Optimizing district heating networks: Exploring the solution space

Transporting geothermal energy to consumers in Delft

MSc Thesis

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by

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Project Duration:	Feb, 2023 - June, 2023
Faculty:	Technology, Policy and Management

Summary

Society is facing a huge challenge in switching the energy sectors dependence on fossil fuels into a energy sector using mostly renewable energy sources. The switch towards using more sustainable energy sources is known as the energy transition. The goal of the energy transition is to lower the greenhouse gas (GHG) emissions emitted by the energy sector. Lowering the GHG emissions helps society limit the global warming caused by GHG [3]. 17.5 % of the global energy usage comes from the energy use in buildings [50]. It is thus very important that the energy use in buildings transitions towards using more sustainable energy sources. One of the renewable energy sources that is ought promising in the energy transition for energy use in buildings is geothermal energy [3]. Geothermal energy is energy that is captured in reservoirs of hot water in the earth's crust. The hot water captured in the hot water pockets is pumped to the surface, to use it in spatial heating. The return pipe returns the cooled water to the geothermal well, where it can heat up again over a certain period of time [63] [23].

In some cases, geothermal energy is applied using a district heating network. A district heating network is an example of a system that provides heating and/or cooling capacities to a group of buildings [65]. A district heating network is a network of pipelines that transport the hot water from the geothermal well to the buildings in the district. A geothermal well in combination with a district heating network is developed in Delft [27]. The district heating network will deliver energy to the TU Delft campus, two neighborhoods in Delft and industry at the Schieweg in Delft [28].

Besides the district heating network in Delft, it is expected that district heating networks will be applied more often to accelerate the energy transition. Yun-Chao and Chen (2012) concluded that most optimization techniques optimize the whole system with its components. Less optimization techniques are applied to the sole components. Besides the fact that most optimization methods optimize the system as a whole, most optimization objectives only include optimizing the cost of the system. Also, effective optimization techniques are required as optimizing large graphs may be computationally time-consuming [36]. In literature there are also clear signals that state that the trade-off between thermal comfort, and efficiency with respect to cost has to be tackled [53]. In this research, optimizing district heating networks for cost is compared to optimizing district heating to maximize thermal comfort or efficiency.

In this research two models are developed: a model that calculates the cost of the district heating network, and a model that calculates the thermal losses of the district heating network. Both models are applied to a district heating networks that is developed in a street network. Furthermore, multiple heuristics are applied to come up with better district heating networks. The optimization technique is tested on 100 small, randomly generated district heating networks. After that, the district heating network in Delft is optimized. The differences in cost, efficiency, etc. will be evaluated. Besides, the performances of the district heating networks are evaluated by introducing energy deficits under different conditions.

Optimizing the district heating networks for cost led to a very consistent result: When compared to their individual starting point, the district heating networks became cheaper and more efficient. A moderate-strong correlation is found between the the increase in efficiency and the decrease in cost while optimizing the district heating networks. In contrast to that, the networks that maximize efficiency are much more expensive than their cost optimized alternative, while the increase in efficiency is in most cases moderate. However, there are rare cases where the efficiency is increased much at a moderate increase in cost. This phenomenon is also found in Delft. Given the result that the efficient district heating network also performed much better than the cheapest alternative during energy deficits, in this research it is shown that choosing an objective function has a very large impact on the characteristics of the network. Therefore it is shown that for future district heating network optimization, it is important to trade off cost against efficiency.

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Nomenclature

Symbols

Symbol	Definition	Unit	Value (if constant)
η_{gen}	General efficiency district heating network	[-]	0.7
η_N	Efficiency of network N	[%]	-
κ	Cost function constant	[-]	-
A_b	Surface area of building b on ground level	$[m^2]$	-
$\overline{A^c}$	Total floor area found in cluster c	$[m^2]$	-
$A^p(r)$	Surface area of the pipelines at r meters from the source	$[m^2]$	-
C^D	Heat demand constant per m^2	$[W/m^2]$	50
C_p	Specific heat capacity water	$[J/kgK]$	4186
d_n^i	Node i with demand belonging to street n	$[W]$	-
$D_{i,j}$	Diameter (pipeline)	$[m]$	-
$E_{i,j}$	Energy contained in the pipeline between node i and j	$[J]$	-
f_b	Floors in building b	[-]	-
$h_{i,j}$	Heat transfer coefficient of the pipeline between i and j	$[W/m^2K]$	-
H_N	Amount of cold houses in network N	[Int]	-
H_b	Heat demand of building b $[W]$	-	
$\overline{H_c}$	Heat demand of cluster c	[W]	-
$K_{i,j}$	Cost of the pipeline between node i and j	[-]	-
K_N	Total cost of network N	[-]	-
$l_{i,j}$	Length of the pipeline between node i and j	$[m]$	-
$l_{P,i}$	Length of the shortest path to node i from the source	[m]	-
$m_{i,j}$	Mass flow through the pipeline between i and j	[kg]	-
m_b	Mass flow to building b	[kg]	-
$\overline{P_c}$	Location of cluster c	-	-
$Q_{i,j}$	Thermal losses in the pipeline between i and j	[W]	-
$Q(r)$	Heat transfer rate at r meters from the source	[W]	-
SP_i	Shortest path to node i from the source	[-]	-
$T_{i,j}^w$	Temperature of the water in pipeline	[K]	-
v_b	Amount of floors in building b	[Int]	-
$V_{i,j}^w$	Volumetric flow between node i and j	[K]	-
$x_{i,j}$	Decision variable that places a pipeline between i and j or not	[Bin]	-

Sets

Symbol	Definition	Unit (if applicable)
B	Set of buildings found in the area	-
$E(G)$	Set of streets in street network	-
E^d	Set of edges that contain a demand	[J]
$F(r)$	Set that contains the heat transfer functions at r meters from the source	[J]
G	The simplified graph of the street network	-
N	Set of pipelines that defines a district heating network	-
$O(r)$	Set surfaces of the pipelines at r meters from the source	[J]
$V(G)$	Set of nodes/intersections in street network	-
$R(r)$	Set that contains all diameters of active pipelines at r meters from the source	-

1

Introduction

As widely known, society is facing a challenge to quickly reduce the greenhouse gas emissions. As the energy sector is a major contributor to the emissions of greenhouse gasses, it is important that the energy sector switches to more sustainable energy sources. However, energy usage is a broad concept that can be divided into multiple components. The three components of the energy sector that contribute most to global emissions are transport, energy use in buildings and energy use in industry. Energy consumption in industry is the largest contributor to global emissions, as it contributes 24.2% of the global greenhouse gas emissions. Energy usage in buildings follows at 17.5% while transport contributes 16.2%. As energy use in buildings is a huge contributor to the GHG emission worldwide, it is important to make the buildings more sustainable, but also using more renewable energy sources for it. There are multiple ways to reduce the greenhouse gas emissions by buildings. For example, the amount of gas needed for spatial heating may be reduced by investing in better insulation, or by switching to a solar heating system. Other examples of alternative or sustainable energy sources are waste heat from industry or making effective use of geothermal energy [3]. Waste heat and geothermal heat may be distributed through an area using a district heating network. It is expected that district heating network, or district energy systems will play a more important role in the future to reduce greenhouse gas emissions. District energy systems are systems that provide heating cooling or air-conditioning services to buildings in a certain area. However, the current most-used fuel in district energy systems remains natural gas [19]. An example of a renewable energy that may replace the natural gas in district heating networks is geothermal energy. There are real-life examples where geothermal energy replaces natural gas, such as in Delft. As the replacement of the gas turbine by a geothermal well is the direct cause of this thesis, geothermal energy and district heating network play a central role in this thesis [64].

Geothermal energy is captured in reservoirs of hot water in the earth's crust. The reservoirs are found at different depths in the crust, and its potential and availability differs from place to place [44]. Iceland is an example of a place where there is a high potential of geothermal energy. In Iceland the geothermal energy has been harvested since the Viking age. Currently 90% of all households in Iceland are heated with geothermal energy. Besides spatial heating, geothermal energy is also used to generate electricity in Iceland. [67]. Due to the intensive use of geothermal energy, the CO_2 emissions per capita are almost 50% less in Iceland when compared to the Netherlands[58]. This shows that exploiting geothermal energy to its full potential may severely reduce the CO_2 emissions of a country. Besides lowering CO_2 emissions, geothermal energy has other advantages. The energy output of a geothermal well remains fairly constant over the whole year. Second, geothermal energy has a low cost. The largest downside of geothermal energy is its geographic availability [38].

The hot water stored in reservoirs is pumped to the earths surface. On the surface, the thermal energy may be used for different purposes. After the thermal energy is used and the temperature of the water has dropped, the cooled water is pumped back into the ground. After the water has heated in the reservoir again, it is ready to use again. Geothermal is a great example of a renewable energy source as it makes use of the processes found in nature. Next to that, geothermal energy does not permanently subtract matter from the ground. The temperature of the water in the reservoir differs from location, but also differs when the depth of the reservoir changes. The temperature of the water in the reservoirs may reach up to 180 ° C and above [18]. In general, a rule of thumb states that per kilometer deeper into the earths crust, the temperature rises 25 ° C. Overall, the deeper the geothermal energy is found, the higher the temperature of the geothermal source is [66]. In many cases, high temperature energy sources are more desirable.

The heated water from the geothermal well is sometimes used in a district heating network. In a district heating network, heat consumers are connected to the pipelines that deliver warm water to their building. If a district heating network is installed, a new device is installed at the consumers, that exchanges the heat between the warm water in the pipeline, and the cooler water in the central heating system of the building. The water in the central heating system of the building is warmed up, such that the heat is eventually used for spatial heating. After the heat from the water is used, it is transported back to the geothermal well using a return pipeline. This contains all the used, cooled water from the consumers in the district heating network [63] [23].

In some cases, geothermal wells have the potential to deliver multiple megawatts of thermal energy. If such a geothermal well is found in a built environment, it has the potential to disconnect many households from using gas for spatial heating [72]. If the geothermal energy is used instead of natural gas for the spatial heating, the use of fossil fuels in buildings may drastically reduce in certain areas. Providing buildings with low CO_2 energy sources reduces the share of energy use in buildings in the global greenhouse gasses emissions. Once a high-potential geothermal well is found in a built environment, there are many choices that have to be made in designing the system [65]. For example, where exactly will the geothermal well be installed? Where will the pipelines of the district heating network be constructed? Are heat- and cold storages necessary, and if so, how large? Also the built environment in which the district heating network is applied has influence on the design of the district heating network.

One of the places where a high-potential geothermal energy source is found, is Delft. A geothermal well will be installed on the TU Delft campus [27]. Currently, a combined heat and power plant delivers electricity and heat to the campus of the TU Delft using a relatively small heating network [8]. The geothermal well that is going to be installed will be connected to this district heating network. This district heating network will be expanded to at least two neighborhoods: Voorhof en Buitenhof. These are the neighborhoods close to the TU Delft campus. It is expected that the geothermal well will deliver heat to 8000 houses in the area [27]. There are two main reasons why the geothermal well is installed at the TU Delft Campus. One, it will act as a low CO_2 emitting source for spatial heating. Two, TU Delft is able to closely research the geothermal well as it is installed on its own campus. [28]. However, there are also some known barriers for deploying geothermal energy.

As most renewable energy sources, geothermal energy is competitive with fossil fuels as it has low variable cost when it runs: There are no fuel costs. One major barrier that is recognized in applying geothermal district heating systems is the connection cost. In district heating networks each consumer has to be connected separately to the district heating network. Connecting each consumer comes with a large investment cost, especially when most consumers are rather small energy consumers. However, as district heating networks are already a long existing phenomenon, much has been learned from past mistakes [59]. To lower the barrier to apply district heating systems, many optimization techniques applied focus on lowering the operational cost, investment cost or maximizing revenue. However, optimizing district heating network is difficult, mostly due to the size of the applications in real world. Besides that, district heating networks have technical properties that are difficult to assess [52]. Also, decision makers on a local scale do not have the required tools to be able to make founded decisions. There should be more techniques that allows people to optimize district heating networks at a local scale [54]. As it is expected that district heating network have an impact on the decarbonization of energy use in buildings, contributing to this field of research is useful and may accelerate the energy transition of the sector.

2

Literature Study: Optimization of district heating networks

A literature study is conducted to research the state of the art of district heating network optimization. This gives insight into pitfalls of district heating network optimization and where a valuable contribution may be made.

As district energy systems are expected to become more important in the future, researchers put much effort in developing and applying methods to optimize district heating networks. Over the last few decades many optimization methods are developed to optimize district heating networks [70]. The methods are applied to various aspects of the district heating networks. In a research by Yun-Chao and Chen (2012) it is seen that the optimization of district heating networks may be separated into two categories. First, there is the optimization of the district heating system. A district heating system contains all components needed to create a functioning heating system. This includes the placement of the pipelines, the heat and cold storages, control technology in the system, etc. In contrast to that, Yun-Chao and Chen (2012) define the district heating network as the set of pipelines that transport the heated water to consumers [70] [72]. From now on, these are the definitions used in this thesis. There are multiple aspects within district heating systems that may be optimized. For example, the charging and discharging may be optimized to maximize revenue or optimizing the placement of pumps in the district heating system [52].

Next to the diversity of components that may be optimized, there is also a large set of optimization objectives found in literature. An optimization objective is a goal towards which a component or the system is optimized. Examples of optimization objectives are investment cost, efficiency, CO_2 emission, revenue, etc. Using weights it is also possible to create a multi-objective optimization problem [52]. The weights indicate the importance of an objective with respect to another objective. This way, a multi-objective optimization may incorporate trade-offs. Some optimization objectives may conflict in the context of district heating networks. For example, cost and emission are often seen as conflicting objectives [52]. In the following section multiple optimization researches are summarized. The researches are separated into two categories. The optimization of district heating systems, and the optimization of district heating networks.

District heating system optimization

In the research conducted by Söderman and Pettersson (2005) a regional energy system is optimized. Next to power lines, this optimization also includes a district heating system. The optimization includes structural as well as operational optimization of the system. The system as a whole is optimized using a single-objective optimization: ’overall cost’. This includes investment cost, annual investment cost and cost of operations. Moreover, the optimization of the district heating network includes multiple sources and consumers, pipelines and heat storages [56].

Sun et al. (2022) proposed another method to optimize the district heating system. The energy distribution in the district heating network is optimized using a control strategy based on indoor temperature and demand forecasting. In this research load-forecasting and indoor temperatures are used to optimize the energy delivery to consumers, such that indoor temperatures are more stable and the consumers experience less discomfort. Besides an improvement on the thermal comfort, the optimized control of the district heating network achieved almost 7% energy savings, meaning that 7% less energy is used. The research states that efficiency and thermal comfort are the most crucial performance indicators of a district heating system. This is due to the fact that the purpose of district heating systems is to deliver good quality energy to consumers such that they are comfortable [57]. Usually load demand forecasting is applied to optimize the distribution of energy [52].

In the study by Weber and Shah (2011) the optimal mix of energy sources in a district energy network is optimized for multiple objectives: cost, resilience and emissions. Moreover, the optimization contains several parts. The pipelines are optimized altogether with the properties of the heat plant, the storages and finally even the operation of the system. All in all, all aspects of the system are taken into account in this optimization. However, the size of the district heating system is still rather small. The district heating network contains roughly 50 buildings, including the heat plant and other necessary structures.

The researches above are examples of researches that optimize different aspects of the district heating systems. Most of the optimization methods found in literature optimize the district heating system as a whole. In other words, the optimization considers different elements of the district heating network and are adjusted to one another to achieve a certain objective such as lowering investment cost or maximizing revenue. As concluded by Yun-Chao and Chen (2012), there are fewer researches that optimize the separate components of the district heating system. However, in literature it is stated the initial investment in the district heating network may act as a barrier for implementing it. In the research conducted by Schmidt and Stange (2021) it is stated that an optimal design of the district heating network is crucial for the feasibility of implementing it. In the research conducted by Wack et al. (2022) the same conclusion is made: ”The upfront investment is a crucial factor for the roll out of this technology”. To conclude, it is known that less research is conducted to optimize district heating networks, while at the same time, the design of the district heating network may act as an important barrier for implementing the technology [54]. As it is known that an optimal design of a district heating network lowers the barrier to implement the technology, in the next section some researches that optimize district heating networks are summarized.

District heating network optimization

The optimization of district heating network concerns the placement of the pipelines that deliver heated water to all consumers. The research conducted by Schmidt and Stange (2021) is an example of a research that optimizes the district heating network such that the initial investment cost of the district heating network is lowered. In this research it is argued that the routing and sizing the pipelines are the most important variables to consider in district heating network optimization. Schmidt and Stange (2021) propose a tool that decision makers, and others may use to design district heating networks. The tool includes accurate spatial data such that the district heating network makes use of the streets in a certain area. In this research, graph theory acts as a foundation upon which the tool is built. Schmidt and Stange (2021) applied a minimum spanning tree and multiple evolutionary algorithms are used to minimize the cost of the pipelines of the district heating network. It is concluded in the research that besides calculating cost, routing and pipeline diameter, the tool can be expanded by including thermal losses.

In the research conducted by Lumbreras et al. (2022) a similar approach is used. The goal of the study is to propose a method that assesses the economical feasibility of a district heating network within an existing urban area. Graph theory is used to determine the pipeline routing through the streets of the area. Kruskal’s algorithm is applied to calculate the network that allows to connect all buildings, using real roads, while minimizing the total length of all pipelines to do so. The minimum spanning tree is the shortest district heating network and should be the optimal design in economic terms [39]. In the calculation of the cost, the diameter of the pipelines plays an important role. Moreover, it is found that the cost to distribute the heat, and thus the economic feasibility, are strongly dependent on the spread of demand. The denser the demand, the higher the odds are that a district heating network is more feasible [39]. However, it does not become clear how the thermal losses that occur in the pipeline are calculated.

In the research conducted by Rooij (n.d.) a district heating network design is proposed for Rotterdam South. Before the district heating network is optimized, the stakeholder's' objectives are researched. These objectives are then translated into key performance indicators for which the different district heating network designs are evaluated. It is noticed that the different actors in the district heating network have different objectives. The municipality wants to connect as many homes to the district heating network, while the housing companies opt to lower the price of the energy. Private home owners want to minimize disturbance and adaptions. It is concluded that some objectives are hard to measure, and are thus left out of the optimization [51]. Also in this research it is concluded that the diameter of the pipelines have a large effect on the price of the district heating network. Also Rooij (n.d.) used graph theory as graph theory is most suitable to test different district heating network designs for the objectives set by the stakeholders.

Another comparable study is conducted by Chen and Zhu (2019). Again, graph theory is used to optimize the pipeline topology of the district heating network. The goal of the study is to create a planning tool that allows optimizing large district heating networks. The researches noticed that recently graph theory is used more often to optimize district heating networks. The objective set in this optimization is minimizing the cost of the district heating network over its whole lifetime. This includes initial investment in pipelines, equipment cost, operating cost, etc.

Last but not least, Wack et al. (2023) also conduct a research that focuses on the same subject: minimizing the investment cost for a district heating network. In this study also the geospatial data of the area is used to determine the streets that may be used by the pipelines. Again, the pipeline diameter is used to determine the cost of the pipelines. However, this study does include a feature that is not encountered in the aforementioned studies. The thermal losses of the pipelines are calculated [62]. The optimization is conducted from an investors perspective, meaning that the investment cost should be minimized.

There are many similarities between the methods applied in district heating network optimization. Graph theory often acts as a foundation for the optimization or design process. In recent years graph theory is used more often in optimizing district heating networks [15]. Next to that, most district heating networks are optimized in a certain urban context. The district heating network will be constructed in the streets of a city. Next to that, the investment cost in district heating networks is dominated by the pipeline lengths and diameters. From the literature it becomes clear that there are not many methods that include thermal losses in the district heating network. Next to that, most methods are applied on small-moderately sized graphs. Now that the state of art of optimizing district heating networks is known, the required data for optimizing district heating networks is summarized.

Building information

As seen in literature, district heating network are optimized in various ways. However, there are some requirements that every optimization method has to take into account. In the research conducted by Cai et al. (2018), the control strategy of the district heating network is optimized which resulted in 11% lower energy costs. It is stated that the demand of buildings in the district heating network depends on environmental conditions and the thermal characteristics of the buildings. Cai et al. (2018) state that for buildings built after 2000, are well insulated. Well insulated require less energy for spatial heating. Furthermore, the type of buildings also affects the energy demanded by the building. Buildings are categorized in commercial and residential buildings. For complete modelling, the building type, construction period, radiator sizes and insulation of every building has to be known. However, for most buildings this information is not documented well. Furthermore, applying this level of detail to the optimization of large district heating networks may not be feasible [13]. In the research conducted by Buoro et al. (2019), the electrical and heating demands of the buildings in the area were indicated using interviews. In the optimization 9 industrial buildings are included, meaning that the amount participants is rather small. As all participants are industrial buildings with similar characteristics, the heat demand profiles are predictable. Furthermore it is noticed that the heating demand of industrial buildings is near zero. It is argued that the energy profiles have to be known in order for effective optimization of the district heating network [12]. Overall, specific information of buildings has to be known in order for effective optimization. In an ideal case, the exact heat demand profiles are known. Else, building type, level of insulation, radiator sizes and construction year may be used to model the heat demand of buildings accurately. However, in both cases scalability remains an issue.

Besides economic optimization

Another reoccurring theme in literature that concerns the optimization of district heating networks is the absence of including social values. Affordable energy supply and low environmental impact are examples of social values that currently are not taken into account sufficiently. Currently, many optimization methods optimize district heating network for purely economic reasons. Buoro et al. (2019) concludes that the purely economic optimization of district heating systems does not suffice anymore. Other concerns such as CO_2 emission and global warming also have to be taken into account. A great example can be found in the research conducted by Falke et al. (2016). In a specific context, a district energy system that costs 4% more reduces up to 29% of the co_2 emissions. As district heating networks are deployed to reduce co_2 emissions, these trade-offs have to be considered more in optimization. This result shows that optimizing for a single objective may lead to district heating systems that perform much worse on other objectives. Besides the fact that environmental impact has to be taken into account during district heating optimization, literature also raises concerns on energy delivery to consumers in the district heating network. Bhattacharya et al. (2019) concludes that there is " A need for developing concrete optimization based frameworks for optimizing social welfare objectives relating to thermal fairness". What is meant is that the distribution of energy is often not included in designing district heating networks, leading to systems where some buildings will be systematically colder than buildings that are close to the source. As the delivery of thermal energy is the main function of a district heating network, more attention must be fixed on maximizing thermal comfort [6]. In a research conducted by Bouw (2016) multiple researches towards consumer satisfaction in Europe are summarized. It is stated that comfort in district heating networks is dependent on the quality of the heat source and the general need for heat. In older buildings, where the level of insulation and the radiator capacity is low, the discomfort is largest. It is explicitly stated that not taking these issues into account during the development of the district heating system, the dissatisfaction of consumers grows. It is also concluded that most households deem the reliability and price of energy above the extent of sustainability of the energy source [11]. In the Netherlands and the UK, district heating systems have a poor image, mostly due to the bad technical performance of existing systems. In Scandinavian countries, district heating network are accepted well as the systems have a good technical performance. It is thus concluded that good technical performance is needed for the general acceptance of district heating networks. This may in return accelerate the energy transition [11]. Last but not least, in a research conducted by Fang, Yua, and Liu (2020) the profit allocation of heat producers in a district heating network is optimized. The authors conclude that further research should include the comfort of consumers in district heating networks. All in all, there are clear signals in literature that the optimization and designing of district heating networks should include more than just economic values. For the acceptance of the technology an increase in technical performance is needed, which accelerates the energy transition. Furthermore, district heating networks are employed to reduce co_2 emissions. The reduction of emissions should therefore play a more prominent role in district heating network optimization and design.

