Fault detection and diagnosis of low delta-T syndrome in air handling unit cooling coils

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FAULT DETECTION AND DIAGNOSIS OF LOW DELTA-T SYNDROME IN AIR HANDLING UNIT COOLING COILS

Karthik Mallikarjun Gunderi
29 October 2022

EINDHOVEN UNIVERSITY OF TECHNOLOGY
Stan Ackermans Institute
SMART BUILDINGS & CITIES

FAULT DETECTION AND DIAGNOSIS OF LOW DELTA-T SYNDROME IN AIR HANDLING UNIT COOLING COILS

By

KARTHIK MALLIKARJUN GUNDERI

A thesis submitted in partial fulfillment of the requirements for the degree of
Professional Doctorate of Engineering

The design described in this thesis has been carried out in accordance with the TU/e Code of Scientific Conduct

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Karthik Mallikarjun Gunderi

ABSTRACT

In the built environment, most energy is used to promote well-being, health, and comfort. The demand for cooling will increase sharply as a result of global warming, better thermal insulation, and the heat island effect. It is therefore increasingly important that cooling installations function optimally. Currently, there are many chilled water installations that suffer from the so-called low delta-T syndrome. The return water temperature from the installations is lower than predetermined and the difference with the supply temperature is smaller, low delta-T. This has adverse consequences for the efficiency of the chillers and/or heat pump and for the energy consumption of the pumps. The result is an energy consumption that is 20-40% higher for cooling than calculated in advance. It is important to be able to detect and analyze the low-dT syndrome properly. Based on this, a software module has been developed that can use the data from a building management system to determine the low-dT syndrome and identify possible causes. Building management systems can be equipped with fault detection and diagnosis module for continuous monitoring of the performance of installations, and continuous commissioning (Cx). This would ensure that the energy consumption of the cooling installations remains as low as possible. Within the project, the first prototype of such a module was built. This will be further refined and expanded in ongoing future projects of other PDEng trainees.

CONTENTS

NOMENCLATURE

FDD – Fault Detection and Diagnosis

HVAC – Heating, Ventilation and Air Conditioning

AHU – Air Handling Unit

BMS – Building Management System

WP – Work package

ML – Machine Learning

DBN – Diagnostic Bayesian Network

4S3F – 4 Symptoms 3 Faults

MFR – Mass flow rate

RWT – Return water temperature

SWT – Supply water temperature

SAT – Supply air temperature

RAT – Return air temperature

CCVP – Cooling coil valve position

CAV – Constant air volume

VAV – Variable air volume

DOE – Department of Energy (United States of America)

EMS – Energy Management System

P-S – Primary-Secondary

CPT – Conditional Probability Table

CHW – Chilled water

XGBoost – eXtreme Gradient Boosting

P&ID – Process and Information Diagram

1 INTRODUCTION

1.1 Background

The large-scale emission of greenhouse gases, including carbon dioxide (CO_2), has led to increasing global temperature levels and a rise in the associated threat of climate change. CO_2 emissions are a direct product of fossil fuel combustion. To ensure a temperature rise of below 2°C from the 1990 levels, the Paris Agreement was created by the European Union member states and close to 190 countries around the world (UNFCCC, 2015) complied with it. Each country has its own methods to achieve this target. In the Netherlands, the Trias Energetica (Duijvestein, 1996) and the 5-step (Gvozdenović *et al.*, 2015) approaches are used to achieve the required targets set for the country. In these methods, reducing the current energy demand is considered a very important step. This has a direct impact on the Built Environment sector where, Buildings are responsible for nearly 36% of the total energy consumption (678 PJ) ('Monitor energiebesparing gebouwde omgeving', 2017) of the country. Further, in the Netherlands, the commercial buildings consume a total of 272 PJ, wherein the Heating Ventilation and Air Conditioning (HVAC) systems alone consume 171 PJ (65% of the energy consumption by commercial buildings)('Monitor energiebesparing gebouwde omgeving', 2019). Studies report that typically 5- 20% savings in energy can be achieved by recommissioning HVAC systems (Mills, 2011). This is principally accomplished by the commissioning process which identifies deficiencies and drifts from intended performance and carries out interventions to put the HVAC systems back on course (Mills, 2011). Hence, reduction of energy demand by HVAC systems represents a low-hanging fruit for the Built Environment industry. Commissioning of the HVAC systems not only leads to energy savings and in turn cost savings but also improved thermal comfort and better rental values for the buildings by positively influencing the market.

Moreover, the energy performance building directive (EPBD) (Parliament, 2018) of 30 May 2018 provides a legal framework to encourage measures to exploit the large potential for energy efficiency gains in the Built Environment sector. The amended EPBD also requires a smart readiness indicator (SRI) for buildings which has an expected advantage of promoting automatic diagnosis and maintenance prediction. It specifies guidelines for the effective implementation of EPBD in two key areas.

1. building automation and controls;
2. optimization of building energy performance under "real-life use conditions" which points to performance under both full-load and part-load conditions.

1.2 HVAC and AHUs of buildings

HVAC systems maintain desired environmental conditions: temperature, humidity, and space pressure within a space inside a building. These systems can be either centralized or decentralized. Central cooling and/or heating systems are particularly used in large buildings. Air conditioning is characterized by a central chilled water (CHW) refrigeration and distribution system. The cooling energy for refrigeration can be supplied by a nonsustainable source (i.e. chillers), a sustainable CHW-installation (i.e. Thermal Energy Storage), or a combination of both (i.e. district cooling). The system flow design which is typically used in a central system is the primary/secondary variable flow system (Figure 1) which decouples the primary production system and commonly incorporates a constant flow. A variable flow secondary piping system distributes the chilled water to the point of use. This is typically the cooling coil in the Air Handling Unit (AHU), which depending on the design of the cooling system, is one of the largest chilled water users (Kirsner, 1995; Taylor, 2002). The primary and secondary piping systems are decoupled using a bypass pipeline between primary and secondary systems.

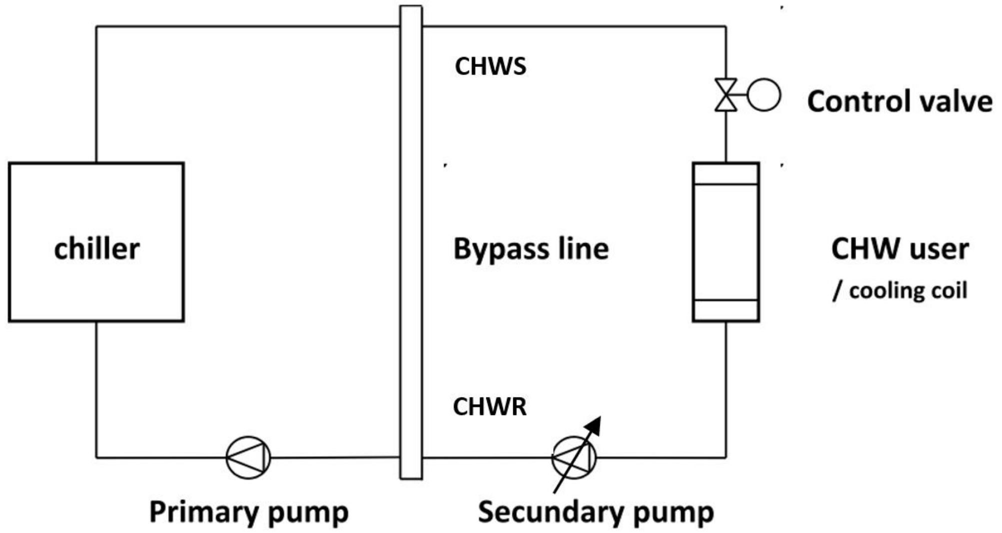


Figure 1: Primary/Secondary flow diagram of a chilled water system

1.3 Chilled water systems: Problem identification

Most primary/secondary variable flow chilled water systems as described in the previous section are designed based on the assumption that the delta-T which is the difference between return and supply chilled water on the secondary side, remains constant with the cooling load being matched by the variable flow rate of the chilled water (Taylor, 2002). However, in almost all real chilled water systems, the delta-T falls below the designed value and this is recognized as the low delta-T syndrome. It has been known for approximately three decades and is encountered in most larger CHW-installations (Kirsner, 1995). The low delta-T syndrome has been known to cause at least three problems: increased pump energy usage and an increase in chiller energy usage which could also lead to failure in meeting the cooling loads (Taylor, 2002). Taylor et al. (Taylor, 2002) reported a total of 17 causes of the low delta-T syndrome and further classified them into 3 groups: avoidable causes, mitigable causes, and inevitable causes based on whether these causes can be resolved or not. They are principally related to:

- cooling coil – improper sizing;
- reduced coil effectiveness;
- commissioning – improperly piped coils;
- valves used in the hydraulic circuit – poorly sized valves and improperly controlled valves;
- distribution of water in the hydraulic circuit – flow in the bypass line;
- and control strategies – improper setpoints and missing control valve interlock.

These causes can take different forms when the system flow design is not the simple primary/secondary variable flow system. As a result, they are not yet fully understood.

Some causes of the low delta-T syndrome have been detected and diagnosed using Fault Detection and Diagnosis (FDD) systems (Gao *et al.*, 2012, 2016). The main objective of FDD systems is early detection of symptoms and diagnosis of the faults, which enables the service engineers to act on the faults which cause the symptoms in a timely manner. It consists of two steps. First, the detection of observable faults, and second, the diagnosis of the faults. The sequence of these two operations can be different. In some cases, the detection program runs continuously, and the diagnosis comes online when a fault is detected. In other cases, both detection and diagnosis run parallelly, while in some instances detection and diagnosis happen in a single stage. Zhao et al.(Zhao *et al.*, 2019) classify detection and diagnosis models into the below-mentioned categories.

1. process-history /data-based models: which use patterns in measurements of data for detection or diagnosis;

2. knowledge driven based models: which use domain knowledge and the models have clear physical meanings.

While considering FDD for the case of low delta-T syndrome, the main symptoms include, but are not limited to, increased pump energy usage and chiller energy usage as described previously. The faults which cause these symptoms include, but are not limited to, the 17 causes listed by (Taylor, 2002) that are further discussed in Section-2 of this report. In literature, low delta-T syndrome FDD in chilled water systems report the use of both data-based and knowledge-based approaches.

Gao et al.(Gao *et al.*, 2012) diagnosed low delta-T syndrome occurring as a symptom deficit flow in the bypass line of primary-secondary CHW systems by using a rule-based detection method. In a subsequent study, Gao et al.(Gao *et al.*, 2016) used a combination of data-based and knowledge driven-based grey box model. These studies evaluated individual faults and diagnosed them. However, when several faults (from the 17 causes listed by (Taylor, 2002)) occur together and cause overlapping symptoms, using FDD for diagnosing low delta-T syndrome faults in cooling coils of AHUs is a challenging task. Additionally, in-situ measurements and investigations have been reported in order to detect, resolve, or to mitigate low delta-T syndrome (Kirsner, 1995; Gao, Wang and Shan, 2016). This task is complicated especially in modern buildings with CHW systems consisting up to hundreds of AHUs with different working conditions and cooling coil configurations (Almeida, 2014).

This problem is tackled by creating a project carried out by consortium of market parties (Kropman Installatietechniek and SystemAir), a research institute (Eindhoven University of Technology), a knowledge institute (ISSO), and representative of end-users (Radboud UMC and Stichting ROC Nijmegen). Kropman specializes in building automation for controlling, measuring, and monitoring the performance of the building and its installations with their proprietary Building Energy Management System (BEMS) software *InsiteView suite*. Technological innovation is a crucial strategy for market and product development in the field of maintenance and building management. In this view developing a solution for improving the energy efficiency of HVAC systems is in their interest - as it can lead to better performance in maintenance contracts and better economic gains along with providing their customers the most up-to-date and sustainable solutions. The other project partners:

- SystemAir, manufacturer of HVAC equipment, which will provide technical expertise and support for the project; is interested in making guidelines for improvement of AHU cooling coil issues;
- ISSO, a knowledge institute for the building installation industry; is interested in disseminating the results of the project to the Dutch industry;
- Radboud UMC and Stichting ROC Nijmegen, educational institutions, which will provide opportunities for user experience information; are interested in identifying extent of low delta-T syndrome problem in their installation and the causes of the problem.

1.4 Design Project Scope and Objectives

Considering the above-mentioned aspects, the goal of this project is to design, build and test a fault detection and diagnosis (FDD) tool to better detect and diagnose the low delta-T syndrome. This project will focus on one of the most frequently encountered CHW users: cooling coils in Air Handling Systems. The main design project questions are formulated as follows.

1. What are the low delta-T syndrome symptoms and related faults observed and reported in the literature for the cooling coil in an AHU which have the largest impact on the operation of CHW systems?

To answer this question, both scientific and technical literature was followed. This literature provides many causes(faults) for the low delta-T syndrome in a cooling coil of an AHU. In order to determine the combination of most impactful and most encountered causes (faults), Pareto analysis was used.

The characteristics of these shortlisted causes were then determined using a combination of literature study, simulation, and experimental testing.

2. What type of fault detection and fault diagnosis methods are most appropriate for detecting and diagnosing the faults related to low delta-T syndrome in the cooling coil of an AHU?

From academic literature, a fit-for-purpose FDD tool, for the specific purpose of detecting and diagnosing faults in the cooling coil of AHU which leads to the low delta-T syndrome, is selected and implemented. The improvement in detection and diagnosis rate with the addition or absence of particular sensors or control data was also determined. The FDD tool will be of little value unless it is tested on an operational CHW system. Therefore, the features of the FDD system are checked and the ability to detect and diagnose low delta-T syndrome causes with a high level of confidence is verified by implementing the FDD tool in a real building.

1.5 Project approach

In the followed approach, the entire project is broken up into four work packages as illustrated in Figure 2. The methodology requires the execution of some parallel steps hence the bi-directional arrows between WP1-WP2 and WP3-WP4.

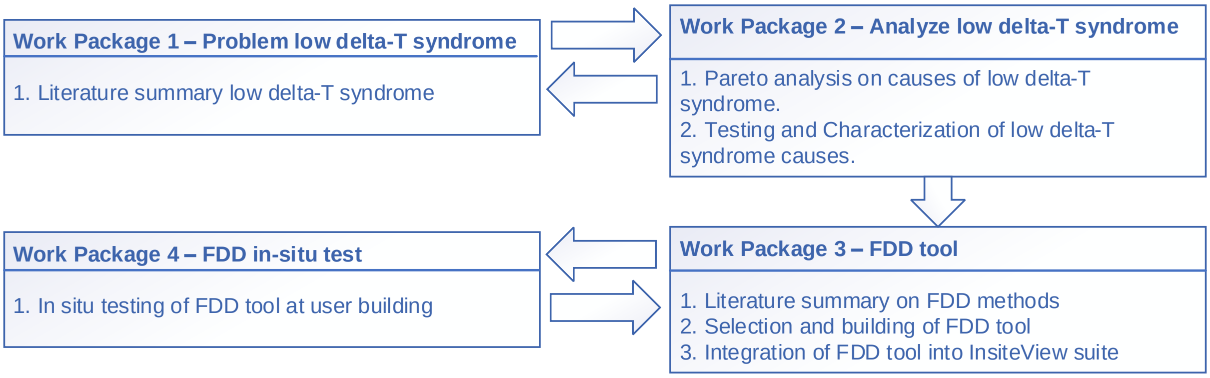


Figure 2: Proposed methodology

Work Package 1 – Problem of low delta-T syndrome

- **Literature summary on causes of low delta-T syndrome:** A literature summary using Science Direct and Google scholar was carried out along with using expert knowledge from engineers at Kropman to identify the reported causes of low delta-T syndrome.

Work Package 2 – Analysis of low delta-T syndrome

- **Pareto Analysis to determine the causes with most impact**: This was performed on the causes of low delta-T syndrome reported in academic literature and technical reports. This step was done to reduce the number of causes to the ones having the largest impact. According to Pareto's Law, the top 20% of the causes contributing to 80% of the adverse impact [ref]. This was applied to the causes of low delta-T syndrome by considering the most encountered causes and literature along with their reported impact.
- **Testing and characterization of low delta-T syndrome causes**: Historical data collected from BMS and experiments at the CHW system were carried out at Kropman office building and the end-user partners of this project. These collected data were analysed for characterization of the properties of the low delta-T syndrome and its causes from real building data.

Work Package 3 – FDD tool build and testing

- **Literature summary on FDD for detecting the low delta-T syndrome causes:** Requirements of the FDD software tool are determined based on interviews with potential users and developers. A literature summary of state-of-the-art FDD systems with a focus on the detection and diagnosis either as a single step or a sequential step was made, and their pros and cons were analysed.
- **Selection and building of FDD tool:** Based on information gathered from the FDD literature, three options will be shortlisted and compared to make the best selection. The FDD tool was programmed using Python, making it freely usable and distributable even for commercial use. Further, the Spyder IDE and Jupyter Notebook were used for developing the code along with libraries such as Scikit-learn, Numpy, and Pandas.
- **Integrating FDD tool into InsiteView suite:** InsiteView suite is the Building Energy Management System (BEMS) being developed by Kropman capable of communicating with different control systems, handling large amounts of data, and capable of integration with other data analysis systems. The Python based FDD tool will be linked to the data reporting engine of InsiteView suite so that operational data from CHW systems can be used to perform FDD.

Work package 4 – FDD tool for in-situ testing

- **In situ testing at operational CHW system:** The HVAC data from CHW systems at one office building was analysed. The data engineering and data check were performed for the data streams available from the building. With this, validation was performed to ensure that the FDD tool is robust and is able to detect and diagnose faults.

1.6 Outline of the report

The report is divided into 6 chapters. Chapter 2 focuses on the literature summary of Low delta-T syndrome. The results from the academic and technical literature review for the low delta-T syndrome are summarized in this chapter. Following this, Chapter 3, presents the analysis of low delta-T syndrome using Pareto study and experiments. Next, Chapter 4 describes the selection of FDD methods for the project and the design of the FDD tool. This chapter concludes with the development of algorithms for FDD of low delta-T syndrome. Chapter 5 presents the integration of the proposed FDD tool with the Kropman BMS system and discusses the results of in-situ testing of the FDD tool. Finally, Chapter 6 presents the Conclusions for the whole PDEng design project. The overall structure is shown below in Figure 3.

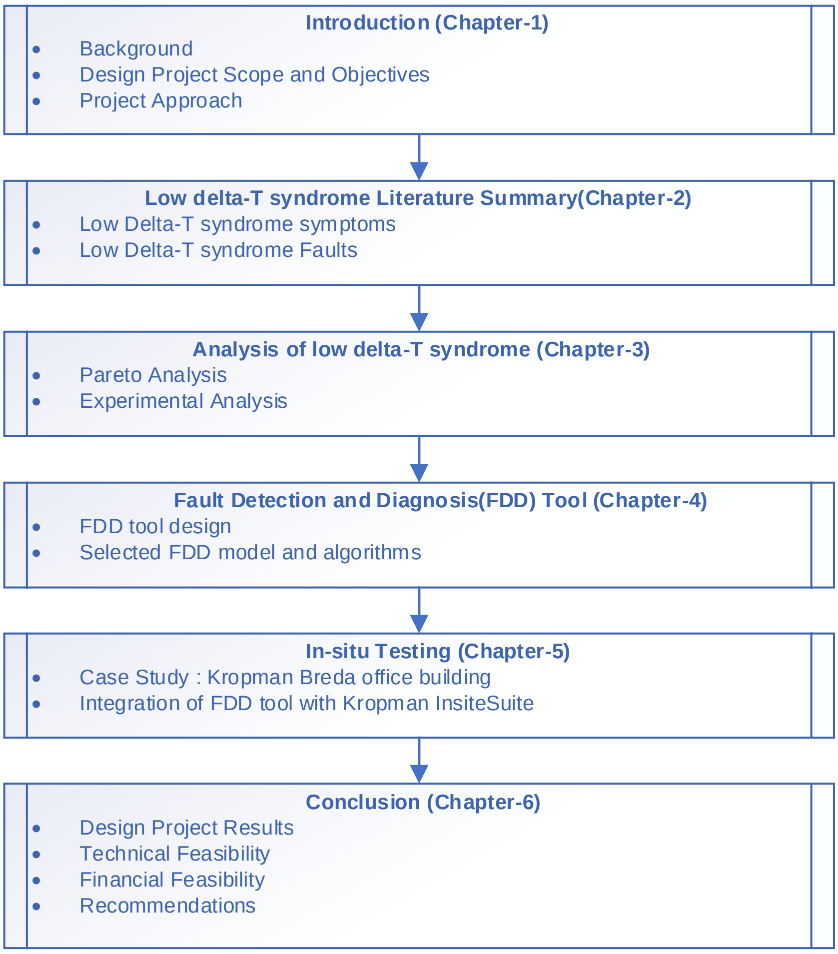


Figure 3: Diagram of the report structure

2 LOW DELTA-T SYNDROME LITERATURE SUMMARY

This section gives a description of the low delta-T syndrome. Further, it lists the symptoms and faults of low delta-T syndrome while focusing on the problems at the cooling coil. This is further used for the purpose of detecting the low delta-T syndrome in an AHU cooling coil.

