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A MINLP Optimization Method to Solve Hydraulic Bottlenecks on Existing District Heating Networks

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Abstract. The efficiency of district heating networks may be improved by reducing the supply temperature. In existing networks, some technical issues occur especially in pipes, whose velocity increase sometimes over the maximal recommended limit. Two solutions may address the problem, the first one is to replace critical pipes, the second one is to introduce storage downstream critical pipes, named distributed storage, to shift peak demand to off-peak time. To find the best retrofit solution, an exploration with optimization tool is required. In the literature, some approaches compatible with the context of hydraulic congestion are developed. A previous work compares them and concludes that a MINLP optimization initialized with a MILP optimization is appropriate for the introduction of distributed storages. This work proposes to expand this method with the option of replacing pipes. The obtained method is applied on the same case study for a supply temperature between 120°C and 80°C. Distributed storages prove to be more profitable than replaced pipes because they can also do some peak-shaving the rest of the year. When the congestion is too significant, pipes are replaced.

Keywords: District Heating Network, Thermal Energy Storage, Retrofit, Optimization

1. Context

The reduction of the supply temperature is considered on many district heating networks in order to introduce more low-carbon sources and reduce losses [1]. For existing networks, this results in some technical issues especially for the distribution part [2]. Indeed, reducing the fluid temperature in pipes requires increasing its velocity, which can sometimes exceed the maximum recommended limit. Two solutions may address the problem. The more obvious is to replace critical pipes with larger diameter ones but construction works are not always possible and very expensive. The second option is to introduce storage units downstream critical pipes to shift demand peaks to off-peak time [3]. For both solutions, many locations, size and operation patterns are possible. To find the best retrofit configuration, a wide exploration of the different options with optimization tools is required. In the literature, metaheuristics are usually used for this kind of problems; however, they may be limited in efficiency due to the very wide spectrum of possible options. Another approach is deterministic exploration with a linear formulation of the system; unfortunately, this solution does not take into account the thermo-hydraulic behaviour of the network. This calls for a method that combines the reliability of deterministic explorations with the accuracy of non-linear formulation [4]. To this aim, a MINLP optimization method has been developed [5] to introduce storage in a network facing hydraulic bottlenecks due to the reduction of the supply temperature. In this work, we propose to extend the previous study by allowing another network modification in order to solve hydraulic congestion, namely replacing critical pipes with larger diameter ones.

2. Methodology

2.1 MINLP optimization

As explained in the first section, the MINLP optimization method proposed by [5] is used. This method tries to find the minimal total costs – investment, maintenance and operation costs – of a district heating network under some non-linear and linear constraints representing its behaviour: mass and energy balance in pipes, heat exchanges at the production site and substations, maximal production plant power, minimal substation temperatures and maximal pipe velocities. Solving this problem with a supply temperature lower than the design network temperature increases the velocity, sometimes exceeding the maximal recommended one. The latter study analysed the possibility of introducing storage not to exceed this maximal velocity. This work allows another option to solve hydraulic congestion, the replacement of critical pipes with larger diameter ones.

A pipe catalogue is defined in Table 1, with the costs come from [6]. The set $I_{diameter}$ lists the diameters of the catalogue. The parameter d refers to the diameters expressed in meter, and $c_{invest,pipe}$, its linear cost in €/m.

Table 1. *Pipe catalogue*

$I_{diameter}$	$d\ (m)$	$c_{invest,pipe}\ (€/m)$
1	0.0545	503
2	0.0703	603
3	0.0825	628
4	0.1071	691
5	0.1325	766
6	0.1603	879
7	0.2101	980
8	0.263	1055
9	0.3127	1256
10	0.3444	1382
11	0.3938	1508
12	0.4446	1621
13	0.4954	1734

In the optimization problem, the pipe diameters become a variable. For each pipe (i,j), the diameter is equal to the sum over the pipe catalogue of the product of a binary variable $Z_{i,j,d}$ with the diameter d_d. A second constraint imposed that the binary $Z_{i,j,d}$ gets the value 1 for only one index d.

