Automated Design of District Heating Networks through Topology Optimisation

How can modern District Heating Networks be designed as cheap as possible, while accounting for specific requirements like low temperature operation? In this article it is shown how a new numerical optimization strategy is able to automatically generate District Heating Network designs based on a realistic physical model of the network temperature and pressure distribution.

With modern District Heating Networks (DHN), large shares of presently untapped renewable and wasteheat sources can be harnessed. The present emphasis lies on 4th generation district heating networks that aim at fully exploiting the district heating potential and integrating renewable heating sources while minimizing grid losses [1]. The low network operation temperatures of 4th generation networks, however, put a lot of pressure on the (re-)design of district heating networks.

Recently, a number of researchers have explored the use of numerical optimisation to obtain optimal network topologies, dimensioning, and operation parameters. Given the difficult nature of this discrete problem, many authors simplify the underlying physics to obtain a Mixed-Integer Linear Program (MILP) for the optimal network (e.g. [2]). But this linearization cannot capture some important intrinsically nonlinear features of 4th generation networks, like head and heat losses in the network pipes. Other authors therefore started solving the non-linear features at least partially in a Mixed-Integer Non-Linear Program (MINLP) with gradient free methods or combinatorial optimisation (e.g. [3]). The applicability of this methods suffers from a steep computational cost scaling though, strongly limiting the amount of design variables that can be dealt with.

The authors of this article therefore introduced a scalable approach for thermo-economical optimal design of district heating network topologies (figure 1) that simultaneously optimises discrete pipe size and operational parameters. The methodology of this approach that is based on adjoint gradient calculations was published in [4]. In contrast to simplified linearized approaches used in MILP optimisation, it is first of all based on a complete transport model accurately accounting for the influence of non-linear effects on the design of 4th generation district heating networks. By being based on the adjoint approach, it is secondly not limited to street level assessments, but shows the potential to consider districts and/or small cities [4]. This article aims at highlighting recent results that were obtained with this approach in the area of economic DHN optimisation and achieving discrete pipe design.

New topology optimisation algorithm for district heating networks

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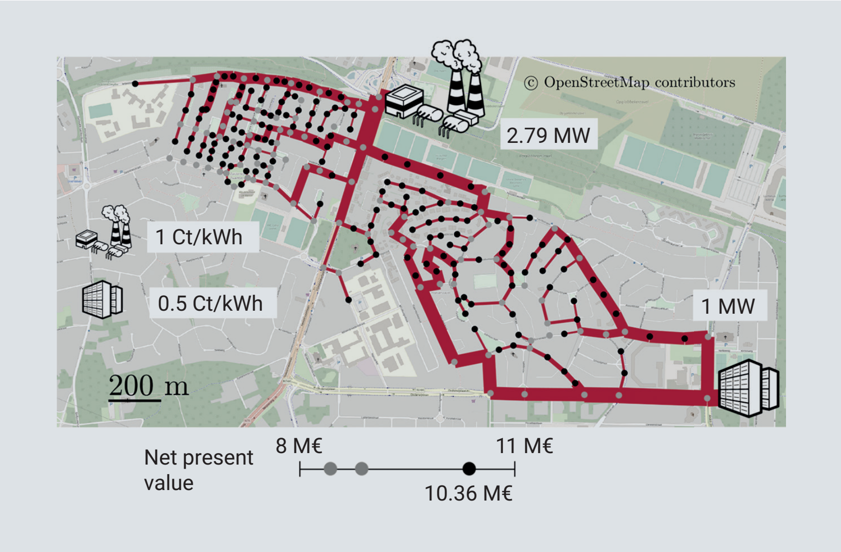

Figure 1. Optimal topology for two heat producers. Placed pipes are drawn as red lines; removed pipes are drawn in grey. Introducing a low-temperature waste heat source in the south results in two separate networks Source: [5]

this paper in [4] and [5]. An extensive explanation and derivation of the following approach can be found there. To highlight the potential of adjoint based topology optimisation for DHN, important parts of the method will be discussed in this section.

The aim of the presented method is to optimise the topology and configuration of a DHN by minimising a cost function (e.g. maximising the net present value) while accounting for the non-linear physical behavior of the network. In order to solve this optimisation problem numerically, a gradient-based Quasi-Newton algorithm is employed. The sensitivity of the cost with respect to all design variables is calculated simultaneously using the adjoint approach. It can be obtained at a cost of the same order of magnitude as a single simulation of the model equations. Thus realising a significant speed-up for the optimisation process as compared to other strategies.