To conclude, many of the researcher that opt to optimize district heating systems, optimize the system as a whole. Besides the fact that most researches optimize the district heating system, the most optimization objective that is considered in most researches is reducing some sort of cost [15]. In some researches only the investment cost in considered, while in other researcher the cost over the lifetime of the system is considered. It is known that lowering the investment cost of the district heating network is important for its feasibility. Lowering the cost will accelerate the energy transition. The researches that did optimize the district heating network separately from the system used graph theory. In most cases the district heating network is optimized in a certain urban context using a street network. In most cases, the amount of buildings or consumers in the district heating network is small-moderate (< 200 consumers), while there is a need to develop methods that are applicable on large systems [52]. In contrast to the optimization objectives chosen in literature, there is a clear signal found in literature that states that the optimization of district heating networks should encompass more than just cost. As concluded by Sameti and Haghighat (2017), most optimization methods do not include emissions. Besides emission, literature clears out that there is a need to incorporate the customers view in the optimization of district heating networks. As the primary objective of a district heating network is to transport heat to consumers, it is important the performance of the district heating system is evaluated from a consumers perspective, especially the thermal comfort experienced by consumers.

2.0.1. Thermal comfort

As it is clear that more attention has to be given to the consumers district heating network optimization, this section will clear out what consumers desire from a district heating network and how thermal comfort may be measured. In the research conducted by Bhattacharya et al. (2018) When the environmental conditions are cold, consumers expect that the district heating network suffices in heating the buildings [6]. However, in cases where the environmental conditions are more extreme, or the energy source in the district heating network shows fluctuations in available energy, the distribution of energy may be at stake. Especially in the absence of good control methods, differences in thermal comfort between consumers may exist. In the research conducted by Bhattacharya et al. (2018) thermal comfort is defined as the extent to which the indoor temperature approaches the desired indoor temperature. It is concluded that the discomfort of consumers increases as the heat source reduces the energy output. Next to that, if the environmental conditions are colder, the thermal discomfort also increases among consumers. In the research conducted by Shin et al. (2017) it also stated that comfort of consumers is dependent on the indoor temperature. Overall, thermal comfort is achieved when the indoor temperature ranges between acceptable values. It is stated that an indoor temperature of 20 - 25 $^\circ C$ is considered comfortable. However, the exact temperature differs per person [55]. Concluding, thermal comfort is achieved when the indoor temperature approaches the desired indoor temperature of 20 - 25 $^\circ C$. If the indoor temperature is below the desired indoor temperature for longer periods of time it may lead to dissatisfied consumers [6]. The satisfaction of consumers is important as this may increase the acceptance of district heating networks in society. The satisfaction of consumers in district heating network is dependent on multiple factors, among which reliability of energy supply and comfort [4]. Improving the technical performance of district heating networks may lead to better acceptance and may thus accelerate the energy transition. Incorporating consumers needs is thus not only important for the consumers themselves, but also for the general acceptance of the technology [4]. From a technical perspective reliability of energy supply and comfort are factors that should be adopted in district heating system design to accelerate the energy transition.

Performance criteria

In short, there are two barriers recognized in the wide application of district heating networks: Upfront investment cost and technical performance from a consumers view. This includes reliability of energy supply and thermal comfort [62] [4]. The cost as well as the technical performance of the district heating network are dependent on the design of the network. Distance of the consumer to the source, as well as the thermal losses that occur in the network may induce more thermal discomfort [6]. In other words, limiting the thermal losses that occur as well as limiting the distance of consumers to the source may improve the comfort experienced by consumers. Overall, district heating networks will increase in efficiency if the thermal losses are limited [4]. It is therefore argued that maximizing the efficiency of the district heating network is in the consumers best interest. Besides the fact that maximizing efficiency increases the thermal comfort for consumers, it also lowers energy prices which also increases acceptance of the technology [4].

Optimization objective 1: Minimize investment cost of the district heating network
Optimization objective 2: Maximize efficiency of the district heating network

Graph theory

Over the recent years graph theory has gained traction in optimizing district heating networks [15]. In this section the use of graph theory in optimizing district heating networks illustrated as well as what graph theory entails. Graph theory is a study within mathematics that concerns structures that can be represented by edges and nodes. In figure 2.1 an example of a graph can be seen. The points denote a node, which are linked in pairs using edges. Naturally, graph theory is highly relevant for district heating networks as the pipelines can be represented with edges and nodes [14]. Each pipeline in the network may be represented by an edge. Placing nodes in certain locations, with edges that connect the nodes, a graph is made. However, graph theory may be used in many other applications too. An example of an application we all use is for route planning. Using graph theory, the fastest, or the shortest route between point A and B is calculated. All in all there are many applications to graph theory ranging from representing social networks, to modelling district heating networks. Thus, it can be concluded that the theory is versatile and applicable on many problems [68]. Graph theory is used in many district heating network optimizations as it allows to quickly come up with different network designs. There are certain well-known algorithms applicable in graph theory that are able to minimize the total length of the pipelines necessary. For example, Kruskal's algorithm may be used to calculate the minimum spanning tree which gives insight in the amount of pipelines needed to connect all consumers to the heat source. Another The second reason why graph theory is highly relevant for optimizing district heating networks, is the ability to deal with large data sets or networks [14].

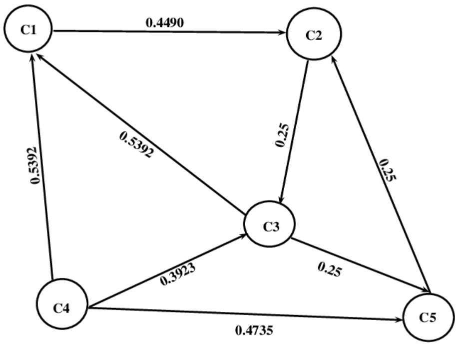


Figure 2.1: Example: A directed and weighted graph of a set of roads
" Weighted graph of a road network", by M. Akral et al. (2016), Journal of Multiple-valued Logic and Soft Computing 27(5-6):553-572

Now that the use of graph theory is explained, its use in optimizing district heating network is explained in more detail. In multiple researches, such as the researches conducted by Schmidt and Stange (2021), Lumbreras et al. (2022) and Rooij (n.d.) a street networks defines the solution space for the district heating network. In other words, the pipeline can only be constructed where the streets are located. The set of different streets in an area is called a street network. Only these streets may be used to construct pipelines to reach the consumers in the area. Once a set of pipelines is defined, multiple properties of the pipelines may be defined. It should be noted that every pipeline in the network may have different properties. Examples of properties that are encountered in literature are length and diameter of the pipeline. In the research conducted by Wack et al. (2023) also thermal losses and pressure losses are calculated. Besides the edges in the graph, that may represent pipelines or streets, there are also nodes in the street network. These nodes represent intersections between streets. However, nodes may also represent sources or consumers in the district heating network. This way there will be nodes that inject a certain amount of energy into the network, and nodes that subtract energy from the network. All in all, using graph theory a functioning district heating network may be modelled.

As clearly explained by Sameti and Haghighat (2017), for large networks the calculation times are often very high. This is characterizing for graph theory. If the size of a graph grows, and thus the number of edges and nodes increases, the number of potential solutions increases fastly. For smaller graph the optimal solution may be calculated by trying all different solutions. However, as the number of nodes and edges increases, it quickly becomes impossible to calculate all possibilities and choose the optimal solution to the problem. To explain this in the context of district heating networks: If size of the district heating network grows, the number of streets, consumers and potentially sources grows as well. The number of possibilities in which the consumers may be connected to the sources grows exponentially. To come up with good solutions to the problem within reasonable calculation time, heuristics are applied. A heuristic is a method that is applied to limit the number of proposed solutions, while trying to come up with better solutions to the problem. Within a heuristic there is always a trade-off between the quality of the solution, and speed of the calculations [46].

Besides the heuristics that may be applied, there are also several algorithms that may be applied to estimate good district heating networks. In literature multiple algorithms are found that are used to calculate the minimum spanning tree, or the shortest path in a graph. The difference between the algorithms and heuristics is that the algorithms guarantee to find, for example a minimum spanning tree. A heuristic does not guarantee to find the optimal solution of a problem. For example, Kruskal's algorithm is applied to quickly calculate the minimum spanning tree [51], [39]. As can be seen in figure 2.1, edges have a weight that represents the length of the edge, the cost, or any other characteristic. A minimum spanning tree is the tree where the total sum of all weights of the edges is minimal. If the edge weights are lengths of streets, then a minimum spanning tree is the tree that connects all nodes while the total length of all edges is minimal. The application of a minimum spanning tree is used to estimate the amount of piping needed to connect a set of customers to a set of producers [14]. Another algorithm that is often encountered in literature is Dijkstra's algorithm. This algorithm is applied to find the shortest paths from consumers to the source. [17]. Connecting users to the district heating network using the shortest path may limit thermal discomfort [6]. Concluding, graph theory naturally occurs in optimizing network that contain pipelines, as pipeline networks can be represented easily by edges and nodes i.e. a weighted graph.

In optimizing district heating design there are also non-linear processes that are more difficult to include in the optimization. The first difficulty is that thermal losses have to be taken into account to accurately model the performance of the district heating network. Next to that, there is flow in the pipelines. The flow has a certain direction and amount. Small changes in the design of the pipeline network may change the flows in the network, requiring a recalculation of the flows. Therefore, using graph theory to optimize district heating networks is considered complex and requires multiple steps. Efficient methods are needed to calculate the effects on larger district heating networks as current methods have very long calculation times on large systems. [36].

2.0.2. This research

Research questions

In summary, to reduce the emission of greenhouse gasses by the energy use in buildings, sustainable energy sources have to be used for spatial heating. Using a district heating network the geothermal energy is delivered to consumers. As a district heating network is a set of pipelines, graph theory is often used to optimize the district heating network. In most cases, the district heating networks are optimized to lower the cost of the system. In literature there are clear signals that more research has to be done to incorporate different objectives in the optimization. To accelerate the energy transition, the acceptance of district heating networks has to be enhanced by improving the technical performance from a consumers perspective. Literature states that reliability of energy supply and thermal comfort are criteria desired by consumers. However, in most researches thermal losses are not taken into account, meaning that the quality of energy that consumers receive can not be assessed. This is where a knowledge gap is recognized. It is argued that limiting thermal losses, and thus increasing efficiency, leads to a district heating network performs best for the consumers. In the field of district heating network optimization many valuable contributions can still be made. In order to make a valuable contribution to district heating network optimization, the following research questions are formulated.

How does the performance of a cost optimal district heating network compare to a district heating network optimized to maximize efficiency?

1. *How can thermal comfort of consumers in a district heating networks be assessed?*
2. *How can thermal losses and thermal comfort be incorporated effectively in the optimization of large district heating networks?*

Relevance

This work will focus on optimizing the district heating network i.e. the pipelines in the ground that deliver heat to consumers. Affordability is important for district heating networks as the initial investment cost is very large, However, the primary functions of a district heating network is to deliver thermal comfort to consumers. Currently there is a knowledge gap on how different district heating networks perform on delivering energy to consumers. Thermal losses and thermal comfort are rarely incorporated in the optimization. In other words, it is not known what the effect of using a cost-optimal district heating network is on the delivering thermal comfort to consumers. Furthermore, it is not known how to choose the weights between the different objective functions. The goal of this research is to contribute to the knowledge on district heating network optimization, by researching the performance difference of district heating networks, optimized for different cost and efficiency. Last, the method that is developed is used on the street network (graph) of multiple neighborhoods in Delft. The application on a large graphs leads to more insight on how the method performs on large graphs. An affordable alternative of the district heating network in Delft, is compared to an alternative that is optimized from an end-user perspective. The difference in performance between these networks leads to insight in the relevance of choosing the optimization objective.

2.0.3. Outline of the report

In chapter 3 the methodology that is applied in this research is explained. Following, in chapter 4 the cost model is explained, and in chapter 5 the thermal model is clarified. Also the correlation between both models is explained. In chapter 6 the heuristics that are applied in the district heating network optimization are clarified. In chapter 7 the method that is used to retrieve a street network in the area of Delft is explained. Then in chapter 8 the whole method as illustrated in figure 3.1 is applied to 100 random street networks in chapter 8. The generation of the random networks is explained in this chapter as well. In chapter 9 the method is applied to the street network in Delft. In chapter 10 the findings of the research and the conclusion are given. Last but not least, chapter 11 the discussion on the research is given.

3

Methodology

The aim of this research is to gain insight in the performance of district heating networks from a consumers perspective. The consumers in a district heating network should experience thermal comfort. Currently there is no insight in how different network designs may affect the consumers in a district heating network. In this research, a method is developed that is able to evaluate district heating networks from a consumers perspective. To do this, the energy received by every consumer in the district heating network is assessed. The following section describes the methodology that is developed to gain insight into this problem.

To assess the problem, mathematical modelling is applied. Mathematical modelling is chosen as it allows to investigate the dependence of the performance of the district heating network over certain parameters such as the temperature of the ground [60]. Graph theory is used to quickly evaluate different network designs. Furthermore, graph theory allows generating different designs in a structured manner to obtain better solutions. The data that is used in this research is analytical in nature: Real spatial data will be used to model the district heating network in Delft. Besides the district heating network in Delft, a random street network generator is used to generate different networks. These networks will also be analyzed to create a broad foundation for the conclusions. Certain relationships may be discovered that may apply to other district heating networks as well. As the research is concerned with analyzing numerical data and unraveling relationships between certain properties that may apply to district heating networks in general, the research is quantitative in nature [5].

The spatial data will be collected using a python library that retrieves all data from OpenStreetMap. Furthermore, the random street networks are generated using a tool supplied by P. Heijnen (n.d.). All data will be analyzed using python where all models and methods will be developed. However, it should be noted that the developed methods may also be used in other programming languages. All calculations are conducted on a laptop with the following (relevant) specifications: Intel(R) Core(TM) i7-8750H CPU @ 2.20GHz with 16 GB of RAM.

Retrieving the spatial data, and the 100 random street networks went fluent without problems. Analyzing the 100 random networks also went smoothly, which is demonstrable by the results. Analyzing the large networks has been much more difficult due to the size of the graph and the many particularities that appeared. In the large graph there are many possibilities of results that may occur, that were initially not thought of. For example, a new method has to be developed to deal with the cycles that naturally may appear in a district heating network. As there are many sorts of errors that may appear in the optimization, and the high calculation time, troubleshooting the method was extremely time-intensive. If a correction was made in the script, the optimization process was partially, or completely done again. To tackle this problem, over time multiple check points were built in generating and analyzing the different designs. The check points ensured that the result is a feasible and correct district heating networks. Besides that, multiple intermediate saving points were introduced to limit the time needed to optimize the district heating network again. The consistency in the results eventually showed that the method that is used is correct and generates correct district heating networks. For example, analyzing the 100 random district heating networks is done in a single attempt and no incorrect or unexpected results occurred.

The results of the research are conclusive and consistent, and support in answering the research question. The method applied has been effective in answering the research questions. Mathematical modelling allowed to quickly change certain parameters in the models, which resulted in more insight in the relationships between them. Graph theory has proven to be very helpful in optimizing the district heating networks. The calculation method applied allowed to effectively generate and analyze the different district heating network designs. Besides that, graph theory allowed for great visualization of the problem, which helped in grasping why certain network designs led to better solutions. In the next section, the developed method is explained in more detail, and summarized in a graphical overview.

Methodology overview

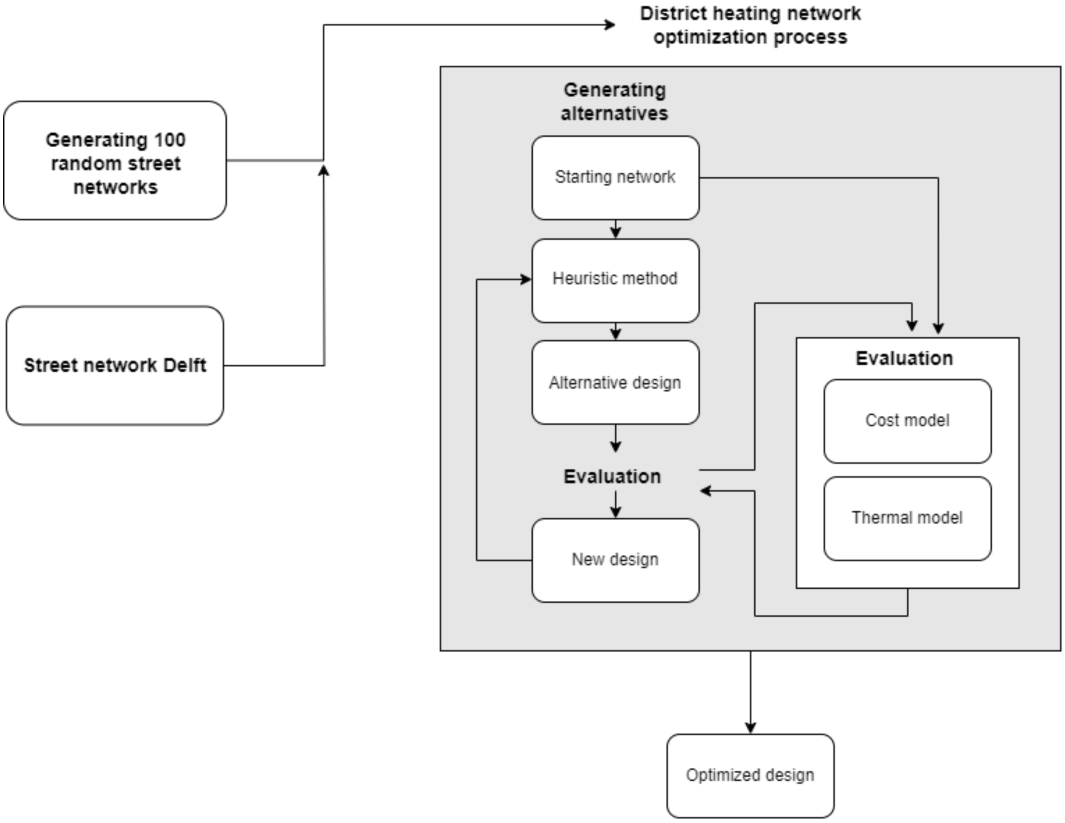


Figure 3.1: Overview of the methodology

In figure 3.1 a graphical overview of the methodology is seen. Beginning on the left, there will be two sorts of streets networks in which the district heating network will be optimized. 100 random street networks, and a street network in Delft. For both street networks, the optimization process will be exactly the same. The optimization process can be divided into two parts: Generating alternative designs using heuristics in graph theory, and the evaluation of these different designs. The generation of alternatives starts at a starting network, for which different alternatives are generated. Using the cost and the thermal model, each alternative is evaluated for the optimization objective. This can be either minimizing cost or maximizing efficiency. This means that for every street network there will be two optimized designs. A cost and an efficiency optimized design.

4

Optimization problem

This chapter focuses on describing the optimization problem for district heating networks in general terms. The description that will be given in this chapter will apply to all district heating networks and may be used in different settings. As stated, district heating networks are developed in urban areas. Many of the researches as summarized in the literature review, use a certain urban context in which the district heating network will be built. Many researches argue that it is important to use the streets in the area to construct the pipelines in. Therefore a street network of the area is required. This street network contains all streets and intersection found in the area. Moreover, there are buildings along the streets in the street network that have to be connected to the district heating network. A district heating network is thus a set of pipelines, that is placed along the streets of a defined street network, that connect the consumers in the area to the source. The pipelines may use all streets in the street network to create a viable district heating network.

To give a general description of the problem in terms of graph theory: Let G be the graph of the street network in the area. Let $E(G)$ be the edges or streets of the graph, and $V(G)$ the nodes/intersections of the graph of the street network. Each edge of $E(G)$ is specified by the nodes between the edge exists, and a length.

$$\forall\ e_{i,j} \in E(G): \quad e_{i,j} = (i, j, l_{i,j})$$

Let B be the set of buildings in the area. For now, each buildings is connected to street of the street network in the area. The energy demand of the buildings must be fulfilled by delivering energy through that street. H_b is the heat demand for building b. It may appear that there are multiple buildings along one street. For now, assume that the demand is summed and projected onto one street:

Let e_b be the edge from the street network that is nearest to building b.
$e_b = (i, j, H_b)$, where i and j define between which nodes the edge occur, and H_b its demand.
E_b is the set of streets that contains all streets with demand.

In any district heating network problem there will be two sorts of streets. Streets in the street network that may be used to lay pipelines and streets with buildings that have a certain demand. As all the streets with demand contains buildings that have to be connected to the district heating network, they all have to be included in the district heating network. In other words, a part of the district heating network design is fixed. The other streets in the street network may be used to connect the streets with demand to the source. All the pipelines of the district heating network taken together form the whole network, which will be denoted by N. Using a decision variable, denoted by $x_{i,j}$, it is chosen which streets are used for the district heating network. It is important to realise that $x_{i,j}$ is a binary variable. A pipeline is either built along a street or not. If a pipeline is building along a certain street, $x_{i,j} = 1$.

N is the district heating network that contains pipelines that run through the streets of $E(G)$

$$N = \{e_{1,2}, ..., e_{i,j} \mid \forall\ e_{i,j} \in N\colon x_{i,j} > 0\ \}$$

However, in order to determine whether a network N is a viable solution to the problem, multiple constraints are introduced. Next to that, it is also needed that network N may be evaluated for different objectives in order to optimize it. First, the constraints are given and explained. After that, the objective functions are given.

Constraints

1: A network is a viable solution if and only if all streets with demand are included in the district heating network.

2: and all streets with demand can be reached from the source.

If a proposed network N adheres to the constraints as defined, then network N is a viable solution to the problem. For this network, different objective functions are calculated that determine the quality of the solution. As stated before, in literature there is an emphasis on optimizing the cost of a district heating network. Thus, one of the objective functions is the cost of network N. Besides the cost, the district heating network will also be evaluated for efficiency. Moreover, it is also needed to calculate the consumer satisfaction in the district heating network. The consumer satisfaction is a measure of the extent to which the demand is satisfied. The objective functions will be fully specified in chapter 4 and 5, where the models that calculate the cost and the thermal losses of district heating networks are constructed.

Optimization objectives

Cost of network N: K_N

Efficiency of network N: η_N

5

Cost calculations model

As found in the literature review, most methods used to optimize district heating networks focus on minimizing cost. As initial investment is often a barrier in applying a district heating network, optimizing the investment cost may lower the return on investment, and may thus accelerate the adaption of district heating networks [54]. The researches by Schmidt and Stange (2021) and Wack et al. (2022) are two examples where the design of the district heating network is optimized, such that the investment cost of the district heating network is minimized. As cost is an important aspect of deploying district heating networks, a model is developed that is able to calculate the cost of a district heating network. In this chapter the principles and the methods used to calculate the cost of a district heating network are explained. Before the cost model is explained, a more exact problem definition is given in mathematical terms.

Cost model

In many researches the cost function is dominated by the length and the diameter of the pipelines. For example, in the research conducted by Wack et al. (2022). In this research the diameters of the pipelines are chosen from a set diameters that are known to exist in real life. Furthermore, all the pipeline diameters may be delivered in all required lengths. In the research conducted by Schmidt et al. (2021) the cost function of a pipeline also contains the length and the diameter of a pipeline. In this research also the cost of underground obstacles is included in the cost function. It is assumed that this cost is related to the diameter of the pipeline. In this research the pipeline diameter is calculated on the basis of hydraulic processes in the pipeline. In contrast to the previously mentioned research, in this research the inner diameter of the pipeline may have any diameter, meaning that the diameter of the pipeline is part of the optimization. In the research conducted by Yeates et al. (2021) a similar approach is used. Again, the diameter and the length of a pipeline dictate the cost of a single pipeline. In this research the pipeline again may have any diameter. The cost of the pipeline is calculated using a function that is based on the principles of economies of scale. An exponential function is given, which is called the pipeline cost dependence to capacity [71]. The idea of using an exponential factor to assess the cost of a pipeline originates from the '0.6 rule' that is described by Tribe and Alpine (1986). The 0.6 rule is a rule of thumb that is used to calculate the increase in cost if a pipeline or storage tank is increased in size [40]. In the rule of 0.6 a relationship between cost and capacity is given, with an exponential factor: $C_{a,a}/C_{a,b} = (C_{o,a}/C_{o,b})^{\alpha}$, where C denotes the capacity, and V the cost. As can be seen in the relationship between cost and capacity, cost does not grow at the same rate as the capacity increases. The relationship is non-linear. As the capacity of a pipeline can be expressed by the surface of the passage of the pipeline, the relationship between the surface area and the volume of a pipeline is given by the following function: $A_a/A_b = (C_{o,a}/C_{o,b})^{0.6}$, where A denotes the surface of the pipeline, and V the volume of the pipeline [40]. As the cost of the network is estimated, the most general exponential factor is chosen, namely $\alpha = 0.6$. Applying an exponential factor to estimate the cost of a district heating network is applied in multiple researches, such as the researches conducted by Yeates et al. (2021) and Heijnen et al. (2019). As the method is already used in the field of graph theory and pipeline network optimization, this method is considered suitable for the purpose.

