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Selecting optimal pipeline diameters for a district heating network comprising branches and rings, using graph theory and cost minimization

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Abstract

Choosing the right pipeline diameter is essential for both newly designed district heating (DH) networks and existing ones undergoing upgrades. A multi-stage optimization algorithm was developed for the purpose of selecting optimal diameters of pipelines in a DH network that has a complex layout including branches and rings. The DH network was represented as a set of graphs and then as matrices, which made hydraulic and heat-and-flow calculations possible for any network layout. The optimization algorithm was developed as a Visual Basic program consisting of 37 macros. The program considers hydraulic resistances, heat-balance equations, capital expenditure for DH pipelines of 32 to 1,100 mm in diameter, and the operating cost, including the costs of heat transmission losses and DH water pumping. Microsoft Excel's Solver tool was used to solve the non-linear optimization algorithm with constraints. To provide an example of the program's application, the paper includes calculations used to verify the correctness of selected diameters for part of an existing DH network in a large DH system in Poland.

Keywords: District heating networks; heat cost; optimum pipe diameter; graph theory

1. Introduction

In many countries, the heat demand of large agglomerations is met through heat generation plants and combined heat and power plants (CHP) [1–3]. The heat from a CHP (the producer) is supplied through district heating (DH) networks to consumers. The use of primary fuel for both electricity and heat generation in a CHP translates into higher efficiency of energy conversion and significant energy savings, which can be expressed by indices such as primary energy savings (PES) [4]. CHPs are most often hard coal and gas fired but they also increasingly burn alternative fuels such as biomass [5–7] and domestic waste [8]. Solar [9, 10] and geothermal energy [11, 12] is also used to power CHPs, which contributes to reducing the emissions that are harmful to the environment [1]. Papers discussing the advantages of supplying co-generated heat to consumers through DH networks include [13]. A number of papers can be found that propose optimizing DH system performance through focusing on various cost criteria: using a MATLAB program to reduce the costs of pumping and heat losses [14]; using a simplex method to minimize cost [15–17]; minimizing environmental impact of a DH system [18]; minimizing operating cost [19] by considering the temperatures required by consumers. Models have been developed to determine how to connect new DH consumers with the minimum of infrastructure modification and at minimum operating cost [20].

In Poland, DH systems meet the heat demand of over 40% of inhabitants. The total length of pipelines in these systems is almost 20,000 km, with the Warsaw system accounting for 1,700 km of this.

To a large extent, DH systems satisfy heat demand in many countries, which is why good design is a key issue. They should be designed in such a way that the price of the heat supplied is competitive with that of the heat supplied from other sources and that consumers are encouraged to connect to the DH system. A number of important factors should be considered by DH system designers. One crucial issue is selecting the location of a heat source to ensure that it is not too far away from consumers. Recently, genetic algorithms have been applied to assess the heat source location [21].

The design of a DH network, which is an important component of any DH system, should consider a number of key issues, such as: fluid flow resistances (pressure drops) across pipelines [3, 14, 22–26], heat losses in pipelines [14, 27–31], DH water velocity in pipelines [15, 29, 31], thickness of pipeline insulation [27, 32–34], and water temperatures

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at feed and return connections at consumers and at the heat source [3, 19, 35–37]. In addition to thermodynamic and technical circumstances and constraints, DH network designers should also take account of some essential economic aspects, i.e. capital expenditure (the construction cost) and the operating cost of the DH network, with the capital expenditure depending mainly on the length and diameter of pipelines [38, 39]. Various types of models have been established to ensure good design and multi-criteria optimization of a DH network: linear [40] and non-linear models [41, 42] and recently models based on genetic algorithms [39, 43] and artificial neural networks [44].

For a single section of a DH network, fixed cost (capital expenditure incurred for the network construction, operation and service) and the cost of heat losses are approximately linearly related to the pipeline diameter, whereas the relation of the pumping cost to the diameter is hyperbolic. Therefore, the plot of heat transmission cost as a function of the diameter is non-linear. For a network comprising branches and rings, a change in pipeline diameter is followed by changes in fixed cost and the cost of heat losses, whereas the pumping cost depends on the heat source pressure and the required differential pressure at consumers' heating substations. Oversizing pipelines in the DH network translates into a higher fixed cost, higher heat losses due to the larger heat transfer area, and lower pressure drops in the pipelines. On the other hand, however, using overly small diameters reduces the fixed cost and the cost of heat losses but it can have an adverse effect on service quality in the form of inadequate differential pressures at consumers' heating substations. This clearly shows the importance of determining the appropriate pipeline diameter for the whole DH network.

Selecting the right pipeline diameter is especially important in the case of old DH systems, which are usually oversized, in poor technical condition [24] and should have their pipelines replaced.

The simplest method of evaluating the right pipeline diameters is pressure loss per unit length or target pressure loss (TPL) [23–26] which considers maximum velocities of fluid in pipelines. A second method determines optimal pipeline diameters through minimizing heat transmission cost while taking account of thermodynamic and technical constraints [22, 24, 30, 31].

The issue of choosing the pipe diameter is also encountered with surface-type heat exchangers, such as condensers and regenerative heaters, where economic or thermodynamic criteria are applied [45–49].

Although picking the right pipeline diameter is a key issue linked with large expenditure and thus possible savings, only a few publications and papers can be found on determining the optimal pipeline diameter for DH networks. They include papers [22, 24, 31, 50] in which optimal inner diameters for a DH network were obtained using an objective function, factoring in heat distribution cost. Commercial programs, such as Termis, are also used to calculate optimal inner pipeline diameters [30].

Networks in some systems have a branched layout, while in others they contain both branches and rings. The sections which close parts of the network to form a ring require more capital expenditure for the network, but they significantly increase the reliability of heat delivery to consumers and limit the consequences of network failures. The issue of choosing the right pipeline diameter for the DH network is essential for any heat transmission and distribution company. To satisfy such demands, the authors developed a method for diameter optimization for a complex network comprising branches and rings, a layout used in a number of DH systems in Poland and elsewhere in Europe.

In a numerical sense, it is an optimization problem with equality and inequality constraints. Due to technical conditions, the hydraulic resistances, heat losses and DH water flow rates in all sections of the DH network have to be established. Graph theory was applied so that these calculations could be performed automatically. The DH network was represented as a set of graphs and then written as three matrices: incidence matrix, circuit matrix and cycle matrix. Microsoft Excel's Solver tool was used to solve the non-linear optimization algorithm with constraints; the program was a set of 37 Visual Basic macros which combined heat-balance calculations with optimization calculations considering capital and operating costs for a complex layout DH network. This approach, combining hydraulic and heat-balance calculations, graph properties and an optimization problem with constraints for a complex network comprising branches and rings, is a practical solution to an important issue concerning optimization of the construction and operation of present and future DH systems in Europe [51]. It is important to note that, in the first phase of the proposed optimization model, diameters are determined according to the algorithm without constraints, excluding those sections which close the rings. The essential optimization is carried out in the second and third phases. Here, it is possible to optimize all or only selected sections of the network. In the fourth phase, diameters of connections (final sections at heating substations) are additionally verified. Thus, it is an original effective optimization algorithm, validated with a number of variants of DH network structure.

