

Module 5

Advanced systems in District Heating and Cooling

Part of the SHaKE Educational Package on District Heating and Cooling Systems

Guidebook

Reusable teaching resource for higher education and professional training

Version: 1.0
Date: March 2026

<https://www.shakeproject-dhc.eu/>



Project

Sharing Heat and Knowledge on Energy Communities (SHaKE)
Erasmus+ KA220-HED Cooperation Partnerships in Higher Education
Project No.: 2023-1-HU01-KA220-HED-000160219

Authors

Dr. Antoine Fabre, Dr. Pascal Stabat (Mines Paris – PSL)

Editors

Eva Szalma, Dr. Antoine Fabre, Dr. Pascal Stabat, Ghad Alarnaot Alarnaout

EU funding acknowledgement and disclaimer

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Tempus Public Foundation. Neither the European Union nor the granting authority can be held responsible for them.

Coordinator

Budapest University of Technology and Economics, Hungary

Partner institutions

Universitat Jaume I de Castellón, Spain
Mines Paris – PSL, France

Acknowledgement

This publication has been developed as part of the SHaKE project. The consortium would like to thank all educators, researchers, professionals and stakeholders who contributed to the development, review and improvement of the educational materials.

Licence

Unless otherwise stated, this material is licensed under a Creative Commons Attribution 4.0 International Licence (CC BY 4.0) . Users may share and adapt the material, provided that appropriate credit is given to the SHaKE project and the authors, a link to the licence is provided, and any changes are indicated.

Suggested citation:

Mines Paris – PSL. Module 5: Advanced systems in District Heating and Cooling. SHaKE Project, 2026.

<https://www.shakeproject-dhc.eu/>



Guide to using Module 5

This module is part of the SHaKE educational package developed to support the teaching of district heating and cooling (DHC) systems in higher education and professional training contexts.

Module 5 focuses on advanced approaches for improving the performance of DHC networks. It introduces the operational challenges of existing networks and presents methods for improving efficiency, reliability and sustainability. Particular attention is given to the reduction of return temperatures, the role of building-side hydronic systems, the diagnosis of malfunctions and the use of operational data to support network optimisation.

The module explores common sources of non-optimal operation, including leakages, secondary-side malfunctions, control valve and actuator problems, control system issues and heat exchanger faults. It also addresses the impact of secondary-side design choices, domestic hot water configurations and heat tariff models on overall DHC network performance.

In addition, the module introduces tools and indicators used to detect anomalies and faults in DHC substations and networks. The learning materials support both conceptual understanding and applied engineering work through case studies, technical exercises and numerical modelling activities.

The guidebook is primarily intended as a reusable teaching resource for educators, lecturers and trainers. It can be used to support lectures, blended learning activities, classroom discussions, practical assignments, case studies and continuing professional development training. The accompanying presentation slides, question bank, self-check quiz and practical exercise are designed to help educators adapt the content to their own teaching context.

Students and professionals may also use the module for independent study, especially if they already have basic knowledge of district heating and cooling systems, substations, hydronic systems, heat exchangers and basic data analysis.

Main topics covered in the module

- Current state of district heating and cooling in Europe
- DHC policies, development trends and renewable energy integration
- Performance improvement of DHC networks
- Reduction of return temperatures and its effect on network efficiency
- Common faults and malfunctions in DHC networks
- Leakages, secondary-side malfunctions, control valve and actuator problems
- Control system and heat exchanger faults
- Building-side hydronic systems and their impact on DHC performance
- Domestic hot water configurations and their influence on return temperature
- Heat tariff models and incentives for improving customer-side performance
- Anomaly detection and fault detection methods
- Practical indicators used by DHC operators
- Use of operational data to support malfunction detection
- Simple modelling and analysis of DHC network performance
- Control methods and optimisation approaches for advanced DHC operation



Learning outcomes of Module 5

The module is designed to support the development of the following skills and competences.

Upon completion of this module, learners should be able to:

- Explain why improving DHC network performance is important for decarbonisation and renewable energy integration
- Define the consequences of non-optimal DHC network operation
- Identify the main causes of underperformance and malfunction in DHC networks
- Recognise common faults related to leakages, secondary systems, control valves, actuators, controllers and heat exchangers
- Explain how secondary-side hydronic systems influence primary network return temperature
- Compare technical solutions for improving building-side and substation performance
- Identify suitable operational and design measures for improving DHC network performance
- Explain the role of heat tariff models in encouraging customer-side performance improvements
- Distinguish between anomaly detection and fault detection approaches
- Apply simple fault detection indicators to selected DHC operation problems
- Interpret basic operational data related to DHC substations and networks
- Create or interpret a simple DHC model in the context of performance analysis or optimisation

Estimated workload

This module represents approximately 9.5 learning hours, including lectures, case studies, independent study and assessment.

Educators may adapt the workload depending on the level of the course, the selected materials and the teaching format. The module can be used as:

- a complete teaching unit,
- a set of selected lecture materials,
- a blended learning component,
- a practical exercise package,
- a case study package,
- or a supplementary resource for existing courses.



Activities and Learning Hours

Activity Type	Time Allocation (Hours)	Description
Lectures	5h	Sequence 1: Description of the current state of DHC in EU and the DHC policies Sequence 2: Description of the possibilities to improve the DHC performance Sequence 3: Description of the ways to improve the performance through the building side hydronic systems Sequence 4: Description of the tools and indicators to detect malfunctions Sequence 5: Methodology to model DHC networks and data related to DHC Sequence 6: Description of control methods and alternative optimization approaches
Case Studies	2h	Sequence 2: Analysis of different DHN control and malfunction impact based on a numerical model Sequence 3: Analysis of different DHN architectures based on a numerical model
Self-Study	2h	Preparation for assessment and research for the project
Assessment	30min	Quiz, project
Total Learning Hours	9h30	

Target groups

This guidebook is primarily intended for educators, lecturers and trainers who wish to use or adapt the SHaKE materials in their own teaching or training activities.

The primary target groups are:

- higher education lecturers in engineering, building services, energy systems and related fields,
- trainers involved in professional or continuing education on district heating and cooling,
- educators developing blended, modular or practice-oriented learning activities,
- academic staff seeking reusable teaching resources on sustainable district energy systems,
- trainers and lecturers working with topics related to DHC operation, optimisation, substations and energy efficiency

The materials may also be used by students, professionals and independent learners who wish to study selected topics individually. For independent use, basic prior knowledge in the relevant engineering fields is recommended.



Recommended use by educators and trainers

Module 5 can be used flexibly as a complete teaching unit or as a set of selected teaching resources. Educators may combine the materials according to the level of the course, the available teaching time and the intended learning outcomes.

Teaching need	Suggested Module 5 resource
Introducing the topic	Use the module overview and introductory slides to present the relevance of advanced DHC systems, network performance improvement and the role of low return temperatures.
Preparing learners before class	Assign selected guidebook sections as pre-reading for flipped classroom or blended learning activities.
Supporting lectures or seminars	Use the presentation slides to explain DHC performance challenges, secondary-side hydronic systems, malfunction types, fault detection methods and optimisation approaches.
Checking understanding	Use selected questions from the question bank for discussion, short in-class checks, formative assessment or LMS-based quizzes.
Developing applied engineering skills	Use the practical exercise and case studies for group work, homework, project-based learning, numerical analysis or guided modelling sessions.
Supporting data-based discussion	Use the sections on anomaly detection, fault detection indicators and operational data to initiate classroom discussion on monitoring and diagnosis in DHC networks.
Supporting independent review	Direct learners to the module-level self-check quiz after they have studied the relevant materials.
Adapting to local teaching contexts	Select, combine or modify the guidebook sections, slides, questions and exercise according to the curriculum, participant level and professional context.

Recommended pathway for independent learners

Students and professionals using the module independently may follow the sequence below.

Step	Suggested activity
Review the introductory presentation	Familiarise yourself with the main concepts, terminology and structure of the module.
Study the guidebook materials	Read the detailed explanations, engineering principles and operational concepts presented in the guidebook.



Step	Suggested activity
Watch the module video	Use the module video and its attached assessment questions to explore one selected topic, concept or practical aspect of the module.
Complete the self-check quiz	Test your understanding of the key concepts and technical principles covered in the module.
Attempt the practical exercise	Apply the acquired knowledge through engineering-oriented analysis, modelling or case-based tasks related to DHC network performance.
Review the question bank	Use the questions for revision, discussion or preparation for assessment.

Available supporting materials

The available learning resources and assessment materials include:

- presentation slides for the module subtopics,
- a reusable question bank,
- a module-level self-check quiz,
- a module video with attached assessment questions,
- a downloadable practical exercise package, including Python and Jupyter Notebook files and the required input, model, image and output folders,
- case study and mini-project tasks based on numerical analysis of substation and network-level DHC performance, which may be used for group work, homework assignments, short technical reports or oral presentations.



Table of Contents

Project	2
Authors	2
Editors.....	2
EU funding acknowledgement and disclaimer	2
Coordinator	2
Partner institutions.....	2
Acknowledgement.....	2
Licence.....	2
1. Improvement of DHC network performance	9
1.1. Overview of faults in DHC networks	9
1.1.1. Leakages	10
1.1.2. Secondary system malfunctions.....	10
1.1.3. Control valves and actuators.....	12
1.1.4. Control systems and controller	12
1.1.5. Heat exchanger	13
1.1.6. Conclusion	13
1.2. Design of the secondary side hydronic systems	14
1.2.1. Impact of the type of emitters and secondary flow control	17
1.2.2. Impact of DHW hydronic configuration	21
1.2.3. Conclusion on the best hydronic configuration	22
1.2.4. Heat tariff models	23
1.3. Fault detection	25
1.3.1. Malfunction detection challenges.....	25
1.3.2. What is malfunction detection?.....	26
1.3.3. Anomaly detection	26
1.3.3.1. Visualization & manual analysis	26
1.3.3.2. Thresholds	28
1.3.3.3. Regression	29
1.3.3.4. Classification.....	30
1.3.3.5. Clustering	31
1.3.4. Common indicators used by the DHC operators.....	32
1.3.5. Fault detection	35
References.....	42



1. Improvement of DHC network performance

In order to meet the European objective relative to the District Heating and Cooling (DHC) networks, the performance of existing networks must be improved. For heating networks, improving performance primarily means increasing the share of renewable energy in the energy mix. In practice, this generally involves lowering the overall return temperature of the network, which makes it possible to increase the use of low temperature renewable energy sources such as geothermal energy and waste heat while also reducing the heat losses in the pipes and energy consumption in primary pumps.

Therefore, DHC network operators aim to achieve the lowest possible overall return temperature. Reaching this objective requires a detailed understanding of the network's operation. DHC operators are mainly responsible for managing heat generation plants, the primary network and the primary side of substations. Given the complexity of a DHC network and the relatively simple control strategies typically based on expert knowledge, there remains significant potential for optimization

However, because heat supply in DHC networks relies on numerous control, mechanical, and hydraulic components, malfunctions may occur. Inappropriate or faulty equipment anywhere in the network can negatively impact the overall return temperature. So before considering control optimization, it is essential to ensure that the network is operating properly. However, according to [1], in a study carried out on 2 Swedish networks, only 26% of substations were operating correctly. The malfunctions in the substations do not necessarily disrupt the heat supply, but they can significantly affect the overall performance of the DHC network. It is therefore essential to be aware of the most common malfunctions and those that have the greatest impact on performance.

1.1. Overview of faults in DHC networks

Due to the complexity of the DHC network's operation, causes of malfunctions can be very diverse. A study on multiple Swedish networks carried out by [2] has identified the various possible causes of network malfunctions and their recurrence (see Figure 1)

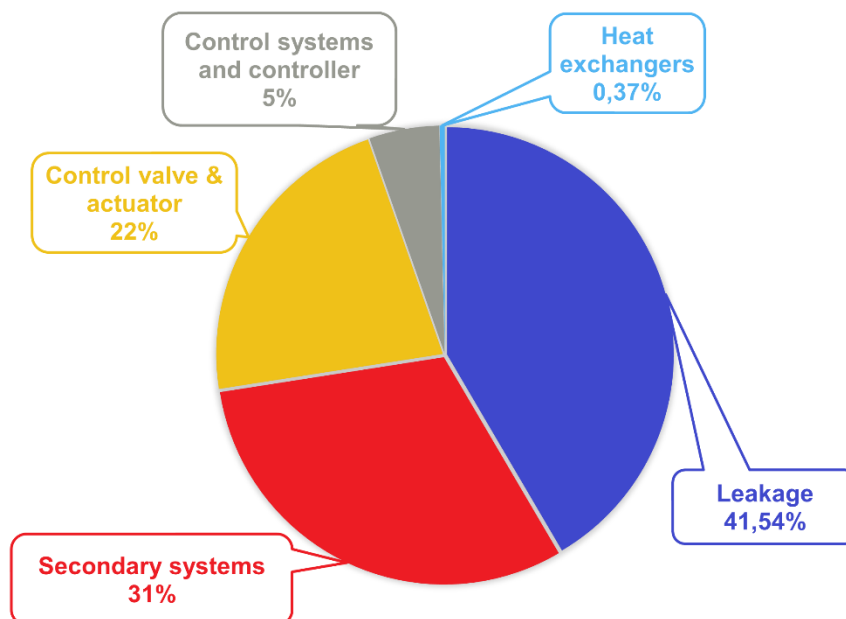


Figure 1 Source and recurrence of DHC network malfunctions (adapted from [2])



The malfunctions are divided into 5 categories depending on the localization or the type of malfunction: leakage, faults in the secondary systems (customer installation), faults due to the substation control valve and actuator, faults in control systems and controllers and faults in the heat exchanger. It appears that the two main sources of malfunction are leaks and problems with customers' hydraulic systems. The localization of the various identified faults are shown in Figure 2. Each category of malfunction is described and explained in the following sections.

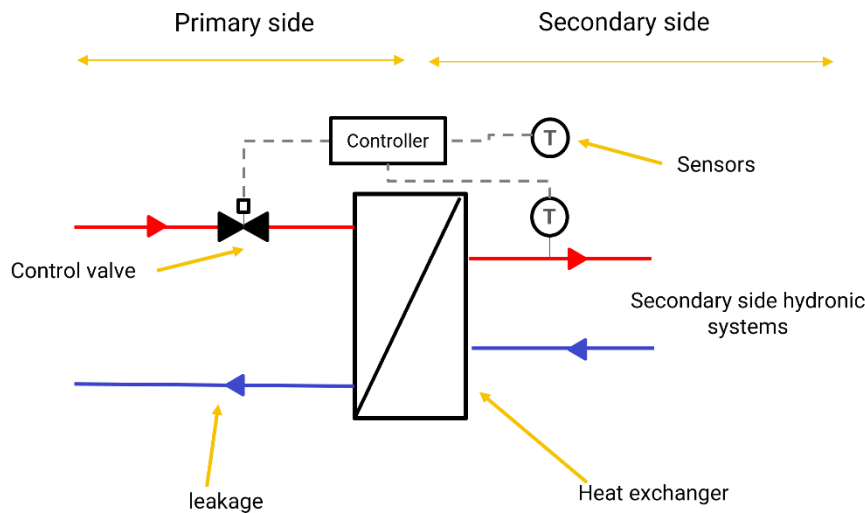


Figure 2 Malfunction localization

1.1.1.1. Leakages

Leaks represent 42% of faults in DHC networks. They are located mostly on the primary network but also on the heat exchanger and the control valves. The leakage can be separated into 2 categories [3]:

- Heat losses due to deterioration of pipe insulation or defects in installation or design
- Water leakage due to materials ageing, accidental damage (i.e. public works near the network) or defects in installation or design.

Some DHC networks can have significant leak rates exceeding 10% of the total volume of distributed water, especially in older networks.

Leakages have direct and indirect consequences for the energy, economic and environmental performance of a DHC:

- Over-consumption of energy to maintain network temperature and pressure
- High operating and maintenance costs
- Health and environmental risks (soil and groundwater contamination)

1.1.1.2. Secondary system malfunctions

The category “secondary system malfunctions” includes all issues detected in the customers’ internal heating systems. The large number of problems in this category is due to the fact that DHC operators generally have no control over, or access to data from, this part of the DHC networks. A more detailed fault distribution is shown in Figure 3 according to [2].

