

Article

Design Optimization of a District Heating Network Expansion, a Case Study for the Town of Kiruna

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Abstract: The urbanization of new areas beyond the existing perimeter of a town implies the expansion of several infrastructures, including the district heating network. The main variables involved in the design of the district heating network expansion are the layout of the new pipes, their diameters, and the capacity of the new heat production sites that are required to satisfy the increased demand of room heating and hot tap water. In this paper, a multi-objective evolutionary algorithm is applied to the minimization of the costs related to the expansion of the district heating network of the town of Kiruna, in northern Sweden. The results show that the spectrum of the optimal design compromises between investment costs for the new pipes and the new heat generation site on one side, and operating costs due to overall fuel consumption and pumping power in the network on the other. The presented methodology is a tool meant for the decision makers in the company who own the district heating network, to evaluate all the possible best design alternatives before making a decision.

Keywords: multi-objective optimization; network structure; complex network; district heating

1. Introduction

The first generation of district heating (DH) systems appeared in Europe in the beginning of the 19th century, and subsequently, there has been continuous development that has led to the current transition between the third and the fourth generation. A DH system is often set up by connecting the boilers of different buildings into small networks; the boilers in the buildings are then replaced by one or more common boilers concentrated in a heat production site, subsequently the different small networks are connected, and so on [1]. DH systems in eastern European countries have followed a different path. They are centrally planned and built with CHP plants as basic heat sources that also supply electricity to the local market, in order to increase overall energy efficiency [2].

The typical stages in the evolution of a Swedish DH network are shown in Figure 1. A similar process occurs with the urbanization of new areas beyond the existing perimeter of a town, when DH is still considered as the best alternative among the technologies providing room heating and hot tap water, and therefore the network is expanded to supply new user areas. In this case, the features that should be evaluated carefully to minimize both the investment and operation costs of the expanded network are: the layout of new piping loops and branches, the diameters of the new pipes, and the capacity of the new heat production site(s) that may be needed to meet the increase in the final user demand. However, rigorous design methodologies and guidelines to determine these features in an optimal way are not well established because of the progressive nature of network expansion, so that the configuration of a network is often the result of several different interventions performed at different times, and largely on the basis of the sole expertise of network designers and operators.

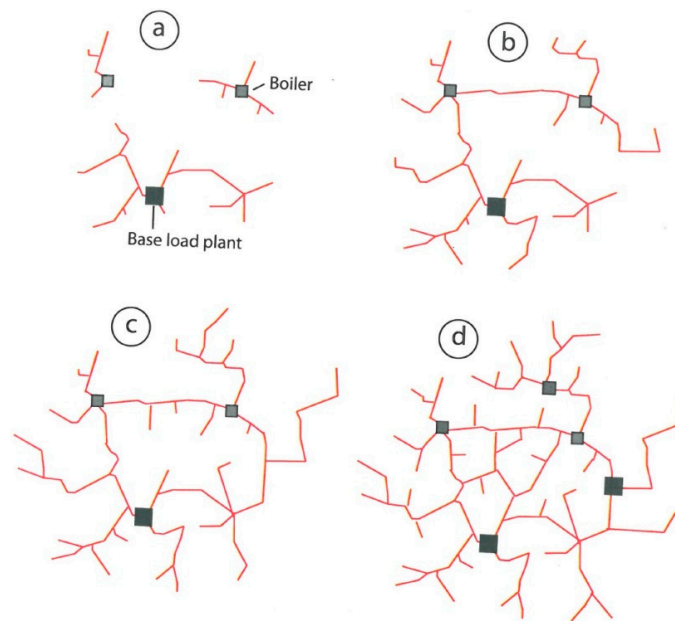


Figure 1. The typical stages of the development of a district heating (DH) network in Sweden: (a) separated islands; (b) tree structure; (c) ring structure; (d) meshed structure [1].

In principle, a trade-off always exists when selecting the proper size for a DH pipe. Pipes with smaller diameters are cheaper than the larger ones, but, for a given mass flow rate through the pipe, a smaller pipe has a higher flow velocity that results in a larger pressure drop and therefore in a greater requirement for pumping power. One design criterion is to determine the pipe diameter by fixing the pressure drop per unit length (often in the range between 50 and 200 Pa/m), but selecting a constant value of this parameter for the whole network may result into overly large variations of flow velocity (in order to avoid this, the Swedish District Heating Association has recommended pressure drops per unit length that are a function of pipe diameter). A more reliable design procedure is to use optimization algorithms to determine the most suitable pipe diameters. Figure 2 shows a simplified representation of how pipe investment cost and pumping power cost vary with pipe diameter [1]. It is apparent from this that a trade-off can be found. However, thermal losses should be taken into account as well, since larger pipe diameters correspond to larger heat transfer surfaces and higher thermal losses, which in turn result in an increase of operational costs due to a higher fuel consumption to satisfy a fixed level of user demand.

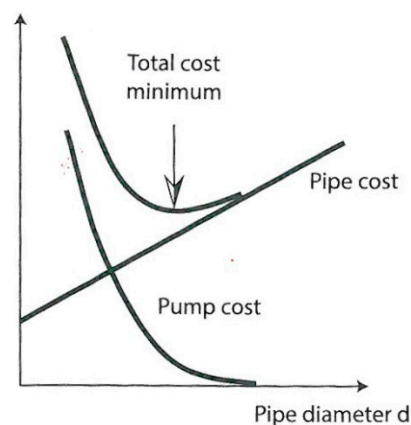


Figure 2. Pipe investment cost and pumping power cost as a function of pipe diameter [1] (thermal losses are not considered to find the trade-off).

A literature review in the field of structure optimization for meshed DH networks shows that current knowledge is still insufficient. Previous studies are usually performed on networks with a small number of heat production sites and/or users, or the tools that are used for the numerical simulations are based on heavy simplifications in the physical description of network behaviour.

For instance, Mertz et al. [3] found the optimal structure for a very simple DH network connecting four consumers and two heat production sites (it should be noted that the piping layout of the supply network piping may not be mirrored by that of the return network, so the number of potential configurations was much larger than usual). The network was modeled in the GAMS environment and mixed integer non-linear programming was used to find optimal solutions by minimizing the overall sum of the operating costs (pumping power and fuel consumption) and the investment costs (trench excavation and piping, heat production sites, and heat exchangers). The authors pointed out the importance of optimizing the network configuration together with some key design parameters, such as the capacity of the heat production sites.

