

DISTRICT HEATING SYSTEM ANALYSIS AND DESIGN OPTIMIZATION

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ABSTRACT

District heating systems have a crucial role in promoting energy efficiency, reducing greenhouse gas emissions and fostering sustainable urban development, in applications related to space heating, water heating, and sometimes cooling purposes of a group of buildings. The analysis and, subsequently, the optimal design of a district heating network can be a challenging task due to its complexity; a number of parameters such as the distance and height between the nodes, the diameter of the pipes and heat consumption requirements may influence the efficiency of the system significantly. The purpose of this research paper is to present an algorithm for the analysis of district heating systems as well as its expansion, which aims to optimize the design of a district heating system, thus providing a useful tool to the system operator in terms of future investments and network expansion. The core of the developed algorithm is generalized and therefore applicable to any system, based on the Newton-Raphson method in order to calculate the pressure drops, the flow velocities and, as a result, the heat losses at the pipes. Furthermore, in pipe network systems it is important to maintain the flow velocity bound between a minimum and a maximum value in order to avoid phenomena such as noise, cavitation and excess heat losses. The selection of the diameter of the pipes could influence significantly the efficiency and the robust operation of the network. The district heating analysis algorithm is applied on a model of the system of Kungsbacka, Sweden, which is a demonstration site of ENFLATE, a Horizon Europe project related to the decarbonization and flexibility enhancement of the energy sector, and comprises centralized and decentralized production. According to the simulation results of the developed algorithm, the model has a good coherence with the measurements obtained from the demo. Finally, the significance of the design optimization algorithm and optimal diameter selection for the reduction of heat losses is demonstrated.

1 INTRODUCTION

The environmental footprint of the energy production that covers the thermal demand constitutes a growing concern and an open research and development field. When it comes to large scale systems, such as a community, district heating seems to be the predominant solution [1]. Such systems may be centralized, decentralized (with distributed energy production), include thermal storage or even be coupled with the electricity network [2]. In this context, their analysis, operation, planning and environmental assessment are topics of interest [3].

For example, Margaritis et al. [4] focus on the district heating systems of Kozani and Ptolemaida, Greece, which are mainly supported by lignite-fired stations. Due to the EU plans to increase RES penetration and reduce CO₂ emissions, the authors investigate alternative scenarios which include the incorporation of RES into the system and biomass mixtures containing wood chips and straws. Gungor et al. [5] present a district heating system based on exhaust gas produced from end-of-life tires. In this case, attention is paid on the thermoeconomic analysis, including specific exergy costing, and optimization of the power plant. Hiris et al. [6] model a district heating system using TRNSYS software. The authors study the effect of distributed supply units, including solar panels and seasonal storage, in

the operation of the system. Chen et al. [7] propose a topology optimization method for district heating systems, considering load uncertainty. According to the results, the algorithm contributes to both the planning of pipeline networks as well as the refurbishment of existing infrastructures.

The purpose of this research is to provide a detailed algorithm for the analysis of district heating systems, taking into consideration the topology, diameters, height differences, insulation thickness and other parameters. The result is the velocity and pressure drop at the pipes, as well as the subsequent heat losses. The proposed algorithm is tested on a model of an existing district heating system, located in Kungsbacka, Sweden, which is a demo site of ENFLATE, a Horizon Europe project. Furthermore, an expansion of this algorithm is proposed, the purpose of which is to optimize the system's architecture in terms of heat losses minimization, having the diameters of the pipes as decision variables. The optimization is based on the genetic algorithm and is able to select the combination with the least losses taking into consideration a discrete set of available diameters.

2 MATHEMATICAL MODELLING

In pipe network systems it is important to determine various parameters such as the velocity of the flow and the pressure drop at each pipe. It is critical to maintain the flow velocities in the system bounded between a minimum and a maximum value in order to avoid phenomena such as noise, cavitation and excess power losses. Furthermore, the pressure drop in every pipe should be calculated in order to obtain the mechanical losses of the network and to determine the required pumps for the smooth operation of the system.

