Geographically informed automated non-linear topology optimization of District Heating Networks.

R. Salenbien[a,b,*], Y. Wack[a,b,c], M. Baelmans[c,b], M. Blommaert[c,b]

[a] *Flemish Institute for Technological Research (VITO), Boeretang 200, 2400 Mol, Belgium*
[b] *Energyville, Thor Park 8310, 3600 Genk, Belgium*
[c] *Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300 box 2421, 3001 Leuven, Belgium*

Abstract

District heating networks are becoming an important component of future sustainable energy systems, providing space heating and hot water to buildings. The design of these networks can be complex and requires accurate consideration of various factors including geographical location, building characteristics, and energy demand. Here we propose a methodology to base automated non-linear optimization of district heating networks (DHNs) on geographical data. By integrating Geographic Information Systems (GIS) data with a non-linear optimization algorithm, an optimal network design and topology are determined that minimize the total cost of the system while ensuring heat demand satisfaction of the served buildings. The potential pipe routing is based on the existing street network and the building heat demands are derived from actual metered demand data. The approach is applied to a case study, hereby demonstrating its effectiveness in finding an optimal design for a challenging problem with producers at different temperature levels and varying consumer characteristics. The study shows that taking into account the geographical constraints and characteristics of buildings, the approach allows for more accurate and efficient system design. Partial automation on the input of optimization process also has the potential to significantly reduce the time and effort required for early stage planning of DHNs.

Keywords: District heating and cooling, GIS, Topology optimization, Network optimization, District heating case study, Optimal design

1. Introduction

District heating networks (DHNs), i.e. networks that connect heat demand and supply through a network of (insulated) water pipes, are considered an important piece of the puzzle towards reaching the sustainability goals [4, 5, 18, 28]. They can operate on multiple temperature levels and thereby couple different types of heat sources to different types of heat storage technologies or other energy networks [11, 13, 19, 29]. This results in a system with potentially great flexibility, even more so if governed by intelligent control frameworks [14, 34, 38]. Whereas traditional district heating systems are usually found in areas with sufficiently large spatial heat density and typically exhibit a network structure oriented towards a centralized production, the newer generations focus more on integration of low-temperature renewable sources and low-grade waste heat and therefore require a more complex, decentralized structure. [19]

During the past years, this newer generation of DHNs has been labelled fourth or even fifth generation. [19, 20] In practice, this increased system complexity calls for novel, automated methodologies in order to obtain economically or energetically sound topologies for the network, since manual or traditional design practices typically fall short in quality or performance or cost. For DHNs, the latter criterion is of particular importance; optimal design can help reduce the typically high upfront investment cost and increase

*Corresponding author
Email address: robbe.salenbien@vito.be (R. Salenbien)

project feasibility.

Smart district heating systems start with a smart and optimal design approach that allows to maximally harvest the global benefits of the DHN technology.. [18, 31] The widespread use of optimization methods in the design phase of District Heating Networks is currently limited by the availability of scalable optimization approaches that accurately represent the network. In recent years, many different approaches have been presented and applied to network topology design, but what makes district heating particulary challenging is the non-linear nature of the problem [3, 32]. Many authors resort to relaxation of the problem by linearizing the physical network model [7, 22, 33]. Often, the global problem is divided and partially treated, with separated focus on operational or design aspects. [6, 8, 10, 30] However, the aforementioned transformation of modern DHNs renders the assumptions most linearized models use invalid. Non-linear representations become necessary to correctly account for this challenging mix of sources, decreasing operational temperatures and heat transport through pipes with discrete diameters. Some approaches have been reported to solve this Mixed Integer Non-Linear Program (MINLP); Li et al. used genetic algorithms [17], Allen et al. proposed a minimal spanning tree heuristic and a particle swarm algorithm [1] and Mertz et al. and Marty et al. applied the commercial methods solver [21, 23]. However, the many discrete design variables in the problem so far limited the applied MINLP approaches to small DHN projects.

