District Heating Network Design

In the current Energy market context, District Heating (DH) has an important role, especially in counties with cold climate, as it often leverages on Combined Heat and Power (CHP) units, capable to reduce the consumption of primary energy to fulfill a given electric and thermal request, as well as on existing significant sources of heat generated by industrial processes or waste-to-energy heat generation. On the top of that heating networks will need to increase its flexibility in operation due to an increasing mix of renewable sources, both heat sources or green electricity utilized by heat pumps, distributed generation and smart consumers as well as DH operational temperature reduction and heat storage integration [1, 2].

From a management standpoint, the design of the district heating network is a strategic business issue, since it requires large investments, due to the cost of materials and civil works for the realization of the network. Proper strategic design of network (i.e. definition of the most convenient backbone pipelines to lay down) and tactical targeting of most promising potential customers both aims at maximizing the Net Present Value (NPV) of the investment.

Finding the extension plan for an existing (or eventually empty) district heating network that maximizes the NPV at a given time horizon is a challenging optimization problem that can be stated as follows.

Given:

- A time horizon (e.g., fifteen years)
- A set of power plants, with specific operational limitations (maximum pressure, maximum flow rate, …);
- An existing distribution network, with information on the physical properties of the pipes (length, diameter, …);
- A set of customers already connected to the network with known heat demand;
- A set of potential new pipes that can be laid down;
- A set of potential new customers that can be reached;

find:

I. The subset of potential new customers that should be reached;

II. Which new pipelines should be installed;

III. The diameter of the new pipes

that maximize the NPV.

Research on modelling approaches for representing the behavior of the thermo-hydraulic network through sets of non-linear equations can be found in the literature (see for example [3] and [4]). Solving systems of non-linear equations is difficult and computationally expensive. For this reason, aggregation techniques of the network elements are often used to model large district heating networks, at the expense of some accuracy [5] [6] [7] [8] [9] [10].

In [11], an integer-programming model is proposed for the optimal selection of the type of heat exchangers to be installed at the users' premises in order to optimize the return temperature at the plant. The authors achieve good system efficiency at a reasonable cost.

[12] present a mathematical model to support district heating system planning by identifying the most advantageous subset of new users that should be connected to an existing network, while satisfying steady state conditions of the thermo-hydraulic system. [13] extend the model proposed by [12] with the selection of the diameter for the new pipes and a richer economic model that takes into account

- Production cost and selling revenues;
- Cost for installing and activating new network links;
- Cost for connecting new customers to the network;
- Amortization;
- Taxes;
- Budget constraints.

Moreover, while the investment on the backbone pipelines is done on the first year, new customers are not connected immediately, but following an estimated acquisition curve (e.g., 25% the first year, 15%, the second year,…). Hence, the corresponding costs and revenues have to be scaled accordingly.

The thermos-hydraulic model must ensure the proper operation of the extended network. The following constraints are to be imposed:

- Flow conservation at the nodes of the network;
- Minimum and maximum pressures at the nodes;
- Plants operation limit: maximum pressure on the feed line, minimum pressure on the return line, minimum and maximum ow rate;
- Pressure drop along the links;
- Maximum water speed and pressure drop per meter.

Continuous variables model pressures at nodes and flow rate on the links and binary variables model decisions on the connection of new customers, on the installation of new links, on the diameter choice and on ow direction on the links. The last ones are necessary since district-heating networks contains cycles: the potential network usually corresponds to the street network. Thus, it is not possible to know a priori the flow direction on the links (at least not for all of them) and such decision must be included into the model. The pressure drop along a pipe is a non-linear function that depends on ow rate, and on the diameter of the pipe. This can be approximated using a piecewise linear function, that translates into a set of linear constraints. The higher the number of segments in the piecewise linear function, the smaller will be the approximation error. At the same time, the number of constraints grows (there is one piecewise-linear function for each combination of pipe and diameter) and the solving time increases. To keep the number of segments small, while obtaining a good accuracy, breakpoints of the piecewise linear function can be concentrated in the most probable range of flow rate.

District heating networks can be quite large (hundreds of existing and potential users, thousands of links) making it difficult to solve the full MILP directly. Solution methods developed in [13] approach the problem in three steps.

1. Solve the linear relaxation of the MILP model and use it to select water direction in all the pipes. Then, solve to integrality the MILP model, with the directions fixed, obtaining a first heuristic solution.
2. In the solution found at step 1, the conflict points, which are the nodes of the network where different water direction meet, are detected. The flow direction is released for the nodes close to conflict points, and the MILP model is solved again, obtaining a second heuristic solution.
3. The full MILP, initialized with the best solution found in the previous steps, is solved, until either optimality or the time limit are reached.

Optit S.r.l. has developed a decision support system, in collaboration with the University of Bologna, based on the modelling mentioned above, that has been successfully used in two of largest multi-utility companies operating in the Italian District Heating market. The application leverages on open source Geographical Information System (GIS) to allow a simple user interface and a number of plug-in tools to manage the specific optimization issue.

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