In general, a pipe network system could be very complex and could have a large number of pipes and nodes. In addition, the consumption requirements (Q_d) at each node is a parameter that could affect significantly the operation of the network especially if it is dynamic with respect to time.

The district heating problem could easily be transformed in a flow network problem if the energy requirements at each node are interpreted as consumptions requirements. However, the heat losses of the network should be calculated in district heating problems since they could have a crucial effect on the efficiency of the system as a whole.

2.1 Generalized Solution of the Pipe Network Problem

The pressure drop in a pipe can be obtained from the following formula taking into account the major losses that are caused from the friction forces between the fluid and the pipe walls [8], [9]:

$$\Delta P = K \cdot \dot{V}^2 \quad (1)$$

where (ΔP) is the pressure drop, (\dot{V}) is the flow rate and

$$K = \frac{8 \cdot \rho \cdot L \cdot f_d}{\pi^2 \cdot D^5} \quad (2)$$

where (ρ) is the fluid density, (L) the length of the pipe, (D) the diameter of the pipe and (f_d) is the linear losses coefficient that can be approximated from the following formula [9]:

$$f_d = \left(\frac{1}{1.14 - 2 \log \left(\frac{\varepsilon}{D} \right)} + \frac{21.25}{Re^{0.9}} \right)^2 \quad (3)$$

Where (ε) is the roughness of the pipe surface and (Re) is the Reynolds that can be calculated from:

$$Re = \frac{4 \cdot \dot{V}}{\pi \cdot D \cdot \nu} \quad (4)$$

where (ν) is the kinematic viscosity of the fluid.

Therefore, from Eq.(1)-(4) the pressure drop for a given pipe and flow rate can be obtained, taking into account the major losses caused by the viscous forces between the fluid and the pipe walls.

Therefore, the flow between two nodes (i) and (j) can be obtained as follows:

$$\dot{V}_{ij} = \sqrt{\left(\frac{|P_i - P_j - \rho g \Delta h|}{K_{ij}}\right)} \quad (5)$$

where (\dot{V}_{ij}) is the flow rate at the pipe, (P_i) and (P_j) are the pressures at node (i) and (j) respectively, (g) is the acceleration of gravity, (Δh) is the height difference between node (i) and (j) and (K_{ij}) are the major losses of the pipe. From Eq.(5) it yields that:

- If $P_i - P_j - \rho g \Delta h > 0$ then flow is: $i \rightarrow j$
- If $P_i - P_j - \rho g \Delta h < 0$ then flow is: $j \rightarrow i$

The Jacobian of the Eq.(5) is:

$$\frac{\partial \dot{V}_{ij}}{\partial P_i} = \frac{1}{2} \cdot \frac{1}{\sqrt{K_{ij}}} \cdot \frac{1}{|P_i - P_j - \rho g \Delta h|^{1/2}} \quad (6.A)$$

$$\frac{\partial \dot{V}_{ij}}{\partial P_i} = -\frac{1}{2} \cdot \frac{1}{\sqrt{K_{ij}}} \cdot \frac{1}{|P_i - P_j - \rho g \Delta h|^{1/2}} \quad (6.B)$$

Since the pressure at each node of the system is not known the iterative process of the Newton-Raphson algorithm will be implemented, as the system is nonlinear. Initially, the pressures (\mathbf{P}_{old}) at each node of the network will be assumed. Then, from Eq.(1)-(5) the flow rate and its direction at each pipe will be calculated, while from Eq.(6) The Jacobian matrix (**JAC**) will be determined.

Therefore the sum (**F**), of the flow rates (\dot{V}_{ij}) and the consumption requirements (Q_d) can be calculated at each node.