As explained, the capacity of a pipeline equals free passage of the pipeline. There is thus a relationship between the capacity of a pipe and its diameter: $A_{pipe} = (\frac{\pi}{4}(D_{i,j})^2)$, where $D_{i,j}$ is the diameter of the pipelines between node i and j. The cost of a pipeline between i and j is calculated as follows:

$$K_{i,j} = l_{i,j} \cdot (\frac{\pi}{4} D_{i,j}^2)^{0.6} \tag{5.1}$$

The cost of network N can be calculated summing the cost of all pipelines in the network.

$$K_N = (\sum_{(i,j)\in E(G)} x_{i,j} \cdot K_{i,j}) \tag{5.2}$$

It is obvious that the diameter of the pipelines play an important role in optimizing the district heating network, but also in the cost function. However, the diameters of the pipelines are not known yet. The pipeline diameters are estimated in a series of steps. First the assumptions and the conditions necessary to estimate the pipeline diameters are explained. Then, the method that is used to calculate the pipeline diameters is explained.

5.0.1. Calculating the pipeline diameters.

Assumptions

Before the diameters of all the pipelines in the network can be calculated, two important assumptions have to be explained.

1. The velocity of the flow is constant throughout the entire network at 1 m/s.
2. Pressure losses and other hydraulic effects are out of scope.

Assuming a constant flow velocity reduces the complexity of the necessary computations a lot. The diameter of the pipeline influences the flow velocity, depending on the volumetric flow that goes through the pipeline. The velocity on its turn influences other characteristics such as Reynolds number, the fictional losses, etc. In a research conducted by Boer (2018), it is seen that in a functioning district heating network, the flow of the water through the pipelines has unique properties throughout the all pipelines in the different network [10]. In the research conducted by Schmidt and Stange (2021), the mass flow and diameter of every pipeline in the network is given. From this, the mass flow velocity is derived. The flow in this particular district heating network model reached velocities up to 0.7 m/s. The model that Schmidt and Stange (2021) developed in this research did include several hydraulic calculations such as friction losses and pressure losses. The velocity of the flows in this model are therefore viable velocities. As the flow velocity in the research by Schmidt and Stange (2021) remains in this order of magnitude, a constant velocity of 1 m/s on all flows is applied. As the flow has unique properties throughout every pipeline in the district heating network, and the district heating network in Delft will contain thousands of pipelines, it is expected that the computational load becomes too high if too many details are included. Therefore it is chosen to limit the functions included in the model, while still being able to calculate pipelines diameters and thermal losses in a consistent manner. Also, optimizing large district heating network are known to be computationally heavy and therefore adding functions should be significantly contribute to the accuracy of the result to make up for the increase in computation time [36]. A third assumption is needed to be able to calculate the pipeline diameter, which is explained next.

1. There is a general efficiency that increases the capacity of the pipelines, such that thermal losses are taken into account before sizing the pipelines.

To be able to calculate the diameters of the pipelines, a general efficiency is applied. As can be envisioned, if the mass flow starts flowing from the source towards all consumers with the exact amount of energy that is required by the consumers, the amount of energy that actually reaches the consumers is much lower due to thermal losses. Therefore, the energy that leaves the source must be increased, such that the consumers still receive their energy as demanded after all thermal losses have occurred. The efficiencies of district heating networks are not easily found in literature. However, there is a case found in Latvia. In Latvia the share of the heat losses of the pipelines in a district heating network may reach up to 30% or even higher. However, the efficiency of a district heating network is dependent on numeral conditions. One of the conditions are the environmental conditions. In lower temperature environments the pipelines will lose more thermal energy, lowering the overall efficiency [10]. As there are real-life examples of district heating networks achieving an efficiency of 70%, the general efficiency that is applied is 70%. In Appendix A, a derivation for the general efficiency of a district heating network is given.

Using the general efficiency, the mass flow in each pipeline is increased such that each pipeline may lose a share of energy, while all consumers will still receive the energy they demand. An increase in mass flow, under the assumption that the flow velocity does not increase, means that the diameter of the pipelines increases. Thus, the diameter of each pipeline is increased according to the increase in mass flow. In the following section, the conditions under which the district heating network operates are explained.

System conditions

For the district heating network in Delft, some conditions are already known. In Delft, the water in the district heating network will be 50 $°C$ at the source. A district heating network where the water is only 50 $°C$ is considered a low temperature district heating network [43]. As the water spreads through the network, the temperature drops and consumers receive lower temperatures water. In some district heating systems the heat in the water is also used for heated tap water. In low temperature district heating networks, the temperature of the water is increased at each household using a 'booster'. The booster increases the temperature of the water above 70 $°C$. This booster is applied such that the temperature of the tap water stays above 70 $°C$, such that Salmonellae bacteria do not survive [10]. As more than 63% of the energy consumption of household is spent on spatial heating, and only 15% on the heating of water, heating tap water is out of scope in this research [22]. Furthermore it has to be assumed that each building in Delft wants to maintain an indoor temperature of 20 $°C$. The last important temperature that has a large influence on the performance of the district heating network is the temperature of the ground. However, in the model the temperature of the ground is changed easily such that changes in environmental conditions may be tested.

A desired indoor temperature: T^{in} = 20 [$°C$]
Temperature of the water at the source: T^{s} = 50 [$°C$]

5.0.2. Calculating pipeline diameters

Now that the assumptions and the conditions under which the system operates are known, the flows through the pipelines can be calculated. Calculating the flows in the district heating network consists out of multiple steps that will be discussed in chronological order.

Shortest paths

For any district heating network design, that is based on the street network of the area, the flows through the pipelines can be calculated. From now on, 'network' is used to describe a set of pipelines within the street network. To be able to calculate the flows in the network, it is assumed that every street with demand is supplied using the shortest path from the source. In figure 5.1 an example of a network within a street network can be seen. The red node denotes the source, the grey edges are the streets, the green edges are streets with demand and the orange edges are pipelines of the network. Pipelines also run through the green edges, as there is demand along the street. It is assumed that every street with demand gets its energy supplied using the shortest path within the pipeline network. The nodes that appear on the shortest path to a street with demand must carry a certain amount of energy, demanded by the consumers. However, applying shortest paths to calculate the flows should be applied carefully as two problems may occur: district heating network may contain cycles as some streets with demand may already form cycles. Secondly, shortest paths are calculated using the nodes of the street. The shortest path to one end of the street may be different than the shortest path of the other end. As a result, no pipeline is laid along the street with demand. Both problems will be explained using figure 5.1. Furthermore it is explained how the problems are solved.

In figure 5.1, three streets with demand in the top right corner form a cycle. As can be estimated, the shortest path from the source to node 2 is a direct connection. The same applied to the shortest path to node 7. If it is assumed that the flows to node 2 and 7 flow along the shortest path in the pipeline network, no pipeline will be constructed between node 2 and 7. To assure that a pipeline is

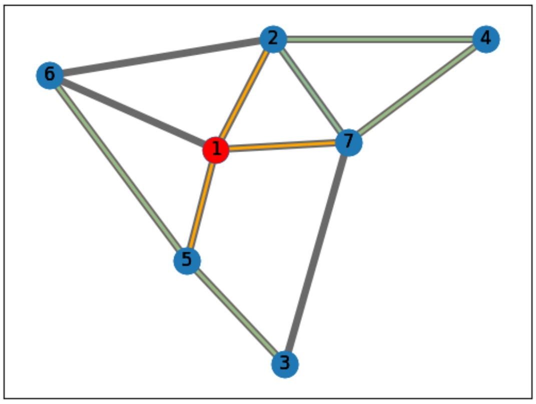


Figure 5.1: An example of a graph with streets with demand

built between node 2 and 7, a condition is introduced. Let one of the two nodes be closer to the source than the other. The node that is closer to the node is the 'closest node', while the other is the 'further node'. To make sure that a pipeline appear along the path to the furthest node is forced through the closest node. In order to guide all the paths of the further nodes of a street, a general rule is applied to all calculate the paths to all nodes of streets with demand.

Let i and j be nodes of a street with demand.
Let SP_i, l_i and SP_j, l_j be the shortest paths and path lengths to node i and j.
if $l_i < l_j$, i is the closest node to the source, else node j is closer to the source.
If $l_i < l_j$: $SP_i = \{s, ..., i\}$, $SP_j = \{ s, ..., i, j \}$
If $l_i > l_j$: $SP_i = \{s, ..., j, i\}$, $SP_j = \{ s, ..., j \}$
Applying these conditions consistently ensures there is a pipeline along every street with demand.

Now that the paths of the flows to the streets with demand is known, a method is introduced that allows to measure the energy that is delivered to a street. As the heat demand is somewhere along the street, the energy delivery to that consumer may be approximated by dividing the heat demand over the two nodes of the street with demand. Take for example node 5 and 3 in figure 5.1. Let H_b be the heat demand of the street (5, 3). If all demand is projected onto node 5, then the thermal losses along the street (5, 3) would not be taken into account. The temperature of the water that the street would receive is higher in the model than it would be in real life. If only node 3 would be used to project the demand on, the thermal losses along street (5, 3) would be taken into account, but the temperature of the water would be lower than the average temperature along (5, 3) in real life. To approximate the average temperature that is received by (5, 3) best, the demand is separated over node 3 and 5 evenly. This way, the street with demand is split into two nodes with each an equal demand. Therefore it is chosen that the real temperature of the water would be approximated best if both nodes receive half the demand of the cluster. It also should be noted that some edges with demand are connected: they share one node. Therefore, there may be nodes in the network that receive two separate demand. This must be treated carefully, as the demand over separate edges may differ greatly.

e_b is street with demand, that contains node i and j and a heat demand. Let n be the street to which both nodes belong. The edge is separated into two nodes that both receive half the demand of the street: $d_n^i = \frac{1}{2} \cdot H_n$, $d_n^j = \frac{1}{2} \cdot H_n$

To summarize, the shortest path to every node with demand indicate the nodes that must pass a certain amount of energy. If all paths are known, some nodes in the network pass more energy than others. All nodes that pass a certain amount of energy are thus nodes that must be connected with a pipeline of a certain size. How the exact amount of energy that a node passes is calculated is explained in the following section.

Energy flow through pipelines.

Now that the paths to all the nodes with demand are known, the flows throughout the entire district heating network are calculated. In short, every node that occurs on a shortest path of a node with demand to the source must pass the energy meant for that node. this principle is explained using figure 5.2. In figure 5.2 an example of a small district heating network is seen. Take for example the pipeline between the red and green node. As the pipeline between the red and green node should only carry 1000 W, meant for the green node, the energy flow the pipeline equals. Two general rules are made that determine the energy flow through a pipeline:

1. A pipeline is necessary between two nodes if the energy flow between them is greater than 0 W.
2. The energy flowing through the pipeline is equivalent to energy flowing through the node with the lower flow rate..

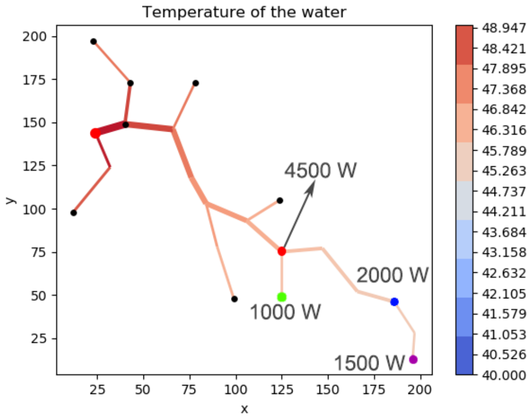


Figure 5.2: Energy flow along edges.

Following from these rules, the energy flow through each pipeline is calculated using the following steps. SP_i contains all the nodes that are on the shortest path from the source to node d_n^i. As all these nodes are on the shortest path, they must pass the energy demand of the node, equal to $\frac{1}{2}H_b$. As nodes may appear on more than one shortest path, the flow through is summed for all energy demands that flow through it. Let o and p be nodes that appear on one or more shortest paths from the source to nodes of streets with demand. Let f_o and f_p be the energy that flows through node o and p.

Let $e_{o,p}^f$ be an edge between node o and node p. f_o and f_p are the flows through node o and node p.

$$\text{if } f_o < f_p\text{:} \quad e_{o,p}^f = (o, p, f_o) \qquad \text{if } f_p < f_o\text{:} \quad e_{o,p}^f = (o, p, f_p)$$

The energy flow is known for each pipeline in the network. A pipeline is considered obsolete if it has zero flow since it performs no function in the network. A pipeline may be excluded from the network if it has no flow. Now, every pipeline transports exactly the quantity that the nodes require. However, as mentioned, thermal losses will cause the pipeline to lose energy. The amount of energy that is available to the consumers decreases as the temperature of the water in the pipeline declines. The energy flow through each pipeline is increased using the general efficiency as stated in section 5.0.1 to account for thermal losses and increase energy flow through each pipeline.

For all the pipelines in the network, the energy flow through it is increased, to take the thermal losses into account.

$$\forall\, e_{i,j}^f \in S\text{:} \quad e_{i,j}^f = (i, j, f_i/\eta_{gen})$$

Pipeline diameters

Now that the energy flow through each pipeline is known, the mass flow through each pipeline is calculated. As stated in the conditions of the system, the temperature of the water at the source is 50 $^\circ C$. The desired indoor temperatures of all clusters are 20 $^\circ C$, while the temperature of the ground is variable. However, in any case the energy that is carries throughout the network is contained in a mass of heated water. Each pipeline with a certain energy flow thus has a certain mass flow of water with a certain elevated temperature. The temperature of the water must be above 20 $^\circ C$ in order for consumers to withdraw thermal energy from it. As the energy in the pipeline is fully carried by the heated water, it is possible to convert the energy in the pipeline into a mass flow. However, the energy content in the pipeline is relative to the temperature difference between the water in the pipeline and the temperature of the ground or the indoor temperature of buildings. The exact temperature of the water in the pipeline may not be used to calculate mass flows, as this would mean that mass is created in the pipeline. In figure 5.3, an example of a district heating network is given. At the source, 100 kW of thermal energy is released at 50 $^\circ C$. Converting this into a mass flow using equations (5.3), the mass flow equals 0.796 kg/s. If the two successive pipelines are evaluated for their mass flow, the mass flows equal 0.082 kg/s and 0.741. Taken together, this would equal a mass flow of 0.878 kg/s, exceeding the mass flow that was there at the source. This is not physically not possible. As a result, the temperature of the source is applied to each pipeline in order to determine the correct mass flow. This leads to correct mass flows, as no more mass is created, and the mass separates according to the demands in the network. Applying this rule is correct as the energy flow released at the source has a certain temperature, and therefore a certain energy content when compared to the environment or indoor environments. The mass of water in which this energy is captures can only change due to consumers that take a share of the mass flow for spatial heating. Therefore it is important to calculate the mass flow through each pipeline using the temperature of the water at the source, with respect to the indoor temperature of buildings.

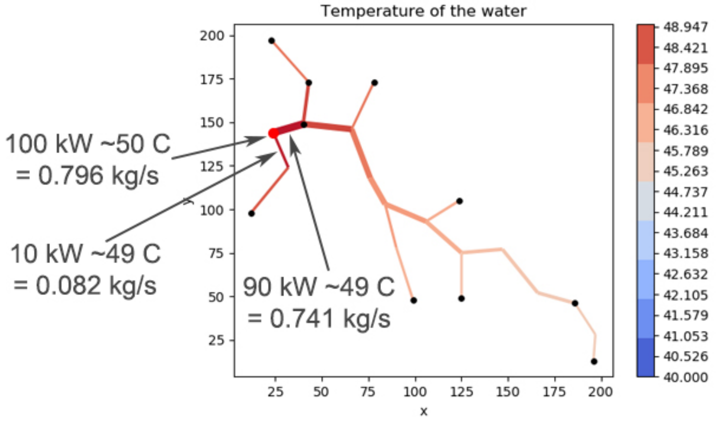


Figure 5.3: An example of increase of mass flow

The mass flow through each pipeline follows from the energy that flows through it. If $f_{i,j}$ is the energy that flows through the pipeline between node i and j, the mass flow is calculated as seen in equation (5.3). Using the volumetric flow in each pipeline the diameter of the pipeline is calculated. The exact details on how the mass flow is translated into the diameter of the pipelines is explained in Appendix A as it consists of a series well known calculations. For now, $D_{i,j}$ is the diameter of the pipeline between nodes i and j and is calculated using equation (5.4).

$$m_{i,j} = f_{i,j}/((T^s - T^{in}) \cdot C_p) \tag{5.3}$$

$$D_{i,j} = \sqrt{\frac{2 \cdot m_{i,j}}{\rho \cdot \pi}} \tag{5.4}$$

After all calculation discussed in this section, the diameters of the pipelines in the district heating network are calculated. For all pipelines in the district heating network the length and its diameter are known. Therefore the cost function can be calculated. Besides solving the cost function, the diameter of the pipelines will also be used to calculate the thermal losses in the thermal model that will be discussed in the following chapter.

Cost function

Now that the diameters of the pipelines in the network are calculated, the cost function of the network can be calculated. The cost function as defined at the beginning of this function is as follows:

$$K_N = (x_{i,j} \cdot \sum_{(i,j)\in E(G)} l_{i,j} \cdot (\frac{\pi}{4} D_{i,j}^2)^{0.6}) \tag{5.5}$$

To conclude, using the shortest paths of the source to every edge with demand, the energy flow through each node in the network is calculated. Using a general efficiency, that increases the energy flow through each node, thermal losses are taken into account for sizing the diameters of the pipelines. The energy flow through each node is translated into an energy flow through each pipeline in the network. In a series of calculations, the flow through each pipeline is converted into a pipeline diameter. Using the lengths and the diameter of each pipeline in the network, the cost function is solved. This cost function is used to optimize the district heating network in a later stadium of the research. Besides using the pipeline diameter to calculate the cost of the network, the pipeline diameters will also be used to calculate thermal losses of the network. In the next chapter, it is explained how the pipeline diameters are used to calculate thermal losses.

6

Thermal losses model

Not that a method is developed that is able to assess the cost of a district heating network, a model is needed that is able to assess the thermal properties. The aim of the model is to accurately model the thermal losses of a district heating network, such that the model may be used to optimize district heating networks for efficiency, which results in thermal comfort. The model will give insight in how different district heating networks perform under a set of conditions such as outdoor temperature, energy availability of the source, etc. Moreover, the model should give insight into the thermal comfort of the consumers in the district heating network. The thermal comfort is calculated by assessing the extent to which their demand is satisfied.

The geothermal well in Delft will deliver water that reaches temperatures up to 75 $^{\circ}C$. This water is pumped through a heat exchanger that lowers the temperature to 50 $^{\circ}C$, before it is pumped into the neighborhoods in Delft [28]. As the temperature of the water, that runs through the pipelines in the soil, is higher than the temperature of the environment, thermal losses will occur. When thermal losses are minimized, more energy can be delivered to the consumers in Delft, which may reduce unnecessary greenhouse gas emissions. In some cases, gas boilers are applied in district heating systems to be able to cover the peak demand. This is mostly in winter, when the outdoor temperatures are lowest. A more efficient network may thus reduce the need for gas boilers to cover the peak demand. This will therefore reduce CO_2 emission and cost of the fossil fuels needed [49]. In the following chapter, the calculation that are needed to assess the thermal processes in the district heating network are explained. First, the material selection and the thermal losses of an underground pipeline are explained. Then using the diameters of the pipelines and the topology of the network, the total thermal losses of a district heating network under certain conditions are calculated.

6.0.1. Material choice

To enhance the performance of the district heating network, insulated pipelines are applied to reduce thermal losses. There are two factors that determine the quality of the insulation: the thickness of the material, and its insulating properties. Kecebas, Alkan and Bayhan (2011) determined that using rock wool as an insulating material is economically speaking the best material to use for insulating the pipelines. Rock wool, as well as other insulating materials have a low thermal conductivity. The thickness of the insulating material increases the applying the insulation to the pipelines. In the research by Kecebas, Alkan and Bayhan (2011) also an optimal thickness of insulating material is given. However, this optimal thickness differs per application (water or oil pipelines), but also pipeline diameter. Besides literature sources, also insulated pipelines that are available on the market are looked up. Hermans Techniek Producten offers the Therma Tube, which is an insulated pipeline with diameters from 0.02 m up until 1.00 m [32]. The insulating material used is polyurethane, which has a lower conductivity than rock wool. However, the thickness of the insulating material is unknown. As the producer claims that this pipeline has already been used for over thousands of kilometers, the properties of this pipeline will be used to model the district heating network. As the thickness of the material is not given, it is assumed that the thickness of the insulating material is 0.025 m for all pipelines. It is given that the material of the pipeline is steel [32]. However, also the thickness of the steel used in the pipelines is not given. As steel has a much higher conductivity than the insulating material, changes in the thickness of the material are negligible. It is therefore assumed that the thickness of the steel is 0.008 m for all pipelines. Next, a summary of the materials and its properties, and known features of the water is given.

Insulating material	Polyurethane	Steel
Thermal conductivity coefficient (k) [W/mK]	0.025	45
Thickness (r) [m]	0.025	0.008

Heat transfer coefficient

Now that the materials used for the pipelines are known, the thermal losses of an underground pipeline are discussed. An underground, insulated pipeline is a considered 'standard problem' in thermal engineering. The situation is sketched in figure 6.1. The white surface shows the open passage of the pipeline. The thin blue layer around the open passage illustrates the insulating material. Between the insulating material and the open passage of the pipeline a structural material gives the pipeline strength. Through the passage of the pipeline, water with an elevated temperature flows through the network. T_w denotes the temperature of the water, while T_g denotes the temperature of the soil. At the source T_w is 50 $°C$ or 323 K. As the soil has a lower temperature, energy flows from the water in the pipeline to the soil. The thermal energy that flows from the pipeline is denoted by Q and is measured in Joules or Watts. Before Q is calculated, first the heat transfer coefficient for the buried pipeline must be known. The heat transfer coefficient is given by the equation given below figure 6.1 [41].

