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Prioritisation of faults in district heating substations: Towards predictive maintenance and optimised operation

Edison Guevara Bastidas [a],*, Stefan Faulstich [a], Holger Dittmer [a], Martin Neumayer [b], Gowtham Sakthivel Mohan [a], Kibriye Sercan-Calismaz [c], Frank Hosenfelder [d], Thilo Glenewinkel [d], Karsten Fischer-Florschütz [e], Anna Cadenbach [a]

[a] Fraunhofer IEE, Joseph-Beuys-Straße 8, D-34117 Kassel, Germany
[b] Institut für nachhaltige Energieversorgung GmbH - INEV, Anton-Kathrein-Str. 1, D-83022 Rosenheim, Germany
[c] Der Energieeffizienzverband für Wärme, Kälte und KWK e. V. - AGFW, Stresemannallee 30, D-60596 Frankfurt am Main, Germany
[d] Enercity Netz GmbH, Auf der Papenburg 18 D-30459 Hannover, Germany
[e] YADOS GmbH, Yados-Straße 1 D-02977 Hoyerswerda, Germany

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ABSTRACT

Effectively detecting and handling faults in district heating substations is vital to ensure the security of heat supply and improve system efficiency. This is a challenging task due to the growing number of substations and limited monitoring and service personnel. Digitalisation on the demand side offers an opportunity to develop data-driven methods for automatic fault detection, enabling utilities to optimise maintenance interventions across multiple customers. A variety of different faults can occur in substations, which can reflect differently on operational data. It is then necessary to prioritise faults to address the most relevant ones in developing adequate detection methods and supporting operators in their Operation and Maintenance (O&M) processes. Failure Modes and Effects Analysis (FMEA) is a widely used methodology to prioritise potential failures, but it misses aspects relevant to O&M. In this study, we propose an adaptation of the original FMEA for the prioritisation of faults with focus on O&M optimisation. The methodology uses a Maintenance Priority Number (MPN) for the ranking of faults based on severity, occurrence, monitoring potential and maintenance capability of the fault. Severe and frequent faults, which have a potential to be monitored and maintained yield the highest MPNs and should be in focus from an O&M perspective. Using the proposed methodology the most relevant faults for predictive maintenance in substations in Germany have been identified. These are the contamination of strainers, pump failures and fouling of heat exchangers. These faults should be in focus when developing automatic fault detection and diagnosis methods.

1. Introduction

The first implementation of district heating in Germany took place in the 1920s [1]. Over the years, these systems have undergone various changes in heat supply, distribution, and consumption. While the first implementations were typically fossil fuel-based, by gradually reducing the operational temperatures from generation to generation, modern district heating systems enable an environmentally friendly and resource-saving heat supply by integrating industrial waste heat, renewable energy sources, and combined heat and power plants [2]. Furthermore, they contribute to the large-scale integration of the increasing deployment of intermittent renewable energy by combining the various energy sectors, e.g., heat and electricity (sector coupling) [3] and using the associated potential for flexibility [4]. To achieve those benefits, the efficiency of district heating networks need to be increased and the distribution temperatures decreased [4]. Current temperature levels in district heating networks account not only for the customers' temperature demand but also for faults in the system [5]. Detecting and correcting faults that increase the network return temperatures from substations is essential to achieving lower network supply temperatures, while decreasing distribution flows and increasing the overall efficiency of the system [6].

On the other hand, district heating systems can supply heat to thousands of consumers and the demand is increasing. The scenario "Klimaneutrales Deutschland 2045" (Climate neutral Germany 2045) [7] foresees an increase from currently 15% to one third of households in Germany that will be supplied by district heating in the future. Due

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* Corresponding author.
E-mail address: edison.guevara@iee.fraunhofer.de (E. Guevara Bastidas).

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to a lack of monitoring and service personnel, it is a challenge for utilities to operate and maintain the increasing number of substations efficiently and guarantee the security of supply. Future district heating networks with low distribution temperatures and supplying an increasing number of consumers will have less tolerance to faults [6]. Hence, the increase of efficiency and reliability are key elements for the further development of district heating networks.

Increasing the level of digital technologies in district heating systems is seen as an important building block for integrating renewable energies. The introduction and utilisation of modern communication technologies and structures in the district heating industry offer great potential for optimisation, particularly in maintenance and servicing processes [8,9]. Optimising maintenance activities would contribute to the cost-effectiveness, increase of efficiency, and security of supply of district heating systems. Therefore, it would also contribute to the transition towards more sustainable heating, reducing greenhouse gas emissions and the reliance on fossil fuels. Particularly at the substations, two digitalisation measures can unlock the optimisation potential:

- The implementation of modern communication technologies for the collection of customer operating data enables not only an increase in energy efficiency through the development of new control strategies, but also the development of data-driven solutions for anomaly detection through the monitoring of operating data and the application of machine learning methods that indicate unusual operating conditions and contribute to operational optimisation. Recent surveys reviewed such methods, focusing on the affected components [10], the used methods and data sets [9], or the influence on the low-temperature operation of district heating networks [11]. In [12], Månsson et al. propose a structured fault-handling process based on data analysis to improve the currently unstructured and incidental detection of faults in practice. Some research has focused on detection methods for a specific fault, e.g., heat exchanger fouling [13–15].
- Service and maintenance information, such as service reports and fault logs contain key information for operation and maintenance (O&M) optimisation. The digitalisation and structuring of this maintenance information is an essential prerequisite for making the valuable information useable. The resulting structured data is necessary for the execution of reliability analysis, the identification of key performance indicators and as basis for the development of fault detection and diagnosis solutions. In [16], the authors emphasise the significance of this issue and propose a taxonomy for labelling deviations in data from district heating substations in collaboration with practitioners. To facilitate the clear and unambiguous identification of faults and to support fault detection methods based on labelled data, the authors develop a taxonomy that is evaluated using feedback from the district heating industry.

On the basis of the customer's operation data and digitalised and structured maintenance information, methods for the early fault detection and diagnosis can be developed, helping utilities to implement predictive maintenance in their O&M processes.

Given that a large number of failure modes can occur in substations [17,18], which can reflect differently on operational data, it is expected that different methods are required to detect the whole spectrum of faults. In this sense, a prioritisation of faults is needed, in order to identify the most relevant faults for the development of fault detection and diagnosis solutions and for utilities to focus their efforts in the optimisation of their maintenance strategies (e.g. implementing predictive maintenance). While most previous research work prioritise faults in substations based solely on fault frequency [11,17,19], other works include additional considerations like significant role in the operation of the substation [18], and expected impact or detectability [20]. Furthermore, M. Valle et al. [21] conduct a Failure Mode, Effect and Criticality Analysis (FMECA) to select relevant faults for simulation. Although frequency, operational effect and detectability are essential factors to be considered in the prioritisation of faults, to the authors' knowledge, there is no study about a methodology to prioritise faults in substations that considers the potential of the fault for predictive maintenance and O&M optimisation.