However, at each node the mass conservation should be satisfied ($\mathbf{F} = 0$). Therefore, the new pressure at each node can be obtained from:

$$\mathbf{F} + \mathbf{JAC} \cdot \mathbf{DP} = \mathbf{0} \quad (7.A)$$

$$\mathbf{P}_{new} = \mathbf{P}_{old} + \mathbf{DP} \quad (7.B)$$

Eq.(7.A) is linear and can be easily solved with the Gauss algorithm. The new pressure at each node will become the next assumption and the process will be repeated until convergence is reached ($\mathbf{DP} < \mathbf{error}$). The process can be summarized in the flowchart presented in Figure 1.

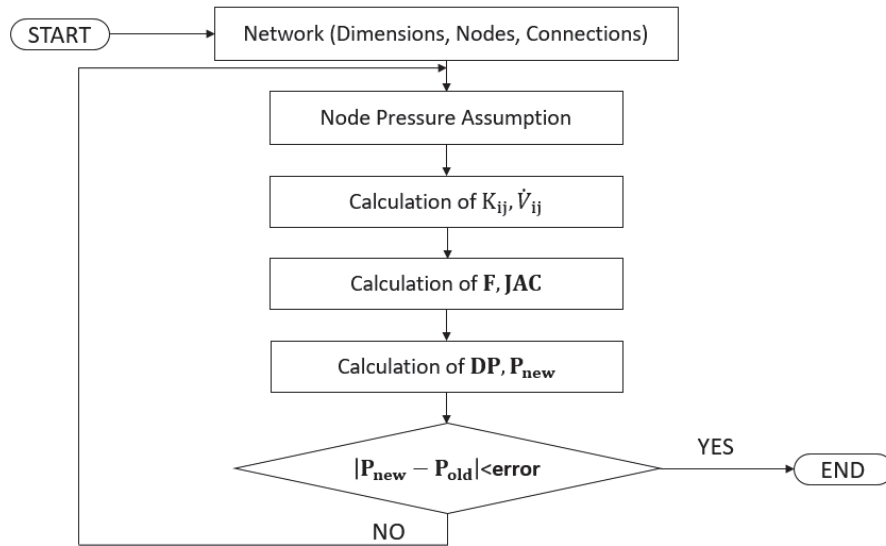


Figure 1: Newton-Raphson Algorithm.

Therefore, for a given pipe network, the flow rates and as consequence the flow velocity (v_{ij}) at each pipe can be calculated:

$$v_{ij} = \frac{4\dot{V}_{ij}}{\pi D_{ij}^2} \quad (8)$$

As stated earlier, it is important to keep the flow velocity bounded between a minimum (v_{\min}) and a maximum (v_{\max}) velocity. If the flow velocity at any given pipe is out of bounds then the diameter of that pipe should be altered according to the flowchart presented in Figure 2.

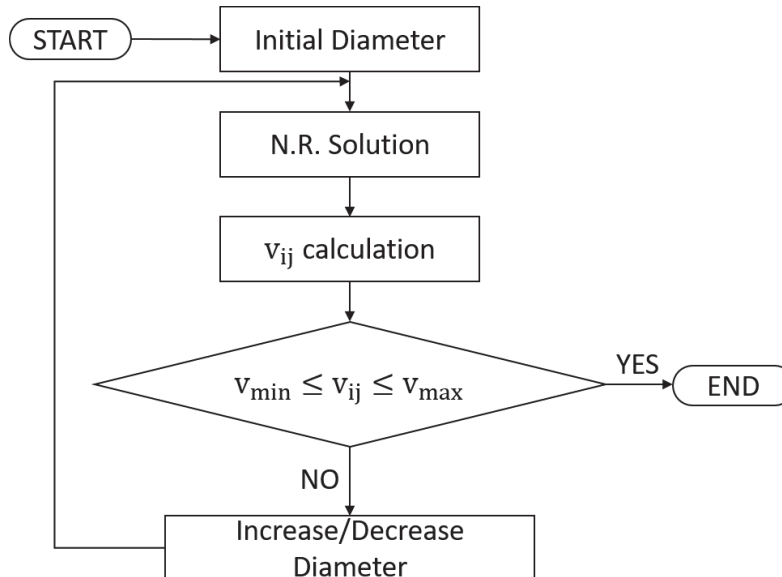


Figure 2: Flow velocity check Algorithm.