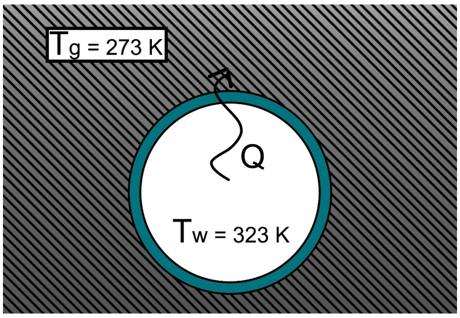


Figure 6.1: Standard situation of an underground pipeline

$$h = (\frac{D_3 \cdot \ln(\frac{D_2}{D_1})}{2k^S} + \frac{D_3 \cdot \ln(\frac{D_3}{D_2})}{2k^I}) \quad [W/m^2K] \tag{6.1}$$

r^I, k^I are the thickness and thermal conductivity coefficient of the insulating material. r^S, k^S of the steel.

$$D_1 = D_{i,j}$$
$$D_2 = D_{i,j} + 2 \cdot r^S$$
$$D_3 = D_{i,j} + 2 \cdot r^s + 2 \cdot r^I$$

Now following from the heat transfer function (h), the thermal energy that flows from the pipeline can be calculated. As the diameter of the pipeline changes from pipeline to pipeline, the heat transfer coefficient also changes from pipeline to pipeline. Also, the temperature along each pipeline drops. The further the hot water spreads through the network, the lower the temperature of the water will be. Equation 6.1 is re-written such that the diameter of each pipeline in the network is used instead.

$$h_{i,j} = (\frac{D_3 \cdot \ln(\frac{D_2}{D_{i,j}})}{2k^S} + \frac{D_3 \cdot \ln(\frac{D_3}{D_2})}{2k^I}) \quad [W/m^2K] \tag{6.2}$$

Following from the heat transfer function, the total heat transfer (energy) from the pipelines is calculated. Before the heat transfer from the pipeline can be calculated, the surface area of the pipeline, and the temperature difference between the water and the soil has to be known. The surface area of the pipeline equals the outer surface of the pipeline and is therefore a function of the diameter. The outer surface of a pipeline is calculated using equation 6.3.

$$A^P_{i,j} = \pi \cdot D_{i,j} \cdot l_{i,j} \tag{6.3}$$

$$Q_{i,j} = h_{i,j} \cdot A^P_{i,j} \cdot \Delta T \tag{6.4}$$

Before the thermal losses of the pipeline can be calculated, the temperature of the water that flows through each pipeline must be calculated. However, it is important to realise that before the water reaches pipelines that are further in the network, it has passed several other pipelines that vary in diameter and have other temperatures of the water that flows through it. Therefore, calculating the temperature of the pipelines in the network must start at the source of the network. Starting from the source, the thermal losses that occur in all pipelines is assessed, such that the temperature of the water at any location in the network can be calculated accurately. Next to that, at many places in the network the mass flow will split into several smaller mass flows. Thus, at certain distances from the source, the mass flow will flow in series of multiple smaller pipelines. The points where the mass flows are introduced, and by how much are dictated by the topology of the network. In the following section, the role of the topology of the district heating network on the thermal losses are explained.

Role of the topology

Now that the diameters of the pipelines, the heat transfer function (h), and the function to assess energy transfer (Q) are known, the role of the topology of the network is incorporated in the calculation. How this topology is used in the calculation, is explained in this section. In figure 6.2 an example of a district heating network is given. Using the methods as explained in chapter 4, the diameters of the pipelines are calculated. The nodes in this particular figure are placed using the Kamada-Kawai algorithm. Kamada-Kawai places the nodes in graph such that the distances between them are proportional to the weights of the edges [35]. From the source, the green centered node, a radius is drawn that represents a certain distance from the source. As can be seen, at the particular distance, the radius intersects with 5 pipelines. All these pipelines contains some mass flow, that all lose thermal energy. All the pipelines that are constructed in series of each other, may all have a different diameter, and thus have a different heat transfer function.

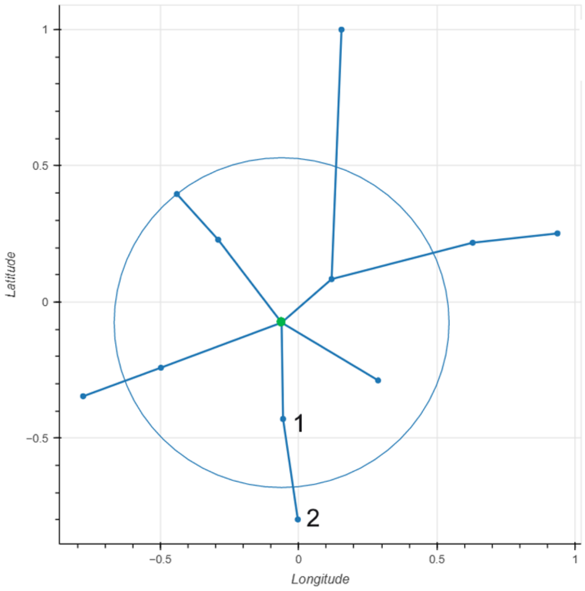


Figure 6.2: Small example network with a Kamada-Kawai positioning.

To be able to calculate the thermal losses, it is important to have insight in which pipelines are constructed at which distance from the source. The thermal losses in the pipelines are calculated every second, and therefore every whole meter, as the velocity of the flow is constant at 1 m/s. Thus, as the flow start at the source, for every instance, the water flows through one or more pipelines at the time. Thus, having information on when the flow passes which pipeline will enable to calculate the thermal losses at each instance in the network.

To be able to calculate at what distance from the source a pipeline is constructed, first all the relevant nodes in the network must be retrieved. As explained in the previous chapter, all the diameters of the pipelines in the network can be calculated. Every pipeline that has a diameter, contains two nodes that are relevant: they pass a certain amount of energy. Thus, all nodes that appear in the pipeline network are relevant nodes. For each pipeline, the shortest path from the source to the start of the pipeline and the end of the pipeline is calculated. The pipeline network in figure 6.2 is used to explain how the shortest paths are used to determine where a pipeline occurs in the network. Node 1 and 2, that appear in the bottom of the figure both have a shortest path to the source. The length of the shortest path from the source to node 1 shows at what distance from the source the pipeline becomes 'active', or in other words, starts losing energy. The length of the shortest path from the source to node 2 shows when the thermal losses by this particular pipeline stops. If all the shortest paths, and lengths, from the source to all nodes that appear in pipelines are known, the activity of particular pipelines can be assessed. In addition to the knowledge where a pipeline appears, it is also known what the diameter of the pipeline is. All in all, this is the information required to accurately calculate the thermal losses that appear in the network.

Now that for all pipelines it is known between which distances from the source it start and ends, and what the diameter of the pipeline is, a 'pipeline profile' of the district heating network is made. An example of a 'pipeline profile' of a district heating network is seen in figure 6.3. The x-axis in this figure shows the distance from the source. The y-axis serves no other purpose than creating space such that the separate pipelines can be seen. The horizontal blue bars depict pipelines that are found in the district heating network. As can be seen, the amount of pipelines that are active at a certain distance from the source varies greatly. The red line shows at what distance from the source the mass flow is located. The pipelines that are intersected by the red line, are the pipelines that are active at this instance. The red line has a comparable function as the radius in figure 6.2. Once all pipelines are recognized at, the red line moves exactly 1 meter up the x-axis to again indicate the active pipelines at that particular instance. This way, for all distances from the source the active pipelines are recognized.

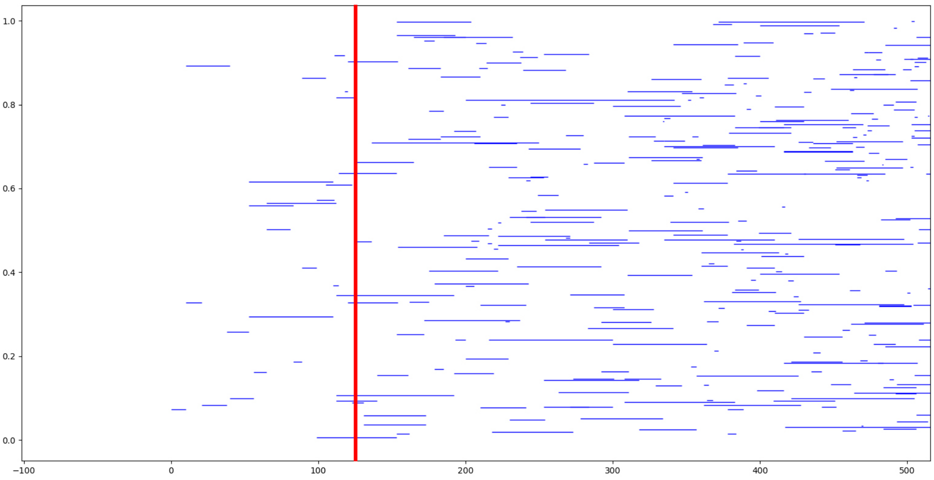


Figure 6.3: Pipeline profile for a network.

As can be seen, there are many instances at which the mass flow will flow through multiple pipelines at the same time. Using equation 6.2 and 6.3, the heat transfer function and the outer surface of every pipeline is calculated. As each pipeline has its own heat transfer function and its own outer surface, each pipeline has its own thermal resistance. As the pipelines run in parallel, the surface area and the total heat transfer function changes. The following equations explain how the heat transfer function changes when there are multiple pipelines at the same instance losing thermal energy.

Let $F(r)$ be the set that contains the heat transfer function of all pipelines constructed at r meters from the source. $F(r)$ = {$h_{1,2}, h_{3,4}, ..., h_{i,j}$}. As the pipelines run in parallel, the overall heat transfer function at r meters ($h(r)$) from the source is:

$$\frac{1}{U(r)} = \sum_{h_{i,j} \in F(r)} \frac{1}{h_{i,j}} \quad [m^2K/W] \tag{6.5}$$

$$h(r) = U(r) \quad [W/m^2K] \tag{6.6}$$

The total outer surface area also changes. The total outer surface area of all the pipeline constructed at r meters from the source is the sum of all outer surfaces of the pipelines found at that particular distance from the source. Let $O(R)$ be the set that contains the outer surfaces of the pipelines at r meters from the source. $O(R)$ = { $A^P_{1,2}, A^P_{3,4}, ..., A^P_{i,j}$ }

$$A^p(r) = \sum_{A_{i,j} \in O(R)} A^P_{i,j} \quad [m^2] \tag{6.7}$$

Thus, the total heat loss that occurs at r meters from the source is calculated as follows:

$$Q(r) = h(r) \cdot A^P(r) \cdot \Delta(T^w - T^g) \quad [W] \tag{6.8}$$

Using the information as presented in figure 6.3, the presence of a set of pipelines can be checked for every distance from the source. As the diameter of every pipeline is known, the heat transfer function of each pipeline is calculated. Combining the individual heat transfer function of each pipeline with the distances between which pipelines are constructed, the thermal losses of the pipelines are calculated for each distance from the source. Now that the topology can be incorporated in calculating the thermal losses, one more aspect of the flow of the water has to be discussed before the thermal losses are calculated: the changes in the mass flow.

Mass flow changes

In the district heating network heated water starts flowing from the source. Besides the temperature of the water, the mass that may be released is also variable. Thus, the water released in the district heating network may be expressed in kg/s. From the source, the water spreads through the district heating network, losing thermal energy, but also supplying consumers with energy. Consumers in the district heating network receive energy by forcing a small share of the mass flow in the pipeline, through the heat exchanger placed in their building. As the heat exchanger lowers the energy content and the temperature of the water from the district heating network, this part of the mass flow has now become unusable for other consumers. After the heat exchanger, the water has cooled down and is sent into a pipeline that returns the water to the geothermal well again. All the cooled down water is pumped into the soil, where it will heat up again. Each consumer thus takes a part of the mass flow in the district heating network, meaning that the further the mass flow gets from the source, the lower the amount of mass that may be used for heating gets. First , a condition that limits the amount of mass that a consumer may consume is explained. Then it is explained how to assess the total amount of mass of the water at certain time steps in the network.

Every consumer in the district heating network gets a heat exchanger placed in their building. This heat exchanger is connected to the central heating system of the building. The energy from the district heating network, is exchanged via the heat exchanger, into the central heating system of the building. Thus, the water of the district heating network does not flow directly through the buildings. The heat exchanger that exchanges thermal energy, has a certain limit on the amount of water that it can process. To indicate this limit, heat exchangers used in district heating networks are looked up for their technical specifications. Specifications of heat exchanger for comparable conditions are found. A dutch company called EnNatuurlijk applies a certain heat exchanger in district heating networks that run between 35-65 $^\circ C$. The heat exchangers are able to process up to 600 l/h or 10 l/min [20]. As can be seen, at every instance warm water is being pumped into the network at the source, while consumers withdraw a certain amount of mass from the pipelines. EnNatuurlijk states that the given specifications are for a home-installation. Therefore it is assumed that this installation is meant for buildings of small sizes. Therefore, it is chosen that the maximum allowable mass, that a building may subtract from the district heating network, is a function of their floor area. It is assumed that a regular house in Delft has a floor area of around 100 m^2. It is assumed that if a building has a larger floor area, the heat exchanger grows with it. As a result, the maximum amount of mass that the heat exchanger may subtract becomes larger. The function below is applied to calculate the maximum mass flow that a buildings may subtract from the district heating network:

Let m_{max} be the maximum mass flow rate that a heat exchanger may receive, while A_b is the floor area of building b.

$$m_{max} = \frac{A_b}{100} \cdot 10 \quad [kg/min] \tag{6.9}$$

Now, the mass that a buildings may subtract from the pipeline is restricted by its heat exchanger is known. However, the amount of heated water a building requires to satisfy its demand is dependent on the temperature of the water. If the water in the pipeline is warmer, the building will require less water to satisfy its demand. Therefore, there is a relationship between the mass flow that a building needs, and the temperature of the water in the pipeline. A heat exchanger as described above contains multiple components that regulate the mass flow. Inside the heat exchanger there is a plate heat exchanger, a control valve and a controller. In the modelling of the district heating network it is assumed that the control valve and the controller will control the mass flow through the heat exchanger without error: The mass flow that flows through the heat exchanger is exactly the amount that the building/cluster needs to maintain an indoor temperature of 20 $^\circ C$. Also, the limit on the mass flow as described in equation 6.9 is regulated by the control valve and the controller. Now that the control valve and the controller are able to control the mass flow perfectly, the mass flow to a building is calculated using its heat demand, its indoor temperature and the heat capacity of water (C_P). Equation 6.10 is used to calculate the mass flow to building b. The statement at 6.11 shows that when the required mass flow to satisfy the demand of the building is higher than the maximum capacity of the heat exchanger, the mass flow is set to capacity of the heat exchanger. This can occur if the temperature of the water in the pipeline has lowered, resulting in a lower energy density of the water. The control in the heat exchanger compensates for the lower energy content in the water by enlarging the mass flow to the building, until its maximum capacity is reached.

$$m_b = \frac{H_b}{C_p \cdot (T^w - T^{in})} \tag{6.10}$$

$$if \quad m_b > m_{max}, \quad m_b = m_{max} \tag{6.11}$$

Now that the exact mass flow to each building in the area is known, it has to be known at what distance from the source this building is located. In a district heating network there are street with demand, that have buildings along the street that have to be connected to the district heating network. The buildings are distributed over the area, which means that the buildings also have a different distance to the source. If buildings are closer to the source, the mass flow to the building lowers meaning that the mass flow to that building is also lower than in a network design where it is further away from the source. As defined in chapter 4, each street with demand is divided into two nodes with each half the demand of the buildings along that street. Therefore, each node with demand has a certain distance to the source. Using equation 6.9 and 6.10, the mass flow that a node with demand subtracts from the network is calculated. As a result, it is known how much mass is subtracted from the mass flow at what distance from the source. This way, the development in the mass flow may be calculated for the district heating network. As the mass flow spreads throughout the network, nodes with demand are passed meaning that the total mass flow in the network reduces. This way, the mass flow that occurs at any distance from the source is calculated.

To summarize, there are now two effects that may occur at any distance from the source: Reduction in mass flow and thermal losses. There are two options for the change in mass flow: either there is a node with demand that subtracts a certain amount of mass flow that is used for heating the buildings along that street, or there is no node with demand, meaning that the mass flow remains the same. However, no matter if a node with demand is encountered, thermal losses will occur at any distance from the source. Now that both the distances at which certain pipelines are encountered, and the distance at which consumers are encountered are known, all information required to construct the thermal losses model is known. The following section will explain how all calculation are used to synthesize the complete model.

6.0.2. Synthesizing the thermal losses model

Combining all equations and conditions as explained in the previous sections, the model is synthesized. All necessary information is known to initiate a mass flow from the source. For each time-step the consumption by consumers and the thermal losses are calculated. The functioning of the model can be explained simply by the following three steps:

1. A certain amount of mass is released at the source of the district heating network.
2. For every meter the water flows down the pipelines, the thermal losses and the mass that is subtracted by buildings is calculated.
3. Depending on the thermal losses and the mass flows to buildings, the mass flow rate and the temperature of the water in the pipeline for the next step are lowered.

Let $\overline{m}$ be the mass flow that is released at the source at 50 $^\circ C$. The water has a certain energy content as it has an elevated temperature when compared to the indoor temperatures of the buildings. For every distance from the source, the thermal losses of the water are calculated using equation 6.8. As the water travels with 1 m/s, the total amount of energy that is lost in this meter equals the heat loss as calculated using equation 6.8. If the flow would travel slower, than the mass of water would remain longer in a pipeline resulting in more thermal losses. After 1 second, the water has traveled 1 meter further into the pipelines of the district heating network, meaning that the set of pipelines may change, or a node with demand is encountered. This will lower the mass flow in the district heating network. All in all, the developments in the pipelines is calculated using the following set of calculations:

$T^w(r)$ is the temperature of the water at r meters from the source. At the source (r=0), the temperature of the water equals to 50 $^\circ C$. Let $\overline{m}$ be the mass of the water in the pipelines. The energy content of the pipeline at r meters from the source, with respect to the indoor temperature, is calculated as follows:

$$E^p(r) = C_p \cdot \overline{m}(r) \cdot (T^w(r) - T^{in}) \quad [J] \tag{6.12}$$

The thermal losses during 1 second are calculated using equation 6.8:

$$Q(r) = h(r) \cdot A^P(r) \cdot (T^w(r) - T^g) \quad [W] \tag{6.13}$$

Thus the energy content of the water in the following second or meter is thus:

$$E^p(r+1) = E^p(r) - E_{loss}(r) \quad [J] \tag{6.14}$$

As the energy content of the water lowers, the temperature of the water drops:

$$T^w(r+1) = \frac{E^p(r+1)}{\overline{m} \cdot C_p} \quad [K] \tag{6.15}$$

It is also possible that a node with demand is encountered at r meters from the source. The mass that a node consumes is calculated using equations 6.10 and 6.11. Let m_b be the mass that is consumed by node b of a street with demand. When a cluster has consumed a share of the water in the pipeline, the mass flow in the pipeline lowers. If no consumer is encountered on r meters from the source, then there are no changes in mass flow through the pipelines. If node b of a street is encountered at r meters from the source, then the mass flow reduction in the pipeline is calculated using equation 6.15.

$$\overline{m}(r+1) = \overline{m}(r) - m_n \quad [kg] \tag{6.16}$$

It should be noted that equation 6.14 is only used to determine the temperature of the water in the following meter. The drop of the energy content is calculated using the new mass $\overline{m}(r+1)$, and the temperature after the thermal losses are calculated $T^w(r+1)$.

$$E^p(r+1) = C_p \cdot \overline{m}(r+1) \cdot (T^w(r+1) - T^{in}) \quad [J] \tag{6.17}$$

Following all previously described calculations, it is now possible to calculate the thermal losses of the water, and the development of the mass flow throughout the network. In figure 6.4 and 6.5 two profiles are given that provide insightful information on the mass flow in a district heating network. Figure 6.4 shows the development of the energy content in the pipelines. The x-axis shows the distance from the source, while the y-axis shows a certain amount of energy. In this example the furthest consumer is just over 5 kilometers away from the source. The light-blue line shows how much energy is in the pipelines, measured in Joules. The orange points depict consumers in the district heating network. As can be seen, the energy demand of the consumers may vary. Its effect seems rather small due to the scale of the y-axis. In appendix B, a more detailed view of the energy profile is given. As can be seen, when a large consumer is passed, the energy content in the pipeline drops accordingly to the energy demand of the building that is passed. This energy is consumed by the consumer. Over the whole district heating network, the energy in the pipeline drops due to thermal losses as well. In figure 6.5 the temperature of the water and the mass of the water are plotted against the distance from the source. In blue the mass of the water is shown and in red the temperature of the water. As can be seen, the temperature of the water drops faster when the temperature of the water is higher, than when the water has dropped to a temperature of 30 $^\circ C$ in the end of the district heating network. The mass of the water in the pipeline stabilizes around 2000 meters from the source, meaning that no large consumers are passed. As can be seen, the energy content of the pipeline around 2000 still has a less steep slope, meaning that around 2000 meters from the source, the main reason for the energy losses is thermal losses. Now that the behaviour of the water in the pipelines is modelled, it is time to switch to the consumers side of the district heating network. In the following section, it is explained how the thermal energy that consumers receive is assessed. For example, do they receive enough energy such that they experience thermal comfort, or is there an energy deficit? Next to that, it will also be explained how the efficiency is calculated.

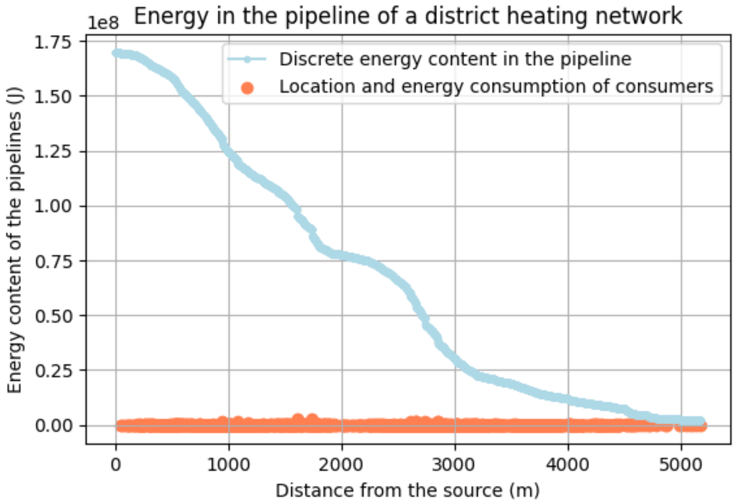


Figure 6.4: The energy content of the pipeline, compared to the demand of consumers.

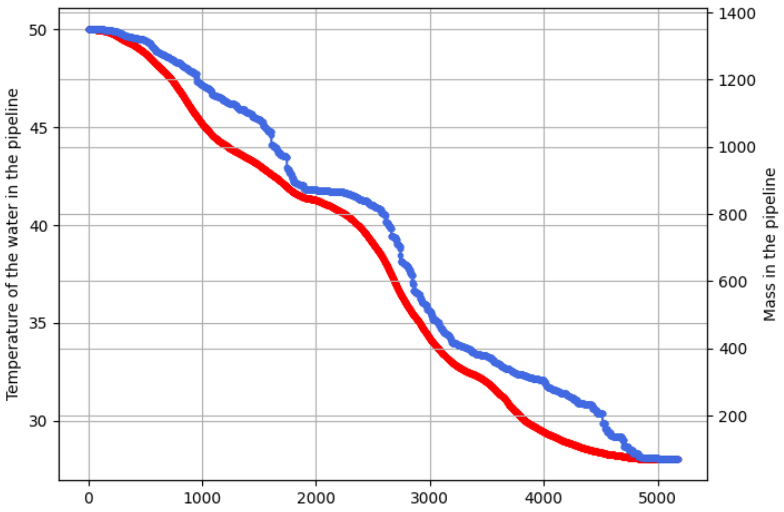


Figure 6.5: The profiles of the mass flow and the temperature of the water in the pipelines.

6.0.3. Quality for consumers

Now that it is insightful how the flow of water develops through the pipelines in the network, the quality of the energy that consumers receive is assessed. As explained in the previous sections, it is already known how much mass a consumer subtracts from the mass flow. Also, it is known that the mass that a consumer may subtract may be limited by the heat exchanger they use. The mass flow that the consumers subtract from the district heating network are calculated using the exact demand of the consumer as shown in equation 6.10. As the temperature of the water in the pipelines drops over a certain distance, the heat exchangers will increase the mass that flows through it in order to satisfy the demand. However, at some point the mass flow is restricted by the capabilities of the heat exchanger. If the heat exchanger is functioning at its full capacity, but still there is an energy shortage, then the consumer will suffer thermal discomfort. The indoor temperature will drop below 20 $°C$. As a result, the consumer is considered 'cold'. For every consumer, the received energy is compared to the demanded energy to gain insight in mow much energy deficit there appears in a district heating network.