2.1 Introduction

Most variable-flow chilled water systems are designed assuming a relatively constant delta-T, the difference between return and supply chilled water temperature. The cooling load (Q) is directly proportional to the flow rate ($\dot{m}_{CHW}$) and the delta-T (between the chilled water return(CHWR) temperature and chilled water supply(CHWS) temperature) as shown below in Equation (1). If the delta-T fails to remain relatively constant and drops below the designed levels, then the cooling system encounters problems that result in higher pump and chiller energy consumption.

$$Q = \dot{m}_{CHW} * C_{p,CHW} * (T_{CHWR} - T_{CHWS}) \qquad (1)$$

This phenomenon has been called by many names including - “low ΔT central plant syndrome” in (Kirsner, 1996). The author describes the problem as the ΔT of the chilled water returning to the campus (central) plant being below the design values for which the chillers and the pumps were selected. (Taylor, 2002) refers to this phenomenon as “low delta-T syndrome” and describes it for variable flow systems where the delta-T falls below the design levels, particularly at low load conditions. Further many of the latest studies on this phenomenon refer to it as the low delta-T syndrome (Gao, Wang and Shan, 2016; Dai, Lu and Xu, 2021).

The chilled water system consists of the supply side – typically the chiller, the demand side – which is typically the cooling coils and the hydronics and controls connecting both sides. In this study, a choice was made to focus on problem of low delta-T at the cooling coil.

2.2 Symptoms of low delta-T syndrome

Symptoms must be observable (is therefore a result of measurement) while faults are system diseases that lead to these symptoms (Taal and Itard, 2020). The observable symptoms of the low delta-T syndrome have been reported to be related to the components in the hydronic circuit, cooling coil, pumps, and chillers and also higher space temperature and humidity levels (Fiorino, 2002).

In this project, the scope is focused on low delta-T syndrome across a cooling coil. Hence the symptoms related to the cooling coil listed in Table 1, are described in the following section. Other symptoms relating to the performance of the chiller and hydronic circuit can be found in Appendix A1.

Table 1: Low delta-T symptoms relating to Cooling Coil

Sl.no	Symptom
1.	Excessive water flow in Cooling Coil
2.	Increased Pump Energy Consumption
3.	Increased CHWS Temperature at Cooling Coil
4.	Unmet LAT setpoint
5.	Power Saturation and Operation in waste zone

2.2.1 Excessive water flow

The load on a chilled water system is directly proportional to the product of the flow rate and the delta-T. A consequence of the fall in delta-T across by the cooling coil is that the flow rate of water increases to ensure that the load is met. Typical primary-secondary (P-S) based systems utilize two basic chiller control strategies: one based on flow and the other based on load. The flow-based strategies stage chillers and primary pumps to keep the primary flow larger than the secondary flow. Therefore, under this strategy, additional chillers and primary pumps are staged in reaction to reduced delta-T at the cooling coil. Meanwhile, the load-based strategy measures system load and brings additional chillers online when the current ones are fully loaded. So this system reacts to low delta-T by increasing the secondary loop flow rate (Taylor, 2002; Bahnfleth and Peyer, 2004).

2.2.2 Increased pump energy consumption

Excessive water flow as a result of the low delta-T syndrome is accompanied by an increase in the pump energy consumption. Pump energy theoretically is proportional to the cube of flow rate, although valid only for fully developed turbulent flow systems with fixed geometry. The actual pump energy impact will be lesser than the theoretical relationship suggests, but the increase will be significant.

2.2.3 Increased Chilled water supply temperature at consumer

The deficit flow in the P-S system results in mixing of the secondary loop return chilled water with the supply chilled water. This mixing leads to an increase in the chilled water supply temperature. Therefore, the chilled water consumers in the secondary loop observe an increased chilled water supply temperature.

2.2.4 Unmet Leaving Air Temperature (LAT) setpoint

In some cases, Low delta-T syndrome is likely to cause high temperature and humidity in the occupied room/zone. This can be attributed to the cooling coil not being able to fulfill the load demand even at the maximum chilled water flow rate under the low delta-T syndrome. Therefore, the Leaving Air Temperature setpoint for the AHU which the cooling coil belongs to cannot be met. In such a case both cooling and dehumidification demands may not be met leading to high space temperature and humidity.

2.2.5 Power saturation and Operation in waste zone

A cooling coil operating with the highest delta-T possible at all load conditions is advantageous in reducing the required water flow rate and associated pump power. Power saturation is a phenomenon due to which operating the cooling coil at the highest delta-T possible becomes difficult. It is identified as the water flow rate at which the rate of change of cooling power to flow rate is below a chosen minimum value, showing a poor increase in cooling power with an increase in flow rate (Bellucci, 2012). Operation of the cooling coil beyond this water flow rate, is said to waste pumping energy and use the reducing delta-T of the cooling coil with increasing flow rate. Operation of the cooling coil beyond the power saturation water flow rate is referred to as operation in the waste zone. Within this zone, the cooling power is almost stagnant showing no change with increasing water flow rate. Therefore, identification and operation of cooling coil outside the waste zone can avoid operating the cooling coil at lower delta-T conditions.

2.3 Faults leading to low delta-T syndrome

Taylor (Taylor, 2002) reported a total of 17 causes of low delta-T syndrome and further classified them into 3 groups: avoidable causes, mitigable causes, and inevitable causes based on whether these causes can be resolved or not. They are principally related to:

- cooling coil – improper sizing, reduced coil effectiveness;
- commissioning – improperly piped coils;

- valves used in hydraulic circuit – poorly sized valves and improperly controlled valves;
- distribution of water in the hydraulic circuit – flow in the bypass line;
- control strategies – improper setpoints and missing control valve interlock.

As the principal focus of this project is the *cooling coil*, the following section (2.3.1-2.3.9) describes nine low delta-T syndrome faults found through literature review, relating to the cooling coil in more detail.

2.3.1 Improper selection of Cooling Coil

Amongst all parameters that need to be chosen when selecting a cooling coil, the delta-T of cooling coil is important. Three advantages of a high delta-T are favorable in reducing the water flow rates, which affects the water side costs and the energy costs. However, it must be noted that high delta-T is detrimental to the air side energy usage. Higher delta-T requires higher overall heat transfer (area in form of fins and rows or higher heat transfer coefficient), which results in higher fan pressure drops and higher fan energy consumption. A common error in cooling coil selection is selecting the cooling coil for a delta-T that is lower than the plant design delta-T (Taylor, 2002). This can occur when engineers are unaware of the plant specifications, typically when a centralized plant serves multiple buildings. Further, replacement of either the chiller plant or cooling coils without confirming match between each other can also lead to this error. The impact of having a lower design delta-T of the cooling coil is that the system has excessive water flow than the originally intended system. Taylor(Taylor, 2002) describes this fault as an avoidable fault.

2.3.2 Fouled Cooling Coil /Damaged Cooling Coil

Heat exchanger effectiveness is defined as the ratio of actual heat transfer to the maximum possible heat transfer (Kays, London and Eckert, 1960). If the actual heat transfer on the water side or the air side reduces, this is an indication of the reduction in effectiveness of the heat exchanger.

On the water side, reduction in heat transfer can occur due to water-side fouling (corrosion, scaling, slime build-up). This will cause an increase in the flow rate of water required to meet the desired delta-T, at the given CHWS temperature and air flow rate. Higher chilled water flow delivered to a given Cooling Coil heat load can result in reduced CHWR temperature and thus reduced Cooling Coil delta-T.

On the air side, reduction in heat transfer can occur due to air-side fouling (dust build up) or air-side deterioration (deteriorating fins). This can cause an increase in the pressure drop on the air side, which can cause lower air flow rates at the same fan power. Therefore, leading to reduced space cooling capacity. Similarly, damage to the Cooling Coil, such as bent fins, which block air flow through it can result in a reduction in the capacity of the Cooling Coil. In response to the reduced maximum airflow, the space thermostat can then cause the chilled water valve to increase water flow rates, to compensate for the lower air flow rates with colder air, leading to low-delta-T syndrome. Further, at part load conditions, the increased pressure drop across the heat exchanger will lead to increased fan energy usage. Ma (Ma and Wang, 2011) reported a drop in delta-T of (0.5°C to 2°C) in both the primary and secondary loop when the simulated HVAC system was operated under air-side fouling of 30%. Taylor (Taylor, 2002) reports this fault as an unavoidable fault.

2.3.3 Flow in Cooling Coil –Transitional regime

At design conditions, flow-through cooling coils is typically in the fully turbulent flow region. At part-load conditions as the flow rate is reduced, the delta-T of the chilled water (CHW) across the coil increases because the flow is reduced to a greater degree than the load as the load falls off (Kirsner, 1995).

Transitional and laminar flow may occur at these partial load conditions when the flow rate of water is further reduced. A simplistic cooling coil model suggests that when the water flow becomes laminar in the cooling coil, the heat transfer coefficient reduces, leading to a drop in the delta-T of the CHW and thereby low delta-T syndrome. However, typical onset of laminar flow with falling flow rates is interrupted due to tube bends at the end of each row in the cooling coil. Li et al. (Li, 2012) studied the heat transfer performance of cooling coils under low cooling loads and concluded that on reaching transitional flow, the delta-T drops suddenly. However, further decrease in water flow rate causes the delta-T to rise. This was attributed to rising effectiveness of the coil with reducing water flow rate. Hence transitional flow does lead to drop in delta-T. However, laminar flow in the coil is not a cause for low delta-T. Taylor (Taylor, 2002) reports this fault as mitigable but further states that such an action may not lead to energy savings.

2.3.4 Oversizing of Cooling coil

Sizing of the cooling coil is a crucial aspect in the selection of the cooling coil for the chilled water system. An undersized cooling coil may not be able to meet the expectations for comfort and may not be able to meet the peak loads. On the other hand, oversizing the cooling coil provides flexibility to handle future loads at no cost impact although they carry a first-cost penalty. Further they provide a safety margin to deal with fouling of coils. Excessive oversizing of the cooling coil would also result in larger operation of the cooling coil in the laminar flow regime. Since the laminar flow regime is not fixed for a complex equipment like a coil, the drop in water side delta-T during transitional flow regime can lead to drop in the average delta-T produced by the coil.

2.3.5 Economizers & 100% Outdoor Air - Air Handling Unit

Airside economizer can be defined as a duct and damper arrangement and automatic control system that, together, allow a cooling system to supply outdoor air to reduce or eliminate the need for mechanical cooling during mild or cold weather. On systems designed with high delta-T, low delta-T syndrome can occur due to outdoor air economizers or 100% outdoor air systems. When the weather is cool but not cold enough to provide 100% of the system cooling load, these systems deliver 100% outdoor air but need a small amount of chilled water to meet cooling demands. Under these conditions, the air temperature entering the coil is low, causing correspondingly low return water temperatures. For instance, we can consider a cooling coil designed for 80°F entering air temperature (EAT), 44°F chilled water supply (CHWS) temperature and 18°F delta-T. At lower outdoor temperatures of 55°F to 65°F, the cooling coil would only be able to achieve a maximum of 11°F to 15°F restricted by the fact that chilled water return (CHWR) temperature must be lower than the leaving air temperature (LAT) (Taylor, 2002). Therefore, the low delta-T can be caused by lower outdoor air temperature in 100% outdoor air systems. Taylor (Taylor, 2002) reports this fault as an unavoidable fault.

2.3.6 Reduced setpoint for Leaving Air Temperature (LAT)

In many cases building operators respond to complaints about lack of cooling by temporarily reducing the set point temperature for Leaving Air temperature (LAT). In cases when this is not reset to the original design setpoint, it can lead to continuous reduction of the LAT set point. With all other conditions being same (air flow rate, air inlet conditions, CHWS temperature), the cooling load of the system increases. This is met by the control system by increasing water flow rate by opening the control valves wide which also leads to a drop in the delta-T of cooling coil. An example in Kirsner et al. (Kirsner, 1995) illustrates that a reduction in LAT set point from 54°F to 51°F can cause the flow rate to more than double and the delta-T to drop in half. This phenomenon leads to drop in the coil water side delta-T at the full load condition. Further, even at part-load conditions the improper set point can lead to excessive flow and reduced delta-T. Hence, reduced setpoint for LAT will lead to observation of low delta-T syndrome. Taylor (Taylor, 2002) reports this fault as an avoidable fault.

2.3.7 Air flow different from design High /Low

The cooling coil in a chilled water system is designed for certain conditions, which includes a chosen air flow rate. Due to changing use of a building, it may be required to run the Air Handling Units in the chilled water system at increased air flow rates. This increased air flow rates can be the cause of reduced waterside temperature difference (delta-T) (Langan, 2018). Langan et al. states an example where a 15% increase in airflow with all conditions kept constant resulted in a degraded delta-T of 1.2°F and a 28% increase in the required water flow. In cases where the water flow rate cannot be increased, reaches its maximum value, the LAT also rises causing complaints in comfort.

On the other hand, reduced air flow can also be a cause for low delta-T syndrome (Taylor, 2002). Increased pressure drop across dirty filters can cause a reduction in air flow. This reduces the air-side heat transfer coefficient and reduces the overall system cooling capacity. Therefore, to satisfy the cooling load, the LAT setpoint can be lowered, causing lower return water temperature and thereby low delta-T syndrome (Taylor, 2002).

2.3.8 Improperly commissioned cooling coil – not counter flow

Cooling coils are typically designed and installed for operation in a counter-flow arrangement. A cooling coil piped in a counterflow arrangement can achieve “overlapping” temperature ranges with the supply air, e.g., the CHWS temperature at 44 °F and CHWR temperature at 60°F while the supply air (SA) temperature is 80°F and LA temperature at 55°F (Taylor, 2002). On the other hand, when coils are installed instead in a parallel flow arrangement with the water and air entering from same side, the CHWR temperature cannot be higher than the LAT. This causes a reduction of the waterside delta-T of the cooling coil. Further, this causes a reduction in the capacity of the cooling coil and excessive water flow at both part-load and full-load conditions. Hence, an improperly piped coil can cause low delta-T syndrome. Taylor (Taylor, 2002) reports this fault as an avoidable fault.

2.3.9 Air bypass or leaks around the cooling coil

Sauer (Sauer, 1989) reported that bypass arrangement around the cooling coil or air leakage around the cooling coil could potentially lead to low delta-T syndrome. The controls at the terminal unit will ask the cooling coil for a lower than design LAT as they measure an increased leaving air temperature due to mixing with the leaked or bypass air. This fault causes reduced LAT which in turn can lead to low delta-T syndrome.

3. ANALYSIS OF LOW DELTA-T SYNDROME

The major faults relating to low delta-T syndrome and the AHU cooling coil were identified from the literature and described in the previous chapter. With the goal of performing FDD on the low delta-T syndrome, analysis of low delta-T syndrome was identified as the next step. This analysis serves two purposes. First, prioritization of the faults according to their impact. This helps in focusing the attention of the FDD tool on the most impactful faults during the initial FDD prototype. And second, the characteristics of the low delta-T syndrome help in choosing the FDD methodology. Therefore the prioritization of the faults is performed using Pareto Analysis and a simulation tool. Further, characteristics of the low delta-T syndrome are identified by performing experiments on a real building.

3.1 Pareto Analysis

3.1.1 Methodology

Pareto analysis can help separate the "vital few" from the "trivial many". It is a quality control tool that ranks data, in descending order, from the highest frequency of occurrences to the lowest frequency of occurrences. The Pareto principle is termed as the 80/20 rule, according to which 80% of the problems are caused by 20% of the possible causes. It is not based on theoretical derivation but is used as a rule of thumb. The value of the Pareto principle lies in the fact it focuses attention and effort on the most frequent problem.

In this study, Pareto analysis is used to prioritize the low delta-T syndrome faults at the AHU cooling coil. The faults are ranked based on their impact. This would aid in identifying the faults which need the most attention. Literature on fault impact analysis (Li and O'Neill, 2019) for HVAC systems suggest ranking based on 1) Energy consumption and 2) Unmet hours of Temperature setpoint. Both these metrics were used to rank the faults.

The methodology followed to perform the Pareto Analysis is described in Figure 4. The first step was the selection of a suitable simulation tool that could perform building performance simulations along with fault simulations. Along with it, a typical building was selected while also selecting a weather file and HVAC system setup. Next, the fault simulation strategies were identified. Further, the building performance simulations for the baseline model and the fault models were carried out. The outputs from the fault models were compared with the baseline model to evaluate the KPIs and finally perform the Pareto analysis. These steps are discussed in the sections below.

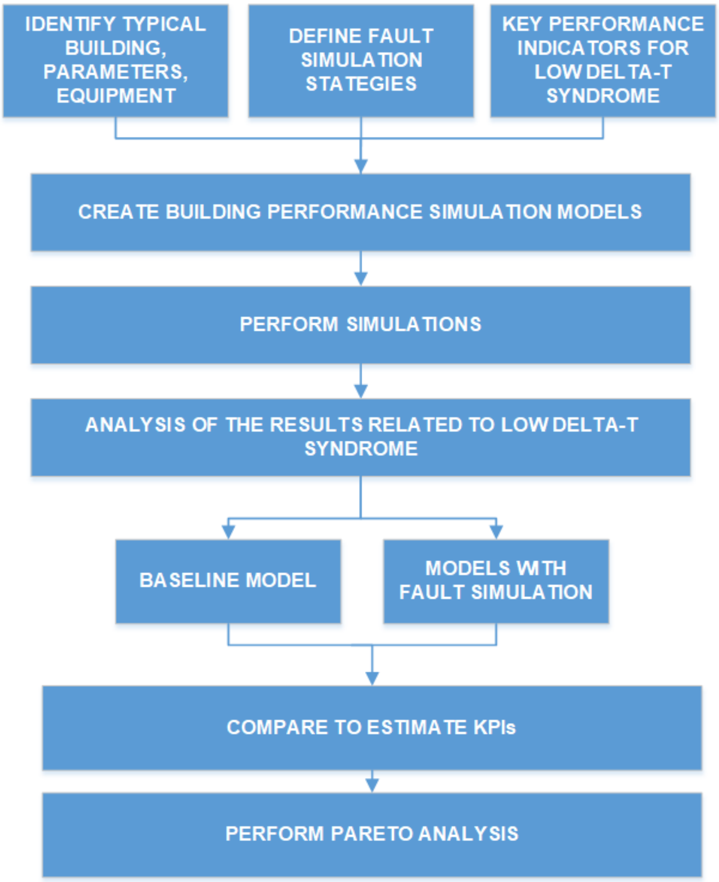
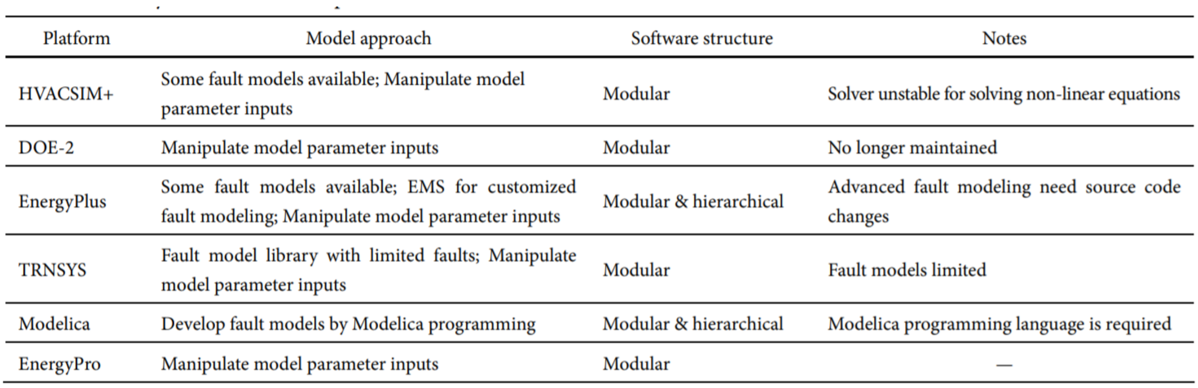


Figure 4: Methodology flowchart for Pareto Analysis

Fault Simulation platforms

Conventional building performance simulation software enables fault simulation modelling for the different HVAC components and systems. Table 2 lists the most commonly used simulation software for fault simulation as per the authors of reference [xx]. Based on a comparison of these, EnergyPlus was selected. Further, Table 3 lists recent literature which uses EnergyPlus for fault simulations. These articles were used to obtain information on how to simulate particular faults relating to the low delta-T syndrome.