The contribution and novelty of this work comprise five key elements:

1. We propose a new adaptation of the well known Failure Modes and Effects Analysis (FMEA) process, for the prioritisation of faults with a focus on O&M optimisation. The methodology uses occurrence and severity from original FMEA and adds the monitoring and maintenance potential as a new evaluation factor.
2. We present a comprehensive list of faults in substations, grouped by affected component, based on a review of previous scientific research and extended by the experience of German district heating.
3. We define, in close collaboration with industry experts, the rating criteria for an application of the proposed methodology on faults in substations.
4. We have ranked the faults in substations using the proposed methodology and rating criteria. By means of a survey study, with the participation of German practitioners of the groups Operator, Original Equipment Manufacturer (OEM) and Expert Association, each one of the identified faults has been evaluated and ranked in terms of relevance for O&M optimisation. While fault frequency has been in the focus of previous works, ranking faults considering also severity and monitoring and maintenance potential allows us to prioritise faults suitable for early detection and predictive maintenance.
5. Finally, by asking German practitioners to evaluate and rank faults, we add a German perspective to previous studies typically based in Sweden [16,17] and other northern European countries [11], allowing for cross-national comparisons.

The remainder of this article is structured as follows: Section 2 describes district heating substations as our subject of investigation; Section 3 describes the methodology for prioritisation of faults in substations; Section 4 presents the results of the evaluation and prioritisation of faults; and Section 5 presents the main conclusions and outlook of this study.

2. District heating substations

District heating systems are an established form of energy supply. The beginnings of district heating in Germany date back to the end of the 19th century. The main components of a district heating supply system can be divided into the segments of heat supply systems, the district heating pipe network, transfer stations, heat transfer media, and the domestic heating pipe network [22].

This paper focuses on transfer stations, which are installed on the property of the heat consumer and can be described as substations. These substations can typically be divided into two categories: direct and indirect connection to the district heating pipe network. The type of design chosen usually depends on the local parameters of the district heating system (e.g., flow temperature, operating mode, pressure, etc.) [22]. The following subsection shows and describes the configuration of an indirectly connected substation in the form of a simplified system diagram.

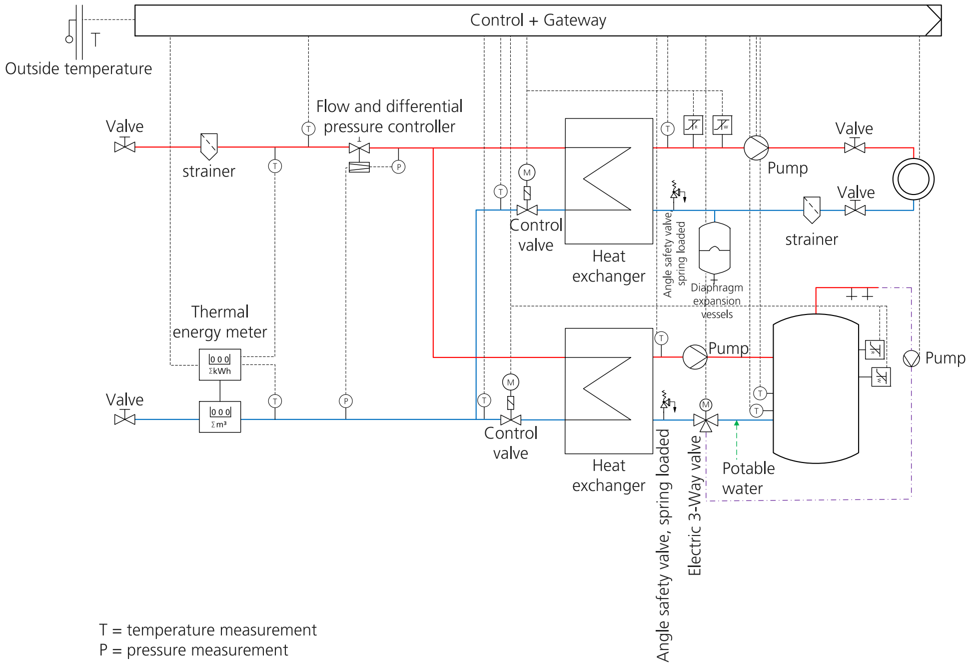


Fig. 1. Schematic diagram of a parallel-connected substation.

2.1. Components of a district heating substation

Fig. 1 shows a simplified system diagram of a typical parallel-connected indirect substation used by the German partner in the joint project. This system configuration enables the supply of heat for heating purposes and for domestic hot water heating. The main features of this indirectly connected substation are the heat exchangers with the associated valves. Changing the valve position changes the flow of the heat transfer medium through the respective heat exchanger. The heat exchanger shown in this figure represents the system separation of the different heat transfer media.

This simplified system diagram shows the relevant components (circulation pumps, temperature sensors, pressure sensors, control valve, thermal energy meter, strainer, flow an differential pressure controller) as well as the heating control unit and the gateway. In addition to the components required for normal operation, the safety-related components (safety temperature monitor, safety temperature limiter, angle safety valve, and diaphragm expansion vessels) are also shown.

2.2. Faults in district heating substations

Most previous studies about relevant faults in district heating substations are from countries of northern Europe. In [17], Månsson et al. divide faults into five categories, i.e., heat exchangers, control systems and controllers, actuators, control valves, and the customer's internal heating system. For each category, typical faults and their effects are examined alongside the current literature on the subject. The authors further survey practitioners from Sweden to report the frequency of the aforementioned faults. Gadd and Werner [5] manually analyse different types of faults found in meter readings of 135 substations of two Swedish district heating systems and partition them into three groups: Unsuitable heat load pattern, low average annual temperature difference, and poor substation control. They investigate how many substations are affected by which fault group and how many substations work correctly. In summary, Gadd and Werner find that only 26% of the analysed substations work free of the aforementioned faults. 30%–40% of the substations in their study suffer from unsuitable heat load patterns, about 70% show a low annual temperature difference, and 14% exhibit poor substation control. The work of Pakanen et al. [18] (Finland) about fault detection and isolation methods prioritise the components: heat exchangers, valves, controllers, actuators, sensors and pipes. Østergaard et al. [11] review different surveys about errors in Swedish and Danish substations. The results of the surveys show that the majority of errors were due to faults and incorrect set-points on the building side, and that most frequent faults are faults in heating system components, control valves and actuators, as well as leakages. Regarding their effects on system temperatures and efficiency, the authors mention that unnecessary high temperature set-points, apart from increasing the temperatures on the secondary side, cause excessive flows on the network side and lead to additional energy losses. On the other hand, oversized valves can result in poor flow control, leading to excessive flows in heat exchangers or domestic hot water tanks and consequently high return temperatures.