The computational complexity of solving said MINLP leaves potential to explore the application of gradient-based topology optimization methods to DHNs. A first step in this direction was published by the authors of this paper in Blommaert et al. [2]. This paper focused on defining a non-linear District Heating Model and developing a fast optimization algorithm by using adjoint gradients on a simplified cost function for heating network design. Building upon that paper, the authors presented a pipe penalization approach for the economic topology optimization [36]. The approach included a medium-sized design study and focussed on the benefits of having calculated discrete pipe diameters in the final topology. Furthermore, the authors perfomed an exhaustive comparison and benchmark between two different approaches to nonlinear topology optimization, highlighting the importance of initialization strategies, i.e. case design and setup. [37]

The use of realistic geographic information is essential for optimizing heating networks because it provides accurate and up-to-date information on the location of buildings, streets and other infrastructure. This information is necessary to accurately model the heating network and can be used in conjunction with other data, such as information on the physical characteristics of buildings and environmental factors. Resimont et al. [33] provided an overview of existing linear heating DHN optimization approaches and proposed a mixed-integer linear decision tool based on Geographic Information System (GIS) input. In this paper we add onto that approach, by automated coupling of GIS input data with the accurate non-linear topology optimization tool of Wack et al [36]. By doing so, we are able to tap into the databases of real heat demands and the street grid of a neighborhood and allow to accurately define the optimal routing problem for a potential heating network. GIS based optimization can capture the fine details, and help obtain a robust network design by further limiting assumptions. The combination of a fast and accurate optimization framework with automated high-resolution spatial input can evaluate all possibilities, rule out suboptimal designs and provides a systematic manner to achieve improved network topologies. [9, 37]

A full description of the mathematical model for non-linear heating network optimization was established previously by the authors in Wack et al [36]. In contrast to most district heating optimization studies, this non-linear model accurately captures the flow and heat transer physics within the network and aims at a detailed economic optimization enriched by GIS information.

The following sections report on the coupling of the framework [36] to GIS, the databases used for consumption and the demonstration of the approach on an urban area near Genk, Belgium. The aim of this work is to demonstrate the increased application potential that geographically informed topology optimization can have, and to provide insights on the new possibilities it creates.

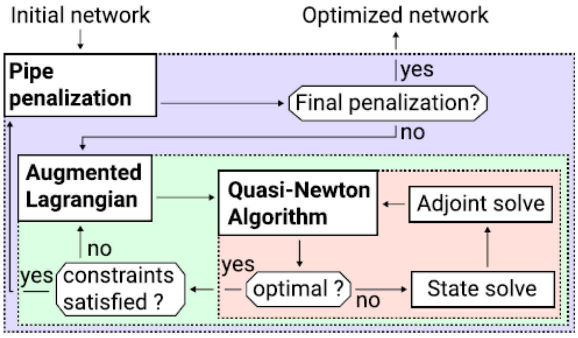

Figure 1: A flowchart illustrating the functioning of the applied methodology. It consist of three nested components: The pipe penalization ensuring near discrete pipe design, the Augmented Lagrangian approach enforcing the technological (state) constraints and the Quasi-Newton algorithm solving the resulting bound-constrained problem. A full explanation is documented in previous work of Wack et al [36].

2. GIS based preprocessing for non-linear heating network optimization

A geographic information system is a type of database that couples data for which a spatial location is relevant to a map. A multitude of software tools exist that can be used for visualizing, mapping, analyzing, or performing more complex operations on that database. For the purpose of this work, the free and open source geographic system tool QGIS was used. Applied to district heating systems, a GIS environment can be used to couple the locations of existing road infrastructure and building stock to relevant information on e.g. the building heat demand or assessment of district heating potential [12, 24]. It becomes an even more valuable tool when the various databases are coupled together and used as input for the optimization of district heating network infrastructure.

Digital Flanders, an agency of the Flemish government, works on the digital transformation and has established Geopunt [26]. The Geopunt portal is the central access point for geographic information made available by the government to the public. As such, it is the Flemish portal of the European geographic data infrastructure and complies to the requirements of the INSPIRE guideline [27]. Geopunt provides information on the Flemish building stock, industrial activity, the public transport infrastructure and road network and energy related aspects such as heat demand mapping or district heating infrastructure. Aforementioned software and database where treated with a stand-alone desktop architecture. In the following section, we describe how these databases are coupled, preprocessed and fed to the heating network optimization framework.