The process of calculating adjoint sensitivities requires the evaluation of the non-linear DHN physics. To formulate the network model equations, four different categories of thermal network components that need modelling are considered: pipes, pipe junctions, consumers, and producers. The pipe and pipe junction model consists of mass, momentum, and energy conservation and accounts for hydraulic friction and heat losses in the pipes. For an estimate on the heat transferred to each consumer, it is supposed that the consumer substation consists of a bypass and a heating system directly connected to the network. The heat transfer to the house by the heating system is modeled using the characteristic radiator equation [6]. The producer is modeled as a heat source with a fixed input temperature and a flow rate of which the size is determined by the optimisation itself.

Showcasing the algorithms potential – a test case

In the following, the functioning and scalability of the network optimisation algorithm on a fictitious test case are demonstrated. Yet, a realistic test case is chosen that aims at designing a medium-sized district in Genk, Belgium. 160 consumers of three different consumer types with varying heat demand are distributed throughout the neighborhood. Assuming a traditional radiator system, the nominal temperature for which the heating systems of all three consumer types is designed is supposed to be T_{nom} = 55 °C. The distribution of the consumers and their heat demand can be found in figure 2 a). As can be seen in figure 2 b), the pipe superstructure, indicating the possible piping routes for the network optimisation, is placed onto a part of the neighborhood's street grid.

Optimising the network design for maximal net present value

In the following, the potential of economic DHN optimisation based on a fully-fledged flow and heat transport model is highlighted. The results have been previously presented by the authors in [5].

A heat producer with a fixed temperature T_N = 70 °C is placed in the north of the neighborhood. The heat delivered by the producer will be matched to the combined heat demand of the consumers and the heat losses in the network by con-

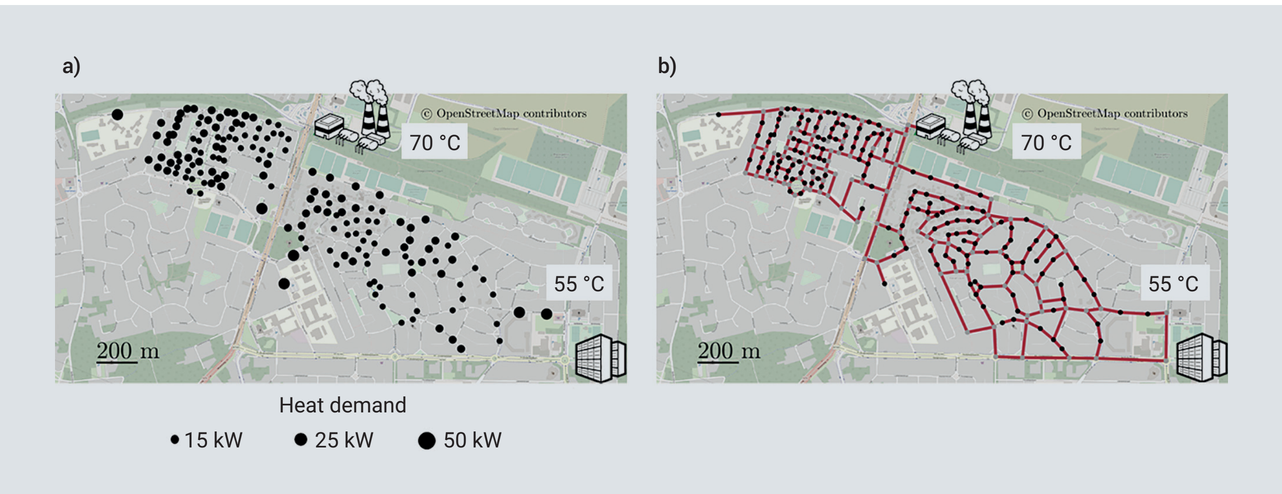

Figure 2. a) Distribution of consumers in the neighborhood. Consumers are represented by black circles of varying sizes corresponding to their respective heat demand (15 kW,25 kW,50kW). The power station icon represents the heat producer of T_N = 70 °C. b) Initial topology and configuration of the network Source: [5]

