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Optimization of multi-source complex district heating network, a case study

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ABSTRACT

The level of complexity for a district heating network increases with the maturity of the network, and this affects the pattern of the distribution of the hot water from the heat production sites to the end users. The majority of district heating systems are also multi-source networks, typically supported with heat from one main production site and other smaller satellite sites that are activated when required. In general, local energy companies have a lack of knowledge regarding how a meshed network behaves when different production sites are operated. The schedule of heat generation at the different sites is often based on staff experience and some general rules of thumb.

In this paper a method for modeling and simulating complex district networks is further developed in order to optimize the total operating costs of a multi-source network, with constraints on the pressure and temperature levels in the user areas and on the heat generation characteristics at each production site.

The optimization results show that the usage of the cheapest resources is preferred to a distributed generation of heat, even if some of the pipes may exceed the recommended thermal load capacity. The main site water supply temperature is found to be the lowest allowed by the constraint on the temperature of the water supplied to the end users, since the decrease of the costs associated with the lower thermal losses in the network is not counterbalanced by the increase of those associated with the pumping power of a larger water mass flow rate.

1. Introduction

The evolution of district heating (DH) systems has been going on for more than 100 years, and in the beginning the first generation of DH networks used to transport steam as heat carrier. Today DH systems are at the end of the third generation, which is characterized by a water supply temperature around 100 °C, material-efficient components, pre-insulated pipes with extruded foam and plastic jacket. DH is definitely a well-developed technology that is used in most larger cities in central and northern Europe [1].

Each DH system has its own piping network in order to transport heat from the production sites to the end consumers. Fig. 1 shows that often the piping network is started as a set of small separate heating islands that successively grow together into one larger network with an increasing degree of complexity, the extent of the complexity being directly correlated with the maturity of the network. The advantage of using a meshed network (the last stage of network maturity) is that the thermal load for the single pipes is reduced and alternative paths can be used in case of pipe failure. However, the disadvantages are an increase in the thermal losses due to the larger heat dissipation area and the difficulty to determine the pattern of the water mass flow rate within the network [2].

More than often, heat generation in a DH system is planned according to the experience of the staff running the production facilities and some general rules of thumb. There is a general lack of knowledge in determining the optimal heat production plan for a system involving multiple sources (usually one main production plant supported by satellite, or just back-up, boiler plants) and a meshed piping network. The challenge is to be able to evaluate how the total heat production cost is affected by the heat output, the supply temperature, the thermal efficiency of each heat production site combined with the thermal and pressure losses in the piping

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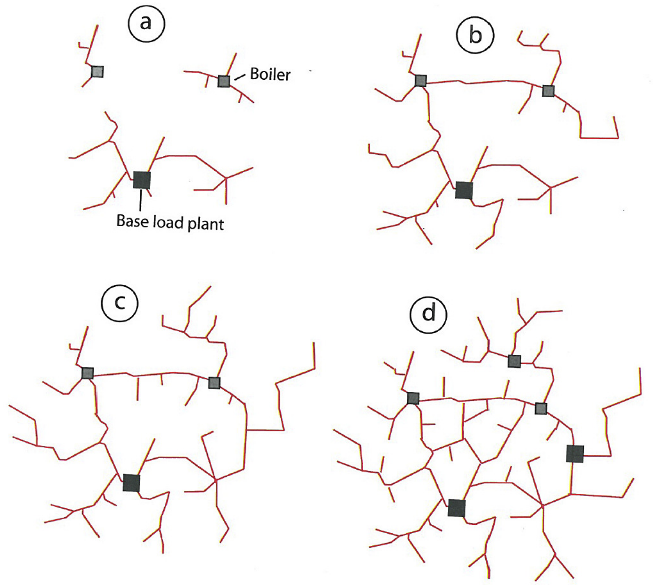

Fig. 1. Evolution of network designs, a) network with islands, b) coherent network with tree structure, c) network with ring, d) meshed network [2].

network for a given scenario characterized by the demand from the end users and the environmental conditions.

A literature review in the field of optimized heat production in meshed DH networks proves that current knowledge is still insufficient. Several studies apply optimization to simple network configurations, or the models of the DH network are built under simplified assumptions, so they do not require detailed simulation tools.

For instance, Åberg and Widén [3] present a study on the cost optimization of heat generation in DH systems considering different fossil and renewable fuels and different types of conversion units for heat generation, but in their method, the DH network is described as a black box characterized only by the overall heat demand of the users (a similar approach was also used by Chinese and Meneghetti [4]). Sartor et al. [5] concentrate on the optimal operation of combined heat and power plant connected to DH networks, and their modelling is far more detailed on the plant side than on the network side of the simulated system.

Pirouti et al. [6] aim at minimizing the capital costs and energy consumption in a DH network by varying the flow rates and supply temperatures. However, their case study, the DH network of Ebbw Vale in Wales, UK, consists of a simple tree structure including just one heat production site and seven user clusters. An in-house software has been developed by Ancona et al. [7] for the design, analysis and optimization [8] of DH networks, which are described with a matricial representation of mass and enthalpy balances at network nodes. The mass and heat flows in the pipes are obtained by solving the matricial system of equations with an iterative procedure (the Todini-Pilati algorithm). The case study shown in the two references features a network with a tree structure supplied by a single heat production site.

A group search optimizer (GSO) algorithm is used by Jiang et al. [9] to optimize the daily operation of the DH station of a small-scale system integrating different energy sources such as wind, solar, electricity and natural gas. Koiv et al. [10] propose a new method for optimizing the size of DH network pipes based on a probabilistic estimation of user consumption. The application of the method is shown for a network with a tree structure comprising ten users and one heat production site.

A mixed-integer linear optimization problem is formulated in Haikarainen et al. [11] for optimizing the structure and the operation of a DH network. The decision variables considered are the types of fuels, the technology and the location of the heat production sites, the layout of the distribution pipes, the capacity and the location of heat storage utilities, in order to obtain optimal conditions from an economic or environmental perspective. A hypothetical urban area in southern Finland is used a test case, the network layout (and its expansion options) having essentially a tree structure. The methodology may not be easily applicable to problems of more realistic size, due to the use of binary variables to represent network structure alternatives and the linearization of some key physical relationships to make the optimization problem a mixed integer linear one.

Fazlollahi et al. [12] demonstrate that the annual operating cost can be reduced by almost 30% and a higher thermal efficiency can be obtained with an optimization procedure that selects the resources, decentralized vs. centralized heat production technologies and the configuration of the piping network. Wang et al. [13] find that the optimal location for a peak load boiler is a peripheral position within the network (i.e. far away from the main plant) close to an area that is dense of end users. On the other hand, the peak load boiler should be placed within the main plant if the electricity from combined heat and power generation can be used on site. Fang and Risto [14] perform the optimization for a multi-source system with two heat production sites, the DH network being simply represented as a sink. It is concluded that in sparse networks thermal losses represent the dominating term in the total cost, which results in a lower supply temperature from the heat production sites and higher water mass flow rates in the pipes.