Haikarainen et al. [4] used MATLAB and mixed-integer linear programming in CPLEX to optimize the structure and the operation of a DH network in southern Finland. The terms of the total cost to be minimized were the investment costs related to the construction of new network components and the operation costs at each heat production site. The network was comprised of six heat production sites (plus two potential sites) and 26 potential user areas that were connected by a piping superstructure having a tree layout. In spite of that, the network model required about 600 binary and 6300 continuous variables. Heat storage and heat pump options were included in the model, so the optimal solution also indicated which sites/user areas were economically viable to connect to the DH network.

Morvaj et al. [5] obtained the Pareto front of the design solutions that minimized total costs (the sum of investment and operation costs) and CO₂ emissions over a 20-year period for a network with 12 users. A detailed time description of user demand and boiler operation was considered, so the mixed-integer linear model of the network consisted of more than 84,000 constraints and 70,000 variables (out of which about 3500 were integers). Some non-linear aspects of network behavior (e.g., thermal losses) were simplified to retain a linear formulation. The multi-objective optimization problem was solved by CPLEX using the ϵ -constraint method, and more than four days were required to solve the problem on a common personal computer. Different network layouts were found for different limits on CO₂ emissions, and the number of buildings connected to the DH network increased as the limit on CO₂ emissions was lowered.

Wu et al. [6] compared three different scenarios for a district energy network supplying the thermal and electric demand of five buildings (a store, a hotel, an apartment, an office and a hospital). In the first scenario each building used a conventional heating system where heat demand was satisfied by a gas boiler, while the electricity demand was satisfied by the grid. In the second scenario CHP units were installed in the buildings and a network was used to transport heat among the buildings. Finally, in the third scenario a thermal storage tank was also added in each building. Mixed integer linear programming was used for the optimization of each scenario, and the results from the second scenario indicated an optimal piping layout. However, this layout only showed how the heat surplus from some buildings should be distributed to other buildings, since the considered model of the network did not take into account a detailed description of pressure drops and thermal losses in the pipes.

Bordin et al. [7] develop a methodology named the District Heating Network Design Problem, which was based on a mixed-integer linear description of the network and used CPLEX to solve the optimization problem. A town in Emilia-Romagna (northern Italy) was considered as a case study, with a tree-shaped network superstructure consisting of 20 existing and 12 potential users, and 4.3 and 1.9 kilometers of pipes for existing and potential users, respectively. The economic objective function included the terms for heat exchanger costs (depending on user demand), new piping costs (depending on diameter and length), pumping costs and the revenue from the heat sold to the consumers. Two scenarios were analyzed, the first considering a 10-year period in net present value calculations, while in the second a 5-year period was considered together with lower piping costs

and increased connection fees. In both scenarios it was possible to identify profitable and unprofitable consumers. Thermal losses in delivering the hot water to the consumers were not considered by the model, and a fixed temperature drop was set in the heat exchangers, although it has been shown that the supply water temperature is strongly correlated with these two aspects [1].

Pengfei et al. [8] investigated the pressure drops per unit length that are currently recommended in the design of DH networks (30–70 Pa/m in China and 100 Pa/m in most of European countries). A tree-shaped DH network in the Hebei province (China) was used as a case study, considering the demand for five outdoor temperatures combined with four operating strategies. The objective of the optimization problem was to minimize the sum of several annualized cost terms, among which the heat distribution cost (related to pumping and heat losses) and the pipe investment cost (related to pipe diameter, length, material, insulation thickness). The results showed that the pressure drops for unit length corresponding to the minimum annualized total costs were lower for the control strategies in which the mass flow rate in the primary side was kept constant (30–50 Pa/m) than for those in which the mass flow rate in the primary side was varied as a function of heat demand (60–100 Pa/m).

Zeng et al. [9] used a genetic algorithm to compare the difference between distributed variable speed pumps and a conventional central circulating pump, in a district heating and cooling system, the objective being the minimization of the annualized total costs. The case study was the system for Binjiang business center in Changsha (China), which has a tree-shaped piping structure connecting 16 stations. The optimal pipe diameters found by the algorithm were almost the same in both cases, except for two pipes that had a small diameter when variable speed pumps were used. The option of optimizing piping layout was not considered in that work.

In the present paper a methodology was proposed to deal with design optimization problems regarding new piping layouts for DH networks that already have a complex meshed structure. As with a series of previous works by the same group of authors, the town of Kiruna, located in the very north of Sweden, was used as a test case. The DH network of this town, which has a mature meshed structure and several heat production sites, has been the starting point for developing a general methodology (outlined in [10]) for modelling and optimizing DH networks of similar complexity using MATLAB and Simulink. A detailed analysis of network behaviour was performed in [11], and local temperature and pressure maps together with the pattern of hot water flow distribution were shown in the results. An optimization of network operation, minimizing the costs due to heat production and distribution along the network, was presented in [12], and the results specified for different levels of user demand the amounts of the different fuels that should be burnt in the boilers of the different heat production sites.

The original contribution of this paper is a further step consisting in the implementation of a multi-objective evolutionary algorithm for the design optimization of the structure of a DH network when a new network is to be built from scratch or an existing one has to be expanded. This multi-objective approach was something unconventional, and it aimed at identifying all of the design solutions that represent the possible best compromises between investment costs (new pipes and heat production sites) and operation costs (heat production and delivery to the final users). This allows the decision makers to have more information about the solutions to the design problem at hand. Moreover, the algorithm was interfaced with a realistic (not oversimplified) model of an existing DH network formed by several piping loops (not a tree structure in which the pattern and the amounts of the mass flow rates are obvious) and contained several heat production sites (not only a central site).

In the following sections of the paper the case study is described, the main features of the planned expansion to the current DH network in the town of Kiruna are described, the optimization problem and the algorithm used to solve it are presented, the Pareto front of the optimal solutions is showed and discussed, and finally some conclusions are drawn.

