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Optimizing district heating networks: Balancing cost, efficiency and consumer benefits

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ABSTRACT

District heating networks (DHNs) are essential for decarbonizing building energy demand and are expected to play a larger role in future energy systems. Optimizing DHN design is vital as it directly impacts system cost and performance. Current optimization methods focus on minimizing cost without considering technical performance or its impact on its end-users. In some regions, there is limited social acceptance for DHN due to poor technical performance, highlighting the need to integrate consumer-oriented performance criteria in the design phase. This study proposes a DHN optimization method that explicitly incorporates user-level performance when evaluating different DHN designs. Two design strategies-a cost-optimal design and a maximum-efficiency design-are compared across 100 small, randomly generated DHNs and on a large real-world case. For small DHNs, the cost associated with efficiency improvements shows high variability. Only 6% of cases exhibit a cost increase below 10% per 1% efficiency gain, and only 3% are within the range of 0.5-2%. In the large DHN case, efficiency optimization increases the network's efficiency from 56.5% to 69.7% at 18% cost increase. Efficiency-oriented designs significantly reduce consumer exposure to thermal discomfort under cold outdoor conditions or heat-source disturbances, and require less energy to meet demand. As network efficiency can potentially yield great benefits for consumers in the DHN, focusing solely on cost optimization is shortsighted. More emphasis on network efficiency may increase social acceptance of DHN and by that accelerate the energy transition.

1. Introduction

Society faces the challenge of rapidly reducing greenhouse gas emissions. Energy use in buildings currently accounts for 17.5% of global emissions [1]. District heating networks (DHNs) are widely regarded as a promising solution for providing near-carbon-neutral heating in dense urban areas [2]. As DHNs become increasingly important in decarbonization strategies, research efforts have intensified towards the designs and planning of these systems. In particular, growing attention is being paid to optimizing the spatial layout of DHNs and the design methods used [3].

Usually, DHN layouts are designed with a focus on minimizing investment cost. Until today, many DHN designs are based on the 'Minimum Spanning Tree' or on the intuition of the designer [4]. However, by now it is known that DHN layouts based on the 'Minimum Spanning Tree' do not result in the minimum-cost DHN design [3]. Research shows that pipeline sizing, thermal losses and the DHN layout strongly affect both investment and operational costs and therefore determine the optimal DHN design [4]. Also, research shows that the largest share of the cost is in the piping and the groundwork of the DHN [5]. Consequentially, this cost determines the economic feasibility of a DHN [6]. To address these challenges, substantial effort has been devoted to developing advanced optimization methods for DHN design. The dominant optimization objective in the literature remains however the reduction of investment and/or operational costs [7]. Due to the criticality of cost, numerous studies propose methods to optimize DHN designs such that investment- and/or operational cost are minimized

A literature review by [8] shows that over 95% of DHN optimizations focus on minimizing cost. Also, Lambert and Spliethoff (2024) propose a DHN layout and pipe sizing optimization method based on two consecutive optimizations. The goal of the research is to propose a fast optimization method that minimizes investment- and operational costs of a DHN [9]. Schmidt and Stange (2021) propose a software tool that optimizes DHN layout and pipe sizing to support decision makers by calculating minimum-cost DHN. Best et al. (2020) propose an optimization method where the total life-cycle cost of a DHN design is considered. The calculation method includes pipe sizing, heat loss and pumping energy. Lastly, [10] propose an optimization method where insulation thickness of the pipe is optimized. The proposed optimization method minimizes the total life-cycle cost of DHN layouts. Literature reviews by Jiang et al. (2022) and Sporleder et al. (2022) prove that most optimization

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methods proposed thus far focus on minimizing investment- and operational costs.

Despite the importance of investment cost, the literature also indicates that more attention must be paid to guarantee thermal comfort for consumers [11]. Bouw (2016) studied consumer satisfaction in DHNs in Europe and concluded that comfort in DHNs depends on the quality of the heat source and on the general need for energy; Consumers in older buildings with a low level of insulation and low radiator capacity are often thermally uncomfortable [12]. Not considering thermal comfort for consumers during the development of the district heating network increases consumers' dissatisfaction and reduces technical performance of the DHN [12]. In the Netherlands and the UK, DHNs have a poor reputation, mostly due to the bad technical performance of existing systems. In Scandinavian countries, DHNs are more socially accepted as the systems have a much better technical performance [12]. The social acceptance is needed to accelerate the energy transition [7]. Also, [13] concludes that further research should include the consumers' comfort in DHN development. Not including thermal performance in the optimization process may lead to DHNs where some buildings, further away from the heat source, are systematically colder than other buildings closer to the source [11]. Despite the need to include consumers'comfort and technical performance in the design of the DHN, a literature review by [8] shows that technical performance and social values are almost never included in an optimization objective.

As consumer satisfaction and technical performance are critical, yet often overlooked, DHN optimization objectives, this paper makes an initial attempt to incorporate effective energy consumption by consumers in the DHN, aiming to enhance comfort and satisfaction. The research evaluates both efficiency and investment cost across different DHN designs, providing insights into the trade-off between these two key factors. Additionally, the impact of varying environmental conditions on different DHN designs is analyzed, offering a deeper understanding of how specific design choices influence the network's performance from the consumer's perspective.

2. Problem definition

A DHN is a pipeline network that supplies heat to buildings. Within the DHN, heated water flows from the DHN towards the buildings. The energy captured in the heated water is used for spatial heating. Using a heat exchanger, installed at every consumer's building, heat is exchanged between the hot water and the indoor heating system [14]. Usually, DHNs are applied in urban areas with high consumer densities. In those areas, streets determine where pipelines can be constructed [7]. Fig. 1 illustrates the key components of the DHN. In 1, the grey lines define the street network in which the DHN is constructed. The red lines are streets that must be included in the DHN due to the presence of buildings. The red central node is the heat source. Blue nodes represent street intersections that may serve as routing points within the network.

The DHN optimization problem under study is summarized as follows: Given an area with one heat source and buildings distributed along certain streets with a given heat demand, the goal is to determine a viable DHN design to either minimize cost or maximize energy efficiency. Two DHN designs are evaluated and compared: a cost-optimized design and an efficiency-optimized design. Calculating both solutions separately leads to insight in the trade-off between cost and efficiency, but also allows for fair assessment of the DHN performance from the perspective of the consumers. To simplify calculations and analysis, this study considers only one heat source in the DHN.

In this paper, graph theory is used to optimize the DHN for two reasons. First, urban areas have a good ontological correspondence with network graphs: streets can be characterized by edges and street-intersections by nodes. The street network and the derived DHN can therefore be modeled as a graph. Second, graph theory has the ability to generate many different network designs computationally fast using heuristics.

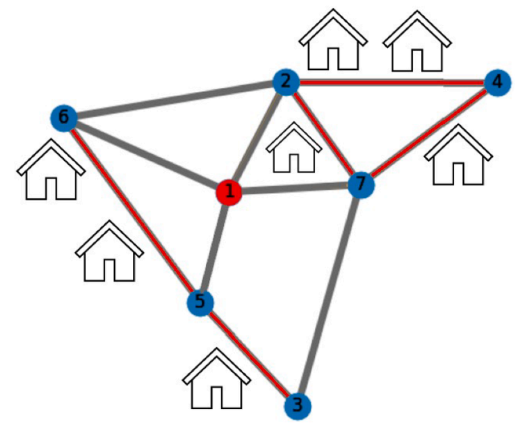


Fig. 1. Schematic representation of a district heating network (DHN) layout over a street network.