Bordin et al. [15] highlight a general need for further development of DH models including meshed networks and multi-source heat production, and present preliminary results showing the potential to solve realistically sized networks.

Mertz et al. [16] proposed a mixed-integer nonlinear formulation for the optimization of the structure and the technologies involved in the design of a DH network, minimizing the total costs evaluated over multiple reference periods for the heat demand in the system. They emphasize the importance of the roles of heat losses and pressure drops in the compromise that decides the water supply temperature in the optimal network Their method is however tested for a series of very simple academic cases characterized by two heat generation sites and 4 consumer areas. Morvaj et al. [17] use a mixed-integer linear approach to the multi-objective (economic and environmental) optimization of the topology, design and operation of an urban distributed energy system including a heating network. Different scenarios about the available technologies, layout limitations and operating constraints are investigated, but some fundamental hypotheses (e.g., the constant supply and return temperatures in the heating network) show that the focus of the work is not on a detailed simulation of DH network behaviour.

Recently, Guelpa et al. [18] have published a work on the optimal operating conditions of DH networks with a special focus on the role played by the power required for pumping the hot water from the heat production sites to the end user. Assessing this contribution to the overall primary energy usage requires detailed simulation tools to evaluate the flow distribution and the pressure losses in network having a complex meshed topology, so a reduced model based on proper orthogonal decomposition and radial basis functions is proposed to cut down the computational time while maintaining an acceptable accuracy. The test case proposed is the large meshed DH network of the city of Turin, the largest network in Italy, and the reduction in computation time compared to a full fluid-dynamic model indicates that this approach could be used as effective tool for network control strategy in normal and malfunctioning conditions.

The present group of authors has already outlined a methodology [19] for dealing with the issues deriving from the complex nature of multi-source meshed DH networks. This methodology was applied in Ref. [20] to the simulation and the analysis of the behaviour of a complex meshed DH network with a single heat production site. The further step introduced in this paper is the coupling of this simulation and analysis procedure with a hybrid evolutionary-MILP algorithm for the optimization of the operation of a multi-source meshed DH network. The objective of the optimization is to minimize the total cost related to the heat generation at multiple production sites and its delivery to the end users. As in the previous works, the DH network of Kiruna, a small town located in northern Sweden, is used as a case study to illustrate the methodology. In the following sections of the paper the specific case study is introduced, the methodology about the simulation model of complex meshed network is described, the optimization problem and the algorithm used to solve it are presented, the results from the optimization runs are discussed, and finally some conclusion are drawn.

2. Case study

The town of Kiruna is located in the very north of Sweden, 150 km above the Arctic Circle, and it is well within the sub-arctic climate zone, with an annual average temperature between −1.5 and −3 °C. This results in a substantial need for room heating in the buildings where the 18,000 inhabitants of Kiruna spend their lives.

The DH network in Kiruna has its origin in the 1960s, when large real estate boilers were connected to other surrounding buildings. In 1980 all heat production was centralized and entrusted to the local energy company Tekniska Verken i Kiruna AB (TVAB). By the middle of the 1980s more than the half of the multifamily and administrative buildings were already connected to the DH network. By the end of 1990s the network had grown approximately to its current size, supplying heat to 30% of the small houses and 95% of the premises. Today the network delivers 250 GWh per year of heat through 120 km of pipes, providing room heating and hot water to the about 1700 end users that are connected. Fig. 2 shows the current network, which apparently is a mature meshed network with a complex structure (the piping forming the meshed part of the network is marked in blue in the figure while the feeding branches are marked in red).

Heat can be supplied to the network from six different sites, which are also shown in Fig. 2: TVAB (the main heat production site, with waste, biomass and oil boilers), Glacier (oil and electricity boilers), School (oil boilers), Bath (electricity boiler), Ferrum (oil boilers) and LKAB (waste heat from iron ore mining). Table 1 summarizes the type, the minimum/maximum capacities and the efficiencies of the boilers in the six sites. The network data recorded in the year 2010 show that during the coldest day of the year a peak demand of about 49 MW occurred for room heating and hot water, the temperature of the water supplied to the end users being in the range between 90 and 99 °C.

3. Methodology

The methodology used in this paper is based on the procedure for modelling complex meshed district heating networks that has already been developed and applied to the Kiruna case in Ref. [20]. A hybrid evolutionary-MILP optimization algorithm is then coupled to the model of the district heating network in Kiruna to minimize the total operating cost due to the heat generation at the production sites and its delivery to the end users.

3.1. The model of the DHS

The model for the simulation of meshed DH networks has been developed in the MATLAB/Simulink environment [20]. The main idea behind the model is to obtain a completely modular simulation tool, so that complex network configurations can be represented by combining few categories of blocks in a custom diagram. The blocks have to be connected in a specific way in order to ensure a correct exchange of information among them, as it appears from the brief summary of block categories that is offered in the following (more details about the model and the main equations involved can be found in the Appendix):

Node blocks: A node block represents a junction in the piping network. In this block mass and enthalpy balances are evaluated both for the supply and the return network according to the incoming and outgoing flows from/to the other blocks (pipes, users, heat production sites type II), in order to determine the local pressure and temperature at the node.

Pipe blocks: A pipe block represents a segment of the piping network, which is made of a supply pipe and a return pipe. From the information about the pressures and temperatures at the nodes connected by the pipe, the mass flow rate in the pipe and the associated enthalpy flows are determined for both the supply and return network. The incoming and outgoing enthalpy flows differ because of the thermal losses in the pipes, which are calculated as a function of the temperature of the water entering the pipes.

User blocks: A user block represents a group of consumers, the demand of which is specified. It has to be connected to a node block, from which the temperature of the supply network is retrieved. The heat demand and the water supply temperature are used to calculate the temperature drop due to the delivery of heat (according to a characteristic surface that is specific for the represented group of consumers), and hence the water mass flow rate that is taken from the supply network and discharged to the return network. The enthalpy flow to the return network also takes into account the thermal losses in the branch of the network that feeds the represented group of consumers.