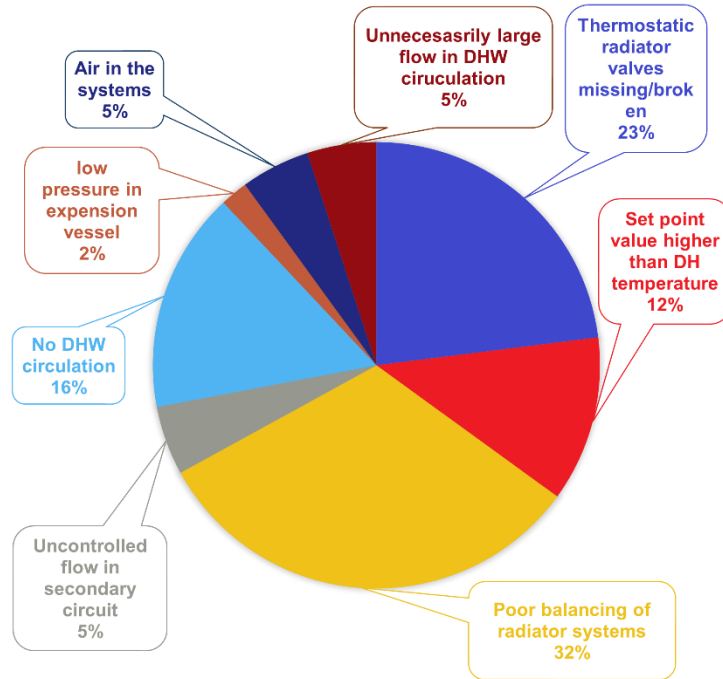


Figure 3 Fault distribution in customers' hydronic system (adapted from [2])

The most common issue is the poor balancing of the secondary network (32%). As presented in Module 2 this malfunction can lead to thermal discomfort for the customers caused by a lack of flow rate in some emitters. As the DHC operators can generally not intervene on secondary systems, they usually increase the secondary supply temperature leading to overconsumption and higher return temperature.

The second most common issue is the thermostatic emitter valves missing or broken (23%). This issue can be gathered with uncontrolled flow in secondary systems (5%) issue. Indeed, broken or missing thermostatic valves lead to uncontrolled flow in the secondary systems resulting in overconsumption or high return temperatures and potential thermal discomfort for customers.

Another frequent malfunction concerns domestic Hot Water (DHW) supply, either due to no DHW recirculation (16%) or excessive DHW recirculation (5%). In DHW systems, the recirculation refers to the flow rate used to maintain a minimum temperature in the DHW hydraulic circuit ($> 55^{\circ}\text{C}$) to prevent legionella growth when hot water is not being drawn. These two issues lead to high return temperatures; however, they are more often the result of inappropriate design choices than true malfunctions.

The last common malfunction is a control issue, a secondary supply set point temperature higher than the primary supply temperature of the DH network. This fault occurs mostly during summer when only DHW is needed, allowing the supply network temperature to be reduced while some customers maintain the same set point temperature year-round. This led to unnecessary high flow rates in the DHC networks causing increased return temperature.

Problems identified by DHC network operators are a mix of malfunctions and unsuitable systems on the customers' hydronic systems. The solution to tackle these issues is discussed in section 1.3.



1.1.3. Control valves and actuators

This fault category includes the mechanical issues on control valves and on devices that adjust the valve opening, called actuators. The distribution of this category of faults is shown in Figure 4.

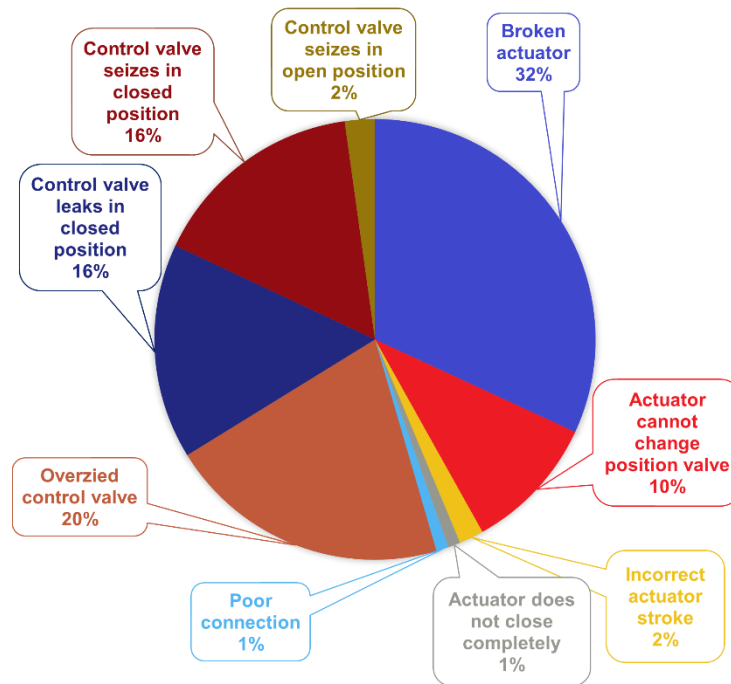


Figure 4 Fault distribution on control valve and actuator issues (adapted from [2])

The most common issues with control valves and actuators (i.e. broken actuator, actuator unable to change the valve position, control valve stuck in a fixed position) lead to an inability of the valve to open or close properly preventing correct control of the primary flow rate. This malfunction represents around 76% of the detected issues due to control valves and actuators. The non control of the primary flow rate can have different impacts for the customer or the network following which position the valve is stuck. It can cause discomfort for the customer and/or an increase in the primary return temperature.

The other common issue is the oversizing of the valves (20%). If a valve is oversized, it will operate mainly in a very partially open position where the control characteristic is and not very accurate. Therefore, it causes rapid and abrupt variation in flow as well as temperature and pressure oscillations. At the end, it may lead to higher pump consumption and premature wear and tear.

1.1.4. Control systems and controller

The category control systems and controller include the issues affecting all devices used to send opening or closing commands to valves such as the sensors, the secondary supply temperature set point and the controller. The distribution of this category of faults is shown in Figure 5.

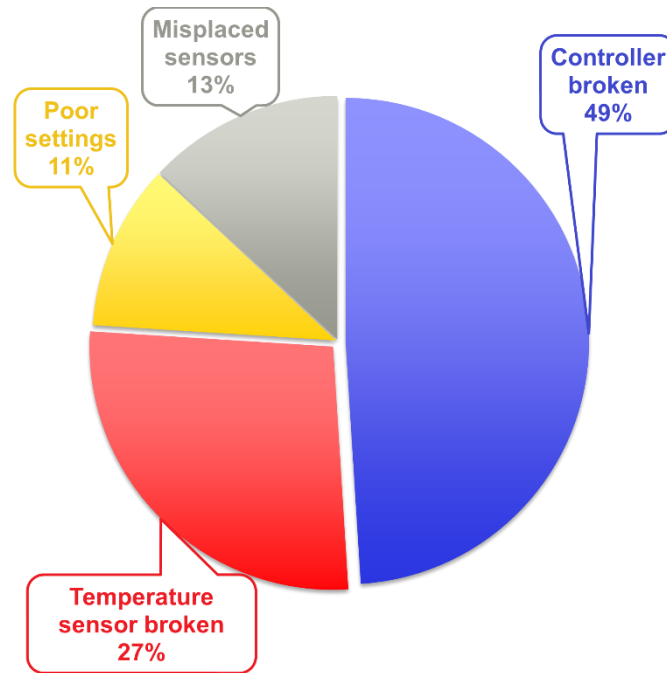


Figure 5 Fault distribution on control systems and controller issues (adapted from [2])

The most common faults concern device failures, controllers or sensors (76%). The operator also experienced that incorrectly located sensors are a frequent issue (13%). All these faults lead to poor control resulting in abnormal temperature levels. The last fault is caused by customers themselves, who manually change the secondary supply temperature set point values.

1.1.5. Heat exchanger

The last category concerns issues related to heat exchangers. Usually, the heat exchangers are well monitored by the DHC operator. However, water quality in the network can sometimes lead to fouling of heat exchangers, resulting in a degradation of the heat exchanger efficiency.

1.1.6. Conclusion

This overview of common malfunctions in DHC networks shows that practically all the malfunctions impact either the customer's thermal comfort and/or the primary return temperature. It is therefore essential to correct these issues. Moreover, malfunctions are present in approximately 75% of substations which makes any optimization useless until these issues are resolved. Although the common and most impactful problems are known, identifying their root causes remains challenging. Indeed, the DHC operators only manage the primary side of the system (including the heat exchanger and the secondary supply temperature sensor) and therefore have limited visibility of the customer or building side. Besides, for billing purposes, only exchanged power data is legally required. This data is measured through an energy meter (see module 2), which can provide information on the primary flow rate, the primary supply and return temperature. Therefore, this lack of data makes malfunction detection particularly difficult. This challenge is further compounded by the fact that malfunctions do not necessarily affect the comfort of occupants.

In conclusion, improving DHC network performance first requires identifying the most suitable hydronic systems to use on the building side as well as accurately and rapidly detecting malfunctions.



1.2. Design of the secondary side hydronic systems

Most of DHC systems have been connected to existing buildings with their own internal heating distribution systems, which are generally not optimised for reducing return temperatures. The previous section showed that 31% of malfunctions or underperformance issues come from the customer side.

Thus, there is a strong potential for improving the performance of existing and new DH. A better operation of substations reduces the return temperatures on the DH network and consequently improves the DH system efficiency. However, it is often difficult for DH operators to implement performance actions on customer installations as they are generally not in charge of their operation and maintenance.

This section aims to bring out some recommendations to improve the design and the operation of secondary heating systems to lower the return water temperatures. The recommendation comes from an IEA report of the Annex XIII [4].

Based on the literature review [4], several types of secondary side hydronic architecture have been selected. The retrofit actions studied can be undertaken on 4 components of the secondary side:

- The substation architecture

The substation architectures have a noticeable impact on the DHN performance. As shown in module 2, the parallel configuration seems to be the best substation architecture in terms of performance and control. However, this study does not compare all the most common architectures, especially one still very common in France with a global heat exchanger (see Figure 6).

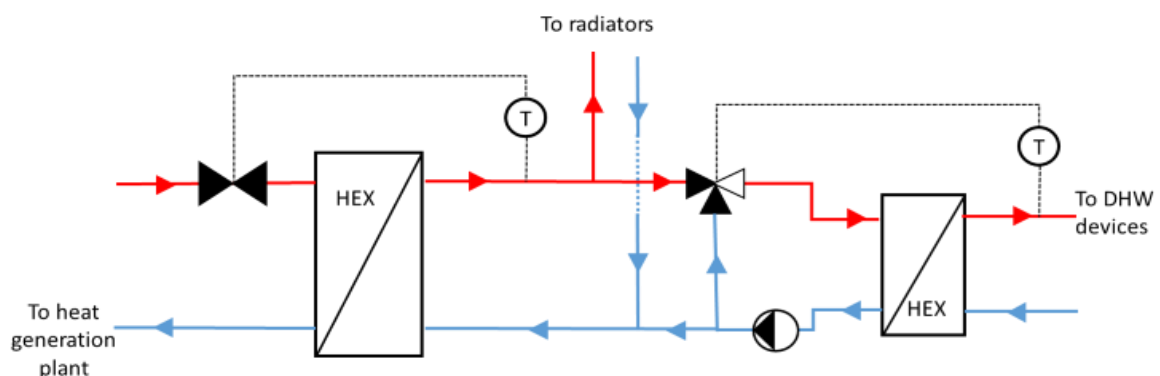


Figure 6 Substation with a global heat exchanger [4]

Contrary to the parallel configuration, only one HEX is used between the primary side and the secondary side to supply SH and DHW. The primary flow rate is controlled in the same way as in the previous configuration. Furthermore, to supply DHW, a HEX is used on the secondary network, where the flow rate passing through the HEX is delivered by a constant flow rate pump and temperature control is ensured by a 3-way valve in which a part of the outflow is mixed with the inflow.

- The secondary flow rate control



The control systems are installed to control the flow rate passing through the emitters. Here, among all existing emitters only radiators are considered. So, the 3 most common flow rate controls have been selected. Two valve technologies are used, the 3-way valves (V3V) and the 2-way valves (V2V) as shown in Figure 7. Nowadays the standard is to use V2V, because it is supposed to be more efficient. However, in old buildings and a few new buildings, V3V is still used because it is easier to achieve a hydraulic balance than with V2V. The V3V can be handled in two ways: either by regulating the flow into radiators by bypassing a part of the inflow (flow control) or by mixing a part of the outflow with the inflow (temperature control). Usually on secondary systems, the V3V is used in flow control. The V3V in temperature control is predominantly used with a HEX supplying DHW in a global HEX configuration (see Figure 6).

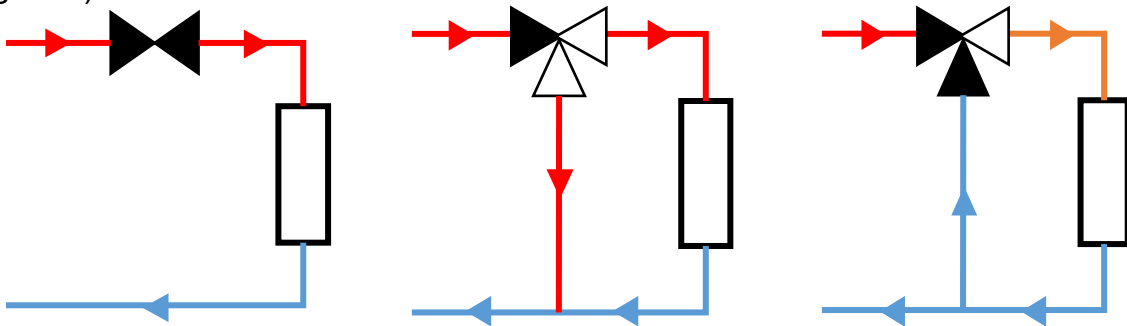


Figure 7 Secondary control valve: two-way valve, three-way valve in flow control and three-way valve in temperature control [4]

Moreover, the secondary flow rate control for SH depends not only on the valve but also on the pump technology. Three pump technologies are widely used: a constant-flow pump, a variable-flow pump and a variable-speed pump. The different characteristics of each technology are presented in Figure 8. Usually, a variable speed pump is not used on the secondary network, but it is standard for the primary network. Therefore, only constant-flow pump and variable-flow pump will be presented in the following.

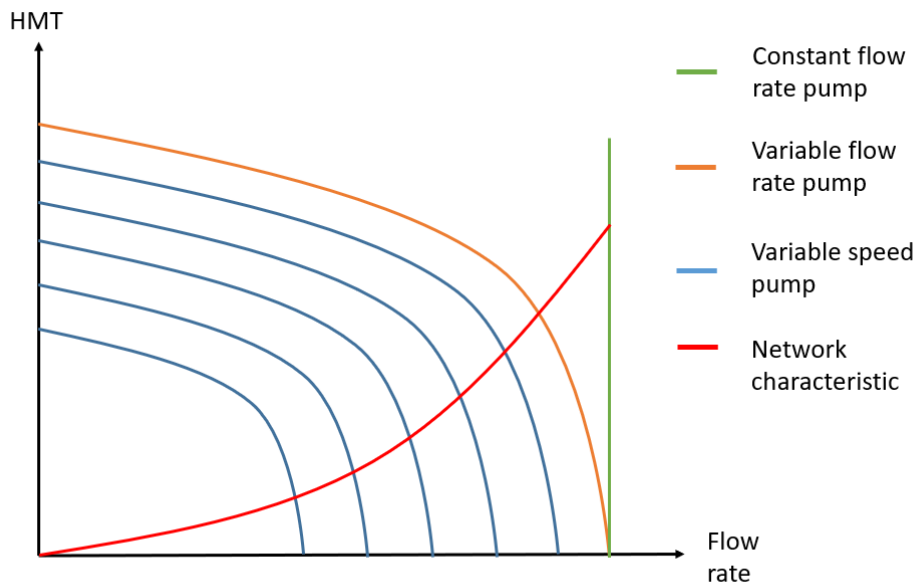


Figure 8 Pump and network characteristics [4]



The valves and the pump must be considered together. Indeed, the choice of the valve depends on the flow rate regime driven by the pump. For example, in our case, a constant-flow pump cannot be used with V2V because the overflow delivered by the pump cannot be handled without a bypass. So, three types of secondary flow rate control are considered: The combination between constant-flow pump and V3V, and the combination between variable-flow pump and a V3V or a V2V.

- The radiator temperature regime

As shown in module 2 different radiator temperature regimes are used. The radiators are designed to deliver a certain heat power for specific inlet and outlet temperatures at the design outdoor temperature (i.e. -7°C in North of France). It has been chosen to compare two widely used radiator temperature regimes: High temperature regime of $80/60^{\circ}\text{C}$ (HT) and low temperature regime of $55/45^{\circ}\text{C}$ (LT).

- The DHW supply architecture

As shown previously (see module 2), to supply DHW several methods are widely used in the use, or not use, of a storage tank. Therefore, the first common architecture is the instantaneous one (see Figure 9) where the DHW secondary network is directly connected to the substation's HEX without storage tank. In this case, the primary flow rate is controlled to reach the secondary supply setpoint temperature equal to 60°C . The cold water and the recirculation flow rates are mixed and come directly in the HEX inlet.

