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Model for optimal malfunction management in extended district heating networks

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Abstract

The increasing number of district heating (DH)systems makes the management of operations both in normal conditions and in case of undesired events (failure of a device, breakups and leakages) a more and more important issue. In this paper, a methodology for the management of malfunctions in looped district heating systems is proposed. The approach is based on the optimization of the water transportation in the district heating network, with the goal of providing the end users with a heat flux as close as possible to their demand despite the failure. The optimizer includes a fluid dynamic model of the network able to take into account the pressure losses along the pipelines as well as the contributions due to pumping. Two kinds of malfunctions have been considered: breakup of pipelines and failure of a pumping station. Both types of malfunctions are managed using two alternative strategies which differ on the type of independent variables that can be modified: a partial operation strategy, where only the pumping settings are modified, and a complete operation strategy, where also the production share of the different plants can be modified. An application to the Turin district heating network is presented.

Keywords: district heating system, operation optimization, leakages, pipeline breakup, pump failure, off-design conditions

1. Introduction

District heating (DH) is a very effective technology to provide heating and domestic hot water to buildings, especially in densely populated areas [1]. Nowadays, this technology covers about 13% of the heating demand for buildings in Europe [2]. In future scenarios, it is expected a further penetration of this technology due to its potential for reducing primary energy needs, CO_2 emissions and costs [3] thanks to the integration of high efficiency plants [4] and renewable energy sources [5-7]. Currently, large attention is focused on the optimization of the operating conditions both in normal and abnormal conditions. Various works available in the literature concern the analysis of variable operating conditions, with the goal of improving the system efficiency [8-12] and exploiting heat available from industrial sites and renewable sources [13]. An important aspect is the optimal management of possible operating conditions originated from the occurrence of malfunctions, such as failures in components of the network or leakages in the pipes. This is especially true in the case of large networks, where the impact of such malfunctions can be very large, but there are also opportunities for overcoming or limiting the consequences.
The possibilities of failures are deeply studied in [14]. Authors investigate the assessment of failure probabilities of the district heating network pipeline. The methodology includes three types of approaches: a pure probabilistic-mathematical approach, a deterministic thermal-hydraulic approach and an integrated deterministic–probabilistic structural integrity analysis. Results

obtained considering an average operating pressure of 0.5 MPa show that the failure probability is 0.126 failures/km/year in the case of a 40 years old piping, and 0.04 failures/km/year in the case of a 30 years old piping. This value is quite high, in particular considering very large networks, with several hundred kilometers of pipelines. The high occurrence of failures suggests the inclusion of this aspect when feasibility studies and techno-economical evaluations are performed [15].

As regards DH networks, the main malfunctions are due to:

1. breakage of the supply lines (hereafter called breakup)
2. failure of a pump in the thermal station or in a booster pumping station located along the supply network

As regards leakage, various papers dealing with leakage detection can be found in the literature. An approach to discover leakages or blocked branches based on analysis of pressures measured in some points of the pipeline is proposed in [16]. In particular, a method for minimizing the number of required measurements and decreasing the effects of measurement errors is presented. Another option for detecting leakages consists in use of thermal cameras installed as remote sensing. An approach based on the idea that hot water leakages increase the surface temperature is discussed in [17]. In [18], the possibility to use distributed fiber optical for temperature sensing is investigated for fast and high precision detection, even in the case of small leakages. In [19], the effectiveness of advanced acoustic leakage detection is studied, focusing on the range of detection in terms of minimum mass flow rate and the accuracy in terms of position. The problem of leakages is usually managed by isolating the portion of pipeline where the failure occurs. Consequences of these failures depend on the fact that the network is tree-shaped or looped. In the latter case, alternative paths can be identified in order to supply water to the various buildings connected with the network, but a proper algorithm is required in order to meet the thermal demand of the end-users.

Pumps are potentially critical devices. These components are located along the network with the aim of distributing water to the various buildings located in the various areas of the town according with their needs. Several papers in the literature address the detection of pump failures in a network and the reduction of their possible effects [20-24]. The availability of multiple pumps installed on the network allows one overcoming or limiting the effects of malfunctions, but proper algorithms for managing abnormal operating conditions are required.

Technician and operators manage pipe breakups and pump failures by means of their experience in order to try to reduce the effects of the undesired events. Nevertheless, experience not always covers the entire spectrum of possibilities and generally leads to sub-optimal or non-optimal operating conditions. This is especially true considering that the effects of a malfunction are highly dependent on its position along the network. This point is also stressed in the result section of this paper where the effects of the same event is quantitatively analyzed as the function of its location in terms of effects on the end-users and action for optimal management.

In this paper, a methodology for the optimal management of large DH networks in case of malfunctions is proposed. The methodology proposed can be used both in case of breakups (or leakages) in the pipeline and failure of pumps. The approach is constituted by an optimization framework, which relies on a fluid dynamic model able to simulate the water distribution within the network as the function of the thermal request of the buildings and the control strategy. The optimization aims at evaluating the best strategy to provide the buildings connected to a DH network with a sufficient water flow rate. The approach is applied to the Turin network, which is one of the largest in Europe, in order to test its potential for malfunction management in a relevant environment.

Two operation strategies are proposed, which differ on the type of independent variables that are handled:

1. a partial operation strategy, which only acts on the pressure rise provided by the booster pumping stations located along the network.
2. a complete operation strategy, where both the pressure rise in the booster pumping stations and the production share of the different plants are freely modified.

The partial operation strategy has shown to be very effective while optimizing the DH system operation in normal conditions [25]. As discussed in the results section, these two strategies have different effectiveness in terms of avoiding negative impacts to the end-users, but also different economic cost and energy efficiency. Selection of the approach to be used should be performed in each scenario considering all aspects in a proper optimization framework. A tool based on the proposed methodology is thus valuable for assisting the operators while managing DH networks in case of malfunction.

This paper aims at covering the research gap defined by the following items:

1. Propose a methodology for tackling the occurrence of malfunctions affecting DH networks;
2. Test the methodology on an relevant environment (main pipeline about 150 km long) in order to show its performance;
3. Define the framework for the development of an automatic tool for optimal management of such events with minimum energy/economic performance of the system.