Let i be a node with an energy demand equal to H_b. Let r be the distance from the source where node i is located. equation 6.10 and 6.11 are used to determine the mass flow through the heat exchanger m to node i. The energy received by node i is calculated as follows:

$$E_i = C_p \cdot m \cdot (T^w(r) - T^{in}) \tag{6.18}$$

The fraction of energy that is received by node i of cluster n is calculated.

$$E_i^F = \frac{\frac{1}{2} \cdot H_b}{E_i} \tag{6.19}$$

Thus, for every node that belongs to a street with demand, the received energy is calculated. Using the received energy and the demand of the node, the extent to which the demand is filled is calculated. As a street with demand contains two nodes, that both have a certain demand fulfillment, the fulfillment of the street is the average demand fulfillment of both nodes. The demand fulfillment of a street with demand is calculated as follows:

$$E_d^F = \frac{E_i^F + E_j^F}{2} \tag{6.20}$$

Now that the extent to which the demand is fulfilled is known for every street with demand, the quality of a district heating network, from the end-user perspective can be evaluated. If one design of a district heating network satisfies more customers in terms of energy delivery, than another design, one design of a district heating network may be better than another. It is important that the designs are evaluated over the same environmental conditions as this may affect the outcome greatly. In figure

6.6 an overview of the district heating network model is seen. The width of the colored lines show how large a pipeline is with respect to other pipelines. The color depicts the temperature of the water in the pipeline. The black lines that are plotted over the pipelines are street with demand. The percentage, shown in a white box, is the extent to which the demand of the street is satisfied as calculated with equation 6.20.

Let E^s be the amount of energy released at the source and Let E^{left} be the amount of energy left when all consumers have their demand fully covered: $E^{left} \geq 0$. Let E^c be the sum the consumed energy by all clusters, then the efficiency of the district heating network is calculated as follows:

$$\eta_N = (E^c + E^{left})/(E^s) \tag{6.21}$$

Now that for all different solution to a district heating network, the cost, the degree of customer satisfaction, efficiency, etc. are calculated, the district heating networks may be optimized for the different optimization objectives. The following chapter explains the steps that are applied to change the topology of the district heating network, to come up with better solutions.

Figure 6.6: Demand satisfaction in a district heating network.

7

Graph of area of interest

7.0.1. Street networks

To be able to optimize a district heating network, a graph of the street network in Delft is required. In this chapter, a method for acquiring the needed graph is described. In this method, a graph of Delft is made. However, this method may be applied to retrieve graphs from places all over the world. Delft is chosen as a case as a geothermal well is built which will be connected to a district heating network. The district heating network in Delft will connect two neighborhoods, the TU Delft campus and industry at the Schieweg to the geothermal well. The geothermal well is constructed at the Rotterdamseweg in Delft, which is on the Campus of TU Delft. The two neighborhoods that will connect to the district heating network are Voorhof and Buitenhof. The municipality of Delft has conducted a research in which the best energy sources are specified for every neighborhood. The research concludes that district heating networks can be applied best in these two neighborhoods [48]. Besides, they are close to the geothermal well, lowering the distance to the source. All in all, the district heating network will deliver heat meant spatial heating of 15000 homes. Most of the homes that will be connected in the district heating area are apartments. [29] [28]. Now that a general description of the area is made, first it will be explained why the street network of the area is used to produce a graph. After that, the method that is applied to retrieve the graph is described.

For district heating networks it is common practice that the pipelines are underground. In densely populated area like Delft, the only way that a district heating pipeline may reach a building, is if the pipeline runs below the streets. J. Unternährer et al. (2017), researched if the district heating networks modelled by using only the streets of an area approaches the district heating network that is actually in place. It is found that using the street network allows for a close approximation of the actual district heating network. They found that the length of a district heating network that uses the street network has a relative error of 3.7% when compared to the length of the actual district heating network. J. Unternährer et al. (2017) also argue that applying streets networks to model district heating network has a much lower relative error than other proposed methods [61]. In a research conducted by Rooij (n.d.) it is stated that using a street network to model a district heating network is essential. Using the findings of these researches, it is argued that using the street network of Delft to model the district heating network is a suitable approach. What exactly is meant with a street network? A street network is a graph of the streets found in a certain area. The nodes of the graph represent intersection, that are connected by edges which represent streets [61].

As discussed, the most accurate way to model a district heating network is by using the street network of an area. The street network contains the streets and intersections found in the area. The streets depict where the pipelines may run, and how they can reach all consumers in the district heating network. Naturally, the pipelines of the district heating network may split where the intersection of the street network are. As it is expected that the street network of the area in Delft will contain thousands of streets, and by that thousands of edges, the street network can not be made manually. Besides, as district heating network will become more applied in the future, a more reproducible and constructive manner is desirable. In the following section, the approach used to create a graph of the street network in Delft is explained.

7.0.2. Acquiring the street network

In literature a popular method is found that allows creating accurate and custom street networks of any location in the world. The street network is retrievable by simple coding in python. G. Boeing (2017) created a Python package that allows creating graphs of street networks for any given location on the earth, the package is called OSMnx [9]. OSMnx retrieves all spatial data from OpenStreetMap. OpenStreetMap is a publicly available map that is constructed using contributions of users worldwide [45]. OpenStreetMap states that, based on the research conducted by Barrington Leigh and Millard Ball (2017), the street network in Western-Europe is 100% complete [2]. Therefore it is assumed that the street network that is retrieved later on is a complete and full image of the street network in Delft. Boeing (2017) states that OSMnx is specifically meant for the application of graph theory onto real spatial data. As OSMnx is an open-source manner to create accurate graphs of spatial locations, and offers multiple ways to analyze and visualize the graph, OSMnx is used to create the graph of the street network in Delft [9].

There are different methods within OSMnx to retrieve the graph of the street network. As the area in Delft includes multiple neighborhoods, a custom polygon is created. A polygon is a closed, two dimensional shape that is defined by three or more edges. A polygon is made that matches the border of the two neighborhoods, the TU Delft campus and the industry at the Schieweg. In the Appendix, the coordinates that are used to create the polygon are given. There are two properties of the graph that is retrieved that are important to know. First, OSMnx creates dead ends of streets where the polygon stops. Thus, the street network that is created only includes the edges that are within the exact borders of the polygon. Another option that is given within OSMnx, that may completely alter the nature of the street network, is the option to include only drivable streets, cycling paths or paths for pedestrians. [9]. As currently there is no information on which streets and paths may or may not be used by the district heating network, all streets and paths will be included in the street network of Delft. In reality it may be true that some streets or paths should not be cut open for the pipelines as it may drastically reduce the lifetime of the road [1]. Next to that, there also may be streets or paths that are not suitable to lay a pipeline. Take for example a bridge or a footbridge. Again, as there is no information on which edges may or may not be included, it is chosen to include all streets in the street network.

The street network that is created can be seen in figure 7.1. Besides the street network, the buildings are also retreived using OSMnx. The information on the buildings and the street network is detailed. For example, for some buildings it is known how many floors they have, what their main purpose is or even if they belong to the TU Delft. The buildings in the area are specified using 96 different data points. As can be seen, in some areas the density of the nodes is very high. This is due to the fact that the street network includes all sorts of streets in Delft (car, bicycle, pedestrians, private, etc.). Based on this street network, a graph is created that is used for the district heating network optimization.

Now that the street network is defined and acquired, the edges that will define the graph are specified. A feature of OSMnx that is convenient for route planning, but unnecessary for the optimization of a district heating network, is that the allowed directions of streets are included. Some streets may only be entered from one direction, while others may be entered from both sides. In most cases, the streets are not one-way streets and may thus be entered from two sides. Therefore, most streets appear 'double', as their direction is not taken into account for district heating network purposes. Therefore, the streets in the graph are filtered such that every street only appears once. This reduces the number of edges in the street network, and may thus lower unnecessary calculation time in the future. Initially, the street network contained 17114 directed streets. With the filter applied, the number of streets is reduced to 9525. From now on, the street network does not consider directions of streets. Besides the large number of streets in the network, there are 7771 nodes and 6122 buildings.

Now that the streets are filtered, a graph is made from the street network: Let G be the graph of the street network in the area. Let $E(G)$ be the edges or streets of the graph, and $V(G)$ the nodes/intersections of the graph of the street network. Each edge of $E(G)$ is specified by the nodes between the edge exists, and a length. The length of every edge is specified by OSMnx, using the data from OpenStreetMap. The length of every street from the street network is expressed in meters:

Figure 7.1: The street network returned from OpenStreetMap using OSMnx and the defined polygon

Let $e_{i,j}$ be an edge in $E(G)$. The length of the edge is: $\quad l_{i,j}\ \forall\ (i,j) \in E(G)$

Last but not least, there is a set of 6122 buildings in the area that have to be connected to the district heating network. OpenStreetMap contains detailed information on every building. As can be seen in the figure, the shape and the location of every building is defined. Next to that, OSMnx also defines the height of every building by the number of floors. Thus, every building in the area is has a set of properties: location, floor area on ground level and a number of floors. It must be noted that the floor area of each building is measured in degrees. A conversion step was needed to convert the floor area of each building to m^2 using the Great Circle Calculator [69]. Also, the number of floors is not known for every building. If the number of floors of a building is not specified, it is assumed that the building only has a single floor. For all the buildings found in the area, the following characteristics are specified:

$\forall\ b \in B$: f_b is the number of floors in building b
A_b is the floor area of building b
P_b is the location (centroid) of building B.

To conclude, a street network and the buildings in the area are retrieved. The street network will be used for the district heating network optimization. For all buildings the size and their location in the area are known. In the next section, the heat demand for every building is determined. Following from the heat demand of every building, a distribution of heat demand in the area is made.

7.0.3. Heat demand

Now that all options for routing the pipelines are known, the heat demand of the buildings must be specified. One part of the network may need more thermal energy, than another part of the network. However, at this stage only the floor area, the number of floors and the location of each building are known. Also, as there is no real-life data of the heat consumption of houses in Delft, the heat demand must be estimated using the size of each building. To estimate the heat demand of the buildings, the floor area of the buildings is used as a measure for heat demand. In the next section, a constant is determined that will be applied to all buildings to calculate the heat demand.

Assessing heat demand of building in district heating networks is complex and depends on a number of circumstances. First of all there are seasonal patterns that influence the demand for heat per time of the year: In winter there is more demand for heat than in summer. Besides seasonal patterns, there are also daily patterns [16]. The daily patterns are mostly dictated by behavior of the consumers. In the weekend there may be a different heat demand than during the working week [37]. Next, there are also differences between buildings in a district heating network. In the area there may be an large diversity of buildings that were built in different times, have different sizes, purposes and levels of insulation. As these all influence the demand, it is desirable that actual heat demand data is used for the optimization of district heating network: Some buildings may consume more or less energy than expected [16] [37]. A huge deal of the researches that concern optimization of district heating networks, research the ability to forecast demand of consumers in the network. These researches deal with the complexity of heat demand in district heating networks in more detail, and even try to predict it. This way, a district heating network may be operated more efficiently. However, as the scope of this research is to optimize the topology of the pipelines of the district heating network, demand forecasting is out of scope and too complex to apply in optimization purposes. Unfortunately, the full complexity of demand can not be captured in the model. The only aspect of heat demand that is taken into account in the optimization is the size of each building. The size of a building may be a good indication of the thermal demand of a building. A larger building has an increased surface of walls, more surface area of windows, often a larger roof, etc [31]. As the exact data on energy usage is unknown, a constant is introduced that represents the heat demand of every building expressed in W/m^2. In a research conducted by Heinz, Rieberer and Mach (2007), multiple types and purposes of the buildings are distinguished. It becomes clear from the research that each type of building, and the purpose have a great impact on the energy demand per square meter surface area. For example, large homes tend to have a larger energy demand, than buildings that are for industrial purposes. Next to that, also a clear trend is revealed in the research: Over the years the heat demand of the buildings become smaller and smaller. Between 1920 and 1990 the heat demand of buildings has roughly halved. The average heat demand of a building in 1990 was 71.5 J/m^2. If a conservative trend is applied, the average heat demand of a building nowadays would be roughly 54.7 J/m^2. The heat demand per m^2 for every building in the network equals = 55 $[J/m^2]$. The accuracy of the heat demand may be increased if the purposes of the building may be linked to the heat demand. However, as there are over 6000 buildings in the area, only the constant is applied.

Let H_b be the heat demand of building b. and C^D be the heat constant. The heat demand of each building is calculated as follows:

$$\forall b \in B : H_b = C^d \cdot A_b \quad [W] \tag{7.1}$$

The heat demand of all the buildings is visualized in the street network, such that an overview is created on the density of the heat demand. In figure 7.2, the heat demand of a part of the area is specified per building. In Appendix B the overview of the whole area is given. It must be noted that for some buildings the energy demand exceeds the limits as stated by the colored bar. This is done on purpose as otherwise the difference in energy demand would not be visible. In the table below the distribution of the sizes of buildings and their heat demand are given.

Share of buildings in the area [%]	Total floor area $[m^2]$	Heat demand
0.004	A_b > 20 000	H_b > 1 MW
0.007	10 000 < A_b < 20 000	0.5 MW < H_b < 1 MW
4.9	1000 < A_b < 10 000	50 kW < H_b < 0.5 MW
19.1	100 < A_b < 1000	5 kW < H_b < 50 kW
75.0	A_b < 100	H_b < 5 kW

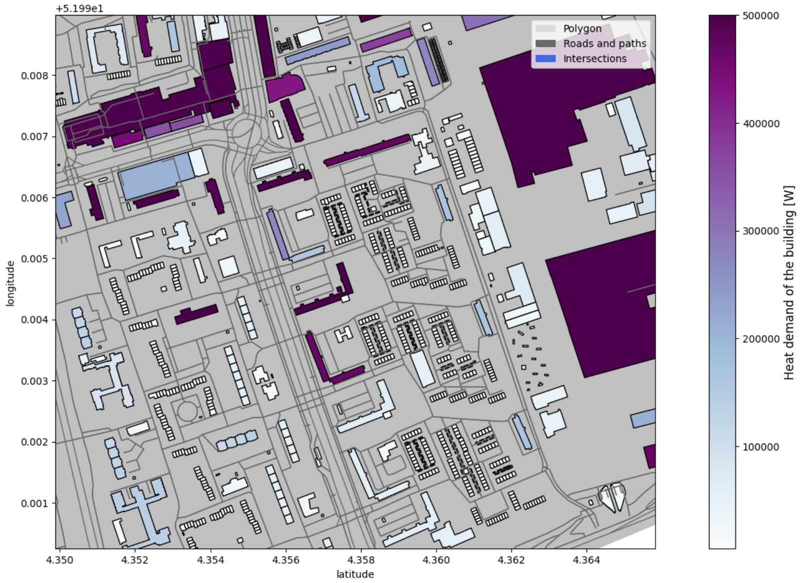


Figure 7.2: The heat demand specified for some building in Delft.

As can be derived from the figure, as well from the table, most of the heat demanding buildings in the area are small buildings. In 75% of the buildings the floor area is smaller than 100 m^2, meaning that the thermal demand of that building is lower than 5 kW. On the other hand, there is a handful of gigantic buildings in the area. Their thermal demand is enormous when compared to the smaller buildings. For some buildings, the thermal demand is well over 1 MW. It is expected that the largest consumers will have a large impact on the sizes of the pipelines in the district heating network.

Another striking observation that is made in the area, is that most small buildings are placed next to each other precisely. As a matter of fact, most of the buildings that are placed close together also have the same floor area: Many of the houses in the area are terraced houses. As most of the terraced houses are built along the same street, the district heating network must be built in that street delivering energy to a series of alike buildings. To reduce the complexity of the buildings in the area, a clustering algorithm is applied. The clustering algorithm will reduce the number of buildings to a number of clusters, reducing the calculation times in the optimization. In the next section the clustering algorithm is explained.

7.0.4. Clustering buildings

To limit the calculation times and the complexity of the district heating network, the buildings in the area will be clustered. To cluster the buildings, a clustering algorithm is applied to the location of the buildings. The location of the each building is specified by its centroid or its center of gravity. This location, which is expressed in longitude and latitude coordinates, is used to cluster the buildings. There are many clustering algorithms to be found online that may be applied to this case. However, there is one condition that limits the number of algorithms applicable: it is not known upfront how many clusters there are. As some clustering algorithms demand for a number of clusters, these algorithms are not considered [47]. As many houses along the same street have the same distances to their neighbors, it can be argued that the density of homes along certain streets is comparable. Therefore, a density based clustering algorithm is used. A density clustering algorithm clusters points in space that have many close neighbors, but excludes points that have different densities and are not within the range of the cluster [21]. A condition for a density based clustering algorithm is that a radius has to be defined that is used in the algorithm. The radius determines how far a neighbor may be from another point. SciKit, which is a package in Python, contains a DBSCAN algorithm that is easily applicable on the centroids of the buildings. It should be noted that the clustering of buildings may be done in any other programming language. DBSCAN stands for Density Based Spatial Clustering of Applications with Noise. The developers of the algorithm state the following about the DBSCAN algorithm: "Finds core samples of high density and expands clusters from them. Good for data which contains clusters of similar density.” Next to that, it is emphasized that the radius, used in the algorithm has to be chosen carefully as this is the most crucial parameter [47]. As DBSCAN satisfied the conditions, and seems very well applicable to cluster the locations of the buildings, DBSCAN is used to cluster the buildings.

Discovering the right radius for the DBSCAN algorithm is done by trail-and-error. If the radius is increased, the number of clusters decreased as more neighboring buildings would be clustered in the same cluster. If the radius decreased, the number of clusters increases. The radius that seems to fit the data well is: $R_{DB} = 0.00013$. Using this radius, many of the terraced houses end up in the same cluster, while the larger building end up in a cluster alone. As the area is defined by longitude and latitude, the radius is also in degree. Converted to meters, the radius equals to roughly 14 meters. After applying the DBSCAN algorithm, all 6122 buildings are clustered into 1215 clusters. Thus, most clusters contains multiple buildings.

All clusters that are recognized by the DBSCAN algorithm are visualized by assigning a random color to each cluster. The result of the clustering can be seen in figure 7.3. The nodes that show the same color are assigned to the same cluster. It is possible that some clusters are assigned the same color, while actually being in a different one. Figure 7.3 only shows a part of the clustering result. The full result of the clustering can be seen in appendix B. As can be seen in the figure, rows of houses with even distances from neighbors are recognized well and consistent. It should be noted that the DBSCAN algorithm only makes use of the spatial locations of the houses: The street network does not play any role at all in the clustering algorithm.

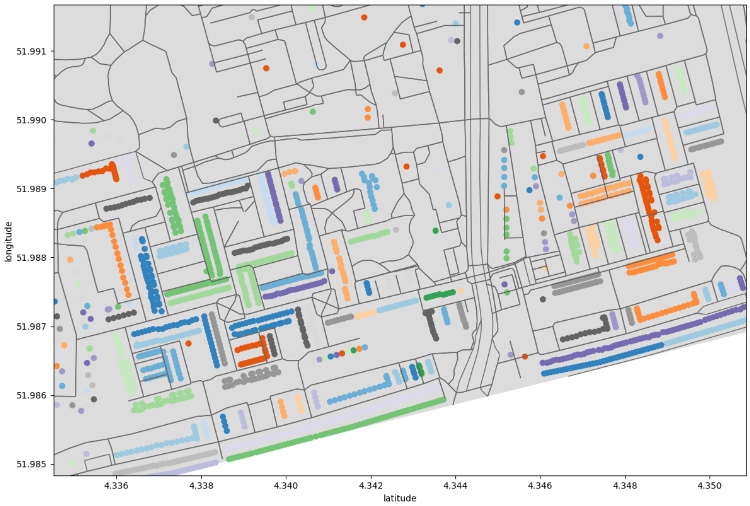


Figure 7.3: Clustering of the buildings in Delft

Now that all buildings are clustered, all their heat demand must be summed. Also, the location of the cluster must be calculated using the locations of the buildings found in that cluster. The heat demand and the location of each cluster is calculated as follows:

Let c be a cluster that contains one or more buildings. For each cluster c, $\overline{P_c}$, $\overline{H_c}$ and $\overline{A_c}$ are its location, heat demand and total floor area. Let m_c be the number of buildings in cluster c. The heat demand and floor area of cluster c is the sum of the heat demands and floor areas of all buildings in the cluster. The properties of each cluster are calculated as follows:

$$\overline{P_c} = (\frac{1}{m_c}\sum_{b=1}^{m_c} x_b, \frac{1}{m}\sum_{b=1}^{m} y_b) \tag{7.2}$$

$$\overline{H_c} = (\sum_{b=1}^{m_c} H_b) \qquad \overline{A_n} = (\sum_{b=1}^{m_c} A_b) \tag{7.3}$$

To verify that the location of each cluster is correct, the location of each cluster is compared to the locations of the buildings in the cluster. In figure 7.4 the locations of the clusters are seen. Each black point shows the location of a cluster. As can be seen, the location of each cluster is centered well for every cluster. Therefore, all buildings in the area are replaced by the cluster centres. Furthermore, each cluster has a heat demand and a total floor area.

Figure 7.4: The centroid of the clusters and the set of buildings that belongs to it.

Figure 7.5: The clusters and their total heat demand

Visually and mathematically, the buildings are replaced by clusters. However, the buildings behind the cluster have a certain heat demand. From now on, the buildings in the cluster will receive their heat demand via the heat that gets to the cluster. As each cluster has a heat demand that represent the heat demand of the buildings, the cluster has to be connected to the district heating network in order to receive thermal energy. It is assumed that each cluster is connected to the nearest street of the street network. In the next step, the nearest street for every cluster is calculated. This will then become an 'edge or street with demand'. From now on, an edge with demand or street with demand are used interchangeably. Finding the nearest edge is a function that is built-in in the OSMnx library. The nearest edge of every cluster is found using R-tree, while calculating the distance to edges in Euclidean space [9]. No further attention is given to the function, other than that for each cluster in the area, the nearest street is calculated.

Let e_c be the edge from the street network that is nearest to cluster c.

e_c = $(i, j, \overline{H_c})$, where i and j define between which nodes the edge occur, and H_c its demand.

The 1215 clusters resulted in 925 nearest streets. Thus, in the street network there are 925 streets with demand. As the number of nearest streets is lower than the number of clusters, some cluster share the nearest street. If this is the case, the demand of the street is the sum of the clusters for which that street is the nearest street. From this point on, the problem can be described purely from a graph theory perspective. All aspects of the area are translated into edges and nodes with certain properties. To summarize, there are two sorts of edges that are relevant: street with and streets without heat demand. First, streets of the streets network, and the defined streets with demand. Furthermore, nodes define the intersection between streets.

In figure 7.6, the actual problem is visualized and summarized. There is a set of streets, distributed over the area. The colored edges in the figure show which streets have a demand that has to be fulfilled. The district heating network can use all streets in the graph to reach the clusters. Due to the size of the graph, there are many different ways to connect the streets to the district heating network [33]. In the following chapters of this thesis, a method is developed that is able to optimize the district heating network for different objective functions.

Figure 7.6: All edges in the area with a certain heat demand.

8
Applied graph heuristics

In this chapter, the heuristics that are applied to optimize the district heating network are explained. Heuristics are used to generate multiple alternatives for a network that may be better than the current solution to the problem. First, the relation between the street network, and the district heating network is explained in more detail. Then, the starting network is determined. The starting network is the network for which the heuristics will find better solutions. Using multiple heuristics, among which a metaheuristic, better solutions for the district heating network are searched for. The same optimization heuristic is applied to find better district heating networks for two purposes: One district heating network may have a lower investment cost, while the other district heating network is better in supplying energy to the consumers in the network.