Furthermore, the pressure at every node and as a result the pressure drop at every pipe can be calculated. As a result, the mechanical losses ($W_{ij,loss}$) at each pipe can be calculated from:

$$W_{ij,loss} = |\dot{V}_{ij} \cdot (P_i - P_j)| \quad (9)$$

It should be noted that only major losses due to viscous forces between the fluid and the pipe walls and gravitational forces are considered. The model could be expanded with the inclusion of minor losses.

An algorithm based on the described methodology and the flowchart presented in Figure 1 was developed in MATLAB environment.

2.2 Temperature Profile and Heat Losses

The temperature profile of a fluid flowing through a uniform temperature pipe can be obtained from [10]. Therefore, for each pipe of the network the temperature profile ($T_{ij}(x)$) is calculated from:

$$T_{ij}(x) = T_{p,ij} + (T_{in} - T_{p,ij})e^{-\frac{\pi \cdot D \cdot h}{\rho \cdot C_p \cdot \dot{V}}x} \quad (10)$$

where (T_{in}) is the inlet temperature of the fluid, ($T_{p,ij}$) is the inner wall temperature of each pipe, (C_p) is the thermal capacity of the fluid and (h) is the thermal convection coefficient that can be obtain from [10]:

$$h = \frac{k \cdot Nu}{D} \quad (11)$$

where (k) is the thermal conductivity of the fluid and (Nu) is the Nusselt number that can be approximated from [10]:

$$Nu = 3.66 + \frac{0.065 \cdot \frac{D}{L} \cdot Re \cdot Pr}{1 + \left(0.04 \cdot \frac{D}{L} \cdot Re \cdot Pr\right)^{2/3}} \quad (12)$$

where (Pr) is the Prandtl number of the fluid.

Therefore, the heat loss in the pipe can be calculated from:

$$Q_{ij,loss} = \rho \cdot \dot{V}_{ij} \cdot C_p \cdot (T_{in} - T_{ij}(L_{ij})) \quad (13)$$

where ($Q_{ij,loss}$) is the heat loss at the pipe and ($T_{ij}(L_{ij})$) is the temperature of the fluid at the end of the pipe that can obtained from Eq.(10).

An important parameter that have not been introduced yet, is the inner wall temperature of each pipe. Assuming, that the temperature of the pipe has reached its steady state, then the heat losses calculated from Eq.(13) should be equal to the heat losses from the pipe to the ground.

Therefore, considering the annular geometry of the pipe the heat losses should also be equal to [10]:

$$Q_{ij,loss} = 2\pi \cdot L_{ij} \cdot k_w \frac{T_{p,ij} - T_{gr}}{\ln\left(\frac{D_{ij,out}}{D_{ij}}\right)} \quad (14)$$

where (k_w) is the thermal conductivity of the insulation of pipe, (T_{gr}) is the ground temperature and ($D_{ij,out}$) is the outer diameter of the pipe. Eq.(14) could be expanded accordingly if additional layers of insulation are present.

From Eq.(10)-(14) the heat losses at each pipe can be determined.

Therefore, the total mechanical losses (W_{loss}), the total heat losses (Q_{loss}) and as a result the total network energy losses (E_{loss}) can be obtained from:

$$W_{loss} = \sum W_{ij,loss} \quad (15.A)$$

$$Q_{loss} = \sum Q_{ij,loss} \quad (15.B)$$

$$E_{loss} = W_{loss} + Q_{loss} \quad (15.C)$$

2.3 Diameter Optimization for Total Network Loss Reduction

The optimization of a district heating network so that it would reduce its total losses could be very beneficial to the industry and could result to energy and cost savings.

An important parameter, whose influence on the total network losses will be investigated in the present work, is the selection of the diameters of the pipes. However, certain parameters should also be considered besides the optimization of the total network losses as obtained from Eq.(15.C). The flow velocity should continue to be bounded between the determined minimum and maximum value at each pipe. Furthermore, since pipes are manufactured in specific diameters the selection of the diameters will be limited to the selection of an appropriate diameter from a given pipe set (\mathbf{D}_p).