The paper is structured as follows:

- in section 2, the methodology proposed in this work is deeply described;
- in section 3, the fluid dynamic model of the network is described;
- in section 4, the case study considered for testing the methodology is presented;
- in section 5, results are reported and discussed;
- in section 6, the outcomes are further discussed together with other possible options that can be adopted for enhancing the effectiveness of the proposed methodology.

3. Modeling approach

2.1 Methodology description

The methodology proposed in this work evaluates the best strategy in order to keep comfort conditions as much heat as possible in the buildings despite the malfunctions. When malfunctions occur, some of the components (pipes, pumps, etc.) become unavailable. In such cases, the hydraulic resistance of the network generally increases and specific actions are requested to avoid large reductions in the heat fluxes supplied to the buildings. Supply temperature in the network is kept constant especially in cold winter days and in case of malfunctions To provide the buildings with amounts of heat as close as possible to their requests it is necessary to operate in two interconnected ways:

1. keep the water flow rate circulating in the network close to that without malfunction.
2. distribute the flow rate to the buildings without large deficit or surplus.

In Figure 1 a schematic of the approach used in this work is reported.

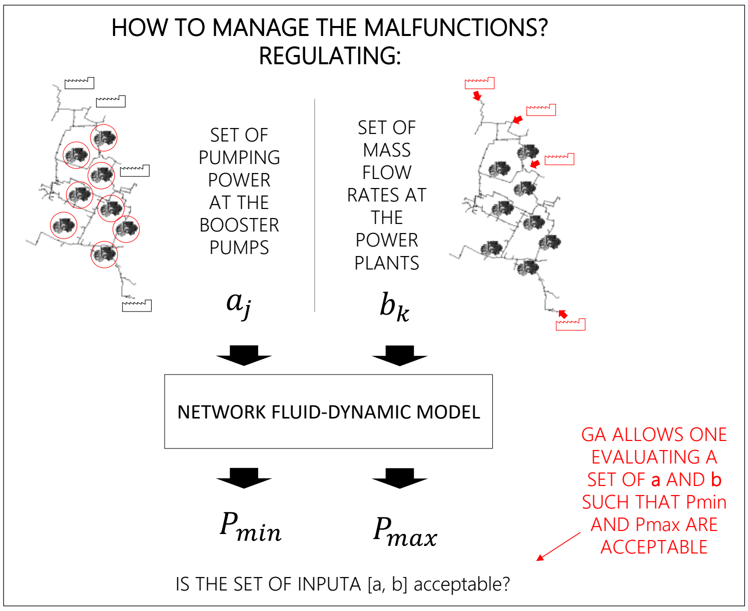

Figure 1. Approach adopted for the methodology proposed in the work

The quantities which can be modified in order to better manage the water distribution are:

1. the fraction of mass flow rate supplied by each thermal plant
2. the pressure rises at the booster pumping stations located along the network.

The pressure rises at the booster pumps are expressed as a fraction between the minimum and maximum pressure difference that are allowed at each pump.

These quantities can be mathematically expressed through two sets of variables: the vector **a** includes the fraction of pumping pressures provided by each pump, while the vector **b** includes the fraction of the total mass flow rate which is provided by each plant. The two sets of independent variables of the problem that can be handled with the aim of increasing the heat provided to the users can be expressed as:

$$\boldsymbol{a} = [\, a_1, a_2, \dots a_{M-1}, a_M \,] \,, 0 \le a_j \le 1 \tag{1}$$

$$\boldsymbol{b} = [\, b_1, b_2, \dots b_{N-1}, b_N \,] \,, \textstyle\sum_{k=1}^{N} b_k = 1 \tag{2}$$

where M is the number of booster pumping stations and N is the number of thermal plants. Values a_j range between 0 (pump does not work) and 1 (pump work at its maximum level), while values b_k range between 0 (the plant does not provide any mass flow rate) and 1 (the plant provide its maximum capacity). The restrictions in case of malfunctions are mainly related to the maximum mass flow rate allowed in each pipe, due to technical issues such as vibrations and pressure drops. Proper restrictions have to be set on the pressure field, in particular on the maximum and minimum values of pressure in the network (respectively called P_{max} and P_{min}). The maximum pressure of the fluid allowed in the network (P_{maxLim}) is due to the mechanical resistance of the pipes. In the considered case, P_{maxLim} is 17 bar. This constraint is imposed to the total pressure. The minimum pressure allowed in the network is due to the prevention from water evaporation. The limit is calculated by considering the highest temperature in the network, i.e. the supply temperature: In the considered case the supply temperature is 120°C, therefore the minimum pressure threshold (P_{minLim}) is about 2.5 bar. In order to limit the numerical analysis to the supply transport network, the minimum pressure must be summed to the fluid-dynamic losses occurring in the distribution networks and in the return pipeline. The total minimum pressure in the supply network becomes thus 11.5 bar. This threshold value is imposed on the dynamic pressure, considering the contribution of the elevation.

The evaluation of the optimal set of independent variables is performed as described in the flow diagram shown in Figure 2. The main steps of the procedure are:

1. At first, normal operating conditions (without malfunctions) in which the desired total mass flow rates is delivered to the various buildings are considered.
2. The optimizer is used to find a set of independent variables which allow to comply with the restrictions on the pressures in the network (as shown in Figure 1). The optimizer receives in inputs the set [a, b] and minimizes the objective function:

$$\min\left(W_p + \mu \frac{G}{\rho} \cdot e(p)\right) \tag{3}$$

   W_p is the power required by the pumping stations located at the thermal plants and by the booster pumps. The second term is a penalty, which allows one taking the deviation with respect to the acceptable conditions into account. This term is calculated as the pressure gap times the volumetric mass flow. The deviation is larger than the first term by means of the weight factor μ. In this way, the cases not satisfying the limitations are automatically diregarded. Once the effect of unacceptability is removed (e=0), the option which allows minimizing the pumping cost is selected.

   Considering the various limitations previously introduced, the deviation e is evaluated as:

   - the difference between P_{minLim} and min(p), when the minimum pressure (min(p)) does not comply with the limitation P_{minLim} (i.e. it is lower than the minimum acceptable limit);
   - the difference between P_{maxLim} and max(p), when the maximum pressure (max(p)) does not comply with the limitation P_{maxLim} (i.e. it is above the maximum acceptable limit);
   - the sum of the difference between P_{minLim} and min(p) and the difference between P_{maxLim} and max(p), when both limitations are not fulfilled.