$$\forall\ \boldsymbol{i,j} \in \boldsymbol{I_{pipe}},\ \boldsymbol{D_{i,j}} = \sum_{\boldsymbol{d}\ \epsilon\ \boldsymbol{I_{diameter}}} \boldsymbol{Z_{i,j,d}} \times \boldsymbol{d_d} \quad (1)$$

$$\forall\ \boldsymbol{i,j} \in \boldsymbol{I_{pipe}},\ \sum_{\boldsymbol{d}\ \epsilon\ \boldsymbol{I_{diameter}}} \boldsymbol{Z_{i,j,d}} = \boldsymbol{1} \quad (2)$$

A set $I_{diameter\_0}$ is defined, containing the initial pipe diameters. Another set $I_{diameter\_diff}$ contains, for each pipe, diameter values higher than the initial one. Thus, applying this set on the binary $Z_{i,j,d}$ gives only the replaced pipes and thus the ones to consider in investment costs in the objective. $L_{i,j}$ is the length of the pipe (i,j).

$$c_{invest} = \sum_{s \in I_{stor}} c_{stor,var} V_{stor,s} + c_{stor,fixed} Y_s + \sum_{i,j \in I_{pipes}} \sum_{d \in I_{diameter\_diff}} Z_{i,j,d} \times L_{i,j} \times c_{invest,pipe,d} \quad (3)$$

The MINLP optimization method has a specific initialization strategy based on the results from an equivalent MILP optimization. The strategy is kept in this work adding a step for the management of the new variables associated with pipes replacement as shown in Figure 1. After a NLP optimization of the network without velocity constraint, the problem is solved with only the option to introduce storages. Then, a second MINLP resolution of the problem is run with the possibility to replace pipes. Both retrofit steps are initialized with binary values obtained with the MILP optimization. At the end, the problem is solved over all representative days simultaneously with all retrofit options.

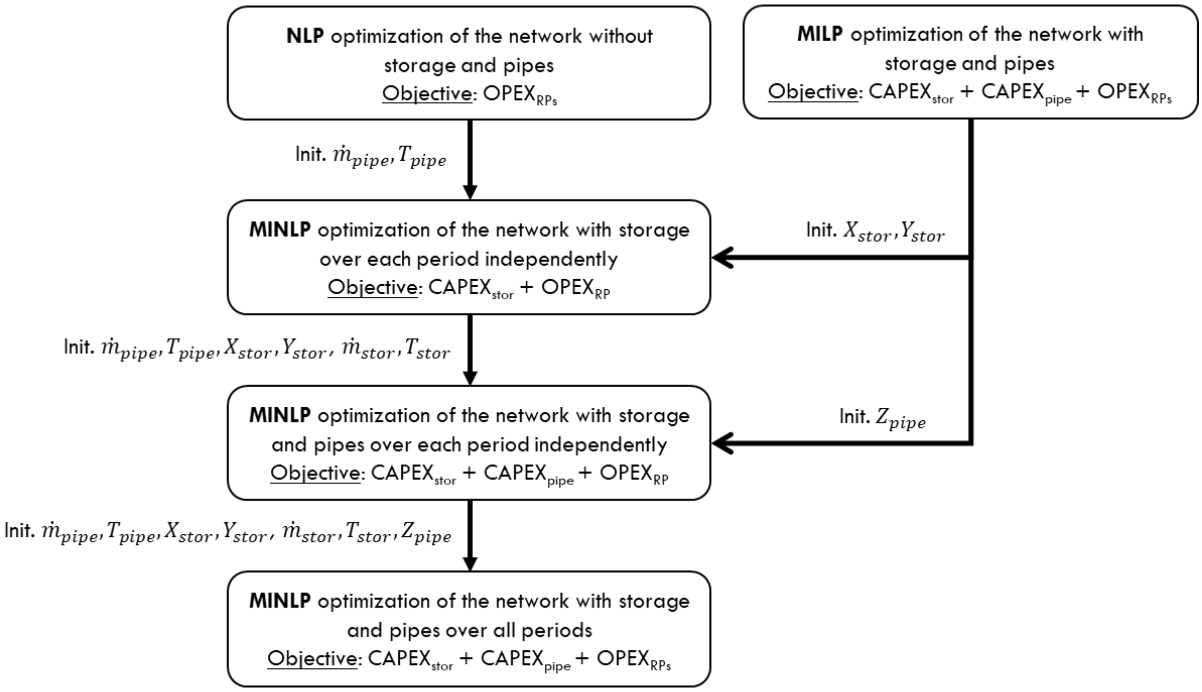

Figure 1. *MINLP problem resolution*

The MILP optimization used in the initialization strategy is improved including a thermal loss coefficient proportional to the supply temperature. The loss in thermal power, $P_{loss,i,j}$, is written with two coefficients, a_d, b_d, obtained from a linear regression of the losses for each pipe diameter and different supply temperatures on a simulation with the tool DistrictLab Simulation Studio [7], all multiplied by the length of the pipe.