Table 2: Summary of Fault simulation platforms (Li and O'Neill, 2018)



Platform	Model approach	Software structure	Notes
HVACSIM+	Some fault models available; Manipulate model parameter inputs	Modular	Solver unstable for solving non-linear equations
DOE-2	Manipulate model parameter inputs	Modular	No longer maintained
EnergyPlus	Some fault models available; EMS for customized fault modeling; Manipulate model parameter inputs	Modular & hierarchical	Advanced fault modeling need source code changes
TRNSYS	Fault model library with limited faults; Manipulate model parameter inputs	Modular	Fault models limited
Modelica	Develop fault models by Modelica programming	Modular & hierarchical	Modelica programming language is required
EnergyPro	Manipulate model parameter inputs	Modular	—

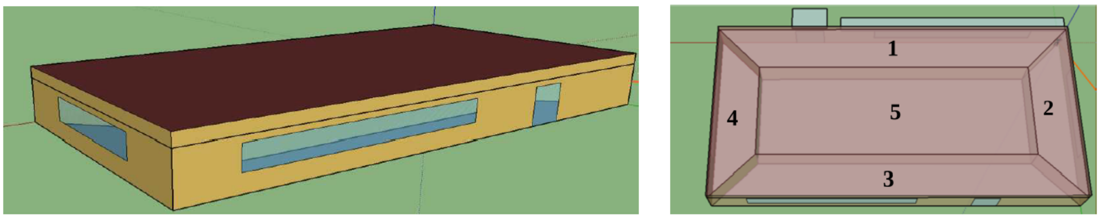
Table 3: Recent Literature using EnergyPlus for fault modelling

Year	Title	Author	Journal	Description
2016	Hybrid Model-based and Data-driven Fault Detection and Diagnostics for Commercial Buildings	(Frank *et al.*, 2016)	NREL	EnergyPlus is used to generate normal and faulty operation data for the year 2012 - 41 full year time series. These are divided into daily simulation results. Used regression and ML for whole building simulation.
2017	Modeling of HVAC operational faults in building performance simulation	(Zhang and Hong, 2017)	Applied Energy	Using EnergyPlus 8.6, standard faults in Economizer sensor, thermostat offset, coil fouling, and dirty air filters investigated for a case study. Annual cooling energy consumption and unmet hours are used for fault impact.
2019	An innovative fault impact analysis framework for enhancing building operations	(Li and O'Neill, 2019)	Energy and Buildings	Building faults are ranked based on impact on energy penalty and occupant comfort using EnergyPlus simulation. 129 fault modes in different components and systems simulated with 12000 EnergyPlus simulations.
2019	Representing Small Commercial Building Faults in EnergyPlus, Part	(Kim, Frank, Braun, *et al.*, 2019)	Buildings	EnergyPlus is used to generate training data for FDD algorithms. 25 fault models are addressed in this study.

	I: Model Development			
2019	Representing Small Commercial Building Faults in EnergyPlus, Part II: Model Validation	(Kim, Frank, Im, *et al.*, 2019)	Buildings	
2019	Early detection of faults in HVAC systems using an XGBoost model with a dynamic threshold	(Chakraborty and Elzarka, 2019)	Energy and Buildings	Synthetic data with building faults are generated using EnergyPlus. This is used for testing fault detection algorithms.

3.1.2 EnergyPlus Simulation Model

An EnergyPlus model representing a single-floor building was chosen from the standard templates available in EnergyPlus example files. Since the main goal was to compare the faults with baseline and obtain a relative ranking of their impact, the single-floor office building was chosen. Subsequently, the faults at different intensity levels were individually implemented on the baseline model and simulated. Finally, the energy and comfort impacts were investigated relative to the baseline model.



(a) (b)

Figure 5: 5zone Building a)Side View b)Top View

The single-floor EnergyPlus model represents a rectangular building of size 30.5 m x 15.2 m as shown in Figure 5. There are 5 zones; 4 exteriors, 1 interior, with a zone height of 2.4 m. The Exterior zone depth is 3.7 m. There is a 0.6 m high return plenum. The overall building height is 3m. There are windows on all 4 facades; the south and north facades have glass doors. The south-facing glass is shaded by overhangs. The walls are wood-shingle over plywood, R11 insulation, and gypboard. The roof is a gravel built-up roof with mineral board insulation and plywood sheathing. The floor slab is 0.1 m of heavy concrete. The windows and glass doors are double pane Low-e clear glass with argon gap. The window to wall ratio is approximately 0.3. The building is oriented with the long axis running east-west.

Table 4: EnergyPlus Model Details

Model Characteristic	Value
Floor Area	463.6 m2
Internal Loads	Lighting: 16 W/m2 Office equipment: 10.8 W/m2 Occupancy: 1 occupant per 7 m2 of floor area (NEN 1824:2010)

Occupancy schedule (occupancy fraction)	Monday-Friday: 8-12 : 1 ; 12-13 : 0.5 ; 13-17 : 1 Saturday & Sunday: 0
HVAC Schedule (on/off schedule)	Monday-Friday: 7-18:1 Saturday & Sunday: 0
Weather file	Amsterdam 062400 (IWEC)
Zone Thermostat Setpoints	Heating: 21.1 °C Cooling: 23.9 °C
Cooling Supply Air Temperature Setpoint	12.8°C
Outdoor Air	100% Outdoor Air Cooling & Heating

The demand side details of the building are listed in Table 4. Further, the building supply-side details are enumerated below:

Air side:
1. Fan - Variable speed fan was chosen
2. Cooling Coil Water– NTU effectiveness model was chosen with a cross-flow configuration

CHW side:
1. Circuit type – Constant Primary – Variable Secondary
2. Pumps – Constant speed; Variable speed pump
3. Chilled water generation – Chiller:Electric:EIR with reference COP of 3
4. Chiller condenser type – Air-cooled

Two main variants of Chillers are used in the simulations. Simulation A (SimA) (Figure 6) uses a single chiller while Simulation B (SimB) (Figure 7) uses multiple (3 chillers for this simulation) chillers to satisfy the cooling load. Each chiller is coupled with a constant speed primary pump. In SimA, the maximum flow rates of the primary constant speed and secondary variable speed pumps are equal. Hence deficit flow in the decoupler is avoided because the primary flow rate is always greater than or equal to the secondary flow. On the other hand, SimB allows the possibility of deficit flow in the decoupler because it has three constant speed pumps on the primary side which switch on along with their respective chillers.

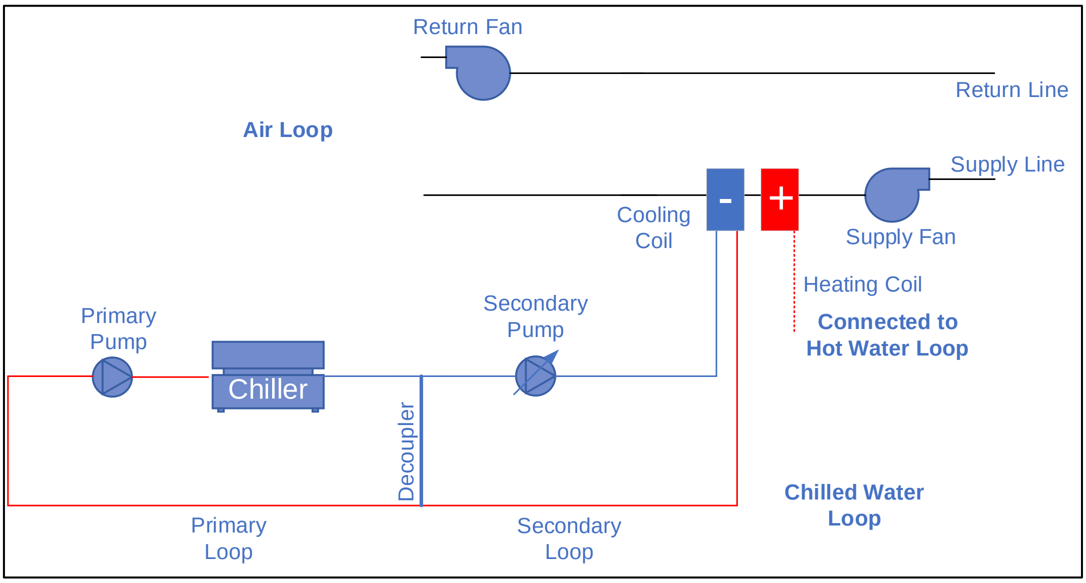


Figure 6: SimA, Schematic of VAV AHU and Primary-Secondary Chilled Water Loop with one chiller

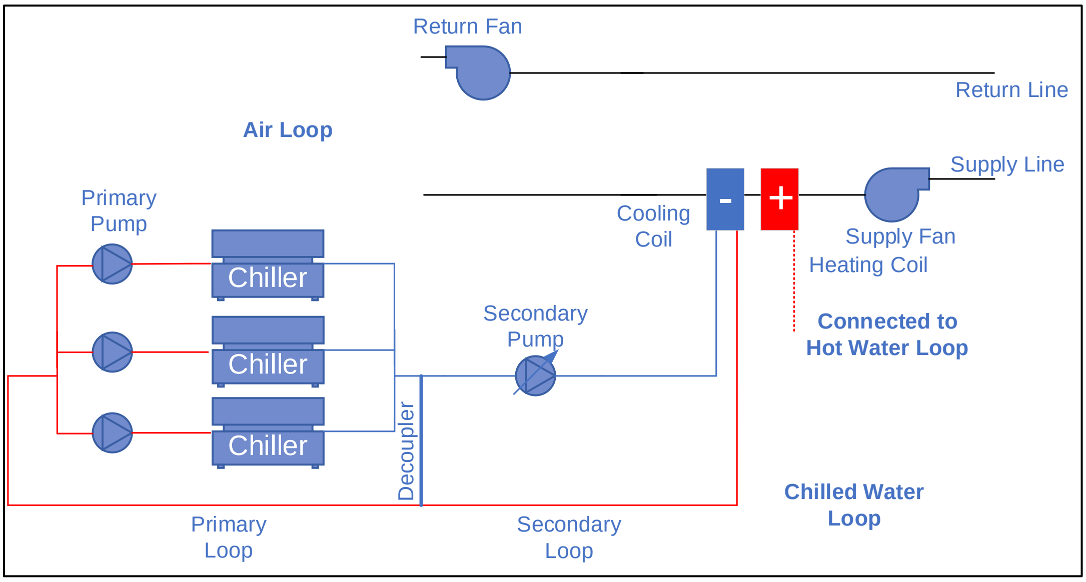


Figure 7: SimB, Schematic of VAV AHU and Primary-Secondary Chilled Water Loop with three chillers

Fault models for the low delta-T syndrome faults at AHU cooling coil

The literature review carried out on low delta-T syndrome faults in AHU cooling coils revealed 9 faults. These are listed in Table 5 along with information on simulating these faults in EnergyPlus for 3 faults: Fouled Cooling Coil, Reduced Setpoint of Leaving Air Temperature, and Airflow different from design. The other faults could not be simulated in EnergyPlus and hence are not considered further.

The fouled cooling coil is simulated by increasing the thermal resistance on the airside and waterside of the cooling coil. This is done by reducing the *Fin Surface Area* for the former and the *Total Tube Inside Area* for the latter. These parameters are used in the *Detailed Geometry Cooling Coil* to calculate the thermal resistance at the beginning of the simulation. Hence by modifying these, fouling can be simulated. This is done at two intensity levels by reducing the areas by 10% and 20%.

Reduced Setpoint of *Leaving Air Temperature* is simulated by changing the setpoint temperature for the supply air measured at the *Supply Fan Outlet*. Three intensity levels are simulated by reducing the setpoint temperature of 12.8°C by 1 °C, 2 °C, and 3°C.

Air flow difference from design is simulated by changing the maximum flow rate of the variable speed fans. This fault is simulated at two intensity levels of +10% (increased flow rate) and –10% (decreased flow rate) from the baseline maximum air flow rate.

Improper selection of cooling coil with design DT of 10°F and 14°F are simulated inplace of the baseline design DT of 12°F. This is achieved by varying the Design water flow rate, keeping all other parameters constant.

Table 5: EnergyPlus simulation of low delta-T syndrome faults

	Low dT Fault - Cooling Coil	**Method**	**Fault Component**	**Faulty Parameter**	**Levels**
1	Fouled cooling coil	Increase cooling coil air side and water side resistance	FaultModel: Fouling:Coil	Total Tube Inside Area, Fin Surface Area	-10%[Foul_10], -20%[Foul_20]

2	Reduced setpoint Leaving Air Temperature (LAT)	Change setpoint Temperatures	SetpointManager: Scheduled	Schedule Name	-1 °C [LAT_1], -2 °C [LAT_2], -3 °C [LAT_3]
3	Air flow different from design High/Low	Vary fan operating conditions	Fan: VariableVolume	Maximum Flow Rate	10% [AF_High], -10%[AF_Low]
4	Improperly sized cooling coil – different design DT of cooling coil	Varying the Design water flow rate, keeping all else constant, varies the design DT	Coil:Cooling: Water	Design Water Flow rate	10°F [LDT], 14°F [HDT]

3.1.3 EnergyPlus Simulation results

The faults of low delta-T syndrome relating to the Air Handling Unit cooling coil need to be prioritized according to their impact. EnergyPlus simulation software was used to simulate the low delta-T syndrome faults for a model building to prioritize the faults according to their impact. The impact was measured on two dimensions, the first being energy usage and the second unmet hours of cooling. The low delta-T syndrome faults are simulated on two variants of a VAV AHU based centralised cooling. The following sections discuss these results.

EnergyPlus Baseline model results

The baseline models for SimA and SimB are generated using the HVAC and building model are described in the previous section. Figure 8 illustrates the variation of the cooling coil delta-T with the cooling load for both SimA and SimB. At outdoor air temperatures below 14 °C (design CHWR temperature), the CHWR temperature cannot go lower than the coil EAT (Entering Air Temperature). In these cases, the low delta-T observed is unavoidable, which is highlighted in the figures. Further, in the SimB-Baseline delta-T values between 1 °C and 3 °C are observed. This can be explained by Figure 9, which shows that the SimB-Basline simulation does not have a constant CHWS Temperature. This is because of deficit flow in the decoupler pipe which causes an increase in CHWS temperature. This phenomenon is not observed in SimA-Baseline simulation because deficit flow does not happen.

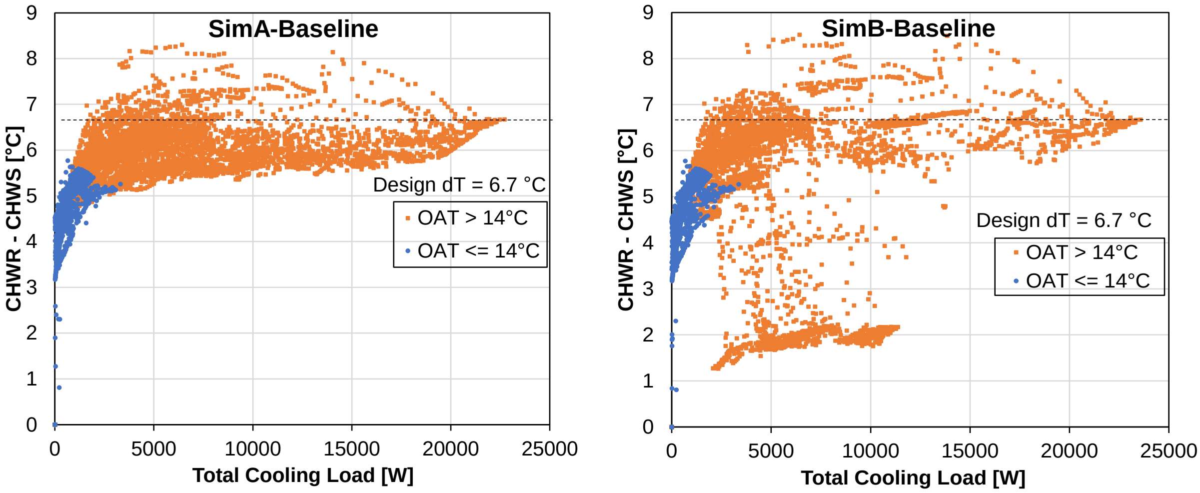


Figure 8: Cooling coil delta-T vs Total Cooling Load; OAT-Outside Air Temperature. The Design dT is highlighted using a dotted line

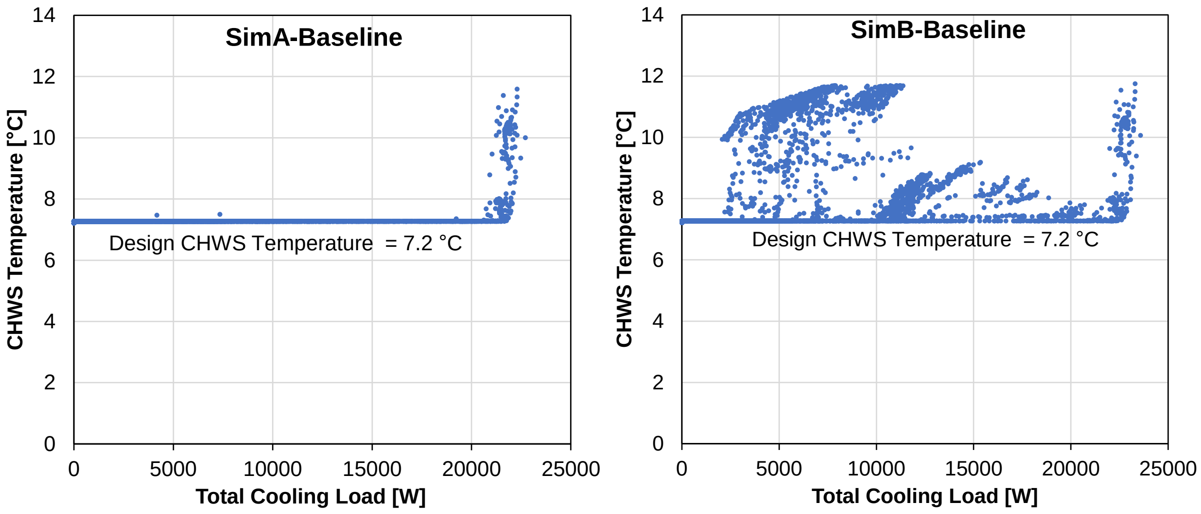


Figure 9: CHWS Temperature vs Total cooling load

Table 6 shows the baseline metrics of the simulations for the two variants of the chiller system SimA and SimB. Both systems were sized with the same total chiller electric power and pump electric power. The total number of unmet hours of cooling determines the sizing of the cooling coils. According to the total cooling setpoint not met time, EnergyPlus automatically sizes the cooling coil. This was kept around 16-20 hours as can be seen in Table 6. The average delta-T for the SimB is lesser than SimA by 0.6°C. This in turn leads to the higher average secondary pump electric power of SimB(33 W) compared to SimA(12W) by nearly three time. However, the advantage of having a multi chiller setup in SimB can be seen for the average chiller electric power which is 23% lesser for SimB compared to SimA. In addition the average primary pump electric power is lesser because the constant speed primary pumps in SimB are coupled to the chillers.

Table 6: Baseline metrics of SimA and SimB. The average is calculated for the hours the HVAC is on – 07:00 to 18:00 during the working days of the week.

	SimA – One Chiller	SimB – Multi Chiller
Average Delta-T [°C]	6.33	5.57
Average Total Cooling Electric Power [W]	3760	2900
Average Chiller Electric Power [W]	2690	2170
Average Secondary Pump Electric Power [W]	12	33
Average Primary Pump Electric Power [W]	132	99
Total Cooling setpoint not met time [hr]	16	20
Total Chiller capacity [W]	29000	29000

EnergyPlus Fault model results

The Baseline models for SimA and SimB are used for calculating the impact of the simulated low delta-T faults. The Figure 10 shows the annual average delta-T normalized with the baseline simulation. The reduced setpoint of LAT has the largest reduction of annual average Delta-T. There is a direct relation to the drop in delta-T to the reduction in LAT setpoint. Next, improperly sized cooling coil with lower design delta-T causes the next highest reduction in annual average design delta-T. It is seen that the higher airflow rate fault causes drop in the annual average delta-T by 2-3% confirming the observation from (Langan, 2018).

Figure 11 and Figure 12 present the impact of the faults on the cooling electricity power consumption and the number of unmet hours of cooling. The total cooling electric power consists of pump electric power, the fan electric power and the chiller electric power. The electric power is the annual average value. The reduced LAT setpoint fault has the highest impact on both the secondary pump electric power and the chiller electric power, followed by the lower design delta-T fault. The same trend is true for the total electric power.