In [19], Leoni et al. present the relevant fault occurrences of components in substations, based on information on 113 faults occurring in Austrian substations in the last years. The article summarises the most frequent faults in: sub-optimal secondary-side design and installation, low-performing secondary-side operations and failures of valves, sensors and control. In [20], Jonne van Dreven et al. prioritise five faults for the study of fault detection and diagnosis: minor valve leak, valve leak, stuck valve, high heat curve and deviation of the secondary supply temperature sensor.

3. Methodology

The methodology for the prioritisation of faults applied in this study consists of four main steps: (1) the adaptation of the original FMEA methodology aiming to better support O&M optimisation; (2) the definition, with the participation of industry experts, of the rating criteria to be applied for substations; (3) the identification of the relevant failure modes based on a review of scientific literature and extending it with the German perspective; and (4) the evaluation and prioritisation of the identified relevant faults based on the defined rating criteria and by means of a survey study, with the participation of practitioners of the groups Operator, OEM and Expert Association. The first subsection presents a review of previous work related with the FMEA methodology and previous use-cases of adaptations of that methodology, before explaining in detail the adaptations carried out in this study in the next subsection.

3.1. The original FMEA methodology

Failure Mode and Effects Analysis (FMEA) is a systematic method used to identify, evaluate, and prioritise potential failure modes within a product, process, or system, while assessing the impact of these failures on functionality and performance. The origins of this method trace back to the aerospace industry in the 1940s, where it was initially employed to enhance reliability and safety. Over time, FMEA has gained widespread acceptance across various sectors, including automotive, healthcare, and energy, due to its structured approach to risk assessment and mitigation [23]. The FMEA methodology can be described as follows:

1. First, the failure modes of the system under investigations are determined.
2. Then, the probabilities of the failure modes **Occurrences** are assessed. These probabilities are then categorised and assigned a scaling number, with the lowest number for the least probable category.
3. The rate of **Severity** of each failure mode is assigned and scaled due to the consequences of the failure and the amount of damage to the equipment.
4. Another scale number is assigned to the fault detection possibility or **Detectability**, with the lowest number to the most likely detection of the failure.
5. Finally, the outcome of the process is the **Risk Priority Number (RPN)** that is obtained by multiplying the three scale numbers (see Eq. (1)). The failure modes are then ranked according to their **RPN**, with the highest **RPN** corresponding to the most important failure.

$$RPN = Occurrence \times Severity \times Detectability \tag{1}$$

FMEA is widely recognised for its capacity to enhance reliability by identifying critical components that require focused monitoring. However, its adaptability to diverse applications is what makes it particularly powerful. In practice, FMEA is often tailored to address specific challenges and contexts, a flexibility that has already proven essential in industries such as wind energy. Wind turbines, whether onshore or offshore, present unique challenges due to their complex systems and exposure to varying climatic conditions. As a result, FMEA has been adapted in numerous ways to enhance its applicability in this sector. For instance, FMEA has been employed to compare the reliability of different turbine designs, thereby aiding in design improvements. [24] effectively applied FMEA to evaluate the reliability of prospective wind turbine designs. Additionally, [25] expanded FMEA to include maintenance actions, facilitating a more integrated approach to reliability-centred maintenance strategies. Furthermore, [26] compared FMEA results for on-shore and offshore wind turbines, highlighting differences in risk factors influenced by environmental conditions. Another extension of this method, Failure Modes, Effects, and Criticality Analysis (FMECA), adds a criticality assessment to quantify the severity and likelihood of each failure mode [27]. FMECA has been performed to optimise maintenance strategies by taking climatic conditions into account, comparing geared and direct drive turbines [28]. The incorporation of advanced techniques, such as fuzzy logic [29] and hybrid cost-FMEA approaches [30], has further enhanced the analysis. More recent studies have introduced machine learning techniques to improve FMEA applications in predictive maintenance, enabling real-time data analysis and more accurate risk assessments [31,32].

A. Rafati et al. [33] review reliability analysis techniques that have been applied on district heating systems. In the paper two studies about FMEA in district heating are presented. The most relevant one is the work of P. Gilski et al. [34]. In their work the authors analysed ten-year of failure and repair data from the Warsaw district heating network using statistics and the FMEA method to identify key factors and critical failure modes of the network pipelines, aiming to determine causes and propose cost-effective, resource-aware solutions to increase the reliability of the system. The methodology applied relies on occurrence and severity as factors for the calculation of the RPN. In a more recent study, M. Valle et al. [21] apply an FMECA on district heating systems to select relevant faults for simulation. As a result of the analysis the fouling of heat exchanger is selected as most relevant fault in substations. However, details about the implementation of the methodology, to the authors knowledge, are not publicly available.

A key application of FMEA lies in the prioritisation of critical components for maintenance planning. Traditional FMEA emphasises the probability of failure, the severity of its impact, and detectability. However, this approach can be enhanced by explicitly accounting for the influence of maintenance on failure probability. Certain components may be more accessible for repair, thereby affecting their risk prioritisation. It is also essential to distinguish between sudden failures and those that develop gradually over time, as this distinction can inform more effectively condition monitoring strategies and targeted maintenance actions. By weighting criteria such as failure development patterns and intervention feasibility, FMEA can provide a more tailored risk assessment that aligns with the operational realities of wind farms. In summary, while FMEA offers a robust framework for identifying and addressing potential failures, its adaptability is crucial for maximising its utility in specific domains. Tailored approaches enable a deeper integration of maintenance strategies, consideration of environmental factors, and advanced prioritisation methodologies. These refinements ultimately ensure that the methodology remains a cornerstone for reliability and risk management in evolving industries.