In formulae:

$$e(p) = \begin{cases} \mathrm{p_{minLim}} - \min(\mathrm{p}) & if \min(\mathrm{p}) < p_{\mathrm{min}Lim} \,\&\, \max(\mathrm{p}) < p_{\mathrm{max}Lim} \\ \max(\mathrm{p}) - \mathrm{p_{maxLim}} & if \min(\mathrm{p}) > p_{\mathrm{min}Lim} \,\&\, \max(\mathrm{p}) > p_{\mathrm{max}Lim} \\ (\mathrm{p_{minLim}} - \min(\mathrm{p})) + (\max(\mathrm{p}) - \mathrm{p_{maxLim}}) & if \min(\mathrm{p}) < p_{\mathrm{min}Lim} \,\&\, \max(\mathrm{p}) > p_{\mathrm{max}Lim} \\ 0 & otherwise \end{cases} \tag{4}$$

   Summarizing, the first three cases in equation (4) are associated with the violation of one or more constraints (the first when the minimum pressure is below the lower limit, the second row when the maximum pressure is above the maximum limit, the third row when both the constraints are not fulfilled). Last row considers the acceptable cases, when the deviation is set to zero. If this optimization allows to find a set of variables such that e=0, the acceptable configuration is obtained and, referring to Figure 2, it is possible to exit the loop.

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3. If this optimization does not allow to find any acceptable set of variables (**a** and **b**) complying with the limitations the mass flow rate supplied to the buildings must be reduced. This reduction should be iterated until an acceptable fluid-dynamic scenario is reached. Such reduction is homogeneously applied to all buildings, by forcing the set points of the substations. This scenario can be then improved as discussed in the last section of this paper. The total mass flow rates provided to the users is defined at each iteration through the quantity x, as follows:

$$G_i = G_{init}(1 - x^i) \tag{5}$$

where G_{init} is the mass flow rate corresponding with the thermal request of the buildings.

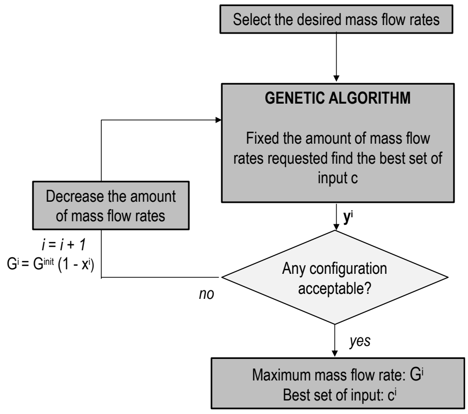


Figure 2. Schematic of the optimization approach

The optimization problem is nonlinear, despite the linear appearance of the objective function. This is due to the non-linear relation between mass flow rate and pressures along the pipes. In addition, the tool is intended for the application to a variety of optimization problems, involving also integer variables, such as the connection of additional buildings, the change in heating schedules, etc.

For these reasons, linear programming and convex programming cannot be applied. A genetic algorithm, has been selected for the following reasons because guarantees robustness and it is not essential to reach the global optimum, while it is important to find a way to find a configuration that is acceptable (e=0).

Genetic algorithm (GA) can be used for both constrained and unconstrained optimization problems. The approach is based on a natural selection process simulating the biological evolution through consecutive improvement in the population. At each step, GA selects the elements for the following generation trough selection, crossover and mutation, evolving towards the optimal result. This approach has been successfully applied in totally different fields with the aim of finding optimal solutions in problems characterized by local minima [26-28]. Mutation is performed using a Gaussian distribution. The number of mutation rate decreases at each generation. Crossover fraction, which is the fraction of each population is obtained by crossover excluding elite elements, is 0.8. A population size of 60 and 40 generations are considered in the analysis. The values are selected to allow extensive ranges of input parameters keeping the computational costs acceptable in the proposed application. Details on running time are provided in the result section.

2.2 Malfunction and operation approaches

In the present analysis, two eventualities are considered:

1. Breakup of a pipeline. In the scenarios corresponding with this type of failures, the branch where the malfunction takes place is considered as isolated. The two nearest valves located upstream and downstream the failure, respectively, are closed. The network is thus the same as in normal conditions, except for the broken branch, which is considered as disconnected in the analysis of this scenario. Failures have been considered to occur in looped portions of the network, which covers most part of the DH network, in order to enable the possibility to supply water to the users using other paths. As a result, the number of loops reduces by one and the hydraulic resistance of the network increases.

2. Failure of a pump. In this case, the pressure rise equal to zero has been considered in the broken pumps. In this case, the network does not change, but the available pumping power reduces.

These scenarios can be managed through two different control approaches, which are named in the following as “complete operation strategy” and “partial operation strategy”, respectively.

- In the complete operation strategy, both the pressure rise at each of the booster pumps and the mass flow rates produced to the various thermal plants are considered as the independent variables in the optimization process. Both sets of input, **a** and **b,** are modified in order to minimize the objective function.
- In the partial operation strategy, only the pressure rise at each of the booster pumps can be modified during the optimization process. Only the input vector **a** is modified in order to minimize the objective function while **b** is kept unchanged.

The complete operation strategy is more effective in reducing the effects of the malfunction but it also affects the production side. The value of the objective function is generally smaller than in the case of the partial operation strategy, which also means that the power required for pumping is minimum. The complete operation strategy gives priority to the coverage of the thermal demand, which implies that the plants such as cogeneration plants are generally managed in a way that does not minimize the total primary energy consumption or the economic incomes. The partial operation strategy is easier to implement and does not affect the production side. The level of independency of the thermal plants is the same as in the case of normal conditions. In this case, the priority is given to the plants, which allow one minimizing the primary energy consumptions, or maximizing the revenues. On the other side, this strategy is less effective because in some cases it leads to a reduction on the water that can be supplied to the users. For both the kind of malfunctions the two approaches (with or without the power plants management) have been considered, in order to evaluate the benefits and the drawbacks.