2. Optimization criterion

To select the optimal pipeline diameter for a DH network with a complex layout, comprising branches and rings, the total heat transmission cost, including annual network construction and operating costs, is taken into account. The selection criterion for such layouts is the minimum total heat transmission cost, which is the sum of the annual construction and annual operating costs for all sections of the DH network under consideration. Meeting this criterion means achieving the minimum heat transmission cost per unit heat, equal to the ratio of the annual total (fixed and operating) costs and annual heat sales, discounted for n years of network operation [52, 53].

A set of optimal pipeline diameters for a DH network is a set of diameters selected from a range that corresponds to

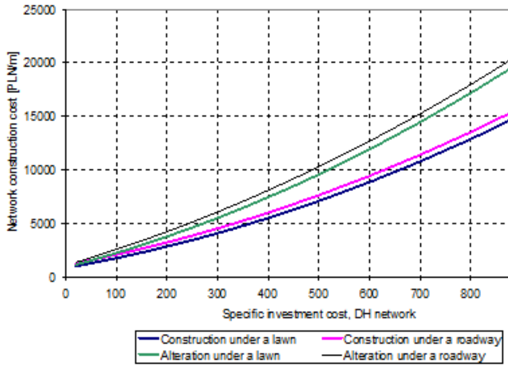

Figure 1: Capital expenditure per meter of pipeline for the construction of sections of a DH network

the minimum heat transmission cost according to the equation 1.

$$k_q = \frac{\sum_{t=1}^{n} K_t \cdot a_t}{\sum_{t=1}^{n} A_t \cdot a_t} \implies min \quad (1)$$

The annual DH system operating cost K comprises: annual capital expenditure (depreciation) for the network K_A, annual financial cost (loan repayment) for the network K_F, annual operating cost (excluding depreciation and financial cost) K_O, annual cost of DH water pumping K_P, and annual cost of network heat losses K_S.

The cost K in one year of DH system operation can be calculated from the equation 2.

$$K = K_A + K_F + K_O + K_P + K_S \quad (2)$$

The annual cost K_A mainly depends on capital expenditure for the network, which in turn is dependent to a great extent on the diameters of each pipeline fragment.

$$K_A = s \cdot I_O; \quad I_O = \sum_{t=0}^{T_b} \sum_{n=1}^{W_S} j_{Di} \cdot L_{Di} \cdot a_t \quad (3)$$

Capital expenditure per pipeline section was considered as related to the nominal diameter and the network construction location. The relation j_{Di} (DN) used in the present paper, based on the analysis of costs incurred in the construction of new sections and replacing old ones in the course of upgrade works in Poland, is shown in Fig. 1.

The annual average financial cost (loan repayment) for the network depends on the required capital expenditure (4).

$$K_F = I \cdot (1 - u_k) \cdot [\frac{i \cdot (1+i)^n}{(1+i)^n - 1} - s] \quad (4)$$

The annual operating cost excluding depreciation and financial cost, is mainly a function of capital costs (5).

$$K_O = e \cdot I \quad (5)$$

The annual cost of DH water pumping varies with the DH water flow rate, head and efficiency of DH water pumps; the cost was evaluated for average values of these parameters in the heating season (Δp_s) and in the summer period (Δp_l).

$$K_P = (\frac{G_{SS} \cdot \Delta p_S \cdot \tau_S}{\rho_S \cdot \eta_p} + \frac{G_{SL} \cdot \Delta p_L \cdot \tau_L}{\rho_L \cdot \eta_p}) \cdot c_e \cdot 10^{-3} \quad (6)$$

Losses Δp_s, Δp_l are a function of differential pressure losses across pipeline sections at heating substations. Pressure loss across a pipeline section is defined as the sum of pressure losses due to friction and local losses determined from the equation 7.

$$\Delta p = (\lambda \frac{L}{d} + \Sigma \xi) \frac{w^2 \rho}{2} \quad (7)$$

The friction factor is calculated from the Colebrook-White equation (8).

$$\frac{1}{\sqrt{\lambda}} = -2log(\frac{2,51}{Re \cdot \sqrt{\lambda}} + \frac{k}{3,71 \cdot d}) \quad (8)$$

The annual cost of heat losses depends on the pipeline diameter and the insulation thickness, and for pre-insulated pipelines with standard insulation thickness it can be calculated from the equation (9).

$$K_S = ((q_{ZS} + q_{PS}) \cdot \tau_S + (q_{ZL} + q_{PL}) \cdot \tau_L) \\ L \cdot b \cdot c_q \cdot 3,6 \cdot 10^{-6} \quad (9)$$

Average heat losses of a new network comprising pre-insulated feed and return pipelines of a given diameter in the heating season per unit length (q_{ZS}, q_{PS}) and in the summer period (q_{ZL}, q_{PL}) was calculated according to [54].

Criterion (1) is relevant to both complex and simple DH network layouts, i.e., single sections of a network. For DH network layouts comprising branches and rings, criterion (1) must be met with the following four constraints (10) to (13) satisfied at the same time:

• the maximum allowable pressure in the DH network, occurring normally at the heat source outlet, must not be exceeded (10);

• the minimum required differential pressure at all heating substations is ensured (11);

• the sums of pressure drops in closed rings of the network are equal to zero (12);

• flows in branches of the network are balanced according to the law of mass conservation (13).

$$P_{CHP_{zi}} = P_{CHP_p} + \Delta p_{zi} + \Delta p_{di} + \Delta p_{pi} \leq p_{max} \\ dla\, i = 1, 2, \ldots, W_W \quad (10)$$

$$\Delta p_{di} \geq \Delta p_{di\,min} \quad dla\, i = 1, 2, \ldots, W_W \quad (11)$$

$$\sum_{j=1}^{ni} \Delta p_j^i = 0 \quad dla\;\; i = 1, 2, \ldots, S \quad (12)$$

$$\sum_{j=1}^{ni} sign_j^i \cdot G_j^i = 0 \quad dla\, i = 1, 2, \ldots, W_R \quad (13)$$

The proposed process of network optimization according to criterion (1) with constraints (9) to (13) is a non-linear programming problem. Due to the complexity of the optimization problem, the numerical process has a number of stages [52]. Its implementation, considering the mathematical representation and the nature of the DH network layout, is shown in Fig. 2, and described in detail further on in the paper.