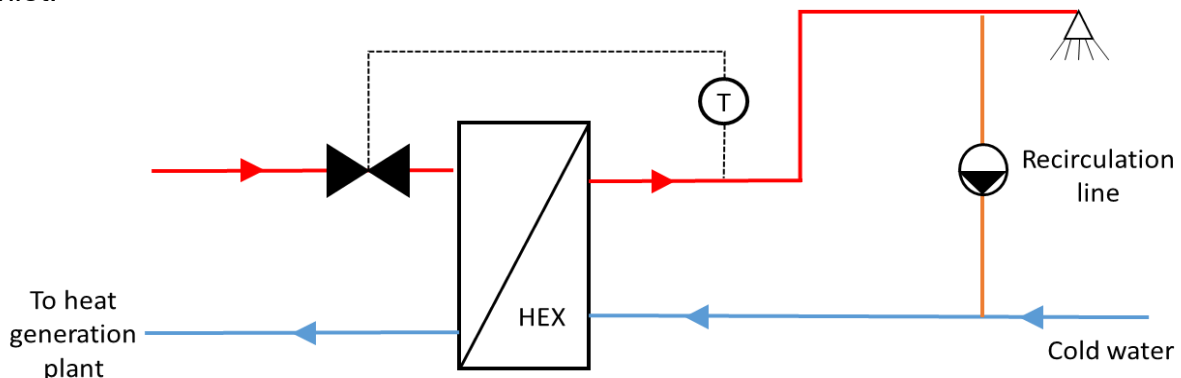


Figure 9 Substation supplying DHW, instantaneous architecture [4]

The second common design is the hot water tank architecture where a storage tank is placed between the substation's HEX and the drawing points (see Figure 10). In this configuration, the primary flow rate is controlled to ensure a temperature above 60°C in the tank. During a DHW demand, the tap water comes directly to the tank's bottom and is mixed with the hot water, whereas the hot water is drawn by the customer from the top of the tank.

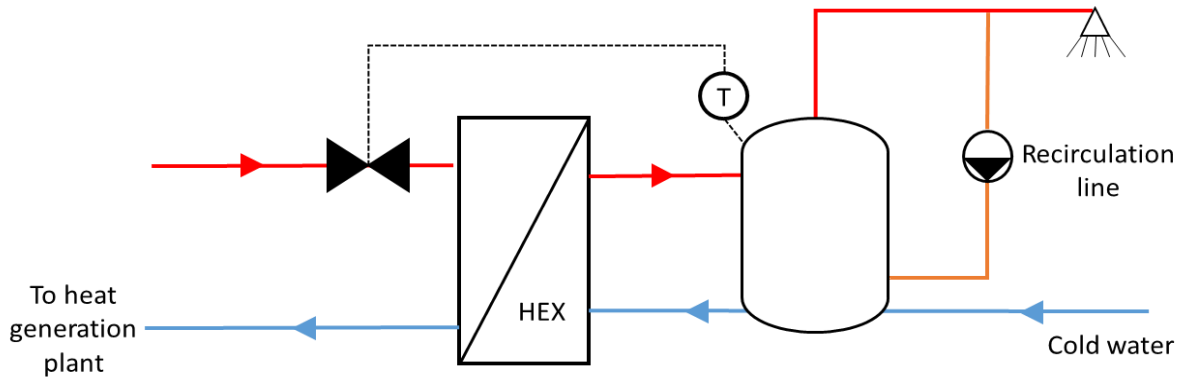


Figure 10 Substation supplying DHW, storage tank architecture [4]

In addition to the previous configuration, a third architecture called bypassed DHW tank is presented. This configuration is a compromise between the two other ones. The objective is to avoid hot returns on the secondary side of the heat exchanger. To do this, when there is no demand for DHW, the recirculation flow rate must be bypassed. As the recirculation temperature is at least 55°C , a sensor is placed just after the mixing of the cold water and the recirculation. If the temperature measured by the sensor is higher than 55°C , the valves close access to the exchanger and the flow goes into the tank. Thus, the storage tank is mainly used to ensure a sufficient temperature for the recirculation. When there is a demand for DHW, the mixture of cold water and recirculation does not pass through the tank and goes directly to the heat exchanger. Indeed, the idea is to only heat the tank and to avoid to consume hot water from the tank during a demand as well as when no DHW is needed to use the tank to supply the recirculation line and so to avoid to connect the recirculation line with hot water to the substation HEX and so to avoid to find hot water in the inlet of the substation (see Figure 11).

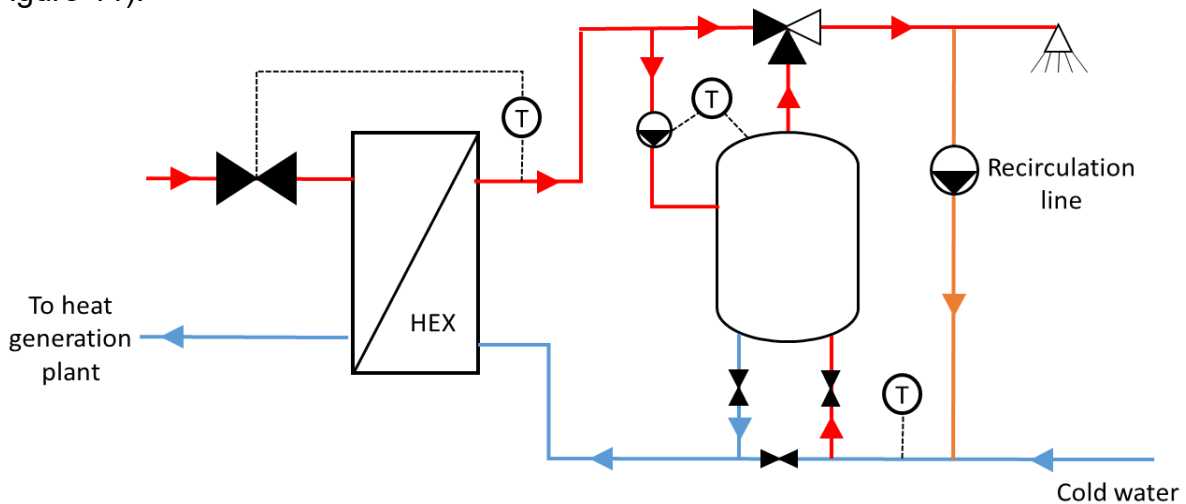


Figure 11 Substation supplying DHW, bypassed tank configuration [4]

Finally, by combining all these different retrofit actions, 36 common cases are possible. Then, all these combinations are analyzed and compared.

1.2.1. Impact of the type of emitters and secondary flow control

The comparison of all the combinations for a global HEX architecture i.e. 18 cases is presented here. Figure 12 presents the mean primary temperature difference of each studied case.

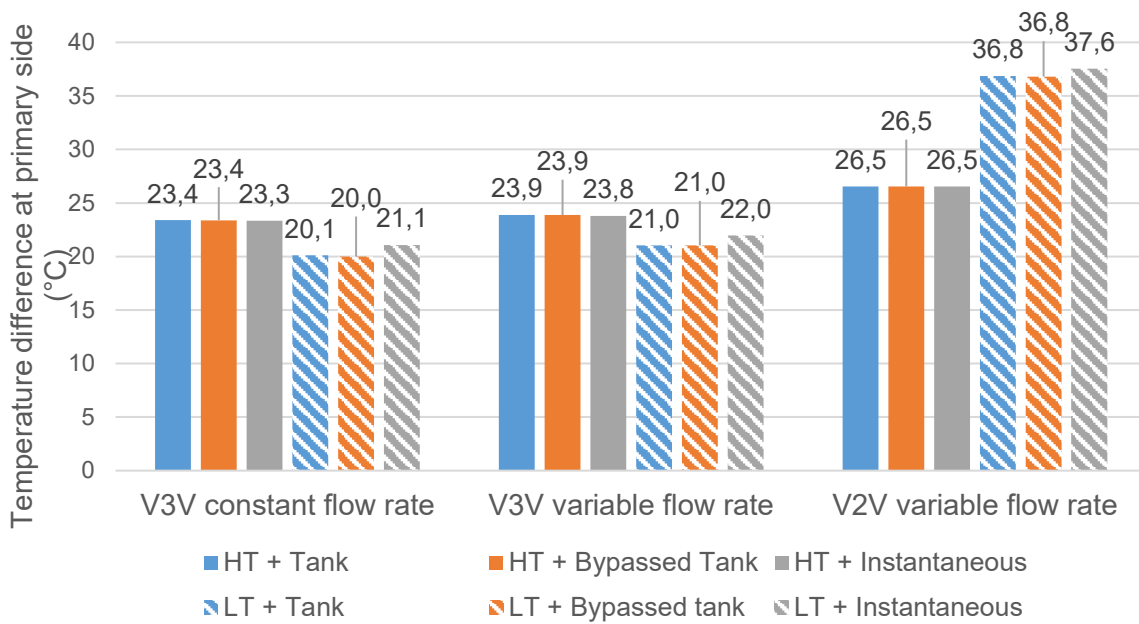


Figure 12 Comparison of the primary temperature differences for all the hydronic configurations in the case of a global heat substation [4]

According to these results, the control strategy using a variable-flow secondary pump coupled with a V2V achieves better performance compared with the other two control types especially when LT radiators are used. Indeed, the temperature difference increase ranges from 3.1°C to 16°C. In fact, with the V3V and a constant-flow pump, the flow rate delivered by the pump is settled to cover the maximal space heating (SH) demand. Therefore, when the demand is far from the maximum, the mass flow rate required by the radiators is considerably lower than the pump flow rate. Accordingly, a large part of the flow is bypassed through the V3V (see Figure 13) and is mixed with the flow rate cooled by the radiator. Consequently, the secondary return temperature is quite high and so the primary return temperature cannot be significantly lowered. On the contrary, with a variable-flow pump and a V2V, the flow rate is constantly adjusted to the thermal demand in the radiator and therefore the secondary return temperature is much lower and so the primary return temperature. In the same way, the performance of the variable-flow pump and the V3V control is worse than the V2V control. However, in this case, the flow rate delivered by the pump is not always equal to the maximum flow rate needed. Consequently, compared to the constant-flow pump and V3V control, slightly less flow rate is bypassed and so, the primary return temperature is lower.

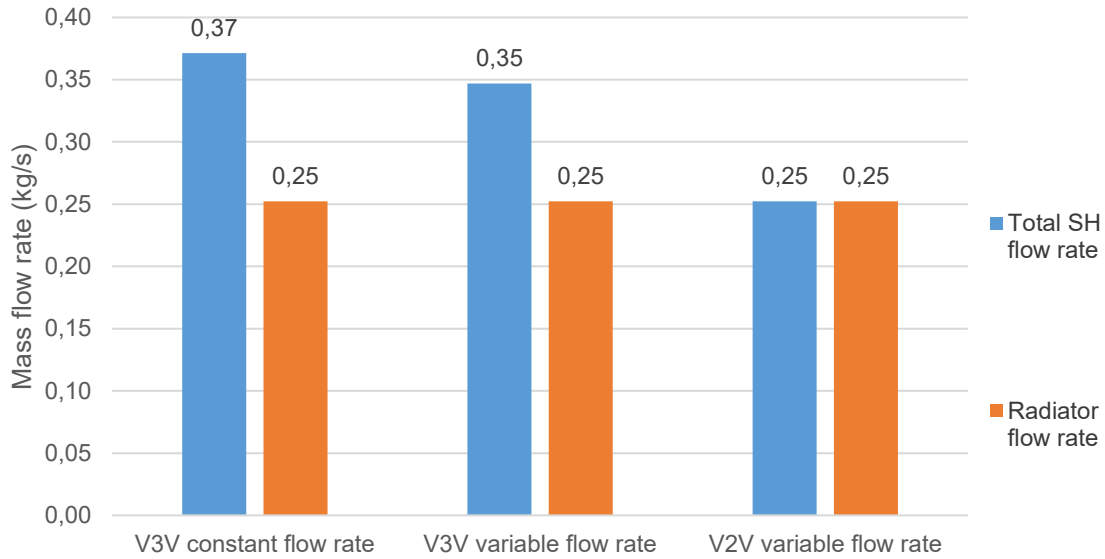


Figure 13 Comparison between the mass flow rate passing through the radiators and through the valve inlet [4]

The choice of the type of radiator can have a major impact on the performance. Two cases can be distinguished. The first case is when V3V are employed (either with constant-flow or variable-flow pump). Even though it may seem surprising, the average primary return temperature is higher with LT radiators than with HT radiators. This can be explained by the respective water laws of the radiators. Indeed, the HT radiator's water law varies between 80°C and 60°C, whereas the LT radiator's water law is kept constant at 60°C regardless of the outside temperature because of the temperature constraint on the DHW supply temperature (Figure 14).

The choice of the type of radiator can have a major impact on the performance. Two cases can be distinguished. The first case is when V3V are employed (either with constant-flow or variable-flow pump). In this case, the total flow rate used for space heating is a little bit lower with LT radiators than with HT radiators. Moreover, the secondary supply temperature differs slightly, when HT radiators are used the temperature varies from 80°C to 60°C (according to the outdoor temperature) whereas when LT radiators are employed in our case study with a constant 60°C setpoint temperature due to the constraint on the temperature supply for DHW (see Figure 14). **Hiba! A hivatkozási forrás nem található.**

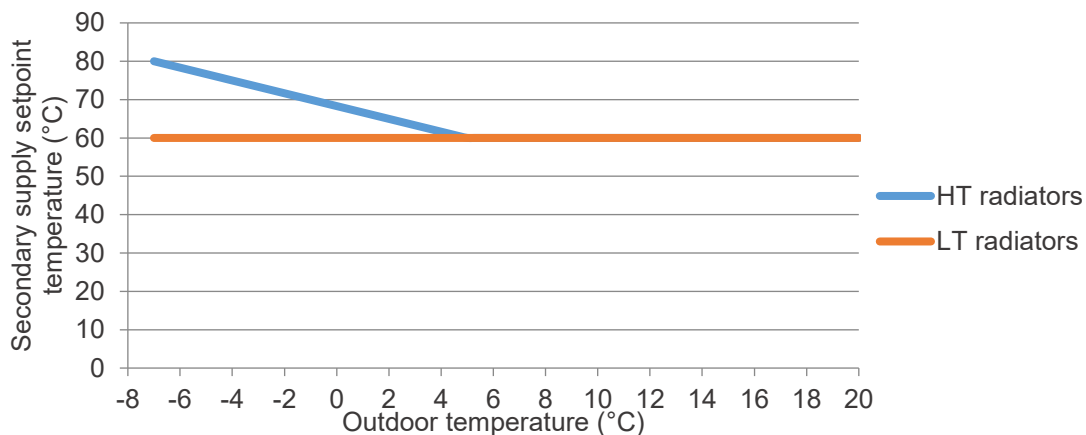


Figure 14 Secondary supply temperature reset control [4]



Furthermore, the nominal temperature difference in LT radiators is 10°C compared to 20°C in HT radiators. Consequently, as can be seen in Figure 15, the inlet-outlet temperature difference in LT radiators is much smaller than in HT radiators. When the outdoor temperature is above 6°C, the return temperature at the secondary is therefore lower with a HT radiator than with an LT radiator.

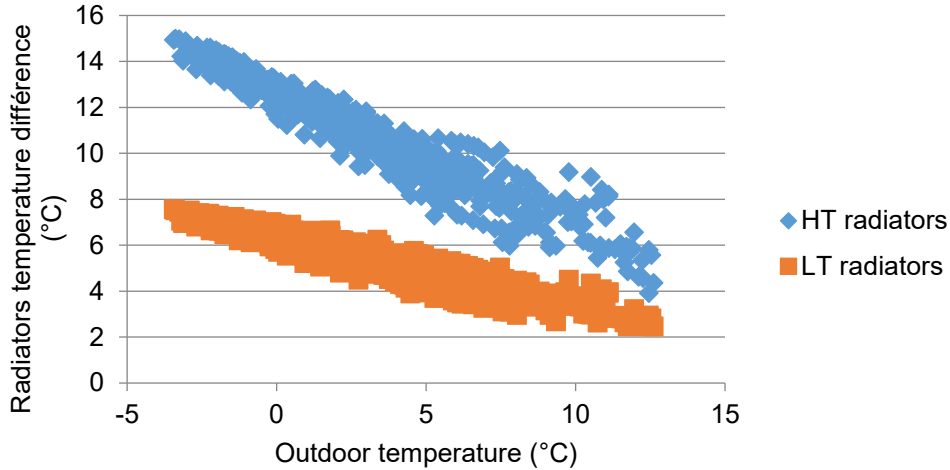


Figure 15 Evolution of the radiator's temperature difference following the outdoor temperature [4]

Therefore, for the same supply temperature and the same exchanged heat, the return temperature is higher when LT radiators are used.