2. Case Study

The town of Kiruna holds 18,000 citizens, and is located in the very North of Sweden, 150 km above the Arctic Circle. The climate is frigid in that region, with an annual average temperature well below 0 °C. The DH network in Kiruna was commenced from the 1960s and is owned by the municipal energy company Tekniska Verken i Kiruna AB (TVAB). It supplies room heating and hot tap water to 1700 customers (30% of the small houses and 95% of the premises), currently delivering 250 GWh/y through 120 km of pipes with a peak demand of 49 MW.

Figure 3 shows a sketch of the current DH network in which the meshed part of the network is marked in blue and the feeding branches in red. The network has several heat production sites: the larger ones are marked with factory symbols (TVAB is the main one, while LKAB represents the waste heat from the nearby iron mining facility) and the smaller boiler houses are marked with boiler symbols.

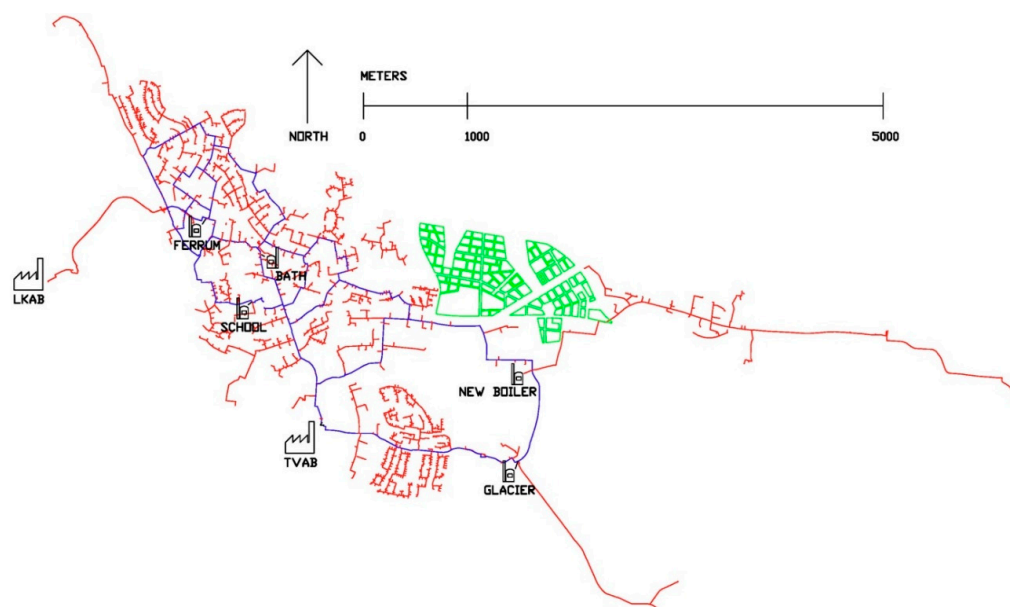


Figure 3. A sketch of the district heating (DH) network in Kiruna: pipes belonging to structure loops are shown in blue, consumer feeding branches in red, new heat production plants with factory and boiler symbol, and new building blocks in green.

The Expansion of the Existing District Heating Network

The town of Kiruna is currently undergoing a deep urban transformation due to progressive geological deformation caused by iron mining activity. Some of the town districts are planned for relocation to safer zones, and a new town center, which should host 7500 person equivalents, is already under construction within a ground area of approximately 420,000 m². The new building blocks are shown as green polygons in Figure 3. While the new areas are being built, the old ones will still be used, so that there will temporarily be a higher heat demand to be satisfied. A new bio-oil boiler, indicated as “New Boiler” in Figure 3, will be installed, the capacity of which was among the variables of the design optimization problem.

According to the plans prepared by Kiruna municipality and TVAB, the piping that serves the new town center will have two connections to the existing network, one at the North East corner of the large south-eastern loop (just close to the location of “New Boiler”) and the other at the feeding branches of the user area that is immediately West of the new town centre.

Figure 4 shows the hypothetical piping superstructure that is considered in this paper to supply the buildings of the new town center. These buildings, which are shown as green polygons, are grouped

into five user areas, and the delivery junctions of these user areas are shown as red double squares. The potential pipes of the superstructure, which are shown as black lines, are placed to connect a series of nodes, shown as black dots, and the delivery junctions of the user areas. The nodes are intermediate piping junctions that are placed to provide a number of alternative paths for the hot water to reach the delivery junctions of the user areas. One of the purposes of the design optimization is precisely to select which alternatives will be implemented in the final piping layout.

The black pipe heading North from the southeastern loop of the existing network has been already built and has a diameter of 400 mm, whereas the existence of, and the diameter of the other pipes in the superstructure, are among the variables of the design optimization problem, and will be determined as the solution of that problem. For sake of simplicity, the series of pipe segments connecting the end of the built 400 mm pipe to the feeding branch of the user area immediately West of the new town center are considered to belong to one single pipe, and all have the same diameter.

It is worth noting that the considered superstructure was conceived with the following spatial constraints: the connections with the existing network (as planned by TVAB and Kiruna municipality), the 400 mm pipe already built, and the delivery junctions to the new user areas (that are located approximately in the barycentre of each area). The layout of the pipes and nodes in the considered superstructure follow the criterion of minimizing distances among these fixed locations, as longer than necessary pipe segments would not be part of the optimal design solution anyway due to higher investment costs.