2.1. Graph notation

Let G be the graph of the street network in the area. Let $E(G)$ be the edges (streets) of the graph, and $V(G)$ the nodes (intersections) of the graph. $l_{i,j}$ is the length of the edge (i, j) between node i and node $j : \forall(i, j) \in E(G)$.

Within the area, each building receives energy via the street that is closest to the building. The energy requirements of the buildings in the street must be met by supplying energy via a pipeline running along that street. The total heat demand of all the buildings in a street $(i.j)$ is denoted as $h_{i,j}, \forall(i, j) \in E(G)$.

The binary decision variable, $x_{i,j}$, determines whether or not a pipeline will be constructed along an edge (i, j). The heat network N is defined as a subgraph of G with

$$E(N) = \{(i, j) | \forall(i, j) \in E(G), x_{i,j} = 1\}$$

The heating network N must satisfy two constraints. First, all streets with demand must be included in the heat network N.

$$x_{i,j} = 1, \forall(i, j) \in E(G), h_{i,j} > 0$$

Second, all streets with demand must be reachable from the source. Let node $s, s \in V(G)$, denote the unique heat source. Let $d_{i,j}, \forall i, j \in V(G)$, be the length (in meters) of the shortest path between nodes i and j in the graph G with $d_{i,j} = \infty$ if there is no path between i and j. For every street (i, j) with heat demand, a valid network design must ensure that both nodes i and j are reachable from the heat source:

$$d_{s,i} < \infty \wedge d_{s,j} < \infty, \quad \forall(i, j) \in E(G), \quad h_{i,j} > 0$$

The goal of this research is to determine both the minimum-cost and the maximum-efficiency design. The performance of these two DHN designs are compared on cost, efficiency, and their impact on energy delivery to the consumers. The following section explains the relation between the two, and the optimization objectives used.

3. Methodology

3.1. Cost model

In order to optimize the DHN for total cost, a cost function based on the DHN design is required. The cost model chosen is based on the principles of economies of scale. Tribe and Alpine (1986) described 'the rule of 0.6' which is called the pipeline cost dependence to capacity, that

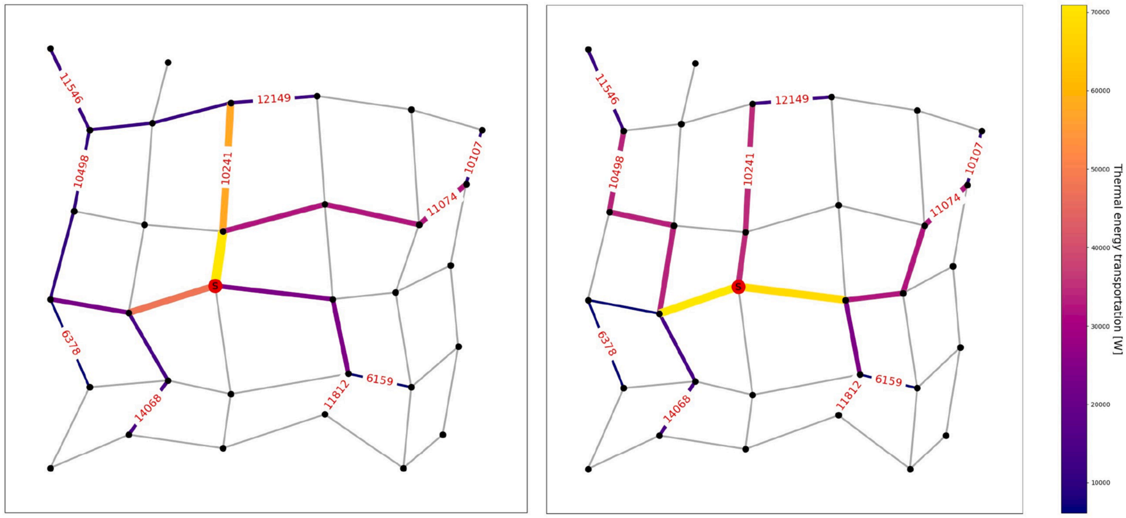


Fig. 2. DHN topology affects energy flow in the network.

uses an exponent to calculate the increase in cost if a pipeline increases in size [15]. An exponential function to estimate the cost of a DHN is applied in related work such as Yeates et al. [16] and Heijnen et al. [17]. Based on the principles of economies of scale, the cost of building a DHN in a given street network is chosen to be:

$$C(N) = \alpha \sum_{(i,j)\in E(N)} l_{i,j} q_{i,j}^{\beta} \tag{1}$$

In which $l_{i,j}$ is the length ([m]) and $q_{i,j}$ is the capacity ($[\frac{m^3}{s}]$) of the pipeline $(i,j), \forall (i,j) \in E(G)$. Parameter β ([-]) is the capacity-cost exponent and is dimensionless and equals 0.7 for the pipes of the DHN [16]. Parameter α is a cost factor ($[\frac{€}{m^4}]$) that denotes the cost ([€]) for 1 m pipe with a capacity of 1 m^3/s. However, since the cost function is only used to compare different network topologies, this constant is assumed to be 1 in the remaining analyses.

It is assumed that pipeline diameters are dimensioned according to the required energy flow. Hydraulic effect and standardized pipeline diameters are not considered in the model. These simplifications are accepted for the purpose of this study as the objective is to compare thermal losses between a cost-optimized and an efficiency-optimized network. Since both designs are derived using the same method, the relative comparison remains valid. Therefore, at a fixed flow velocity v ([m/s]), the pipeline capacity $q_{i,j}$ has a direct relation with the pipeline diameter $D_{i,j}$ ([m]):

$$q_{i,j} = \frac{\pi}{4} v D_{i,j}^2, \forall (i,j) \in E(N) \tag{2}$$

Under the assumption that the pipelines are dimensioned on the required energy flow through them, the topology of the DHN affects the diameter of the pipe. Fig. 2 demonstrates how the DHN design changes the pipeline diameters. In both DHN designs, the underlying street network, consumer location and energy requirements are the same. The left DHN design is based on the shortest paths to all consumers. The right design is a random design based on intuition that includes all consumers. The colored lines show where pipelines are constructed while the color shows the required energy flow through the pipe. The differences in color show that the DHN layout determines energy flows, and consequently, pipeline diameter, cost and efficiency.

To calculate the required pipeline diameter, the energy flow through each node is calculated. The energy flows along the unique path from the source through the pipes to the buildings. Let $f_{i,j}$ be the energy ([J]) that flows in edge (i,j), then $f_{i,j}$ is the sum of the heat demands $h_{k,l}, \forall (k,l) \in E(N), h_{k,l} > 0$ if (i,j) lies on the unique path from source s to node l. Knowing the energy that flows between node i and j ($f_{i,j}$), the mass flow $m_{i,j}$ ($[\frac{kg}{s}]$) in the pipeline (i,j) can be calculated by:

$$m_{i,j} = \frac{f_{i,j}}{(T^s - T^{in}) \cdot C_p \cdot \sigma_{gen}} \tag{3}$$

in which T^s ([°C]) is the water temperature at the source and T^{in} ([°C]) the desired indoor temperature. The parameter σ_{gen} ([-]) is a correcting factor that increases the mass flow due to lost energy via thermal losses. Given the mass flow and the density of water ρ ($\frac{kg}{m^3}$), the diameter of each pipeline in the network can be calculated from the obtained mass flow ($m_{i,j}$):

$$D_{i,j} = \sqrt{\frac{2 \cdot m_{i,j}}{\rho \cdot \pi}} \tag{4}$$

With these equations, the required diameters of the pipes in the DHN are calculated. From this, also the investment cost of a DHN (N) is be calculated using Eqs. (1) and (2).