Heat production site blocks: A heat production site (which may comprise several different thermal facilities in the same site, e.g., a group of boilers fed by different fuels) can be represented in two ways. Type I: The block is characterized by the assigned values of supply pressure and temperature of the water at the production site (therefore it has to be connected to a pipe block, and at least one of these blocks has to be included in the model to set a reference for the calculation of pressure along the network). The heat supplied by the site is one of the simulation outputs and can be calculated from the mass flow rate of the water that is taken from the site and the return temperature of the water that is sent back to the site. Type II: The block is characterized by the values assigned to the amount of heat that is supplied into the network and to the temperature at which it is supplied. The block has to be connected to a node block, which provides the temperature of the water taken from the return network in order to calculate the mass flow rate of the water that is heated in the site.

The model for the meshed DH network in Kiruna is made of 6 heat production site blocks (1 type I, TVAB, and 5 type II), 85 pipe blocks, 75 node blocks and 44 user blocks.

3.2. The optimization problem

The objective of the optimization problem presented in this paper is the minimization of the total operating cost of the DH system in Kiruna. This cost is made of two terms, 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

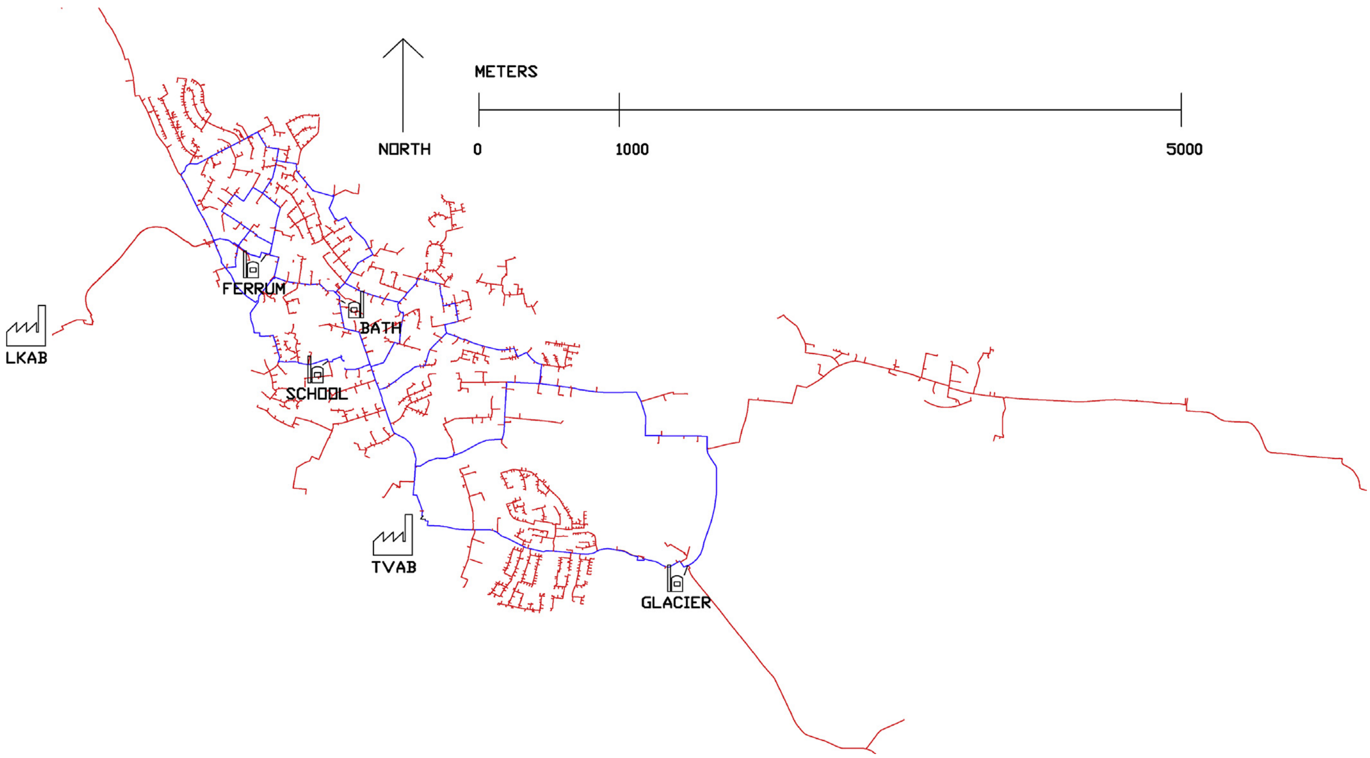

Fig. 2. A scheme of the DH network in the town of Kiruna: piping loops are shown in blue and consumer feeding branches in red [20]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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 of the costs for the resources (fuels, waste heat or electricity) consumed in the boilers at the production sites, the resource input in energy terms being greater than the heat output according to the efficiency of the boilers. The relationship between the consumed resource and the heat output in each boiler is considered linear and is determined using the boiler efficiencies at maximum and minimum loads reported in Table 1. In this way, the cost for resource consumption at the heat production sites is also linear with the heat generation (see further implications of this in Section 3.3 about the algorithm used to solve the optimization problem). The objective function to be minimized can then be expressed in the following way:

Table 1
The main features of the six heat production sites of the DH network in Kiruna.

Site/resource	Power [MW]		Efficiency [%]	
	Min	Max	Min	Max
TVAB				
Bio-boiler	2	6	77	80
Bio-boiler	2	6	71	83
Oil bolier	4	10	82	94
Waste boiler	5.1	27	85	101
Glacier				
Oil boiler	0.6	1.2	82	84
Oil boiler	1.2	2.3	83	85
Oil boiler	1.2	2.3	84	86
Electric boiler	0.4	1.2	89	91
Bath				
Electric boiler	3	10	89	91
Ferrum				
Oil boiler	1.1	2.2	82	84
Oil boiler	1.1	2.2	83	85
Oil boiler	1.5	3	84	86
School				
Oil boiler	1	2	80	82
Oil boiler	1	2	81	83
Oil boiler	1	2	82	84
Oil boiler	1.8	3.5	83	85
Oil boiler	1.8	3.5	84	86
LKAB				
Waste heat	1	15	92	98

$$C_{tot} = \sum_{site} \sum_{res} c_{res} Q_{res,site} + \sum_{site} c_{el} P_{pump,site} + \sum C_{penalty} \quad (1)$$

where c are the specific cost of the resources (in Euro/kJ, subscript el stands for electricity), $Q_{res,site}$ is the amount of a resource consumed in a site (expressed in kW), $P_{pump,site}$ is the power (in kW) used to drive the pumps of the heat production sites. The order of the specific costs for the resources, from the cheapest to the most expensive, is the following: municipal waste (which is negative since TVAB actually gets paid for burning it), biomass, waste heat from LKAB, electricity and oil, the relative magnitude of specific costs being roughly in the proportion −1:0.6:1:2.5:4.5, respectively. The twelve decision variables of the optimization problem are:

- the water supply temperature at the main heat production site (TVAB);
- the pressure at the eastern outlet of TVAB site (TVAB site has two outlets, the northern one towards the city centre and the eastern one towards the airport. The northern outlet has been considered as the reference for the calculation of pressure along the network);
- the amounts of heat supplied by the other heat production sites (LKAB, Glacier, Ferrum, School and Bath);
- the water supply temperatures at the other production sites.

