX algorithm, proved to be particularly  
1151 effective in extracting the crucial operational conditions of the AHU reaching the optimal trade-off  
1152 between data reduction and information loss. Moreover, the association rules were extracted from an  
1153 event-based dataset (i.e., database of transactions) where only information about the discrete-value  
1154 changes of the operational variables is stored. As a consequence, the computational cost related to  
1155 the mining of rules is strongly reduced, increasing the feasibility of such approach in real case studies.

1156 As a reference the whole analytics process takes about 45 min in terms of computational time on a

1157 computer equipped with quad-core processor Intel i7-3632QM CPU (2.20GHz) and 8GB RAM  
1158 DDR4. In more detail the rule extraction phase takes more or less 10 minutes. It means that the most  
1159 onerous parts of the analysis are represented by the pre-processing and post-mining phases. In the  
1160 pre-processing phase the assessment of the optimal quantization of the time series through aSAX is  
1161 validated by using more than 20 metrics (cluster validity indices included in the R Nbclust package  
1162 [68]). Such calculation takes more than 10 minutes. In the post mining phase, the recalculation of  
1163 support and confidence of each rule within the evaluated ACTUAL TIME LAG (instead of the  
1164 window of 60-min), and the violation analysis performed on the testing dataset take about 20 minutes.  
1165 For what concern the analysis of non-transient data, the development of each classification tree takes  
1166 few seconds of computation and can be considered a task easily parallelizable. As a result, the impact  
1167 of the analysis of non-transient data can be considered negligible in terms of computational cost  
1168 compared to the pre-processing, rule extraction and rule post-mining. Indeed, in the perspective of a  
1169 real-time implementation of the whole AFDD process, the update of the discretization intervals, set  
1170 of association rules and estimation models can be accomplished during night-time while the fault  
1171 detection and diagnosis tool can be run online during operation. For what concern the pre-processing  
1172 stage, during the real-time operation the Hampel filter can still be used but considering that its  
1173 intrinsic latency equal to  $(Len-1)/2$  should be added to the latency of the FDD process in detecting  
1174 faults (in this case study the latency of the FDD process is equal to the length of the aggregation  
1175 interval i.e., 15 min). For avoiding high latency in the analysis,  $Len$  can be reduced. As an alternative,  
1176 other pre-processing algorithms, particularly suitable for the analysis of data streams, can be  
1177 employed for detecting statistical outliers in real-time (i.e., before time  $t + 1$  and without any look  
1178 ahead) [71]. Further research will be then conducted to assess the scalability of the methodology to  
1179 other operation modes and systems and to integrate it with knowledge driven-based analysis for better  
1180 addressing the implementation issues characteristic of data-driven tools. Indeed, data-driven based  
1181 FDD tools need a proper amount of data for the development of diagnosis models and cannot  
1182 extrapolate beyond the range of training data [10]. It means that their capability in automatically



1183 extracting pattern from actual performance data is strictly related to the availability of pre-labelled  
1184 monitored data (typically derived from AHU recommissioning or simulated data). On the contrary,  
1185 knowledge driven-based approach can introduce domain knowledge and user experience into the  
1186 FDD process [10], especially in the case initial information is not enough for deploying a data-driven  
1187 process. In this perspective, a perfect integration of both approaches represents the main opportunity  
1188 for significantly improve robustness, accuracy and generalizability of FDD tools conceived for  
1189 application in building energy systems.

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Appendix A

Table A. Discretization intervals for all the analysed variables.