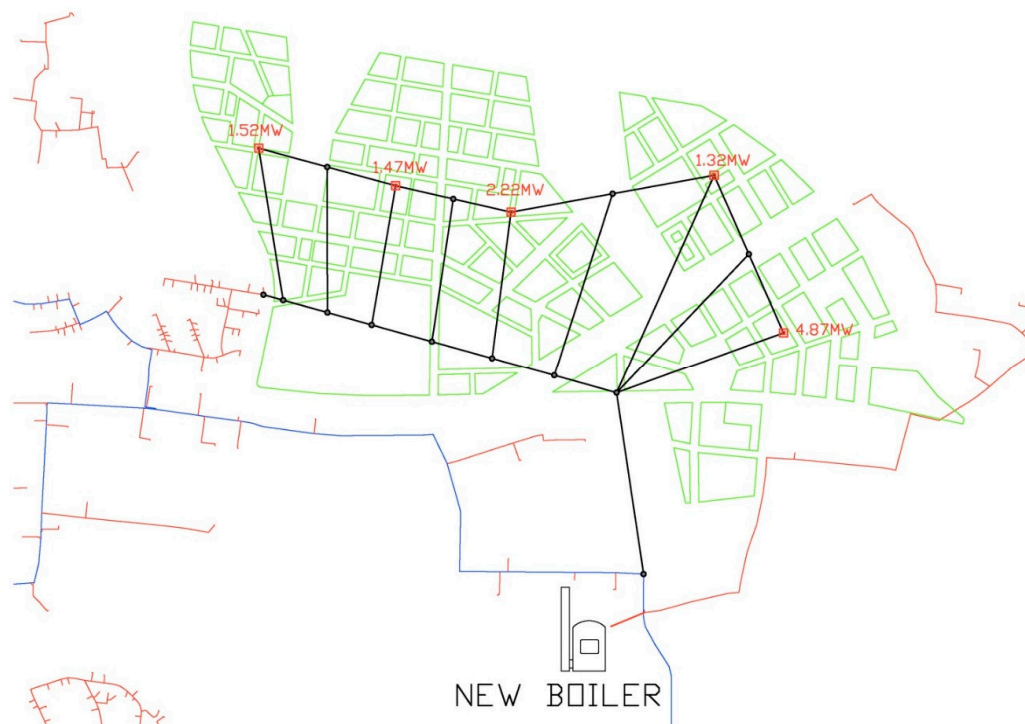


Figure 4. The piping superstructure considered for the expansion of the DH in the town of Kiruna. The existing pipes are shown in blue (loops) and red (feeding branches), new building blocks in green, delivery junctions for the new user areas as double red squares, superstructure pipes as black lines, and piping nodes as black dots.

3. Methodology

This section describes the methodology used to set up and solve the design optimization problem about the expansion of the DH network in Kiruna. The procedure mainly relied on a modelling strategy for complex meshed DH networks that has already been developed in [10], used for the simulation of the DH network in Kiruna in [11], and successively refined for the optimization of the operation of

the same DH network in [12]. In this paper, the model of the DH network in Kiruna was expanded with the piping superstructure described in the previous section, and coupled to a multi-objective evolutionary optimization algorithm in order to identify the solutions that were the possible best compromises between investment and operation costs.

3.1. The Model of the District Heating Network

The strategy proposed in [10] to build the model of a complex meshed DH network in the MATLAB/Simulink environment is simple and powerful at the same time. Its strength is given by the modularity of the approach, with a small number of block types (pipe, node, user area, heat production site) that can be combined into a custom diagram in a very flexible way, even for the most complex layouts.

A detailed numerical representation of the behaviour of a meshed DH network requires the calculation of the local pressure and temperature of the water at all network piping junctions. In fact, these are fundamental to determine the mass and heat flow rates in the network, which are in turn affected by pressure drops and thermal losses in the pipes. The model takes into account all these aspects without any major simplification to the physical nature of the phenomena. This is essential to evaluation of the terms by which the operating costs of the DH network depend, i.e., the pumping power required to make the water circulate in the network, and the fuel consumption at the heat production sites (the total heat generated has to be equal to the overall demand of the users, plus thermal losses along the network piping).

The reader is referred to [12] for a detailed description of model blocks, the interaction among them and the equations that are solved inside each block type. It is worth reminding here that the main idea behind the model is the exchange of information between the blocks in which mass and heat flows are calculated as a function of local pressures and temperatures (pipe blocks of course, but also user area blocks and heat production sites), and the blocks in which the local pressure and temperatures are determined as the values resulting from the balance among mass and heat flows (node blocks).

Thanks to the modular nature of the model, the implementation of network expansion was straightforward. All the pipe segments of the superstructure shown in Figure 4 were added to the model of the DH network in Kiruna already used in [12], as well as to the intermediate junctions and the five new user areas. A heat production site block was also added at the North East corner of the southeastern loop of network to represent the new bio-oil boiler. Comparing the number of blocks of each type with the model used in [12], the model for the expanded DH network in Kiruna consisted of six plus one heat production site blocks, 85 + 25 pipe blocks, 75 + 12 node blocks and 44 + 5 user blocks.

The lengths of the new pipes are set, but not their diameters, which are received as inputs from the optimization algorithm when a particular design solution is evaluated (except for the 400 mm pipe that has already been built). In case a pipe does not exist in that particular design solution, its mass and energy flows at inlet and outlet are set to zero so they do not contribute to the balances in the junctions at pipe ends. The capacity of the new bio-oil boiler is also set according to the particular design solution evaluated by the optimization algorithm.

3.2. The Optimization Problem

The two objective functions to be minimized in the multi-objective optimization problem presented in this paper were the investment cost for the expansion of the DH network in Kiruna (C_{inv} in Equation (1)) and the operating cost to run the network after the expansion had been completed (C_{op} in Equation (2)).

$$C_{inv} = \sum_{pipe} c_{pipe} (D_{pipe}) L_{pipe} + C_{boiler} \quad (1)$$

$$C_{op} = \sum_{site} \sum_{res} c_{res} Q_{res,site} + \sum_{site} c_{el} P_{pump,site} \quad (2)$$

The investment cost is made of two terms: (i) the cost related to the pipes; and (ii) the cost related to the new bio-oil boiler. The investment cost for the pipes is expressed as the sum for all the pipes existing in the considered design solution of the cost per unit length of the pipe (c_{pipe} , which depends on pipe diameter D_{pipe} and includes purchase, digging, welding and installation) multiplied by pipe length (L_{pipe}). The investment cost for the new bio-oil boiler (C_{boiler}) depends on its capacity.

As in [12] the operating cost consists of two terms: (i) the cost for generating the requested heat, which is equal to the overall demand of end users plus the thermal losses along the network; and (ii) the cost for making the water circulate in the piping network, which is the sum of the costs for the pumping power required at the heat production sites to introduce the supply water mass flow rates into the network. In turn the cost for the generation of heat is equal to the sum at all heat production sites of the unit costs of the resources consumed in the boilers of the site (c_{res} in SEK/kJ, where res could be municipal waste, bio-oil, biomass, electricity and oil) multiplied by the resource input in thermal power terms ($Q_{res,site}$ in kW, which is greater than the heat output according to the efficiency of the boilers). It is worth noting that this term is calculated on the resource input required to generate the amount of heat supplied by the sites, so it implicitly takes into account the heat losses along the network and boiler efficiencies. The cost term related to the pumping power is expressed as the sum all heat production sites of the unit cost of electricity (c_{el} in SEK/kJ) multiplied by the pumping power consumed at the site ($P_{pump,site}$ in kW).