3. The model of the real network layout and its representation in the algorithm

The graph method was used to represent and analyze the complex structure of a real DH network comprising branches and rings [55]. This representation includes basic components of the DH system which work together with the DH network considered: heat sources and heating substations. A graph contains points, called vertices, and network sections between the points, called arcs [55]. A vertex is any point where a section of the DH network starts, forms a branch, or ends; thus, vertices represent heat sources, branches of the network, and heating substations. Vertices are designated with the letter W and a number between 0 and the total number of vertices less 1. The vertex W0 is always a heat source, such as a combined heat and power plant (CHP) or a heat generation plant (HOP). There are also vertices representing heating substations (W_W) and branches (W_R). Thus, the number of all the vertices in the graph can be given as:

$$W = W_{CHP} + W_W + W_R \tag{14}$$

Arcs are sections of the DH network between the vertices. A single arc represents a pair of lines: the supply line and the return line. Arcs are designated with the letter U and a number between 1 and the total number of arcs. The following types of arcs are distinguished: source arc (the main line from the heat source) U_{CHP}, ring arc U_P, substation arc (a connection ending at the heating substation) U_W, and any other ordinary section of the network U_S. As with vertices, the total number of arcs in the system can be given as:

$$U = U_{CHP} + U_P + U_W + U_S \tag{15}$$

A closed ring of a part of the network, comprising several arcs (forming a ring), is called a cycle. Cycles are designated with the letter S and a number starting from 1. According to Euler's law [55], the number of cycles is:

$$S = U - W + 1 \tag{16}$$

If $U = W{-}1$, then $S = 0$. Such a system contains no cycles, so its network has a branched layout.

A numerical representation of the DH network graphs is provided by three matrices: A, B and C. They serve as a mathematical representation of the network structure and other information relevant to calculations in the optimization algorithm, the results of which are used in subsequent stages of the optimization. The first matrix is incidence matrix A. Its columns contain all arcs U, while its rows contain all vertices W.

$$A = [a_{ij}] \quad for\, i \in W, \quad j \in U \tag{17}$$

The incidence matrix A is populated with values +1, 0, and –1. The value +1 means that a given vertex is the start of a given arc, while –1 designates a vertex which is the end of an arc. The value 0 indicates that a given vertex is not the start or end of an arc. This can be written in the algorithm as follows:

$$a_{ij} = \begin{cases} 1 & if\ i-th\ vertex\ is\ a\ start \\ & of\ the\ j-th\ arc, \\ -1 & if\ i-th\ vertex\ is\ an\ end \\ & of\ the\ j-th\ arc, \\ 0 & if\ i-th\ vertex\ is\ not\ the\ start \\ & nor\ the\ end\ of\ the\ j-th\ arc \end{cases} \tag{18}$$

The second matrix, B, is the circuit matrix. Its columns also contain all arcs U, but in rows there are only the vertices representing heating substations.

$$B = [b_{ij}] \quad for\, i \in W, \ j \in U \tag{19}$$

The circuit matrix B is populated with only two values: +1 and 0. The value +1 means that DH water has to flow through a given section of the network to supply a given heating substation, while 0 denotes a section of the network that is outside the supply path of a given heating substation.

$$a_{ij} = \begin{cases} 1 & if\ j-th\ arc\ belongs\ to\ the\ supply\ path \\ & of\ the\ i-th\ heating\ substation \\ 0 & if\ j-th\ arc\ does\ not\ belong\ to\ the\ supply \\ & path\ of\ the\ i-th\ heating\ substation \end{cases} \tag{20}$$

The third matrix is the cycle matrix C. Its columns contain all arcs U, while its rows contain cycles S.

$$C = [c_{ij}] \quad for\, i \in S, \ j \in U \tag{21}$$

As with incidence matrix A, cycle matrix C is populated with values +1, 0, and -1. The value +1 means that an arc belongs to a given cycle and the arc direction matches the designed cycle direction, while -1 indicates that these directions are opposite to each other. A 0 denotes arcs that do not belong to a given cycle.

$$c_{ij} = \begin{cases} 1 & if\ direction\ j-th\ arc\ is \\ & consistent\ with\ the\ direction \\ & of\ th\ i-th\ cycle \\ -1 & if\ direction\ j-th\ arc\ is \\ & is\ opposite\ to\ the\ direction \\ & of\ th\ i-th\ cycle \\ 0 & if\ j-th\ arc\ does\ not\ belong \\ & to\ i-th\ cycle \end{cases} \tag{22}$$

Based on values in tables A, B and C, DH water flow rates and pressure drops at all sections of the network considered are calculated by solving systems of relevant balance equations. The first one is a system of linear equations which can be used to determine, according to the law of mass conservation, flows which satisfy constraint (13).

$$[D]_{U\times U}\cdot[E]_{U\times 1}=[F]_{U\times 1} \qquad (23)$$

The second system contains non-linear equations and can be used to determine pressure drops in sections of the DH network, satisfying constraint (12).

$$[G]_{S\times U}\cdot[H]_{U\times 1}=[J]_{S\times 1} \qquad (24)$$

4. Block diagram of the algorithm

Considering the form of the objective function, the constraints, and the fact that the optimization can be applied to both an existing system and a newly designed one, a multistage process of determining optimal diameters for a DH network was implemented.

An initial optimization (stage C in Fig. 2) is performed for all sections of the network except the ring sections. It involves an initial determination of a pipeline diameter for each section, i.e., the diameter for which the heat transmission cost per unit heat is at a minimum. In stage 1, none of constraints (10) to (13) are verified.

The velocity-based stage 2 optimization (D) is used to check whether the flow velocity for the pipeline diameter determined at the previous stage does not exceed the maximum velocity for a given diameter that is applicable during network design. If the velocity is exceeded, the next larger pipeline diameter (within the range provided in the pipeline data sheet) is chosen. Apart from velocities, again none of the constraints are verified at this stage of optimization.

The next part of the algorithm is determining diameters of ring sections (E). The user can input the required diameters of these sections or define them as a minimum (MIN) or maximum (MAX) diameter of adjacent sections of the network, i.e., all sections whose one point is the start or end of a ring section. This approach was taken, because the optimization algorithm tends to exclude these parts of the network which form rings, since the economic criterion does not consider the main purpose of constructing these sections, that is to increase the reliability of supplying heat to consumers.

The aim of stage 3 (F), involving the optimization of selected fragments of the network, is to check whether using a diameter that is the next smaller diameter to the one determined so far for these sections results in lowering the heat transmission cost per unit heat compared to the diameter before the change. If the cost is lower for smaller diameters and all four constraints are satisfied, these diameters are taken as optimal. This stage of optimization allows the correction of diameter selection at the first and second stages, considering the network structure and constraints.

The last step (stage 4) of the algorithm is the optimization of all peripheral sections (step G), i.e., pipe connections to heating substations. A substation section diameter is changed if, for a new pipeline diameter that is smaller than the one determined so far as optimal, the annual total cost of network operation is lower than the current one and the differential pressure at the heating substation supplied by a given section is still higher than the minimum required differential pressure.

Following all the above stages, a set of optimal nominal diameters is obtained for all sections of the network within the part (or all) of the DH network considered. Each stage of the optimization is described in detail in [53].