3.2. Adaptation of the original FMEA: the O&M-FMEA

In order to prioritise faults that can actually be monitored and which can be influenced by O&M measures, the original FMEA has been adapted. **Occurrence** and **Severity** are kept as important factors and **Detectability** has been replaced with a **Monitoring** & **Maintenance** factor. For the ranking of failure modes a **Maintenance Priority Number (MPN)** is introduced in contrast to the **RPN** of the original FMEA (see Eq. (1)). The **MPN** is defined as shown in Eq. (2).

$$MPN = Occurrence \times Severity \times Monitoring\&Maintenance \tag{2}$$

The MPN is used to rank the failure modes, with the highest MPN corresponding to the most relevant failure for O&M optimisation and predictive maintenance.

The adapted FMEA, or O&M-FMEA, focuses on supporting O&M optimisation from a technical perspective, by identifying relevant failure modes, which have the highest potential for the development of automatic detection systems for the early fault detection; and from an organisational perspective, by helping district heating operators to prioritise component faults and hence focus their efforts in the optimisation of their maintenance strategies.

3.2.1. Factors of the original FMEA

The **Occurrence** represents the probability of the failure modes. The probabilities are categorised and rated on a scale from 1 to 10, with 10 being the category for the highest probability. This factor accounts for a prioritisation of frequent faults. The **Severity** of the failure mode is assessed based on the potential or actual detrimental consequences of the failure, and is rated on a scale from 1 to 10, with 10 being the highest severity. This factor accounts for a prioritisation of faults with high risk.

Table 1
Rating of the categories for monitoring potential: (5) a change in the component condition could be detected before the fault by existing instrumentation; (4) a change in component condition could have been detected before the fault with additional effort; (3) the fault could be detected by existing instrumentation; (2) the detection of the fault requires additional efforts; (1) no fault detection possible. The highest monitoring potential is given by rating 5.

Detection	Before the fault	After the fault	No detection
With existing instrumentation	5	3	1
With additional effort	4	2	

3.2.2. *The monitoring & maintenance factor*

The third factor in the O&M-FMEA accounts for the handling potential on the fault during system operation. It is defined with two concepts: the **Monitoring Potential** and the **Maintenance Capability**. From the perspective of O&M optimisation, interesting failure modes are those which can inherently be monitored either through appropriate instrumentation or practicable inspection measures. For instance, changes in the state of components due to degradation processes, which can be detected through monitoring are more relevant than randomly occurring failures. This is because the **Monitoring Potential** of the failure is the basis for the development of data-driven methods for early fault detection and in turn for predictive maintenance. The second concept, **Maintenance Capability**, is related with the capability to prevent or correct the fault through maintenance measures. Faults that can be prevented by means of preventive refurbishment or timely repair offer more potential for predictive maintenance than those that can only be corrected. Therefore, the **Monitoring & Maintenance** factor accounts for a prioritisation of faults with high monitoring potential and high maintenance capability.

The **Monitoring & Maintenance** factor is calculated according to Eq. (3).

$$Monitoring\&Maintenance = 2 \times \sqrt{Monitoring \times Maintenance} \qquad (3)$$

The factor 2 is included, so that all three factors, **Severity**, **Occurrence** and **Monitoring & Maintenance** have a range to a maximum of 10. This produces a maximum possible MPN of 1000, which is consistent with other FMEA implementations.

Monitoring potential. The monitoring potential of a fault is categorised and assigned a rating on a scale from 1 to 5 according to Table 1. The categorisation follows the criteria that failure modes, which can potentially be detected before the failure occurs have higher rating than those which can only be detected after the fault. Additionally, a second criteria categorises failure modes depending on the detection efforts or costs required. Failure modes or faults, which can potentially be detected by existing instrumentation have higher rating than those that require additional efforts to detect e.g., installation of additional instrumentation for the monitoring of system variables not yet covered or manual inspection of the related component.

Maintenance capability. The maintenance capability is categorised and, similarly to the monitoring potential, assigned a rating on a scale from 1 to 5, as presented in Table 2. The categorisation criteria is also twofold. On the one hand, degradation processes that can be mitigated by preventive maintenance (e.g. adjustment, lubrication, corrosion protection, cleaning, repair, replacement of component part), hence avoiding a failure (before the fault), get a higher rating than faults that can only be corrected (after the fault). On the other hand, it is differentiated between repair, deferment and replacement activities, whereby faults that can be handled by refurbishment or repair measures get a higher rating than faults that demand replacement of components or parts of it. In the middle of the rating scale are faults that can be delayed (deferment) to be corrected at a later time, by means of suitable operation (e.g. deferment of heat exchanger fouling, by means of suitable operation, for a replacement at a later time).

Table 2
Rating of the categories for maintenance capability: (5) the fault can be prevented by timely refurbishment or repair; (4) the fault can be prevented by replacing a component part; (3) the fault can be deferred by suitable operation; (2) the fault can be corrected by repair; (1) the fault can only be corrected by replacing the component.

Maintenance measure	Before the fault	After the fault
Repair	5	2
Deferment	3	
Replacement	4	1

Table 3
Occurrence scale for district heating substations.

Occurrence	
Very frequent - every 1 year	10
Every 2 years	9
Every 3 years	8
Every 4 years	7
Every 5 years	6
Every 6 years	5
Every 7 years	4
Unlikely - low likelihood but could occur at some time	3
Rare - may only occur in exceptional circumstances	2
Extremely rare - has never or rarely happened	1

Table 4
Severity scale for district heating substations.

Severity	
Risk of customer injury	10
Material damage to customer	9
Material damage to utility	8
Customer gets no heat	7
Customer does not get enough heat	6
– Separation between faults and efficiency losses –	5
Poor control (e.g. slightly oscillating control of ± 5K)	4
Unsuitable load profile (unsuitable heating curve, unsuitable time schedule)	3
Efficiency losses	2
No noticeable effect	1

3.3. *Rating scale for district heating substations*

Together with industry experts, the assessment criteria and rating scale for the **Occurrence** and **Severity** factors to be applied to district heating substations have been defined. The **Occurrence** factor is based on the frequency of the failure mode per single substation and is categorised on a scale from 1 to 10, with 10 being the highest frequency. As can be seen in the scale definition in Table 3, a rating of 10 corresponds to faults that happen every year, whereas a rating of 1 corresponds to extremely rare faults, that has never or rarely happened.

The **Severity** of the failure mode is assessed based on the potential or actual detrimental consequences of the failure, not only in terms of safety and damage to equipment, but also considering the effect on efficiency losses. It is also rated on a scale from 1 to 10, with 10 being the highest severity (Table 4). The rating scale differentiates between actual faults on the upper part of the scale, which can yield into interruption of the heat supply or even pose a risk of injury at the highest rating and faults that only have an effect on the performance or efficiency of the system, which are located on the lower part of the scale. A rating of 5 in severity is not used. This builds a needed gap between the faults and efficiency losses, in order to separates both effects more clearly.