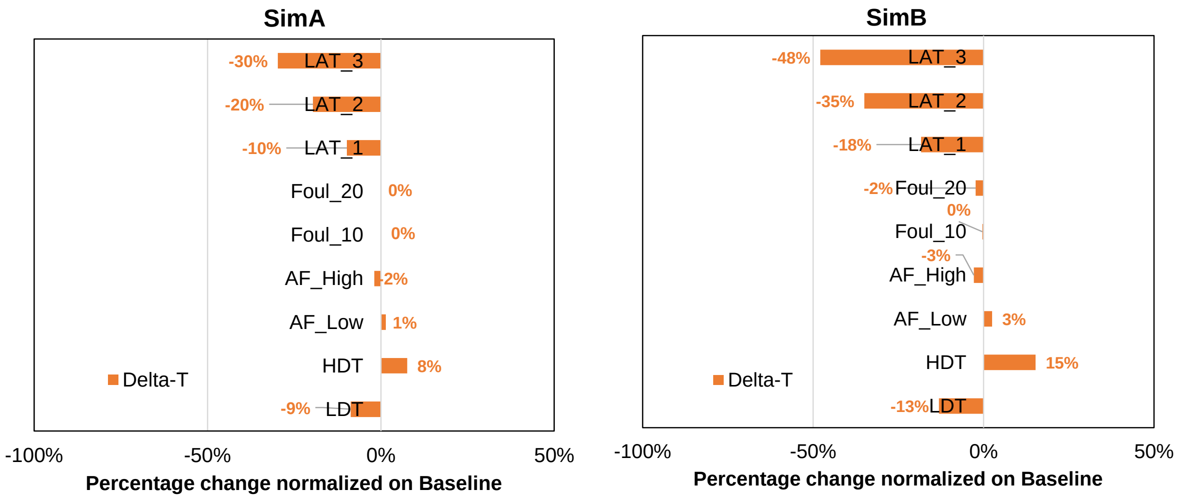


Figure 10: Annual average Delta-T normalized with Baseline simulation. Abbreviations: LAT (Leaving Air Temperature); Foul(Fouling); AF(Air Flow); HDT(High Design DT); LDT(Low Design DT)

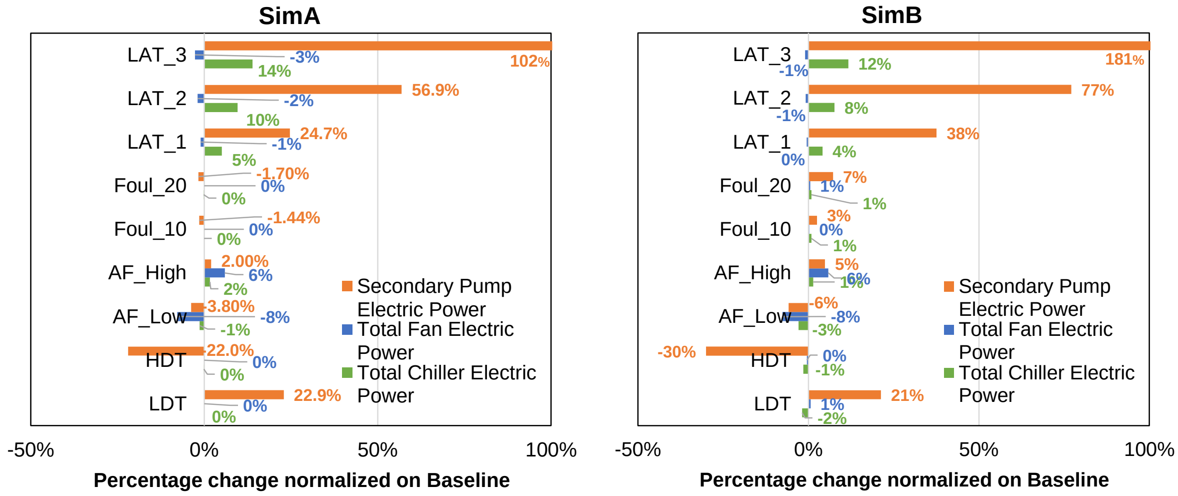


Figure 11: Annual average components electric power normalized on Baseline simulation. Total Chiller includes Chiller, Air Cooled Condenser, and Primary CHW pump. Abbreviations: LAT (Leaving Air Temperature); Foul(Fouling); AF(Air Flow); HDT(High Design DT); LDT(Low Design DT)

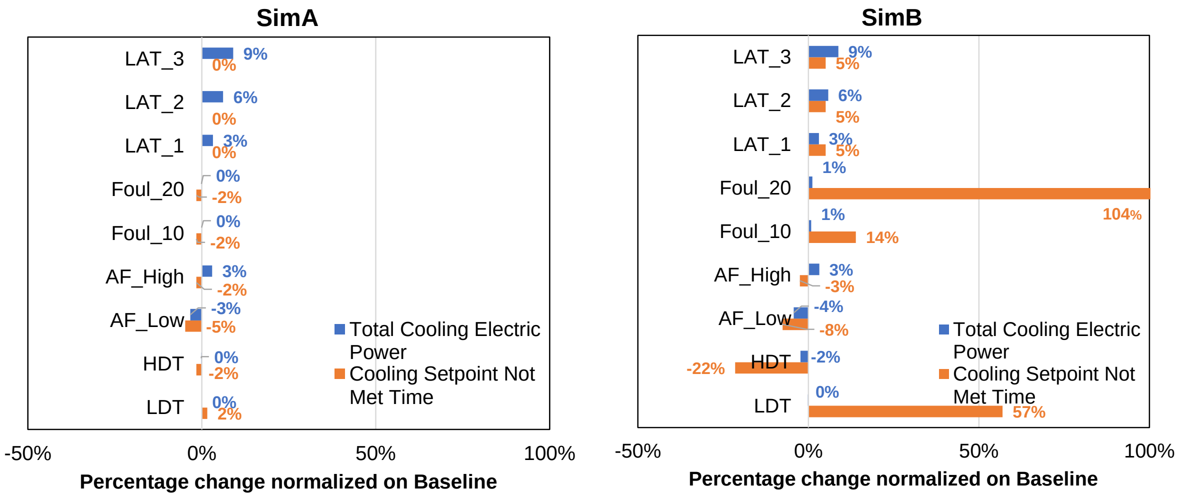


Figure 12: Sum of annual cooling setpoint not met time, and the average of total cooling electric power normalized on Baseline simulation. Abbreviations: LAT (Leaving Air Temperature); Foul(Fouling); AF(Air Flow); HDT(High Design DT); LDT(Low Design DT)

From the EnergyPlus simulations it can be concluded that the reduced LAT fault has the highest impact and needs to identified for effective FDD of low delta-T syndrome. The Leaving Air Temperature of the cooling coil is synonymous with Supply Air Temperature provided by the cooling coil to the cooled zone. Further in this report both LAT and SAT fault refer to the same fault.

In addition the design fault of choosing a cooling coil with lower delta-T than for which the chilled water circuit was designed can lead to increased electricity consumption. Further, due to reduced cooling capacity the HVAC system may not be able to meet the cooling loads, leading to increased number of hours of unmet cooling.

In the next section the lessons from the simulation study applied to experimental study are described.

3.2 Experimental Analysis

In the project there were several options to study the low delta-T situation, see figure 13. Based on literature research, talking to building managers and also internal consultation within Kropman, an inventory was made based on the analysis of the low dT problems. It showed that the low-dT problem is particularly acute for larger buildings.

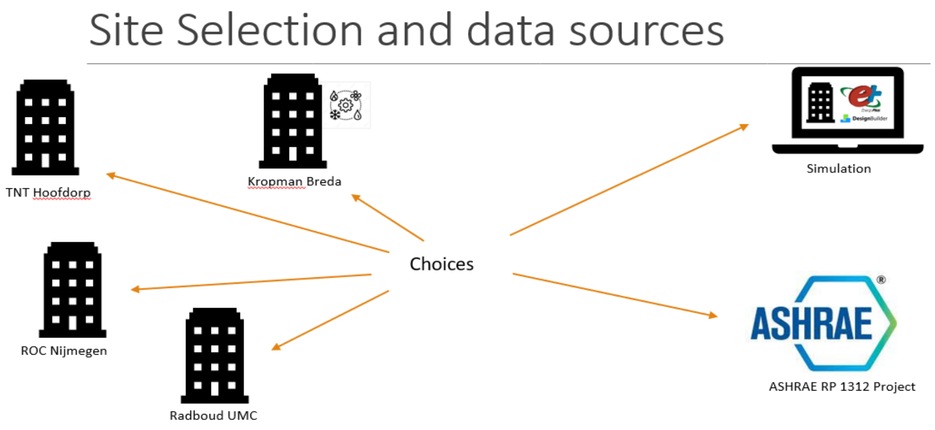


Figure 13: Different options to study the occurrence low-dT

Site visits and interviews were held with the people of the intended projects Radboud UMC, ROC Nijmegen and Kropman Breda. In addition, the TNT Office Hoofdorp was also visited.

One of the problems in practice is that as few sensors as possible are used to control the installations to save investments, figure 14 gives an overview of the sensors present at one of TNT's air handling units.

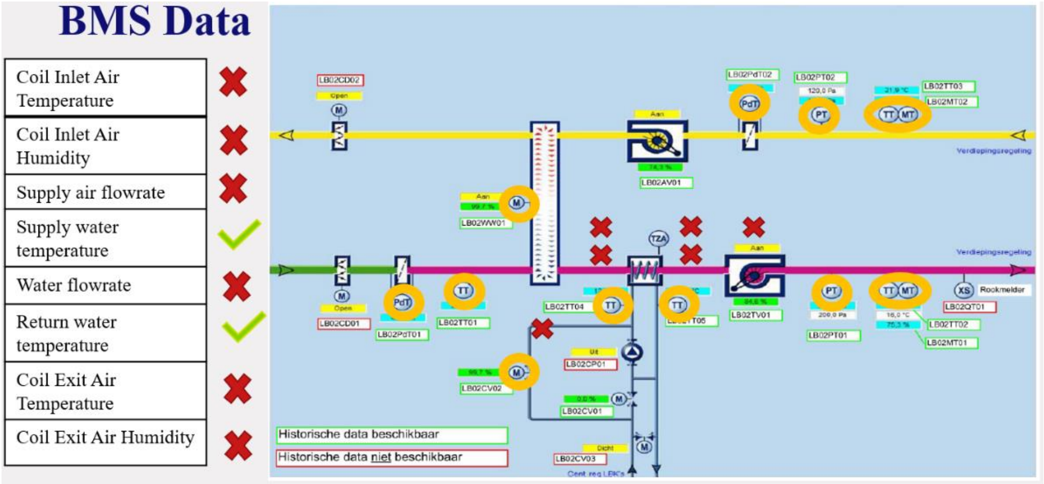


Figure 14: The sensors present in a practical situation

Many of the values you would like to know for condition monitoring of the cooled water battery are missing. To properly validate the model approach that is being developed for monitoring and detecting the occurrence of the low dT syndrome, additional sensors are therefore needed. These are additionally built in at Kropman Breda so that an accurate validation can be done

3.2.1 Methodology

From the simulation studies, Reduced Supply Air temperature and Increased Air Flow rate were identified as the most impactful faults which lead to low delta-T syndrome.

Simulation studies have the strength that many variations of faults can be studied with low investment of resources including money and time. Further, complete sensor information can be obtained within the systems under analysis. However, they are an imitation of the real building and often simplify interactions among the systems. Hence an experimental study was found to be necessary to 1)Observe the effect of the fault in a real dynamic system 2) Identify any new considerations from a real system 3) For the final process of FDD of low delta-T syndrome develop a test data set.

The ASHRAE 1312-RP(Wen and Li, 2011) project is a well-known study where the common AHU faults, including their features and severities, were identified. Experimental data of both faulty and non-faulty conditions from winter, spring and summer seasons were obtained. Stuck valve faults in typical 3-way valves were identified as one of the major faults. Hence this was also chosen for the experiments to be conducted in this study.

Experiments for the analysis of low delta-T syndrome were carried out at Kropman Breda. This section describes the experiments which were selected and carried out to simulate the effect of low delta-T syndrome. Further the data generated was used for building the FDD tool.

3.2.2 Kropman Breda

The Kropman Breda office building is a small sized 3-floors office building with 1650 m2. The office is a living lab allowing testing of innovative research based use cases and user interactions. It has multiple sensors placed in the office enviornment and the HVAC system. It provides a platform to carry out experimental studies in a real building while causing/having minimum distubance from the occupants.

The building has a constant volume air handling system that provides conditioned air to three zones. The AHU has a heating coil and humidifier along with a draw through fan. The three cooling coils are present outside the AHU and function as aftercoolers. The cooling coils are supplied chilled water from a two-stage chiller with a constant speed pump. The chilled water flowing through the cooling coils is regulated using 3-way valves. The P&ID schematics for HVAC can be found in Appendix A2.

The cooling in the building for each of the three zones is controlled using two PID loops as shown in The higher level loop controls the Supply Air Temperature setpoint to achieve required Return Air Temperature, which has a predetermined relationship to outdoor air temperature. The lower level loop controls the cooling coil valve position to achive the required supply air temperature setpoint.

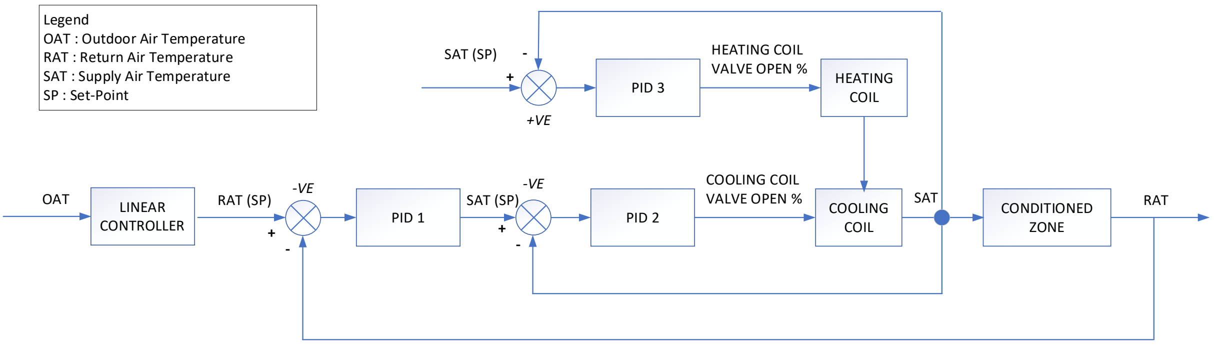


Figure 15: Control Loop for Cooling and Heating in Kropman Breda Office. Single aftercooler is shown

The building management system acquires and stores data from the sensors along with sending instructions to actuators and storing the sent data. Additional sensors were installed to measure the air side temperatures and humidities before and after cooling coil, air flow and water flow measurement meters and water side temperature before and after the cooling coil.

Table 7: Experiments performed at Kropman Breda

Serial.no	Fault	Severities	Number of days	
1.	Leaking Valve (Minimum Valve position)	20% 30%	2 2	Set in Priva BMS 3 Cooling Coils
2.	Stuck Valve (Valve Position)	50% 75%	2 2	Set in Priva BMS 3 Cooling Coils
3.	Reduced Setpoint Supply Air Temperature	16°C 17°C	2 2	Normal Setpoint for Supply Air Temperature is 18°C
4.	Airflow (VFD frequency)	60% 70% 100%	3 1 1	Baseline VFD frequency is 85%

The steps followed to implement the faults described in the Table 7 are described below. It should be noted that all the faults were simultaneously implemented for all the three cooling coils.

1. Leaking valve : This fault was simulated by setting the minimum position of the cooling coil 3-way valve to the two severity levels in the Priva BMS software.
2. Stuck valve : This fault was simulated by by fixing the minimum and the maximum position of the cooling coil 3-way valve to the two severity levels in the Priva BMS software.
3. Reduced setpoint of supply air temperature : This fault was simulated by deactivating the PID loop controlling the required supply air temperature through setting the same minimum and maximum limit for the supply air temperature. This fault is also called the reduced LAT fault for the EnergyPlus simulations.
4. Airflow : This fault was simulated by setting the VFD frequecy for the AHU supply air fan to two levels below the baseline of 85 % and one level above the baseline of 85%

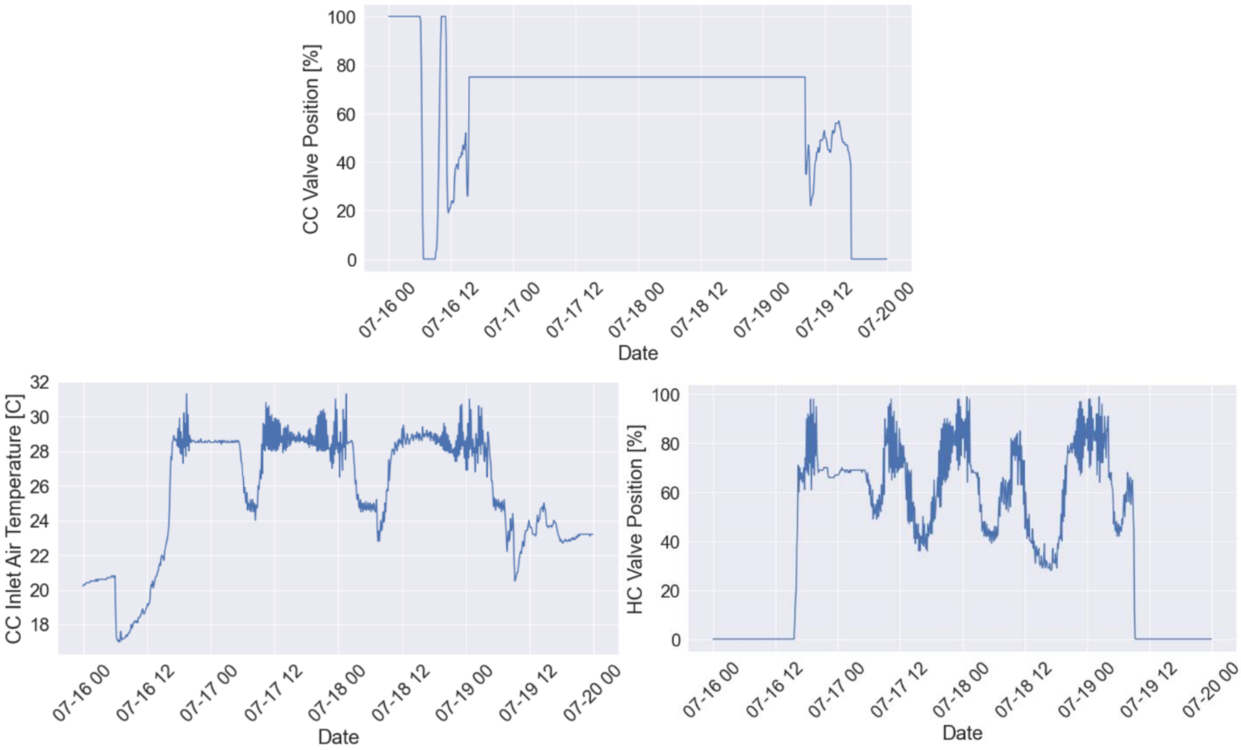


Figure 16: Cooling Coil Valve stuck fault at severity 75% for north cooling coil in Breda office building

Figure 16 shows the experimental data for the 75% stuck valve condition for the north cooling coil. When this fault was implemented it was later observed that the inlet air temperature to the cooling coil was abnormally high ~28°C. On investigating the cause it was found that the heating coil valve also turned open during the stuck valve experiment. Normally the high value of the stuck valve would have driven down the supply air temperature from the cooling coil to very low temperatures. However simultaneous operation of the heating coil prevented this from happening. Thereby preventing detection of this fault, if one were only monitoring the supply air temperature from the cooling coil. Therefore an unexpected finding was that the stuck valve fault also causes simultaneous heating and therefore additional loss of energy. This is true only for this building due to its unique HVAC system setup.

Figure 17 shows the Reduced Supply Air Temperature setpoint fault with severity of 2°C to 16°C. The three CHW delta-T vs CHW flow rate graphs illustrate the low delta-T syndrome. For fixed air inlet side conditions (air flow rate is fixed and air inlet temperature is put in buckets of 2°C), the faulty data points are at a lower delta-T and higher mass flow rate (indicated by the CCVP). Thus low delta-T at partial load due to reduced supply air temperature setpoint was observed.