2.1. Evaluating potential pipe routing based on street network

The first important step is the inclusion of street grid data from GIS in the heating network optimization. Street grid data provides information on the layout of roads and other transportation infrastructure, which is necessary for accurately modeling the distribution of heat throughout the pipe network.

The 'Grootschalig Referentie Bestand' (GRB) is the digital topographical reference map of Flanders, Belgium [25]. This collective geographic database can be used as anchor for other implementations, e.g. DH design. The GRB only lists specific geographic and descriptive information on well defined and conventionally accepted reference data: buildings, roads and road structure, waterways, railroad infrastructure and highway networks. Each element is accurately measured and made available with scaling levels ranging from 1/250 to 1/5000. Since 2013, the full Flemish region is available and continuously updated. In this work, the GRB is used to obtain detailed information on the road infrastructure in Flanders, shown as white lines for an urban zone in Waterschei in figure 2. This information includes the geographic location, length, surface type, lane count, presence of other (sub)surface installations and much more. Also shown as dark grey polygons is the existing building stock ground level surface, including information on date of construction, height, address, energy performance, ...

2.2. Accurate heat demand representation (Warmtekaart Vlaanderen)

In addition to GIS based street grid data, the accurate representation of building heat demands is another important input for heating network optimization. This information helps to accurately model the heating needs of individual buildings, and can impact the overall efficiency of the network. This specific aspect will be shown in the case study in section 3.

For Flanders a GIS database of heat demands can be found in the 'Warmtekaart Vlaanderen'.

Figure 2: Selected data from the Warmtekaart Vlaanderen [15, 16] and the GRB [25] for an urban zone in Waterschei, Belgium. Shown as colored street segments is the annual heat density, and as colored dots the heat demand for larger consumers in the area.

The 'Warmtekaart Vlaanderen' was commissioned by the Flemish Agency for Energy and Climate to comply with EU guidelines 2012/27/EU for energy efficiency and the promotion of use of energy from renewable sources (EU) 2018/2001. The Warmtekaart couples geographic location and background information of i.a. heat demand densities per statistical sector, per municipality or per street segment and heat demand for consumers above 0.2 GWh.

The aforementioned data was the result of a study by the Flemish Institute for Technological Research (VITO) in collaboration with the Belgian DSO Fluvius [35]. For GIS-supported topology optimization of a district heating network, the Warmtekaart Vlaanderen is a unique source of realistic information on location and performance of the building stock and potential trajectories for the piping infrastructure.

2.2.1. Heat demand density: small consumption

For energy users with a total annual demand below 200 MWh, the heat demand density is depicted per sub-street segment in figure 2 [16]. The database is generated using heat demands calculated from the exact, measured gas and electric consumption provided by Fluvius and supplemented with estimates following from the biomass and oil consumption taken from the energy balance. To comply with the General Data Protection Regulation (GDPR), this exact heat demand is aggregated to a minimal of 5 consumption addresses, and shown on map as heat demand density via the total heat demand of a segment with respect to the segment length. For the calculation of street segment lengths, the road network as defined in the GRB (see section 2.1) is used. The minimal segment length is 10 m and clustered according to GDPR. 1.8% of the total number of small consumers, corresponding to 3.2% of the total heat demand, are labelled as confidential. Street segments with zero heat demand are limited to 200 m. Full details on the calculation methodology can be found in the report on the Warmtekaart [35].

2.2.2. Heat demand: large consumption

For energy users with an annual heat demand larger than 0.2 GWh, a separate GIS database is available. These large consumers are shown with their exact known location in figure 2 [15], however the heat demand is categorized. Similar to the approach for small consumers, the total heat demand is calculated using measured data for gas and electric consumption from Fluvius, gas consumption as reported in the Integraal MilieuJaarVerslag (IMJV) framework and supplemented with estimates following from the biomass and oil consumption taken from the energy balance. IMJV is the decree issued by the Flemish government to comply with energy and environmental reporting.