The second case concerns the use of a V2V control strategy, in which there is no bypass flow. As a result, the secondary return temperature is lower with LT radiators than with HT radiators.

The next analysis deals with the comparison between all the combinations for a parallel architecture substation. The Figure 16 presents the mean primary temperature differences of each investigated case.

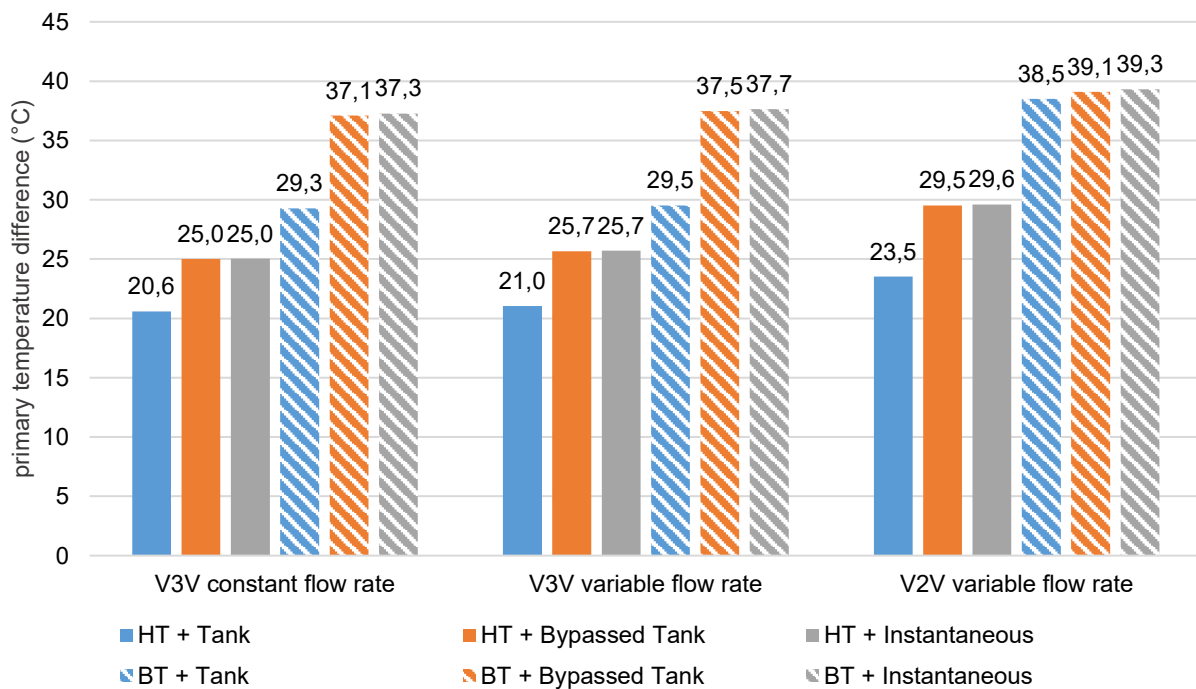


Figure 16 Comparison of the primary temperature differences for all the hydronic configurations in the case of a parallel substation [4]



Regarding the impact of the control strategy, the analysis is the same as explained in the previous part. The choice of a control strategy with a variable flow rate pump and a V2V achieves the best performances, the gains compared with the other two solutions range from 2°C to 9.2 °C.

Next, the use of LT radiators enables to increase ΔT at the primary side. Indeed, a LT radiator implies a smaller return and supply temperature and temperature difference at the secondary side than a HT radiator. This results in a larger flow rate at the secondary side as shown on Figure 17 (for the same exchanged power). Consequently, for the same HEX characteristics, the primary flow rate is lower when LT radiators are used. So, the primary return temperature is lower for similar primary supply temperature.

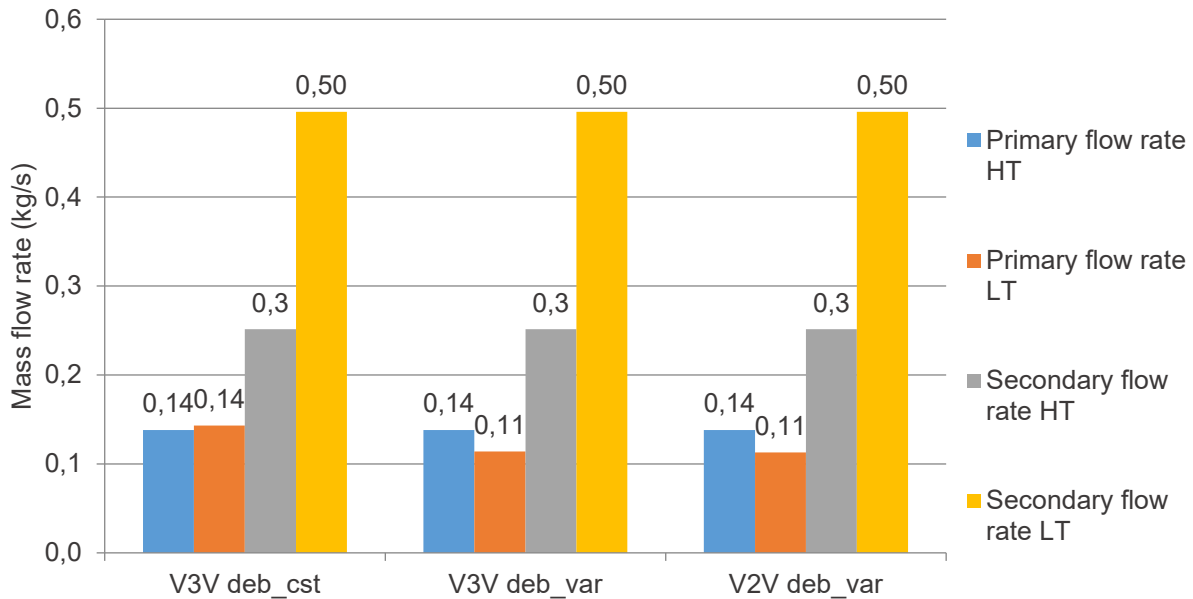


Figure 17 Comparison of the primary and secondary mass flow rates between all the radiator controls in the case of a parallel substation [4]

The next point is the comparison between the two substation architectures. No matter which types of radiators are used, the parallel architecture is far better. Indeed, in this case, the supply of DHW and SH depends on two separate HEX. Consequently, to provide space heating, the secondary supply temperature can be less than 60°C. As a result, the secondary flow rate can be greater than the primary flow rate, causing the primary return temperature to be smaller.

1.2.2. Impact of DHW hydronic configuration

Depending on the buildings, the impact of the DHW supply architecture is different because the weight of the DHW consumption on total consumption is not the same. Indeed, DHW represents 10% and 30% of the global consumption respectively for old buildings and renovated residential buildings. Concerning the old buildings, if a global HEX is used, the choice of DHW supply architecture has no impact on the overall performance. Moreover, if a parallel substation is used, the architecture with a storage tank presents the worst performance. Indeed, with the tank, the HEX inlet at the secondary side is not directly connected to the cold-water supply contrary to the two other architectures. Therefore, the secondary return temperature is close to 55°C i.e. the lower limit of the tank temperature whereas in the other configurations the temperature is often close to the cold water network temperature (see Figure 18).

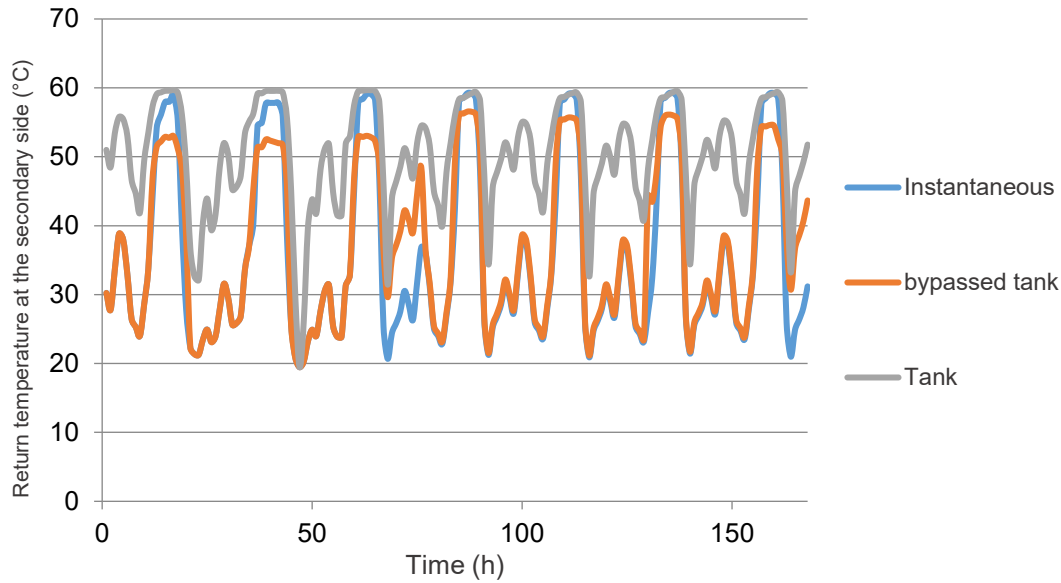


Figure 18 Temporal evolution of the return temperature for all the DHW supply architecture [4]

Concerning the renovated buildings, the analysis remains the same. However, the gain on the global primary return temperature due to a more suitable DHW supply architecture is higher since the DHW consumption represents a larger share of the total consumption.

1.2.3. Conclusion on the best hydronic configuration

To conclude, all the results are summarized in a decision tree (see Figure 19, Figure 20 & Figure 21). This one is separated into four layers representing the 4 types of retrofit actions. On each layer several options are possible. The best option(s) are represented by a green line while the worst option(s) are represented by a red line. The best options are those that allow lowering the return temperature of the substation on the primary side. The black dotted arrows represent the gains (on the return temperature) that can be obtained by switching from one combination to another.

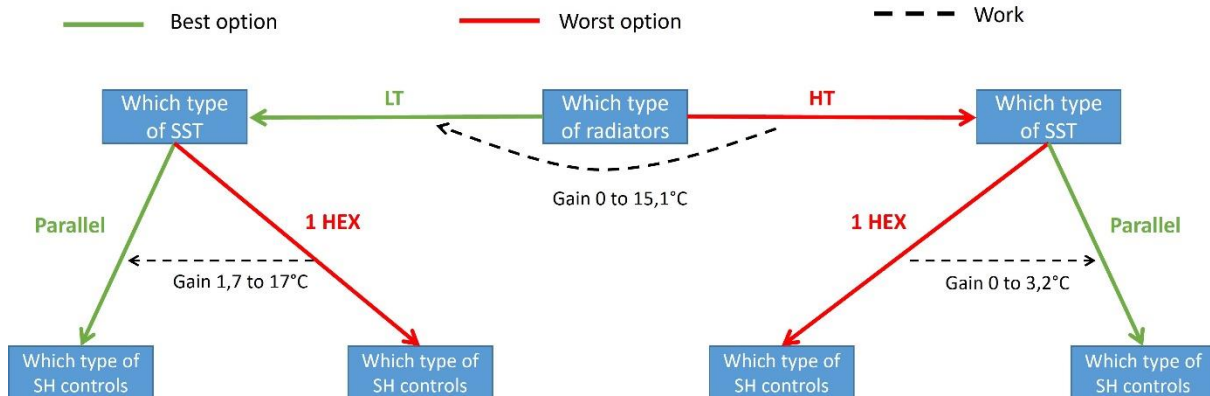


Figure 19 Decision tree summarizing the numerical results part 1 [4]

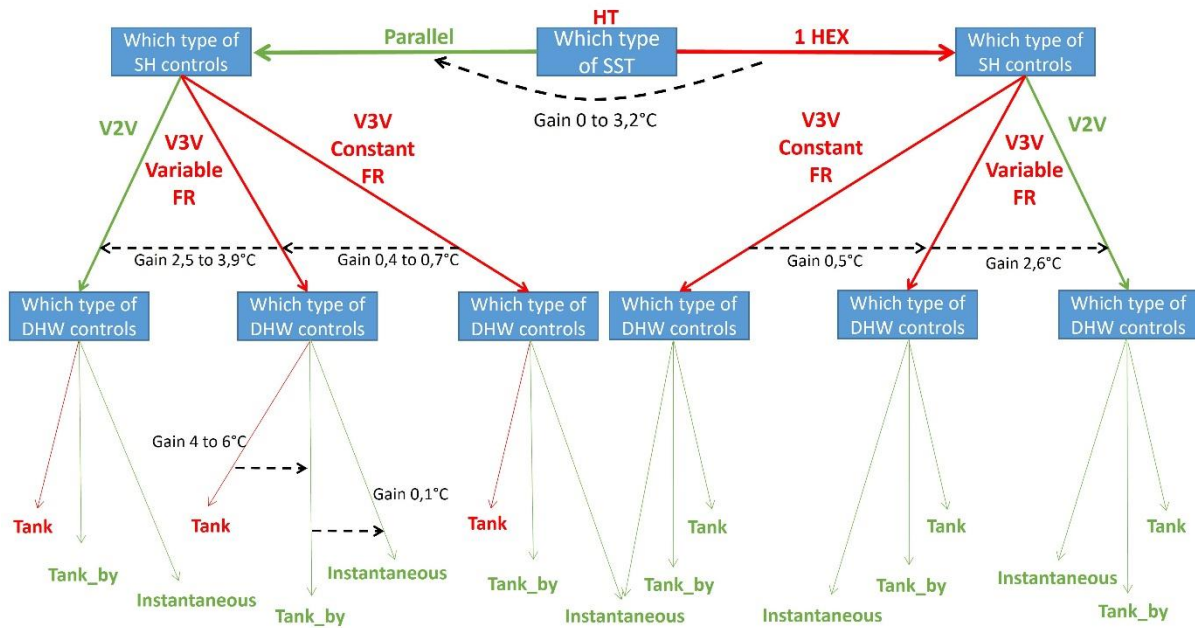


Figure 20 Decision tree summarizing the numerical results in case of HT radiators [4]

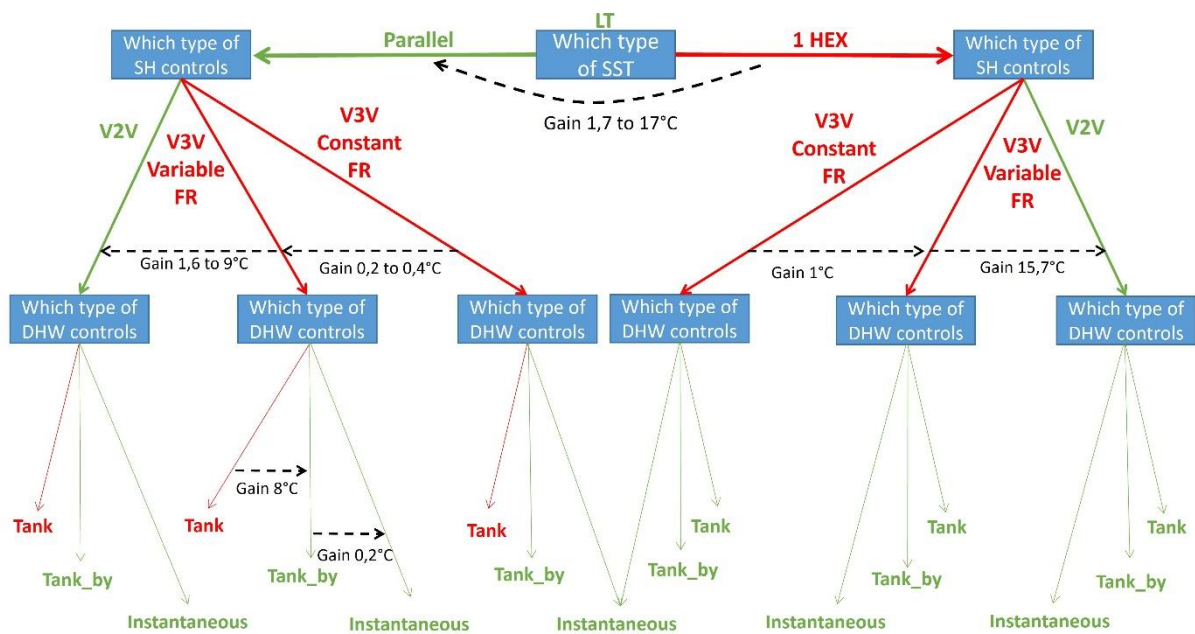


Figure 21 Decision tree summarizing the numerical results in case of LT radiators [4]

1.2.4. Heat tariff models

Based on the results, the decrease in return temperature thanks to retrofit actions has translated into annual energy gains for the DH. This, along with the cost of retrofit actions, allowed us to assess the payback times for an action (or combination of actions) and the monetary savings resulting from the lower gas demand that the action enables. In the Figure 22, the payback time for the best combination of actions is visualized for one, two, three, and four actions. As the results indicate, a situation with the upper level of natural gas prices leads to a significantly lower payback time for the actions, ranging from 0.9–1.3 years, whereas gas prices at lower levels yield payback times of around 6–9 years. Assuming that the reduced costs are fully transferred to the



customer, all these combinations of actions could be considered good investment opportunities.