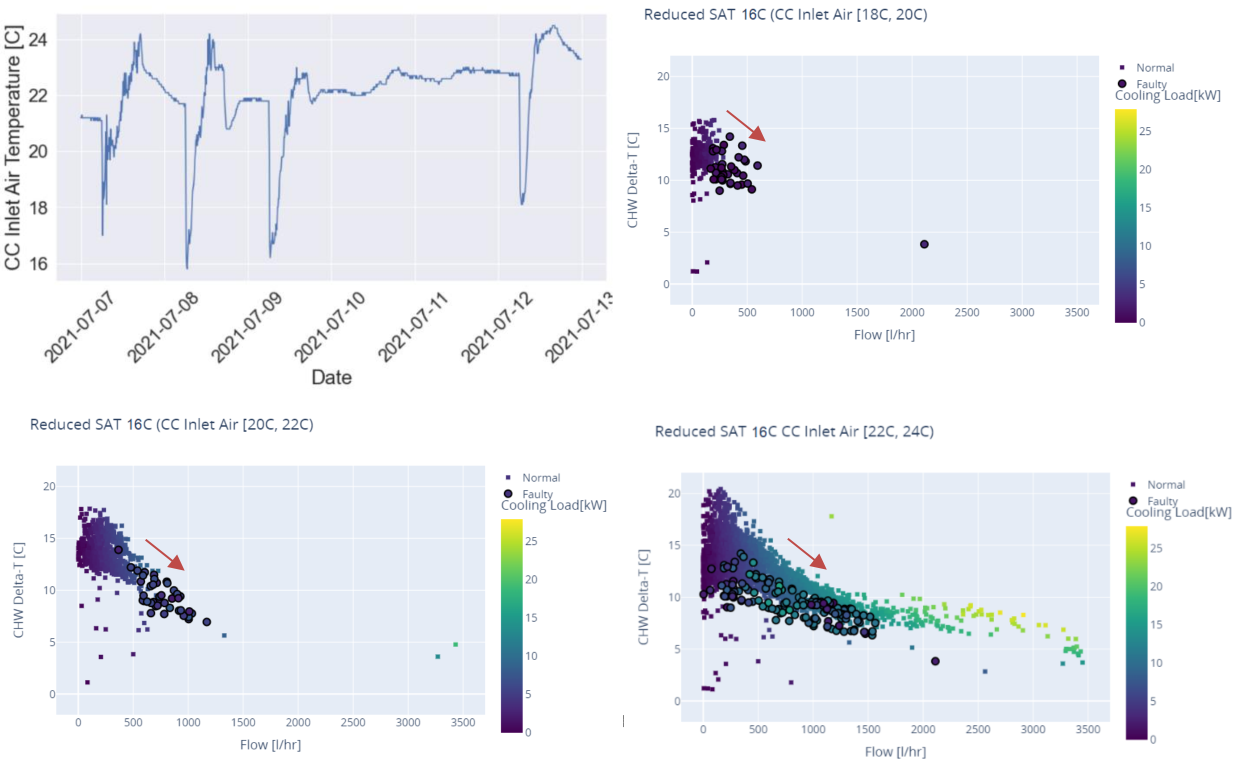


Figure 17 : Reduced Supply air temperature setpoint at 16°C for north cooling coil in Breda office building

In the next chapter the process of FDD tool development and FDD algorithm selection and functioning is explained in detail. The normal non-faulty data were used to train the models and the faulty data was used to validate the models.

4. FAULT DETECTION AND DIAGNOSIS(FDD) TOOL

One way to tackle the problem of low delta-T syndrome described in the previous two chapters is by the use of Fault Detection and Diagnosis (FDD) tools. The primary objective of a FDD tool is the detection of faults and the diagnosis of their causes so that the faults can be corrected early, avoiding damage to the system or loss of operation of the system. The use of FDD tools for HVAC systems began in the early 1980s and 1990s. They have come a long way since then with the increase of digitalization and availability of more data from the building HVAC systems.

This chapter describes the development of the FDD tool for the low delta-T syndrome. First, the requirements of the tool were developed using the Customer objectives, Applications, Functional, Conceptual and Realization (CAFCR)framework(Muller, 2004). Based on the developed requirements, a prototype was developed which is also described in this chapter.

4.1 FDD tool design

The design of the tool needs to focus on establishing, balancing, and integrating the goals of the stakeholders. Further, the purpose of the tool and the success criteria of the tool need to be established. Since the tool needs to be used to solve the problems of customers, their actual and anticipated needs also need to be established. Following this, the operational concept and required functionality can be developed. Next, based on these requirements the prototype can be synthesized and tested against the required functionality. The CAFCR model has been used to design the FDD tool.

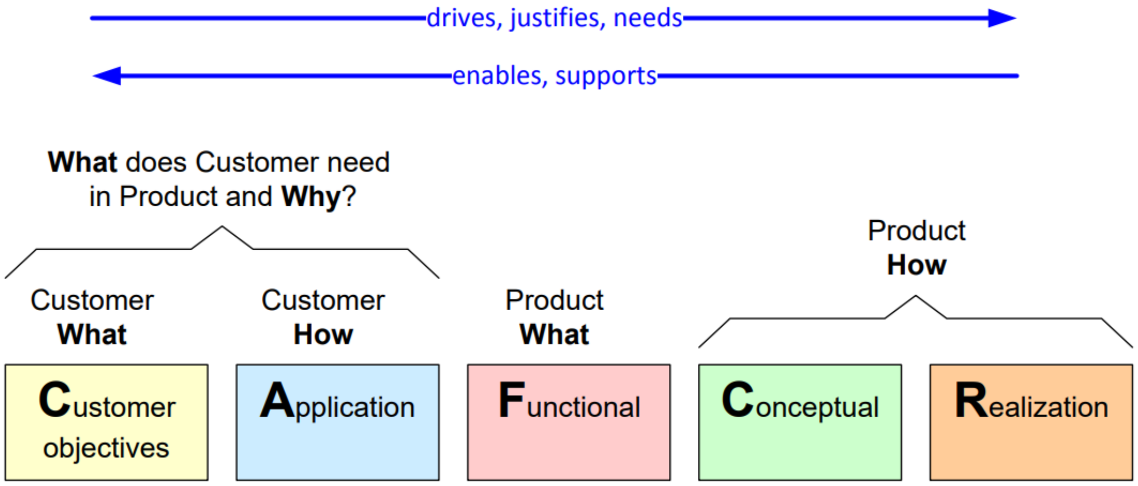


Figure 18: The CAFCR model (Muller, 2004)

4.1.1 Customer Objectives

The first step is to identify and establish the stakeholders in the project. Further, their concerns, key drivers, and the scope of their interest were identified.

The stakeholders for this project include the main product owner Kropman Installatietechniek, the customer groups, one supplier, one knowledge institute, and the project funding agency. Through interviews, the main roles within each stakeholder were identified who has a stake in the project. Further, the scope of the project was defined to be commercial real estate buildings. Table 8 provides the summary of the stakeholders.

1. Kropman Installatietechniek: Kropman specializes in building automation for controlling, measuring, and monitoring the performance of the building and its installations with their proprietary Building Energy Management System (BEMS) software InsiteView suite. Technological innovation is a crucial strategy for market and product development in the field of maintenance and building management. In this view, developing a solution for improving the energy efficiency of HVAC systems is in their interest - as it can lead to better performance in maintenance contracts and better economic gains along with providing their customers with the most up-to-date and sustainable solutions. The key drivers for Kropman to get involved in this project are: save energy, save maintenance costs, reduce the number of complaints from occupants – Provide consistent comfort levels, reduce the number of employee hours required for maintenance of a building, ensure constant/ at design / or better performance of building services with time.
2. Customers – ROC Nijmegen: They have a large University building. They are interested in providing thermal comfort for their occupants, reducing the energy consumption of their equipment, reducing the number of complaints, and the number of faults in their HVAC

equipment. They want to know how their HVAC system is performing and a system to detect and diagnose faults before they become a major problem.

3. Customers – Radboud UMC: They have a large hospital with a large number of Air Handling Units. They are interested in providing optimal thermal comfort, reduced downtime of equipment, and reduced energy costs. They want to know how their HVAC system is performing and a system to detect and diagnose faults before they become a major problem.
4. Supplier HVAC – SystemAir: They are the supplier of AHU equipment. They want to improve their product and provide better solutions to their customers than their competitors. They are interested in knowing what improvements if any in the AHU can lead to reduced low delta-T syndrome problems. Whether they can improve their design or provide better operational advice to their customers
5. Knowledge institute – ISSO: They are interested in advancing the knowledge of HVAC systems in the Netherlands. They are interested in knowing if there are any general/specific designs and advice the HVAC industry – suppliers, installers, maintenance companies, and customers – can use to reduce the problem and ill effects of the low delta-T syndrome.

Table 8: Stakeholder summary

Stakeholder type	**Stakeholder**	**Designations**
Product owner	Kropman	Account Manager
		Service Technician
		Remote service engineer
		HVAC Advisor
		Data Engineer
Customer	ROC	Facility Manager
	Radboud UMC	
Equipment Supplier	SystemAir	Technical Consultant
Knowledge Institute	ISSO	Projectleader

4.1.2 Customer Application

This section tries to understand how the customer achieves his objectives. Kropman makes maintenance and performance contracts with the customer. They need information from the supplier to solve specific problems, perform maintenance on parts of the installation, or order replacements from the supplier. They perform periodic maintenance by checking all installations. They generate periodic reports of the maintenance work.

User groups have performance-based maintenance contracts. They want to understand things they can do to aid in achieving their objectives of better comfort and lower costs. They contact the service engineer or the remote engineer. If it is not solved it is escalated to the maintenance manager.

4.1.3 Product Function

This section describes the required functionalities of the product (Table 9) taking into account both functional aspects and non-functional/performance aspects. They were developed following the interviews with the stakeholders in the project.

Table 9: Required functionalities of the product

Typical use cases	Worst case
Functional aspects	Functional aspects
Display the layout of the HVAC system	If too complicated, show only relevant system
View and analyse historical data	Handle missing / incomplete data
Identify/detect faults	Need to show the trust level/accuracy level of detection
Diagnose faults	Need to show the trust level/accuracy level of diagnosis
Database of models	
Generate periodic reports- with KPIs displayed	
Non-functional (performance)	Non-functional (performance)
Perform all actions in a single application	At least have connected applications
Allow different levels of access to the stakeholders	Enable/ plan for such possibility
Allow simultaneous viewing by multiple users	Use a tool/architecture which allows this possibility

4.1.4 Concept

Kropman has its own SCADA system called *InsiteView* which has been around for about twenty years. InsiteView is a building management system that can communicate with several control systems common in the market. The solution consists of a user application (SCADA) and a design application (Wizzard). With the Wizzard application, authorized users can build active screens themselves.

In most building management systems (BMS) there is the possibility to store measured values in a database over a longer period. For some buildings, data has been available for several decades. This information is often consulted to provide insight into incidents from the recent past by means of a limited reporting option within the system. This wealth of multi-year information can provide insight into the BMS, which can be beneficial. Unlocking this information and presenting it clearly can be done with *InsiteReports*. InsiteReports is a web-based reporting tool that can run as an addition to your current building management system. Users can use the application with a web browser, after logging in. InsiteReports can make dashboards, slideshows, and reports.

Dashboards are windows that can be assembled themselves with various elements such as graphs, images, and texts and the dashboards can then serve as a slide in a slideshow. InsiteReports *Historical Data Export* Interface lets you retrieve historical data from selected data sources and datapoints from a specified period. It allows you to download the data as an Excel file or a CSV file.

The different concepts developed and their strengths and weaknesses. Then the chosen architecture.

Table 10: Comparison of FDD tool implementation methodologies.

	Features	**InsiteView Next(IVN) Native**	**Hybrid (InsiteReports)**	**Hybrid (Dashboard+IVN)**
		NodeJS & Java based	Python based	Python based
Functional	Generalization(with 3rd party applications) capability	Limited	No	Yes
	Differentiate abrupt & incipient faults	Yes	Yes	Yes

	Visualization	Restricted	Restricted	Advanced & Flexible
	Data processing	Realtime	Near Realtime	Near Realtime*
Realization	ML model development	Yes	Yes	Yes
	DBN framework development	Restricted	Yes	Yes
	Code upkeep & development time	Software experts required	PDEngs, PhDs & Students	PDEngs, PhDs & Students
	Rapid prototyping	No	Yes	Yes
	Development Time needed	High	Low	Medium
	Software Development Phase	Suitable for Production	Suitable for Prototyping	Suitable for Prototyping

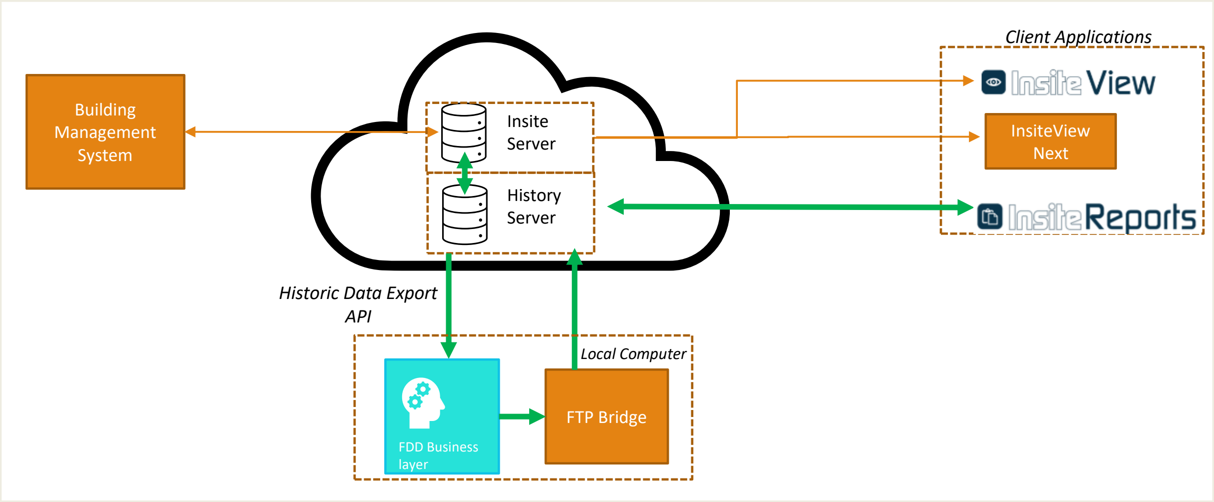


Figure 19: Hybrid(InsiteReports) implementation of FDD tool

4.1.5 Realization

The Realization section of the CAFCR model delves into how the product can be actually realized and what constraints need to be adhered to when realizing the product. This includes budgets, safety, reliability and security. Budgets refers to limited quantity of resources which the product needs and the design decisions surrounding that. Further design decisions need to be made based on an evaluation of value vs cost of the design options. And the granularity of the design options need to also be considered. High granularity can give added flexibility and fine tuning abilities at the expense of more overhead per option.

Since the development stage of the FDD tool is still at the prototype stage these realization aspects are considered implicitly in the development of the prototype version 1. Going into the next rounds of the prototype development after this project, these realization constraints need to be addressed.

4.2 Selected FDD model and algorithms

This section describes the FDD algorithms used in the FDD tool. First the chosen Fault detection algorithms are described. Next the chosen Fault diagnosis algorithm is described. These chosen algorithms are coded into the FDD prototype tool and its application is described in Chapter 5.

Fault detetction algorithms

A common method for finding faults is anomaly detection, which separates unexpected or aberrant data from typical data devoid of errors. The common method for doing this is to compare the predicted data with the measured data using supervised learning regression models. It is safe to conclude that a defect in the system occurs when there are significant residuals between the measured value and the expected value. Decision Tree algorithms such as Random Forest and eXtreme Gradient Boosting (XGBoost) are some of the ML algorithms that have been employed for regression.

The performance of the different algorithms were compared based on performance metrics like the root mean square error (RMSE) and the coefficient of determination, which is the R2 score. The algorithm with the highest R2 score and the lowest RMSE would be the most successful algorithm which can detect the low delta-T syndrome.

The low delta-T syndrome can be detected using two symptoms – decrease in RWT from the cooling coil and increase in the chilled water mass flow rate in the cooling coil. In the absence of mass flow rate measurements through the cooling coil, which are typically not measured, the cooling coil valve position can be used. The cooling coil valve position and the mass flow rate relation stays constanct when the pressure differece across the cooling coil and the valve remains constant. This is accurate for smalland simple HVAC systems and less accurate for large and comple HVAC systems with more brances and subsystems.

Algorithm selection was done by collaborating PDEng students in the project. It was found that XGBoost was the best-suited regression algorithm for fault detection. This was based on choice of R^2 score and RMSE score for both RWT and CCVP prediction models.The models selected had an R^2 score above 0.9 so that it is ensured that 90% of variance of RWT and CCVP can explained by the variance of their respective features. Further, the models had an RMSE lower than 0.5 K for RWT and 5% for CCVP.

Fault Diagnosis

Bayesian networks are a type of Probabilistic Graphical Model that can be used to build models from data and/or expert opinion. They can be used for a wide range of tasks including prediction, anomaly detection, diagnostics, automated insight, reasoning, time series prediction and decision making under uncertainty. The 4S3F Diagnositic Bayesian Network (Taal & Itard 2020) is capable of diagnostic inference.

The 4S3F method stands for 4 symptoms and 3 faults. The architecture for the 4S3F FDD method describes four types of symptoms and three types of faults. Ther four types of generic symptoms include: balance, energy performance, operational state and additional symptoms. A balance symptom is said to be detected when there is deviation in mass balance, energy balance or pressure balance in a system. Energy performance symptom is said to be detected when an energy perfomance indicator such as EER/COP/Energy Efficiency is lower than expected or reduced over time. Next an operational state symptom is said to be detected when a system state value such as temperature, relative humidity or pressure deviates from its usual value/levels. Lastly additional symptoms are based on inspection or maintenance observations which give added information for the process of FDD. A symptom must be observable either through measurements or applied calculations. The three generic types of faults include model, component and control faults. Model faults include faults in assumptions in models estimating missing values. Component faults include faults in components and systems which are malfunctioning. Lastly control faults refer to faults in the HVAC systems which include sequence faults, setpoints and PID control faults.

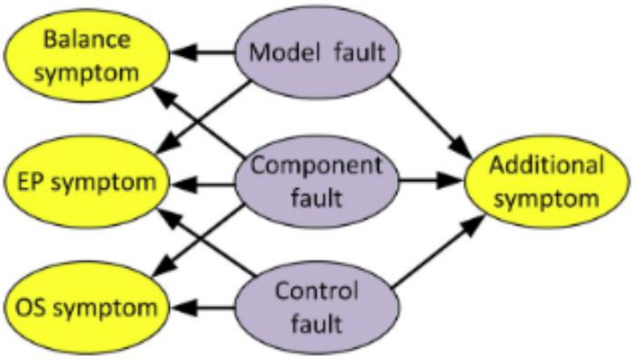


Figure 20: The 4S3F model: Relations between symptoms and faults(Taal and Itard, 2020)

The process of developing BN structure is to generate a cause-and-effect inference. Usually, expert knowledge is used to develop the system rule which will be mapped to the BNs. During the development process, the first step is to determine the network layers according to the nature of the problem. Suggested by the literature, a two-layer of network, which include fault layer and fault symptom layer are employed to develop BNs for whole building fault diagnosis in this study

The steps for developing a DBN network are decribed below and is show in Figure 21.

1 Model development: The nodes of the DBN which include the symptom nodes and the fault nodes need to be selected based on the problem to be solved.

2 Parameter development - Usually, two probabilities, i.e., prior probabilities and the conditional probabilities need to be determined when developing a DBN model.

When developing BNs parameters, one challenge is that the number of parameters for the evidence nodes growsexponentially with the increasing number of the fault node as the network structure becomes more complex . In this study, Noisy-MAX gate is adopted to develop the BN parameters for each evidence node, and LEAK probabilities are determined in the Noisy-Max distribution model in this study (Zagorecki et al., 2013).

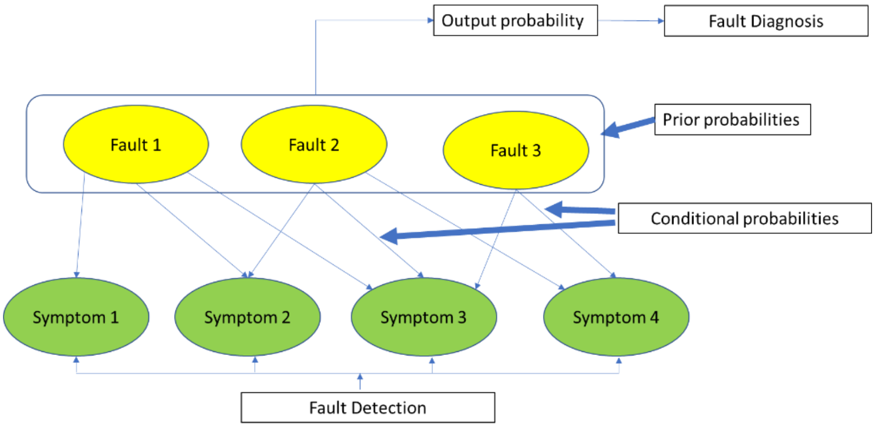


Figure 21: DBN network nodes

FDD Model development

Figure 22 shows the DBN for the cooling developed for cooling mode operation of the Air Handling Unit. The network includes the most impactful faults leading to low delta-T syndrome which include Lower airflow across the cooling coil, reduced Supply Air Temperature setpoint fault and the stuck valve fault. Oerational symptom nodes are used for this DBN network. The ML models for RWT and CCVP are used for the symptom detection as shown in the figure below. Further, additional symptom detection models when used alongside the ML symptom detection models help increase the probability of accurate diagnosing the faults. The Table 11 shows the rules used for the threshold to decide (in terms of Boolean 1/0) if a symptom is detected.