3.2. Thermal model

The other optimization objective is to maximize the energy efficiency of the DHN. Inevitably, a share of the thermal energy that is pumped into the DHN is lost due to thermal losses. Thermal loss is defined as the share of energy that is lost while transporting thermal energy to consumers. Minimizing thermal losses increases effective energy consumption by consumers in the DHN as there is more energy to be received by the consumers. Insulated pipelines limit the thermal losses and are often applied in a DHN [1]. Fig. 3 shows a schematic overview of the thermal loss through an insulated pipeline. Note that the temperature of the ground (T_g) and the temperature of the water (T_W) are variable. Depending on the temperatures of the ground and the water, a certain amount of heat (Q) is exchanged.

The heat loss through the pipes depends on the size of the pipe, the ground temperature, the temperature of the water and insulation thickness. A heat transfer coefficient describes how well heat is transferred per area of the surface. Let $U_{i,j}$ ($[W/m^2K]$) be the heat transfer function of the insulated pipe between node i and j. r^s and r^i are the thicknesses of the steel and the insulation respectively. Following [18] the

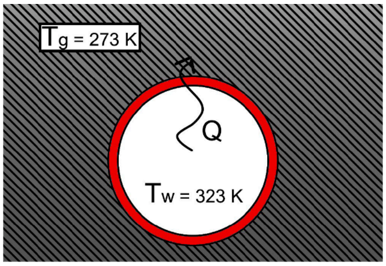


Fig. 3. Schematic heat loss of a pipe with heated water.

heat transfer coefficient is described by:

$$U_{i,j} = \frac{1}{\left(D_{i,j} + 2(r^s + r^i)\right) \cdot \left(\frac{\ln\left(\frac{D_{i,j}+2r^s}{D_{i,j}}\right)}{2k^S} + \frac{\ln\left(\frac{D_{i,j}+2(r^s+r^i)}{D_{i,j}+2r^s}\right)}{2k^I} \right)} \quad [W/m^2K] \tag{5}$$

The heated water may flow through multiple pipes at the same instance. If the heated water flows through multiple pipes at the same instance, the heat transfer coefficient is affected. Let $P(r)$ be the set of heat transfer coefficients at r meters from the source. The total heat transfer, $U^T(r)$, of the heated water flow that passes multiple parallel pipes equals:

$$\frac{1}{U^T(r)} = \sum_{U_{i,j} \in P(r)} \frac{1}{U_{i,j}} \quad [m^2K/W] \tag{6}$$

Let $A^P(r)$ be the total outer surface area of the set of pipelines at r meters from the source. Using the inverse of the flow velocity, the time it takes for the head of the flow to pass the distance $(r+1) - r$ is calculated. Let $T^w(r)$ be the temperature of the water at r meters from the source and T^g be the temperature of the ground. The total heat loss $Q(r)$ that occurs at r meters from the source is calculated as follows:

$$Q(r) = U^T(r \cdot A^P(r) \cdot (T^w(r) - T^g) \cdot \frac{1}{v} \quad [W] \tag{7}$$

Using the topology of the DHN design the thermal losses of the whole system can now be calculated. Changing the topology, and thus re-calculating the pipeline diameters and thermal losses, may lead to a DHN where the cost and total thermal loss may be higher or lower.

3.2.1. Mass flow changes

In addition to the temperature decrease when the water flows through the network, the mass flow rate also decreases. Consumers in the district heating network receive energy by diverting a portion of the mass flow from the pipeline through the heat exchanger in their building. This energy is intended to meet their specific heat demand, ensuring a comfortable indoor temperature. The heat exchanger adjusts the amount of water each consumer draws from the system to deliver the precise amount of energy required for the building's central heating. A set of assumptions is used to calculate the mass that each consumer draws from the DHN.

The heat exchanger model is developed based on parameters derived from a heat exchanger in operation. The capacity of a DHN heat exchanger for regular houses (100 m^2), that operates between 35–65 °C is 10 kg/min [14]. Eq. (8) is used to calculate the maximum amount of mass flow a building may subtract from the DHN as a function of the floor area in that building.

It is assumed that the parameters of the heat exchanger as described above, can be applied proportionally to buildings with other amounts of total floor area of the building. If a heat exchanger for a 100 m^2 is limited to 10 $\frac{kg}{min}$, the allowed mass flow to building b is defined by its total floor area (A_b) as described by the following equation:

$$M_{max} = \frac{A_b}{100} \cdot 10 \quad [kg/min] \tag{8}$$

It is assumed that the heat exchanger is able to control the mass flow into the building perfectly: The heat exchanger passes the exact amount of mass flow a building requires. If this required mass flow passes the limit imposed by the heat exchanger, the limit is set by the capacity of the heat exchanger.

$$M_b = \min\left(\frac{H_b}{C_p \cdot (T^w(r) - T^{in})}, M_{max} \right) \tag{9}$$

Knowing the mass flow a building receives (M_b), the temperature of the water at r meters from the source ($T^w(r)$), the desired indoor temperature (T^{in}) and the heat capacity of water (C_p), the energy building b receives equals:

$$E_b = C_p \cdot M_b \cdot (T^w(r) - T^{in}) \quad [J/kgK] \tag{10}$$

Now,the energy received by b (E_b) is compared to its heat demand (H_b). The fraction between those two determines the consumer satisfaction (S_b):

$$S_b = \frac{E_b}{H_b} \tag{11}$$

At one instance, multiple buildings may subtract different amount of mass from the DHN. Let $B(r)$ be the set of buildings that are connected to the DHN at r meters from the source. The mass left in the pipeline then equals:

$$\overline{m}(r+1) = \overline{m}(r) - \sum_{b \in B(r)} M_b \tag{12}$$

Due to heat losses as calculated with Eq. (7) and mass exchange with the buildings as calculated with Eqs. (9) and (12), the mass flow through the DHN reduces in energy content. The change in energy content (E^p) is calculated as follows:

$$E^p(r+1) = E^p(r) - Q(r) - \sum_{b \in B(r)} E_b \tag{13}$$

Due to heat loss, the temperature of the water in the pipe lowers. The temperature of the water at $r+1$ meters from the source has reduced to:

$$T^w(r+1) = \frac{E^p(r+1)}{C_p \overline{m}(r+1)} + T^{in} \tag{14}$$

When all buildings in the DHN have received their share of energy from the DHN, some energy may remain in the pipeline. This energy, E^{left}, is calculated after the last building has passed at a distance of r^f meters from the source.

$$E^{left} = C_p \cdot \overline{m}(r^f) \cdot (T^w(r^f) - T^g) \quad [J] \tag{15}$$

The efficiency is defined as the amount of energy that is not lost, compared to the input of energy the DHN received at the source. When the total losses are added up, the efficiency of the DHN may be calculated. Efficiency of network N (η_N) equals:

$$\eta_N = 1 - \frac{\sum_{r=0}^{r^f} Q(r)}{\overline{m}(r=0) \cdot C_p \cdot (T^s - t^g)} \quad [-] \tag{16}$$

Using the calculation as described above, a functioning model is made. The functioning of the model is seen in Fig. 4 where the temperature of the water, pipeline diameter and consumer satisfaction are displayed. In this example, the heat source is located in the bottom-right corner, depicted as a yellow cross. The red-colored lines show where pipelines are constructed and show the corresponding temperature in the pipe. The white boxes, that are placed on individual buildings or clusters of buildings, show to which extent the heat demand of those buildings is satisfied. Note, due to the nature of the models, maximizing efficiency will lead to maximum energy consumption by buildings meaning the total consumer satisfaction of the DHN is maximized.