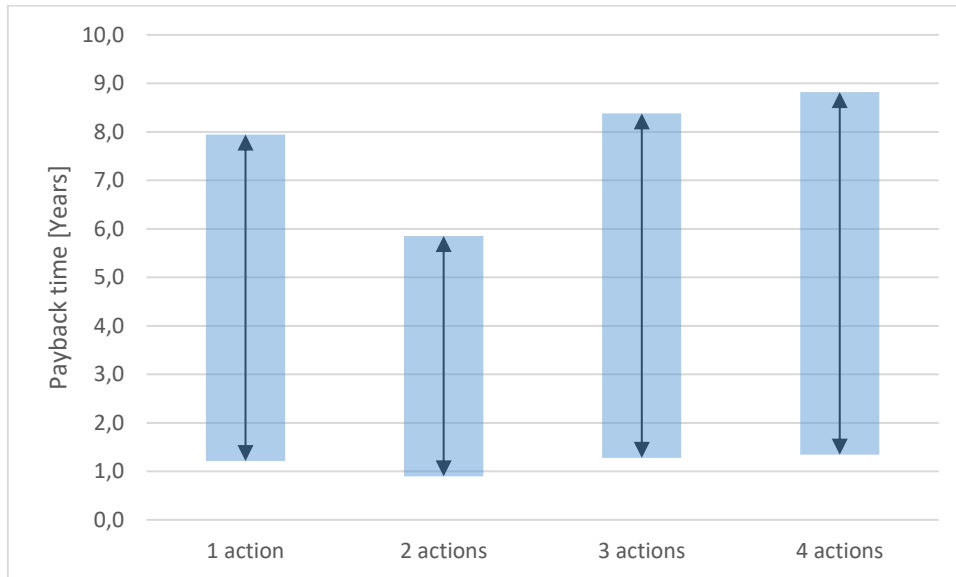


Figure 22 Payback time for the best combination of actions for a low (20 EUR/MWh) and high (130 EUR/MWh) gas price. Actions represented are 2V (for 1 action), 2V+LT (for 2 actions), 2V+LT+parallel (for 3 actions), and 2V+LT+parallel+instant (for 4 actions) [4]

The question asked is how to help the heating customers retrofit their building heating systems to improve DH performance. Indeed, the DHC operators do not have the control and the knowledge on the hydronic building side. A retrofit action of the building system will not change customer consumption but will help to increase the use of renewable energy on the whole network. Therefore, the customers have only an indirect interest in upgrading their systems.

Motivational heat tariffs have been studied as a solution to encourage building owners to retrofit their low-efficiency systems. Usually, the tariff is divided into two components, the subscription corresponding to a fixed tariff depending on the substation maximal power and a variable tariff corresponding to the cost of the energy consumption. From a literature review, some recommendations have been drawn up. A good DH price model from the customer perspective was described as easy to understand and “fair”. Moreover, it is essential to engage in a close dialogue with customers to explain the way that motivational tariffs can generate a win-win solution for both the customer and the energy company.

The most important factors to consider for motivational tariffs based on mature heat market motivational tariff practices identified in the literature are summarized in Table 1.

Table 1. Summary of motivational tariffs in use and the components that are measured [4]

Tariff in use	Measured component
Flow/Bonus Malus	m ³ /MWh
Bonus Malus	Return temperature can include a separate measurement of cooling performance through the substation
Discount	Customers using return line heat
Compensation	Feed-in tariff for waste heat deliveries



The proposed heat tariff models build on the classical tariff structure and introduce additional components, such as pricing based on water consumption per unit of energy, an incentive tariff for reducing primary return temperatures, and a reward for utilizing waste heat in the secondary circuit. Existing incentives from mature markets should be maintained, such as flow-based charges and fees related to installed capacity, while new factors—such as lower substation temperatures and the use of secondary-side waste heat—should be incorporated into future pricing models. Once the secondary side is using the right equipment, the next step is to focus on detecting malfunctions for a proper operation of the DHC.

1.3. Fault detection

Detecting the cause of malfunctions in a heating network is a major challenge for the operators and managers of these infrastructures. Heating networks, as complex and extensive thermal systems, are subject to numerous uncertainties linked to operating conditions, the variability of thermal loads, the condition of equipment and the interaction between substations and the main network. The scientific literature emphasizes that these systems are characterized by strong hydraulic and thermal coupling, which makes it difficult to analyze each component independently [3] & [6].

1.3.1. Malfunction detection challenges

The observed disturbances, such as temperature drops, pressure losses or excessive energy consumption, can result from a multitude of causes - leaks, valve sticking, poor hydraulic balancing, faulty sensors or even control errors. However, these symptoms can be similar regardless of the actual cause, making precise identification of the source of the malfunction particularly complex. In addition, the absence or low resolution of real-time data in some older networks still limits automated diagnostic capabilities. Moreover, each heating network has a specific configuration, with a wide range of equipment, substations, consumption profiles and technologies used. This heterogeneity makes it difficult to standardize fault detection approaches and limits their transferability from one network to another [7].

It is therefore becoming necessary to use hybrid approaches combining physical modelling, data analysis and machine learning techniques to improve the location and the understanding of anomalies. However, even these innovative approaches remain dependent on the quality of the data available and detailed knowledge of the network under study [8].

Indeed, only few data are legally mandatory and usually available at substation level (see Figure 23):

- Primary supply and return temperatures
- Secondary supply temperature
- Exchanged power at the substation
- Primary flow rate

However, to better understand the substation behavior other data are highly needed such as the secondary return temperature and the secondary mass flow rate. In addition, the return temperature at each emitter could be very useful.

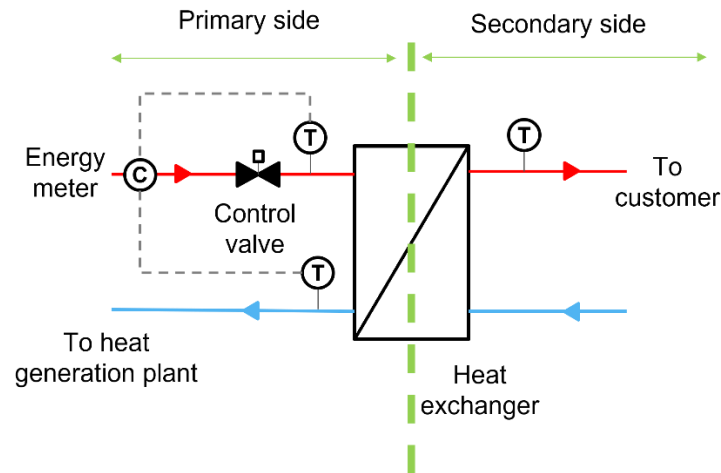


Figure 23 Substation scheme

1.3.2. What is malfunction detection?

Whether it is the tools used by operators or the tools proposed in the literature, two major trends emerge the anomaly detection and the fault detection. The anomaly detection aims to find patterns in data that do not conform to a previously defined notion of expected and “normal behavior”. This kind of detection allows to find outliers and deviations in measured data and also atypical behavior and abnormal patterns. However, it is not possible to directly determine the origin of the anomaly and so to correct the system. Moreover, to perform the anomaly detection, a normal behavior must be defined which can be complex. The second trend concerns effective fault detection which aims to identify the changes occurring in the system so that it can no longer operate properly. This kind of detection enables to find the malfunction cause and so to correct it. However, it is harder to perform.

The malfunction detection of either an anomaly or a fault is carried out through 5 methods [8]:

- Visualization & manual analysis
- Thresholds
- Regression
- Classification
- Clustering

Each method can be used separately or in combination. These five methods are detailed and illustrated through tools used for anomaly detection.

1.3.3. Anomaly detection

1.3.3.1. Visualization & manual analysis

Visualization and manual analysis are the simplest and oldest methods to detect anomaly. Manual analysis involves human experts reviewing substation measurements or derived indicators, often supported by visualization tools. This approach offers high flexibility due to expert judgment, but it is inherently subjective. In practice, manual analysis can be used to detect anomalies and faults, or to conduct a more in-depth investigation of issues that have already been identified by other methods.

For example, the method proposed by [1] seeks to compare the behavior of a reference substation (considered to operate without major issue) to other ones. They



proposed comparing the evolution of the demanded power according to the outdoor temperature and the hourly average water flow rate throughout the week according to the 4 seasons (see Figure 24).

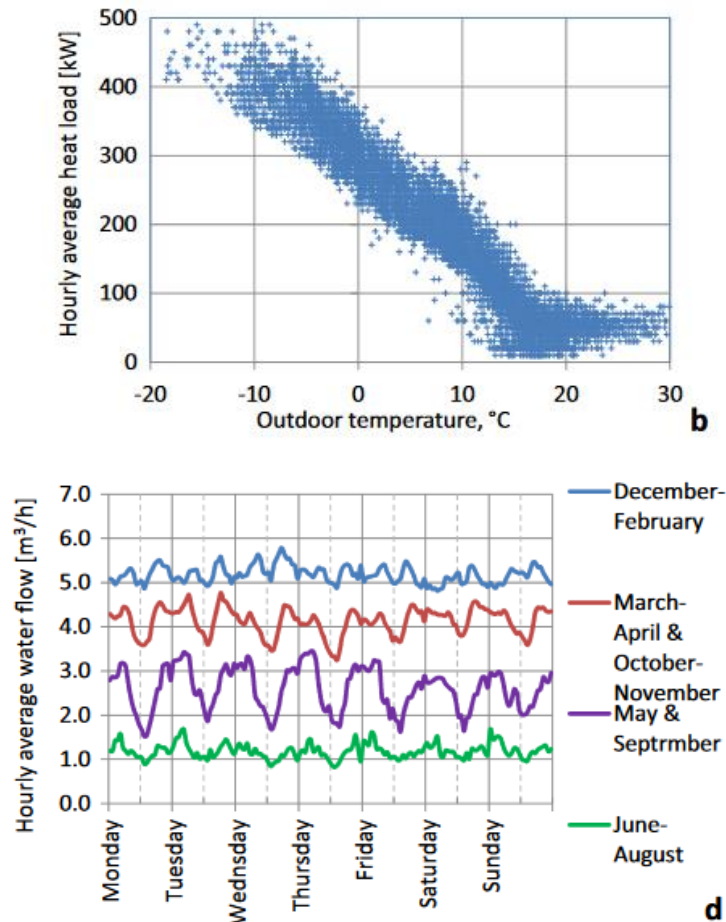


Figure 24 Correct behavior of a substation [1]

The hourly average heat load is supposed to be linear according to the outdoor temperature (thermo-sensibility of the space heating) and stay constant from the outdoor temperature as soon as the outdoor temperature is high enough that space heating is no longer required. The hourly average water flow is supposed to be stable and higher in cold seasons.

The Figure 25 shows the same data but for a faulty substation. The hourly average heat load is less linear as expected and the water flow is unstable underlying a problem.

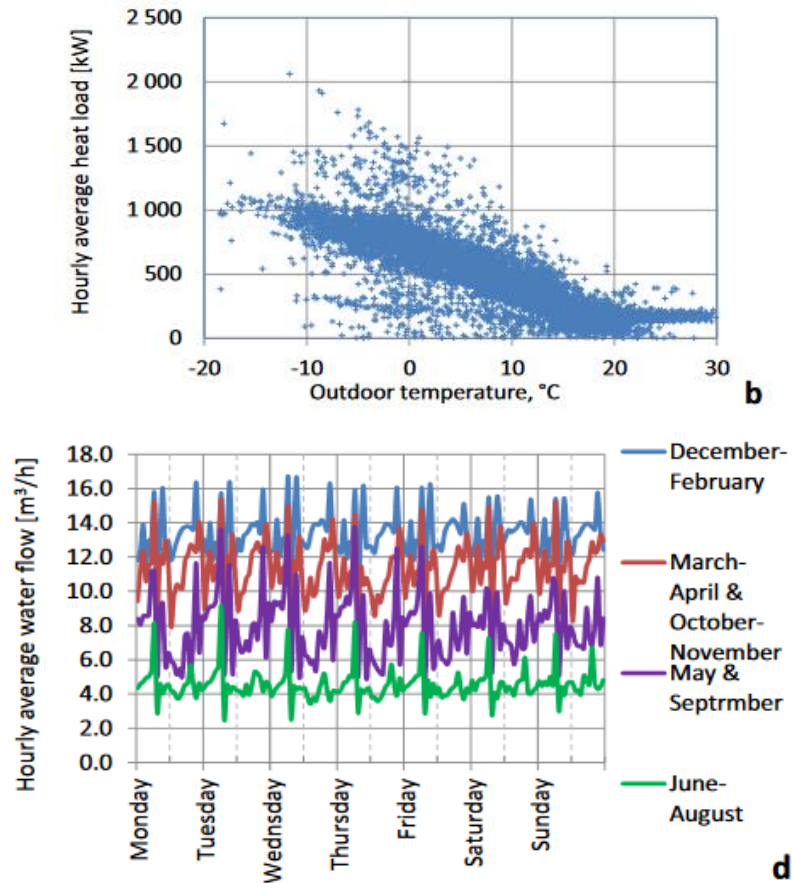


Figure 25 Abnormal behavior of a substation [1]

1.3.3.2. Thresholds

Threshold-based methods determine the operational state of a district heating system by comparing measurements against predefined limits. These thresholds may be manually set by experts based on assumptions regarding acceptable error rates (i.e., a 5% error margin), or they can be established through statistical analysis, such as using three standard deviations from the mean.

For example, the indicator created by [9] compares the control valve opening measured in-situ with the one calculated by a machine learning model without malfunction (see Figure 26).

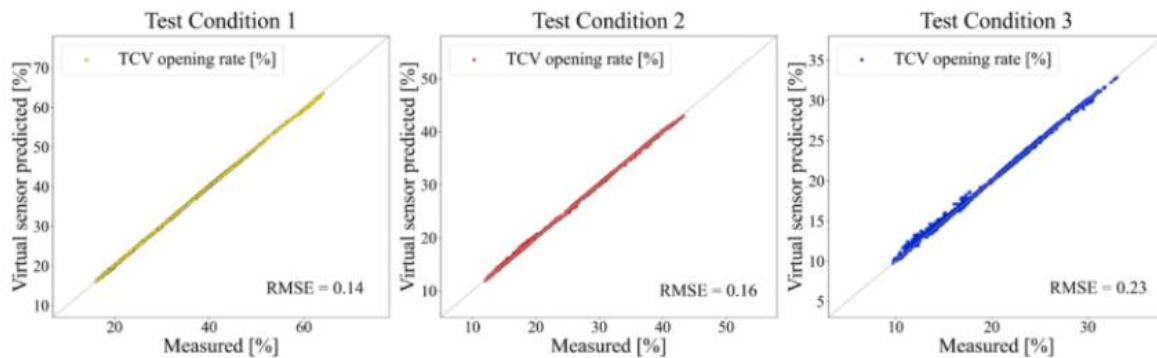


Figure 26 Correlation between measured and simulated valve opening [9]

Then, the normalized residual is calculated between the simulated and measured values. An anomaly is detected when the residual is higher than 3% corresponding to



the false alarm rate (see Figure 27. This method is used to detect fouling on a substation heat exchanger.

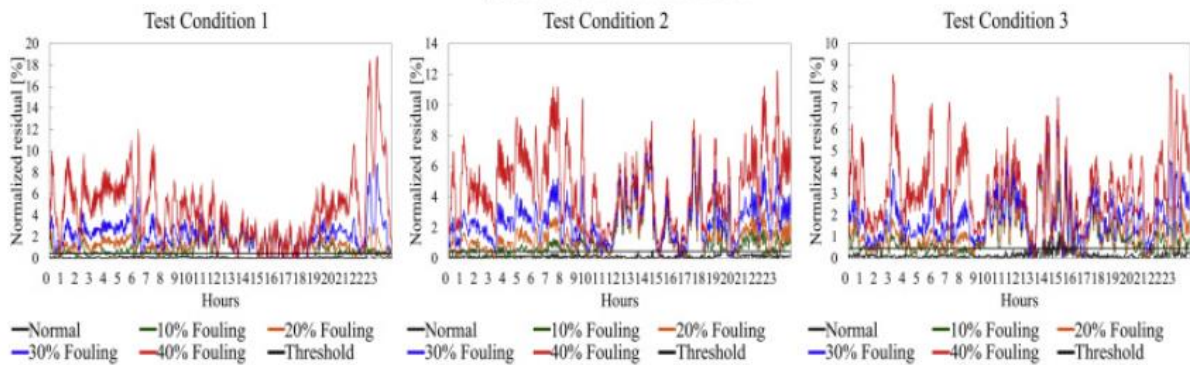


Figure 27 Normalized residual according to the time and to the fouling rate [9]

According to the results of [9], this indicator based on a threshold is able to detect fouling, but it hadn't been tested on other types of malfunctions.