| Variable | ID | Unit   | Sym. A       | Sym. B             | Sym. C            | Sym. D            | Sym. E       |
|----------|----|--------|--------------|--------------------|-------------------|-------------------|--------------|
| SF_WAT   | 1  | [W]    | < 522<br>OFF | 522 – 1265<br>ON   | 1265 – 2440<br>ON | > 2440<br>ON      | -            |
| RF_WAT   | 2  | [W]    | < 181<br>ON  | 181 - 337<br>ON    | 336 – 502<br>ON   | > 502<br>ON       | -            |
| SA_CFM   | 3  | [m³/h] | < 591<br>OFF | 591 – 2276<br>ON   | 2276 – 3414<br>ON | 3414 – 4706<br>ON | > 4706<br>ON |
| RA_CFM   | 4  | [m³/h] | < 838<br>OFF | 838 – 2712<br>ON   | 2712 – 3527<br>ON | > 3527<br>ON      | -            |
| OA_CFM   | 5  | [m³/h] | < 477<br>ON  | 477 – 1146<br>ON   | > 1146<br>ON      | -                 | -            |
| SA_TEMP  | 6  | [°C]   | < 15,9<br>ON | 15,9 – 23,5<br>ON  | 23,5 – 32,4<br>ON | > 32,4<br>ON      | -            |
| MA_TEMP  | 7  | [°C]   | < 20,3<br>ON | 20,3 – 30,8<br>ON  | > 30,8<br>ON      | -                 | -            |
| RA_TEMP  | 8  | [°C]   | < 25,7<br>ON | 25, 7 – 31,5<br>ON | >31,5<br>ON       | -                 | -            |
| HWC_DAT  | 9  | [°C]   | < 20,2<br>ON | 20,2 – 26<br>ON    | 26 – 35,7<br>ON   | > 35,7<br>ON      | -            |
| CHWC_DAT | 10 | [°C]   | < 14,4<br>ON | 14,4 – 22<br>ON    | 22 – 30,7<br>ON   | > 30,7<br>ON      | -            |
| SF_DP    | 11 | [Pa]   | < 324<br>OFF | 324 – 562<br>ON    | 562 – 770<br>ON   | > 770<br>ON       | -            |
| RF_DP    | 12 | [Pa]   | < 46<br>ON   | 46 – 114<br>ON     | > 114<br>ON       | -                 | -            |
| SF_SPD   | 13 | [%]    | < 50<br>OFF  | 50 – 67<br>ON      | 67 – 75<br>ON     | 75 – 87<br>ON     | > 87<br>ON   |
| RF_SPD   | 14 | [%]    | < 30<br>OFF  | 30 – 43<br>ON      | 43 – 57<br>ON     | 57- 69<br>ON      | > 69<br>ON   |
| OA_TEMP  | 15 | [°C]   | < 18,3<br>ON | > 18,3<br>ON       | -                 | -                 | -            |
| CHWC_EWT | 16 | [°C]   | < 1,3<br>ON  | 1,3 – 2,8<br>ON    | 2,8 – 6,7<br>ON   | > 6,7<br>OFF      | -            |
| CHWC_LWT | 17 | [°C]   | < 13,3<br>ON | 13,3 – 19,9<br>ON  | 19,9 – 21,2<br>ON | > 21,2<br>OFF     | -            |
| CHWC_GPM | 18 | [m³/h] | < 0,9<br>ON  | 0,9 – 1,7<br>ON    | > 1,7<br>ON       | -                 | -            |
| E_ccoil  | 19 | [kW]   | < 11,7<br>ON | > 11,7<br>ON       | -                 | -                 | -            |
| CHWC_VLV | 20 | [%]    | < 41<br>ON   | 41 – 75<br>ON      | > 75<br>ON        | -                 | -            |
| EA_DMPR  | 21 | [%]    | < 20<br>ON   | 20 – 70<br>ON      | > 70<br>ON        | -                 | -            |
| OA_DMPR  | 22 | [%]    | < 20<br>ON   | 20 – 47<br>ON      | 47 – 77<br>ON     | > 77<br>ON        | -            |
| RF_SST   | 23 | [-]    | < 0,5<br>OFF | > 0.5<br>ON        | -                 | -                 | -            |

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Table A summarizes the transformation results obtained, with the specification of the numerical range corresponding to each symbol for all the analysed operational variables.

Table B. Most representative extracted temporal association rules.