2.3. Graph construction

Topology design of DHNs, i.e. the routing problem, is usually based on an optimization of a cost function, e.g. the net present value, inclusion of renewable energy sources, emission reduction, ... or a combination thereof. For DHNs in particular, where the capital investments represent a large fraction of the total cost, it is crucial to not only keep these costs as low as possible but to also determine them as accurately as possible. The advantages of using non-linear techniques have been highlighted previously [2, 36], but the result is also dependent on the quality of the input graph. A graph representation of a network is a set of edges, i.e. streets, connected via nodes, i.e. junctions, consumers and producers. A schematic overview of how to combine the databases described into a graph representation is given in figure 3. Here, the edges and nodes are given properties described in sections 2.1 and 2.2.1. Using this graph representation, mass and energy balance equations can be discretized and solved for flow rates, velocities and temperatures, when appropriate boundary conditions are applied [36].

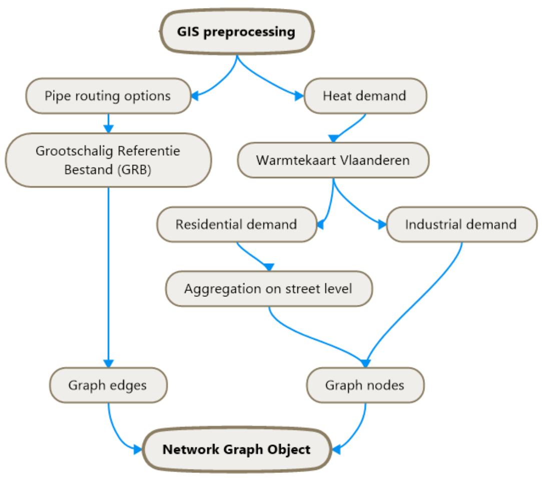

Figure 3: Schematic overview of the preprocessing steps followed to create a network graph object that is input for the optimization framework.

Technically, this graph can be constructed using connection nodes and segments for every building polygon defined in the GBR. The heat demand of those buildings can be actual metered data if available, calculated data using simple or complex models, standard load profile sets or any other methods of assigning thermal load to a building. For real applications, this exact link between spatial context and energetic considerations is the full potential of GIS based design. For this work, meant as a demonstration of the approach and taking into account the privacy constraint in the GDPR, some aggregation of the available data has been done and it was chosen to report results on street level rather than on individual building level. The graph of heat demand density per sub-street segment from the Warmtekaart does not align with the street pattern graph from the GRB. A reprojection of the first to the latter was done, in order to create the heat density per road segment as given by the GRB. The total heat demand on street level is thereby not altered, but the heat demand density can decrease in case were a GBR defined street overlaps with a sub-street segment of zero or confidential heat demand. To resolve this, a virtual consumption node is also created in the middle of every street and allocated the total heat demand.

This approach has been followed for an area in the city of Waterschei, Belgium, and the resulting graph is given in figure 4. The street pattern, heat density and large consumers were obtained via the databases described in sections above. All data is online and publicly available. Compared to figure 2, the graph edges overlap with the existing street pattern and are colored according to the total edge heat demand, the graph nodes are divided into junctions (black dot), consumption (red dot) and heat production locations (chimney symbol). The nodes with large consumption have individual colors assigned depending on the consumption category they belong to.

3. Case study: Waterschei

The optimal topology of a DHN project is very case specific and dependent on local context; the local heat density, availability of (waste) heat, the specific street pattern and properties of the building stock, the local legislation, ... Hence, the design should ideally not be based on a standardized assumptions. Successful implementation of an automated design process does not only relate to the

Figure 4: Final graph representation of an urban area in Waterschei, Belgium. The graph edges overlap with the existing street pattern and are colored according to the total edge heat demand, the graph nodes are divided into junctions (black dot), consumption (red dot) and heat production locations (chimney symbol).

reliability of the results and the speed with which they are obtained, but equally on the flexibility the input methods with which it can account for al possible scenarios. The approach described in section 2 proposed a method to couple various databases and collect properties of DHN components to a specific set of geographic coordinates. In this section, a case study with 3 different scenarios for the heat supply is presented to demonstrate that GIS-supported automated network design can indeed be used for project feasibility studies.