1.3.3.3. Regression

Regression is a method used to estimate the relationship between one or more independent variables and a dependent variable within a dataset. By taking the independent variables as input, a regression model generates a real-valued prediction for the dependent variables. In the context of district heating systems (DHS), regression is commonly employed to forecast specific variables and to assess the discrepancy between predicted and actual measured values.

For example, the indicator defined by [10] aims to detect fouling in a substation heat exchanger. For a heat exchanger, there is a linear regression between the power exchanged \dot{Q} (W) and the global heat transfer coefficient UA (W/K):

$$UA = \frac{1}{LMTD} * \phi = a * \phi$$

With $LMTD$ the logarithmic mean temperature difference in K. The fouling of a heat exchanger modifies the UA and so the slope a of the linear regression (see Figure 28).

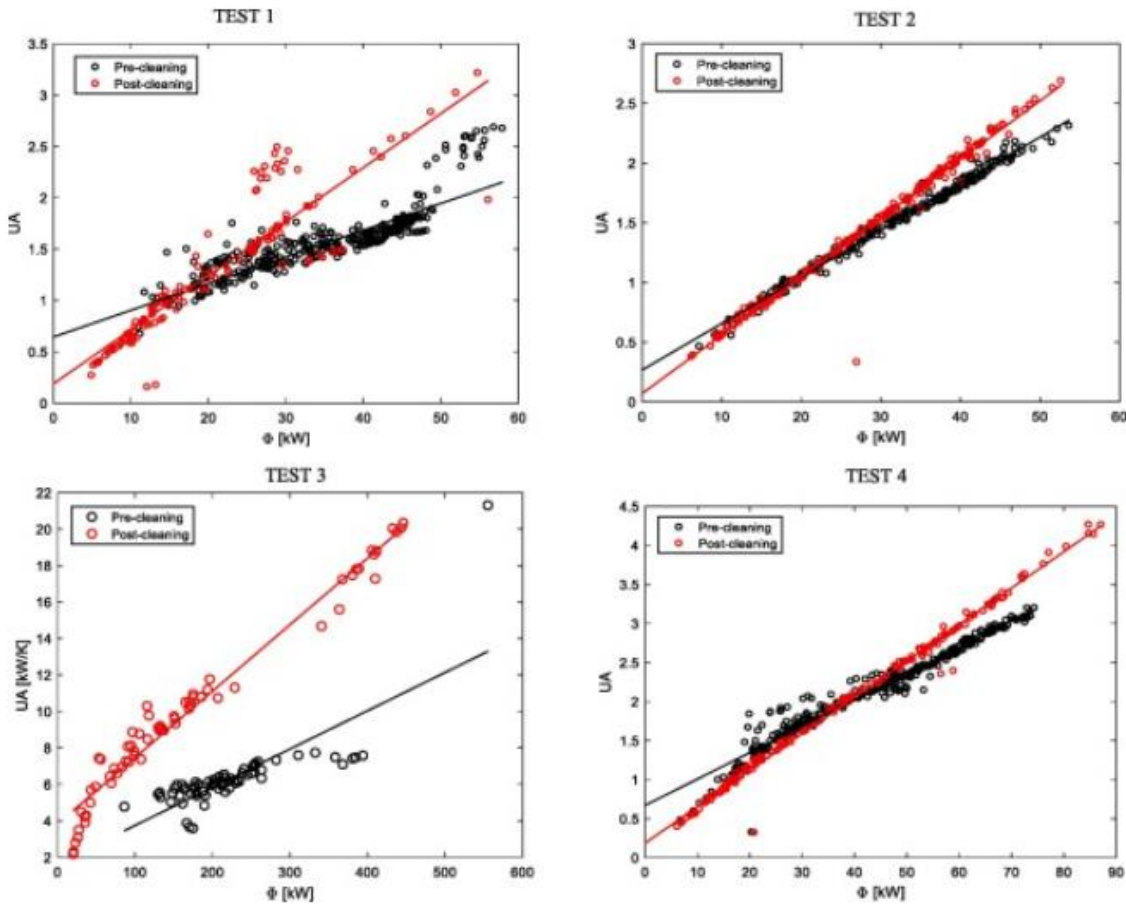


Figure 28 Linear regression between the global heat transfer and the exchanged power for heat exchanger with and without fouling [10]

In order to improve the indicator, three thresholds are defined on the slope variation to estimate the level of fouling:

- If the slope variation is inferior to 15%, the heat exchanger is considered as clean
- If the slope variation is between 15% and 25% the heat exchanger is considered as partially fouled
- If the slope variation is superior to 25% the heat exchanger is considered as fouled.

1.3.3.4. Classification

Classification is a machine learning task that involves assigning an instance to one of several predefined categories. Although various techniques may serve this purpose, this category specifically refers to methods that use classification algorithms to directly identify whether a fault has occurred and, if so, which type. Unlike regression models that produce continuous numerical outputs, classifiers assign inputs to discrete classes, typically represented by integer labels. In contrast to clustering, which operates on unlabeled data, classification relies on labeled examples of known faults for training. Common classification algorithms include neural networks, decision trees, and support vector machines.



For example, Zimmerman et al. [11] used a Bayesian network to probabilistically describe the cause-and-effect relationships of known quantities for automatic detection of faults. They used this method to classify the temporal evolution of pressure and mass flow rate in pipes. According to this evolution, the algorithm classifies the pattern between normal behavior, abnormal behavior due to a leak (see Figure 29) or a sensor fault (see Figure 30).

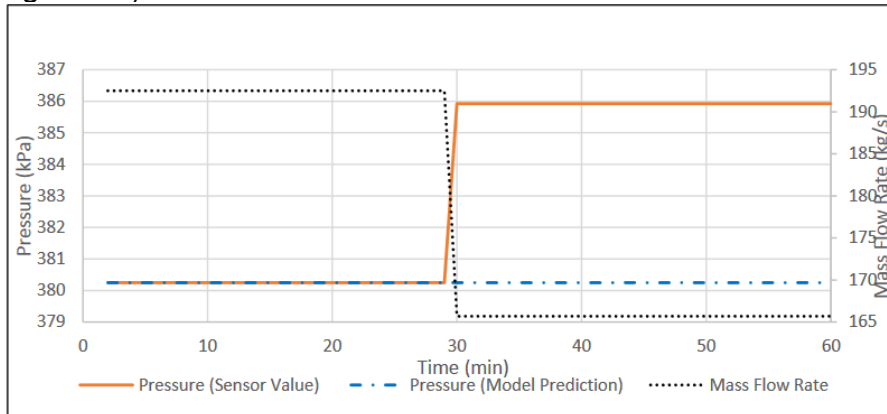


Figure 29 Evolution over time of the pressure in a pipe with and without leak [11]

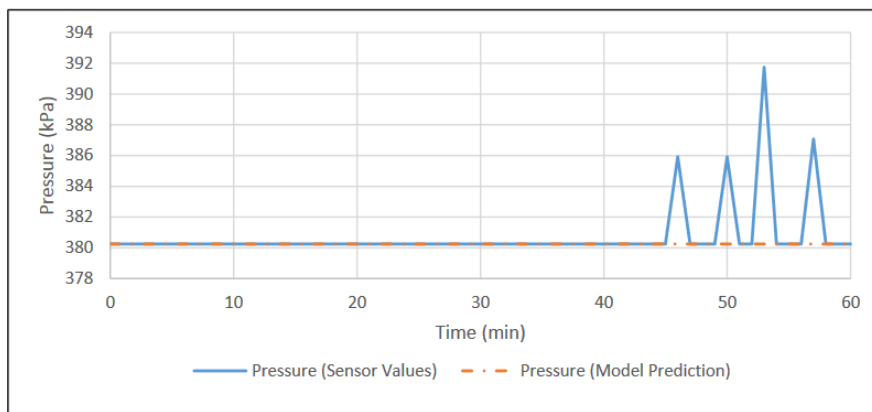


Figure 30 Evolution over time of the pressure in a pipe with and without sensor fault [11]

At this point, this method can detect obvious faults and their causes, and it appears promising.

1.3.3.5. Clustering

As classification, clustering also involves assigning items to groups, or clusters, but unlike classification, it does not rely on labeled data. Instead, clustering algorithms group items based on similarity, ensuring that items within the same cluster are more alike than those in different clusters. This unsupervised approach is often used to categorize district heating substations (DHS) based on performance indicators or consumption patterns. Once clusters are formed, outliers or marginal groups can be detected and examined in more detail. Common clustering algorithms include k-means, k-shape, and k-nearest neighbors.

Par example, according to [12], the clustering analysis can identify the seasonal and daily operating patterns. They identified different patterns according to different control strategies such as (see Figure 31):

- A relationship between the primary temperature difference and the exchange heat
- A relationship between the secondary mass flow rate and the exchanged heat



- A relationship between the secondary mass flow rate and the secondary side pressure difference
- A relationship between the exchanged heat on the secondary and primary sides

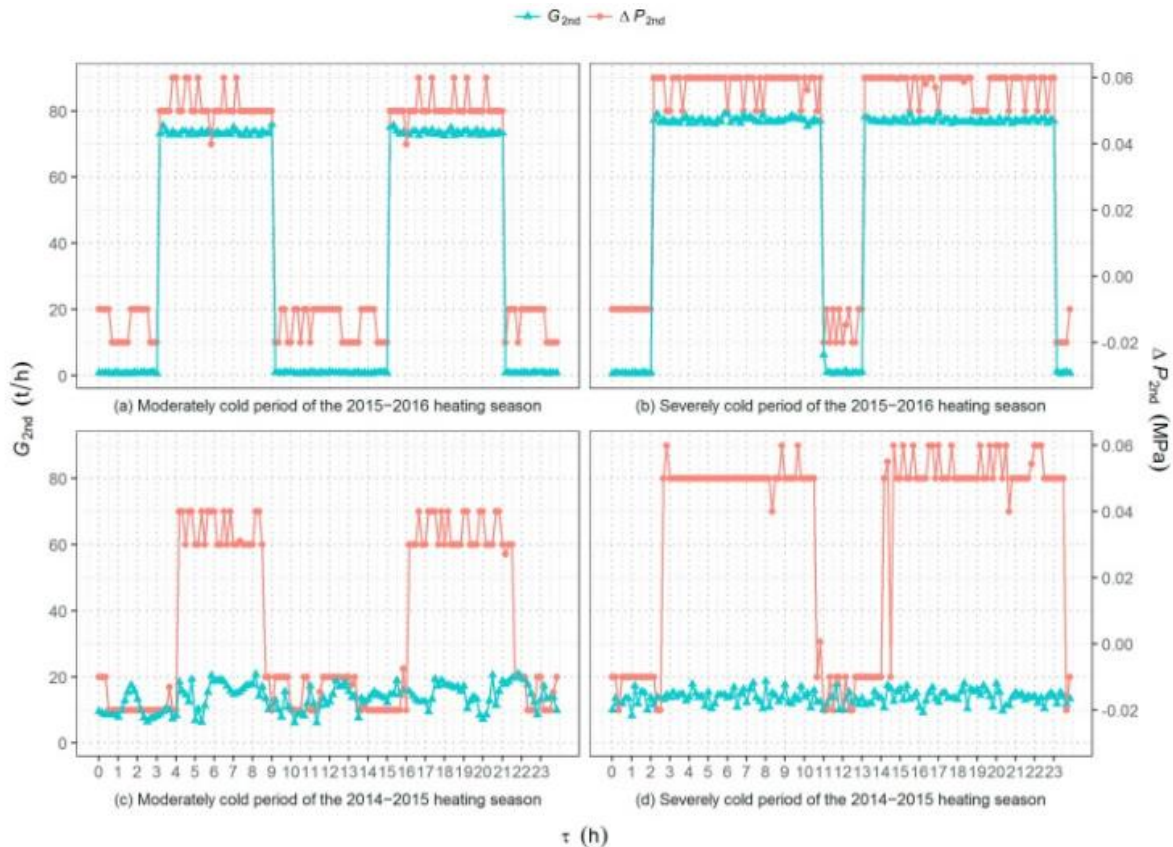


Figure 31 Definition of normal pattern and cluster [12]

An anomaly is detected when one of the patterns does not correspond to an existing cluster. At this point this method can detect obvious anomaly, and it appears promising.

1.3.4. Common indicators used by the DHC operators

As malfunctions can cause underperforming DHC networks or discomfort for the customer, DHC operators have already implemented methods to detect anomaly. They usually used simple methods based on data visualization, regression and thresholds. They check the monthly customer billing data to detect excessive consumption, quality index based on the installation performance such as the return temperature level or substation mass flow rate. Some simple indicators are proposed in the literature such as the excess flow method and the thermal signature.

The excess flow method [13] allows, with the help of temperature drop measurements at the primary and the consumption of each SST, to establish an order of priority for the inspection of the substations of the network based on the calculation of a volume of water in excess. Indeed, a failing substation has a lower temperature drop than expected, which leads to an increase in the volume of water consumed. An ideal water volume consumed by the SST is calculated from the annual heat consumption of the SST and a reference temperature drop. Then, the actual water volume consumed is calculated from the annual consumption of the substation and the average temperature drop, and then the actual and ideal water volumes are compared to determine the



excess volume. Thus, the greater the excess volume, the more the SST degrades the overall performance of the network (see Figure 32).

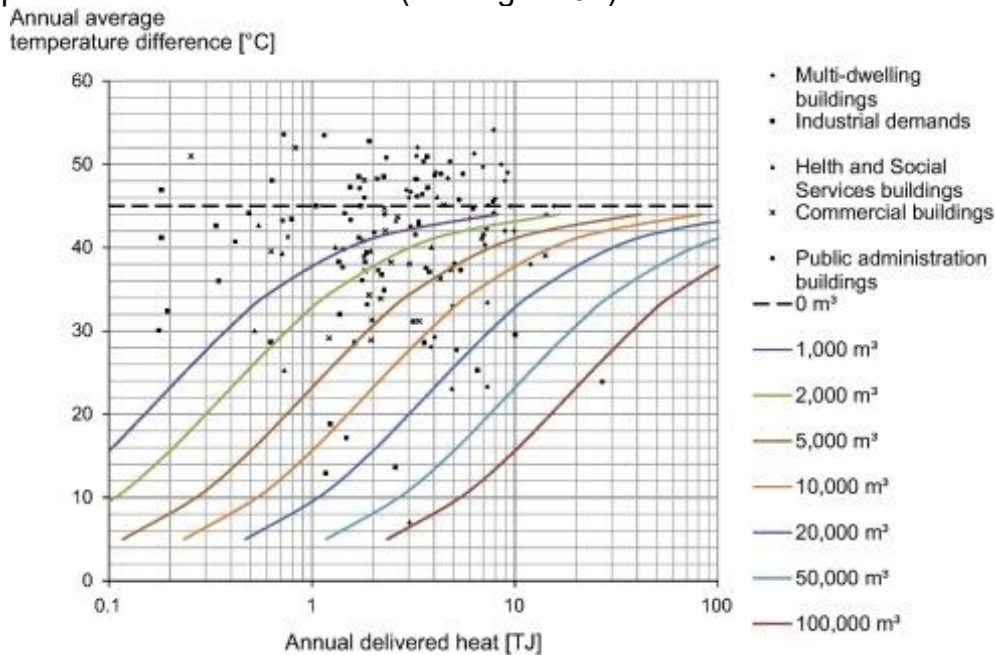


Figure 32 Excess flow method indicator [13]

However, this method has limitations: it only allows for corrective maintenance because data are needed over a long period of time. Moreover, the determination of a reference temperature drop makes the implementation of the method delicate. Indeed, it is difficult to propose the same reference for all the SST because they have different uses (high or low temperature heating, DHW) and configurations that impact the maximum temperature drop they can have. To determine this reference temperature difference, numerical simulation can be used. The average measured temperature difference representative of the system is also questionable.

In order to have a more accurate and faster detection of malfunctions, predictive maintenance indicators can then be considered which can be done by the thermal signature method [13]. Using the measurement of the outside temperature and the temperature drop at the primary of each SST, the performance of the SST is monitored on a daily basis. The measurements are compared to a reference which corresponds to the ideal operation of the SST. From this reference and the historical data on the SSTs, an intervention threshold is determined which corresponds to ± 3 times the standard deviation between the reference and the historical data (see Figure 33).