The Solver tool is used in the optimization process in the last step of step E and in step F (where ring sections with defined diameters are considered) to solve systems of balance equations for flow rates and pressures in the DH network. Thus, constraints (10) to (13) can be effectively taken into account in the process of seeking the minimum of the objective function (1).

5. Case study—part of the DH network under consideration

The effectiveness of the optimization algorithm was tested with many variants of the DH network structure. The tests confirmed that the algorithm worked correctly and provided useful data. Later in this paper, the application of the optimization algorithm will be demonstrated in relation to part of an existing DH network which, due to long-term operation, is being upgraded through replacing the most worn-out sections (Fig. 3). Since the network was designed many years ago for much higher consumer heat demand, the optimization algorithm indicated that the diameters of some pipeline sections of the network should be significantly reduced.

The actual part of the DH network circled by a dotted blue line in Fig. 3 was "collapsed" by assigning capacities of actual heating substations to equivalent substations found in branches of the actual network and represented as a graph in Fig. 4. The purpose of such compensation of part of the network was to highlight sections with pipelines larger than DN 150. Thus, the model of the network subject to optimization has 30 arcs (U=30), 28 vertices (W=28), and 3 cycles (S=3).

Basic data concerning the part of the DH network under consideration is set out in Table 1. The "Number of arcs" and "Number of vertices" are dictated by the system structure provided by the user, while the "Number of cycles" is the number of closed rings, which is also imposed by the structure. The number of "Cycles found" is the number of all the closed rings found by the algorithm for cases where the rings have common parts. For a DH network, it is recommended that cycles include heat sources. Hence, three cycles S1, S4 and S5, chosen according to graph theory, include those sections of the network which were indicated in the description of matrix C. "Number of cases – COMB" is the number

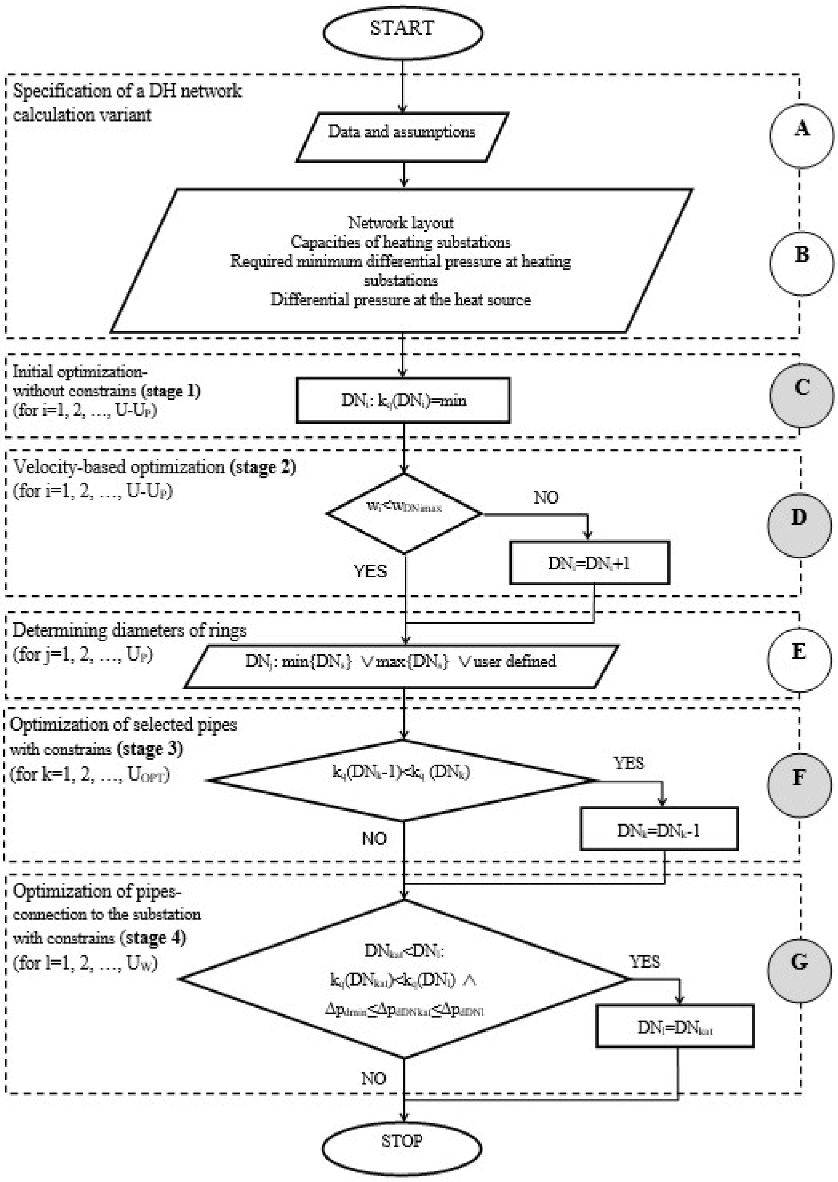

Figure 2: Block diagram of the DH network optimization algorithm. A to G – calculation steps and main stages (1-4)

Figure 3: Part of the DH system under consideration

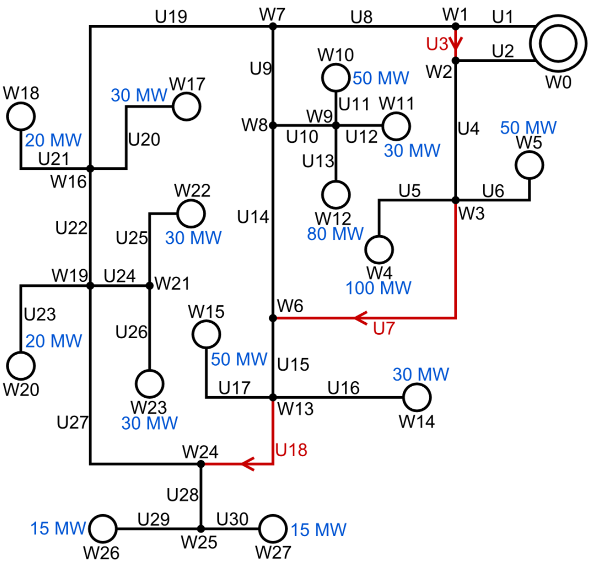

Figure 4: Graph of the part of the DH network under consideration

of section combinations for the optimization of sections selected by the user for a number of such sections defined by the user, equal to UOPT. The sections which are to be replaced and fall under the special optimization mode (part F in Fig. 2) are sections U3, U7, U14, U18 and U22, with U3, U7 and U18 being the sections closing the rings.

For the analyzed part of the DH network, incidence matrix A, circuit matrix B and cycle matrix C take the following form:

Incidence matrix A for the part of the DH network under consideration.

Circuit matrix B for the part of the DH network under consideration.