The decision variables of the optimization problem are:

- The diameters for each pipe segment in the superstructure shown in Figure 4. These are 18 discrete variables that can assume the values of 0 (the pipe does not exist), 100, 200, 300 and 400 mm;
- The capacity of the new bio-oil boiler. This is another discrete variable that can assume the values between 7 and 18 MW at 1 MW intervals.

Some constraints were also imposed to the values of the local pressures and temperatures in order to ensure the correct operation of the DH network. The maximum pressure difference within the supply network is not supposed to exceed 12 bars, considering the height of the nodes, while the temperature of the water supplied to a group of consumers is not allowed to be lower than 65 °C (for further details see [12]).

3.3. The Optimization Algorithm

The multi-objective optimization problem defined in the previous section was performed by the evolutionary optimization algorithm proposed in [13], which was particularly suitable to distribute the population of solutions along the optimal Pareto front, thanks to its original diversity-preserving mechanism.

The flowchart of the multi-objective evolutionary algorithm was sketched in Figure 5. A set (old population) of design solutions is available at the beginning of each iteration (generation) of the algorithm (the old population is randomly initialized before the first iteration). A pool of parent pairs that are selected at random from the old population is formed, and genetic mathematical operators (crossover and mutation) are applied to the decision variables of the pairs in this pool to create a new set of candidate design solutions (offspring population).

It is worth noting that in this specific application of the algorithm, the design solutions that were apparently unfeasible (e.g., there are pipes with dead ends, or user areas not served), were automatically removed from the offspring population in order to avoid their evaluation and, therefore, save computational time.

The investment and operating costs associated with a given candidate solution were evaluated by simulating the expanded network model with the piping configuration and the capacity of the new bio-oil boiler that are defined by the values of its decision variables. The simulation identified key quantities to determine the pumping power at the heat production sites and the heat output at the TVAB site (note that this must be equal to the difference between the overall user demand and the

output of the other sites, plus the thermal losses along the network). The cost for generating the heat requested from the TVAB site was determined by solving a nested mixed integer linear programming (MILP) optimization subproblem that distributed in the most convenient way the thermal load among the boilers in the TVAB site. After this post-processing step all the information required to evaluate the operating cost was available, whereas all the information required to evaluate the investment cost was already available from the knowledge of the decision variable values.

The iteration of the algorithm ended with a selection of set of design solutions (new population) that was passed to the next iteration (in which it became the old population). All the design solutions of the old population and those of the offspring population were considered according to their objective function values (Pareto ranking), but also according to their genetic diversity, in order to avoid a premature convergence to a limited region of the true Pareto front.

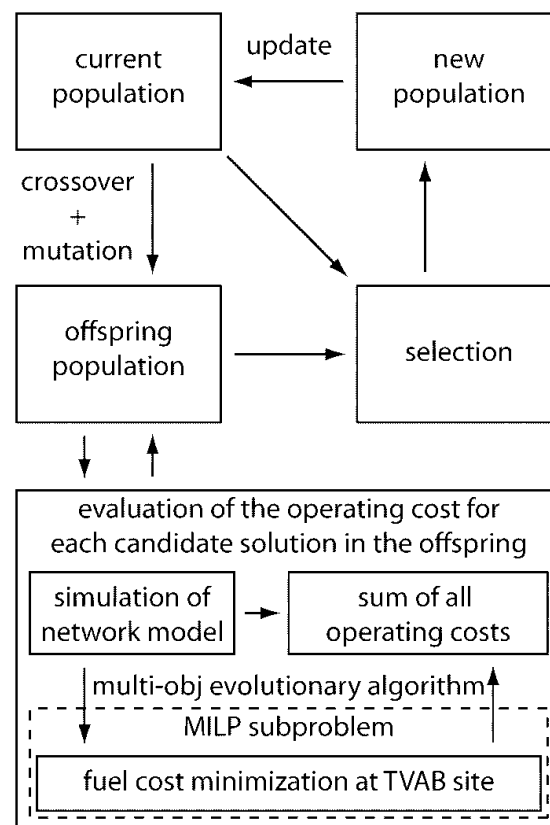


Figure 5. Flowchart of the multi-objective evolutionary algorithm used to solve the design optimization problem about the expansion of the DH network in Kiruna..MILP: mixed integer linear programming. TVAB: Tekniska Verken i Kiruna AB company.

The number of individuals was set at 100 in order to have a sufficient variety of features within the population to be evolved by the algorithm, given the number of decision variables. The iterative search procedure was terminated after 250 generations, when it was clear that the population of design solutions had converged to the Pareto front of the best possible compromises between the two objectives.

4. Results and Discussion

The multi-objective design optimization minimizing the investment and operating costs for the expansion of DH network in Kiruna was performed considering not the peak thermal load, but a frequent demand level that registered in about 40% of the days in the three coldest months of the winter period. This was the demand level that has already been considered for half of the operation

scenarios optimized in [12], and amounted to 39 MW for the existing user areas (including room heating and hot tap water). The planned new user areas will require an additional 11.4 MW in the same outdoor conditions (see the demand for each area in Figure 3).

Table 1 shows the values for the heat output and the supply temperature at the heat production sites that were taken from the optimal results of the “39 MW no LKAB” case in [12]. The new bio-oil boiler is supposed to run at full load at the capacity set by the optimization algorithm, whereas the heat output of the TVAB site is the result from the overall balance of the heat loads in the network (it must be equal to the difference between the overall user demand and the output of the other sites, plus the thermal losses along the network).