Fig. 4. Spatial representation of the functioning district heating network (DHN) model.

3.3. *Optimizing the district heating network using heuristic methods*

Heuristic methods are employed to optimize the district heating network (DHN) by iteratively making small adjustments to the design. These modifications can lead to a cheaper, more efficient DHN, or even achieve both improvements simultaneously. Heuristics are used as the solution space is too big to consider all possible DHN designs and no algorithm exists that may find the optimal solution within an acceptable timeframe [19].

3.3.1. *Starting network*

Hassine and Eicker (2013) concluded that thermal losses can be reduced by 10% if the largest consumers are located close to the source. As the distance between these consumers and the source increases, both costs and thermal losses rise [20]. Since minimizing this distance helps to reduce cost and thermal losses, the initial network design connects all consumers to the source using the shortest path within the street network. The starting network is hereafter referred to as the shortest paths network.

3.3.2. *Heuristics used*

Two heuristics are applied to the starting network. As these heuristics introduce topological changes to the DHN design, they also impact its cost and efficiency. A topological modification may lead to a better, worse, or equally performing DHN. In both heuristic methods, the first-descent approach is used.

The first heuristic applied is the Edge Turn Heuristic (ETH), introduced by Heijnen et al. (2019). The ETH is a highly efficient heuristic [16]. Fig. 5 illustrates its functioning. In the first step, a randomly selected pipeline from the DHN is removed, temporarily disconnecting the network. The two separated sections must then be reconnected to ensure the DHN remains fully connected to the source. The bottom three designs show different alternatives. Depending on the optimization objective, one of these alternatives is selected as the new DHN configuration to iterate from [17]. The ETH is classified as a 'local heuristic' because each newly generated design differs from the previous one by only a single edge.

The second heuristic that is applied is the High Valency Shuffle metaheuristic (HVS) Yeates et al. (2021). The study proves that using the HVS in combination with a fast, steepest-descent heuristic, such as the ETH, leads to results close to the optimal solution. In this study it is therefore chosen to use the HVS in combination with the ETH. Fig. 6 shows an example of how the HVS functions. In this example node 3 is a high-valency node; it is connected to three other nodes. The nodes 1 to 4 are nodes that are part of a street with heat demand. Node $S1$ and $S2$ are nodes that may be used to create a DHN design. In the High Valency Shuffle the pipeline connections are transferred to the node closest to the high-valency node which is in this case node 's2'. Using the shortest path from node 's2' to all nodes originally connected to node 3, a new design is made. This way, alternative district heating networks outside the 1-neighborhood of the original network are found [16]. The HVS is a metaheuristic, meaning that the heuristic is not limited to local changes. A metaheuristic is able to 'escape' from local optima.

4. Application of optimization method

The optimization method includes a cost model, a thermal loss model and a heat exchanger model. Each optimization cycle starts with a street network, a heat source and a distribution of consumers and demand which are context dependent. The network from which the optimization starts is the shortest paths network as explained in chapter 3.3.1. Using the thermal- and cost models, the investment cost and the efficiency of the starting network are determined. Using the heuristic methods as explained in chapter 3.3.2., alternative DHN designs are generated. The cost and efficiency of the alternative designs are calculated until a lower-cost or more efficient solution is found, depending on the optimization objective (cost or efficiency). The first-descent principle is applied to limit calculation times. If a better solution is found, it immediately replaces the previous design and is used

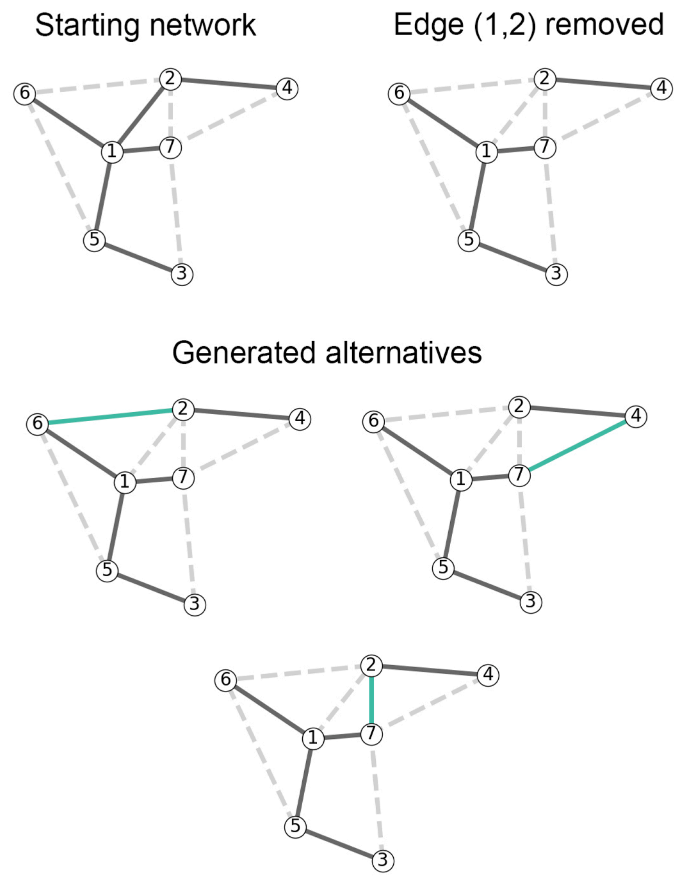


Fig. 5. Graphical functioning of the edge turn heuristic.

to iterate further from. This process repeats itself until no further improvements are found. To validate the method, it is applied onto 100 random street networks. Afterwards, the method is applied on a real case in the Dutch city Delft. Fig. 7 graphically shows the optimization process.

4.1. Application on 100 random DHN

The randomly generated street networks all have the characteristics summarized by the table below. Fig. 8 shows an example of a random street network. In the figure, black edges represent the streets. The yellow node 'S' represents the heat source. Streets with red nodes must be included in the DHN due to the buildings along that street. Streets with heat pipes are shown with a color and a box: 'T' indicates the water temperature and 'CS' shows consumer satisfaction. Each pipe is color-matched to the temperature of the water. The thickness of the pipe correlates with the mass flow in the pipe. For the 100 random DHN, the temperature of the ground (T^g) is $0°C$. The desired indoor temperature (T^{in}) is $20°C$.

Setting	Value
Surface area [m]	200 x 200
Streets with consumers	8
Sources	1
Intersections	40
Heat demand street [kW]	6 – 10

4.2. Application on DHN in Delft

In the near future a large DHN will be commissioned in Delft, a city in the Netherlands. This case is used to apply the optimization method on. Using OSMnx [21] a street network of the involved area is constructed. Fig. 9 gives an overview of the street network with the heat demand, based on the buildings along the street. The street network includes 9525 streets and 7771 intersections. 925 streets have heat demand. The colored streets in Fig. 9 are streets with heat demand. The color of the streets also indicates how much heat demand each street requires and varies between 0 and 1 MW.

5. Results

Both the random streets networks as the real network of Delft are optimized and evaluated separately on two objectives: cost and efficiency. Comparing the cost and efficiency of the least-cost alternative and the maximum-efficiency alternative leads to insights in the trade-off between cost and efficiency. In Figs. 10 and 11 a cost-optimized DHN is compared to an efficiency-optimized DHN. Both DHN designs are based on the same street network with the same heat demand. The source is located at the same location.