$$\forall\, i,j \in I_{pipe},\ P_{loss,i,j} = \left(a_d\, T_{supply} + b_d\right) \times L_{i,j} \quad (4)$$

Finally, a constraint is added to ensure the same energy level in the storage system at the beginning and at the end of the day. That allows the storage to charge during the night in order to discharge in the morning. For the non-linear formulation, assuming that the hot (resp. cold) temperature in the storage is quite the same during a day, the energy loop constraint is written only on the storage volume. The thermal loss coefficient in the storage is equal to 0.8% per hour.

$$\forall\, s \in I_{stor},\ E_{stor,s}(t_{start}) = \left(1 - K_{loss,s}\Delta t\right) E_{stor,s}(t_{end}) + \left(P_{in,s}(t_{end}) - P_{out,s}(t_{end})\right)\Delta t \quad (5)$$

$$\forall\, s \in I_{stor},\ V_{hot,s}(t_{start}) = V_{hot,s}(t_{end}) + \frac{\left(\dot{m}_{ch,s}(t_{end}) - \dot{m}_{dch,s}(t_{end})\right)}{\rho} 3600\Delta t \quad (6)$$

2.2 Case study

The expanded method is applied on the same case study used in [5]. The district heating network has four consumers – shop, residential, hospital and office – whose demand is satisfied with one production site composed of a waste, a biomass and a gas plant. Pipes and substations are designed for a supply temperature of 120°C. One centralized (n°9) and three distributed storages (n°1, 2 and 5) may be installed in the network. The maximal recommended velocity in pipes is 2 m/s. The optimization problem is solved on GAMS with the Knitro solver [8]. The time horizon is composed of three representative days [5], each one with a specific weight in the formulation of the economic optimisation objective: day 3 (21.3%), day 17 (0.2%) and day 307 (78.5%).

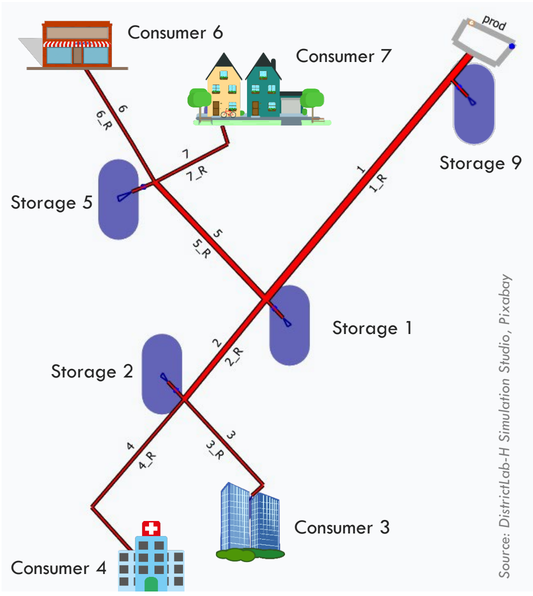

Figure 2. *Case study*

3. Results

Different supply temperatures are explored, from 120°C to 80°C. Gradually, hydraulic congestion appears in pipes, storages should be introduced or pipes replaced to ensure the satisfaction of the demand under the maximal recommended velocity in pipes. Figure 3 shows which retrofit options are chosen according to the supply temperature. Total cost over 20 years of operation is also highlighted below the network schematics.