Table 1. Setup of the heat production sites in the model of the expanded network in Kiruna (see also the results of the “39 MW no LKAB” optimized case in [12]).

| Site | Heat Output (MW) | T _{supply} (°C) |
|------------|----------------------|--------------------------|
| TVAB | balancing heat loads | 103.2 |
| LKAB | inactive | |
| Bath | 8.9 | 75.7 |
| Ferrum | inactive | |
| Glacier | 0.8 | 82.4 |
| School | inactive | |
| New Boiler | to be optimized | 100 |

Figure 6 shows the Pareto front of the design solutions representing the optimal compromises between the operating costs (expressed in SEK/s on the ordinates of the diagram) and the investment costs (expressed in MSEK on the abscissae).

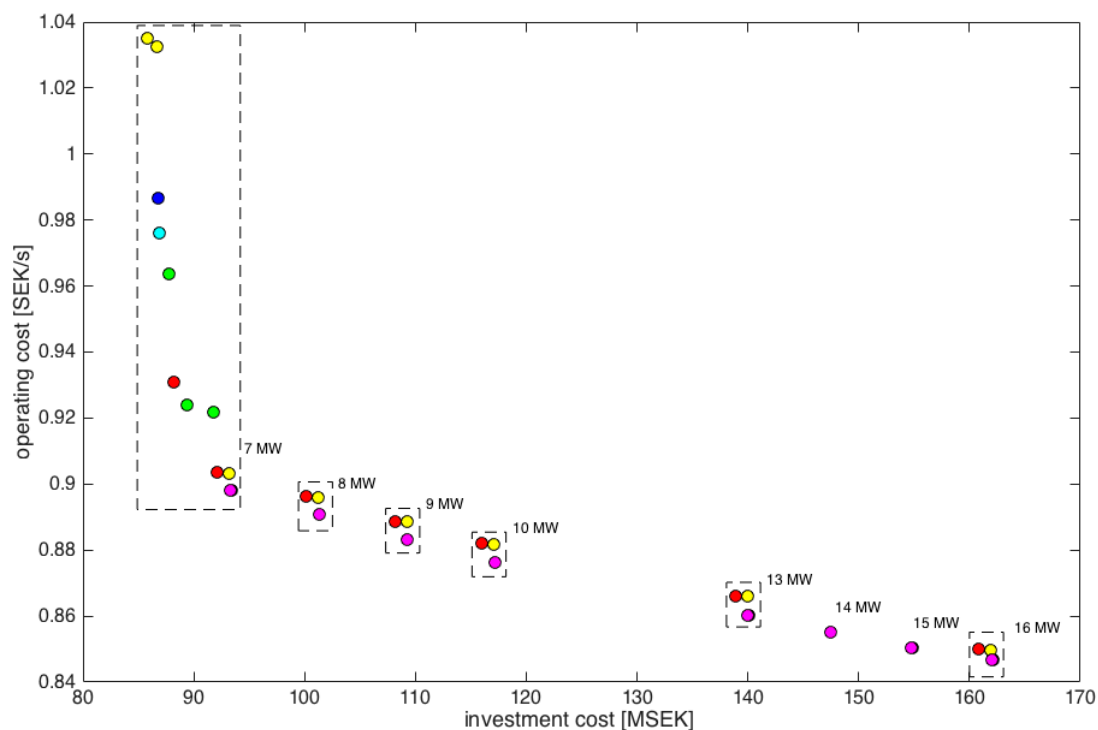


Figure 6. Pareto front of the optimal design solutions that represent the best compromises between investment and operating costs for the expansion of the DH network in Kiruna. The markers are colored according to the configuration of the piping layout in the design solution (which are shown in Figure 8).

It was immediately apparent that the front was far from continuous, it rather appeared quite scattered. This was a direct consequence of the discrete nature of the decision variables of the optimization problem. For the same reason, the shape of the front was not perfectly convex. In particular, it showed a major concave region close the lowest investment costs, just before the operating costs started to grow significantly.

The design solutions belonging to the Pareto front were able to be sorted into different groups according to the capacity of the new bio-oil boiler. Each group occupied a well-defined portion of the front (see Figure 6), as it is logical to expect. In fact, a higher capacity of the new bio-oil boiler resulted in higher investment costs, obviously, and in lower operating costs, since the pumping power required to deliver the hot water to the new user areas is reduced when more and more hot water is produced close to the new town center, and for the same reason the thermal losses are also reduced. Surprisingly, not all of the considered bio-boiler capacities had a corresponding group of optimal design solutions along the Pareto front. For example, the group of solutions with a 10 MW bio-oil boiler was immediately adjacent to the group with a 13 MW boiler, while there was no optimal design solution having a bio-oil boiler with a capacity of 11 or 12 MW.

This anomaly could be clarified if the investment and operating costs of all the design solutions forming the new population in last generation of the optimization algorithm were re-evaluated for all the considered capacities of the new bio-oil boiler. The results of this re-evaluation are plotted in Figure 7. It can be seen that there exists a Pareto front of optimal compromises between the investment and operating costs for each of the considered bio-oil boiler capacities (dashed lines are plotted in Figure 7 along each of these fronts to help the reader identify them). According to the concept of Pareto dominance, it is logical that the overall Pareto front shown in Figure 6 is the envelope of the Pareto fronts for a fixed value of the new bio-oil boiler capacity.