The graph shown in figure 4 is used as input for the optimization framework previously reported by the authors [2, 36]. Two possible (fictive) heat production locations are selected; a combined heat and power (CHP) plant location in the North-East and a low temperature-source South-East. This region of Flanders has a rich history of coal mining, and the area is dotted with now flooded mine shafts with depths exceeding 1 km. The low-temperature source is located on one of those shafts and studies are ongoing to determine whether these flooded mines can be used as a geothermal source in local district heating systems. This research question can be covered with the new GIS-supported design tool. Both sources are considered to generate enough thermal power to cover the total demand, the CHP output is set at 80°C, whereas the low-temperature source is assumed to supply 60°C. Renewable or waste heat sources are of great interest for DHN applications as they usually can be integrated with lowered cost of heat. To represent that, the heat cost of a CHP is fixed to 100 € /MWh and that of the mine shaft to 50 € /MWh, respectively. The building heating system is designed with an inflow design temperature of 60°C.

The mostly residential, 1.9 km^2 large, area under consideration has 3800 buildings and 340 road segments listed in the GRB [25]. The heat demand density of the buildings is represented by 308 clusters [16], and a total of 8 large consumers are included [15]. For this study, the heat demand of the large consumers is set to the bottom value of the category to which they belong: 6 nodes with a demand of 0.2 GWh per year and 2 nodes with a demand of 1 GWh per year (an event hall and a soccer stadium). After reprojection on street level, the resulting graph consists of 645 edges and 545 nodes, of which 323 have been assigned for consumption and 2 for production of heat. Note that some nodes can effectively have a zero demand if the demand is zero, unknown, or confidential. Here a total of 217 nodes remains with an effective heat demand. For this case study, the same physical and economic assumptions are taken as in the study by Wack et al. [36]. Deviating assumptions are reported in this section.

3.1. Scenario 1: Two CHPs as heat sources

As a first scenario, both heat production locations are taken to be a CHP installation. Both installations can supply the network at 80°C and are assumed to have sufficient thermal power to cover any and all demand. In the optimization objective, capital investments and operational costs are included, but it was chosen to exclude heat revenue. The latter depends critically on the project specifics, the business model, the legislative framework, while for this study the focus is placed on the technical aspects. Capital investments include cost of the pipe infrastructure (piping and a fixed unit cost for installation), cost of the network pumping installation and cost of the production plant. Operational costs include maintenance, heat generation and network pumping cost. Furthermore, it is assumed that all consumers connect to the network and that the resulting network topology is able to guarantee thermal comfort. For full details on the approach and models used, the reader is referred to previously published work by the authors [36].

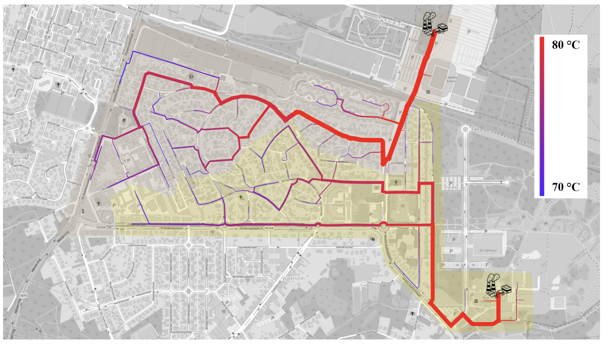

Figure 5: Optimized network topology for a case study in Waterschei, Belgium. Two CHPs are considered as possible heat production facilities, with a supply temperature of 80°C towards the network. The color of the lines is indicative for the supply temperature, the thickness of the lines for the diameter of the pipe infrastructure in that location.