The considered range for water supply temperatures is between 75 °C and 110 °C at all heat production sites.

Some constraints are also considered about the values of pressure and temperature along the DH network. The maximum pressure difference within the supply network (considering the height of the nodes) is not supposed to exceed 12 bars, while the temperature of the water supplied to a group of consumers is not supposed to go below 65 °C. Penalty terms ($C_{penalty}$ in Eq. (1)) are added to the objective function when these constraints are violated. The magnitude of the penalty terms is proportional to the entity of constraint violation (e.g., if the maximum pressure difference within the supply network is 14 bars, then the constraint on it is violated and the exceeding 2 bars are multiplied by a fixed coefficient of proportionality to get a penalty cost term related this constraint that is added to the objective function. On the other hand, if the maximum pressure difference within the supply network is lower than 12 bars, then the penalty cost term related to this constraint is zero). The coefficients of proportionality are chosen appropriately for each constraint in order to guarantee that the objective function value for any candidate solution violating a constraint is always higher than the minimum of the total operating costs among the candidate solutions that satisfy the constraints.

3.3. The optimization algorithm

The minimization of the total operating cost for the DH network in Kiruna is performed by a hybrid evolutionary-MILP optimization algorithm, which has been specifically developed for the solution of this problem. The algorithm is organized hierarchically in two nested levels (i.e. the lower level algorithm performs its search process within each iteration of the upper level algorithm). The overall search process is driven from the upper level by an evolutionary algorithm that is a modified (single-objective) version of the algorithm proposed in Ref. [21]. The procedure implemented in the hybrid algorithm is illustrated in Fig. 3 and is briefly described in the following.

At the beginning of each iteration of the upper level algorithm a set (current population) of candidate solutions is available. The usual genetic operators (crossover and mutation) are then applied to the decision variables of a pool of parent pairs that are randomly extracted from the population in order to generate a new set of candidate solutions (offspring population).

The evaluation of the objective function value associated with a given candidate solution starts with the simulation of the network operating conditions identified by its decision variable values. The simulation returns important information, namely the pressures and the mass flow rates in the network, from which the pumping power at the heat production sites can be determined, and the heat output at the TVAB site. Note that this is the only heat output that is not fixed by the decision variables, so 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. The information about the heat output of the production sites is then passed to the lower level optimization algorithm, which solves for each site a MILP problem that minimizes the costs for the heat generation in the site by selecting the loads of the available boilers. The results are returned to the upper level algorithm, which has finally all the pieces of information to evaluate the total operating cost for the candidate solution.

At the end of the iteration of the upper level algorithm, the solutions of the current population and those of the offspring population undergo a selection step in order to form the population (new population) for the next iteration. The selection criterion is of course based on the ranking of the objective function values, but

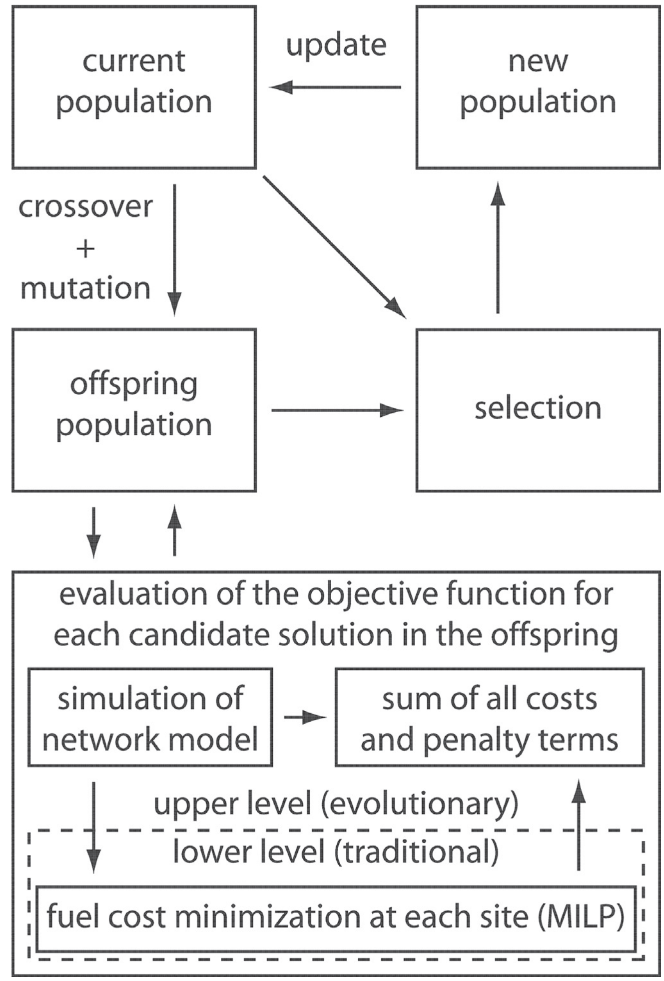

Fig. 3. Scheme of the hybrid evolutionary-MILP optimization algorithm used in this paper for the minimization of the total operating cost of the DH network in Kiruna.

also on the genetic diversity of the solutions in order to avoid a premature convergence to sub-optimal solutions.

The algorithm was run with a population of 100 solutions, and 300 to 400 generations were usually sufficient to get a clear indication that the search process had converged around the current best solution.

3.4. Limitations of the model

The DH network model considers only a steady state picture of network operation, with daily averaged figures for both the thermal demand of the end users and the hot water supplied from the heat production sites. No dynamic effect can be captured by the model, including ramps for the variation of thermal load of the boilers at the heat production sites and the use of short- or long term thermal storage to smooth the peaks and the valleys of thermal demand time history.

In the specific application to the DH network in Kiruna, end users were grouped into the same area when they belong to the same tree structure of pipes that starts with a feeding branch departing from one of the loops of the network. A finer resolution, with several smaller user areas as "leaves" of those tree structures, is of course possible in order to get more details about mass flow rates, pressures and temperatures in a large number of shorter and thinner pipes that are very close to the actual location of the end users.

4. Results and discussion

4.1. Optimized heat generation

The optimization of the total operating cost of the DH network in Kiruna is performed considering six cases, which result from the combination of two levels of end user demand and three scenarios involving different sets of available heat production sites.

The selected levels of end user demand are 49 MW, which is the peak daily averaged demand recorded in 2010, and 39 MW, which is a common demand level that is registered in about 40% of the days in the three coldest month of the winter period.