The optimization problem described above is a complex problem due to the discrete nature of the pipe set (\mathbf{D}_p). In fact the problem is a NP-complete problem since it is an integer non-linear programming problem (INLP problem). The integer part of the problem arises from the fact that the optimal selection of the diameter of the pipes could be interpreted as the optimal selection of position of the diameter in the pipe set (\mathbf{D}_p). The non-linearity of the problem arises from the fact that the objective function Eq.(15.C) of the problem (total network losses) is non-linear as shown from Eq.(1)-(15). Furthermore, the constraints of the problem (bounded flow velocity) are non-linear since they are also obtained from Eq.(1)-(8). The genetic algorithm will be used in order to minimize the objective function.

The problem becomes exponentially harder in terms of computational time, as total number of pipes and nodes increases. In order to reduce the required computational time, an initial selection of the diameters of the pipes will be obtained according to the methodology described in the flowchart presented in Figure 2. Then, a search bandwidth (s) will be applied in order to restrict the possible selection choices of each pipe in the genetic algorithm. Therefore, each pipe diameter selection will be limited to the initial diameter and (s) positions lower and higher on the (\mathbf{D}_p) set. In this way the genetic algorithm can be restricted from investigating intuitively wrong configurations (i.e. small diameters in the first pipes of the network). This is a crucial parameter, since it is expected that a significant number of diameter choices will fail to meet the velocity constraints (on at least one pipe) especially if the constraints are close to each other, or if the diameters of the pipes in the available pipe set (\mathbf{D}_p) have a relatively large step. As a consequence, it is more likely to obtain an adequate number of solutions with a small population size of the genetic algorithm thus maintaining the computational time relatively low.

3 RESULTS AND DISCUSSION OF ESTABLISHED NETWORK

The Kungsbacka district heating network located in Sweden, has been used in order to validate the developed model. A simplified version of the network is presented in Figure 3. The system comprises a central source as well as distributed production for self-consumption and thermal energy storage units. Its topology includes loops and branches that connect twenty areas. This system, which is a demo site of the ENFLATE project, shall be coupled with the electricity network within the next years. Therefore, its operation and planning analysis is an issue of importance for the operator.

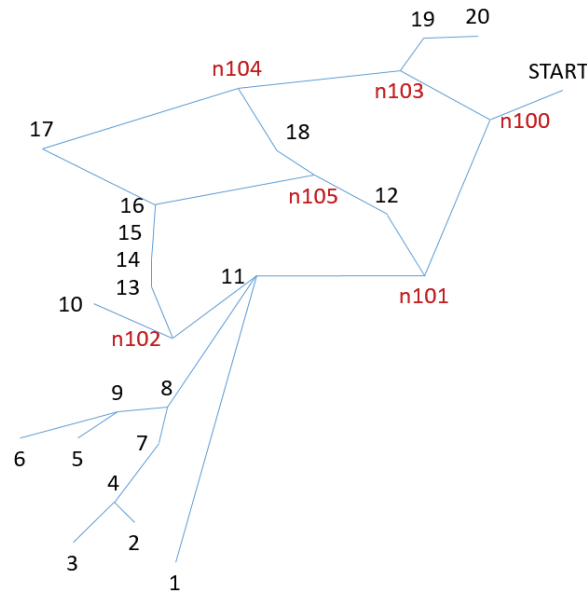


Figure 3: Kungsbacka district heating network.

In Table 1 some additional information regarding the heat requirements of each node and a result the required flow rates are presented. In the Kungsbacka region the height difference between each node is not significant and therefore not taken into consideration.

Table 1: Node Information.