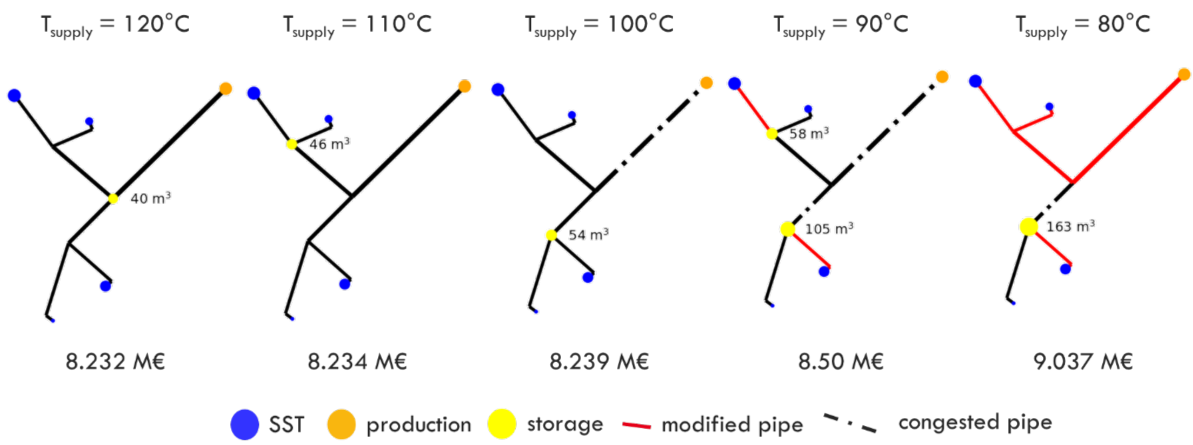

Figure 3. *Retrofit of the network according to the supply temperature reduction*

Hydraulic congestion appears on the network for a supply temperature of 100°C. Before, i.e. 120°C and 110°C, a storage is introduced in order to perform peak-shaving in order to favor the use of least expansives production units. The latter results in a storage of 38 m^3 (resp. 43) at 120°C (resp. 110°C). Between those cases, the volume difference is due to the temperature difference between the hot and cold storage, which decreases with the supply temperature. For both cases, the same energy is managed by the storage since the objective in this case is to optimize peak shaving. At 100°C, the storage remains sized for peak-shaving but also deals with hydraulic congestion in the main pipe. Storage is preferred over the replacement of pipes because it also provides peak shaving capabilities the rest of the year. This results specifically highlights the interest of distributed storage with respect of centralized storage. At 90°C, hydraulic congestion occurs in pipes downstream the potential storage, so the only solution to solve it in this zone is to replace the corresponding pipes. In addition, the storages installed are now much bigger than before, which means that they are sized for hydraulic congestion instead of peak-shaving. At 80°C, the hydraulic congestion is so important that it is either necessary or more beneficial to replace upstream pipes than adding more storage capacity. As shown in Figure 3, the corresponding costs are increasing with the supply temperature due to the investment in retrofit options. It was expected that reducing the operating temperature would lead to lower thermal losses, resulting in reduced heat production and thus economic savings. However, this is not observed in the present work, where the network size may be too small and the retrofit investment costs outweigh the heat loss savings.

Figure 4 represents the storage operation, the velocity in the main pipe (pipe 1 in Figure 2) and the heat production over the three representative days according to the supply temperature.