3. Fluid-dynamic model

The model used for the evaluation of the pressure values along the network is a one-dimensional fluid-dynamic model and it considers the network topology through a graph approach (pipes are considered as branches that start and end in two nodes) [29]. The connection between nodes and branches is described using the incidence matrix **A**. The general element A_{ij} is equal to 1 if the branch j enters the node i, -1 if the branch j exits the node i and 0 otherwise. The model is based on the application of mass conservation equation to all the nodes of the network and momentum conservation equation to the branches of the DH network . As regards the fluid-dynamic model, a series of hypotheses are considered:

- The unsteady term is not considered since fluid-dynamic perturbations travel the network much faster than usual operational changes.
- Density is kept constant, and therefore velocity does not change in each branch.

The mass balance of a node can be written as:

$$\sum m_{in} - \sum m_{out} = m_{ext} \tag{6}$$

where m_{in} are the mass flow rates entering the nodes from the upstream branches, m_{out} the mass flow rates exiting the node and entering the downstream branch and m_{ext} a mass flow rate exiting (+) or entering (-) the system from the outside. The mass balance equation can be written for the entire network using matrix formulation:

$$\mathbf{A} \cdot \mathbf{m} + \mathbf{m_{ext}} = 0 \tag{7}$$

where m is the includes the mass flow rates in all the branches of the network. As regards the momentum equation, it can be applied to a branch as follows:

$$(\mathrm{p_{in}} - \mathrm{p_{out}}) = \frac{1}{2}\frac{\mathrm{f}}{\mathrm{D}}\mathrm{L}\frac{\mathrm{m}^2}{\rho\mathrm{S}^2} + \frac{1}{2}\sum_\mathrm{k}\beta_\mathrm{k}\frac{\mathrm{m}^2}{\rho\mathrm{S}^2} - \mathrm{t} \tag{8}$$

where p is the total pressure, the first and the second terms on the right-hand side terms are, respectively, the distributed and the localized pressure losses, and the last term is the pressure rise due to the pumps. Equation (8) can be rewritten in matrix form through the use of the incidence matrix as follows:

$$m = Y \cdot A^T \cdot P + Y \cdot \Delta p_{pumps} \tag{9}$$

where $\mathbf{Y}$ is a diagonal matrix representing the fluid dynamic conductance of branches that can be expressed as follows:

$$\mathbf{Y} = \mathbf{R}^{-1} = \left[\frac{1}{2}\frac{\mathbf{m}}{\rho\mathbf{S}^2}\left(\frac{\mathrm{f}}{\mathbf{D}}\mathbf{L} + \sum_\mathrm{k}\boldsymbol{\beta}_\mathbf{k}\right)\right]^{-1} \tag{10}$$

The pressure gap due to the booster pumps located along the network can be evaluated as:

$$\boldsymbol{\Delta p_{pumps} = b\ \Delta p_{max}} \tag{11}$$

where Δp_{max} is the maximum pressure gap that a pump can provide to the water flow.

The solution is obtained using a SIMPLE (semi implicit method for pressure linked equation) algorithm [30], because of the dependence of the terms in $\mathbf{Y}$ on pressure. For further details and for the model validation the reader can refer to [25, 31, 32].

The thermal equation it is not considered in this particular application, for two main reasons:

1. the dispersion along the transportation network can be assumed as constant for the purpose of this work. When the circulating mass flow rate is large, as in the scenario which make sense to consider for malfunction analysis, losses are about 1-2% of the thermal load. This means that temperature changes in the transport network are small.
2. the transportation network is kept at constant supply temperature.

The temperature entering the building substations is thus considered as equal to that measured in normal conditions. Consequently, it is possible to provide the thermal power request to the building in normal conditions, just supplying the same mass flow rates. For the above mentioned reasons, the full analysis is performed considering fluid flow without solving the energy equation.

4. Case Study

The Turin DH network is about 550 km long and serves 57% of the inhabitants located in the urban area, about 600000. The DH system is mainly fed with three cogeneration plants and various storage units, which are used during thermal peak loads and when the electricity cost is high. Various boilers complete the thermal capacity of the system. The characteristics of the system are reported in Tab. 1. The DH network is composed of two interconnected parts: the transport network, constituted by pipes with large diameter, and 182 distribution networks, which have smaller diameter and link the transport network to the thermal substations in the buildings. The transport network presents 6 large loops, while the distribution networks are typically operated in tree-shaped configuration. The network is fed with water at a constant temperature of about 120°C. Thermal load variations are managed varying the circulating mass flow rate. Water in the return pipeline varies between 70 °C, when the average daily load is large, and 50 °C, when the thermal load is small.

Plant site	***Cogeneration [MW]***	***Boiler [MW]***	***Storage [m³]***

Moncalieri	520	140	-
Torino Nord	250	340	5000
Politecnico	-	255	2500
BIT	-	255	2500
Martinetto	-	-	5000

Tab. 1. Characteristics of power plant

The model adopted for the present study considers the entire supply transport network, which consists of 685 branches and 677 nodes. The distribution networks are modeled considering the corresponding fluid dynamic resistances, in order to reduce the computational efforts required in the optimization. This does not constitute a limitation in the analysis, since no operational actions are performed in these portions of the DH.
The network topology has been designed as a series of concatenated loops with the aim of creating a more flexible management during operations. This characteristics is particularly useful in the case of leakages, breakup of network, and failure in pumps, thanks to the possibility of isolating the part of the pipeline where the problem occurs and provide heat to the users by using alternative paths. In the Turin network, the 6 large loops can be used for this purpose. Concerning the pumping system, a pumping group is installed in each thermal plant. Furthermore, the long distances involved (the network extends to an area of over 30 km^2) lead to the necessity of additional pumping groups. Currently, 9 booster pumping stations are located along the network. Booster pumping station characteristics are shown in Tab. 2.

Booster pumping station	***Number of groups***	***Direction***	***Line***
RP1	2	North - East	Supply
RP2	2	North - East	Supply
RP3	1	East	Supply
RP4	1	North	Return (operated in the case of P increase)
RP5	3	North – East - Southwest	Supply

Tab. 2. Characteristics of the booster pumping groups

In Figure 3, a schematic of the transport network is reported. The figure shows the position of the thermal plants and the booster pumping stations. Most of the pumps are installed to support the water flow from south towards north direction because most of the thermal capacity is in the south part and in order to compensate the elevation.