Node	Map	Heat (MWh)	$Q_d(m^3/h)$
1	START	0	0
2	n100	0	0
3	n101	0	0
4	n103	0	0
5	19	481	9.71
6	20	60.1	1.21
7	n104	0	0.00
8	18	817	16.50
9	17	443	8.95
10	12	410.6	8.29
11	11	329.7	6.66
12	n105	0	0
13	n102	0	0
14	13-16	139.7	2.82
15	10	27.5	0.56
16	1	42.4	0.86
17	8	465.8	9.41
18	9	163	3.29
19	7	91	1.84
20	5	44.8	0.90

21	6	40	0.81
22	4	17.8	0.36
23	3	51.5	1.04
24	2	14.9	0.30

It can be observed that a total number of 26 pipe lines are present therefore the linear system that will be constructed in order to calculate the pressure at each node and the flow velocity at each pipe will have 26 equations and 26 variables (the pressure at each node). The diameter and length of each pipe are presented in Table 2. At each pipe an insulation thickness of 15% of the nominal diameter with a thermal conductivity of $k_w = 0.05 \frac{W}{mK}$ is considered.

After the convergence of the Newton-Raphson algorithm the temperature profile and as a consequence the heat losses at each pipe will be calculated.

The results regarding the flow velocity, the pressure drop and the heat losses at each pipe are also presented in Table 2.

Table 2: Network Parameters and Results.

From	To	Length (m)	Diameter (mm)	v(m/s)	DP (bar)	Q _{loss} (kW)
START	n100	10	145.8	1.22	0.017	1.61
n100	n101	300	113.2	0.96	0.205	47.16
n100	n103	150	113.2	1.07	0.158	23.74
n103	19	30	70	0.79	0.015	4.95
19	20	20	30	0.48	0.009	3.35
n103	n104	150	113.2	0.77	0.083	23.96
n104	18	50	113.2	0.52	0.020	8.13
n104	17	70	50	1.24	0.249	11.50
n101	12	60	70	0.54	0.148	9.89
n101	11	180	113.2	0.75	0.179	28.60
11	n102	30	30	0.73	0.107	4.97
12	n105	40	30	0.32	0.036	6.66
n105	18	30	50	0.35	0.056	4.98
n105	13-16	100	30	0.67	0.254	16.58
13-16	17	70	20	0.16	0.081	11.66
n102	13-16	40	30	0.51	0.079	6.63
n102	10	50	30	0.22	0.078	8.30
11	1	250	30	0.34	0.139	41.31
11	8	70	50	1.30	0.211	11.31
8	9	20	50	0.71	0.123	3.30
9	6	20	30	0.32	0.085	3.31
9	5	20	30	0.36	0.049	3.31
8	7	30	30	1.39	0.020	4.95
7	4	40	30	0.67	0.230	6.61
4	3	40	30	0.41	0.113	6.61
4	2	20	20	0.27	0.087	3.31

It can be observed that the flow velocity in all the pipes is lower than 1.5 m/s. Therefore, the network is inherently protected against phenomena such as noise and cavitation, since the flow velocity is within the recommended limits [8]. Furthermore, it can be observed that the pressure drops at each line are

relatively small and as a result the mechanical losses due to friction and gravitational forces are low. The total mechanical losses in the network are $W_{\text{loss}} = 0.88 \text{ kW}$, while the total heat losses in the network are significant and equal to $Q_{\text{loss}} = 306.71 \text{ kW}$.

From Table 1, it can be observed that the total heat requirements of the plant are $Q_{\text{req}} = 1011 \text{ kW}$. Therefore, the total losses of the network are 23.3%, a value that is in good coherence with measurements in the district heating plant.

Furthermore, in Figure 4 the pressure drop at each node as calculated from the Newton-Raphson method is presented.. It can be observed that the maximum drop is almost equal to 1 bar.