Cycle matrix C for the part of the DH network under consideration

Based on the values in tables A, B and C, optimization calculations were performed and DH water flow rates and pressure drops in all sections of the network considered were determined. Table 5 lists the results of heat and hydraulic

Table 1: Specification of the part of the DH network under consideration

New DH Network		
Number of arcs	U	30
Number of vertices	W	28
Number of cycles	S	3
Current system		
Structure		
Arcs:	U	30
Source arcs	U_{CHP}	2
Ring arcs	U_P	3
Substation arcs	U_W	14
Other arcs	U_S	11
Vertices:	W	28
Sources	W_{CHP}	1
Substations	W_W	14
Branches	W_R	13
Cycles	S	3
Cycles found	S'	6
Optimization		
Arcs for optimization	U_{OPT}	5
Number of cases	COMB	31

calculations for the optimal variant, marked as DEF2 in Table 6.

Table 6 lists pipeline diameters of sections in subsequent stages of optimization for the optimal variant, marked as DEF2 in Table 7.

Table 7 contains all results of optimization calculations, including technical details and components of the heat transmission cost for four variants, MIN, DEF1, DEF2, and MAX, which differ from each other in terms of the diameters of ring sections U4, U7 and U18; and for the ACTUAL variant assuming current diameters. For the existing network (the ACTUAL variant), the heat transmission cost per unit heat is 5.00 PLN/GJ. The optimal variant is DEF2, for which diameters DN for ring sections U4, U7 and U18 are equal to 500, 600 and 350, respectively. Although the MIN variant has a lower cost per unit heat, it fails to satisfy the constraints, since differential pressures in several heating substations are too low.

Table 8 shows an analysis of errors generated by the algorithm following the optimization calculations. The analysis serves to check whether constraints (11) to (13) are met. Constraint (10) is satisfied, since during the optimization process, for a given return DH water pressure of 2 bar, pressure at the source outlet does not exceed the allowable value of 16 bar, while the differential pressure pd at the source does not exceed 14.0 bar. Columns C and D refer to constraint (11). Column C contains minimum allowable differential pressures at heating substations, and in column D actual differential pressures are given. Columns F and G refer to constraint (12) for rings S1, S4 and S5, for which the sum of pressure drops approaches zero. Column E concerns constraint (13) and provides the mass balance for branch substations. For all the substations, the sum equals or approaches zero.

The program can also produce a visualization of pressure drops between the heat source and any final heating sub-

Table 2: Full incidence matrix A

	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12	U13	U14	U15	U16	U17	U18	U19	U20	U21	U22	U23	U24	U25	U26	U27	U28	U29	U30
W0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W1	-1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W2	0	-1	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W3	0	0	0	-1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W4	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W5	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W6	0	0	0	0	0	0	-1	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W7	0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
W8	0	0	0	0	0	0	0	0	-1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W9	0	0	0	0	0	0	0	0	0	-1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W10	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W11	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W12	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
W14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0
W16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	1	1	1	0	0	0	0	0	0	0	0
W17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
W18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0
W19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	1	1	0	0	1	0	0	0
W20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
W21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	1	1	0	0	0	0
W22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0
W23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0
W24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	-1	1	0	0
W25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	1	1
W26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
W27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1

Table 3: Circuit matrix B

110	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12	U13	U14	U15	U16	U17	U18	U19	U20	U21	U22	U23	U24	U25	U26	U27	U28	U29	U30
W4	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W5	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W10	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W11	1	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W12	1	0	0	0	0	0	0	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W14	1	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W15	1	0	0	0	0	0	0	1	1	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
W17	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
W18	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
W20	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0
W22	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	1	0	0	0	0	0
W23	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	1	0	0	0	0
W26	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	1	1	0
W27	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	1	0	1

Table 4: Cycle matrix C

	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12	U13	U14	U15	U16	U17	U18	U19	U20	U21	U22	U23	U24	U25	U26	U27	U28	U29	U30	Choice 3
S1	1	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	X
S2	0	0	1	1	0	0	1	-1	-1	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
S3	0	0	1	1	0	0	1	-1	0	0	0	0	0	0	1	0	0	1	-1	0	0	-1	0	0	0	0	-1	0	0	0	
S4	-1	1	0	1	0	0	1	-1	-1	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	X
S5	-1	1	0	1	0	0	1	-1	0	0	0	0	0	0	1	0	0	1	-1	0	0	-1	0	0	0	0	-1	0	0	0	X
S6	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	1	-1	0	0	-1	0	0	0	0	-1	0	0	0	

Table 5: Capacities, DH water flow rates, velocities, and pressure drops in the optimal variant DEF2

U	Type	Diameter	Length,	Capacity,	Flow rate,	Velocity,	Pressure drop Δp		Pressure	
-	-	DN	m	MW	kg/s	m/s	Pa/m	bar	At the feed line	At the return line
U1	EC	900	2000	398.181	**1584.880**	2.574	59.179	**1.505**	16.000	2.000
U2	EC	600	2000	151.819	**604.283**	2.210	71.748	**1.737**	14.495	3.505
U3	P	500	1000	48.980	**194.956**	1.031	19.621	**0.231**	14.263	3.737
U4	S	600	1500	200.799	**799.240**	2.923	125.511	**2.279**	11.985	6.015
U5	W	500	1000	100.000	**398.030**	2.105	81.787	**0.965**	10.306	7.694
U6	W	350	500	50.000	**199.015**	2.178	137.521	**0.774**	10.712	7.288
U7	P	600	1500	50.799	**202.195**	0.739	8.033	**0.146**	11.839	6.161
U8	S	900	3000	349.201	**1389.923**	2.258	45.515	**1.737**	12.758	5.242
U9	S	700	1000	198.136	**788.639**	2.119	54.611	**0.675**	12.083	5.917
U10	S	600	500	160.000	**636.847**	2.329	79.689	**0.482**	11.601	6.399
U11	W	350	100	50.000	**199.015**	2.178	137.521	**0.155**	10.980	7.020
U12	W	300	200	30.000	**119.409**	1.585	82.187	**0.183**	10.173	7.827
U13	W	450	300	80.000	**318.424**	2.093	92.478	**0.322**	10.412	7.588
U14	S	450	1000	38.136	**151.792**	0.998	21.015	**0.244**	10.511	7.489
U15	S	450	1000	88.935	**353.987**	2.327	114.288	**1.328**	10.236	7.764
U16	W	300	300	30.000	**119.409**	1.585	82.187	**0.275**	10.001	7.998
U17	W	350	200	50.000	**199.015**	2.178	137.521	**0.310**	11.898	6.102
U18	P	350	1000	8.935	**35.564**	0.389	4.391	**0.049**	10.558	7.442
U19	S	600	1000	151.065	**601.284**	2.199	71.037	**0.860**	10.629	7.371
U20	W	300	600	30.000	**119.409**	1.585	82.187	**0.550**	10.913	7.087
U21	W	250	400	20.000	**79.606**	1.494	90.687	**0.397**	10.119	7.881
U22	S	500	1000	101.065	**402.269**	2.128	83.539	**0.985**	10.467	7.533
U23	W	250	800	20.000	**79.606**	1.494	90.687	**0.794**	10.192	7.808
U24	S	350	200	60.000	**238.818**	2.614	198.030	**0.446**	10.101	7.899
U25	W	300	300	30.000	**119.409**	1.585	82.187	**0.275**	10.461	7.539
U26	W	300	400	30.000	**119.409**	1.585	82.187	**0.366**	10.187	7.813
U27	S	300	1000	21.065	**83.845**	1.113	40.522	**0.452**	10.008	7.992
U28	S	300	300	30.000	**119.409**	1.585	82.187	**0.275**	10.008	7.992
U29	W	200	100	15.000	**59.704**	1.756	166.224	**0.178**	16.000	2.000
U30	W	200	100	15.000	**59.704**	1.756	166.22421	**0.178**	14.495	3.505