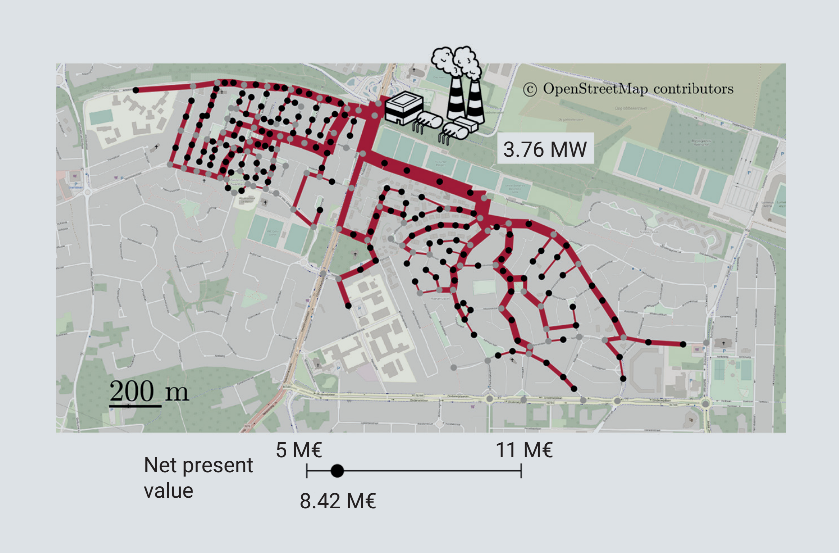

Figure 3. Optimal topology for a single heat producer. Placed pipes are drawn as red lines; removed pipes are drawn in grey Source: [5]

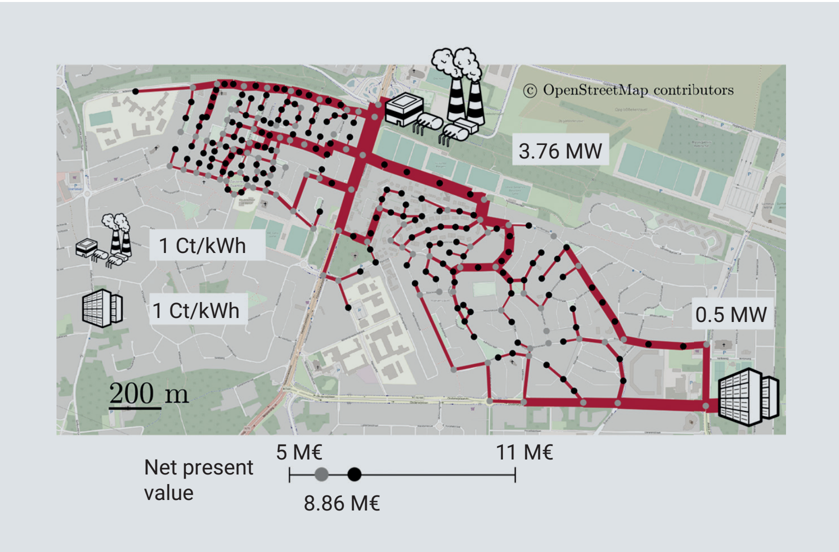

Figure 4. Optimal topology for two heat producers. Placed pipes are drawn as red lines; removed pipes are drawn in grey. By decreasing the heat acquisition price to Ct0,5 /kWh for the waste heat source, the share of waste heat is increased Source: [5]

trolling the rate at which the hot water flows into the network. To ensure the thermal comfort of all consumers, a constraint is imposed, assuring that the heat delivered to the consumers does not deviate more than 5% from their respective heat demands. Additionally, the maximum pressure in the network is constrained to stay below 10 bar.

Now, the optimisation algorithm is used to find the optimal routing topology and the optimal pipe diameters. Simultaneously, the heat inflow by the producer and the valve controls at the consumers are optimised. For this purpose, an economic cost function is defined that includes the pipe and heat production Capex, as well as the pump and heat production Opex. These costs are properly weighted and combined with the revenue from selling the heat by using the net present value of the network for an investment horizon of 30 years and a discount rate of 5%. The optimisation problem therefore directly results in a network with maximal net present value. For this first economic optimisation, the need for discrete diameter choices is relaxed and only the discrete choice of the topology is enforced.

The resulting optimal topology for this two producer case is shown in figure 3. A tree-like network structure was found that branches out from the producer towards the different consumers with pipes of decreasing size. In this first case, the optimal network has a net present value of €8,42 million. The average heat loss was minimized to only 8.43%.