Figure 5 presents the optimized network topology for the double CHP scenario. Here, the network supply temperature is represented by the color scale, while the thickness of the piping is represented by a scaling with the thickness of the plotted lines. Heat is brought to the area from both sources, each with their own branched structure and without interconnection. For visual aid, a brown and yellow tinted polygon is overlayed with the respective areas. In this scenario, preference of being connected to a particular source is dominated by the distance to the source, resulting in a higher connection rate and a larger backbone structure of the upper network, i.e. utilizing thicker diameters. The effect of the large consumers on the network structure is rather limited; their heat demand is of similar magnitude as the residential clusters and does not clearly impact the network structure.

Some key statistics on the energetic and economic aspects of the network are given in table 1. For scenario 1, the information is shown in the second column. The total heat demand of the network, 4.72 MW, is fully matched by the combined production of both CHPs. Of the total heat input, 4.19 MW is delivered to the customers and the rest is lost throughout the network. The estimated total cost of this network topology is M€29.68.

3.2. Scenario 2: A CHP and an underground mine storage as heat sources

In a second scenario, the output temperature of the bottom production plant is lowered to 60°C to represent the mine shaft system. Accordingly, the heat cost is also decreased to 50 € /kWh. All other assumptions in this scenario are taken identical to those of section 3.1. Intuitively, one could expect an increase in the number of connected consumers to the low-temperature source given the favourable heat generation cost.

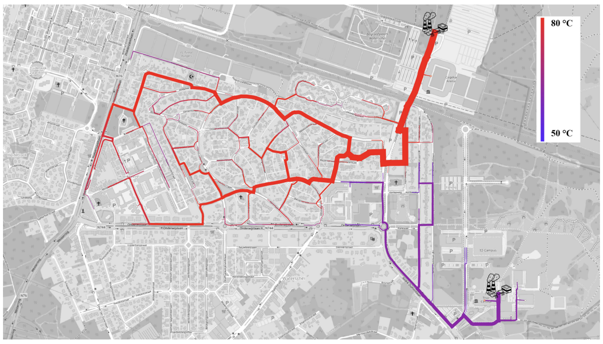

Figure 6: Optimized network topology for a case study in Waterschei, Belgium. A CHP installation with a supply temperature of 80°C towards the network and an underground mine storage with a supply temperature 60°C are options for the consumers to connect to. The latter has a heat cost reduced by half compared to the CHP scenario.

Figure 6 presents the obtained optimized network topology for the second scenario, and the third column of table 1 provides the economic and energetic aspects. Surprisingly, the majority of the consumers is connected to the CHP and supplied with higher temperatures. The color scale of the figure clearly differentiates both networks, with the low-temperature portion confined to the South-East part of the area.

The combined heat load of this scenario, 4.80 MW, is slightly higher than the double CHP case. The average connection distance to the CHP here is longer than in scenario 1, which results in a slight increase in heat losses (12.77% vs 11.26% average relative). However, the impact on the total cost of the network more significant with a roughly 5% increase in total cost, up to M€31.30.

This small utilization of the low-temperature source is a direct consequence of the building heating system design. In order to guarantee thermal comfort under worst case scenario, i.e. peak demand design, the building is required to operate at its design temperature of 60°C or above. The non-linear framework accurately accounts for heat losses in the distribution network, and for a given network supply temperature at 60°C the water temperature in the pipes soon drops below design values effectively limiting connections to the immediate surroundings of the production plant. The high-temperature CHP source compensates for this effect.

This result therefore perfectly underlines the importance and potential impact of using proper topology methodologies and the benefit of a non-linear approach. Classical rule-of-thumb based design or methods that resort to simplification to maintain project scalability would not be sensitive enough to capture these effects, potentially harming project feasibility.

3.3. *Scenario 3: A CHP and an underground mine storage with increased temperature*

In the third scenario, the output temperature of the mine system is again slightly increased to 65°C. All other assumptions in this scenario are taken identical to those of section 3.2. Intuitively, one could again expect an increase in the number of connected consumers to the low-temperature source given the favourable heat generation cost and the now high enough network injection temperature to compensate for distribution losses.