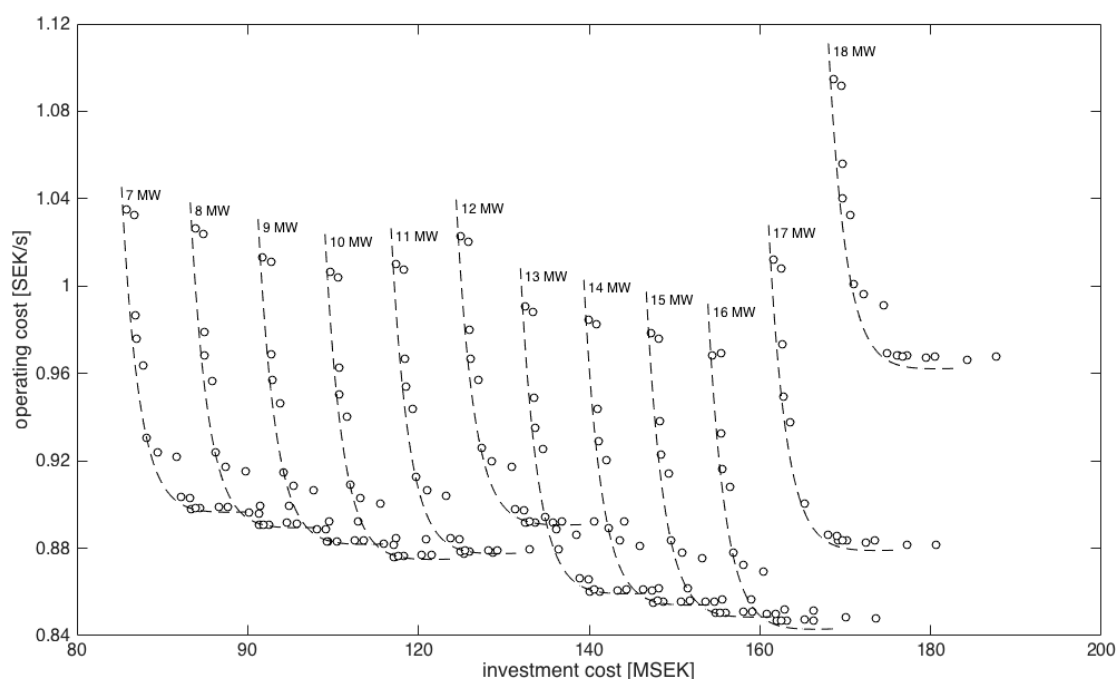


Figure 7. Pareto fronts of the best compromises between investment and operating costs for each of the considered capacities of the new bio-oil boiler (dashed lines do not represent the actual fronts, they are just added to help the reader locate the solutions having a given boiler capacity).

It is apparent in Figure 7 that the fronts obtained for 11 and 12 MW do not contribute to forming the envelope of the Pareto fronts, because the design solutions belonging to these fronts result in higher operating costs for similar investment costs if compared to some of the optimal design solutions

having a bio-oil boiler with a higher or lower capacity. The reason for these higher operating costs is due to the distribution of the heat loads among the boilers at the TVAB site. As the capacity of the new bio-oil boiler is raised from approximately 10 MW, the load of one of the two biomass boilers at the TVAB site is reduced until it reaches its operational minimum. At this point, the load of the second biomass boiler, which was running at full load, would have to be reduced in order to compensate a further reduction of the heat output requested from the TVAB site. In this situation, the operating costs would increase due to the low combined efficiency of the two biomass boilers running at minimum and partial load, until a further increase in the capacity of the new bio-oil boiler (around 13 MW) allows the shutdown of one of the two boilers, so that the other can return to operate at full load.

Both Figures 6 and 7 shows that the minimum of the operating costs is around 0.85 SEK/s, which is found for a new bio-oil boiler capacity of 16 MW. Again this is due to the way in which the boilers at the TVAB site are used to balance the thermal loads in the DH network. When the capacity of the new bio-oil boiler is larger than 16 MW, the municipal waste boiler at the TVAB site has to reduce its load. Since TVAB is actually paid to burn the municipal waste, this load reduction causes a significant increase in the operating costs, as can be seen in Figure 7 from the Pareto fronts obtained with new bio-oil boiler capacities of 17 and 18 MW.

The investment and operating costs of the optimal solutions in Figure 6 can be further analyzed to understand which terms provide the most significant contributions. The new boiler investment cost is of course a function of its capacity and goes from 60.2 MSEK for 7 MW, to 84 MSEK for 10 MW and up to 128.9 MSEK for 16 MW. It always is the larger share of the overall investment cost, while the investment for the piping layout is almost constant, around 33.1 MSEK, at least for the optimal solutions having a low operating cost. On the other hand, the solutions having a much higher operating cost and a new boiler capacity of 7 MW feature piping layouts with smaller pipe diameters, and in this case the piping investment costs could go down to 25.6 MSEK. Nearly all of the operating cost comes from the cost for heat generation, which rises from 0.834 to 0.867 SEK/s as the capacity of the new boiler is reduced from 16 to 7 MW. The pumping cost has a marginal influence (from 0.015 SEK/s at 16 MW to 0.03 SEK/s at 7 MW) until it grows significantly, up to 0.16 SEK/s, when the diameters of the pipes in the layout are reduced.

A deeper analysis of the optimal design solutions along to the Pareto front in Figure 6 has pointed out that they all belong to six piping layout configurations. These six layouts are shown in Figure 8 in different colours (blue, yellow, red, cyan, green and magenta), and the markers representing the optimal design solutions in Figure 6 are filled with the colours corresponding to these layout categories. It may happen that the same piping layout appears more than once in the Pareto front with the same capacity of the bio-oil boiler, this means that there must be some variations in the diameters of the pipes for the same layout.

It is worth noting that piping loops are not present in any of the six layout configurations. In fact, the possible advantages of piping loops (e.g., providing alternative paths to deliver the hot water in case of some portion of the network has to be bypassed due to a failure) are not taken into account in the considered objective function, so their presence would only increase investment costs rise. The six configurations in Figure 8 show just minor differences about:

- the way the hot water is delivered to two of the five new user areas (the second and the third from West to East), in series (from West to East in the blue and yellow configurations, from East to West in the cyan and green configurations) or in parallel (with a common pipe in the magenta configuration, with separate pipes in the red configuration);
- the way the hot water is delivered to the two east-most user areas, in parallel (blue and cyan configurations) or in series (the other four).

As a final remark to the results, it is worth mentioning that the proposed methodology offers the opportunity to obtain the full spectrum of the best possible compromises between the investment and operating costs. Naturally, these two costs, which are expressed in different measurement units, could

have been weighted into a single objective function according to standard accounting techniques, given the life time of the project and the fixed charge rate. However, a single objective optimization would have reduced the amount of information available to the decision makers to a single design solution (the optimal one found by the optimization procedure). The knowledge of the whole spectrum of optimal design solutions makes it possible for the decision makers to make more strategic choices based on other considerations, e.g., forecasts on the future trend of fuel cost, availability of capitals, or options for future design modifications that were not included in the present planning process.