5.1. Results 100 randomly generated, small networks

Each optimization round starts from the shortest paths network. Fig. 12 shows the difference in cost between the shortest paths network and the minimum-cost network for the 100 random examples. Fig. 13 shows the difference in efficiency of the least-cost design and shortest paths network. As can be concluded from the boxplots, the cost of the shortest paths network decrease with a mean of 6.5% and a maximum of 19%. In 17 cases, the optimization method was not able to find a more affordable DHN when compared to the shortest paths network. In 75% of all cases, optimizing towards cost also increases the efficiency of the DHN, as can be seen in the right boxplot of Fig. 13. The change in efficiency is between −0.3% and 2%, with a mean of 0.5%. The increase in efficiency when optimizing for costs can be explained by the structure of the initial network. In the starting network, each street with demand is connected by its shortest path to the source. In some cases this may lead to many parallel pipelines. Optimizing the network for cost, will lead to the removal of parallel pipelines, reducing cost but also increasing efficiency.

Visual comparison of the cost-optimized and efficiency-optimized networks reveals that efficiency-optimized networks tend to use larger pipelines with fewer branches, as illustrated in Figs. 10 and 11. A similar pattern is observed for the large DHN in Fig. 16 and 17. However, due to the non-linear relationships between pipeline cost and thermal losses, the underlying mechanics of this effect are difficult to predict with certainty.

Subsequently, each starting network is optimized on efficiency. The characteristics of the maximum-efficiency DHN are then compared to the minimum-cost DHN. Fig. 14 shows the trade-off between cost and efficiency for the 100 small DHN. The x-axis in Fig. 14 shows the change in cost, the y-axis shows the change in efficiency. The number shows to which random network the result applies. The colored dashed lines are used to roughly categorize the results. If costs increase by less than 25% in exchange for efficiency gains of more than 1%, the solution is considered potentially promising and is given a green color. If a solution increases costs by more than 50% while the gain in efficiency is smaller than 1% it is colored red as the solution is considered unpromising. Intermittent solutions are colored orange. There are 50 red colored solutions, 26 orange colored solutions and only 24 green colored solutions. Fig. 14 shows that in most cases, efficiency comes at a rather high increase in cost. In only a few cases, the increase in efficiency seems to be proportional to the increase in cost.

For the 24 solutions that are considered as potentially cost-effective to improve efficiency, the marginal cost of increasing network efficiency is examined in greater detail. Fig. 15 shows the results. On average, a 1% increase in efficiency leads to a 15.1% increase in investment cost for the small DHNs. However, there are several cases in which marginal costs are significantly lower. In three cases, a 1% efficiency gain costs only

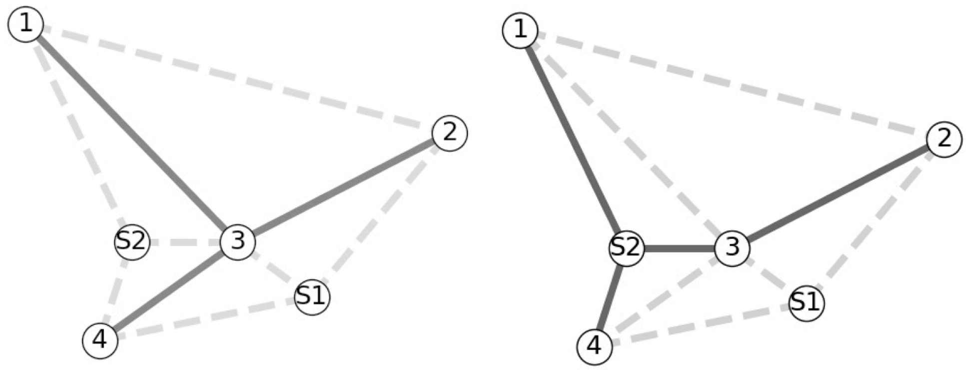


Fig. 6. Graphical functioning of the high valency shuffle.

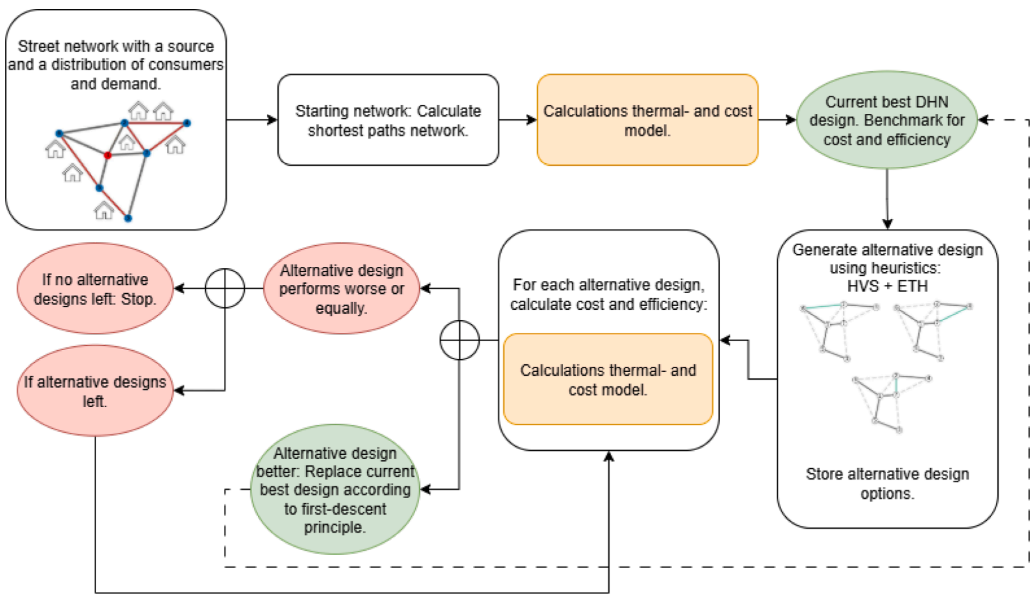


Fig. 7. Flow diagram of the DHN optimization process, illustrating iterative heuristics for cost and efficiency improvement.

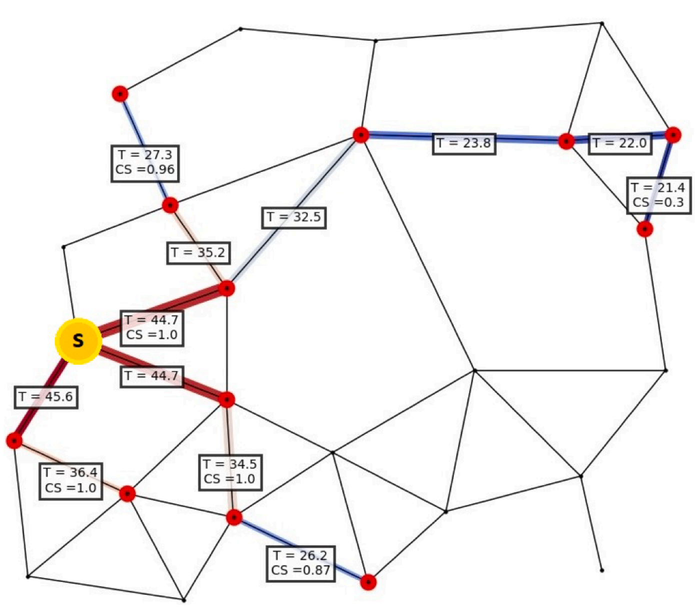


Fig. 8. Example of a random generated street network and DHN. The thermal losses are exaggerated for visualization purposes.