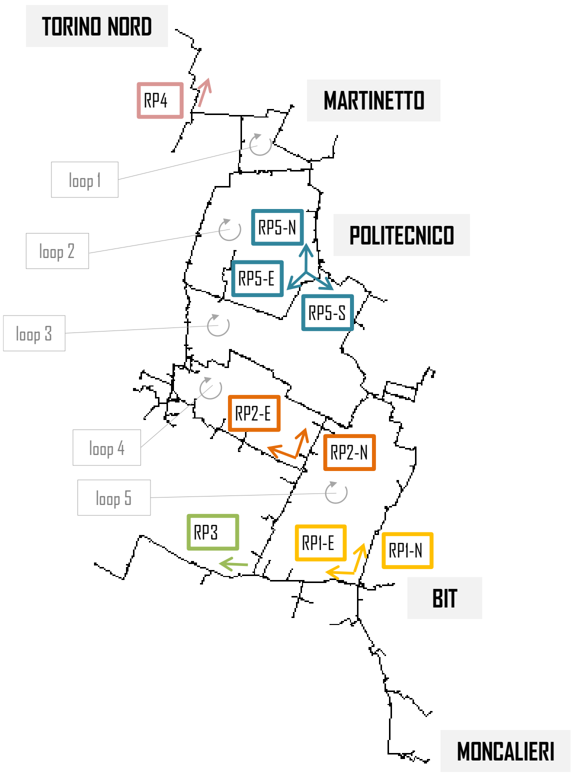


Figure 3: Schematic of the Turin transport network

In this work, the typical demand of a very cold winter day with an external temperature of about -5°C is considered. This is done for examining the unfortunate combination of large thermal demand and an unexpected malfunction. The peak thermal request of the buildings referred to a very cold day is considered as the heat flux to be supplied, despite the malfunction.
When the external temperature is higher, the thermal demands reduce and so the water mass flow rate circulating in the network. This make malfunctions easier to manage. In other words, the impact of possible malfunction reduces with increasing external temperature.

5. Results

Two types of malfunctions together with the possible optimizations to minimize their impact on the end-users are presented in the following sections. The analysis has been performed considering the thermal demand of the buildings in a typical winter day.

5.1 Pipeline breakup or leakage

In this section, the case of a breakup in a pipeline or a considerable leakage is examined. Different scenarios are considered in order to take into account various possible positions of the failure. Failures are considered to take place in the large loops of the network. This assumption is considered because it is the most probable occurrence in the examined network and because the breakup in a tree-shaped portion of network cannot be overcome.
The branches where breakups occur in the various scenarios have been randomly selected. From a certain point of view, there are some areas that are affected by higher breakup risk. This is because of the different periods of construction and the different mass flow rates (where high mass flow rates flow the pipes are subjected to larger vibrations). Nevertheless, considering a wide time-span, both changes in mass flow conditions within the loops and retrofitting of portion

of pipeline, make the use of a random selection more suitable for showing the effectiveness of the proposed methodology. Scenarios are reported in Tab. 3 , together with the loop where they occur, and their position. Position of the breakup are also indicated in Figure 4.

Failure n°	***Loop where the breakup is located***	***Position in the loop of the breakup***
1	*3*	*E*
2	*2*	*W*
3	*5*	*S*
4	*3*	*W*
5	*2*	*E*
6	*5*	*SW*

Tab. 3. Scenarios considered in the analysis of pump failures

Figure 4 also reports the values of the normalized input variables in each failure scenario, in the case of the complete operation strategy. The value of variables a_i, referred to the pressure difference at each booster pumping station, are depicted as asterisks in the points where pumps are located. The variables b_i, referred to the mass flow rates coming from the different thermal plants, are indicated as squares in the points where the plants are located. Color scales refer to the fraction of pressure increase in pumps (asterisks) and fraction of mass flow rate supplied by the plants (squares).

The best strategy to overcome failure 1 consists in increasing the water flow rate produced by the boilers located in Politecnico. Consequently, large pressure increase is operated by the three booster pumping stations near that plant (RP5-N, RP5-E, RP5-S).

In failure 2 a small mass flow rate is supplied by the cogeneration system and the storage units in TN, which are located near the failure point. Large mass flow rate is instead supplied by the other power plants.

Failure 3 is managed by providing large mass flow rates from the thermal plants located in the south area, particularly the boilers located in Bit. A small pressure rise is applied by the pumping system RP1-N, which operates towards the breakup.

In failure 4, due to the central position of the failure, small mass flow rates are produced in the plants located in the central area of the town. Consequently, a small input is required in the booster pumping station located in that portion of network.

In failure 5 a small mass flow rate is supplied by the storage units in the Martinetto plant and very low pressure input is provided by RP5-N, because of the position of the breakup.

Failure 6 is quite complex to manage, despite the optimization approach. The mass flow rate flowing the network should be significantly reduced and redistributed between the various plants. The largest reductions are applied to the Bit plant, while the smaller reductions are applied to the cogeneration plant and the storage units in TN. A very small pressure rise is applied by the pumping system in RP1-E, because of the position of the breakup.