8.0.1. A district heating network

As explained, the street network of the area indicates where pipelines may be constructed. All the pipelines taken together shape a district heating network that transports thermal energy from the geothermal well to all consumers. Thus, a set of pipelines that transport heat to consumers is considered the district heating network. A solution to the district heating network is thus a set of pipelines that run underneath the streets of a street network that adheres to the different constraints. Using the cost and thermal-losses calculations, the different solutions are evaluated. As a heuristic searches for many different viable solutions, one can evaluate the different solutions for the following question: Is the new set of pipelines cheaper, or more efficient than the previous solution? If so, a better network is found that is able to solve the problem. In short, each solution that is found that solves the problem for the district heating network, only consists out of a set of streets that the pipelines are constructed in. Thus the following definition is made:

Any viable solution to the district heating network is a set of pipelines, that is defined using the streets found in the street network of the area and adheres to the defined conditions and constraints.

8.0.2. Starting network

As a solution contains a set of pipelines that is constructed beneath the streets of street network, a first decision must be made: What is a good initial solution to connect all consumers in the district heating network to the source? To obtain a solution for the district heating network that is sufficient to start iterating from, literature is used to determine how to connect all consumers to the source. To find a good ,initial solution to the district heating network, first two important characteristics of district heating networks is urban areas are explained. First, the street network contains steiner nodes, which automatically result that the district heating network may also contain Steiner nodes. Steiner nodes are nodes in the street network that may be used to reach the streets with demand, while the node itself does not belong to a street with demand [25]. In other words, steiner nodes are possible routes to reach streets with demand. Next to that, street networks of urban areas are sparse graphs: The number of edges is much lower than the total number of possible edges. The total number of possible edges in an undirected graph is calculated using $n \cdot (n-1)/2$ where n denotes the number of nodes in the street network. If the street network in Delft is used as an example, there would be over 30 million connections possible between the nodes. In the street network there are only 9525 streets. As can be concluded, the amount of actual streets is much smaller than the possible number of possible connections. Therefore the street network is considered a sparse graph [7]. Both these characteristics of the graph may be important in choosing the right starting network and heuristics.

In dispersed district heating network, the upgrading of heat and the required pumping energy to consumers that are far away from the source, is considerably higher when compared to denser, more uniform networks. In a research conducted by Hassine and Eicker (2013) it is calculated that a uniform network requires 4.4% less pumping energy. Next to that, the thermal losses are 7.7% lower [30]. Hassine and Eicker (2013) concluded that thermal losses can be reduced with 10% if the largest consumers are close to the source. Therefore it is desirable that the large consumers are as close to the source as possible. In general, the distance between a consumers and the heat source is often a barrier to use certain heat sources. Some heat sources have a lower temperature, meaning that it becomes more difficult to transport it over large distances. Also, cost of the infrastructure to transport the heat must be taken into account. As the distance of the source to the consumers increase, the cost increases as well [34].

In literature, there are multiple reasons found why the distance of a consumer to the heat source is important. First, Hassine and Eicker (2013) concluded that it is important to minimize the distance of large consumers to the heat source, as this may reduce thermal losses with 10%. In other researches, the average shortest path length between consumers and the heat source is used to determine the quality of a district heating network, and last, as the distance between a consumer and the heat source partly determines the temperature of the heat the consumer receives, the distance between the source and consumers is considered important. As the distance between consumers and the heat source is proven to be important, the starting network will be constructed using the shortest paths from the source to all streets with demand. The set of pipelines is constructed using the following steps:

1. All pipelines are chosen from the streets found in the graph of the street network of the area. As all streets with demand are found in the street network, each street with demand contains two nodes: One where the street with demand begins, and one where the street ends. For both those nodes, the shortest path and the shortest path length to the source are calculated:
2. P_i with l_i and P_j with l_i are the shortest paths to node i and j that belong to a street with demand.
3. The route to the street with demand equals the path to the furthest node from the source. This way, the street with demand is also adopted in the network.
4. A street is adopted in the district heating network if it appears at least once on a shortest path to a street with demand.

Now that the starting network is known, it is explained which heuristics exactly are applied on the pipelines of the district heating network, such that the cost or efficiency may be optimized.

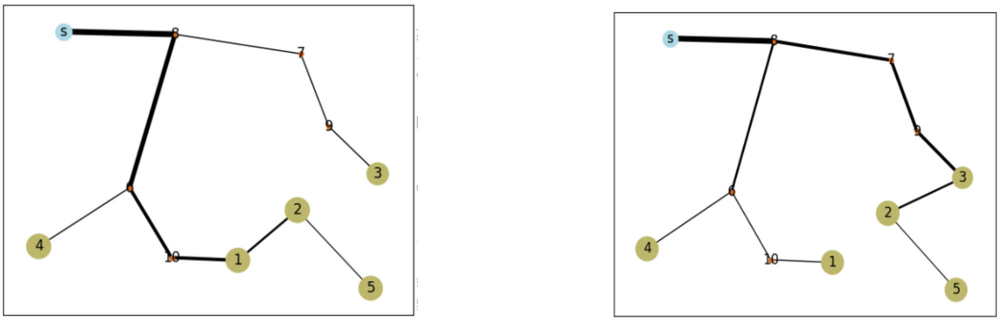
8.0.3. Heuristics

Now that a starting network is known, different methods will be applied in order to search for better network. As stated there is a very large solution space. Somewhere is the solution space, there are optimal networks that minimize cost or maximize efficiency. Applying the constraints as explained in chapter 3, the amount of viable solutions will immensely reduce. However, the amount of possible solution remains far too large to consider them all. Starting from the start network that connects all consumers using its shortest path to the source, different pipeline topologies are generated and evaluated. The generation of different alternatives, in order to find a better solution, is done using heuristics.

In practice, heuristics are applied to find a better solution than the previous network. Heuristics are needed to come up with a good solution, while the computational time is in acceptable limits [71]. Heuristics will make local changes in the current topology of the pipeline network, which creates a new alternative to the district heating network. For the new alternative, the cost, efficiency, etc. may be calculated. If the newly generated alternative is a better solution with respect to the optimization objective, this design is used instead. There are many heuristics that apply local changes in graphs. Examples of heuristics are the Delta Change heuristic by Rothfarb et al. (1970) or the Edge Turn heuristic by Heijnen et al. (2020). In the following sections two different types of heuristics are distinguished: local heuristics and metaheuristics.

Local heuristics

Now that is known why a heuristic is applied, the functioning of local heuristic is explained. First, a local heuristics can be specified by explaining 'how far' the heuristic is able to explore in the solution space. Some heuristics only generate alternatives that are just one operation apart from the original solution. An alternative that is only one operation apart from the original graph, can be said to be in the 1-neighborhood of the original graph [71]. An example of a generated alternative that is only one operation apart from the original solution is seen in figure 8.1. In the example, the original solution is seen on the left. As can be seen, an edge exists between node 1 and 2. In the 1-neighborhood of the original solution, the right graph is found. The edge between node 1 and 2 is replaced by an edge between node 2 and 3. As can be seen, the flows in the network are altered. Searching in the 1-neighborhood thus delivers alternative solutions that may perform better than the original solution. Many local heuristics are produced by a single, or a series of simple steps: the removal of an edge or the addition of an edge. Once a better solution is found, this solution may be used to iterate further on. This way, network that perform better than the original network are searched for. However, there are different mechanisms that may be used to adopt improvements.



(a) The original network

(b) The network after a single Edge Turn

Figure 8.1: A demonstration of a single operation. The nodes with demand are represented by the yellow nodes. The size of the nodes with demand indicate the amount of demand they have. The thickness of the edges represent the amount of energy that flows along an edge. The small orange nodes are the steiner nodes. The operation that is shows in this example is the replacement of (2,1) by (2,3).

Is is important to realise that a certain network, for example the network on the left in figure 8.1, only has a certain amount of alternatives in its 1-neighborhood. Assume that a local heuristic is applied that searches for alternatives in the 1-neighborhood of the network on the left. The local heuristic finds multiple improvements in the 1-neighborhood of the network. There are two different mechanisms that may be applied to adopt better networks: The first is according to the steepest-descent principle. Out of all alternatives in the 1-neighborhood of a network, the alternative with the highest gain in performance is adopted. To apply this methods, first all alternatives and their qualities must be calculated. Another mechanism that may be applied is using the better alternative, as soon as it is found. This one, not all qualities of all alternatives in the 1-neighborhood of the network are calculated, which saves time. However, as this is not according to the steepest-descent principle, it is possible that one misses out on finding a better alternative [71]. No matter what mechanism is applied to find better alternatives, the search for better alternatives stops when no alternative in the neighborhood shows better qualities. The size of the neighborhood where alternatives are found depends on the size of the graph, but also on the local heuristic applied.

As the street network of Delft is a large graph, applying the steepest-descent mechanism may be too time demanding. However, what can be considered a reasonable calculation time is dependent on the application. For infrastructure planning, such as optimizing a district heating network, higher calculation times are more acceptable as it may save a lot of money. However, if someone is planning a route a low calculation time is more important. As stated, the starting pipeline network in Delft consists out of 3915 pipelines, from which 925 pipelines run through a street with demand (there are 925 streets with demand). An educated guess is made to estimate the 1-neighborhood of the starting network, taking into account the different constraints. It is estimated that the 1-neighborhood of the starting network may contain 3000 alternatives to the starting network. Therefore, the steepest-descent method is not applied. If first all 3000 alternatives have to be evaluated for cost and efficiency before one operation is introduced, the calculation time would increase vastly. Therefore it is not an option to apply the steepest descent mechanism. As an alternative, if an improvement is found in the 1-neighborhood of the district heating network it is immediately adopted. This mechanism is called first-descent. It must be noted that applying the first-descent mechanism may lead to worse results when compared to applying the steepest-descent mechanism [71].

Metaheuristics

Besides exploring the 1-neighborhood of a solution, it is also possible to apply a searching algorithm that proposes solutions that lie outside of the 1-neighborhood of the current network. The heuristics that search for more global optimum solutions are called metaheuristics. Using only local heuristics, it is possible that the heuristic converges towards a local optimum. However, the local optimum may not be the global optimum: There is a different pipeline network that performs better, but cannot be found using local heuristics. A difference with the local heuristics is that metaheuristics are capable of producing options that are not one operation apart from the original graph. Thus, a metaheuristic may be applied to generate alternatives that may have a better performance than the solutions found with the local heuristic. Therefore, it is chosen to also apply a metaheuristic to the pipelines of the district heating network. In the following section the choices for the local heuristic and metaheuristic are explained. Next to that, their working principle is explained, and how they are adopted.

8.0.4. Edge turn mechanism

In the research conducted by Yeates et al. (2021), heuristic methods to search for cost-optimal pipeline networks are discussed. Using an intensive heuristic a cheapest alternative is found. The heuristic embeds a heuristic within a metaheuristic allowing to search for local changes in global changes. This way, many different solutions are proposed. The minimum cost network that is found using this method took over 25 hours to calculate. The calculation time, and the cost of the solution is compared to networks found with other heuristics. Out of all methods that are compared in the research, it is concluded that the Edge Turn heuristic is the fastest heuristic independent of the size of the network. When compared to the minimum cost solution as described before, the network found with the Edge Turn heuristic is 2.6% more expensive, while the calculation time is over 80 times lower at only 18 minutes. In the same research, the performance of the Delta Change heuristic is also evaluated. The reduction in cost and the increase in calculation time seem linear. The network found with the Delta Change heuristic is 0.9% more expensive than the optimal solution, while the heuristic takes three times longer than the Edge Turn heuristic. As the Edge Turn heuristic is by far the fastest heuristic, it is applied as the local heuristic in the district heating network. However, the Edge turn mechanism has to be adopted to fit the problem of district heating network. How the Edge Turn heuristic is applied in case of the district heating network that includes streets with demand is explained next.

The Edge Turn mechanism is applied using the following steps. As the constraints of the district heating network may be different than for other problems, the Edge Turn mechanism as explained here may differ from the original description as described by Heijnen et al. (2019). The following explanation will be a general explanation of how the heuristic works. To clear out, the district heating network consists out of a set of pipelines that connect the streets with demand to the source. The streets of the street network in the area can be used to construct pipelines. In figure 8.2 the steps of the Edge Turn heuristic as applied in this research are visualized.

- 1. Remove a pipeline from the district heating network.

First of all, the pipeline that is removed may in no case be a pipeline that lays in a street with demand. If the pipeline does not lay in a street with demand, than in most cases the district heating network will be split into two unconnected components.

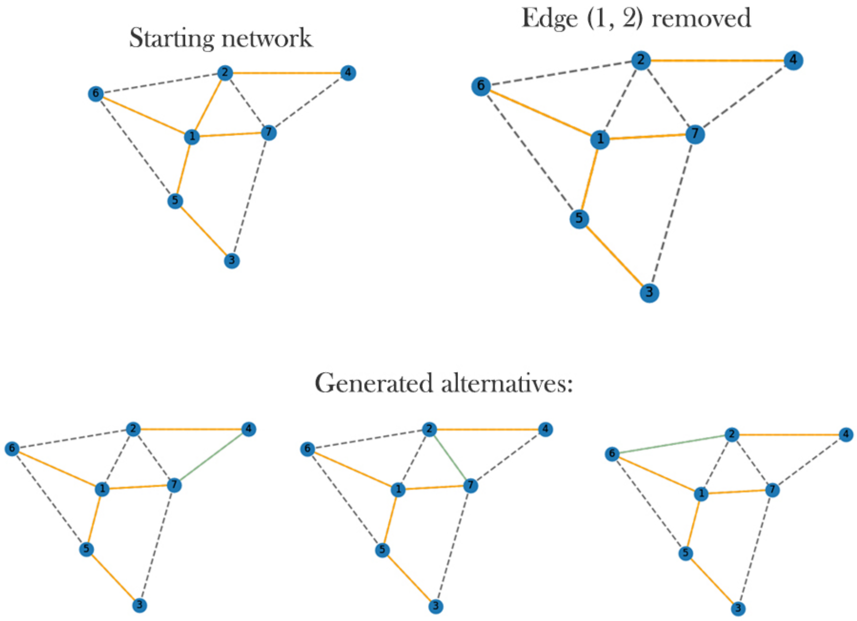
- 2. Reconnect the two disconnected of the district heating network using different streets.

The two separate components of the district heating network are reconnected when a pipeline is constructed between one node of each component. If the only option to connect the two components, is the pipeline that is removed then no new alternative is produced. If pipelines can be constructed in streets that previously did not contain a pipeline, one or more new alternatives are generated.

- 3. Calculate cost and the efficiency of the alternative district heating networks. Depending on the optimization objective, if a better alternative is found, apply the first-descent method.

Using the models as described in chapter 4 and 5, the qualities of the district heating network are calculated. If an alternative shows better performance, it is immediately adopted to replace the previous district heating network.

- 4. Repeat the process until no further improvements are found in the topology of the district heating network, and all generated alternatives are evaluated.


Starting network

Edge (1, 2) removed

Generated alternatives:

Figure 8.2: Generating alternative networks using the Edge-Turn heuristic

For all alternatives generated, the constraint as described in the problem formulation apply. After applying the Edge Turn heuristic, a metaheuristic is applied that broadens the optimization space.

8.0.5. Node Valency Transfer Metaheuristic

Yeates et al. (2021) proposed a new metaheuristic that is based on the observations made in the research. In many cases, there are nodes in a pipeline network that play a significant role in distributing the flow. These nodes are characterized by having many pipelines connection to neighboring nodes. A node is considered a high-valency node if they have 3 or more pipeline connections to neighboring nodes. The idea behind the high-valency shuffle is that a high-valency node may have neighboring nodes that could make the same connections as the high-valency node, possibly resulting in a better performing network. In figure 8.3 an example of a high-valency shuffle can be seen. In the high-valency shuffle, the pipeline connection of a high-valency node are shifted to a neighboring node of the high-valency node. This thus results in a network outside of the 1-neighborhood of the network. In the research, the high-valency shuffle is combined by incorporating a local heuristic in the metaheuristic. It is found that the high-valency node shuffle combined with the Edge Turn Heuristic leads to the best results. In small graphs (up to 28 nodes), the high-valency shuffle constantly leads to results as close as 95% when compared to the optimal solution [71]. As the valency shuffle has proven to improve pipeline networks, it is chosen to apply the valency shuffle as a suitable metaheuristic for this application. However, there are some caveats in applying the high-valency shuffle directly onto the problem at hand.

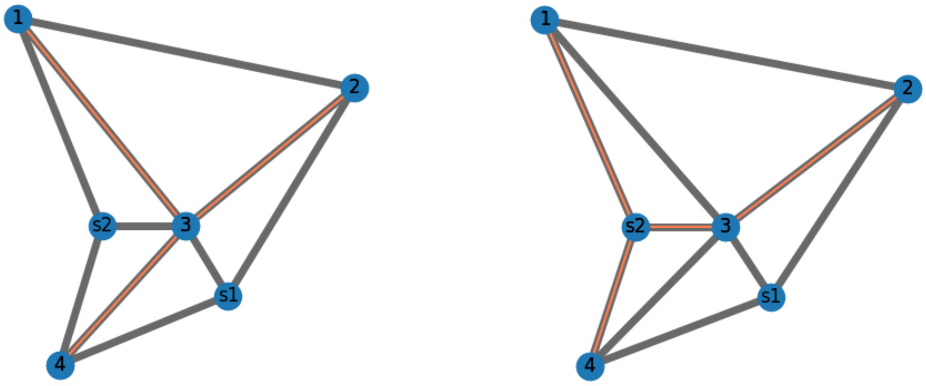


Figure 8.3: Example of a high-valency shuffle applied on a network with steiner nodes. The gray lines denote where the streets lay that may be used by the pipelines. The orange lines show where a pipeline is located. The nodes 1 to 4 denote nodes that have a demand and are thus connected to the district heating network. Node s1 and s2 are two steiner nodes that may be used to reach the other four nodes. As can be seen, node 3 is a high-valency node as it has three pipeline connections. From node 3, the closest four nodes are searched for. One of the closest nodes is node s2. Thus, all pipeline connections from node three are transferred to node s2. However, as there is no street that allows for a direct connection between s2 and 2, the shortest path and shortest path length between node s2 and 2 are calculated. As a result, the street street between s2 and 3 and the street between 3 and 2 is used to connect s2 to 2. This way, the high-valency shuffle is applicable to networks with steiner nodes, while alternative district heating networks outside the 1-neighborhood of the original network are found.

In the development of the high-valency shuffle metaheuristic, the pipeline networks did not contain steiner nodes. As the district heating network in Delft does contain steiner nodes, a fitting solution is developed. Next to that, the best solutions in the research by Yeates et al. (2021) were found by combining the metaheuristic with a local heuristic. Incorporating a local heuristic into the metaheuristic is not viable option in applying it to a large district heating network as the amount of proposed alternatives as the amount of proposed solutions would grow significantly. Again, the high-valency shuffle applied in this research differs slightly from the original description as there are steiner nodes in the district heating network. The applied high-valency shuffle applied is explained in the following steps:

- 1. Indicate all nodes in the district heating network that have 3 or more pipeline connections and start with a high-valency node.

The following step is where the applied method differs from the method as described by Yeates et al. (2021). In the problems considered in the research by Yeates et al. (2021), the neighboring nodes of the high-valency nodes are either sinks or sources: They have to be adopted in the pipeline network no matter what. In case of the district heating network in Delft, the neighboring nodes of the high-valency node may not be adopted in the pipeline network as there are steiner nodes. However, the reasoning behind the high-valency shuffle may remain the same. As Yeates et al. (2021) state: ”a node situated in proximity to it may play a similar role in distributing flow but for a lower cost.” Therefore, a neighboring node of the high-valency node in the district heating network may take over the pipeline connection of the high-valency node, resulting in a better district heating network. Therefore, the neighboring nodes that are considered are in this case, the four nodes closest the the high-valency node either included or not included in the district heating network.

- 2. The pipeline connections of the high-valency node are shifted to the neighboring nodes, one at a time.

As the four neighboring nodes are considered for the high-valency shuffle, four different alternatives are generated for the district heating network.

- 3. Evaluate the four alternatives for the different optimization objectives.

- 4. If a better solution is found, adopt it according to the first-descent mechanism.

In order to use the high-valency shuffle, the networks that are fed into the metaheuristic already have to be a good solution to the problem. Therefore, as suggested, the Edge Turn heuristic is applied before the high-valency shuffle metaheuristic. All in all, generating alternative district heating networks follows three consecutive steps: First a starting network is created using the shortest paths to all streets with demand. Second, the Edge Turn heuristic is applied to find local improvements. All improvement found are adopted using the first-descent mechanism. Last, the high-valency shuffle is applied to find global improvements. The same method is applied to find the cheapest and most efficient alternative of the district heating network. Each district heating network will result thus result in two different designs with different properties.

9

Random network application

Now that the different properties of the different district heating networks may be evaluated using the developed models, and a series of suitable heuristics are found, different district heating networks are optimized. As a first step, the method in its totality is applied to 100 random street networks. In the first section of this chapter the random network generation method is explained. After that, the results that are achieved optimizing the district heating networks for the different objective functions is explained.

9.0.1. Random network generation.

To sufficiently test the method that is applied to optimize the district heating network in Delft, the heuristic method and the models are first tested on smaller, randomly generated test networks. As the district heating network will make use of the street network, it is important that the random generated networks show similar characteristics. For example, it is important that the small graphs are sparse graphs: many nodes compared to the number of edges. Next to that, in the network there must be steiner nodes as well as nodes with a certain demand. This is done to imitate the nodes of the streets with demand in the district heating network in Delft. Last, the random network must contain a source from which the heated water starts flowing.

The random network generator is based on a python script supplied by Heijnen (n.d.). The random network generator has certain settings that can alter the characteristics of the developed networks. First, there is the option to choose how large or small the surface area of the problem may be. Next to that, the amount of nodes with demand, including the source is chosen. Also the amount of steiner nodes can be chosen freely. Furthermore, the upper and lower bound of each node with demand can be chosen. Based on a trial-and-error process, the following settings for the random generated networks are chosen:

Setting	Value	Lower bound - Upper bound
Surface area of the network	200 x 200	-
Amount of nodes with demand	10	-
Amount of sources	1	-
Amount of steiner nodes	40	-
Random demand of the nodes	-	6100 - 9200

Using the settings as explained above, random street networks are generated. In figure 9.1 a random street network is seen. The red node depicts the location of the source. The light-blue nodes are nodes with a heat demand between 6100 and 9200 Watts. The orange nodes are steiner nodes, while the gray edges depict the streets of the street network. As can be seen, the random networks may contain dead-ends which is also the case for the large graph in Delft. Furthermore, the ratio between amount of streets and nodes for the example of the random street network is 69 streets over 51 nodes. This ratio shows the average amount of streets connecting to a single node. In the street network of Delft there are 7771 nodes on 9525 streets. The ratio in Delft is 1.23 streets per node, while for the example street network the ratio equals 1.35. Therefore, the density of the amount of street connections per node is comparable. It should be noted that the amount of streets change for every random generated network. Therefore, the ratio between the amount of streets and nodes change for every generated street network. However, as the amount of streets will not increase or decrease significantly, it is shown that the density of streets per node is comparable for the large street network in Delft, and the small, randomly generated street networks.

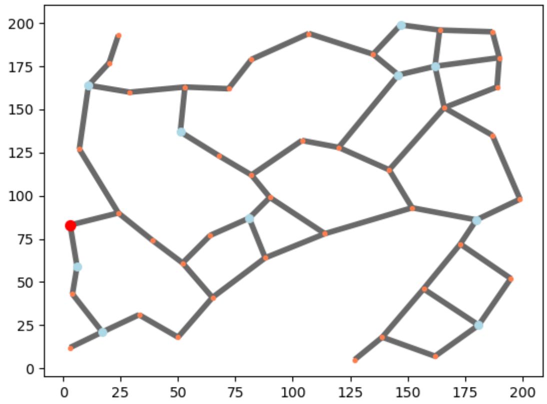


Figure 9.1: Example of a randomly generated street network.