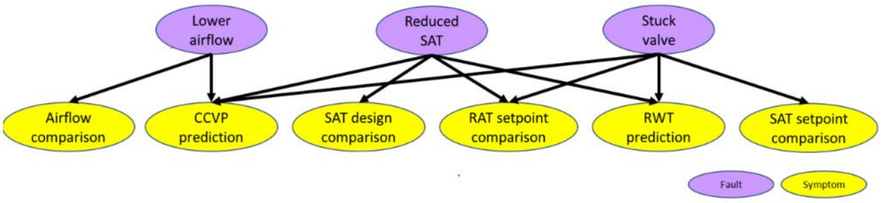


Figure 22: 4S3F DBN for low delta-T syndrome during cooling mode operation

Table 11: Thresholds for fault detection in the symptom nodes

Node Name	Model Type	Equation
Airflow comparison	Moving Average	$V_{measured} - V_{ma} > 0.5\ m/s$
CCVP prediction	ML model	$U_{measured} - U_{predicted} > 5\%$
SAT design comparison	Rules based model	$T_{measured} - T_{design} > 1K$
RAT setpoint comparison	Rules based model	$T_{measured} - T_{design} > 1K$
RWT prediction	ML model	$T_{measured} - T_{predicted} > 1K$
SAT setpoint comparison	Rules based model	$T_{measured} - T_{setpoint} > 1K$

Low delta-T syndrome fault is said to occur when there is detected simultaneous lower RWT and higher CCVP level. Figure 23 and Figure 25show the CCVP prediction and RWT prediction for stuck valve fault at 75% severity level. The residuals for both are greater than 5% and 0.5K respectively, therfore successfully detecting low delta-T syndrome. Further, shows the posterior probability for the stuck valve case, which is easily diagnosed with a probability of close to 1. This is affected by 4 symptoms – CCVP prediction, RAT setpoint comparison, SAT setpoint comparison and RWT prediction.

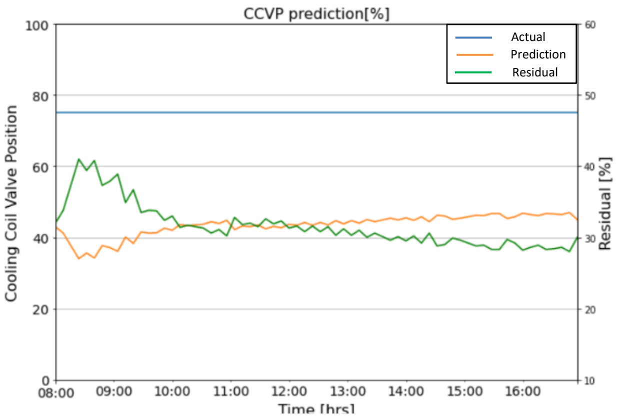


Figure 23: CCVP prediction for 75% stuck valve for north cooling coil in office building in Breda.

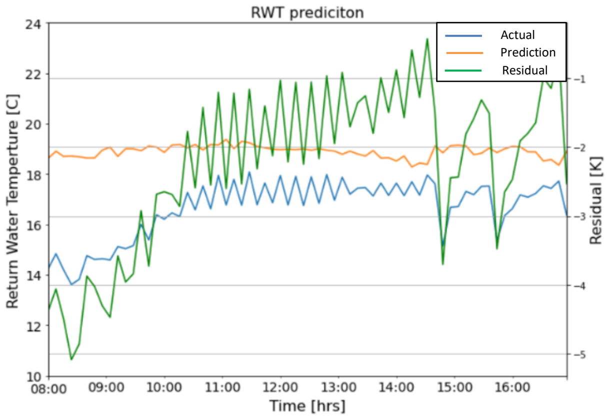


Figure 25: RWT prediction for 75% stuck valve for north cooling coil in Breda office building

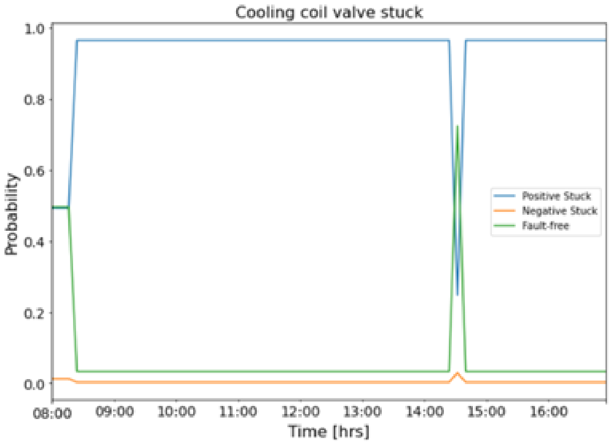


Figure 24:Posterior probability for 75% stuck valve for north cooling coil in Breda office Building

Similar analyses were conducted for the detection and diagnosis of the SAT setpoint and Lower Air Flow condition. The detailed results can be found in the PDEng reports of the project collaborators.

In the next chapter, the FDD prototype developed for the analyis of the Breda office is discussed along with its architecture and results summary.

5. FDD Prototype – KROPMAN Breda office

This chapter provides an overview of the FDD prototype focusing on the intended users, product architecture and the product features.

5.1 FDD tool intended users

The FDD tool is developed for the detection and diagnosis of faults in the Air Handling Unit with a focus on the low delta-T syndrome. The identified intended users include the following: They can be granted access to different Dashboards.

1. Data Engineer : The goal is to maintain and develop the FDD tool. Further assist in building models and maintaining the data quality.
2. HVAC Expert : The goal is to analyse, identify and predict faults in the HVAC system. Make visualizations and provide insights into performance of the HVAC system.

3. Account Manager : The goal is to have an overview of the performance of the systems for which the account manager is himself responsible. Receive notifications of severe faults.
4. Remote Service Engineer : The goal is monitor the performance of the system remotely. Have access to alarm history from the projects he/she is responsible for.
5. HVAC Technician : The goal is to see the corrective actions which need to be taken to resolve faults. Further have access to historical list of alarms.
6. Facility Manager / Building Owner – Client : The goal is to have an overview of the performance of the system. And receive notifications of alarms and correction of alarms.

5.2 FDD tool architecture

As discussed in section 4.1.4 the Hybrid implementation methodology with InsiteReports was chosen for this project. The principal reason being that this methodology allows reuse of the InsiteReports database and visualization tools. When this is coupled with a python based analysis tool, a functional FDD prototype can be created.

Figure 26 shows the functional flow of the FDD tool. This involves 4 main blocks and 5 steps of actions. The 4 main blocks includes the InsiteReports environment, the email server, local computer with the python environment and the FTP server. In the first step, the user interacts with the FDD tool on the InsiteReports environment via a custom HTML form to initiate model training-testing or Inference actions. This is communicated from InsiteReports via an email to the dedicated email address of the FDD tool. For the initial version, a Microsoft Outlook based email address is used. Later a dedicated Kropman email account can be used for the same purpose. The email contains the information about the desired action and other relevant parameters.

In the second step the local computer with the Python environment periodically checks the email server for new emails. This can be automated on a Microsoft OS machine with the help of Batch scripts and the Microsoft Task Scheduler application. Python has dedicated libraries to login and connect to email servers from different providers including Microsoft Outlook. Once a new email has been received and its contents identified appropriate action can be taken in the next step.

In step 3, the InsiteReports Historical Data Export interface is accessed via an API call. The necessary historical data is downloaded according to the instructions from the email. Here two operations are possible. Either model training and testing or model Inference. In the former case, the ML model is developed based on the parameters chosen in the step 1. The ML model training and testing results in the form of R^2 score and RMSE are generated. This is stored in the form of a CSV file with appropriate columns. In the latter case of model inference, predictions are generated on the new data using the stored ML models. The new inference results are stored in a CSV file with appropriate columns. The generated CSV files are ready for the next step/

In step 4, the CSV files are uploaded into the Kropman FTP server. This action is performed by a dedicated python script which also uploads a CSV file indicating the success or failure of step 3. Next in step5, the FTP server has a batch script which is running periodically to read the CSV files and upload the results into the InsiteReports database with the correct time stamps and columns. InsiteReports has a time series database which can store numeric information in the form of integer, Booleans or floating numbers.

Finally the results are visible on the InsiteReports environment in the form of Reports and Dashboards. The InsiteReports Dashboards allows creation of rich visualizations with user interactable graphs and charts. In addition images and external HTML pages can be embedded along with custom navigation buttons and alarms. It also has a periodic reporting service which allows to send notifications and dashboard reports.

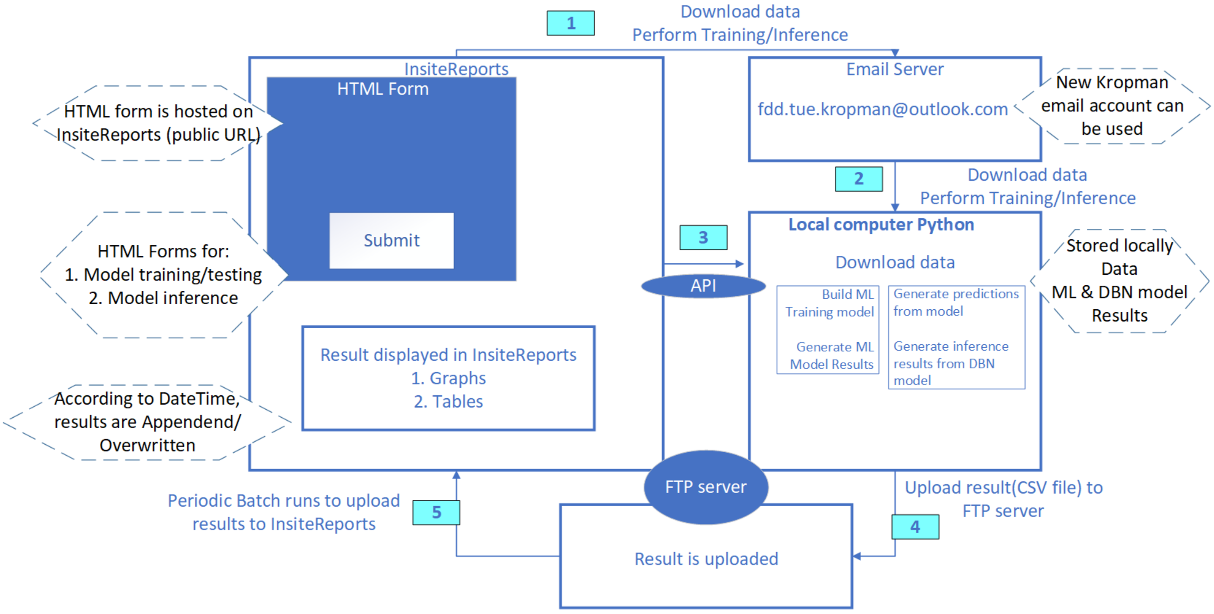


Figure 26: Functional flow of FDD Prototype

The template of the FDD tool as shown in **Error! Reference source not found.** was developed with the following sections based on the requirements of the intended users described in section 5.1 and product function from section 4.1.3. The main dashboard include :

1. PID diagram : The PID diagram of the AHU system of interest provides information of the layout of the AHU. Further, the various sensors and controllers along with their live data provide instant information about the status of the system.
2. FDD Training & Testing setup : The Fault detection models can be developed by selection of the training data and the model parameters.
3. FDD Training & Testing results : The model library shows the results of the developed models. The results refer to the R^2 scores of the training and testing process of the developed ML models.
4. FDD Inference Setup : The Fault Diagnosis Inference setup allows the user to setup the inference frequency and the parameters for the inference procedure.
5. FDD Inference Results : The results of the FDD inference procedure can be viewed in these set of dashboards along with the alarms. Further advanced visualization relating to Low Delta-T syndrome can be seen here.

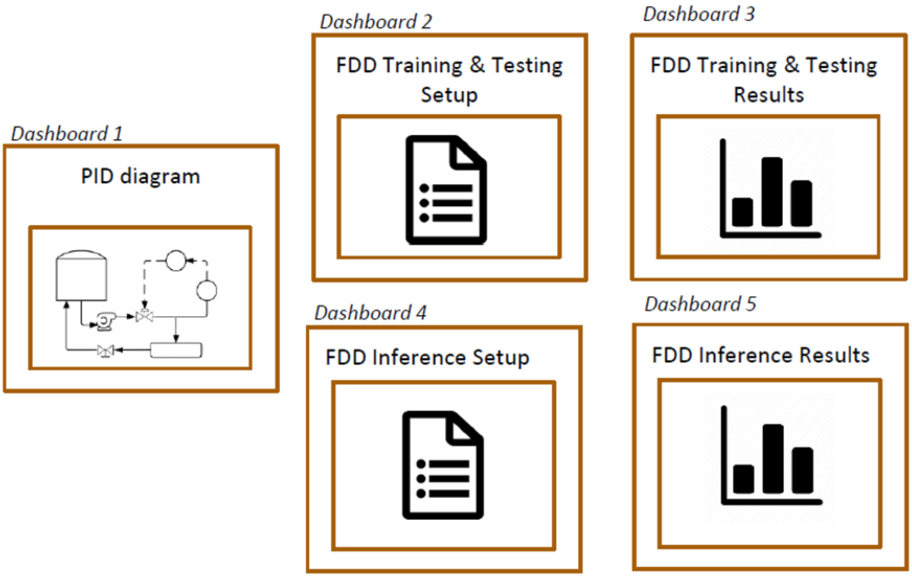


Figure 27: FDD module dashboard template version 1

5.3 FDD tool on InsiteReports

The set of 5 dashboards described in the previous section were expanded in to a total of 10 dashboards with 9 functional dashboards and 1 navigational dashboard. Each cooling coil has these 10 dashboards to enable its analysis and FDD operations. Figure 28 shows the navigational dashboard. This dashboard is usually pinned to allow easy navigation from/to one dashboard to the next. The setup dashboards can be found in the Appendix A3.

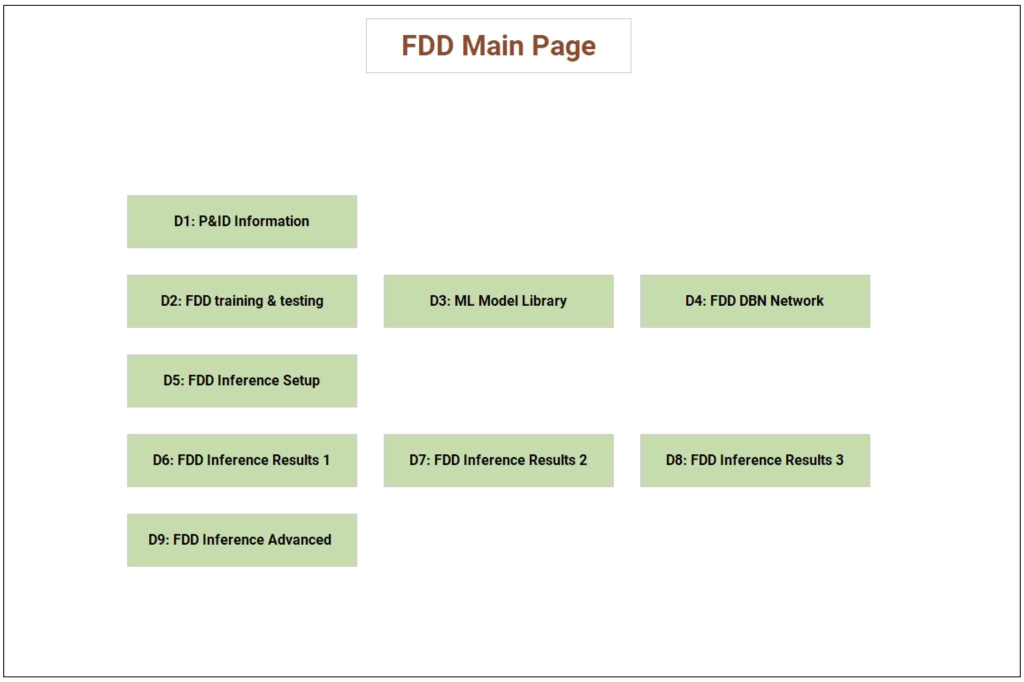
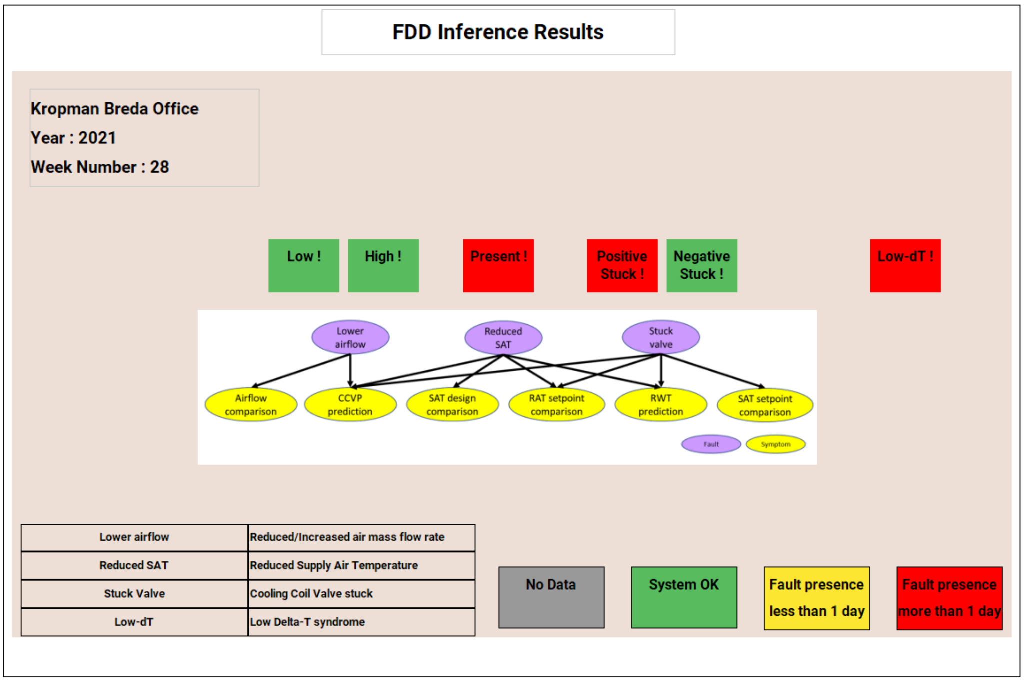


Figure 28: FDD Tool navigational dashboard

5.4 FDD Tool Results

The screenshots below show the FDD prototype tool for the week number 28, with the 75% stuck valve fault. Figure 29 shows week overview where in three kinds of alarms - system ok, fault present for 1 day and fault present for more than 1-day. The alarms are aggregated posterior probabilities. Stuck valve – positive stuck and reduced SAT fault appear to be present for more than 1 day. This is correct according the experiment data and can be confirmed in Figure 30 where the probability distribution of the faults is shown. The results can be explored in greater depth in Figure 31 where the probability distribution of the symptoms can be found.