Table 6: Summary of pipeline diameters in subsequent stages of optimization for the optimal variant DEF2

Summary of pipeline diameters in subsequent stages of optimization								
U	Initial opt. (stage 1)	Velocity-based opt. (stage 2)	Opt. for selected pipe (stage 3)	Opt. of pipes- connection to the substation (stage 4)	Final opt	Actual	Diameter Comparison (final opt-actual)	Diameter Difference (actual-final opt)
1	800	900	900	900	900	1100	Lees	-2
2	500	600	600	600	600	1000	Less	-4
3	500	500	500	500	500	400	Greater	2
4	500	600	600	600	600	900	Less	-3
5	450	500	500	450	450	400	Greater	1
6	300	350	350	300	300	300	Equal	0
7	600	600	600	600	600	900	Less	-3
8	800	900	900	900	900	900	Equal	0
9	600	700	700	700	700	700	Equal	0
10	500	600	600	600	600	500	Greater	1
11	300	350	350	250	250	200	Greater	1
12	250	300	300	200	200	200	Equal	0
13	400	450	450	350	350	300	Greater	1
14	400	450	450	450	450	600	Less	-2
15	400	450	450	450	450	500	Less	-1
16	250	300	300	300	300	350	Less	-1
17	300	350	350	300	300	250	Greater	1
18	400	400	350	350	350	300	Greater	1
19	500	600	600	600	600	800	Less	-2
20	250	300	300	250	250	300	Less	-1
21	200	250	250	200	200	350	Less	-3
22	450	500	500	500	500	600	Less	-1
23	200	250	250	250	250	200	Greater	1
24	300	350	350	350	350	250	Greater	2
25	250	300	300	300	300	200	Greater	2
26	250	300	300	300	300	250	Greater	1
27	250	300	300	300	300	500	Less	-4
28	250	300	300	300	300	500	Less	-4
29	150	200	200	200	200	200	Equal	0
30	150	200	200	200	200	200	Equal	0

Table 7: Final results of optimization of pipeline diameters for DH network DEF2—the optimal variant

Final results of optimization of pipeline diameters for the DH network							
Item	Symbol	ACTUAL	MAX	DEF1	DEF2	MIN	Unit
Source							
Source capacity	Q_{CHP}	550	550	550	550	550	MW
Design flow rate at the source	G_{obl}	2189	2189	2189	2189	2189	kg/s
Design head at the source	Δp_{EC}	14	14	14	14	14	bar
Lengths and diameters of the network							
Actual length of the network	L	24300	24300	24300	24300	24300	m
Equivalent length of the network	L_z	5025	4621	4561	4541	4338	m
Hydraulic length of the network	L_c	29325	28921	28861	28841	28638	m
Percentage of main pipelines (DN≥350)	L_{mag}/L	80.25	79.01	79.01	78.19	68.72	%
Percentage of transmission pipelines (DN<350)	L_{prz}/L	19.75	20.99	20.99	21.81	31.28	%
Largest DN used	DN_{max}	1100	900	900	900	900	-
Smallest DN used	DN_{min}	200	200	200	200	200	-
Pressures							
Maximum system pressure	p_{max}	16.000	16.000	16.000	16.000	16.000	bar
Minimum system pressure	p_{min}	2.000	2.000	2.000	2.000	2.000	bar
Highest differential pressure at a heating substation in the system	p_{dmax}	11.037	4.059	3.940	3.960	4.377	bar
Lowest differential pressure at a heating substation in the system	p_{dmin}	2.524	2.019	2.002	2.004	**-0.122**	bar
Costs							
Capital expenditure	I	263243	213720	208680	207802	197890	tys. PLN
Annual fixed cost (depreciation and the fixed operating cost)	K_s	23692	19235	18781	18702	17810	tys. PLN/a
Annual pumping cost	K_{pomp}	1897	1871	1867	1866	1852	tys. PLN/a
Annual cost of heat losses	K_{str}	1831	1665	1653	1640	1611	tys. PLN/a
Annual total cost of network operation	K	27420	22770	22301	22208	21273	tys. PLN/a
Percentage of the fixed cost	K_s/K	86.40	84.47	84.22	84.21	83.72	%
Percentage of the annual pumping cost	K_{pomp}/K	6.92	8.22	8.37	8.40	8.71	%
Percentage of the cost of heat losses	K_{str}/K	6.68	7.31	7.41	7.39	7.57	%
Heat transmission cost per unit heat	k_{qi}	0.21	0.17	0.17	0.17	0.16	$PLN/(GJ \cdot km)$
	k_q	5.00	4.14	4.05	4.04	3.87	PLN/GJ
Diameters DN for ring pipes U4, U7 and U18 in variants: ACTUAL: 900, 900, 3000; MAX: 800, 600, 400; DEF1: 400, 700, 600; DEF2: 500, 600, 350 (optimal); MIN: 500, 300, 250.							

Table 8: Error analysis following optimization calculations for the optimal variant DEF2

Substation	Substation type	Minimum differential pressure	Differential pressure	Mass balance for substations Δm	Total pressure drop Δp across rings	
-	-	bar	bar	kg/s	Ring	bar
A	B	C	D	E	F	G
0	EC	14.0	14.0		-	
1	R	–	–	0.00000000	S1	-2.3529E-06
2	R	–	–	0.00000000	S4	2.0984E-05
3	R	–	–	-7.67386E-13	S5	-2.187E-06
4	W	2.0	2.6112597	–	–	–
5	W	2.0	3.4246052	–	–	–
6	R	–	–	0.00000000	–	–
7	R	–	–	0.00000000	–	–
8	R	–	–	0.00000000	–	–
9	R			0.00000000	–	–
10	W	2.0	3.9604387	–	–	–
11	W	2.0	2.3462615	–	–	–
12	W	2.0	2.8241272	–	–	–
13	R			4.26326E-13	–	–
14	W	2.0	2.4720116	–	–	–
15	W	2.0	2.0037572	–	–	–
16	R			0.0000000	–	–
17	W	2.0	3.1153983	–	–	–
18	W	2.0	3.2584599	–	–	–
19	R			0.0000000	–	–
20	W	2.0	2.2372752	–	–	–
21	R			0.0000000	–	–
22	W	2.0	2.3848845	–	–	–
23	W	2.0	2.2016545	–	–	–
24	R	–	–	0.0000000	–	–
25	R	–	–	0.0000000	–	–
26	W	2.0	2.0161635	–	–	–
27	W	2.0	2.0161635	–	–	–