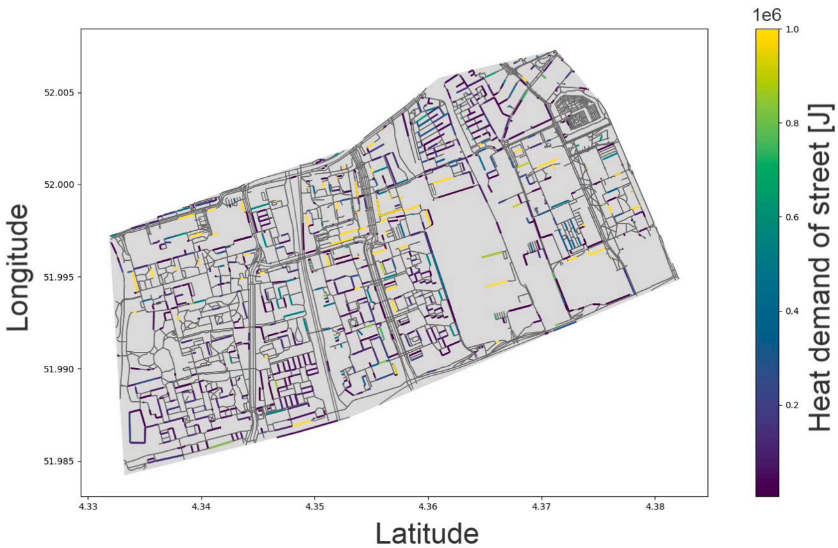


Fig. 9. Street network in Delft with specified heat demand.

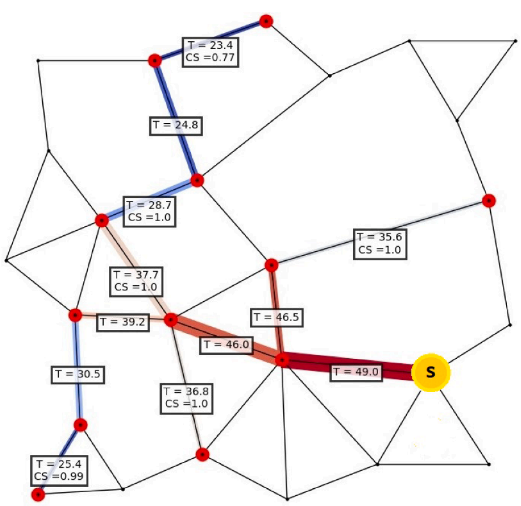


Fig. 10. Cost-optimized DHN.

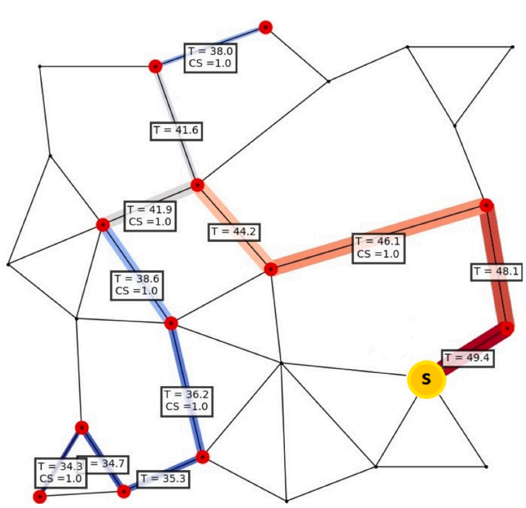


Fig. 11. Efficiency-optimized DHN.

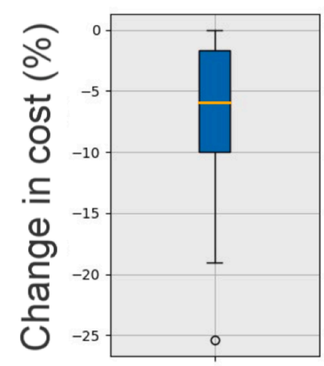


Fig. 12. Change in cost between shortest paths network and minimum-cost network for the 100 random examples.

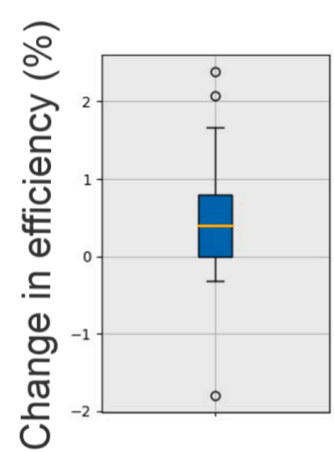


Fig. 13. Change in efficiency between shortest paths network and minimum cost network for the 100 random examples.

a 0.5-2.0% more. In addition, three cases show slightly higher values, with an efficiency gain of 1% corresponding to a 7.3-9.9% increase in costs. In all other cases, a 1% improvement in efficiency led to a cost increase of more than 10%.

To summarize:

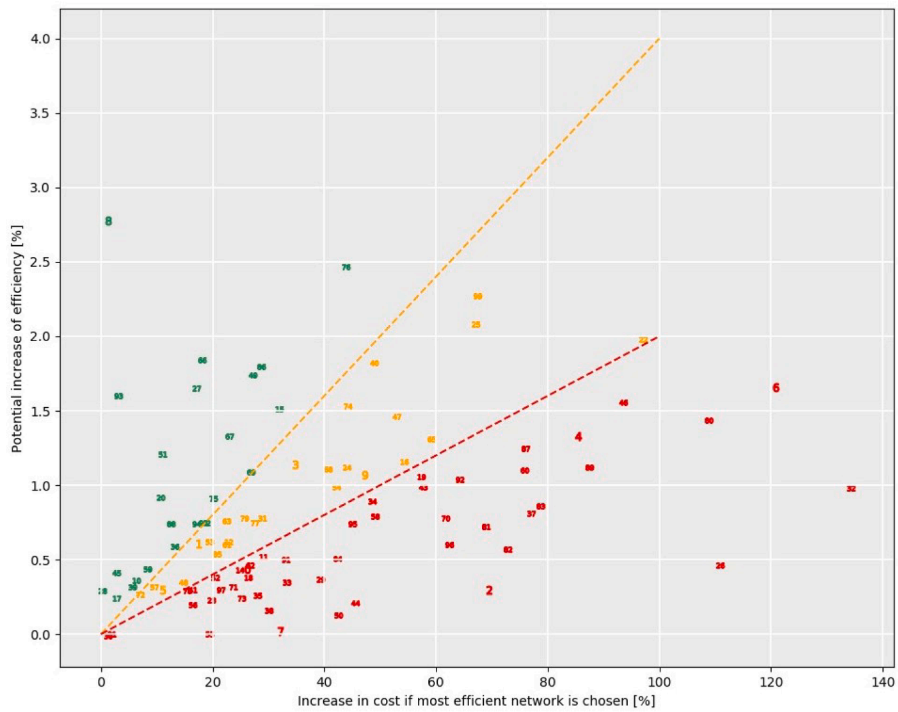


Fig. 14. Comparison of the efficiency optimized DHN to the cost optimized DHN.