In the first of the three considered scenarios (“all plants”) all the heat production sites are considered to satisfy the network thermal requirement. However, under particular conditions the LKAB company can refuse to sell to the network the waste heat from the iron mining facilities, in order to use it internally. Since LKAB can cover a large share of the network requirement with a relatively cheap resource, this situation is worth to be represented in a specific scenario (the second, “no LKAB”), in which all the heat production sites but LKAB are considered as potentially active. A third scenario is finally considered, in which the 10 MW electric boiler of the Bath site is also inactive (“no LKAB and Bath”). In fact, it is expected that the Bath site will be often used instead of the oil boilers because of the lower price of electricity and the large capacity of the electric boiler, so in this third scenario at least some of the oil boilers (which are present at TVAB, Glacier, School and Ferrum sites) should be forced into operation.

Table 2 summarizes the results of the optimization runs, showing the details of the operating conditions of the heat production sites (boiler heat output and temperature of the water supplied to the network) that minimize the total operating cost for heat generation and delivery in the six considered cases. Note that the difference between the sum of the amounts of heat generated at the production sites and the end user demand is equal to the thermal losses in the network.

It appears that in all cases the largest share of the network heat requirement is covered by the waste boiler and the biomass boilers at the TVAB site, which are always active and at full load since municipal waste and biomass are the two cheapest resources. When LKAB site is active (“all plants” scenario) the rest of the requirement is covered with waste heat from the iron mining facilities and, in the case of peak end user demand, with Bath electric boiler as well.

When LKAB site is inactive (“no LKAB” scenario) Bath and Glacier electric boilers are used at partial or at full load. If their capacity is not sufficient to satisfy the network requirement, the large TVAB oil boiler comes into play. In case Bath electric boiler is also unavailable (“no LKAB and Bath” scenario) and the end user demand is 49 MW the network requirement quota exceeding the capacities of Glacier electric boiler and TVAB oil boiler is covered by smaller oil boilers at Glacier and Ferrum sites.

These results clearly show that the minimization of the total operating cost for the Kiruna DH network privileges the cost of the resources over a distributed generation of heat. Cheapest resources are always used first in the boilers with the highest efficiency, the efficiency being a function of the load with highest efficiency at maximum boiler capacity. Only when one of the two most expensive resources has to be used in more than one boiler at partial load (e.g. electricity in the “no LKAB”-39 MW case or oil in the “no LKAB, Bath”-49 MW case), then the share of the load that has to be covered with that resource is split by the optimizer among different heat production sites in different city locations. A better geographical distribution of heat generation in the network would probably be achieved if all the secondary heat production sites had at least one electric boiler of small-to-medium size (from 3 to 5 MW), and in that case the results may be similar to those obtained in Ref. [13].

The optimal temperatures at which the hot water is supplied to the network at the heat production sites are generally in the upper

Table 2
The optimal conditions that minimize the total operating cost of the DH network in Kiruna for all the six considered cases.

		49 MW (all plants)		39 MW (all plants)		49 MW (no LKAB)		39 MW (no LKAB)		49 MW (no LKAB, Bath)		39 MW (no LKAB, Bath)	
Site/resource	Max [MW]	Power [MW]	Temperature [°C]	Power [MW]	Temperature [°C]	Power [MW]	Temperature [°C]	Power [MW]	Temperature [°C]	Power [MW]	Temperature [°C]	Power [MW]	Temperature [°C]
TVAB		39	100.7	39	104.3	47	98.9	39	103.2	49	99.6	48	103.2
Bio-boiler	6.0	6		6		6		6		6		6	
Bio-boiler	6.0	6		6		6		6		6		6	
Oil boiler	10	0		0		8		0		10		9	
Waste boiler	27.0	27		27		27		27		27		27	
Glacier		0.7	106.3	–	–	1.2	76.1	0.8	82.4	3.4	86.2	1.2	79.8
Oil boiler	1.2	–		–		0		0		0		0	
Oil boiler	2.3	–		–		0		0		0		0	
Oil boiler	2.3	–		–		0		0		2.2		0	
Electric boiler	1.2	0.7		–		1.2		0.8		1.2		1.2	
School		–	–	–	–	–	–	–	–	–	–	–	–
Oil boiler	2.0	–		–		–		–		–		–	
Oil boiler	2.0	–		–		–		–		–		–	
Oil boiler	2.0	–		–		–		–		–		–	
Oil boiler	3.5	–		–		–		–		–		–	
Oil boiler	3.5	–		–		–		–		–		–	
Bath		5.6	75	-	-	10	97.2	8.9	75.7	X	X	X	X
Electric boiler	10.0	5.6		-		10		8.9		X		X	
Ferrum		–	–	–	–	–	–	–	–	6.1	83.2	–	–
Oil boiler	2.2	–		–		–		–		1.1		–	
Oil boiler	2.2	–		–		–		–		2.0		–	
Oil boiler	3.0	–		–		–		–		3.0		–	
LKAB		15	88.4	11.5	83.8	X	X	X	X	X	X	X	X
Waste heat	15.0	15		11.5		X		X		X		X	

half of the range set in the optimization problem (above 90 °C and up to 105 °C). This should correspond to low water mass flow rates in the pipes, but nevertheless high flow rates are found in some cases (see Section 4.2). A careful analysis of the results show that the optimum is always very close to a condition in which at least one of the constraints on the temperature of the water supplied to the end users would be violated. This indicates that:

- The decrease of the pumping costs due to lower water mass flow rates at higher water supply temperatures is not sufficient to overcome the savings from the lower fuel consumption at lower water supply temperatures as a consequence of the reduced heat losses in the network. For instance, starting from the optimal conditions found for the “all plants”-49 MW case, a decrease of 1 °C in the water supply temperatures at the heat production sites results in a saving of about 17 Euros/day in fuel consumption costs against an increase of about 2.5 Euros/day in the pumping costs.
- There are few user areas which particularly suffer from significant thermal losses (as it has been confirmed by TVAB). In light of the above-mentioned trends of fuel consumption and pumping costs, these user areas have a decisive role in determining the optimal water supply temperatures. In fact, they practically impose that the whole DH network is operated at temperatures that are at least 10–15 °C higher than those that would be sufficient for the large majority of the user areas.

This result confirms both the findings in Ref. [14] and the relatively high water supply temperatures that are currently used in the real network (see the simulations in Ref. [20]).

It is reasonable to affirm that the water supply temperatures should assume the lowest possible values that comply with the constraint on the temperature of the water supplied to the end users (which has to be greater than 65 °C). This is however difficult to achieve in just some hundred generations of the hybrid optimization algorithm, since the objective function is much more sensitive to a variation of the amount of heat generated in the sites than to a variation of the water supply temperatures.