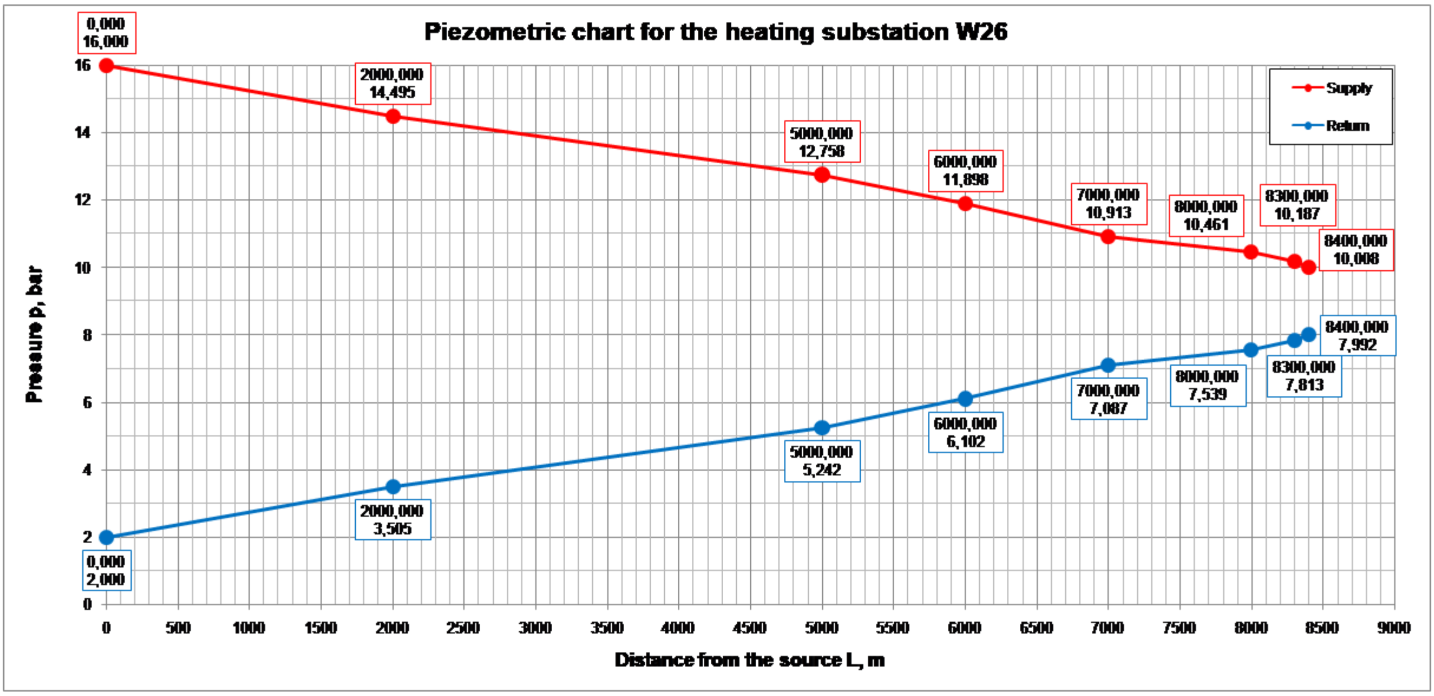

Figure 5: Pressure distribution between the source and the heating substation (HS) and differential pressures for HS W26

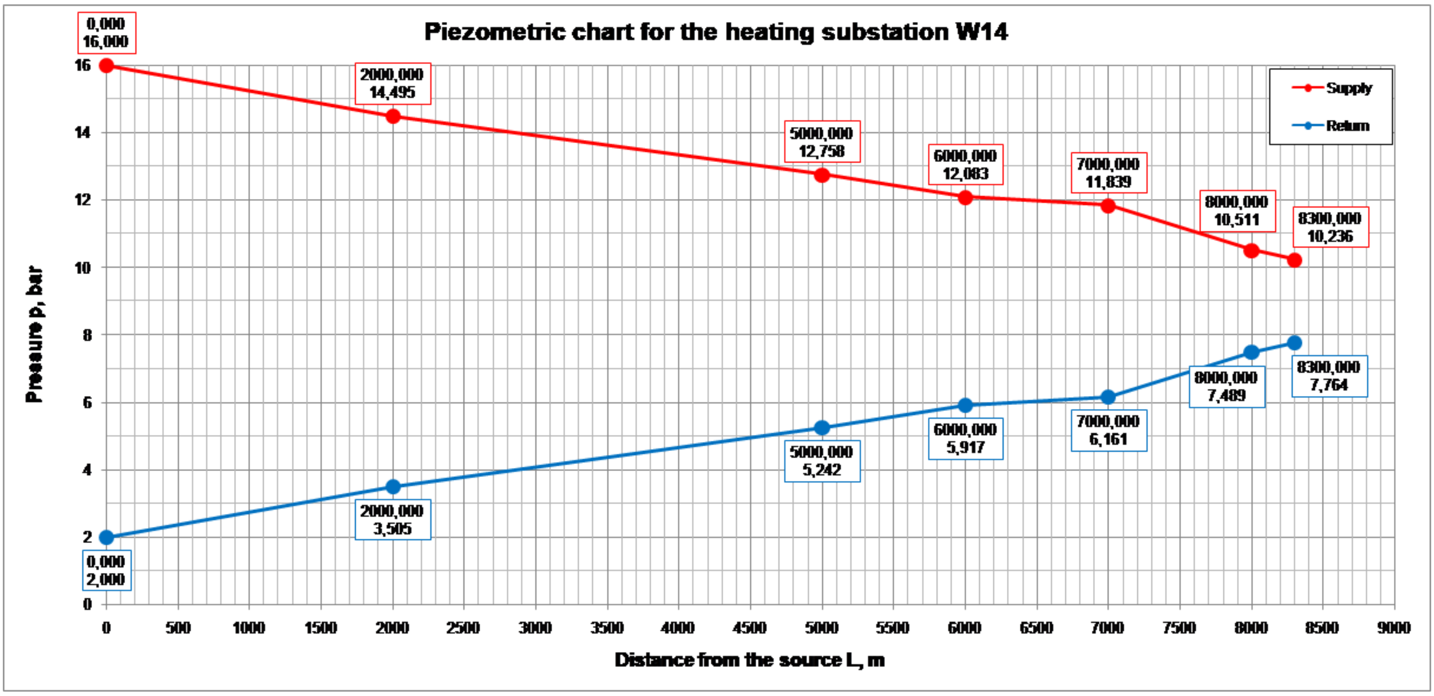

Figure 6: Pressure distribution between the source and the heating substation (HS) and differential pressures for HS W14

station. As an example, a piezometric chart and differential pressures for heating substations 26 (Fig. 5) and 14 (Fig. 6) are provided—according to Fig. 4.