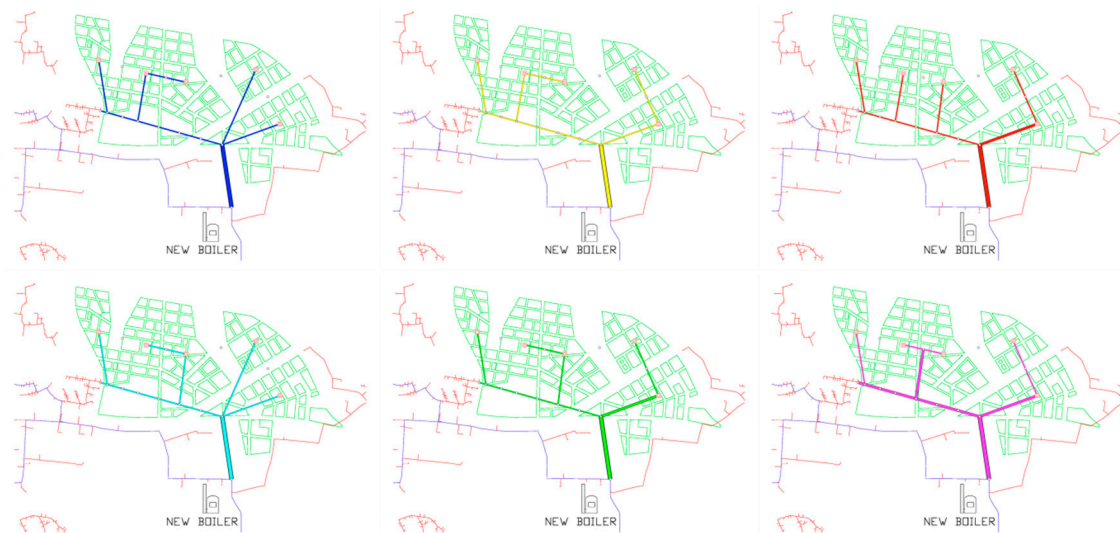


Figure 8. The six piping layout configurations of the optimal design solutions along the Pareto front in Figure 6. The colours of the markers in Figure 5 correspond to the colours of the piping layouts in this figure.

5. Conclusions

This paper has presented a methodology for the multi-objective optimization of the design of DH networks when the configuration of the new piping layout and the capacities of new heat production sites have to be decided. A modular modelling and simulation tool for complex meshed networks was coupled to an evolutionary algorithm to search for the Pareto front of the best compromises between the investment and operating costs. The real case of the expansion of the DH network in the town of Kiruna (Swedish Lapland) was used as an example of application.

The results of the design optimization for this specific case have shown that:

- The appearance of the set of the optimal design solution is quite scattered, due to the discrete nature of the decision variables of the optimization problems, and different groups of solutions can be identified according to the capacity of the new bio-oil boiler, which was among those decision variables.
- There is little variety in the optimal design configurations of the piping layout feeding the new user areas. Significant changes in the values of the operating and investment costs instead are due to different diameters of the piping segments, rather than variations in the piping layout.
- The minimum operating cost is obtained for a large capacity of the new bio-oil boiler that should be installed close to the new user areas. This means that a more distributed heat generation, resulting in lower thermal losses and requiring lower pumping power (in this case however, the investment costs are higher, due to the larger capacity of the new heat production site).

The multi-objective nature of the design optimization problem set up with this methodology allows the decision makers to be aware of the whole spectrum of the best compromises between investment and operating costs. Then, the design solution to be adopted can be selected in a more

conscious way, perhaps also using a broader perspective including other aspects, compared to a case in which only one solution is obtained as the result of a single objective optimization procedure.

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References

1. Frederiksen, S.; Wener, S. *District Heating and Cooling*, 1st ed.; Studentlitteratur: Lund, Sweden, 2013.
2. Wojdyga, K.; Niemyjski, O. Hydraulic analysis for a district heating system supplied from two CHP plants. *Energy Build.* **2012**, *54*, 81–87. [[CrossRef](#)]
3. Mertz, T.; Serra, S.; Henon, A.; Reneaume, J. A MINLP optimization of the configuration and the design of a district heating network: Academic study cases. *Energy* **2016**, *117*, 450–464. [[CrossRef](#)]
4. Haikarainen, C.; Pettersson, F.; Saxén, H. A model for structural and operational optimization of distributed energy systems. *Appl. Ther. Eng.* **2014**, *70*, 211–218. [[CrossRef](#)]
5. Morvaj, B.; Evins, R.; Carmeliet, J. Optimizing urban energy systems: Simultaneous system sizing, operation and district heating network layout. *Energy* **2016**, *116*, 619–636. [[CrossRef](#)]
6. Wu, Q.; Ren, H.; Gao, W.; Ren, J. Multi-objective optimization of a distributed energy network integrated with heating interchange. *Energy* **2016**, *109*, 353–364. [[CrossRef](#)]
7. Bordin, C.; Gordini, A.; Vigo, D. An optimization approach for district heating strategic network design. *Eur. J. Oper. Res.* **2016**, *252*, 296–307. [[CrossRef](#)]
8. Jie, P.; Kong, X.; Rong, X.; Xie, S. Selecting the optimum pressure drop per unit length of district heating piping network based on operating strategies. *Appl. Energy* **2016**, *177*, 341–353. [[CrossRef](#)]
9. Zeng, J.; Han, J.; Zhang, G. Diameter optimization of district heating and cooling piping network based on hourly load. *Appl. Ther. Eng.* **2016**, *107*, 750–757. [[CrossRef](#)]
10. Vesterlund, M.; Dahl, J. A method for the simulation and optimization of district heating systems with meshed networks. *Energy Convers. Manag.* **2015**, *89*, 555–567. [[CrossRef](#)]
11. Vesterlund, M.; Toffolo, A.; Dahl, J. Simulation and analysis of a meshed district heating network. *Energy Convers. Manag.* **2016**, *122*, 63–73. [[CrossRef](#)]
12. Vesterlund, M.; Toffolo, A.; Dahl, J. Optimization of multi-source complex district heating network, a case study. *Energy* **2017**, *126*, 53–63. [[CrossRef](#)]
13. Toffolo, A.; Benini, E. Genetic diversity as an objective in multi-objective evolutionary algorithms. *Evol. Comput.* **2003**, *11*, 151–167. [[CrossRef](#)] [[PubMed](#)]



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