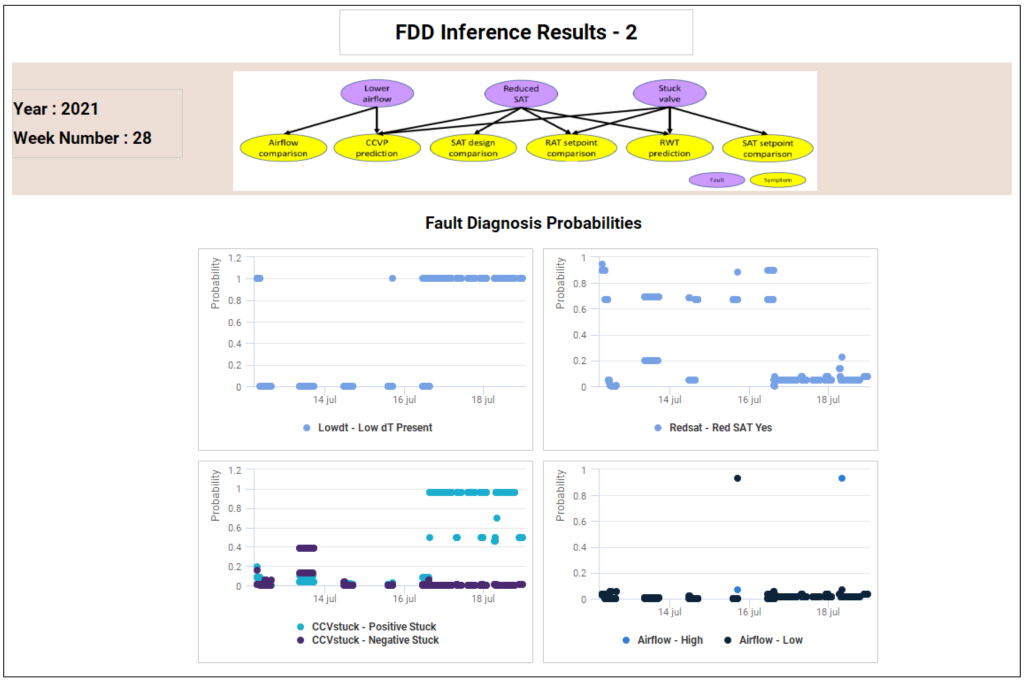


FDD Inference Results

Kropman Breda Office
Year : 2021
Week Number : 28

Lower airflow	Reduced/Increased air mass flow rate
Reduced SAT	Reduced Supply Air Temperature
Stuck Valve	Cooling Coil Valve stuck
Low-dT	Low Delta-T syndrome

Figure 29: FDD prototype Inference dashboard



FDD Inference Results - 2

Year : 2021
Week Number : 28

Figure 30: Fault Diagnosis posterior probabilities of faults

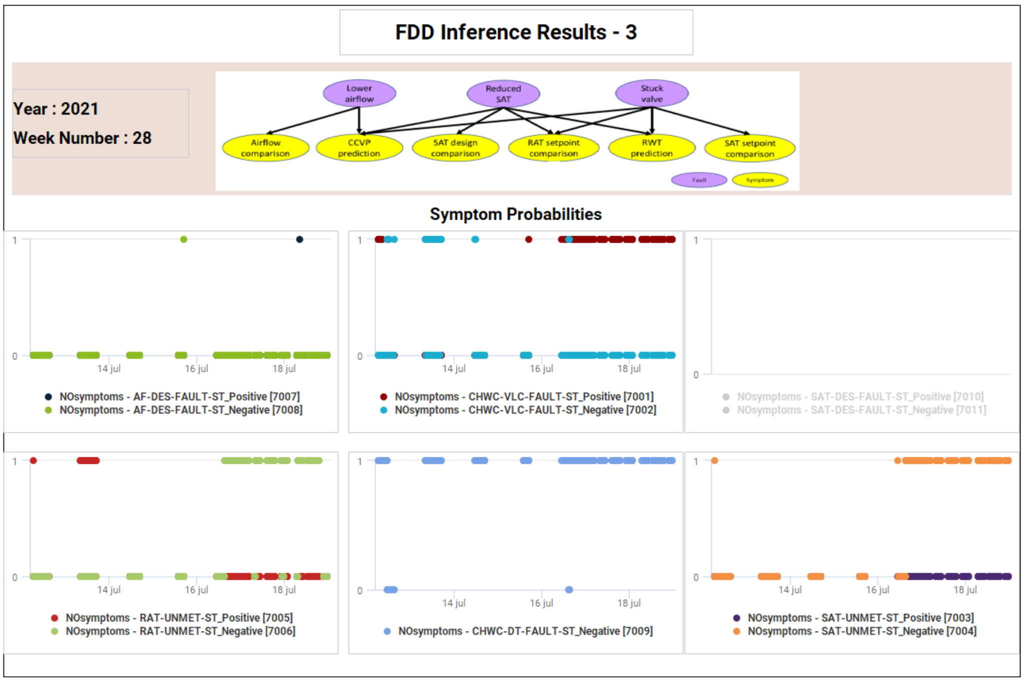


Figure 31: Symptom probability distrubution

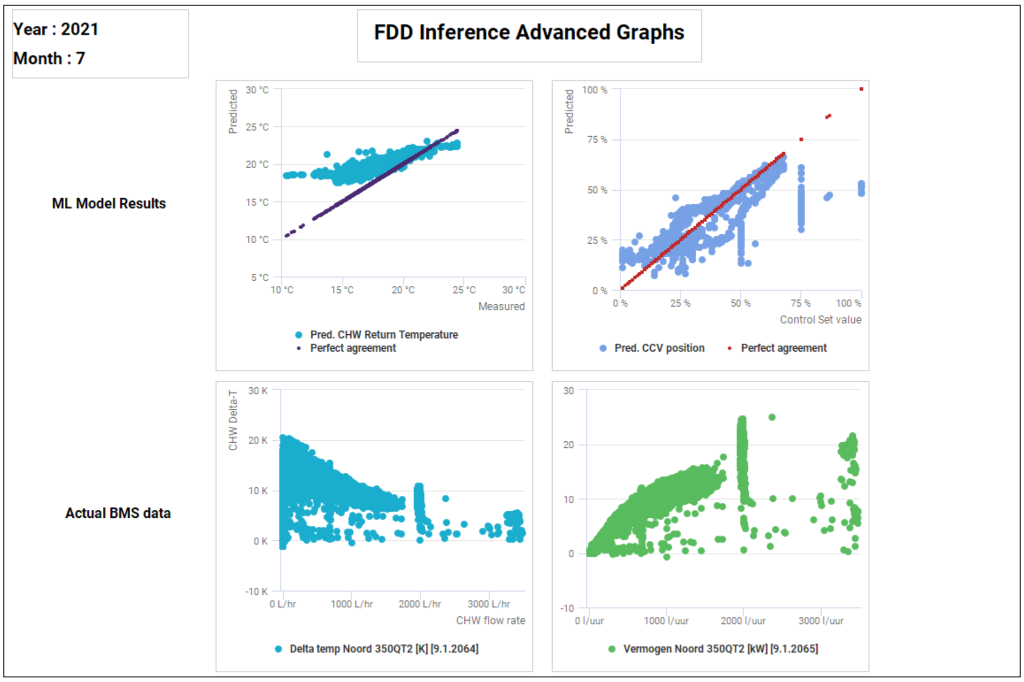


Figure 32: FDD prototype Advanced Graphs

Lastly, Figure 32 shows the advanced graphs dashboard where the ML model results and the Actual BMS data for the month of July 2021. In the ML model results the predicted RWT and CCVP are compared against the measured RWT and the control set CCVP. This is a monthly navigation dashboard.

Results functional integration:

1. Functional integration of analysis tool in InsiteReports enables FDD of low delta-T syndrome

2. ML models for CCVP and RWT can be developed and their results can be observed in the ML model library dashboard.
3. Multiple faults can be simultaneously detected using the DBN network.
4. The faults can be prioritized according to their severity, in terms of period of positive detection. This is shown as alarms in colors of Red, Yellow and green.

6. CONCLUSIONS

6.1 Design Project Results

To get a good overview of the different results of the project it is good to summarize them:

1. Improved identification of causes of low delta-T syndrome:

The project offers the following contribution to the international state-of-the-art: improved classification of causes of low delta-T syndrome. A better layout ensures that designers, installers, and operators can make motivated decisions to minimize or even eliminate the negative effects of low delta-T syndrome.

2. Characterization of the properties of the causes of low delta-T syndrome:

At present, the causes of low-dT syndrome are largely characterized by a combination of a reduced return water temperature, an increased flow rate, and a "reverse" flow direction in the bypass pipe. Improved characterization allows the selection of an appropriate analytical method, which would facilitate the effective detection of low delta-T syndrome. Together with the two participating users, Kropman has the possibility to collect the necessary data. The latest techniques from data analysis have been applied to make the data selection process run more efficiently and focus is applied to clarify the most important causes.

3. In-situ testing and validation of the developed analysis module:

The performance of the newly developed analysis module will be of little value if it has not been sufficiently tested in operational CHW installations. The ability to isolate and identify fault situations from single has been established and optimized. In order to test the analysis system, the detection of the low delta-T syndrome effects in the CHW installations must be carried out with a high degree of reliability. Important here is the collection and analysis of data from existing CHW installations that can be used as a test and training dataset for the analysis system. Due to the testing on an actual HVAC system in an office building, this was guaranteed.

Use of acquired knowledge

Kropman will further develop the functional modules for itself and for its key customers, such as ROC Nijmegen and Radboud UMC. Based on the existing projects of the participants, new knowledge and insights are developed. ISSO will incorporate the insights gained into its publications and courses. This is to make the added value of commissioning of cooling installations and specifically the low delta-T problem clear to customers, managers, institutional investors, (network) operators, etc. The research results provide a new representation of the partial load behavior of a cooling battery in non-design conditions and identify the causes and symptoms of possible solutions to low delta-T syndrome. The low delta-T syndrome results in its severe form in a reduced waterside temperature difference, an increased waterside flow resulting in increased energy consumption, and a decreased efficiency or SPF of a well system. The research provides insight into the fundamental background of low delta-T syndrome. The information has been reviewed by Systemair and has contributed to the awareness and deepening of this matter. This is important for Systemair because the air treatment systems, of which the cooling batteries are an important part, will increasingly be supplied with control technology built up in the factory as a result of the European Ecodesign legislation. The results of this research will be used in the future to optimize the control strategies for cooling batteries.

6.2 Technical Feasibility

Technical feasibility is needed to assess whether a product or service is technically possible to manufacture. Answers to the following questions can help the company, in this project Kropman Installatietechniek, to determine whether they have the technical resources to convert the idea into a fully functional and profitable system.

1. **Is it possible to develop the product with the available technology in the company ?**

   Yes. Since the prototype uses an existing product and combines it with applications developed in open source language like Python, it is possible to develop the product with the available technology in the company.

2. **Are there technically strong employees who can deliver the product on time and within budget using the available technology?**

   Although the use of Python is becoming popular, developing applications and ML models is still a task which is new for the construction industry. The PDEng trainees working for this project could be an option to help deliver this product.

3. **Is the developed prototype scalable for buildings with hundreds of AHUs ?**

   The FDD prototype is not directly scalable. The python application needs to be customized to the data point names of each equipment. The missing technology is data tagging using formats such as Project Haystack or Brick Schema. Then a generic code could be developed which would be easily applied on hundreds of AHUs.

6.2 Financial Feasibility

The socio-technical system, in addition to the regime, comprises of actors who have agency-ability to carry out actions which are deliberate, value driven and dependent on available resources. They work within the system and hence can influence the agency of other actors. An analysis of the actors within the system informs about who are the critical actors for the innovation and what are their capabilities to affect and interest to affect the innovation considered.

For the incumbent socio-technical system Figure 33 shows the actors involved. The producer network shows the current producers of BEMS software tools such as Kropman InsiteView and Priva BMS. They are connected to the suppliers who provide software packages, HVAC equipment, network and control equipment and cloud infrastructure. The products they produce are governed by regulations given by the Ministry for Infrastructure and Environment in the Netherlands and the regulations of European Union. Further Figure 34 shows the interest and power of actors towards innovation. Currently, the traditional BMS suppliers have high power in the market and low interest in innovation. If Kropman Installatietechniek further increases its endeavors in innovation, it will lead to even more market potential in the future.

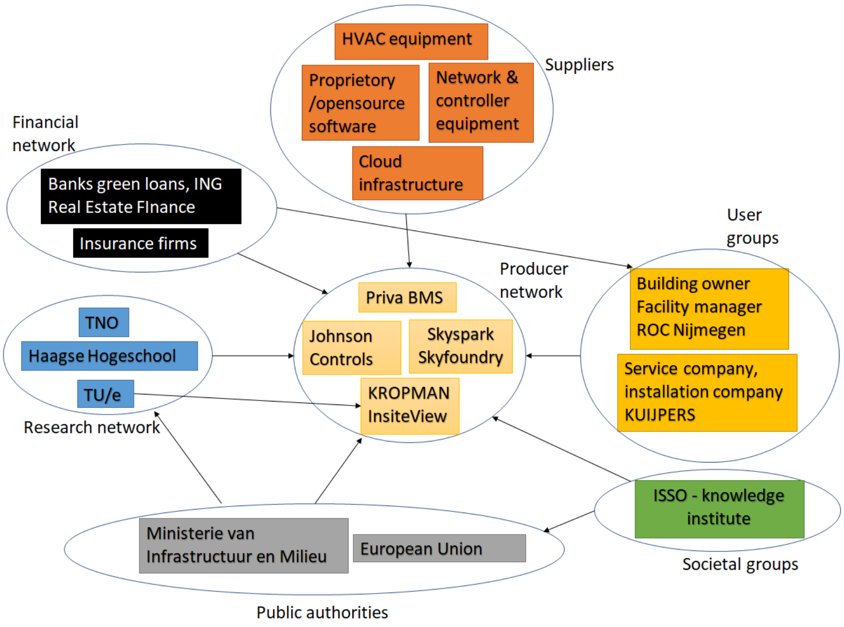


Figure 33: Actor network of incumbent system

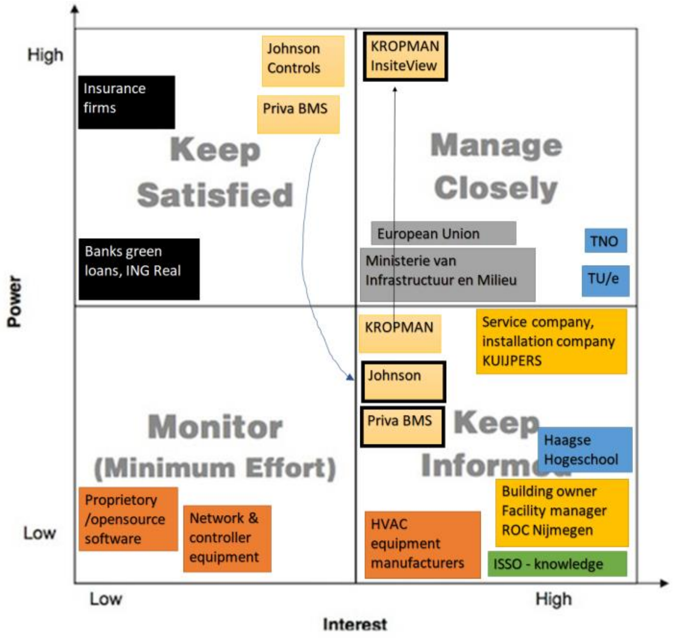
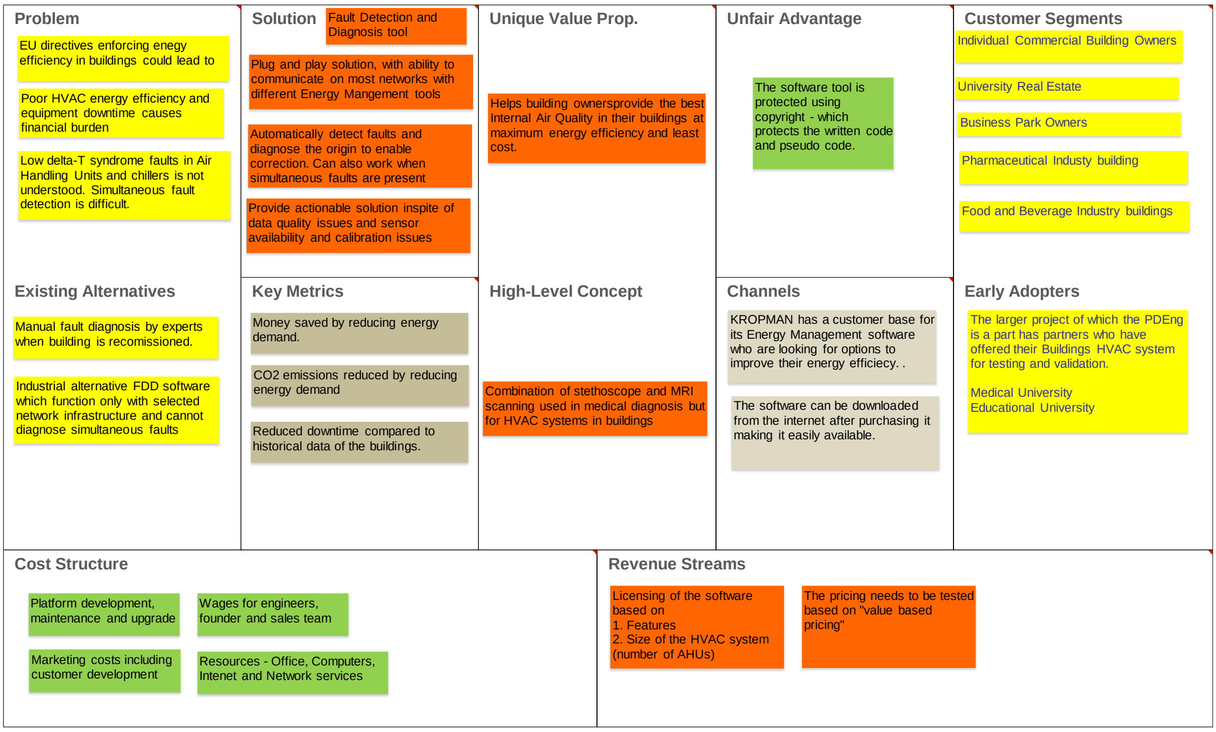


Figure 34: Interest and power of actors towards the innovation - FDDtool for HVAC systems in commercial buildings. The arrows show change when Kropman has a functioning product of the innovation

The path to making a product available for the market can be a difficult one. The Business Model Canvas shown in Figure 35 below, is a strategic management template used for developing new business models. It has elements which describe a products value proposition, customers and finances.



Problem

EU directives enforcing enegy efficiency in buildings could lead to

Poor HVAC energy efficiency and equipment downtime causes financial burden

Low delta-T syndrome faults in Air Handling Units and chillers is not understood. Simultaneous fault detection is difficult.

Solution

Fault Detection and Diagnosis tool

Plug and play solution, with ability to communicate on most networks with different Energy Mangement tools

Automatically detect faults and diagnose the origin to enable correction. Can also work when simultaneous faults are present

Provide actionable solution inspite of data quality issues and sensor availability and calibration issues

Unique Value Prop.

Helps building ownersprovide the best Internal Air Quality in their buildings at maximum energy efficiency and least cost.

Unfair Advantage

The software tool is protected using copyright - which protects the written code and pseudo code.

Customer Segments

Individual Commercial Building Owners

University Real Estate

Business Park Owners

Pharmaceutical Industy building

Food and Beverage Industry buildings

Existing Alternatives

Manual fault diagnosis by experts when building is recomissioned.

Industrial alternative FDD software which function only with selected network infrastructure and cannot diagnose simultaneous faults

Key Metrics

Money saved by reducing energy demand.

CO2 emissions reduced by reducing energy demand

Reduced downtime compared to historical data of the buildings.

High-Level Concept

Combination of stethoscope and MRI scanning used in medical diagnosis but for HVAC systems in buildings

Channels

KROPMAN has a customer base for its Energy Management software who are looking for options to improve their energy efficiecy. .

The software can be downloaded from the internet after purchasing it making it easily available.

Early Adopters

The larger project of which the PDEng is a part has partners who have offered their Buildings HVAC system for testing and validation.

Medical University
Educational University

Cost Structure

Platform development, maintenance and upgrade

Wages for engineers, founder and sales team

Marketing costs including customer development

Resources - Office, Computers, Intenet and Network services

Revenue Streams

Licensing of the software based on
1. Features
2. Size of the HVAC system (number of AHUs)

The pricing needs to be tested based on "value based pricing"

Figure 35: Business Model Canvas for the FDD for HVAC systems product.

The cost structure for the business model includes costs for the following:

1. Software tool development
2. Wages for employees
3. Marketing costs including customer discovery
4. Resources cost – office space, hardware and software.

Since the main product is a software product, Software as a Service (SaaS) is now a largely used business model. It is a delivery model in which a centrally hosted software is licensed to customers via a subscription. A SaaS company maintains the servers and database to run the services. The advantage of such a model includes recurring payments, customer retention and consistent updates. There are several pricing models which include

1. Flat rate pricing
2. Usage based pricing
3. Tiered pricing strategy
4. Per user pricing
5. Per feature pricing

6.3 Recommendations

The project's design for analyzing problems that occur in daily situations in real-life installations and are responsible for 15-20% energy loss in the cooling installations has proved successful. The linking of data analysis and the use of the data from building management systems with modeling and simulating the performance of specific climate installation systems make it possible to build up fault detection and diagnosis modularly and to have it automatic in the future. Already during the execution of the project, we, therefore, looked for further expansion of this approach, which resulted in awarded research projects Eindhoven Engine CM-FDD-HVAC as well as the RVO project MOOI B4B in particular work package 1 as well as the Eindhoven Engine project B4B-APK 2.0.