6. Conclusions

- The paper presents an algorithm for selecting a pipeline diameter for a complex DH network. The algorithm can be used to optimize parts of a DH network in newly designed or existing DH systems. It finds a set of diameters for each section of the part of the network considered for which the following is met: the economic criterion of the minimum heat transmission cost per unit heat and hydraulic constraints regarding heat sources, heating substations, and closed rings and branches of the network. If both this criterion and all the constraints are satisfied, the heat transmission cost is reduced, while technical and heat-flow requirements are met.
- The issue of selecting optimal pipeline diameters for a DH network comprising branches and rings, which, in a mathematical sense, is the non-linear objective function (1) with constraints (10) to (13), was solved with a four-stage optimization algorithm (Fig. 2). Graph theory, the non-linear optimization algorithm with constraints GRG used by the Microsoft Excel's Solver tool, and a set of 37 Visual Basic macros which combine heat-balance calculations with optimization calculations for a complex layout of the DH network were applied to solve the algorithm.
- The calculations for a number of DH network variants and for parts of networks in large DH systems show that choosing the right pipeline diameter can reduce the heat transmission cost by 0 to 10% for a newly constructed network or by 0 to 20% for an existing largely oversized network.
- The example provided in the paper demonstrates the optimization process and permits verification of selected pipeline diameters for an existing network that is going to be modernized. The network with a total length of 24.3 km takes 560 MW from the heat source (a combined heat and power plant). The heat is transmitted through two main pipelines from CHP and 26 main and distribution lines with diameters listed in Table 3. The heat transmission cost per unit heat for this network is 5.00 PLN/GJ. Calculations for this part of the system using the optimization process proposed in the paper indicated that by changing pipeline diameters of selected sections the cost per unit heat could be reduced to 4.04 PLN/GJ, thus resulting in a saving of 0.94 PLN/GJ which is equal to 19% of the current cost.
- The optimization algorithm discussed in the paper produces satisfactory results of heat, hydraulic, and economic calculations for projects such as construction of new systems or extension of existing ones. Using such calculations and implementing changes based on their results helps district heating transmission and distribution companies to control costs. Thus, by optimizing the design (diameters) of a DH network in DH systems based on the proposed algorithm, improvements can be achieved in energy and economic efficiency of heat generation in DH systems.

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Nomenclature

Δp_{dimin}	minimum required differential pressure at the i-th heating substation, bar
Δp_{di}	pressure drop, Pa
Δp_l^i	pressure drop, Pa
Δp_{pi}	pressure drop across the return line between the i-th heating substation and the heat source, bar
Δp_S, Δp_L	average total pressure drop of the DH network (supply and return) in the heating season and in the summer period, bar
Δp_{zi}	pressure drop across supply pipelines between the heat source and the i-th heating substation, bar
Δ_p	pressure drop, Pa
η	efficiency of DH water pumps
λ	pipe friction factor
ν	kinematic viscosity of water at average pipe temperature, m2/s
ρ	DH water density, kg/m3
τ_L	time DH operation in summer period, h/y
τ_s	time DH operation in heating season , h/y
ξ	resistance coefficient (according to data sheets)
A	incidence matrix
A_t	amount of heat transmitted through the network in t-th year, GJ/a
a_t	discount rate in t-th year
B	circuit matrix
b	average coefficient of heat loss increase over lifetime, (for DH network under consideration assumed to be 1.5)
C	cycle matrix
c_e	electricity price, PLN/MWh
c_q	heat price, including variable component according to the tariff, PLN/GJ
D	square matrix made of selected rows of the incidence matrix A and selected rows of the cycle matrix C
d	pipeline inner diameter, m
E	vertical vector of flows for arcs of the network
e	average annual share of the operating cost of the network considered; (a percentage of 4.3
F	vertical vector of sums of flows for vertices and cycles of the network
G	matrix made of selected rows of the cycle matrix C
G_{SS}, G_{SL}	average flow rate of DH water in the heating season and in the summer period as percentage of the design flow rate (80
G_j^i	the j-th flow in the i-th branch of the network, kg/s
H	vertical vector of pressure drops for arcs of the network
i	interest on capital (assumed to be 7
I_o	total discounted capital expenditure for the DH network, PLN
J	zero vertical vector of pressure drops for cycles of the network
j_{Di}	capital expenditure per pipeline fragments with a nominal diameter DNi, PLN/m
K	annual DH system operating cost, PLN/y
k	absolute pipe roughness, m
K_A	the annual capital expenditure (depreciation) for the network, PLN/y
K_F	annual financial cost (repayment of credit) for the network, PLN/y
K_O	annual operating cost (excluding depreciation and the financial cost), PLN/y
K_P	annual cost of DH water pumping, PLN/y

k_q discounted heat transmission cost per unit of heat, PLN/GJ

K_S annual cost of network heat losses, PLN/y

K_t total annual network construction and operation costs in t-th year, PLN/y

L length of a pipe fragment of the DH network, m

L_{Di} length of a pipeline fragment with a nominal diameter DNi, m

n network lifetime (period of depreciation and repayment of credit), assumed to be 30 years

n_i number of fragments of the DH network in the i-th ring

p_{CHPp} pressure at the return line at the heat source, bar

p_{CHPzi} pressure at the feed line at the heat source, resulting from the designed differential pressure at the i-th heating substation and the sum of pressure losses in the network supplying heat to the substation, bar

p_{max} maximum allowable pressure in the DH network system, bar

q_{ZL}, q_{PL} average heat losses of a new network comprising pre-insulated feed and return pipelines of a given diameter in the summer period per unit length, W/m

q_{ZS}, q_{PS} average heat losses of a new network comprising pre-insulated feed and return pipelines of a given diameter in the heating season per unit length, W/m

Re Reynolds number

S number of closed rings in the network

s depreciation rate

$sign_i^j$ the sign of the j-th flow in the i-th branch: "+" denotes the flow into the branch, while "–" the flow out of the branch

T_b years of construction of pipeline sections

U number of arcs

U_{CHP} source arc (the main line from the heat source)

u_k share of own resources for the network construction (assumed to be 0.5)

U_P number of ring arcs

U_S arcs for other ordinary section of the network

U_W number of substation arcs (a connection ending at the heating substation)

v kinematic viscosity of water at average pipe temperature, m2/s

W number of vertices

w flow velocity, m/s

W_{CHP} number of heat sources

W_R number of branches in the network

W_S number of pipeline sections

W_W number of heating substations in the network