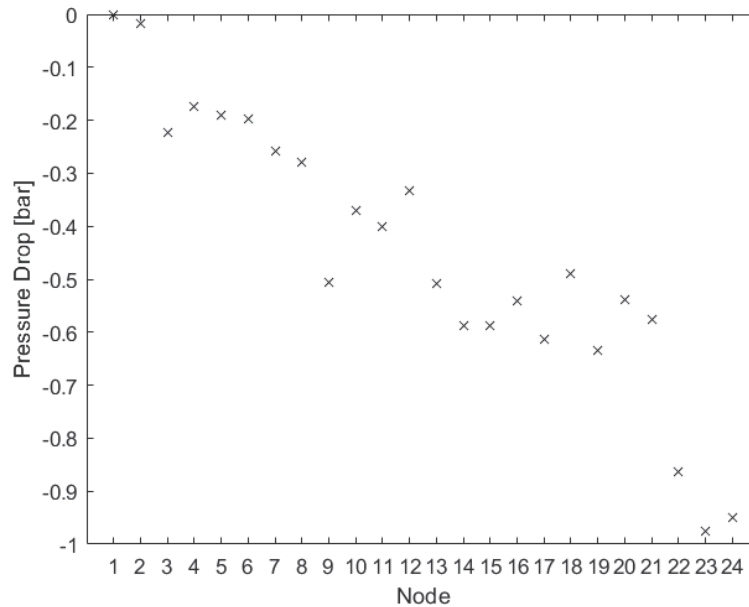


Figure 4: Pressure drop at each node.

4 NETWORK OPTIMIZATION

The diameters of the pipes have a crucial role on the linear losses of as shown from Eq.(2) and therefore the pressures and the flow velocities are greatly affected by their selection. Furthermore, the flow velocity is a critical parameter in the heat losses between the fluid and the ground as shown from Eq.(10)-(14). Moreover, the selection of the diameters affects the initial capital cost (pipe and insulation cost). In addition, since lower diameters yield higher flow velocities, the network could experience deterioration due to phenomena such as cavitation. Therefore, the operational cost could be increased due to more frequent maintenance demands. All of the above parameters, share a common factor namely the diameter of the pipe. Thus, the appropriate selection of the diameter of the pipes (which is not a restrictive parameter such as length of the pipe and height difference) is the most important parameter to be considered when designing a district heating network.

For that reason, a possible optimization of the network (theoretically as the network is already operational) will be investigated. The objective function will be the total network losses as calculated from Eq.(1)-(15). In the objective function the initial capital cost and the maintenance cost of the network could also be taken into account, providing a more thorough optimization investigation in financial terms. However, in the present work it was deemed appropriate to include only the total network losses to demonstrate the importance of the selection of the diameters of the pipes. Similarly to the initial network the maximum flow velocity was constrained to be lower than 1.5 m/s. The diameters that could be selected were given by a predetermined pipe set D_p . The pipe set that was considered is the following:

$D_p = [10\ 15\ 20\ 25\ 30\ 40\ 50\ 60\ 70\ 85\ 100\ 113.2\ 129.6\ 145.8\ 161.6\ 181.8]$

The optimization method implemented was the genetic algorithm in MATLAB environment. The parameters of the genetic algorithm are presented in Table 3. In addition, in order to maintain a low computational cost the search parameter was limited to $s = 2$.

Table 3: Genetic Algorithm parameters.

Parameter	Value
Population Size	50
Maximum Generations	100
Elite Count	5

In Table 4, the optimal diameters are presented. In addition, the flow velocity at each pipe and the heat losses are shown and compared to the initial values of the network.

Table 4: Optimized Network.