Now that there are 100 different, randomly generated street networks, the developed heuristics and model are applied. The model may be separated into two parts: from the topology of the pipelines, and the demand of all consumers, the diameters of all pipelines are calculated. From the diameters the cost is specified. Furthermore, the pipeline diameters are used in the thermal-losses model, that also uses the topology of the pipelines, and the pipeline diameters to calculate the efficiency, the energy left, and the degree of consumer satisfaction. As argued, the two optimization objectives that are used for optimizing the district heating networks are cost and efficiency. The heuristic method contains three important steps: initializing a starting pipeline network, based on the shortest paths to all consumers from the source. Next, the Edge-Turn heuristic is applied to search for better alternatives. Last, the high-valency shuffle metaheuristic is applied to search for further improvements. The goal of this chapter is to come up with two different designs for a district heating network in the same random street network.

To explain the process further, there are 100 random district heating networks that are optimized for two different objectives. The street network, and the starting network are in both cases exactly the same. Thus, for every street network there is a starting network, a cost optimal design and a design that maximizes efficiency. The cost-optimal design, and the most efficient design are both compared to the original design. Without further ado, in figure 9.2 an example of the three different designs is seen. On the left, the starting network is given. All black nodes are nodes with demand. The smaller grey nodes are steiner nodes. For the starting network two optimization processes start: one that optimizes towards a cost-optimal design, maximizing the efficiency benefiting the consumers. In the middle figure the most cost-effective design found by the heuristic is seen. On the right, the most efficient network design is shown. As can be seen, there are significant visual differences between the designs.

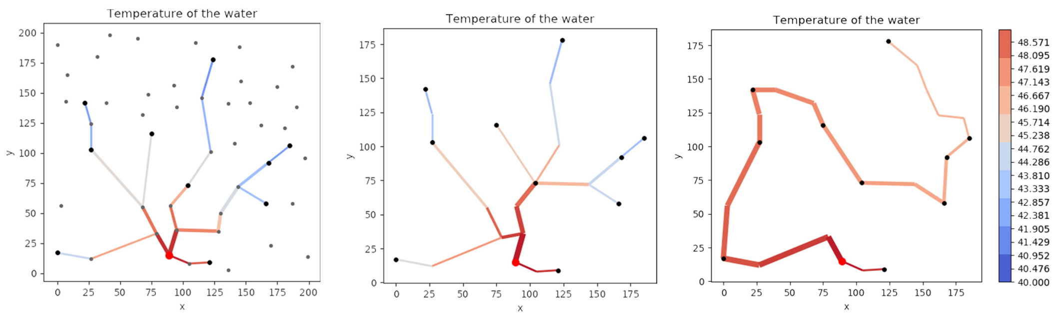


Figure 9.2: An example of the starting network and its cost and efficiency alternatives.

To monitor the improvements that the heuristic found, intermittent results in optimizing the 100 small district heating network are tacked. In the process there are three important measurement points that determine the improvements found with optimizing. The first is the quality of the starting network. Second, the quality of the network after the applying the Edge-Turn heuristic. The third and last measurement point is after the high-valency shuffle. The results are summarized using boxplots as can be seen in figure 9.3 and figure 9.4. The upper boxplots shows the results when the district heating networks were optimized to minimize cost. The lower boxplots show the results when the district heating network were optimized to maximize efficiency. In both figures, the yellow boxplots denote the changes in cost of the network, while the blue boxplot shows the change in efficiency. The change of both is measured in % and is compared to the previous measurement point. Thus, the cost and efficiency after the Edge-Turn heuristic is compared to the starting network, while the cost and efficiency of the network after the high-valency shuffle is compared to the result after the Edge-Turn heuristic.

For both optimization processes it can be seen that the largest, relative improvements are found in the Edge-Turn heuristic. This is to be expected as this the first heuristic applied on the starting network. Also, in many cases the high-valency shuffle found further improvements. In both maximizing the efficiency, and minimizing the cost, the Edge-Turn heuristic and the high-valency shuffle found significant improvements. In total the Edge-Turn heuristic failed to find an improvement in two networks. The high-valency shuffle failed to find improvements in 41 networks. In other words, the high-valency shuffle finds less improvements than the Edge-Turn heuristic. Still, in most cases the high-valency shuffle did find an improvement. What is also a striking observation is that minimizing cost in most cases led to an improvement of efficiency. As can be seen in the blue boxplots of figure 9.3. Most cost lowering solution are also more efficient in terms of thermal losses. Maximizing the efficiency of the district heating network led to more extreme changes in cost of the network. As can be seen in the yellow boxplots in figure 9.4, the upper limit of the boxplot reaches up to 93 % increase of cost, in exchange for a more efficient solution in the high-valency shuffle. As seen in the right boxplot, the increase in efficiency was in most cases small. Therefore the increase in efficiency resulted in a 93% more expensive network. Most changes in the network to maximize efficiency lead to more expensive networks.

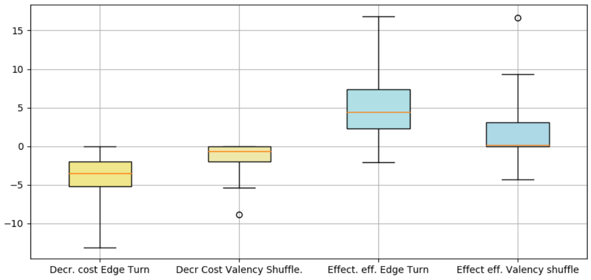


Figure 9.3: Improvements found for optimizing district heating networks for cost.

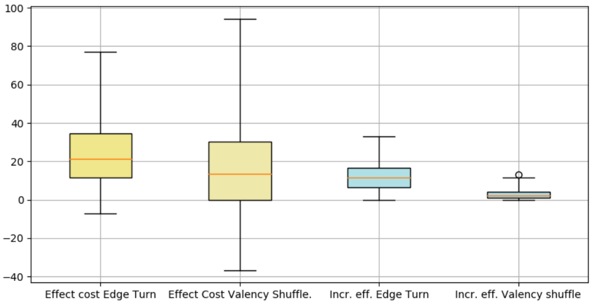


Figure 9.4: Improvements found for optimizing district heating networks for efficiency.

As some results seem extreme, multiple networks were inspected in more detail to see where the change occurs and how this leads to the large changes as seen in the boxplots. In figure 9.5 an example of an 'extreme' result is seen. In the left figure in the starting network is given, while the right figure shows the most efficient alternative. In the appendix two more examples of the optimization result can be seen. As can be seen by the calculated temperature of the water in the pipelines, the water in the efficient network is kept at a higher temperature when it reaches the end of the network. Another observation that occurs is that the most efficient design of the district heating network have a tendency to reduce the number of pipelines to one major pipeline. This limits the thermal losses that occur. The district heating network that are most efficient seem to trade the distance it has to travel extra to maintain one pipeline, against the option to have a second pipeline go to the node and save in pipeline length. From the examples that were inspected it is concluded that the difference between the design of the cheapest alternative and the starting network is less significant than the difference between the most efficient alternative and the starting network.

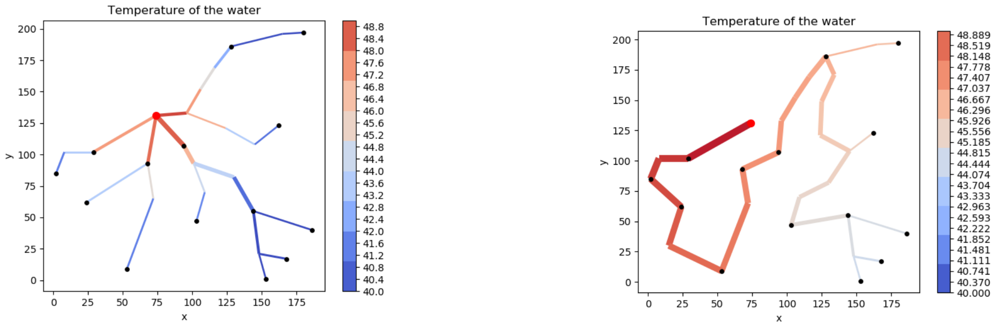


Figure 9.5: Example of the biggest gain in efficiency.

However, the extent to which the heuristics found an improvement also depends heavily on the context where they are used. Applying the heuristics on the street network mostly led to less extreme changes as can bee seen by the medians in the boxplots. However, the boxplots do not give insight into the total improvement found on every network. To gain insight in the total decrease of cost, or the total increase in efficiency, both designs to every street network are compared to the starting network. Therefore, a relative decrease of cost and increase in efficiency is measured for every final design, compared to the starting network. In figure 9.6 the result of the two optimization objectives is shown. On the x-axis the decrease and increase of the network is shown. The negative domain of the x-axis is a reduction in cost, while the positive domain shows a increase in cost. On the y-axis, the increase or decrease in efficiency is given. The positive domain on the y-axis is an increase in efficiency, while the negative domain is a decrease in efficiency. The green integers denote cost optimized networks, while the red integers denote the efficiency optimized networks. The integer denotes to which randomly generated street network the solution belongs. For every random generated network, this plot contains two points: a minimized cost and a maximized efficiency network. As can be seen, apart from two cost optimal solutions, all district heating network that are optimized for cost as well as for efficiency are more efficient than the starting network. What is also striking, is that the cost optimal solution are clustered better: the decrease in cost and increase in efficiency is for most random generated street network alike. This is different than the scattering of the solutions of the maximum efficiency solutions. In other words: The increase in cost, and the corresponding increase in cost is less/not predictable.

For the cost optimized networks, a correlation of -0.683 is found between the extent to which a network became cheaper and the increase in efficiency. This means that there is a moderate - high correlation between a district heating network becoming cheaper, but also more efficient when compared to the starting network. The correlation between the extent to which a network became cheaper and the increase in efficiency for efficiency optimized networks is 0.169, meaning that the correlation is negligible [42]. In other words, there is no relation between a network becoming more efficient and the extent to which is becomes more expensive. On average, the cost optimized network became 5.2 % cheaper and 6.8% more efficient: a win-win situation. The cost of one percentage efficiency is on average -0.76% cost. On average, the efficiency optimized networks are 48.7 % more expensive but

15.3 % more efficient. The cost of a percentage efficiency, for efficiency optimized networks is a 0.31 % increase in cost. However, this average should be handled with caution. The average is not a good prediction of the results that can be booked if efficiency optimization is used on district heating network: the spread of result is too big. In other words, for each individual street network, the most efficient network may be to a more or less extent more expensive. In the worst case, the most efficient network is 140% more expensive but 25% more efficient.

In figure 9.6, some sets of solutions are connected. As can be seen, the sets connected with light blue lines are more horizontally displaced, while the sets connected with the dark line are more horizontal. The steepness of lines measures the value of the trade-off. The more horizontal a line is, the more expensive a percentage gain in efficiency becomes. The steeper a line is, the cheaper a percentage gain in efficiency is:

Light blue: Each percentage gain in efficiency results in an increase of cost of at least 5%.
Dark grey: Each percentage gain in efficiency results in an increase of cost of 1.25% or less.

As a result, adopting the more efficient network costs significantly more for the light blue sets than it does for the sets connected by the dark line. There are two sets of solutions with a dark line, as shown in the figure. In contrast, there are 63 sets connected by a light-blue line, indicating that each percentage increase in efficiency increases the cost with at least 5%. In only two cases, each percentage gain in efficiency only increases the cost of the network with 1.25%. However, it should be noted that the two networks depicted are the two outer extremes: the cheapest alternative, and the most efficient alternative. In between those two designs there may be solutions with intermittent properties. Therefore it is important to research the solution space in between these two solutions.

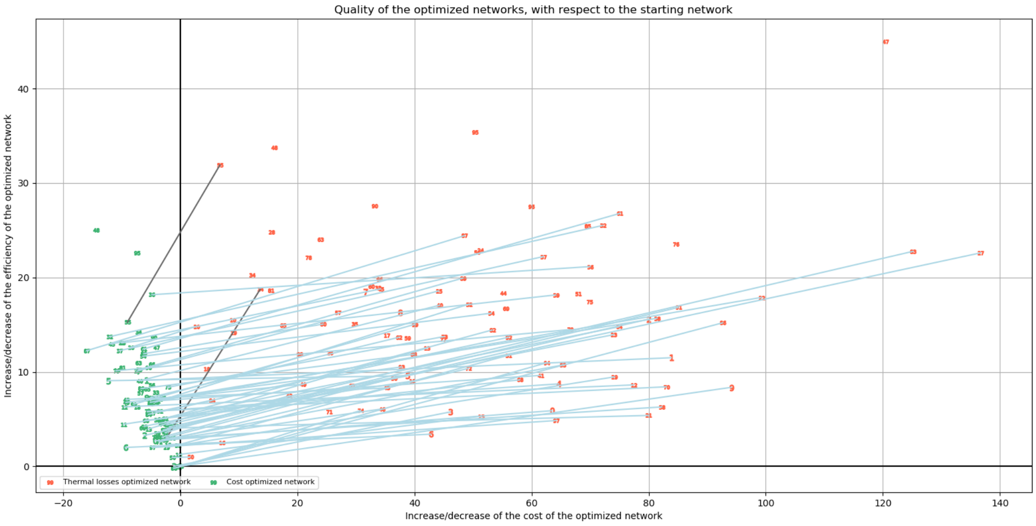


Figure 9.6: Comparing the solutions.

10

Heuristic applied on Delft

Now that the heuristics are applied on the 100 smaller district heating networks, the heuristic is applied on the large district heating network that is planned in Delft. Again, two different designs of the district heating network are compared, leading to insight between the differences in performance. First, the differences between the two district heating network designs is shown. Then, the performances of the two district heating networks are evaluated using a set of scenarios. In the scenarios, the temperature of the ground, as well as the thickness of the insulation is changed. For all scenarios, the customer demand satisfaction is measured in different scenarios with different available mass flows.

Visually, the differences between the cost optimal district heating network and efficient district heating network are hard to determine. However, when both networks are compared to the starting network, the differences are more obvious. In the three figures below the traces of the three networks are given. The color indicates the temperature of the water in the pipeline, while the thickness is an indication of the diameter of the pipeline. As can be seen, in both the optimized district heating networks, the temperature of the water stays higher for longer.

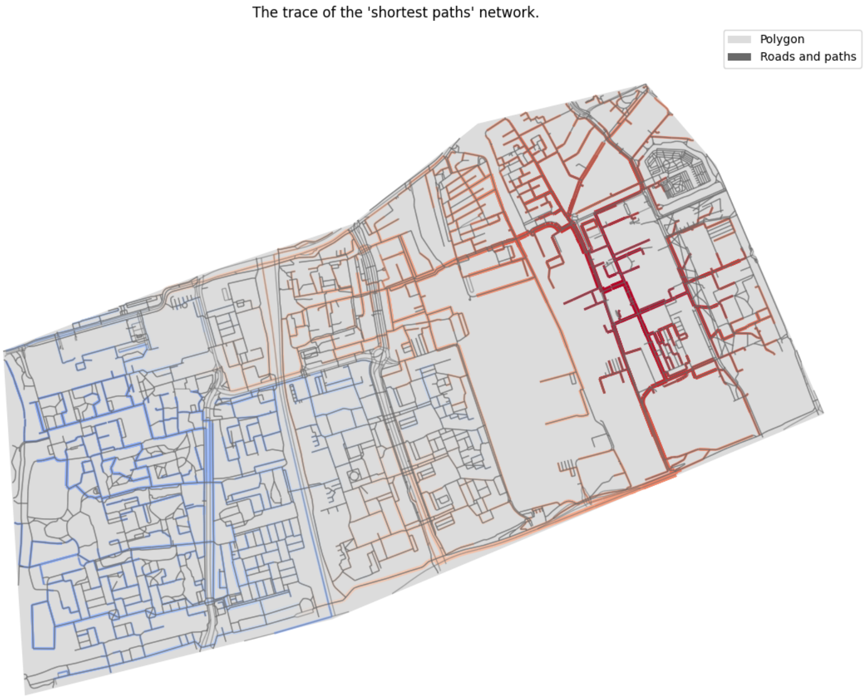


Figure 10.1: Trace of the starting network.

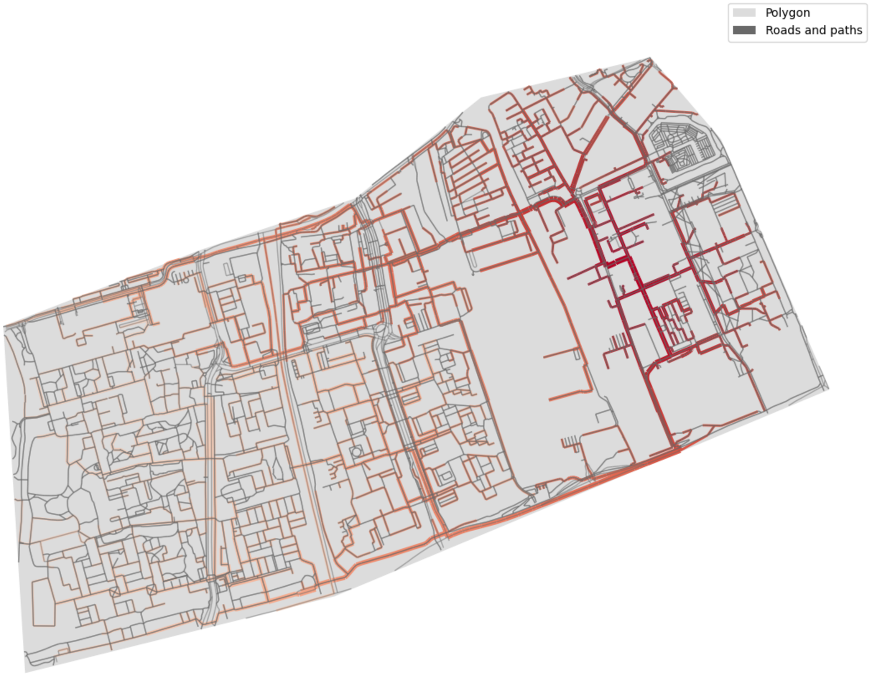


Figure 10.2: Trace of the cost optimized network design.

Figure 10.3: Trace of the most efficient network design.

The following table summarizes different properties of the different district heating network under the same conditions. The temperature of the ground is set at 0 $^{\circ}C$, the thickness of the insulation 2.5 cm, and the mass flow released at the source is 1300 kg/s.

Criteria	Starting network	Cost network	Efficiency network
Cost [-]	10164	7675.7 (-24.5%)	9068.4 (-10.8%)
Efficiency [%]	43.2	56.5 (+30.8%)	67.9 (+57.2%)
Thermal loss [%]	56.8	43.5	32.1
Cold cluster	309	0	0
Avg. energy deficit [%]	95.2	-	-
Usable energy left [MW]	0	2.4	24.5

When these results are compared to the results found in the analysis of the 100 random district heating networks, the improvements are larger than expected. However, the decrease in cost of each percentage increase in efficiency equals -0.79%, which is almost the same as the -0.76% found while analyzing the improvements of the 100 random district heating networks. On the large graph of Delft, optimizing for cost decreased cost as well as an increase in efficiency. This is in line with the expectations when compared to the results of the small district heating networks. However, the efficiency optimized district heating network in Delft shows results that were not encountered in the 100 random district heating networks. Optimizing the district heating network in Delft towards maximum efficiency led to an increase in efficiency as well as a decrease in cost. This is not encountered in the random district heating network. From the cost optimized network, each percentage increase in efficiency increases the cost of the network with 0.52%. Comparing this trade-off to the trade-offs found in analyzing the random district heating networks, the trade-off is much 'steeper' than any found. In other words, the gap between an increase in efficiency in return for higher investment cost lowers.

In the figure below the district heating network that is optimized for customer satisfaction is shown. It shows the degree to which the demand of the consumers is satisfied. In appendix B a detailed overview is seen.

In order to get a systematic overview of the differences in performance between the cost optimized and the efficiency optimized district heating network, four scenarios are created. In the scenarios, different ground temperatures and different thicknesses of insulation are applied to both pipeline designs. The difference in performance is evaluated from the perspective of the consumers: How much clusters do not receive enough heat to maintain an indoor temperature of 20 $^\circ C$ at different available flow rates from the source. This way, it is investigated whether limiting the thermal losses will also close the gap in performance between the two district heating network designs. The four scenarios are created by introducing two different insulation thicknesses over two different ground temperatures. From top left to the bottom right, the applied scenarios are: 2.5cm insulation in 0 $^\circ C$, 4cm insulation in 0 $^\circ C$, 2.5cm insulation in 12.5 $^\circ C$ and 4cm insulation in 12.5 $^\circ C$.

As can be seen, there is a very significant gap in performance between the district heating network that is optimized to maximize efficiency, and the district heating network that is optimized for cost minimization. The biggest different in performance difference is seen in the scenario where the ground has a temperature of 0 $^\circ C$ and the thickness of the insulation is 2.5cm. It is expected that this severe difference in result is due to the lower temperature of the ground, and the thin layer of insulation. It is expected that the effect for optimizing for efficiency is more noticeable when the thermal losses are high. As can be seen, the smallest difference in performance is seen when the ground temperature is 12.5 $^\circ C$ and the thickness of the insulation is 4cm, resulting in the lowest thermal of all four scenarios. The further the mass flow decreases, the less significant the performance difference between the two designs become. The performance even equalized when the mass flow from the source is extremely disturbed. Therefore it is seen that the difference in performance is noticed best when the disturbances in the mass flow of the source are not extreme. If the source shows small disturbances in its mass flow, the district heating network that is optimized for customer satisfaction outperforms the cost optimized design. Thus, optimizing the district heating network to be more efficient, lowers the energy that is subtracted from the source: There will be less thermal losses and more of the energy ends up with the customers. As a more efficient district heating network requires less energy, and perhaps less mass flow, the variable cost of the efficiency optimized network is lower. On the other hand, the cost of the pipelines in the cost-optimized design is 15.4% less. A trade-off is found between lowering running cost and lowering initial investment cost.

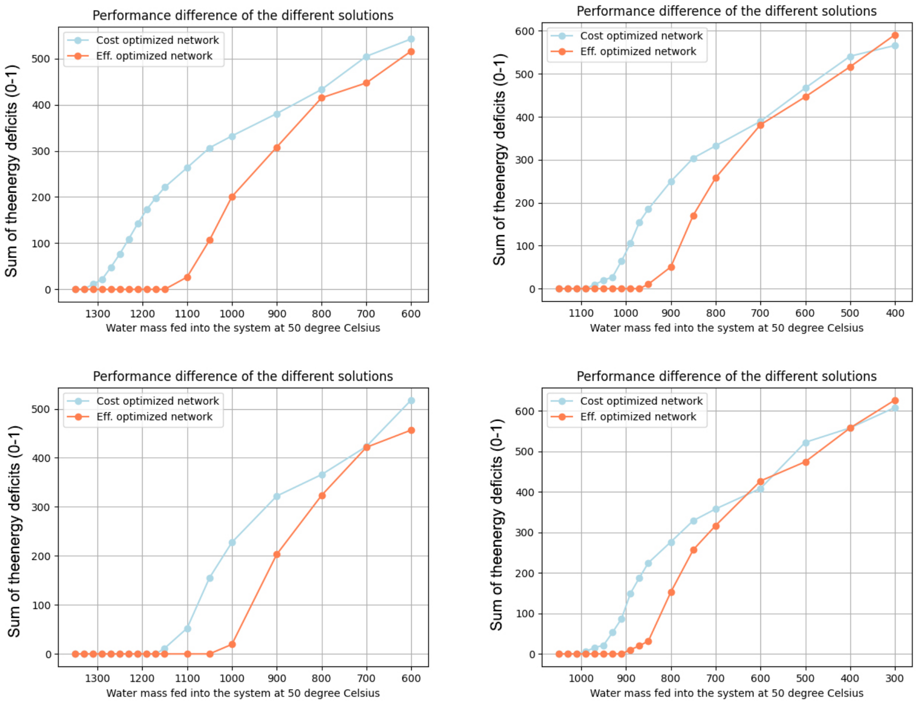
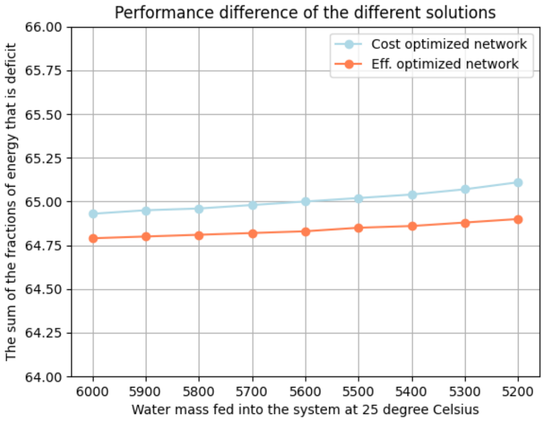


Figure 10.4: Measuring consumer satisfaction in different scenarios.