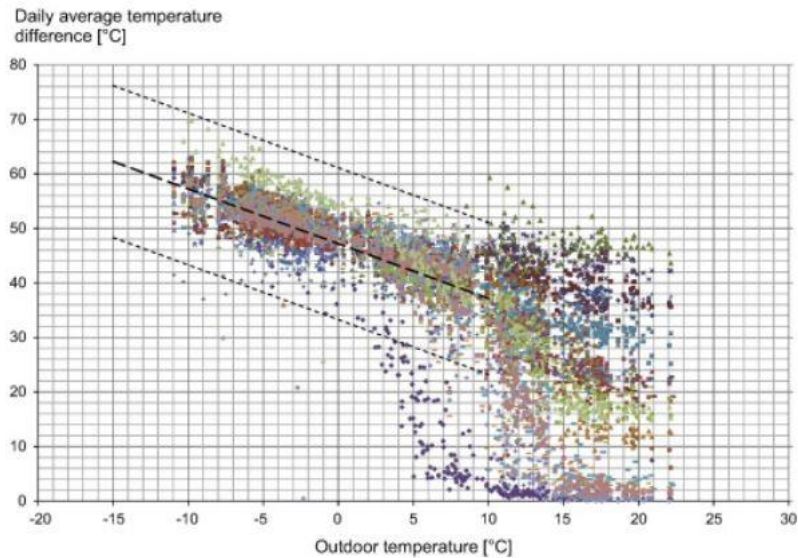


Figure 33 Thermal signature indicator [13]

As before, this indicator requires the establishment of a reference that can be determined by simulating a real network. Moreover, this method does not work for high outdoor temperatures as shown on Figure 33, because from the threshold of 10°C, the energy consumption of the DH networks comes mainly from the DHW which is not very thermosensitive. Thus, this method can only be used on SSTs providing heat for heating. This method has been improved by [14] and [15] using the exchanged energy or heat exchanger pinch instead of the primary temperature difference. The use of this data allows to extend the thermal signature method to DHW substation. To have a more accurate indicator Manson et al. [14] proposed also to create piecewise linear regression and threshold (see Figure 34).

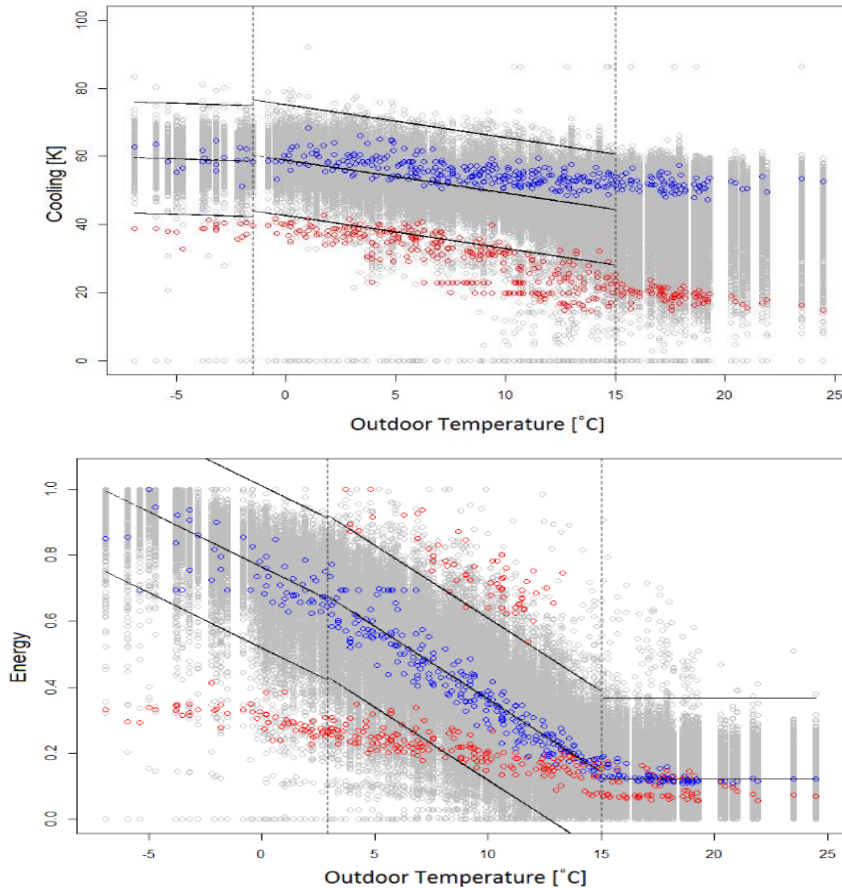


Figure 34 Thermal signature method improved by [14] (in blue a normal behavior, in red an abnormal behavior)

The thermal signature method has been also improved by [16] and [17] by adding clustering in the method. Indeed, [16] and [17] proposed to do clustering on heat load pattern to identify different types of end-users and so create adaptive threshold. To conclude, these two methods are simple to use, need few data and enable fast detection nevertheless there is still no clue on the fault origin.

1.3.5. Fault detection

Fabre & al [4] proposed an indicator to detect a blocked valve on an opening position. As presented in Figure 35, when a valve is stuck on a position, the flow rate is no longer controlled by the control valve and for all the malfunction cases (except for the 10% opening) the mass flow rate is higher than needed most of the time. Moreover, the figure underlines that a blocked valve implies instability of the flow rate passing through the valve. This is the specific signature of a blocked valve. Thus, to detect a blocked primary control valve an indicator based on this specific signature has been developed.

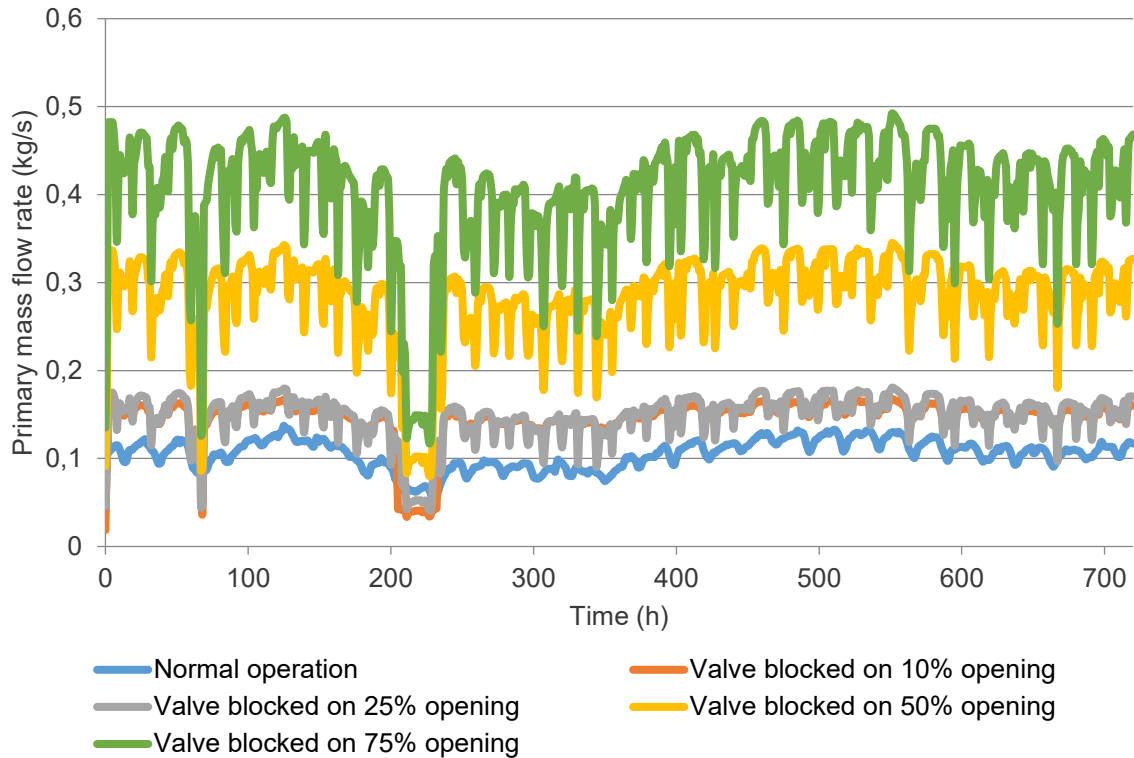


Figure 35 Temporal evolution of primary mass flow rate

To fully understand the instability of the mass flow rate, a spectral analysis has been done. The results underline that, for normal operation, the most evident mass flow rate variations appear each 24h, 12h and 8h in line with the major heating demand variations. On the other hand, when the valve is blocked, the most significant variations appear at lower frequency, inferior to 6h, which means high variations of the flow rate appear more than 4 times a day.

Thus, to have an easy-to-use indicator, an indicator based on the mass flow rate relative variation is proposed. According to the spectral analysis, when a valve is blocked, the high mass flow rate variations appear more than 4 times a day. By measuring the mass flow rate every hour, it is possible to plot the evolution of the relative mass flow rate. A mass flow rate relative variation of $\pm 15\%$ in one hour is considered as a high variation.

$$D_m = \frac{\dot{m}_t - \dot{m}_{t+\Delta t}}{\dot{m}_{t+\Delta t}}$$

The Figure 36 shows the use of the indicator in the case of a blocked valve and a normal operation valve. For normal operation, the 15% threshold is not exceeded. So, as expected, no fault is detected. For the blocked valve case, the malfunction is detected as the threshold is exceeded (red points on Figure 36) more than 4 times a day.

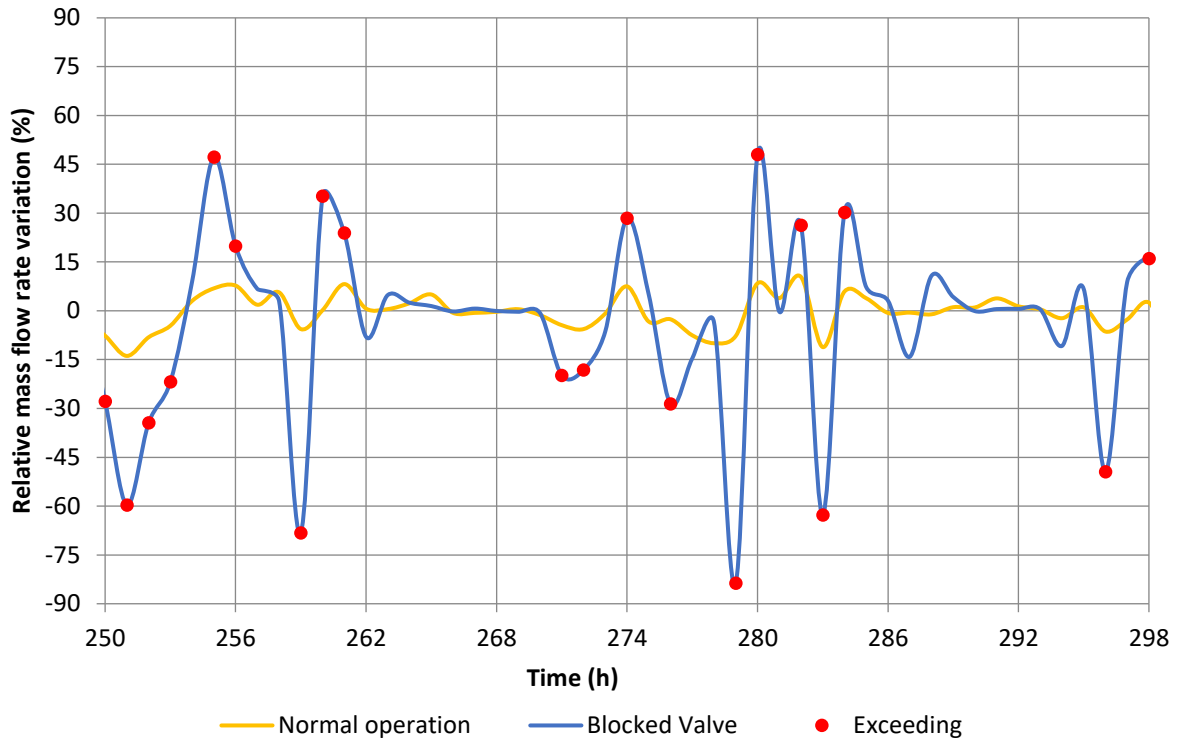


Figure 36 Temporal evolution of relative mass flow rate variation for blocked valve and valve under normal operation

This indicator can detect a specific fault; it is easy to use, needs few data and has been validated through in-situ data. However, it can't be used on control valves in DHW substation.

Fabre & al [4] proposed an indicator to detect fouled heat exchanger. The indicator is based on the same assumption than [10]. To build an indicator of fouling, one assumes first that most of the HEX employed on DHN are plate heat exchangers in counter flow. The specific signature of the fouling is the increase of the HEX global thermal resistance. Indeed, without fouling, thermal resistance can be expressed as:

$$R_{global, clean} = \frac{1}{h_p S} + \frac{1}{h_s S}$$

However, according to the Dittus-Boetler correlation, the convective heat transfer coefficient can be expressed in function of the mass flow rate as:

$$hS = \gamma \dot{m}^{0.8}$$

Where the coefficient γ only depends on the HEX geometry and the fluid characteristics, so in our case it is a constant. Assuming the conductive resistance of the plates is negligible, the thermal resistance can be rewritten as:

$$R_{global, clean} = \frac{1}{\gamma \dot{m}_p^{0.8}} + \frac{1}{\gamma \dot{m}_s^{0.8}}$$

$$R_{global, clean} = \frac{1 \dot{m}_p^{0.8} + \dot{m}_s^{0.8}}{\gamma \dot{m}_p^{0.8} \dot{m}_s^{0.8}}$$

$$R_{global, clean} = \frac{1}{\gamma} \dot{M} \quad \text{with} \quad \dot{M} = \frac{\dot{m}_p^{0.8} + \dot{m}_s^{0.8}}{\dot{m}_p^{0.8} \dot{m}_s^{0.8}}$$

According to the previous equation, the thermal resistance without fouling linearly evolves with the variable \dot{M} . However, when fouling appears the global thermal resistance is no longer linear (see Figure 37):



$$R_{total} = R_{global,clean} + R_{fouling}$$

Moreover, it is needed to identify a threshold to have a limit from which the impact of the fouling significantly degrades the substation performance. According to the study the return temperature drops over 5°C when the ratio between the thermal resistance with and without fouling is over 1.4. It is considered that a drop of 5°C is important enough to notably downgrade the performance. Therefore, a malfunction will be detected when:

$$R_{total} > 1.4 R_{global,clean}$$

The thermal resistance without fouling can be calculated through the measured data (the temperatures on both sides and the exchanged power) just after a complete cleaning of the HEX. Thanks to the same data, the thermal resistance during operation can also be calculated:

$$R_{total} = \frac{DTLM}{P} \quad \text{with} \quad DTLM = \frac{(T_{p,in} - T_{s,out}) - (T_{p,out} - T_{s,in})}{\ln(T_{p,in} - T_{s,out}) - \ln(T_{p,out} - T_{s,in})}$$

Therefore, by measuring the temperatures and flow rates on both sides, the evolution of the thermal resistance can be plotted as well as the threshold not to be exceeded. Figure 37 illustrates the methodology by plotting data on a graph. When a thermal resistance data is over the threshold, the effect of fouling is important enough to require cleaning.