From	To	Initial Diameter (mm)	Initial v (m/s)	Initial Q_{loss} (kW)	Optimal Diameter (mm)	Optimal v (m/s)	Optimal Q_{loss} (kW)
START	n100	145.8	1.22	1.61	161.6	1.00	1.54
n100	n101	113.2	0.96	47.16	145.8	0.68	45.01
n100	n103	113.2	1.07	23.74	145.8	0.54	23.01
n103	19	70	0.79	4.95	85	0.53	4.76
19	20	30	0.48	3.35	50	0.17	3.21
n103	n104	113.2	0.77	23.96	100	0.76	23.24
n104	18	113.2	0.52	8.13	85	0.65	7.86
n104	17	50	1.24	11.50	60	0.80	11.06
n101	12	70	0.54	9.89	100	0.42	9.45
n101	11	113.2	0.75	28.60	145.8	0.49	27.45
11	n102	30	0.73	4.97	50	0.56	4.76
12	n105	30	0.32	6.66	50	0.49	6.37
n105	18	50	0.35	4.98	50	0.46	4.78
n105	13-16	30	0.67	16.58	20	0.21	15.98
13-16	17	20	0.16	11.66	30	0.31	11.18
n102	13-16	30	0.51	6.63	50	0.48	6.35
n102	10	30	0.22	8.30	30	0.22	7.97
11	1	30	0.34	41.31	40	0.19	39.69
11	8	70	1.30	11.31	100	0.63	10.88
8	9	50	0.71	3.30	70	0.36	3.17
9	6	30	0.32	3.31	20	0.71	3.18
9	5	30	0.36	3.31	20	0.80	3.18
8	7	30	1.39	4.95	30	1.39	4.76
7	4	30	0.67	6.61	50	0.24	6.35
4	3	30	0.41	6.61	50	0.15	6.35
4	2	20	0.27	3.31	30	0.12	3.18

The total heat losses of the optimized network are $Q_{loss} = 294.75$ kW and therefore the heat losses are reduced up to 3.9%, which is a value that illustrates that the diameter selection could be an important

factor for the reduction of the total network losses. In all pipes the heat losses have been decreased, however it can be observed that in most cases the diameters of the pipes have been increased. In the present work only heat losses have been considered in the optimization of the network. Additional parameters such as the initial cost of the pipes and their insulation could also be incorporated to the objective function that could affect the optimal design [11]. Therefore, the alternative design proposed to the already operational network in Kungsbacka could be explained due to a different objective function selection. Furthermore, it can be observed that that all flow velocities are lower than 1.5 m/s and thus the constraints are satisfied. In future work, it would be important to investigate the performance and efficiency of the network in quasi-dynamic heat requirements, since the present model had only taken into account the heat requirements of a typical winter time step. In addition, a generalized objective function that would include the present numerical model for the calculation of the network heat losses and other parameters such as the initial and operational costs could be developed in order to provide a valuable tool for the optimal design of district heating networks.

5 CONCLUSIONS

In the present work, a model for the analysis of district heating systems has been developed based on the Newton-Raphson method. As a result, important parameters such as the pressure drops, the flow velocities and the heat losses at the pipes can be calculated. A simulation of the district heating system located in Kungsbacka Sweden, which is a demonstration site of ENFLATE, a Horizon Europe project, was carried out. According to the simulation results, the model has a good coherence with the measurements obtained from the plant. Furthermore, an optimization process for the reduction of the total heat losses of the network is proposed. An important decision variable is the selection of the diameters of the pipes. However, certain constraints should also be considered besides the optimization of the total network losses. The flow velocity at each pipe should be bounded between a minimum and maximum value in order to avoid phenomena such as noise and cavitation. Furthermore, since pipes are manufactured in specific diameters the selection of the diameters will be limited to the selection of an appropriate diameter from a discrete pipe set. The optimization problem was solved implementing the genetic algorithm. The derived optimized network had almost a 4% reduction of the total network losses, a result that illustrates the effect that the diameter selection has on the efficiency of the network. The proposed optimization process should be further enhanced by taking into account additional parameters that the selection of the diameters of the pipes affect, such as the initial capital cost and the maintenance cost in order to obtain the optimal district heating network design. Therefore, with the proposed method an optimization of district heating networks could be achieved leading to higher efficiencies and energy savings.

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ACKNOWLEDGEMENT

This research has received funding from the European Union’s project ENabling FLExibility provision by all Actors and sectors through markets and digital TEchnologies (ENFLATE), Grant Agreement ID: 101075783. The authors would like to thank EKSTA Bostäder AB and particularly Mr. Christer Kilersjö for his kind contribution.