3.4. *Relevant faults in district heating substations*

To apply the previously described O&M-FMEA methodology to the use case of district heating substations in Germany, the relevant faults need to be identified and structured.

To identify relevant faults in substations a literature review has been conducted (see 2.2) and the faults have been associated with the

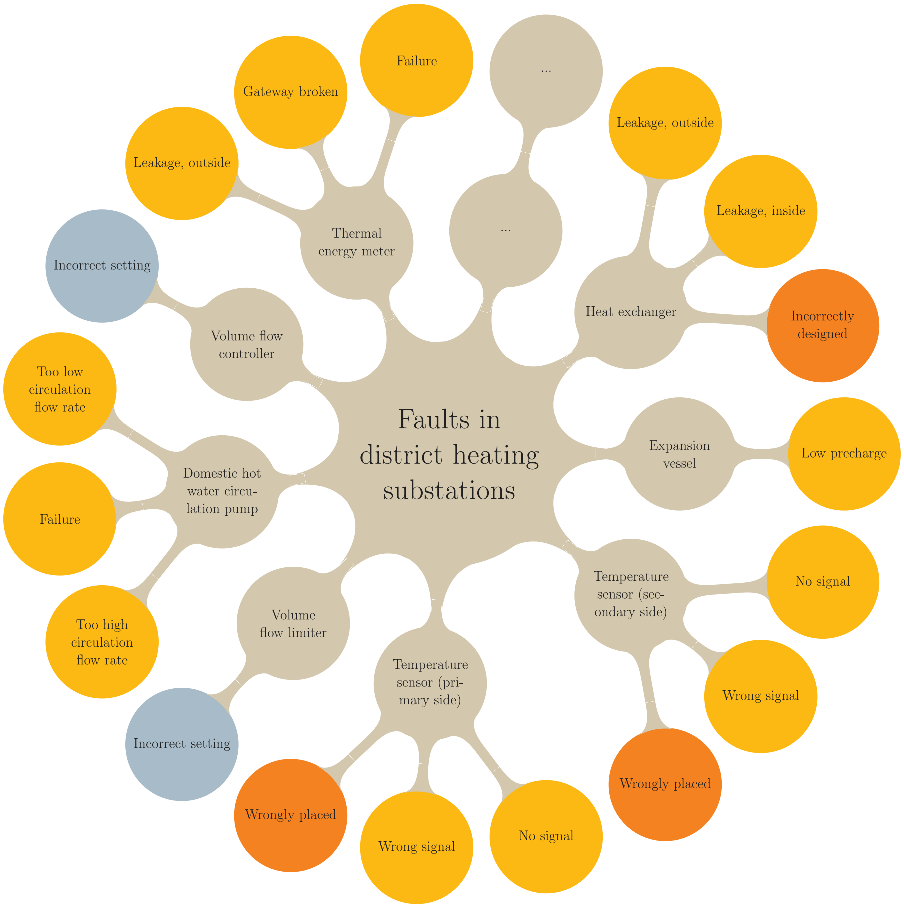


Fig. 2. Excerpt of the faults in substations grouped by the affected component and coloured by fault type.

affected components in a preliminary list. Previous research work is mainly based on substations in district heating networks of Sweden and Denmark. In a workshop with industry experts of Germany, the preliminary list has been extended, including the experiences in German district heating.

The O&M-FMEA methodology described in this study, in contrast to the original FMEA, omits an extensive analysis of all possible faults, their effects on the functionality, connections between components and their relations. Instead, only faults actually occurring in practice are considered, since from an O&M point of view, only faults with a minimum of occurrence are relevant. An excerpt of all identified faults grouped by the affected component is presented in Fig. 2. The identified faults cover installation errors (dark orange), wrong settings (grey) and actual faults during operation (light orange). On the other hand, it is differentiated between components installed on the primary and secondary side. The full list, containing a total of 81 faults, including the affected component and a short description, is presented in Table A.5.

3.5. *Survey study*

By means of a survey study, German practitioners were asked to evaluate each one of the identified 81 faults in substations using the defined rating criteria for **Occurrence**, **Severity**, **Monitoring Potential** and **Maintenance Capability**. The survey study is conceived as an online questionnaire covering four scales (one separate scale per each rating criteria) for each fault and space for comments, requiring a total of around 1.5 h from each of the 13 participating German experts. Each participating expert belong to either one of the groups Operator, representative from Expert Associations or OEM, ensuring a diverse range of professional expertise. Emphasising quality, the survey was designed to get in-depth responses.

After the data collection and pre-processing, the following procedure was carried out for the ranking of faults: firstly, the mean occurrence, severity, monitoring potential and maintenance capability was computed for each fault over all participants; secondly, an MPN for each fault was calculated based on the computed means of the different factors and using Eqs. (2) and (3); and thirdly, faults were ranked according to the calculated MPN. By calculating first the means of the individual factors, the method accounts for the different subjectivity among the participants to get a mean opinion on the different factors. The use of mean over median is also preferred, in order to consider all participant's rating the same way and to not exclude any outlier. The list of faults ranked according to the calculated MPN is shown in Table A.5 together with the mean occurrence, severity, monitoring potential and maintenance capability used for the calculation.

4. Prioritisation of faults

Fig. 3 shows the frequency distribution of the MPNs presented in Table A.5, as a result of the survey. The histogram shows a right-skewed distribution with a tail containing few faults with the highest MPNs.

Fig. 4 shows the results for the 10 highest ranked faults. As can be seen in the figure, the occurrence rating (blue bar) goes from 4.3 to 6.1, meaning a frequency of fault of 5 to 7 years for those faults. The severity rating (orange bar) goes from 5.6 to 7.5, meaning the faults have an effect on the delivery of heat to the customer, partially or even completely.