One last scenario is used to validate the model. In this scenario the thickness of the insulation material is increased to 70cm, the temperature of the water from the source is reduced to 25 $^\circ C$, and the temperature of the ground is set to 12.5 $^\circ C$. The goal of this scenario is to remove the significance of the thermal losses. In this scenario, some clusters will not receive their full demand due to the mass flow constraint to the heat exchanger. As seen, the difference between the two design is negligible small (y-axis). This proves that the choice of material, the conditions of the environment but also the quality of the heat source greatly influence the difference in performance between the two solutions. In other words, the lower the thermal losses due to material choice, environmental conditions and properties of the heat source, the lower the difference in performance between the two district heating networks become. It is thus important to realise that the difference in performance only applied to a really specific context.



11

Conclusion

The aim of this research was to gain insight in how different optimization objectives will influence the performance of the district heating network, from an end-user perspective. In practice, most district heating networks are optimized to minimize cost while no attention is paid to the effects that it might have on the performance of the system. Graph theory and modelling founded the base on which this research is performed. Using the developed models and a set of heuristics, the district heating network were optimized towards two objectives: minimizing cost, and maximizing consumer efficiency. The optimization is conducted on 100 small, random district heating network. It is also applied on a case in Delft where a large district heating network is planned. Finally, the large district heating networks in Delft were, under different conditions, subjected to energy deficits of different size to measure their performance. In the following section of this chapter, the answers to the research questions are given. Also subjects for future research and the contribution of this research are given.

How does the performance of a cost optimal district heating network compare to a district heating network optimized to maximize efficiency?

To answer the main research question, the findings found in analyzing the 100 random network and the findings from optimizing the district heating network in Delft are combined, leading to the following insight: Choosing an optimization objective for a district heating network results in very different solutions. For the 100 random district heating networks the cost optimized networks are compared to the network optimized to maximize efficiency. It can be concluded that optimizing for cost leads to win-win situations: The cost of the district heating network lowers, and the efficiency increases when compared to the starting network. However, the network optimized for efficiency is in all cases more efficient than the cheapest alternative. In all cases, the most efficient alternative is more expensive than the starting network, and thus also more expensive than the cheapest alternative. The efficiency of all cost optimized district heating networks may be increased, but in most cases at a large increase in price. In rare cases, the cost of an increase in efficiency is rather low when compared to the other cases. Despite the fact that these cases are rare, it proves the importance to research the solution space between the cost optimal, and the most efficient alternative. There may be designs with intermittent values that show gains in efficiency for less cost.

The same conclusion is drawn when the minimum cost and the maximum efficiency district heating network are compared in the context of Delft. The value trade-off between cost and efficiency in Delft is 'steeper' than encountered in any random district heating network. For each percentage that the network is more expensive, the network is 1.92% more efficient. Therefore, each percentage in efficiency gain may be considered. Thus, in the specific context of Delft it can be researched whether the decrease in cost outweighs the decrease in efficiency and the corresponding worse performance when faced with energy deficits. To generalize this conclusion, if one designs a large district heating network, it is worthwhile to explore the solution space between the cost optimal, and the most efficient solution. Despite the fact that the cheapest alternative increases efficiency and reduces cost, when compared to the starting network, it could appear that the efficiency may be increased at a relatively low cost.

Using the optimization results of the 100 random district heating networks, and the large district heating network in Delft, the value trade-off between cost and the performance from an end-user perspective is compared. In most cases, the most efficient district heating network is much more costly than the cost optimized district heating network. The results show that optimizing towards cost may have a great influence on the thermal losses of the district heating network. However, the difference in thermal losses between a cost optimized and a network optimized for to maximize efficiency, depends very much on the context. The difference in performance between the minimum-cost and the maximum-efficiency district heating network is very significant when the district heating network is struck by energy deficits of different size. Overall, district heating network that are optimized to maximize efficiency i.e. efficiency, supply much more energy to consumers when compared to the cost optimized district heating network. However, as the thermal losses are lessened due to choice of material or changes in environmental conditions, the difference in energy delivery to consumers becomes smaller. Generally speaking, it is concluded that efficiency optimized district heating network deliver more energy to the consumer, leading to more consumer comfort. The difference in performance when compared to a cost optimized network increases when the thermal losses are higher. When pipelines have thin insulation, and the ground gets close to freezing temperature, much more thermal comfort is experienced in a efficiency optimized network than the cost optimized network. In more ’soft’ conditions, the difference between the two designs in consumer satisfaction lowers. Therefore it can be concluded that optimizing towards efficiency, maximizing consumer satisfaction, is most noticeable in cold conditions. If the environmental conditions are soft and thermal losses from the pipelines are limited, the difference in performance is small. However, is the environmental conditions are cold and thermal losses occur in a higher rate, the efficiency optimized network delivers much more energy to consumers than the cost optimal one.

11.0.1. Future work

Based on the results and the conclusions, it is important that more research is conducted towards quantifying the value trade-off between efficiency and cost in a certain context. Currently it is unclear how much increase in cost, a percentage gain in efficiency may cost in a certain context. Once this value trade-off is quantified, it can be used to come up with different alternatives to a district heating network that differ in cost and efficiency. This way, different weights may be attached to efficiency and cost. This way, an optimal design of a district heating network may be made that incorporates both properties.

Furthermore, research is needed such that the discomfort of consumers may be economized. This way, the whole district heating network may be optimized such that the variable cost, including the occurrence of thermal discomfort, is minimized. This creates insight in what is most effective in terms of spending money: limiting thermal losses by investing in insulation, limiting thermal losses by investing in another network design or solving thermal discomfort by upgrading heat in certain parts of the district heating network.

11.0.2. Contributions

The main contribution made in this thesis is providing insight in the effect of choosing the objective function in optimizing district heating network. Optimizing the 100 random district heating networks shows that optimizing towards cost result in a reduction in cost and an increase in efficiency. In Most cases, the most efficient network is very expensive when compared to the cost optimal design. However, in some rare cases the most efficient design is much closer to the cost optimal solution in terms of cost, while the efficiency is higher. This proved that it is necessary to investigate the solution space between the two extreme designs. There might be a design in between that shows the most favorable properties. This can be done by assigning weight to the objectives. As argued, future work should focus on establishing the weights. This research did prove that optimizing purely for cost is too short-sighted as there may be a solution ’close’ to the cost optimal one that is more efficient, at a moderate increase in cost.

Furthermore, it is proven that the difference in consumer satisfaction is biggest when the thermal losses are largest. In winter, when the ground is colder, the efficient alternative will perform better than the cost optimized alternative. If the outdoor conditions are soft, and the pipelines are isolated very well such that the thermal losses are low, the difference in consumer satisfaction is less significant. Therefore it can be concluded that consumers are more vulnerable if thermal losses are not minimized in the district heating network, especially when the outdoor conditions are cold.

Furthermore, a method is developed that models the heat exchanger in buildings in the district heating network. This addition leads to insight in how a district heating network performs from the consumers side of view. It can be calculated how the demand of every building is satisfied under a set of conditions. This relates strongly to the findings of the literature study. In the literature study it became clear that thermal comfort is not part of the district heating network optimization. If consumers are not taken into account, the dissatisfaction of consumers grows [11]. This may limit the development of district heating networks in the future. Therefore this method is valuable: consumer satisfaction is taken into account, which may increase the acceptance of district heating network and thus accelerate the energy transition.

Last but not least, this research proposed a method that allows optimizing large district heating networks. Using a publicly available data-source, an accurate urban area is modelled and translated into a graph that may be used for optimization purposes. Despite that Delft plays a central role in this research, this method may be applied to any area of any size. In the literature study it is also found that local decision-maker or governments to not have the resources to design district heating networks. The method as proposed in this research may help in assisting local government or decision-makers to design district heating networks.

12

Discussion

Results

The results that were found in analyzing the 100 random district heating networks is found to be consistent and logically explainable. As explained there is a moderate to strong correlation in the reduction of cost and increase in efficiency of the cost optimal designs. Despite the fact that all district heating network were randomly generated, there is consistency in result which improves the credibility of the results. In contrast to the predictability of the cost optimal solution, optimizing towards the most efficient network resulted in much more extreme and random behavior. In one case, the most efficient network was 140% more expensive than the starting network. However, when the gain in efficiency is compared to the increase in cost, it is seen that for most district heating networks, one percentage gain in efficiency increases the cost of the network with 5% or more. In very rare cases, one percentage gain in efficiency only increased the cost with 1.25% or less. While optimizing the large district heating network in Delft it was noticed that Delft is such a rare occasion where an additional gain in efficiency is cheap. Despite the fact that there is randomness in graphs, this result was surprising when compared to the results of the 100 random district heating networks. It is expected that the sheer size of the graph is related to this result. It could be that the starting network in the Delft resulted in such an inefficient and expensive network, that optimizing for both cost and efficiency was partly done by reducing the amount of parallel pipelines. However, this expectation cannot be proven in any way.

The models that were developed during this research did result in consistency in the results. However, it is noticed that it is very difficult to proportion the different components of the district heating network. In other words, the ratio between thickness of insulation, temperature of the ground, available mass flow and the temperature of the water at the source is hard to grasp. Therefore sizing the components of the district heating network depended much on trail-and-error. As the performance of the district heating network depends much on thermal losses and the available mass flow, for each scenario the mass flow and needed insulation have to be reconsidered. Colder environments lead to more thermal losses. An increase in thermal losses makes the temperature of the water drop quicker which increase the volumetric consumption by consumers. All in all, this behavior is hard to predict and increased the amount of trial-and-error that had to be applied.

Validation and verification

Validation

First of all, the correctness of all result are tested within the script using the set of constraints as given within this thesis. The intermittent results are often tested on these constraints to make sure that the result is feasible. During the development of the model many errors that were different in nature. For example, initially it was unknown that cycles within the network could be problematic. All the constraints that are applied in the model came forth from these errors. This eventually led to smooth and consistent results. For example, analyzing the 100 random street networks can be done in a single loop without any errors. It is also noticed that no matter how many times this process is repeated, the results are the same. There is thus no amount of randomness in the model. This also shows in the consistency in the cost optimized networks. There is a moderate-strong correlation between the decrease in cost, and increase in efficiency.

It is also noted that the efficiency of the district heating networks change when the environmental conditions are set differently. Thus, when optimizing a district heating network, the environmental conditions should be set to conditions that are suitable for the area. This is also a point of attention. If a district heating network works sufficient under a set of conditions, it could appear that that same design does not satisfy all consumers under another set of conditions. In this research, only cold conditions were used during the optimization, magnifying the thermal losses. Therefore, the model may be validated such that the optimization takes place under a set of different conditions. This gives more insight in how the model behaves, and if the results of the optimization differ much under different conditions.

Verification

However, the model has not been verified using empirical data or any other experimental results. It would be interesting to see how the results of this model would compare to real-life district heating networks. It is also necessary to use more accurate data on the model. As discussed, more accurate data on the energy demand of consumers is needed. Applying this data results in more accurate measurements of the pipelines, thermal losses, etc. Also, if this data would be available over time, the model may be used to evaluate district heating networks over time. This way, the pipelines may also be optimized over time. For example, the industry at Schieweg have may demand energy at a different pattern than the buildings meant for housing. Therefore, there is still much room for applying more accurate data in the optimization of district heating networks. As this data is not publicly available, verifying the model and the results is difficult. Also, existing district heating networks do not publish data.

Limitations

To be able to calculate the pipeline diameters from only the topology of the pipelines and the spread of consumers demand did come with a set of influential assumptions. For example, the flow of the velocity is assumed, as well as that frictional losses and other hydraulic effect are neglected. To assess the heat consumption by consumers, only the thermal losses were taken into account. Therefore it is assumed that all other effects, such as pumping effects, pressures, etc. will not influence the consuming of the buildings. However, it is not known what the effect is of excluding these effects.

Besides that, the general efficiency that is applied to all flows in the network may lead to a district heating network that is over-dimensioned. As every flow in the network in increased by roughly $(1/0.7 =)$ 1.43, such that thermal losses may occur while all consumers still receive their demand is an over-estimation of thermal losses for many flows in the network. The flow to buildings that are close to the source do not lose 30% of their energy content to thermal losses. For buildings further from the source this general efficiency is better applicable. Therefore it is expected that the pipelines close to the source are over-dimensioned. However, it is now known exactly what the limits of this over-dimensioning is. However, as this over-dimensioning is done in both the network that minimizes cost, ad the network that maximizes efficiency the properties of each network may still be compared well to each other.

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A
Calculations

Calculating the efficiency of a district heating network

The efficiency of a single pipeline is calculated as follows:

$\eta_{i,j}$ = ($E^{in}_{i,j}$ - $E^{out}_{i,j}$) / ($E^{in}_{i,j}$)

A series of pipelines thus has an efficiency that is calculated as follows:

$$\eta_{gen} = \frac{\sum_{(i,j)\in N}(\eta_{i,j} \cdot E^{in}_{i,j})}{E^{in}}$$

Calculating the diameter of the pipelines

The heat capacity of water, C_p = 4186 [j/kg K]

The temperature difference between the source and indoor temperature is given by: ΔT = 30 [k] As all energy flows in the network are known, the mass flows are calculated using equation (4.5):

$$E_{water} = C_p \cdot \Delta T \cdot m \tag{A.1}$$

$$m_{i,j} = f_{i,j}/(\Delta T \cdot C_p) \tag{A.2}$$

Now that the mass flows are known, using the assumption that the velocity of the flow is constant at 1 m/s throughout the district heating network, the diameters of the pipelines can be calculated. Using the mass flow and the density of water, the volumetric flow rate in each pipeline is determined. From the volumetric flow, the diameter is determined as follows:

The density of water, ρ = 1000 [kg/m^3]

Let υ be the constant of the flow velocity. $\upsilon = 1$ [m/s] Let $D_{i,j}$ be the diameter of the pipeline between node i and j.

The open passage, $A_{i,j}$, of the pipeline between i and j is calculated using equation

$$A_{i,j} = \pi \cdot \frac{1}{2} \cdot D^2_{i,j} \tag{A.3}$$

The volumetric flow, $V_{i,j}$ rate between node i and j equals:

$$V_{i,j} = m_{i,j}/\rho \tag{A.4}$$

$$A_{i,j} = \frac{\pi}{2} \cdot D^2_{i,j} = V_{i,j}/\upsilon \tag{A.5}$$

$$D_{i,j} = \sqrt{(2 \cdot V_{i,j})/\pi} \tag{A.6}$$

B

Supporting figures

In the figure below the result of the clustering algorithm is seen. The color of the nodes denote to which cluster a buildings belongs. As there are many cluster, some colors may appear twice.

Figure B.1: Clustering of the buildings in Delft

In the figure below, all buildings in the area have a specified demand. As can be seen, the very large buildings have an immense energy demand.

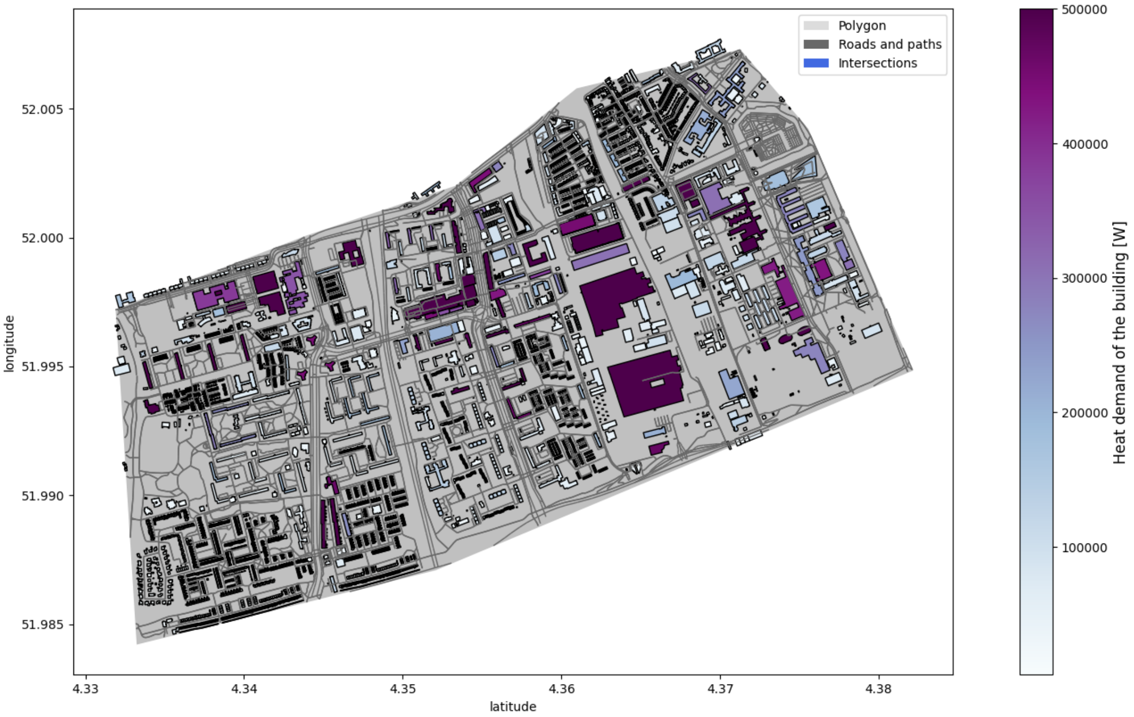

Figure B.2: Clustering of the buildings in Delft

The figure below shows the energy content of the pipelines in the district heating network with respect to the distance from the source. As each consumer is placed at a certain distance from the source, these are placed on the x-axis on their corresponding distance from the source. The y-axis shows the energy demand of the buildings. As can be seen, there are some very large heat consumers in this part of the network. When a large consumer is passed, the energy is the pipeline is also reduced noticeably as the consumer subtracts a certain amount of mass flow from the pipeline.

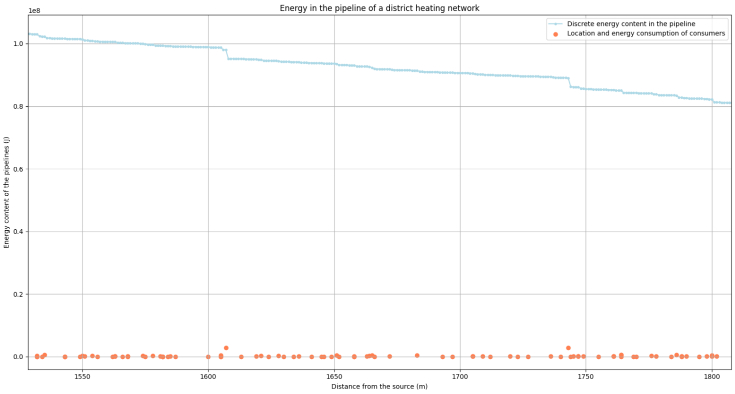

Figure B.3: An example graph with nodes with demand

In the two examples below, two additional examples of optimization results are given. The two impages support the explaination given in the main text.

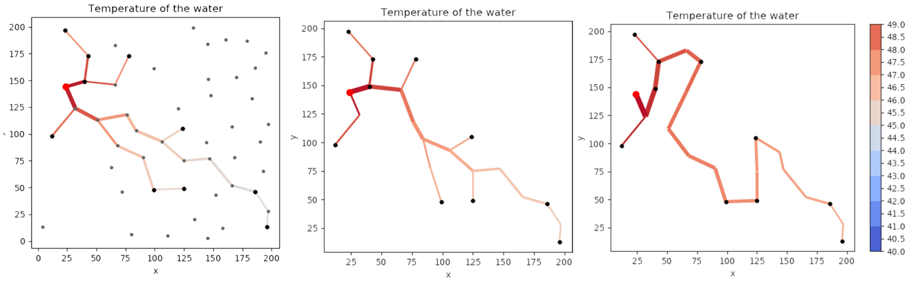

Figure B.4: The mechanism that leads to obsolete edges

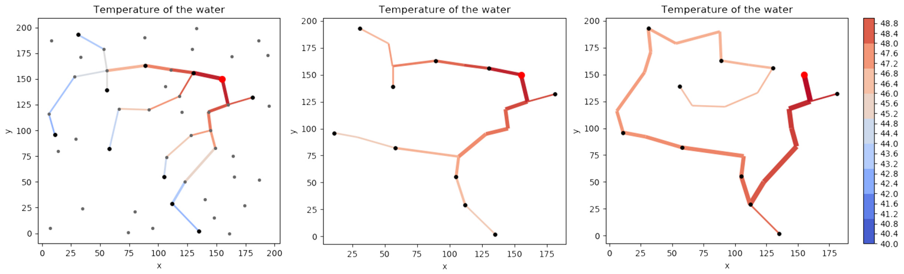

Figure B.5: The mechanism that leads to obsolete edges

In the following figure the full details of consumer satisfaction can be seen for a set of conditions. For each cluster, the percentage in the white box denotes the extent to which the demand is fulfilled. The image is of very high quality so when you zoom in the full details are seen.

Figure B.6: Example measuring the consumer satisfaction in a district heating network.

C

Code

On Github multiple scripts are made available that are used in this research. The scripts include the model used to calculate the cost and the model that assesses thermal losses. Also the script that optimized the district heating networks is included. Also, the script used to create the street network is available. The link below gives access to the scripts.

https://github.com/mpiket/DHN-optimization/tree/main

A polygon is needed to download the street network graph with. The polygon is defined by the following arrays based on latitude and longitude coordinates of multiple points. The first value of the latitude array should be used with the first value from the longitude list, the second with the second and so on.

```
lat_point_list = [52.007293, 52.004223, 51.994843, 51.987100, 51.984220, 51.997222,
    52.000075, 52.002004,52.005782, 52.007293]
lon_point_list = [4.371272, 4.375550, 4.382159, 4.352076,
    4.333236,4.331905,4.343922,4.353320,4.360959, 4.371272]
```

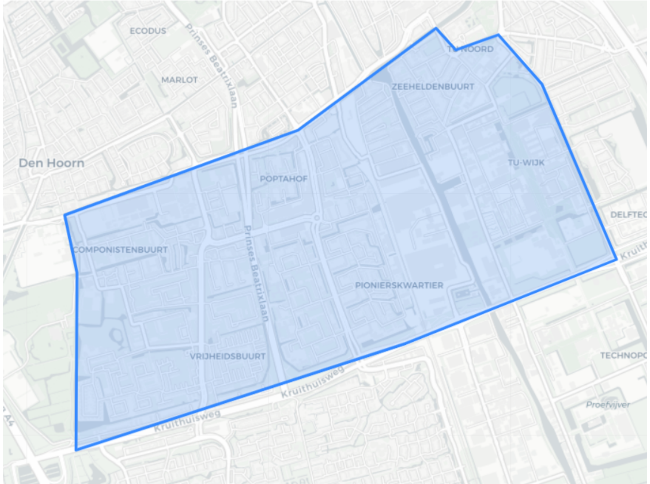

Figure C.1: The polygon as defined by the longitude- and latitude coordinates.