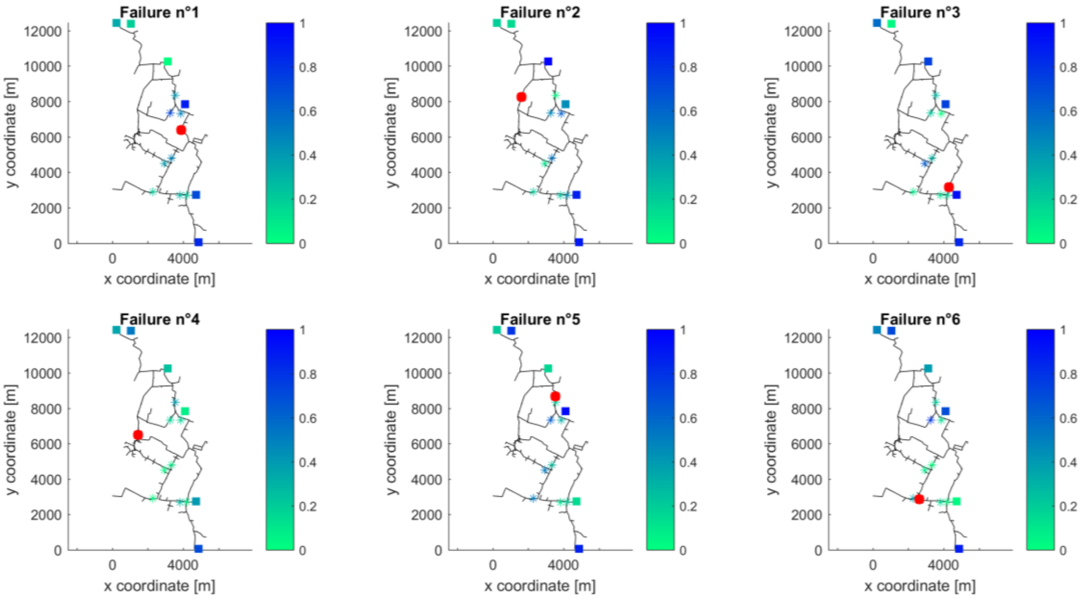
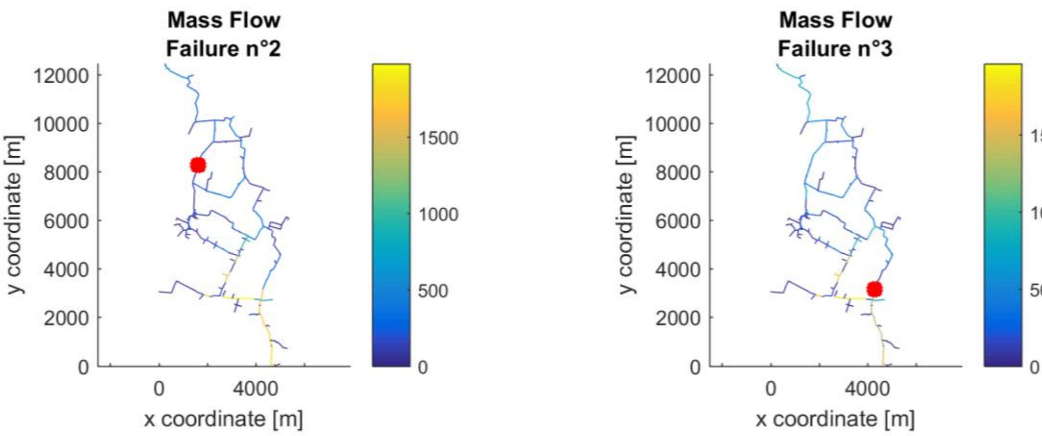


Figure 4: Management of the failure on the pipelines

Additional information can be obtained considering Figure 5, which depicts the mass flow distribution along the network in two of the considered failure events: failure 2 and failure 3. Breakups occur in opposite sides of the network. The sets of input obtained using the optimization are used for simulating the fluid dynamic behavior of the network. In the figure all the branches of the network are depicted with different colors, depending on the values of the mass flow rate circulating in the branch. In the case the breakup is located in the south area of the network (Failure n°3), the Moncalieri plant (which is located in the south of the town) provide a smaller mass flow rates than in case of Failure n°2. Indeed, when Failure n°3 occurs there is only a pipeline available for transporting the mass flow in the central area and therefore the production in Moncalieri cannot exceed a certain value. For the same reason, when Failure n°2 occurs, the mass flow rate produced in Torino Nord power plant (which is located in the north of the town) is lower than in the case of Failure n°3. The other plants have a smaller contribution, which is adjusted in order to compensate the production of the main plants.



In Fig. 5, the total mass flow rates supplied to the buildings in the different scenarios are shown. In five of the six considered cases, the complete operation strategy allows one to fulfill the entire thermal demand, despite the failure occurrence. In the case of failure n°6 the maximum amount of mass flow rate that can be provided to the users is about 70 % of the requested value. This means that the pipeline where the sixth failure takes place is the most sensitive and difficult to manage when a breakup or a leakage occurs. In the case the failure occurs in typical winter days with outdoor temperatures of about -5 °C (high thermal load and therefore high mass flow rates requested), the control strategy should be then accompanied with an extension of the time the heating system in the buildings is switched on during nighttime. Such failure can be instead managed without particular issues in the case it occurs in periods with an outdoor temperature above 3-4 °C.

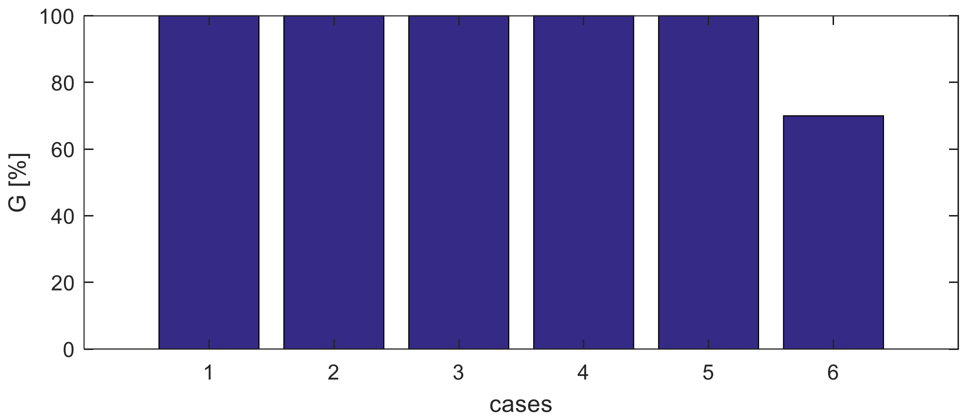


Figure 5: Total amount of mass flow rates provided in the various scenarios (Complete operation strategy)

The results obtained by applying the partial operation strategy to the same scenarios considered in Fig. 4 are reported in Fig. 6 in terms of maximum amount of mass flow rates that can be supplied to the buildings. As expected, when the partial operation strategy is used, the energy supplied to the users decreases. In scenarios 1-2 and 4-5 it is possible to supply the buildings with their thermal demand, keeping the preferred production scheduling of the plants. This is advantageous since it typically coincides with the minimization of the primary energy consumption associated with heat generation or the maximization of revenues.

In the case of failure 3, it is not possible to supply the full amount of water, but it is necessary to limit it to about 90% of the request. This means that it is possible to use this type of control if the outdoor temperature is above -2 °C. In the case the temperature is below this value, it is necessary to couple this strategy with an increase of the time the heating systems in the buildings operate. Failure 6 is the most critical. The partial operation strategy allows one providing only 30% of the total heat demand.