As a next step in the design study, an additional waste heat source in the south-east region of the neighborhood is considered. It provides heat at T_S = 55 °C. Given that it is a waste heat source, the heat Capex is supposed to be free of charge here at €0 /kW, while the Opex is taken identical to that of the hot source. The optimal network considering the waste heat source can be seen in figure 4.

It can be seen that a number of consumers in the south are now provided with heat from the waste heat source. This results in two separate networks for this neighborhood: A high-temperature network in the north and a low-temperature network in the south.

To increase the overall waste heat share of this network, the heat acquisition price for the waste heat source is now decreased to Ct0,5 /kWh. This leads to a bigger low-temperature network and more consumers being connected to the waste heat source (figure 1). The overall lower costs of heat produc-

Diameter [m]	0	0,032	0,065	0,1	0,15	0,2	0,3	0,4
Piping cost [€/m]	0	2.202	2.218	2.258	2.448	2.461	2.665	2.922

Table 1. Discrete diameters available and their respective pipe investment cost

tion of the waste heat source lead to an increase of the networks net present value to €10,36 million.

The (economic) difference in the resulting network designs and topologies for different planning scenarios, even those that appear quite similar, highlights the importance of basing the optimisation of DHN on an accurate physical model. If done properly, such an optimisation can be a valuable tool to study different investment scenarios or pave the way for sustainable energy planning.

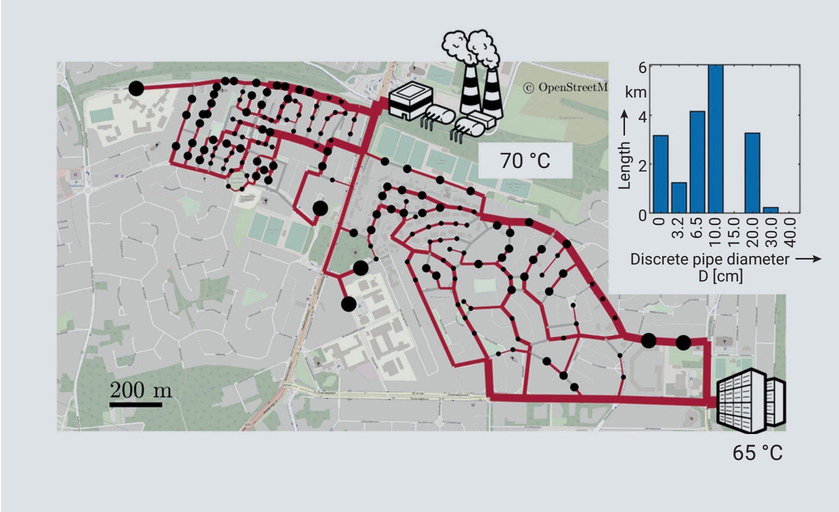

Figure 5. a) Optimal discrete network topology and configuration. Placed pipes are drawn as red lines; removed pipes are drawn in grey. b) Total length of all placed discrete pipe diameters in the feed network Source: [4].

Optimal network topology considering discrete pipe diameter choices

Now it is showcased how it is possible to achieve optimal discrete pipe design while minimizing the network's pipe Capex and pump Opex. For a detailed description of this case, the reader is referred to [4]. The setup is similar to that of the previous case (figure 2), with an inflow temperature of the south producer equal to T_S = 65 °C. The optimisation now minimises the pipe Capex and pump Opex of the network, while using a penalisation method to slowly drive the optimal pipe design towards discrete values. The catalogue of discrete pipe diameters and their respective cost is noted down in table 1.

For this test case with 632 design variables, the optimisation procedure converged after 46 minutes on a standard laptop. The resulting network topology is given in figure 5a). The installed pipes all have discrete diameters. The total length of pipe installed for each of the different pipe size options can be seen in figure 5b).

Conclusion and outlook

First results of a numerical optimisation strategy were presented that efficiently optimises the routing strategy, pipe diameters, and operational configuration. And its potential on a district heating network with 160 consumers, and two producers at different temperatures was demonstrated. The algorithm was able to find an optimum within minutes.

The shown design study highlights the influence of the non-linear heat transport problem on the optimal routing strategy and design, and the clear benefit of accounting for these non-linearities in the design phase. By directly evaluating the profitability of the optimal networks, different valorization scenarios can be compared.

This makes the approach a promising tool for future large-scale design studies of modern, low-temperature district heating networks and opens the door for widespread integration of renewable and low-grade heat sources.

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Yannick Wack won the second place in this year's DHC+ Student Awards.