4.2. Network behaviour

Each scenario considered above can be visualized with data post-processing techniques in order to study several features of the flow patterns in the meshed part of the supply network, such as:

- the directions of the flows and the thermal loads in the pipes,
- non-obvious paths followed by the hot water (paths that are longer than needed are used to transport the water from one bifurcation of the meshed network to an end user along a loop),
- bottlenecks (pipes through which a high mass flow rate is forced, also characterized by excessive thermal loads),
- and sinks (the nodes which have two or more flows as inlets, the only outlet being the user group served by the node).

Figs. 4–6 show the visualization of flow patterns for three cases with peak end user demand (the other three cases are not shown here for sake of brevity). In the figures, the active heat production sites are shown in red, while the inactive ones are shown in black. The pipes of the meshed network are coloured according to the ratio between the actual pipe thermal load and the capacity recommended by the manufacturer, with a colour scale that ranges from black (0–30%) to red (above 100%). The direction of the flow is indicated with black arrows on the pipe segments. The sinks are also shown as blue circles.

There is a significant difference in the features of the flow patterns between the scenario in which LKAB site is active (Fig. 4) and the other two in which it is inactive (Figs. 5 and 6). In the “all plants” scenario with peak end user demand the LKAB site introduces into the northern part of the network a considerable water mass flow rate. This results in a general reduction of the thermal loads in the pipes, in particular along the “backbone” of the network, i.e. the piping transporting the hot water from the northern outlet of the TVAB plant to the northern districts of the town. It is apparent that in Figs. 4 and 5 the main pipes along the backbone and some of their ramifications have a load between 70% and 100% of the recommended capacity (yellow and orange colours). Overloaded (red) pipes are present in the network at LKAB site outlet (Fig. 4), in a minor loop in the north-eastern part the network (Figs. 5 and 6), at the outlet of the Bath site (Fig. 5) and in parts of the southern loop of the network (Figs. 4 and 5), all being the consequence of undersized diameters in the design procedure.

Another difference caused by the operation of the LKAB site is the inversion of the flow direction in the pipes going south from the node at which the LKAB hot water enters the meshed network. This causes the formation of a third and fourth sink in the network, immediately south of the Ferrum site, where the water coming from the LKAB site meets that coming from the TVAB site along the backbone in Fig. 4. The hot water coming from the Bath site has also a similar effect on the flow directions in the piping going east from the site, with a third sink appearing in Fig. 5 where the water coming from the Bath and TVAB sites meet.

It is also worth noting that the sink in the large southern network loop, i.e. the sink where the water mass flow rates coming from the two outlets of the TVAB site meet, changes its position from the easternmost node of the network (Fig. 4) to one of the nodes along the branch between the TVAB and Glacier sites (Figs. 5 and 6). This creates a long non-obvious path from the northern outlet of the TVAB site to the sink, since the distance between the eastern outlet of the TVAB site and the sink is shorter by several hundred meters.

5. Conclusions and future work

A case study about the optimization of multi-source DH networks has been presented in this paper for the town of Kiruna. A modular modelling and simulation tool for complex meshed networks is used to investigate the conditions that minimize the total operating costs for not only the generation of heat at the production sites but also for its delivery to the end users. A hybrid evolutionary-MILP algorithm has been developed and coupled to DH network model simulations in order to solve this specific optimization problem.

The results of the optimization show that:

- due to the specific characteristic of the DH network in Kiruna a distributed heat generation is not able to reduce the total operating cost. The cheapest resources are consumed in the most efficient boilers irrespective of their location inside the network.
- The influence of the pumping power terms on the total operating cost is also minor, the optimal supply temperature at the heat production sites being the lowest compatible with the service to the end users in order to reduce as much as possible the thermal losses along the distribution network.
- The features of the flow patterns within the meshed part of the network are significantly affected by the hot water produced at the LKAB site using the waste heat from the iron mining facilities.

Future work will be devoted to add new features to the model, to

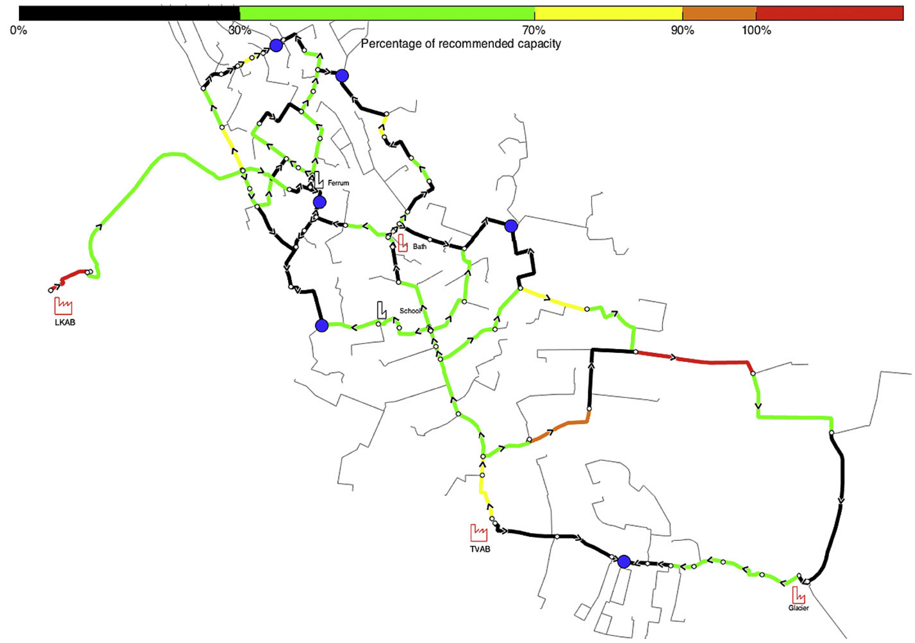

Fig. 4. Flow pattern of case “all plants”-49 MW.

make it even more flexible in representing the structure and the operation of real DH networks and to make its interface more user-friendly. The idea is to develop the overall methodology into a software that can be used by local energy companies to search for more cost-effective strategies in the operation of the DH networks they manage, by selecting more convenient supply temperatures, boiler loads and fuels.

Another possible use of such software would be the evaluation of potential design alternatives to the size and layout of the pipes and to the capacities of the heat production sites in order to reduce the operating costs. That would allow obtaining a more rational pattern of flow distribution (without excessive pressure drops due to overloaded pipes) and a lower fuel consumption (a more distributed heat generation would result in lower thermal losses). The final step would be to analyze and optimize alternative scenarios including new heat production sites and deep changes to network structure while planning for future expansions to a DH network.