There are different types of faults present in the table. Two faults are not related with O&M: incorrect parameterisation of the control

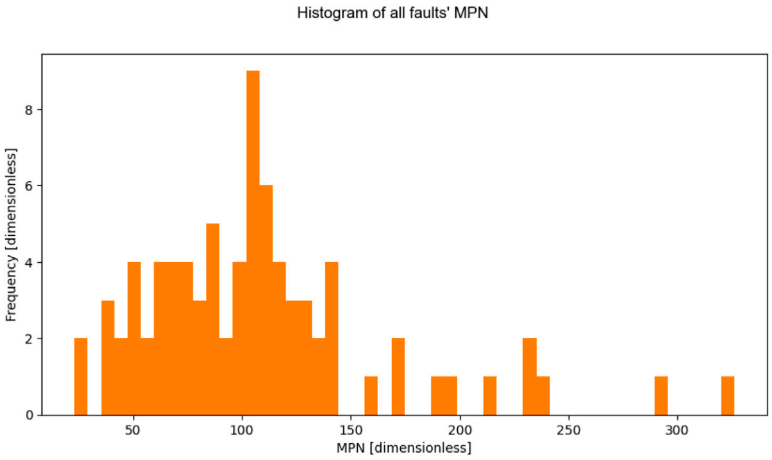


Fig. 3. Frequency distribution of MPNs.

unit and the wrong placement of the outdoor temperature sensor. Other faults, which are at the bottom of the list, have a relative low **Monitoring & Maintenance** potential: air in the piping system has a monitoring potential (grey bar) of 2.1, meaning it can only be detected after the fault occurred and only with additional efforts; and two faults associated with the three-way valve for domestic hot water have a maintenance capability (yellow bar) of around 2, meaning they can be repaired but only through corrective actions after fault occurred. And finally, 5 faults have a high potential for predictive maintenance. These are poor flow rate through the strainer on both the primary and the secondary side, failure of the heating circuit pump, failure of the storage charging pump for domestic hot water and the fouling of heat exchangers. These faults have a **Monitoring Potential** in the range from 3.6 (contamination of the strainer on the secondary side) to 4.2 (fouling of heat exchanger), meaning a detection before fault is possible and a **Maintenance Capability** in the range from 2.6 (failure of the heating circuit pump) to 4.2 (contamination of the strainer on the primary side), meaning a deferment of the fault or even preventive actions are possible.

The information gathered in the comments field of the survey help to further interpret the survey results. For instance, one participant argued that cleaning a brazed heat exchanger only works in an ultrasonic bath, which is often more expensive than a new heat exchanger. This supports the obtained maintenance capability for the fouling of heat exchanger of 3.2, meaning the fault can be deferred by suitable operation. If the preventive action of cleaning the heat exchanger is not economically feasible, then the next best strategy would be to defer the fault for the replacement of the component at a convenient time (i.e. out of the heating period in case of a heat exchanger in the heating circuit).

Other comments concerned the ambiguity of some fault descriptions. While some of those fault descriptions were corrected and rephrased in a more concrete way during the survey study, some others remained ambiguous, that is the case of the failures of the pumps. A failure of the pump can be many different things and can have different causes: can be a failure of the motor (e.g. rotor is blocked), a failure in the pump itself (e.g. wearing or blockage of the impeller) or an issue with the sensors or electronics. Each fault of the list in Table A.5 can potentially be further divided into specific faults, making it longer and more complex to evaluate. Therefore, the level of detail covered in the list is considered appropriate. Prioritised faults, such as the failure of the heating circulation pump and failure of the charging pump for domestic hot water, can and should be further investigated to identify relevant failure modes in order to support the development of fault detection methods.

There has been no limitations to the substation typology when asking the German practitioners. Hence, the results of the prioritisation reflect the general situation of district heating substations in Germany.

5. Conclusions

This study has presented a novel methodology for the prioritisation of faults, aimed at supporting the optimisation of O&M. The methodology, which is based on the FMEA process, introduces a monitoring and maintenance evaluation factor. Based on a literature review of previous research, the relevant faults of district heating substations in the north European countries have been extended including the experiences in German district heating. The rating criteria for substations has been defined, and the methodology has been applied on all identified faults by means of a survey study with the participation of German practitioners. In the survey study all faults have been evaluated according to their occurrence, severity, monitoring potential and maintenance capability, and ranked according to the calculated priority indicator MPN. The 10 faults with the highest MPNs have been discussed in detail, considering their impact on O&M optimisation.

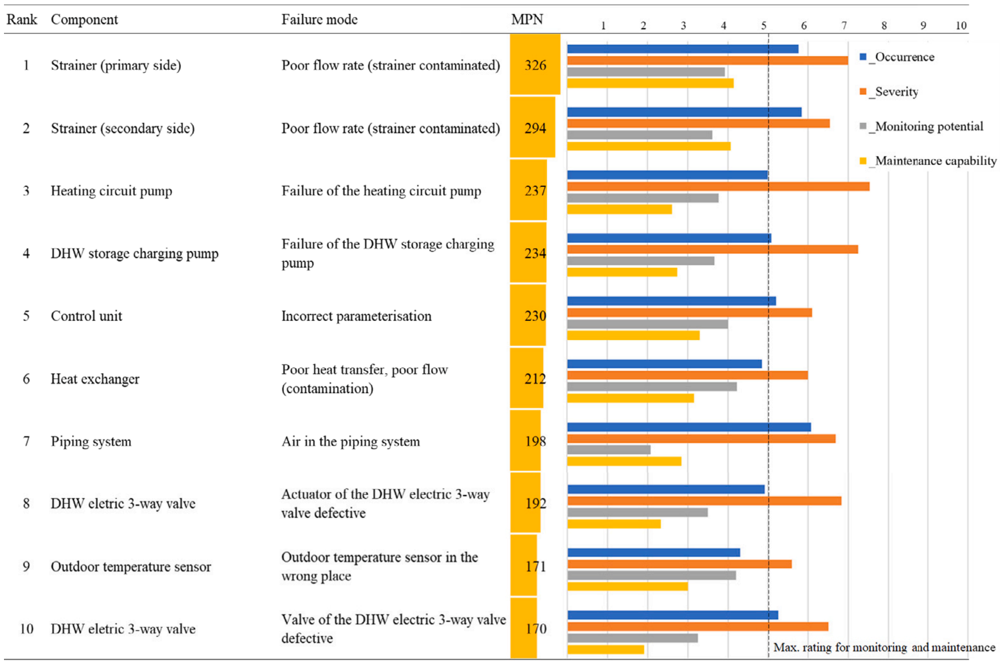
The study has identified relevant faults for predictive maintenance, these are the contamination of strainers, failure of the heating circuit pump, failure of the storage charging pump for domestic hot water and the fouling of heat exchangers. These faults and their failure modes need to be further investigated to support the development of early fault detection methods.

The study has identified relevant faults with low monitoring and maintenance potential, these are air in the piping system and defective actuator or valve of the domestic hot water electric 3-way valve. In this case, operators need to develop organisational measures to optimise O&M, like strategies to prevent or correct relevant faults and optimal logistics and supply chain management.

The study has identified relevant faults that are not related to O&M, these are the incorrect parameterisation of control unit and wrong placement of outdoor temperature sensor. In this case, utilities need to develop adequate strategies for installation, commissioning and auto-commissioning.