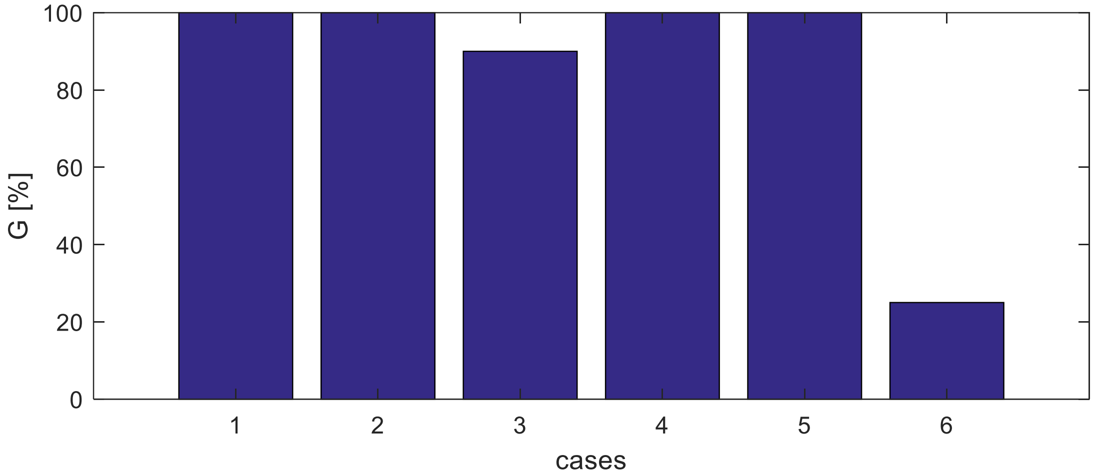


Figure 6: Total amount of mass flow rates provided in the various scenarios (Partial operation strategy)

5.2 Malfunctions in a booster pumping station

In this section, results regarding the failure of the booster pumping stations are reported. The DH network behavior is examined in the scenarios summarized in Tab. 4.

Failure n°	***Booster pumping station failed***	***Pumping direction of the failed pump***
1	*RP1- N*	*N*
2	*RP1- E*	*E*
3	*RP2- N*	*N*
4	*RP2- E*	*E*
5	*RP3*	*E*
6	*RP5- E*	*SE*
7	*RP5- N*	*N*
8	*RP5- S*	*SW*

Tab. 4. Scenarios considered in the analysis of pump failures

The location of the failures pump is reported in red in Fig. 7. The map shows the values of the independent variables which have been obtained through the optimization, in each scenario. As explained in the case of Figure 3, the variables a_j are indicated as asterisks while the variables b_k are indicated as squares in the points where the thermal plants are located. Color scale indicates the fraction of pressure rise (asterisks) and mass flow rate (squares), respectively. The complete operation strategy is considered.

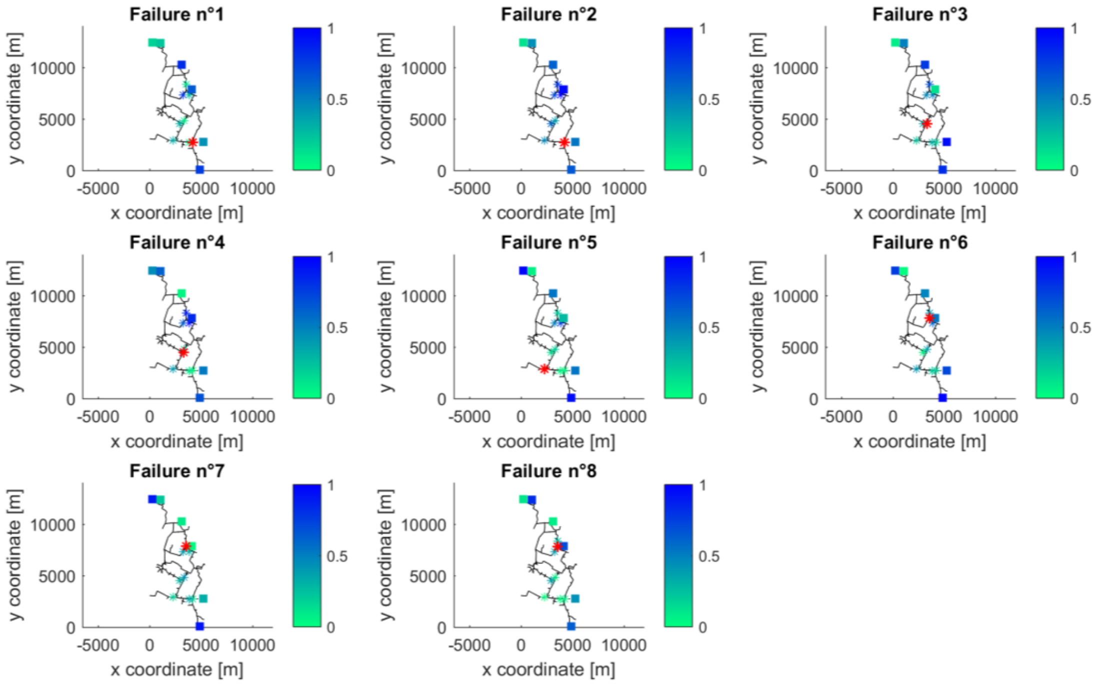


Figure 7: Position of the failure on the pipelines and optimization results

The mass flow rate requested by the end-users is guaranteed in all scenarios using both the complete operation strategy and the partial operation strategy. This means that it is possible to overcome the issues related with pumping systems without affecting the production scheduling of the thermal plants. Nevertheless, the complete strategy is able to extend the operational flexibility and generally allows a larger circulation of mass flow rate, which can be very important in the case the failure occurs before the morning peak load. This condition is characterized by larger thermal request by the end-users than the daily request. This is accompanied by a larger request of mass flow rate, even if less than proportional to the additional heat flux, thanks to the large temperature difference between the supply and return networks when the heating systems are switched on. In addition, the complete strategy requires less use of the pumping system, therefore it is advantageous in possible scenarios with double malfunctions.