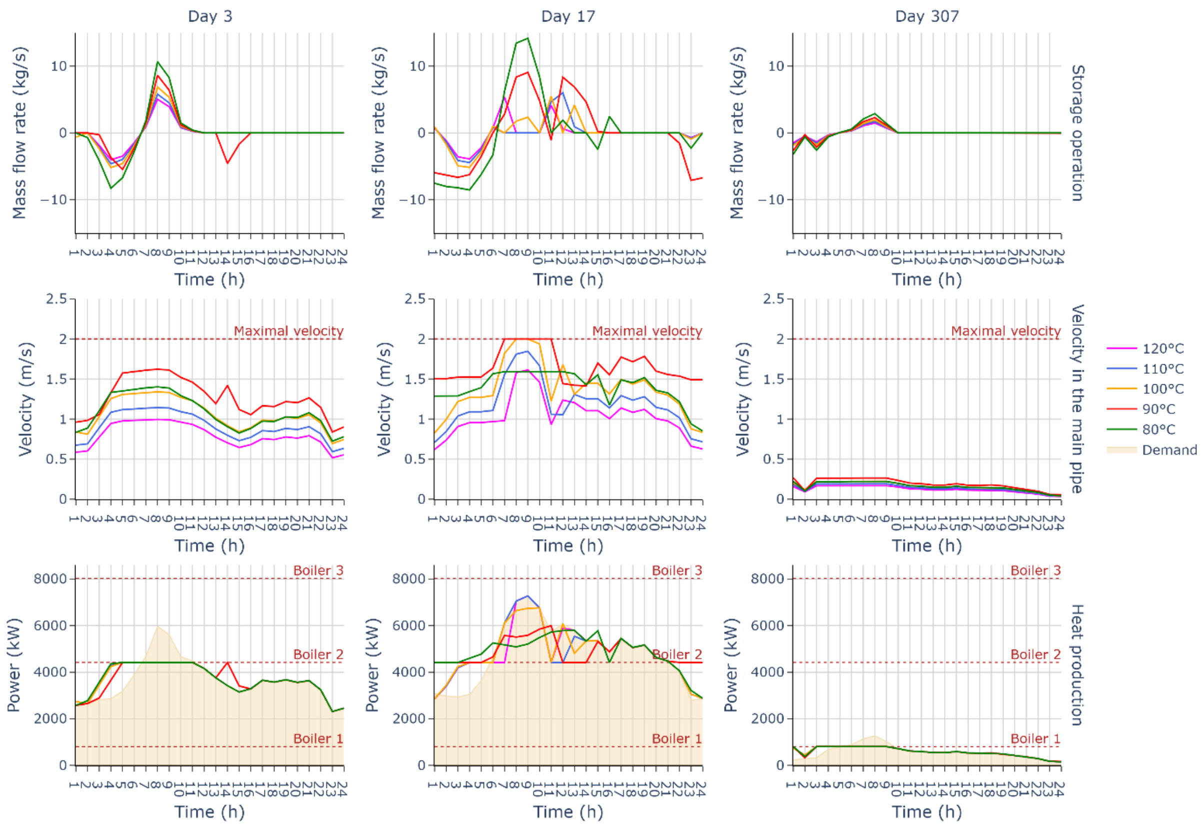

Figure 4. *Storage operation, velocity in the main pipe and heat production over the three representative days according to the supply temperature*

As shown on the first row, the storage mass flow rate increases as the supply temperature decreases. Indeed, the temperature difference is lower so to shift the same energy volume, the mass flow rate must increase. The plots in the second row confirm that the velocity in pipes rises as the supply temperature drops. As well, hydraulic congestion appears only on the day 17 which is the day with the higher demand. The third row compares the heat production with the demand. On the day 3 (resp. 307), peak shaving is performed in order not to avoid using the boiler 3 (resp. 2) whatever the supply temperature, On the day 17, the main goal is to reduce the heat required in the main pipe between 7 A.M. and 11 A.M. when the velocity exceeds 2 m/s. Thus, the storage is discharged at this time and charged before, during the night. After the congestion episode, there is some peak-shaving until 3 P.M.. At a supply temperature of 80°C, the velocity in the main pipe presents a threshold around 1.6 m/s that is lower than 2 m/s. Indeed, as observed in Figure 3, at this supply temperature, the main pipe is replaced with a larger diameter one and the congestion is only in one of its downstream pipes. So, the threshold observed corresponds to the limit of 2 m/s for the diameter of the downstream pipe.

4. Conclusion and further works

A previous work developed a MINLP optimization method for the location, the sizing and the operation of an existing district heating network facing hydraulic congestion due to the reduction of its supply temperature. The congestion was solved with the introduction of distributed storages. This work expands the previous method adding the option of replacing critical pipes with larger diameter ones. Distributed storages prove to be an attractive retrofit solution as they can also do some peak-shaving the rest of the year. When the hydraulic congestion is too significant, the storage volume to install cannot be made profitable over the year, the solution is then to replace critical pipes. Further work will focus on applying this method to a larger district heating network, closer to real-world application cases.

Data availability statement

All data used for this work are specified in the article.

Author contributions

Anne-Geneviève Lemelle: methodology, formal analysis, visualization, writing – original draft; **Nicolas Lamaison**: conceptualization, supervision, validation, writing – review & editing; **Nicolas Vasset**: conceptualization, supervision, validation, writing – review & editing; **Jean-Michel Reneaume**: conceptualization, supervision, validation, writing – review & editing; **Sylvain Serra**: conceptualization, supervision, validation, writing – review & editing

Competing interests

The authors declare that they have no competing interests.

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