Since the results reflect the general situation in district heating substations in Germany, the recommendations presented here are particularly relevant for district heating operators in Germany and for researchers and developers working on fault detection methods with a focus on the German market. At the same time, the results lay the foundation for the design of experimental set-ups to further investigate in detail the failure modes of the identified relevant faults, in the context of the research project PreDist “Predictive Maintenance for District Heating”, founded by the Federal Ministry of Economic Affairs and Climate Action of Germany.

Furthermore, this study presents a novel methodology that can be directly applied to evaluate substations in other district heating scenarios, e.g. substation in other countries. At the same time, the methodology can be easily adapted to other areas of the industry to prioritise faults and support in the optimisation of O&M strategies.



Rank	Component	Failure mode	MPN
1	Strainer (primary side)	Poor flow rate (strainer contaminated)	326
2	Strainer (secondary side)	Poor flow rate (strainer contaminated)	294
3	Heating circuit pump	Failure of the heating circuit pump	237
4	DHW storage charging pump	Failure of the DHW storage charging pump	234
5	Control unit	Incorrect parameterisation	230
6	Heat exchanger	Poor heat transfer, poor flow (contamination)	212
7	Piping system	Air in the piping system	198
8	DHW eletric 3-way valve	Actuator of the DHW electric 3-way valve defective	192
9	Outdoor temperature sensor	Outdoor temperature sensor in the wrong place	171
10	DHW eletric 3-way valve	Valve of the DHW electric 3-way valve defective	170

Fig. 4. Prioritised faults in district heating substations with MPN results. To the right of each fault there is a bar chart showing: occurrence (blue), severity (dark orange), monitoring potential (grey) and maintenance capability (light orange).

Table A.5
List of faults in district heating substations along with the affected component and their occurrence (Occ), severity (Sev), monitoring potential (Mon) maintenance capability (Main) ratings ranked by their maintenance priority number (MPN). Displayed values are rounded, which might result in slight deviations when recalculating the MPN.

Rank	Component	Fault description	MPN	Occ	Sev	Mon	Main
1	Strainer (primary side)	Poor flow rate (strainer contaminated)	326	5.8	7.0	3.9	4.2
2	Strainer (secondary side)	Poor flow rate (strainer contaminated)	294	5.8	6.5	3.6	4.1
3	Heating circuit pump	Failure of the heating circuit pump	237	5.0	7.5	3.8	2.6
4	Domestic hot water storage charging pump	Failure of the domestic hot water storage charging pump	234	5.1	7.3	3.7	2.8
5	Control unit	Incorrect parameterisation	230	5.2	6.1	4.0	3.3
6	Heat exchanger	Poor heat transfer, poor flow (contamination)	212	4.8	6.0	4.2	3.2
7	Piping system	Air in the piping system	198	6.1	6.7	2.1	2.8
8	Domestic hot water electric 3-way valve	Actuator of the domestic hot water electric 3-way valve defective	192	4.9	6.8	3.5	2.3
9	Outdoor temperature sensor	Outdoor temperature sensor in the wrong place	171	4.3	5.6	4.2	3.0
10	Domestic hot water electric 3-way valve	Valve of the domestic hot water electric 3-way valve defective	170	5.3	6.5	3.3	1.9
11	Expansion vessel	Low pre-charge at the expansion vessel	160	4.9	5.0	2.9	3.6
12	Domestic hot water circulation pump	Circulation flow rate too low (e.g. inadequate hydronic balancing of domestic hot water circulation circuit)	142	4.3	5.8	3.2	2.5
13	Domestic hot water circulation pump	Failure of domestic hot water circulation pump	142	4.1	5.5	3.4	2.9
14	Pressure reducer (direct substation)	Pressure fluctuations in the system	141	3.0	7.5	3.1	3.1
15	Motorised control valve (primary side)	Actuator defective	140	3.6	7.4	3.4	2.0
16	Control unit	Control unit defective	138	4.0	6.5	3.5	2.0
17	Differential pressure regulator	Incorrect setting of the differential pressure regulator	138	4.3	5.3	3.1	2.9
18	Motorised control valve (3-way valve, secondary side)	Actuator defective	131	4.1	6.1	3.2	2.1
19	Motorised control valve (primary side)	Oversized control valve (inadequate valve authority)	129	4.3	5.8	3.3	2.0
20	Differential pressure regulator	Differential pressure regulator jams when closed	127	3.4	6.8	3.3	2.3
21	Temperature sensor (secondary side)	Temperature sensor is defective and gives no signal	125	3.3	6.4	3.5	2.5
22	Temperature sensor (primary side)	Temperature sensor gives wrong signal	124	3.3	6.2	3.4	2.7
23	Domestic hot water circulation pump	Domestic hot water circulation flow rate too high (e.g. due to inadequate hydronic balancing of domestic hot water circulation circuit)	123	4.5	4.4	3.3	3.0
24	Heat exchanger	Incorrect design: flow rate too high for the heat exchanger, low heat transfer	119	3.8	5.9	3.2	2.2
25	Heat exchanger	Leakage, inside (cracking)	118	3.3	7.2	2.8	2.2
26	Motorised control valve (primary side)	Control valve jams when closed	116	3.5	6.6	3.2	1.9
27	Temperature sensor (primary side)	Temperature sensor in the wrong place	115	3.3	5.6	3.2	3.0
28	Safety relief valve	Water loss, does not close properly	113	3.9	6.9	2.0	2.2
29	Volume flow limiter	Incorrect setting of the volume flow limiter	112	3.4	4.8	3.5	3.4
30	Outdoor temperature sensor	Outdoor temperature sensor is defective and does not give a signal	112	3.4	5.1	4.2	2.5
31	Volume flow controller	Incorrect setting of the volume flow controller	111	3.2	5.0	3.5	3.5
32	Pressure independent control valve	Actuator defective	110	3.2	6.7	3.3	2.0
33	Safety temperature limiter	Safety temperature limiter defective	110	3.0	8.1	2.4	2.1
34	Outdoor temperature sensor	Outdoor temperature sensor is giving the wrong signal	108	2.9	5.7	3.6	2.9
35	Shut-off valve	Shut-off valve closed	108	2.4	7.4	2.8	3.4

(*continued on next page*)

Table A.5 (*continued*).