6. Discussion

Results of the various optimizations performed in the previous sections have shown that both the booster pumps and the adjustment of the production from the various thermal plants concur to the management of possible failures in the network. A complete strategy acting on the two sets of variable allows to fulfill the thermal demand of the buildings in most scenarios, overcoming or limiting to the minimum the impact on the comfort conditions of the end-users. Such strategy gives the network the maximum flexibility and, thus, allows the maximum circulation of mass flow rate in the network, which might be important in the case of extremely low outdoor temperatures, or when peak requests occur.

The methodology proposed information about the effects of the malfunctions and their relevance. It can be very useful for technicians in charge of tackling the emergencies. In fact, once the location of the breakup (or the pump that failed) and the total load required to the network are known the tool can be run for obtaining the set of inputs for an optimal management of the malfunction.

An important strength regards the time that the simulation needs to provide the results. The computational time needed to obtain optimization results on a single 3.3 GHz CPU is less than an hour. This allows using the proposed methodology for tackling malfunctions event in real time, also when low computational resources are available.

The model allows one obtaining information useful for taking decisions related to the way to provide heat to the buildings. Indeed, when the model outcomes indicate that it is not possible to supply the full amount of water to the buildings additional measures can be implemented with the aim of limiting the effects at the user level. The first option consists in modifying the overall thermal request profile, through proper modifications of the thermal demand of each single building. This approach is called virtual storage [33, 34] and it is usually adopted to reduce the thermal peak load. It can be obtained by varying the time when the heating systems in the various buildings are switched on. The optimal change is calculated considering the position of the buildings on the network, their thermal demand and the network topology. This is obtained through a thermo-fluid dynamic model of the system, which allows one to maximize the effects on the plant load profile. The thermo-physical characteristics of the buildings are considered in order to set proper constraints, so that the indoor temperatures are not affected by the profile change. Such strategy can be coupled with the set-points of the heating systems, in order to increase the flexibility in operation and further limit the undesired effects on the buildings. Virtual storage allows thus reducing the maximum peak value and then easily reach, through the operation strategy selected, the correct amount of mass flow rate for each user. This effect can be further stressed by extending the operating hours of the heating systems.

A second option consists in a massive use of the storage units, which could be installed in strategic areas of the network. This option can be implemented with a double goal: 1) to overcome possible bottlenecks, i.e. branches of the networks characterized by relatively small diameter which, in some cases, force one to limit the mass flow rate flowing the network. In the case storage units are installed downstream these bottlenecks, these can be charged when the thermal request is small (i.e. at night) and discharged when the request is large; 2) to feed areas which might have been cut-off by the malfunctions.

A further option regards the use of specific surfactants. Such kind of substances reduce friction, thanks to the formation of an extra viscous sublayer along the pipe walls, buffering the turbulence [35]. Finally, mobile heat stations or mobile storages can be also considered provided that the network is equipped with proper hydraulic connections.

All these opportunities can be considered separately or combined, depending on the possibility of the network and on the entity of the malfunction effects.

7. Conclusions

In this paper, a methodology to manage the effects of incidental events in a district heating network is proposed. Two kind of malfunctions are considered:

1. leakages or breakups in pipes;
2. failures in the pumps located along the network.

The approach consists of an optimization tool, which relies on a fluid dynamic model based on conservation equations applied to all the nodes and branches of the network. The optimization allows to find the best set of input able to limit the impact to the end-users.

Two alternative optimization strategies are examined. The two strategies are: 1) a partial operation strategy, where only the pressure rise at the various booster pumps is managed, leaving the production share of the various plants unchanged. 2) a complete operation strategy, where also the production share of the various plants can be modified.

The methodology proposed in this paper has been tested on the Turin district heating system, to prove its capability of managing failures in extended networks. As regards the possibility of a pipeline breakup, results show that in some cases it is possible to manage the emergency just trough proper control of the pumping system (partial operation strategy) without modifying the desired production of the various thermal plants. In four of the six considered cases (failures: 1, 2, 4, 5), both the partial and the complete regulation strategies allow to provide the desired amount of water, despite the failure occurrence. In one case (failure n°3), the use of the complete regulation allows to supply the total mass flow rate to the end-users, while the partial operation strategy leads to a 10% reduction of the mass flow rate circulating. In the most problematic case (failure 6) the maximum amount of mass flow rate which can be supplied to the end-users is about 70% of the when a complete operation strategy is applied and only 30% when the partial operation strategy is considered. The partial operation strategy allows one to optimize the operation of the thermal plants, e.g. minimizing the primary energy consumption for heat generation or maximizing the revenues, but in some scenarios, it results as less effective. As regards the complete operation strategy, it enables the possibility of varying both pumping and the change in plant heat production increases the network flexibility and thus allows one better manage the malfunctions, especially the most critical ones. On the other hand, this approach does not take into account the energy efficiency of the system. For some failures the methodology may indicate a massive request of mass flow rate from the boiler systems and a low exploitation of the cogeneration plants, with a consequent high primary energy consumption. Nevertheless, this kind of disadvantage can be accepted as soon as the malfunction occurs and the emergency arises, because it involves a limited time period.

Regarding failures in the pumps, in all the scenarios considered in this paper, both strategies allow to fulfill the entire request of the end-users without limitations on the circulating mass flow rate. The partial operation strategy is more advantageous in terms of management of the thermal plants, while the complete operation strategy is more advantageous in terms of management of the pumping system and network. The latter should be adopted in more critical scenarios such as peak load of possible multiple malfunctions. Further options for limiting the effects of malfunctions, which can be combined with the control strategies, are proposed in the discussion section.

Nomenclature

A: incidence matrix

a: vector of the pumping pressures

b: vector of the plant flow rates

D: pipe diameter [m]

e: deviation [Pa]

f: distributed friction factor

G: total mass flow rate [kg/s]

L: pipe length [m]

M: number of booster pumping stations

$\dot{m}$: mass flow rate [kg/s]

N : number of power plants

p: pressure [Pa]

P: pressure matrix [Pa]

S: pipe section [m^2]

t: time [s]

T: temperature [°C]

W_p: pumping power [kW]

x: additional amount of total mass flow rate [kg/s]

Y: fluid dynamic conductance [kg/ms^2]

Greek symbols
β: localized friction factor
μ: weight factor
ρ: density [kg/m^3]

Subscript and superscript:
i : at the ith iteration
init : inital
maxLim : minimum limit
minLim : maximum limit

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