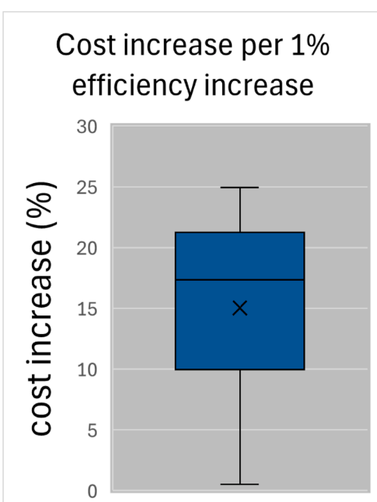


Fig. 15. Comparison of the efficiency optimized DHN to the cost optimized DHN.

- In 83% of all cases, the optimization method identified a more cost-effective solution than the shortest-paths network.
- Optimizing the shortest-paths network for total investment costs resulted in an average cost reduction of 6.5%, with a maximum reduction of 19%.
- In 75% of all cases, the cost-optimized network was also more efficient than the shortest-paths network.
- All minimum-cost DHNs that were subsequently optimized for efficiency became more expensive than their respective minimum-cost counterparts.
- Of the 100 efficiency-optimized DHNs, 76 exhibit a cost increase exceeding 25% per 1% efficiency gain; in 50 of these cases, the cost increase even exceeds 50%.
- Among the 100 randomly generated small DHNs, only three cases achieve a 1% efficiency gain with a cost increase of 0.5-2.0%, while another three require a 7.3-9.9% increase. In all remaining cases, a 1% efficiency improvement results in a cost increase exceeding 10%.

5.2. Results large DHN in Delft

The same analysis is performed on the large street network in Delft. Compared to the shortest paths network, the minimum-cost network has reduced the costs by 24.5% while the efficiency rises has increased 43.2% to 56.5%. Compared to the minimum-cost network, the maximum-efficiency network increases cost by 18% while efficiency rises from 56.5% to 67.9%. In this case, a 1% efficiency increase increases cost by 0.9%. Figs. 16 and 17 show the traces of the two different DHN designs. The two traces allow for a clear comparison of the traces of the cost- and efficiency-optimized network. Note that, the cost-optimized design has more branches with smaller pipeline diameters, while the efficiency-optimized network consists of fewer pipelines with a larger diameter that follow relatively straight paths. Visually, there is a big difference between the two.

5.3. Testing comfort in scenarios

Lastly, both the cost-optimized and efficiency-optimized district heating networks (DHNs) in Delft were subjected to a series of scenarios to evaluate their performance from a consumer's perspective. These scenarios simulate cold outdoor conditions or disruptions in the heat source, which are common challenges in real-world DHNs. The scenarios vary by pipeline insulation thickness and ground temperature, as outlined below:

- 2.5 cm insulation at 0°C
- 4 cm insulation at 0°C
- 2.5 cm insulation at 12.5°C
- 4 cm insulation at 12.5°C

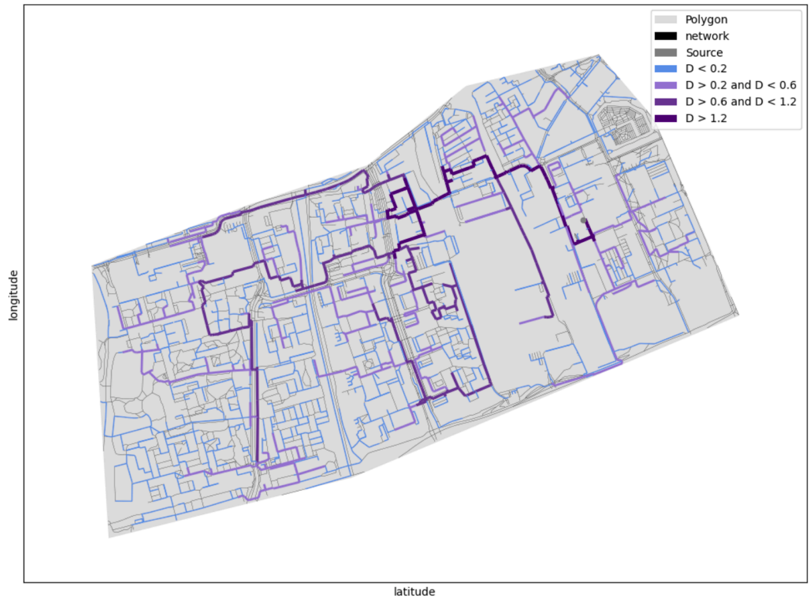


Fig. 16. Graphical representation of the cost optimized topology of the DHN in Delft.

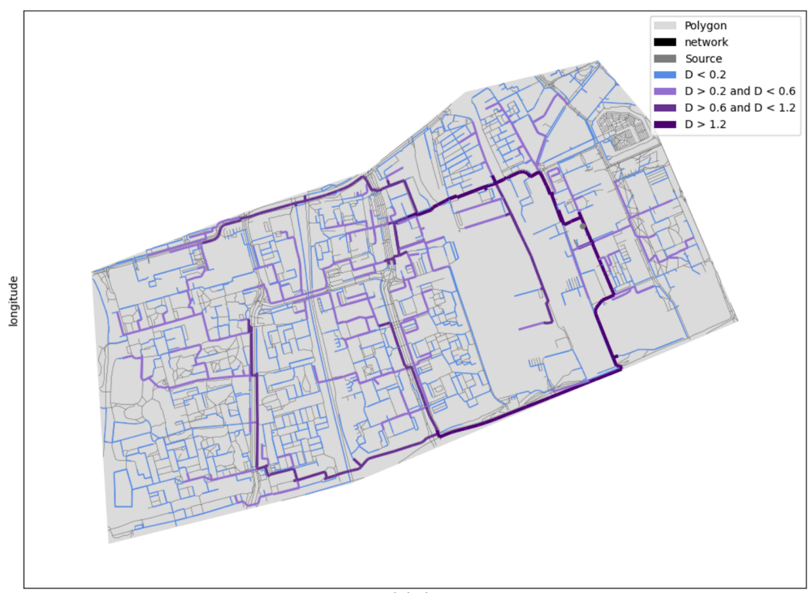
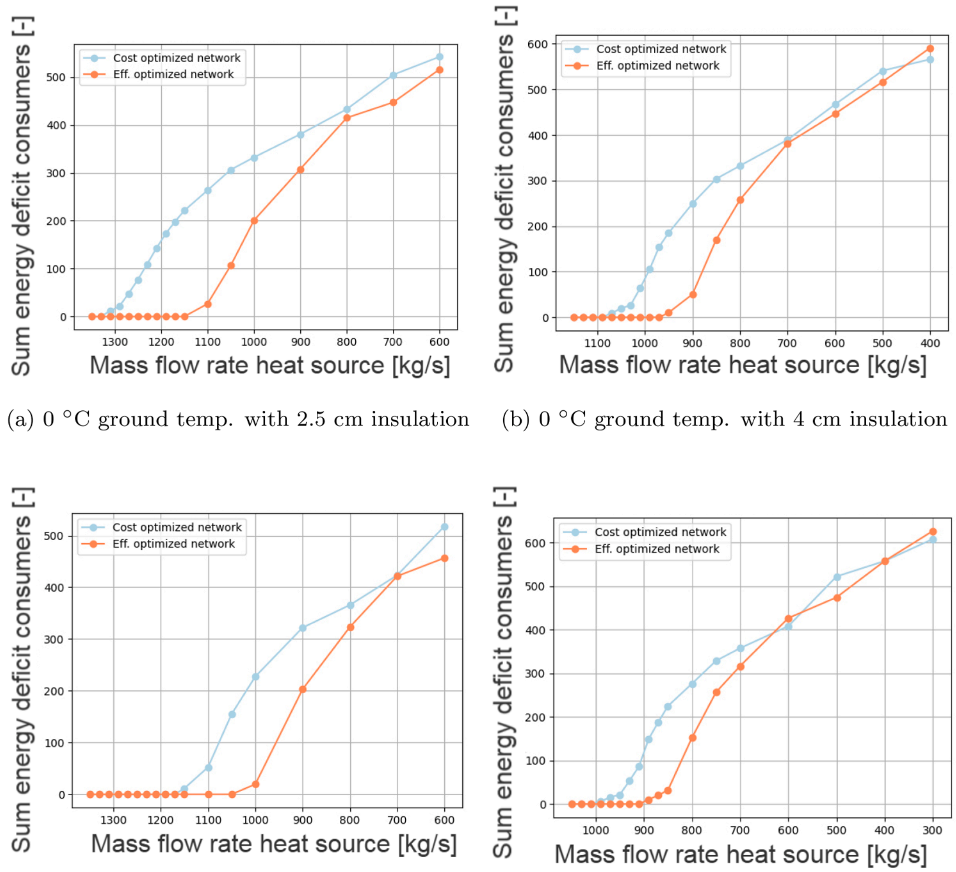