| ID N°       | Antecedent                                       | Consequent                                       | Supp.       | Conf.      | ACTUAL<br>TIME<br>LAG | SUPP.<br>DAY<br>FAULTY |
|-------------|--|--|-------------|------------|-----------------------|------------------------|
| 1077        | SF_SPD [A-B], EA_DMPR [A-B], RF_WAT [A-B]        | CHWC_DAT [B-A]                                   | 0.70        | 0.8        | 15                    | 0.27                   |
| 1078        | SF_WAT [A-B], EA_DMPR [A-B], RF_WAT [A-B]        | CHWC_DAT [B-A]                                   | 0.70        | 0.8        | 15                    | 0.27                   |
| 1526        | SF_SPD [A-B], EA_DMPR [A-B], RF_WAT [A-B]        | CHWC_DAT [B-A],<br>CHWC_LWT [B-A]                | 0.70        | 0.8        | 15                    | 0.27                   |
| 1527        | SF_WAT [A-B], EA_DMPR [A-B], RF_WAT [A-B]        | CHWC_DAT [B-A],<br>CHWC_LWT [B-A]                | 0.70        | 0.8        | 15                    | 0.27                   |
| 1864        | SF_SPD [A-B], EA_DMPR [A-B], RF_WAT [A-B]        | CHWC_DAT [B-A],<br>CHWC_LWT [B-A], SA_TEMP [B-A] | 0.75        | 0.8        | 15                    | 0.27                   |
| 1865        | SF_WAT [A-B], EA_DMPR [A-B], RF_WAT [A-B]        | CHWC_DAT [B-A],<br>CHWC_LWT [B-A], SA_TEMP [B-A] | 0.75        | 0.8        | 15                    | 0.27                   |
| 8661        | RF_SPD [A-B], CHWC_LWT [C-B],<br>EA_DMPR [A-B]   | CHWC_DAT [B-A], RF_SPD [B-C]                     | 0.9         | 1          | 30                    | 0.09                   |
| 8750        | RF_SPD [A-B], EA_DMPR [A-B], RF_SST [A-B]        | CHWC_DAT [B-A], RF_SPD [B-C]                     | 0.8         | 0.89       | 30                    | 0                      |
| 6255        | RF_SPD [A-B], CHWC_LWT [C-B],<br>RA_CFM [A-B]    | CHWC_DAT [B-A], RF_SPD [B-C],<br>CHWC_LWT [B-A]  | 0.89        | 0.8        | 15                    | 0.18                   |
| 6256        | RF_SPD [A-B], CHWC_LWT [C-B], RF_SST [A-B]       | CHWC_DAT [B-A], RF_SPD [B-C],<br>CHWC_LWT [B-A]  | 0.89        | 0.8        | 15                    | 0.09                   |
| 6226        | RF_SPD [A-B], CHWC_LWT [C-B], RF_SST [A-B]       | CHWC_DAT [B-A], RF_SPD [B-C],<br>SA_TEMP [B-A]   | 0.89        | 0.8        | 15                    | 0.09                   |
| 6936        | RF_SPD [A-B], CHWC_LWT [C-B]                     | CHWC_DA T [B-A], RF_SPD [B-C],<br>SA_TEMP [B-A]  | 0.889       | 0.8        | 15                    | 0.18                   |
| 1933        | SF_SPD [A-B], EA_DMPR [A-B], RF_WAT [A-B]        | CHWC_LWT [B-A], SA_TEMP [B-A]                    | 0.75        | 0.8        | 15                    | 0.27                   |
| 1934        | SF_WAT [A-B], EA_DMPR [A-B], RF_WAT [A-B]        | CHWC_LWT [B-A], SA_TEMP [B-A]                    | 0.75        | 0.8        | 15                    | 0.27                   |
| 5257        | RF_SPD [A-B], EA_DMPR [A-B], RA_CFM [A-B]        | RF_SPD [B-C]                                     | 0.82        | 1          | 30                    | 0.18                   |
| 5259        | RF_SPD [A-B], EA_DMPR [A-B], RF_SST [A-B]        | RF_SPD [B-C]                                     | 0.82        | 1          | 30                    | 0.09                   |
| 6415        | RF_SPD [A-B], CHWC_LWT [C-B],<br>RF_WAT [A-B]    | RF_SPD [B-C], CHWC_LWT [B-A]                     | 0.8         | 0.8        | 15                    | 0.09                   |
| 6416        | RF_SPD [A-B], CHWC_LWT [C-B], RF_DP [A-B]        | RF_SPD [B-C], CHWC_LWT [B-A]                     | 0.8         | 0.8        | 15                    | 0.09                   |
| 6126        | RF_SPD [A-B], CHWC_LWT [C-B],<br>RF_WAT [A-B]    | RF_SPD [B-C], CHWC_LWT [B-A],<br>SA_TEMP [B-A]   | 0.89        | 0.8        | 15                    | 0.09                   |
| 8309        | RF_SPD [A-B], CHWC_LWT [C-B],<br>EA_DMPR [A-B]   | RF_SPD [B-C], CHWC_LWT [B-A],<br>SA_TEMP [B-A]   | 0.78        | 0.78       | 15                    | 0.09                   |
| 15268       | RF_SPD [A-B], EA_DMPR [A-B], RF_WAT [A-B]        | RF_SPD [B-C], SA_TEMP [B-A]                      | 0.8         | 0.89       | 30                    | 0                      |
| 15269       | RF_SPD [A-B], EA_DMPR [A-B], RF_DP [A-B]         | RF_SPD [B-C], SA_TEMP [B-A]                      | 0.8         | 0.89       | 30                    | 0                      |
| <b>1253</b> | <b>SF_SPD [A-B], EA_DMPR [A-B], RF_WAT [A-B]</b> | <b>SA_TEMP [B-A]</b>                             | <b>0.70</b> | <b>0.8</b> | <b>15</b>             | <b>0.27</b>            |
| 1254        | SF_WAT [A-B], EA_DMPR [A-B], RF_WAT [A-B]        | SA_TEMP [B-A]                                    | 0.70        | 0.8        | 15                    | 0.27                   |
| 1406        | SF_WAT [A-B], EA_DMPR [A-B], RF_WAT [A-B]        | CHWC_DAT [B-A], SA_TEMP [B-A]                    | 0.70        | 0.8        | 15                    | 0.27                   |
| 5240        | CHWC_EWT [D-C], EA_DMPR [A-B],<br>RF_WAT [A-B]   | CHWC_DAT [B-A], SA_TEMP [B-A]                    | 0.70        | 0.8        | 30                    | 0.27                   |

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1397 Table B reports 26 rules (two for each unique consequent transaction) extracted from the transient

1398 dataset with the specification of the event chains of antecedent and consequent, the value of support

1399 and confidence within the ACTUAL TIME LAG and its duration (evaluated on the training dataset),  
1400 and the SUPP.DAY<sub>FAULTY</sub> (evaluated on the testing dataset).