Since more than 90% of the buildings are already there before 2030 and the new buildings will still perform far from optimally, it is extremely important that more attention and resources are paid to research and development in the field of fault detection and diagnosis. The low-hanging fruit can thus contribute enormously to the actual realization of the intended performance as well as contribute to a higher experienced comfort level by users and optimized maintenance and technical management.

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APPENDIX

A1: Additional low delta-T syndrome symptoms

1. Deficit flow in P-S systems

Variable flow systems are the standards for larger systems due to their lower operating costs (Bahnfleth and Peyer, 2004). In the most used constant flow primary/variable flow secondary system a decoupler line separates the primary and the secondary sides. In the load controlled strategy, the consequence of low delta-T is that the secondary loop flow rate increases more than the primary loop and this is observed as deficit flow/reverse flow in the decoupler line.

2. Reduced chiller capacity

The chiller and the pumps in the primary loop are selected according to a design delta-T, which for optimal conditions is the same on the chiller side and the consumers side. Because in a fixed speed chiller the evaporator flow rate is constant, full cooling capacity can be achieved only when the chilled water temperature difference across the evaporator is at its design value (Bahnfleth and and Peyer, 2004). Hence low delta-T syndrome at the cooling coil leads to low delta-T across the chiller evaporator, thereby reducing the chiller capacity.

3. Increased number of chillers and auxiliary equipment

In the flow-based control system, additional chillers are staged to keep the primary system flow rate higher than the secondary flow. When the delta-T falls below the design value, the online chiller capacity reduces as described above. Hence to satisfy the load additional chillers and associated primary pumps need to be brought online where they function at a reduced capacity. As the load further increases, the system maybe unable to meet the load with all the chillers brought online and the secondary pumps running at maximum flow rate.

4. Reduced efficiency of chillers

Reduced delta-T causes the chillers to operate at a lower capacity. Efficiency is typically maximized in the 65% to 85% load range for fixed speed chillers (Bahnfleth and and Peyer, 2004). When they are operated at lower capacity due to low delta-T poor efficiency causes increased energy use. However, in case of variable speed chillers which have a higher efficiency in the range of 40% to 80% load (Hartman, 2001), this situation can be mitigated.

A2: Breda Office building

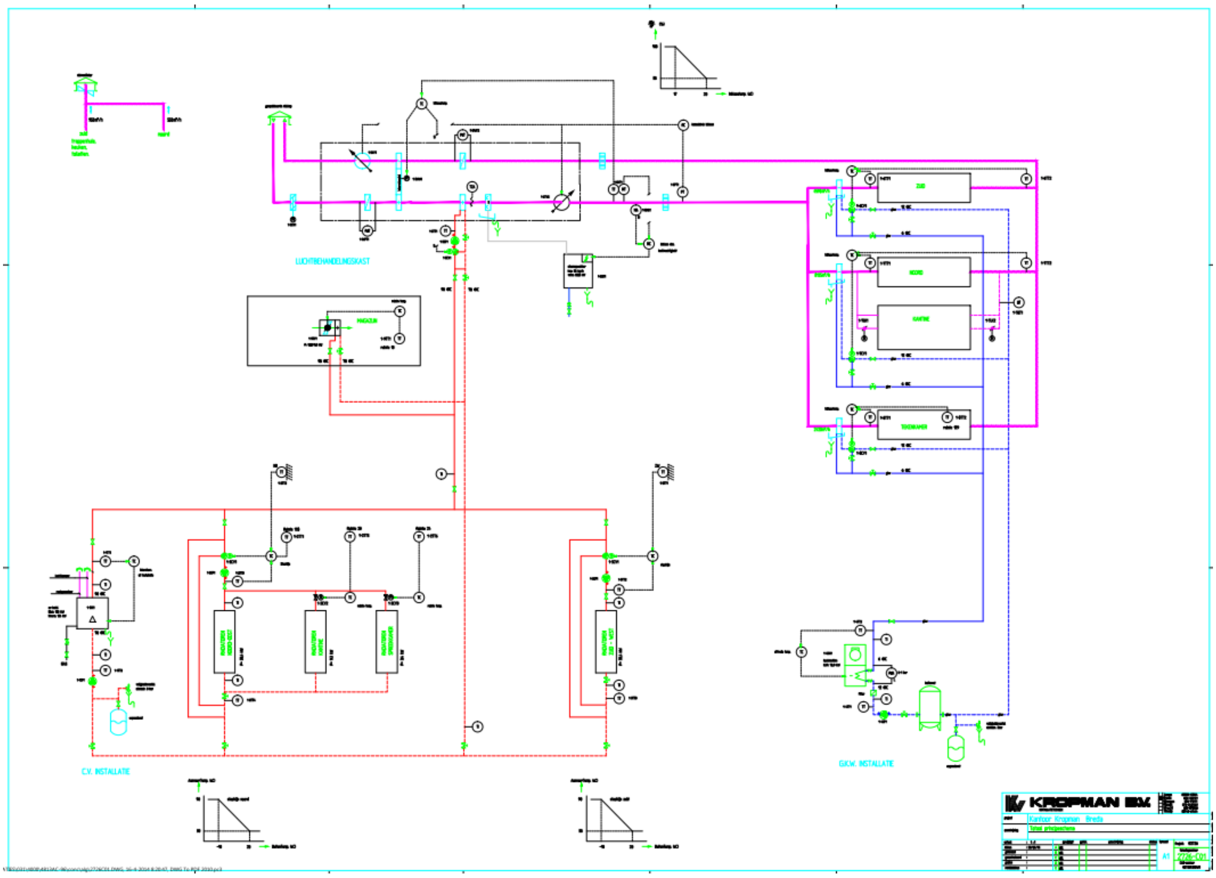
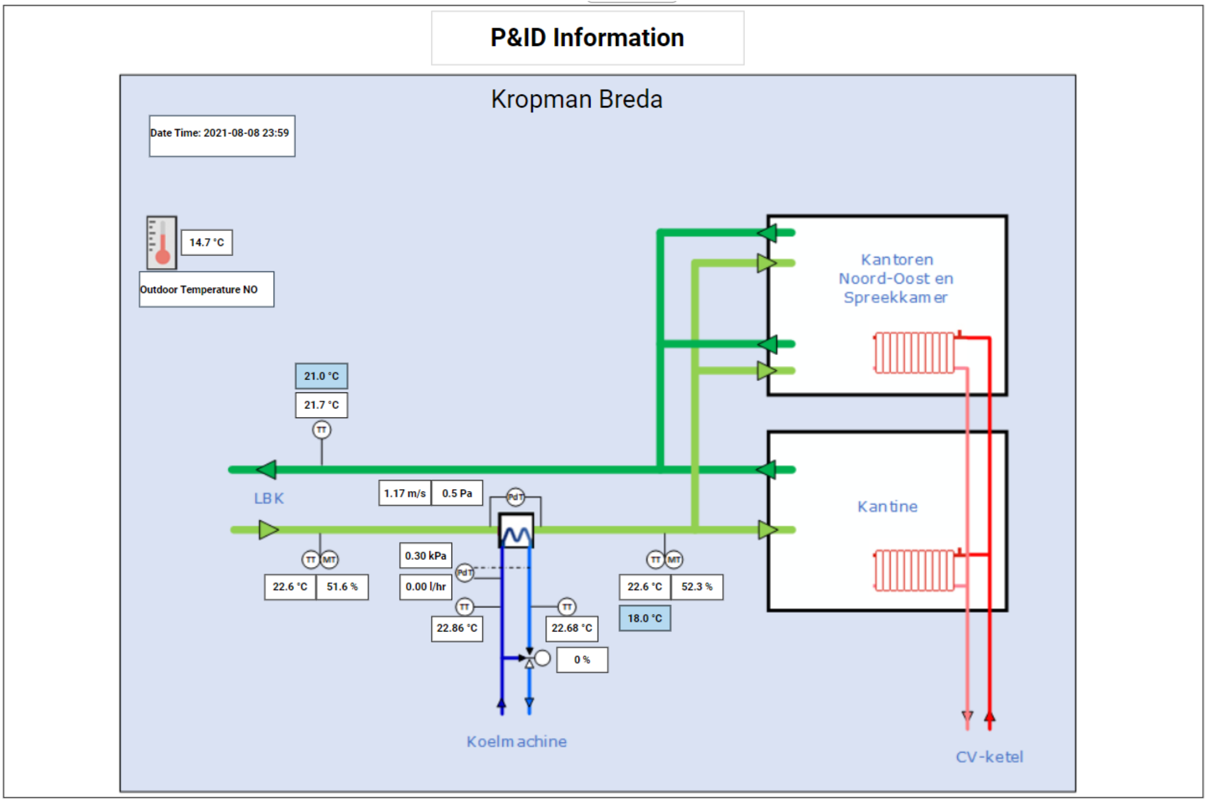
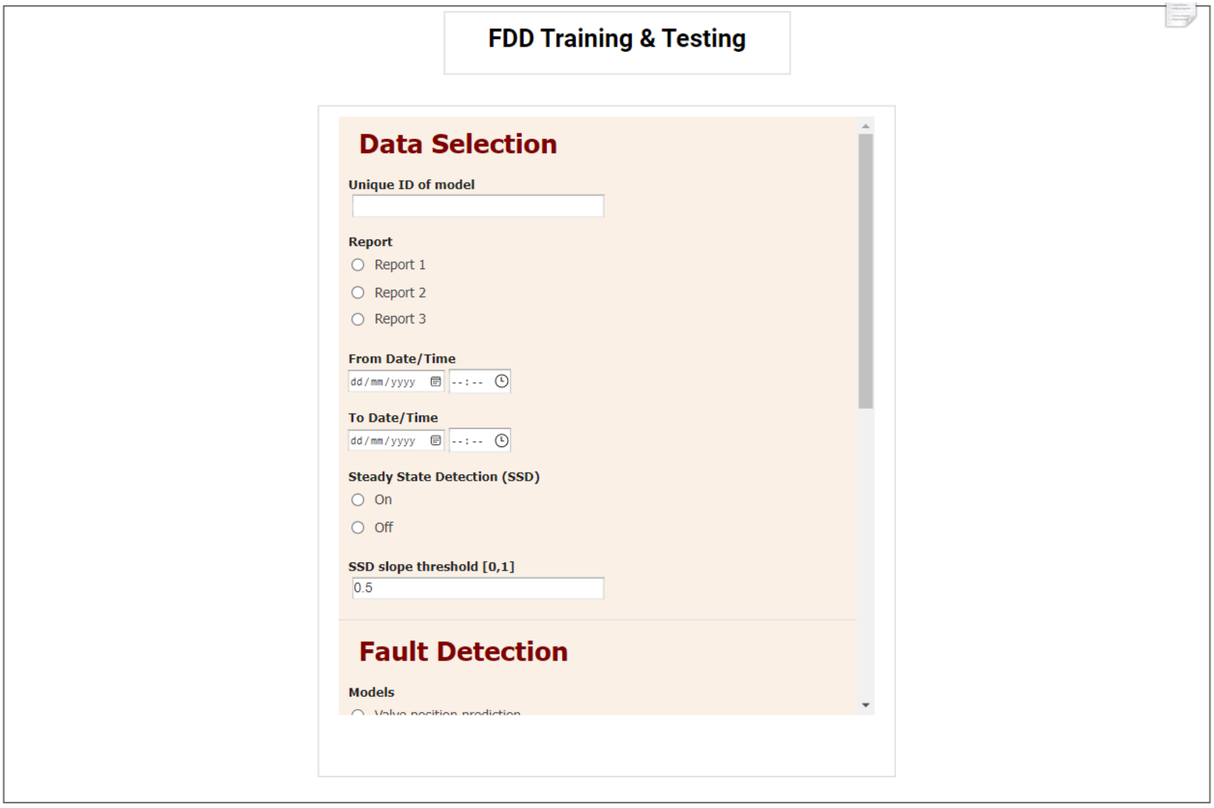


Figure 36: P&ID diagram of Breda office building

A3: FDD Hybrid InsiteReports Dashboards





Data Selection

Unique ID of model

Report
○ Report 1
○ Report 2
○ Report 3

From Date/Time
dd/mm/yyyy --:--

To Date/Time
dd/mm/yyyy --:--

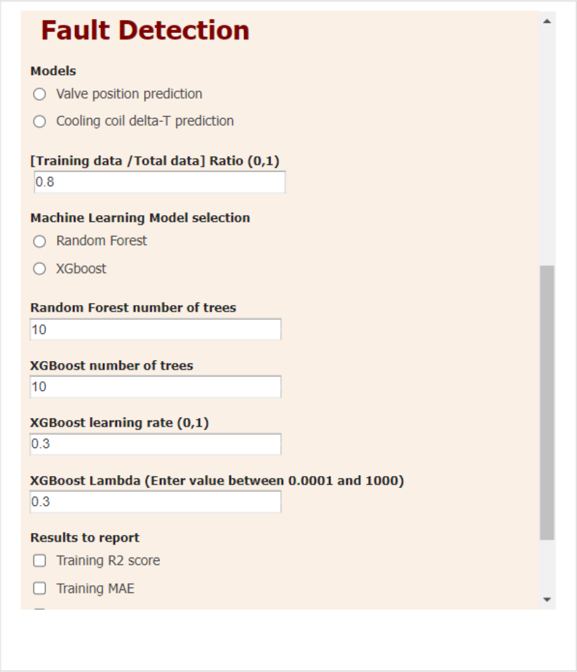
Steady State Detection (SSD)
○ On
○ Off

SSD slope threshold [0,1]
0.5

Fault Detection

Models
○ Valve position prediction

FDD Training & Testing



Fault Detection

Models

○ Valve position prediction

○ Cooling coil delta-T prediction

[Training data /Total data] Ratio (0,1)

0.8

Machine Learning Model selection

○ Random Forest

○ XGboost

Random Forest number of trees

10

XGBoost number of trees

10

XGBoost learning rate (0,1)

0.3

XGBoost Lambda (Enter value between 0.0001 and 1000)

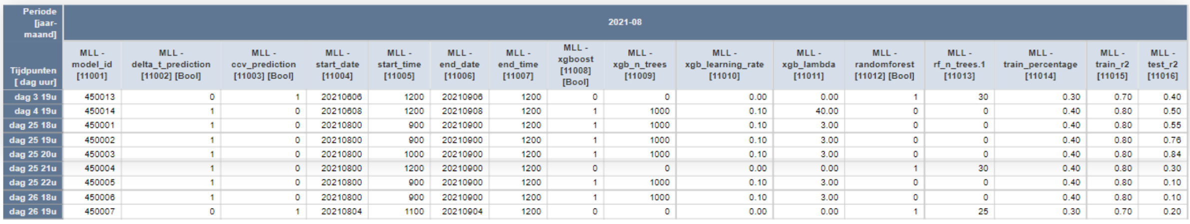
0.3

Results to report

☐ Training R2 score

☐ Training MAE

ML Model Library



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dag 4 19u	450014	1	0	20210608	1200	20210908	1200	1	1000	0.10	40.00	0	0	0.40	0.80	0.50
dag 25 18u	450001	1	0	20210800	900	20210900	1200	1	1000	0.10	3.00	0	0	0.40	0.80	0.55
dag 25 19u	450002	1	0	20210800	900	20210900	1200	1	1000	0.10	3.00	0	0	0.40	0.80	0.76
dag 25 20u	450003	1	0	20210800	1000	20210900	1200	1	1000	0.10	3.00	0	0	0.40	0.80	0.84
dag 25 21u	450004	1	0	20210800	1200	20210900	1200	0	0	0.00	0.00	1	30	0.40	0.80	0.30
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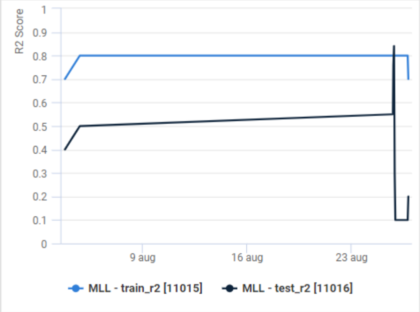
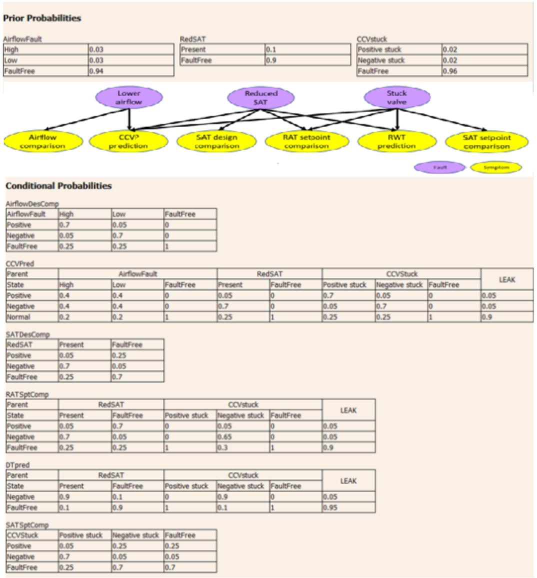


FDD DBN Network



Prior Probabilities

AirflowFault

High	0.03
Low	0.03
FaultFree	0.94

RedSAT

Present	0.1
FaultFree	0.9

CCVstuck

Positive stuck	0.02
Negative stuck	0.02
FaultFree	0.96

Conditional Probabilities

AirflowDesComp

AirflowFault	High	Low	FaultFree
Positive	0.7	0.05	0
Negative	0.05	0.7	0
FaultFree	0.25	0.25	1

CCVPred

Parent	AirflowFault			RedSAT		CCVStuck			LEAK
State	High	Low	FaultFree	Present	FaultFree	Positive stuck	Negative stuck	FaultFree	
Positive	0.4	0.4	0	0.05	0	0.7	0.05	0	0.05
Negative	0.4	0.4	0	0.7	0	0.05	0.7	0	0.05
Normal	0.2	0.2	1	0.25	1	0.25	0.25	1	0.9

SATDesComp

RedSAT	Present	FaultFree
Positive	0.05	0.25
Negative	0.7	0.05
FaultFree	0.25	0.7

RATSptComp

Parent	RedSAT		CCVstuck			LEAK
State	Present	FaultFree	Positive stuck	Negative stuck	FaultFree	
Positive	0.05	0.7	0	0.05	0	0.05
Negative	0.7	0.05	0	0.65	0	0.05
FaultFree	0.25	0.25	1	0.3	1	0.9

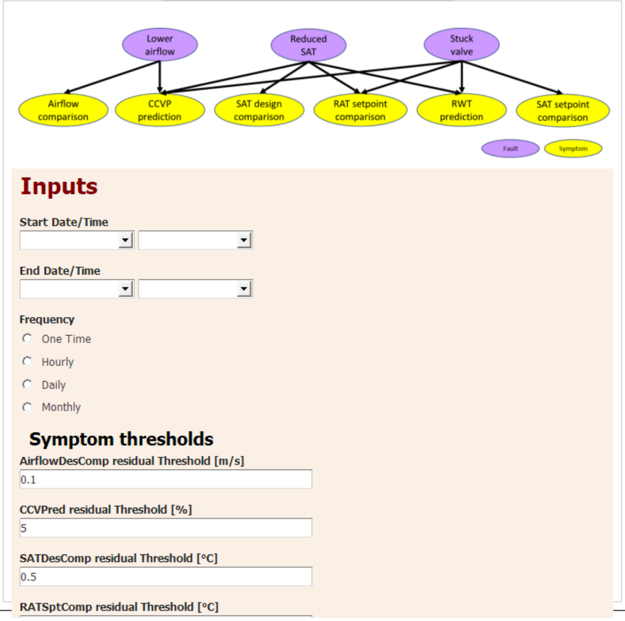
DTpred

Parent	RedSAT		CCVstuck			LEAK
State	Present	FaultFree	Positive stuck	Negative stuck	FaultFree	
Negative	0.9	0.1	0	0.9	0	0.05
FaultFree	0.1	0.9	1	0.1	1	0.95

SATSptComp

CCVStuck	Positive stuck	Negative stuck	FaultFree
Positive	0.05	0.25	0.25
Negative	0.7	0.05	0.05
FaultFree	0.25	0.7	0.7

FDD Inference Setup



Inputs

Start Date/Time

End Date/Time

Frequency

○ One Time
○ Hourly
○ Daily
○ Monthly

Symptom thresholds

AirflowDesComp residual Threshold [m/s]: 0.1

CCVPred residual Threshold [%]: 5

SATDesComp residual Threshold [°C]: 0.5

RATSptComp residual Threshold [°C]