Fig. 17. Graphical representation of the efficiency optimized topology of the DHN in Delft.

A 2.5 cm insulation thickness is considered viable based on the economic optimum for insulation thickness in the transport of hot water, which is close to 2.5 cm [22]. The 4 cm insulation scenario has been included to reduce thermal losses and assess its effect on consumer comfort in the DHN. In each scenario, the energy output from the source is varied to simulate potential disruptions in the heat supply.

Fig. 18 shows the difference in consumer satisfaction between the cost- (blue) and efficiency optimized (orange) DHN. The vertical axis shows the total sum of energy deficit that the consumers in the DHN experience. (The energy deficit of a single client varies between 0 and 1. An energy deficit of 1 means a client receives no energy while an energy deficit of 0 means that the client experiences no deficit.) The horizontal axis shows the amount of heated water that is pumped into the network. As can be seen, the amount of consumers with an energy deficit is much lower in the maximum-efficiency network compared to the minimum-cost network. In general, as the pipeline insulation becomes poorer and the ground temperature decreases, the difference in performance increases. The lower the mass flow from the source, the less significant the performance gap becomes. The difference between the two networks disappears when the heat source is extremely disturbed. Fig. 18 also shows that the maximum-efficiency network requires significantly less energy than the minimum-cost network.



(a) 0 °C ground temp. with 2.5 cm insulation (b) 0 °C ground temp. with 4 cm insulation

(c) 12.5 °C ground temp. with 2.5 cm insulation (d) 12.5 °C ground temp. with 2.5 cm insulation

Fig. 18. Consumer satisfaction under four scenarios varying insulation thickness and ground temperature for cost-optimized (blue) and efficiency-optimized (orange) DHNs. (a)0° C ground temp. with 2.5 cm insulation. (b)0° C ground temp. with 4 cm insulation. (c)12.5° C ground temp. with 2.5 cm insulation. (d)12.5° C ground temp. with 2.5 cm insulation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

6. Conclusion

This research quantifies the trade-off between cost and efficiency for optimizing district heating networks. For 100 random small problems, a cost-optimized DHN and an efficiency-optimized DHN are obtained. The results show that the different objectives lead to very different network designs. Compared to a starting network in which every street with heat demand is connected to the source in the shortest way, 83% of cost-optimized DHN are cheaper and more efficient. Costs fell by a mean of 6.5% while the efficiency increased by a mean of 0.5%. A comparison of the minimum-cost networks with the maximum-efficiency networks shows that an increase in efficiency often incurs a great increase in cost. In 76% of all cases, a 1% increase in efficiency increases the cost of the network with more than 25%. In only six specific cases did a 1% led to an increase in cost by less than 10%, ranging between 0.5–9.9%, demonstrating the wide variance in results.

For the large DHN case in Delft, increasing efficiency is more cost-effective. The maximum-efficiency design increased efficiency from 56.5% to 67.9% with an 18% increase in cost when compared to the minimum-cost network. In this case, a 1% efficiency increase lead to a 0.9% increase in cost. It should be noted that these results are very specific to this case. The results are influenced by the location of the source, the locations of the largest consumers, the distribution of consumers in the area, but also by the specific street network. It is expected that the size of the DHN has a major influence on the ratio between the gain in efficiency and the gain in cost.

For the district heating network in Delft, the performance in terms of energy delivered to consumers is assessed using a set of four scenarios. Cold conditions and severe disruptions in the heat source have significantly less impact on consumers in an efficiency-optimized network. The colder the outdoor conditions and the thinner the thermal insulation of the pipelines, the greater the difference in technical performance between the cost-optimized and the efficiency-optimized network. This research demonstrates that optimizing DHN designs purely to minimize costs is short-sighted. Increases in efficiency can, depending on the specific scenario, be cost-effective and yield major benefits for users in the DHN. An efficient DHN reduces the needed energy supply required from the source and increases the performance in terms of energy supply to consumers. Consumers in an efficiency-optimized network are less at risk of having thermal discomfort due to cold outdoor conditions or disruptions of the heat source. Improving the performance of the DHN from the consumer's point of view can increase social acceptance, which is beneficial for the energy transition.

Declaration of generative AI in scientific writing

During the preparation of this work the author(s) used OpenAI in order to improve readability and language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication

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This article does not contain any studies with human participants or animals performed by any of the authors.

CRediT authorship contribution statement

Martijn Piket: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization; **Petra Heijnen:** Writing – review & editing, Supervision, Methodology, Formal analysis; **Martijn Warnier:** Writing – review & editing, Supervision, Conceptualization.

Data availability

All data used in this research is fully available on Github. The link for Github: https://github.com/mpiket/DHN-optimization. All data is captured in the Excel files found in the directory. Besides the data, the directory also shows multiple python scripts used for the district heating network optimization. Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Nomenclature

Symbol	Definition	Unit	Value (if constant)
$A^P_{i,j}$	Outer surface of the pipeline between node i and j	[m^2]	[-]
C	Capacity of a pipeline	[-]	[-]
C_p	Heat capacity of water	[J/kg °C]	[4,186]
$D_{i,j}$	Diameter of the pipeline between node i and j	[m]	[-]
$e_{i,j}$	Edge between node i and j	[-]	[-]
e_b	Edge closest to building b	[-]	[-]
E	Energy	[J]	[-]
$h_{i,j}$	heat transfer coefficient of the pipeline between node i and j	[W/m °C]	[-]
$H_{i,j}$	Heat demand of the street between node i and j	[W]	[-]
$\kappa_{i,j}$	Cost of the pipeline between node i and j	[-]	[-]
k	Thermal conductivity coefficient	[W/m °C]	[-]
K_N	Cost of district heating network N	[-]	[-]
L	Length of the shortest path	[m]	[-]
$l_{i,j}$	Length of the street between node i and j	[m]	[-]
$m_{i,j}$	Mass flow between node i and j	[kg/s]	[-]
M	Mass flow	[kg/s]	[-]
Q	Heat loss from pipeline	[W]	[-]
r	Thickness of pipeline material	[m]	[-]
S	Fraction of received energy, compared to heat demand	[%]	[-]
T	Temperature	[°C]	[-]
V_a	Cost of pipeline a	[$]	[-]
$x_{i,j}$	Decision variable to construct a pipeline between node i and j	[-]	[-]
σ_{gen}	Correcting factor equal to estimated efficiency of DHN	[-]	[0.7]

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