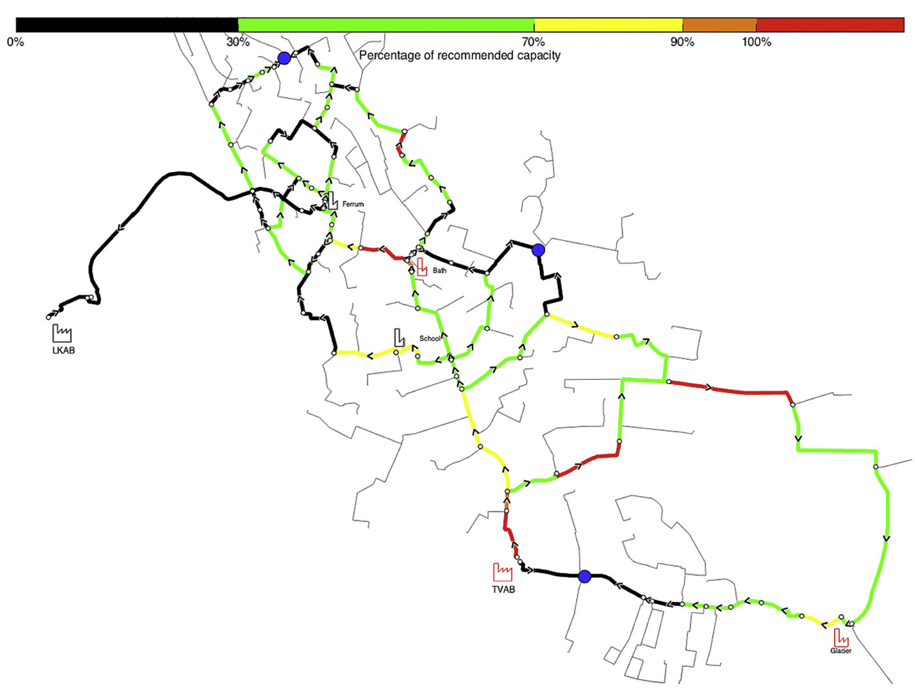

Fig. 5. Flow pattern of case “no LKAB”-49 MW.

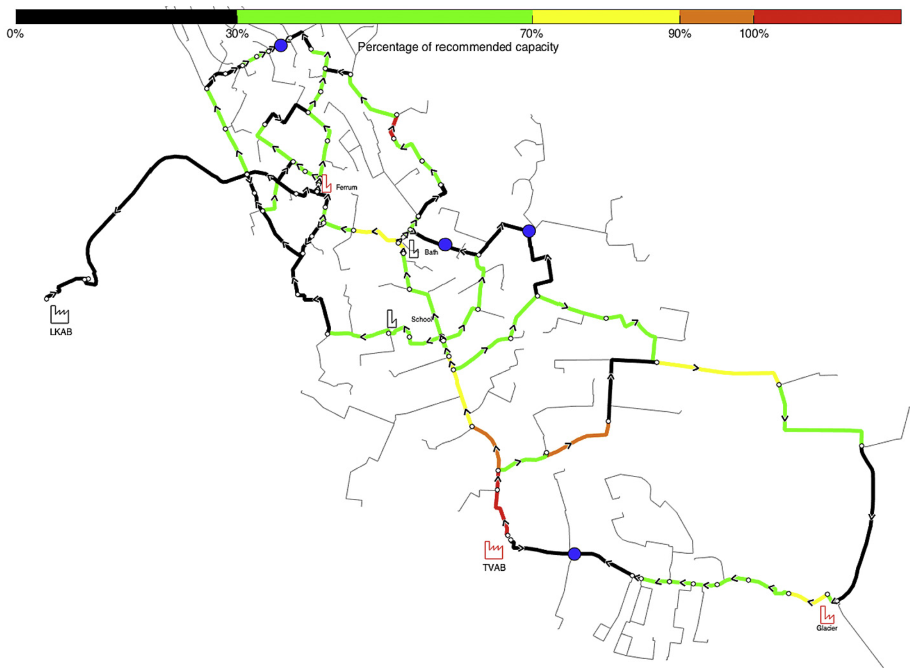

Fig. 6. Flow pattern of case “no LKAB, Bath”-49 MW.

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Appendix

A Simulink model was developed to simulate the distribution of the mass and enthalpy flows in the pipes of a meshed DH network. Due to the particular nature of meshed networks, two main aspects must be taken into account and reproduced numerically:

- the distribution of the mass flow rates of hot water in the network depends on the local pressure at piping junctions;
- the temperature of the hot water progressively decreases due to the thermal losses in the pipes as the hot water is transported from the heat production sites to the final users through the supply pipes and then back from the final users to the heat production sites through the return pipes.

Accordingly, the two fundamental variables that must be calculated by the model are the local pressure and temperature at the piping junctions in the network.

The developed Simulink model reproduces the original structure of a meshed network without any need of altering the several loops that characterize its topology, and at the same time it fully takes advantage of the opportunity to build a modular representation of the real network using just few component types. The Simulink diagram of the model for a DH network is made of four types of blocks (see a detail of it in Figure A1): pipe blocks (in red) and node blocks (in purple), which are used to define the physical layout of the network, and heat production site blocks (with the factory symbol) and user area blocks (in blue), which are used to define the boundary conditions of network operation. Each type of block is briefly described in the following.

Pipe blocks

Pipe blocks represent a piping segment made of a supply pipe and a return pipe of constant diameters. In these blocks the calculations to evaluate the mass and enthalpy flows in both pipes are performed separately with the same set of equations. The mass flows at the inlet and outlet of each pipe are the same, but the associated enthalpy flows are not, since the temperature of the water at the outlet of a pipe is always lower than that at the inlet due to the thermal losses.

The mass flow rate ($\dot{m}$) through a pipe is obtained from the difference of the local pressure (Δp) between the nodes at its ends according to Eq. (A1), which also requires specific information about the pipe such as the length (L), the diameter (D) and the Darcy friction factor (f, evaluated using a standard equation in the literature)

$$|\Delta p| = f\,\frac{L}{D^5}\,\frac{8\dot{m}^2}{\rho\pi^2} \tag{A1}$$

Please note that the direction of the mass flow rate, and the definition of upstream (inlet) and downstream (outlet) node for the calculation of the enthalpy flows, is subject to change according to the sign of Δp.