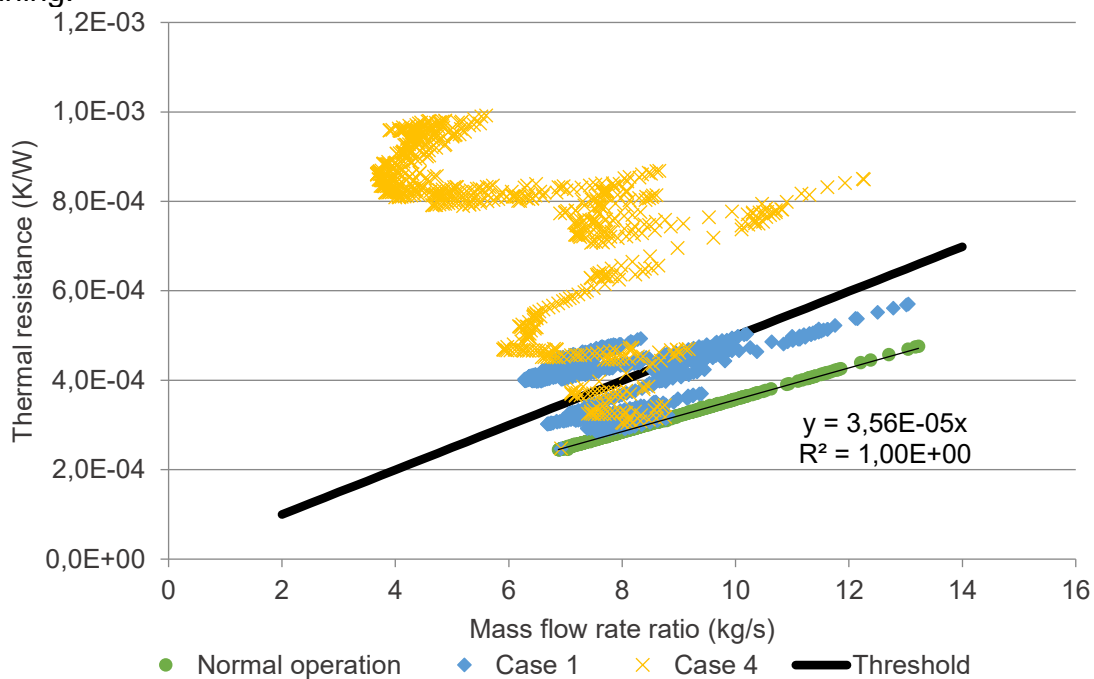


Figure 37 Fouling detection indicator (case 1 and 4 represent fouled heat exchangers)

This indicator can detect a specific fault; it is easy to use and has been validated through in-situ data. However, it needs data from the secondary side.

Fabre & al [4] proposed an indicator to detect a blocked valve on the secondary side. The specific signature on abnormal secondary valve operation is a mass flow rate almost constant. Meanwhile, measuring the mass flow rate in radiators is quite difficult to implement and quite expensive. Therefore, a measure based on the inlet and outlet radiator temperatures is easier and more accurate. So, the question is what is the impact of a constant flow rate on the radiator temperature? The relation between



temperature and mass flow rate in this case can be expressed by these following equations:

$$= Cp \dot{m}_{rad} (T_{in,rad} - T_{out,rad}) = KS DTLM_{rad} = KS \frac{(T_{in,rad} - T_{out,rad})}{\ln\left(\frac{T_{in,rad} - T_{indoor}}{T_{out,rad} - T_{indoor}}\right)}$$

$$Cp \dot{m}_{rad} = \frac{KS}{\ln\left(\frac{T_{in,rad} - T_{indoor}}{T_{out,rad} - T_{indoor}}\right)}$$

In the previous equation, all the parameters are constant when a valve is blocked except for the temperatures. Indeed, for temperature range Cp is constant, \dot{m}_{rad} does not vary due to the malfunction and KS depends on the flow rate which is constant in this case. Consequently, the factor $DTLM' = \frac{1}{\ln\left(\frac{T_{in,rad} - T_{indoor}}{T_{out,rad} - T_{indoor}}\right)}$ must be constant if there

is a blocked valve and must vary in normal operation. This reasoning is validated by the Figure 38.

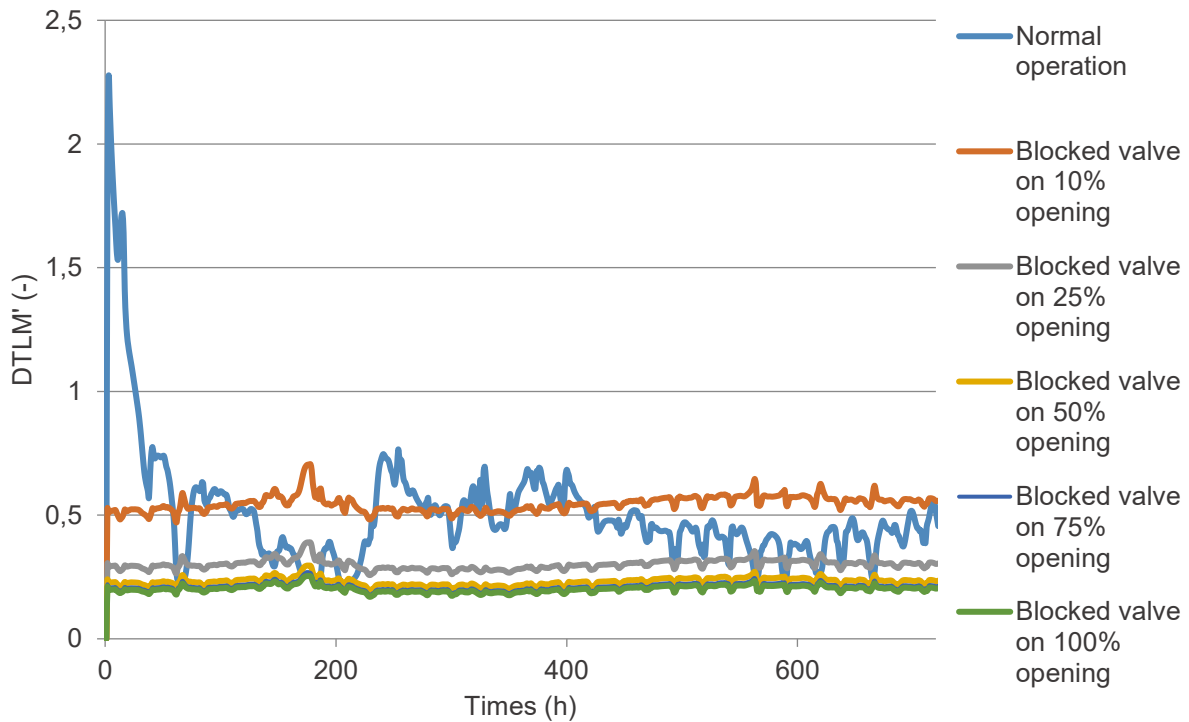


Figure 38 Temporal evolution of the degraded radiators DTLM' for each case

In order to detect the non-variation of the factor, a performance indicator based on the relative variation of $DTLM'$ has been developed (see Figure 39). The idea is to follow the relative variation and to send an alert when a threshold of 10 % is not exceeded at least 2 times a week. However, the threshold must be validated through in situ data.

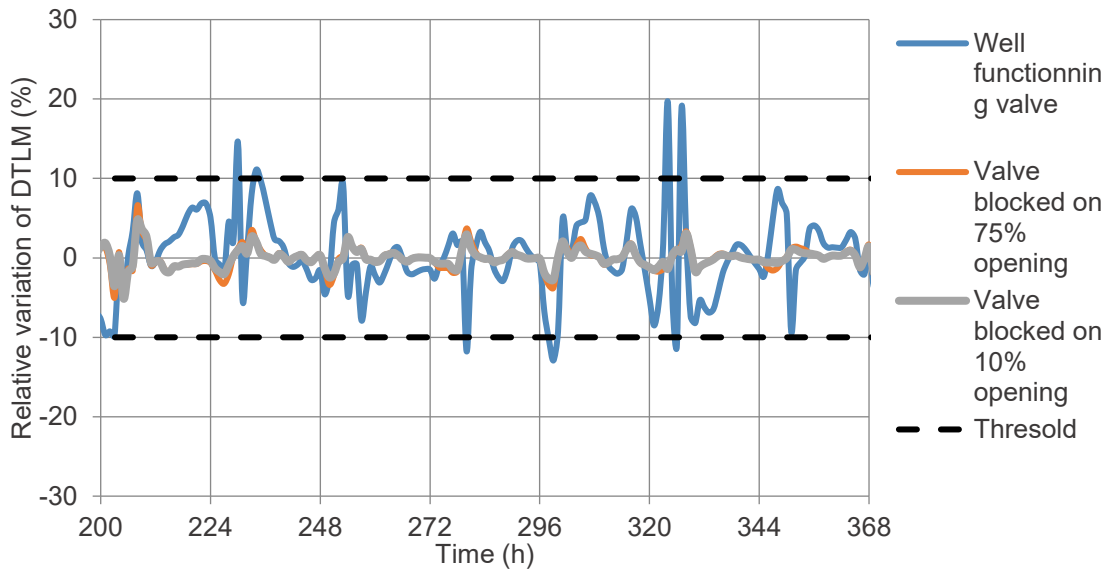


Figure 39 Temporal evolution of the DTLM' relative variation over 1 week

Fabre & al [4] proposed an indicator to detect an unsuitable DHW primary return temperature. Indeed, the augmentation of the recirculation mass flow rate downgrades the performance of the substation. Therefore, the important factor is the ratio between the recirculation mass flow rate and the daily mean demand mass flow rate:

$$F = \dot{m}_{recirc} / \dot{m}_{demand}$$

The higher the ratio F , the less efficient the system is. However, it is hard to measure it because the data on DHW HEX secondary side are not available usually. Therefore, the indicator must use available data i.e. data on the primary side. The concept of the indicator is therefore to compare the efficiency of the DHW exchanger of each substation with reference cases using only the inlet and outlet temperatures on the primary side of the exchanger (see Figure 40).

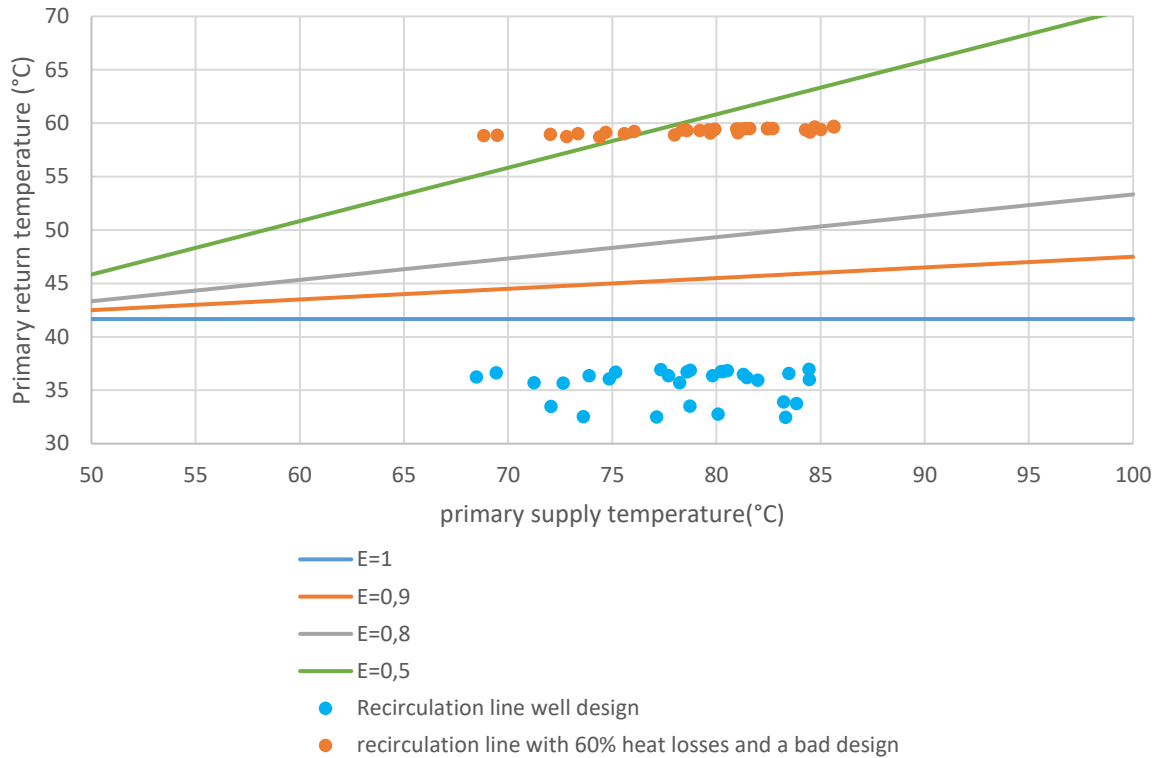


Figure 40 Indicator for detection of too high DHW return temperature

The reference cases are represented by the constant efficiency lines (see **Hiba! A hivatkozási forrás nem található.**). To build these lines, 3 assumptions are necessary: on the city cold water temperature, on the return temperature of the recirculation loop and one on the F ratio. They are determined using the following equations:

$$E = \frac{(T_{p,in} - T_{p,out})}{(T_{p,in} - T_{s,in})}$$

$$(\dot{m}_{recirc} + \dot{m}_{demand})T_{s,in} = \dot{m}_{recirc} T_{recirc} + \dot{m}_{demand} T_{cold,water}$$

$$T_{p,out} = (1 - E) T_{p,in} + \frac{E}{1 + F} (T_{recirc} F + T_{cold,water})$$

By measuring the temperature on the primary side, it is possible to determine the efficiency of the DHW exchanger under certain assumptions. Indeed, as shown on **Hiba! A hivatkozási forrás nem található.**, the measurement points corresponding to a faulty system (orange point) are close to the 0.5 efficiency line. Usually, a DHW heat exchanger on a DH has an efficiency value between 0.8 and 0.95. Therefore, the indicator detects a malfunction in the DHW system. On the contrary, the measuring points corresponding to a non-faulty system (blue point) are below the efficiency line 1. This only means that the hypotheses taken to build the indicator are too strong. So, the DHW supply works better than expected.



References

- [1] H. Gadd et S. Werner, «Fault detection in district heating substation,» *Applied energy*, vol. 157, pp. 51-59, 2015.
- [2] S. Mansson, P.-O. Johansson Kallioniemi, M. Thern et T. Van Oevelen, «Faults in district heating customer installations and ways to approach them: Experiences from Swedish utilities,» *Energy*, vol. 180, pp. 163-174, 2019.
- [3] S. Frederiksen et S. Werner, *District heating and cooling*, Studentlitteratur, 2013.
- [4] A. Fabre, C. Duchayne, T. Nyberg, V. Gavan, K. Lygnerud et P. Stabat, «Cost benefit study on the building secondary network for improving DH performance,» IEA DHC/CHP, 2023.
- [5] P.-O. Johansson, P. Lauenburg et J. Wollerstrand, «Improved cooling of district heating water in substations by using alternative connection schemes,» *22nd International Conference on Efficiency, Cost, Optimization Simulation and Environmental Impact of Energy Systems*, pp. 843-852, 2009.
- [6] S. Buffa, M. Fouladfar, G. Franchini, I. Lozano Gabarre et M. Andrés Chicote, «Advanced Control and Fault Detection Strategies for District Heating and Cooling Systems—A Review,» *Applied sciences*, vol. 11, n° 11, p. 455, 2021.
- [7] A. Rafati et H. R. Shaker, «Predictive maintenance of district heating networks: A comprehensive review of methods and challenges,» *Thermal Science and Engineering Progress*, vol. 53, p. 102722, 2024.
- [8] M. Neumayer, D. Stecher, S. Grimm, A. Maier, D. Bücken et J. Schmidt, «Fault and anomaly detection in district heating substations: A survey on methodology and data sets,» *Energy*, vol. 276, p. 127569, 2023.
- [9] R. Kim, Y. Hong, Y. Choi et S. Yoon, «System-level fouling detection of district heating substations using virtual-sensor-assisted building automation system,» *Energy*, vol. 227, p. 120515, 2021.
- [10] E. Guelpa et V. Verda, «Automatic fouling detection in district heating substations: Methodology and tests,» *Applied energy*, vol. 258, p. 114059, 2020.
- [11] N. Zimmerman, E. Dahlquist et K. Kyprianidis, «Towards On-line Fault Detection and Diagnostics in District Heating Systems,» *Energy procedia*, vol. 105, pp. 1960-1966, 2017.
- [12] P. Xue, Z. Zhou, X. Fang, X. Chen, L. Liu, Y. Liu et J. Liu, «Fault detection and operation optimization in district heating substations based on data mining techniques,» *Applied energy*, vol. 205, pp. 926-940, 2017.
- [13] H. Gadd et S. Werner, «Achieving low return temperatures from district heating substations,» *Applied energy*, vol. 136, pp. 59-67, 2014.



- [14] S. Mansson, K. Davidsson, P. Lauenburg et M. Thern, «Automated Statistical Methods for Fault Detection in District Heating Customer Installations,» *Energies*, vol. 12, n° 11, p. 113, 2018.
- [15] A. Fabre, «Développement d'indicateur de performance et de détection de défauts sur les réseaux de chaleur dans une démarche d'optimisation de leur pilotage,» PhD thesis, MINES ParisTech, 2020.
- [16] F. Theusch, P. Klein, R. Bergmann, W. Wilke, W. Bock et A. Weber, «Fault Detection and Condition Monitoring in District Heating Using Smart Meter Data,» *PHM Society European Conference*, vol. 6, n° 11, p. 11, 2021.
- [17] S. Farouq, S. Byttner, M.-R. Bouguelia, N. Nord et H. Gadd, «Large-scale monitoring of operationally diverse district heating substations: A reference-group based approach,» *Engineering Applications of Artificial Intelligence*, vol. 90, p. 103492, 2020.