Rank	Component	Fault description	MPN	Occ	Sev	Mon	Main
36	Motorised control valve (primary side)	Incorrect setting of the actuator travel time in the control unit	107	4.0	4.5	3.3	2.6
37	Temperature sensor (secondary side)	Temperature sensor gives wrong signal	107	3.3	6.0	3.0	2.5
38	Motorised control valve (primary side)	Control valve jammed in open state (imminent danger if type-tested unit with safety function)	106	2.2	9.0	3.6	2.0
39	Temperature sensor (primary side)	Temperature sensor is defective and gives no signal	106	3.5	4.7	3.6	2.7
40	Safety temperature monitor	Safety temperature monitor defective	105	3.1	7.9	2.6	1.8
41	Shut-off valve	Leakage, external	104	3.0	7.2	2.1	2.8
42	Motorised control valve (primary side)	External leakage (e.g. stuffing box leaking, seal leaking)	103	3.5	6.9	1.5	3.0
43	Control unit	Incorrect control sequence (incorrect connection)	100	2.5	6.7	3.1	2.9
44	Heat exchanger	Leakage, external	100	3.0	7.5	2.0	2.5
45	Motorised control valve (3-way valve, secondary side)	External leakage (e.g. stuffing box leaking, seal leaking)	99	3.5	6.7	1.6	2.8
46	Pressure independent control valve	Differential pressure regulator jams when closed	96	2.9	6.9	2.9	2.0
47	Pressure independent control valve	Incorrect setting of the actuator travel time in the control unit	94	3.8	4.2	3.2	2.7
48	Motorised control valve (3-way valve, secondary side)	Oversized control valve (inadequate valve authority)	92	4.3	4.8	3.1	1.7
49	Temperature monitor/controller	Temperature monitor/controller defective	88	2.8	7.0	3.0	1.8
50	Pressure reducer (direct substation)	Diaphragm rupture: Leakage to the outside	85	2.5	7.6	2.0	2.5
51	Motorised control valve (primary side)	Control valve leaking when closed (leakage volume above standard)	85	2.9	5.0	3.4	2.5
52	Motorised control valve (3-way valve, secondary side)	Control valve jammed when closed	84	3.2	5.8	2.9	1.8
53	Expansion vessel	No pre-charge (membrane rupture)	84	2.8	6.2	2.5	2.4
54	Differential pressure regulator	Differential pressure regulator jams when open	84	2.9	5.0	3.2	2.6
55	Pressure independent control valve	Control valve jammed when open (imminent danger if type-tested unit with safety function)	81	2.0	8.1	3.1	2.0
56	Motorised control valve (primary side)	Actuator cannot change the position of the valve (incorrectly designed)	78	2.0	7.7	3.6	1.8
57	Safety relief valve	does not open, risk of over-pressure	78	2.0	9.5	1.9	2.2
58	Pressure independent control valve	Incorrect setting of volume flow limiter	76	2.8	4.8	3.0	2.6
59	Pressure reducer (direct substation)	Incorrect setting	76	1.8	8.3	2.8	2.2
60	Temperature sensor (secondary side)	Temperature sensor in the wrong place	72	2.5	5.2	2.7	2.8
61	Motorised control valve (3-way valve, secondary side)	Control valve leaking when closed	72	3.0	5.4	2.8	1.8
62	Shut-off valve	Leakage inside	70	2.8	5.5	2.1	2.4
63	Motorised control valve (3-way valve, secondary side)	Incorrect actuator travel time (built-in actuator does not match the travel time set in the control unit)	70	3.2	4.4	3.0	2.0
64	Motorised control valve (3-way valve, secondary side)	Control valve jammed when open	70	2.6	5.6	2.9	2.1
65	Pressure independent control valve	External leakage (e.g. stuffing box leaking, seal leaking)	62	2.7	5.6	1.6	2.7
66	Motorised control valve (primary side)	Incorrect actuator installed (travel time not suitable in the context of the control circuit)	61	3.1	4.5	3.1	1.5
67	Pressure independent control valve	Control valve jammed when closed	61	2.4	5.5	3.0	1.8
68	Pressure independent control valve	Oversized control valve (inadequate valve authority)	61	2.6	5.1	2.7	2.0
69	Motorised control valve (3-way valve, secondary side)	Poor connection between actuator and valve (force-fit)	54	2.3	5.1	2.0	2.6
70	Motorised control valve (primary side)	Poor connection between actuator and valve (form-fit)	54	2.3	5.2	2.2	2.3
71	Motorised control valve (primary side)	Poor connection between actuator and valve (force-fit)	53	2.3	5.1	2.2	2.3
72	Motorised control valve (3-way valve, secondary side)	Actuator cannot change the position of the valve (incorrectly designed)	53	2.2	5.2	2.9	1.8
73	Pressure independent control valve	Actuator cannot change the position of the valve (incorrectly designed)	50	1.9	5.8	3.2	1.6
74	Motorised control valve (3-way valve, secondary side)	Poor connection between actuator and valve (form-fit)	48	2.4	4.3	2.0	2.6
75	Pressure independent control valve	Control valve leaks when closed	44	2.1	4.1	3.0	2.2
76	Pressure independent control valve	Poor connection between actuator and valve (force-fit)	43	1.9	4.7	2.1	2.8
77	Thermal energy meter	Leakage outside (leaking)	41	2.0	4.9	1.7	2.5
78	Pressure independent control valve	Poor connection between actuator and valve (form-fit)	41	1.8	4.7	2.1	2.8
79	Pressure independent control valve	Incorrect actuator installed (travel time not suitable in the context of the control circuit)	41	2.1	4.3	3.0	1.7
80	Thermal energy meter	Failure of the thermal energy meter	24	2.4	2.1	3.2	1.8
81	Thermal energy meter	Gateway defective	23	2.4	1.9	3.6	1.8

CRediT authorship contribution statement

Edison Guevara Bastidas: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Stefan Faulstich:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Conceptualization. **Holger Dittmer:** Writing – review & editing, Writing – original draft, Validation, Formal analysis. **Martin Neumayer:** Writing – review & editing, Writing – original draft, Visualization, Validation. **Gowtham Sakthivel Mohan:** Writing – review & editing, Investigation, Data curation, Conceptualization. **Kibriye Sercan-Calismaz:** Writing – review & editing, Investigation. **Frank Hosenfelder:** Writing – review & editing, Validation, Resources, Methodology. **Thilo Glenewinkel:** Writing – review & editing, Validation, Resources, Methodology. **Karsten Fischer-Florschütz:** Writing – review & editing, Validation, Resources, Methodology. **Anna Cadenbach:** Writing – review & editing, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Ranked list of faults in district heating substations

See Table A.5.

Data availability

The authors do not have permission to share data.

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