The enthalpy flow from the upstream node ($\dot{Q}_{up}$) is evaluated as:

$$\dot{Q}_{up} = \dot{m}\,c\,\left(T_{up} - T_{ref}\right) \tag{A2}$$

being c the specific heat of water, T_{up} the hot water temperature at the upstream node and T_{ref} a reference temperature for the calculation of enthalpy flows. The enthalpy flow to the downstream node ($\dot{Q}_{down}$) is then determined by subtracting the thermal losses in the pipe ($\dot{Q}_{loss}$),

$$\dot{Q}_{down} = \dot{Q}_{up} - \dot{Q}_{loss} \tag{A3}$$

The actual thermal losses are calculated with respect to those in a reference condition supplied by the manufacturer ($\dot{Q}_{loss,ref}$ under a temperature difference ΔT_{ref}) according to the following equation:

$$\dot{Q}_{loss} \Big/ \left(T_{up} - T_{ground}\right) = \dot{Q}_{loss,ref} \Big/ \Delta T_{ref} \tag{A4}$$

where T_{ground} is the temperature of the ground surrounding the pipe.

Node blocks

A node block corresponds to a physical junction between/among two or more different piping segments of different diameter, or to a location from which a feeding branch departs to supply a user area with some hot water that is extracted from the network loops. A node block actually comprises two nodes, one connecting the supply pipes and the other connecting the return pipes, and the same set of equations are used to perform separately the calculations related to both nodes.

The local pressure and temperature at a node are determined using differential equations expressing the balances of all the mass and enthalpy flows (which are calculated in the pipe blocks) arriving to and departing from the node.

$$k_p \frac{dp}{dt} = \sum_{pipes} \dot{m} \tag{A5}$$

$$k_T \frac{dT}{dt} = \sum_{pipes} \dot{Q} \tag{A6}$$

The built-in Simulink solver is used to find the equilibrium pressure and temperature that satisfy these balances after a fictitious transient that leads to the steady state behavior of the network.

As it appears, node blocks rely on the information about the quantities calculated in pipe blocks and vice versa. This exchange of information, i.e. pipe mass and enthalpy flows vs. node pressure and temperature, is critical for the simulation process, so the model is essentially built on the strict alternation of pipe and node blocks (see Figure A1). This closely resembles the real topology of a physical network, which is based on the alternation of piping segments and junctions.

Heat production sites blocks

These blocks represent the plants at which the hot water is generated and are used to mathematically specify the boundary conditions of network operation at the sources of mass flow rates that are pumped in the network. There are two sub-types of heat production site blocks according to the quantities that are imposed as boundary conditions.

In the first sub-type supply pressure and temperature are specified (this kind of boundary condition must be used at least in one of the heat production sites to set a reference for the pressures in the whole network). This block is to be connected to one or more pipe blocks, since it provides information on the local pressure and temperature as node blocks do. The amount of heat generated at the site is an output of the block, and is calculated from the specified supply temperature (T_{supply}), the mass flow rate leaving the site ($\dot{m}_{site}$, as calculated by the piping block(s) connected to the site) and the return temperature (T_{return}, obtained from the enthalpy flows returning to the site):

$$\dot{Q}_{site} = \dot{m}_{site}\, c \left(T_{\text{supply}} - T_{return}\right) \tag{A7}$$

In the second sub-type the amount of heat generated at the site and the temperature at which it is supplied are specified. This block is to be connected to a node block, since it provides information on a mass flow and its associated enthalpy flow as pipe blocks do. The mass flow rate of water taken from the return node of the junction and going back to the supply node of the same junction is an output of the block, and is calculated from the specified amount of heat generated at the site ($\dot{Q}_{site}$), the specified supply temperature (T_{supply}) and the temperature at which the water is taken from the return node of the junction (T_{return}, calculated by the node block connected to the site):

$$\dot{m}_{site} = \frac{\dot{Q}_{site}}{c\left(T_{\text{supply}} - T_{return}\right)} \tag{A8}$$

In both cases, the pumping power required to supply the network with the hot water from the site is obtained from the water mass flow rate heated by the site ($\dot{m}$) and the difference Δp between the local supply and return pressures at the site/junction:

$$P_{pump} = \dot{m}\, \frac{\Delta p}{\rho} / \eta_{hyd} \tag{A9}$$

being ρ the density of the water and η_{hyd} the hydraulic efficiency of the pump(s).

User area blocks

A user area block represents a group of consumers fed by the network and is used to mathematically specify the boundary conditions of network operation at the sinks of the mass flow rates that are supplied by the network. The heat demand of the group of consumers ($\dot{Q}_{demand}$) must be specified, but this is not sufficient to determine the difference between the enthalpy flows entering and leaving the block because the thermal losses from the tree of feeding branches have to be considered as well. These losses are calculated for the supply and return pipes using an equation similar to Eq. (A4) with a reference loss for the area to be specified. As a result, a difference exists between the supply and return temperatures at the junction from which the main feeding branch departs and the supply and return temperature at the users, so that $T_{node,supply} > T_{user,supply} > T_{user,return} > T_{node,return}$. The mass flow rate $\dot{m}_{user}$ that is needed to supply the heat requested by the user area (and that is extracted from the junction from which the feeding branch departs) is calculated as

$$\dot{m}_{user} = \frac{\dot{Q}_{demand}}{c\left(T_{user,\text{supply}} - T_{user,return}\right)} \tag{A10}$$

where the temperature difference $T_{user,supply}$ - $T_{user,return}$ is the water temperature drop in the area due to users' demand. This temperature drop is calculated as a function of the demand ($\dot{Q}_{demand}$) and the user supply temperature ($T_{user,supply}$) by using a characteristic response surface that is specific for each user area. In this way it is apparent that the mass flow rates extracted from the network by the users depend not only on the demand of the groups of consumers, but also on the temperature of the hot water at the junction in which the extraction takes place (which is in turn a function of the thermal losses along the network and the distribution pattern of water mass flows).

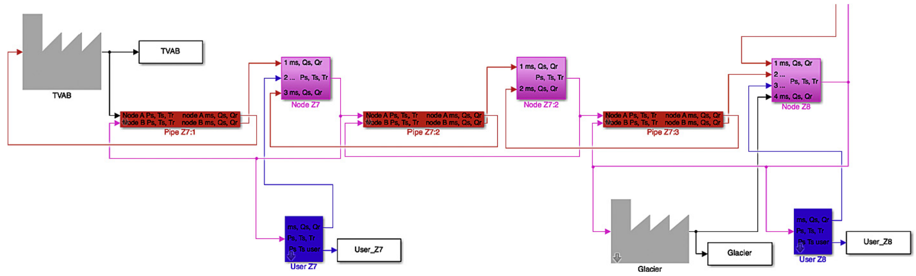

Fig. A1. Detail of the block diagram of the Simulink model for a meshed DH network.

The pressure losses in the user area are calculated again using Eq. (A1), with the assumption that the pipes in the tree of feeding branches are reduced to a single pipe of equivalent diameter and length.

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