However, the shift of the optimized network topology towards the low-temperature source is rather limited as can be seen from figure 7. A few more street segments are now supplied by the mines, but the majority of the heat load is still covered by the CHP plant in the North. The existence

Overview			
Heat load	4.72	4.80	MW
Heat demand	4.19	4.19	MW
Avg. rel. heat loss	11.26	12.77	%
Production			
Heat load	4.72	4.80	MW
Pressure drop	11.68	10.90	bar
Heat source 1	80	80	°C
Heat cost 1	100	100	€/MWh
Heat source 2	80	60	°C
Heat cost 2	100	50	€/MWh
Costs			
Heat revenue	0	0	€
Pump OPEX	614.25	569.52	k€
Pump CAPEX	4.15	3.84	k€
Heat OPEX	11.08	11.14	M€
Heat CAPEX	8.23	9.62	M€
Pipe CAPEX	9.76	9.98	M€
Total cost	29.68	31.30	M€
Energy/Heat balance			
Producer input	4.72	4.80	MW
Pipe losses	427.56	421.82	kW

Table 1: Energetic and economic comparison of the optimized topologies for both scenarios. Column two is for the scenario with 2 CHPs and column three for the CHP/mine scenario.

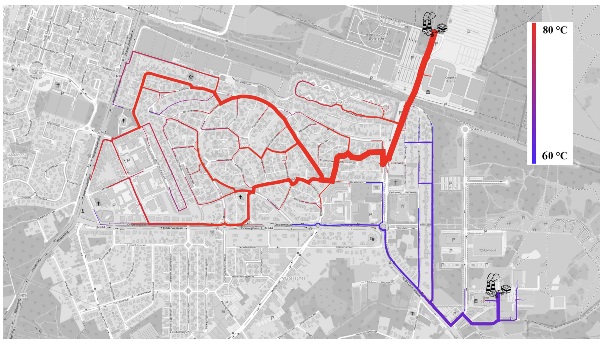

Figure 7: Optimized network topology for a case study in Waterschei, Belgium. A CHP installation with a supply temperature of 80°C towards the network and an underground mine storage with a supply temperature 65°C are options for the consumers to connect to. The latter has a heat cost reduced by half compared to the CHP scenario.

of a network backbone from that CHP to the outskirts of the neighbourhood limits the penetration rate the low-temperature mine system. That backbone infrastructure is required to supply heat to the consumers located further away. Note that the majority of the consumers located on the right hand side of that backbone are connected to the mine system, despite their proximity to the backbone, where the tradeoff between heat cost and losses favors economics of scale in piping infrastructure.

Table 2 provides the energetic and economic numbers for this topology. The 5°C increase in output temperature of the mine system results in a decreased total system cost of M€29.96, but is still slightly higher than the double CHP scenario.

As mentioned in the introduction, successful implementation of an automated design process does not only depend on the reliability of the results or the flexibility of the input methods, but also on the speed with which results can be obtained. Table 3 lists the total calculation times of the optimization framework, which was run on a standard laptop. Achieving an optimized result for a realistically sized DHN project can be done in roughly an hour or less, making the approach very suitable for project developers and cities or municipalities looking to compare various scenarios with a reliable level of accuracy.

4. Conclusions

This work demonstrates the increased application potential of geographically informed topology optimization of DHNs. To achieve these goals, GIS-

Overview		
Heat load	4.77	MW
Heat demand	4.19	MW
Avg. rel. heat loss	12.31	%
Production		
Heat load	4.77	MW
Pressure drop	10.96	bar
Heat source 1	80	°C
Heat cost 1	100	€/MWh
Heat source 2	65	°C
Heat cost 2	50	€/MWh
Costs		
Heat revenue	0	€
Pump OPEX	556.48	k€
Pump CAPEX	3.76	k€
Heat OPEX	10.57	M€
Heat CAPEX	8.95	M€
Pipe CAPEX	9.88	M€
Total cost	29.96	M€
Energy/Heat balance		
Producer input	4.77	MW
Pipe losses	422.99	kW

Table 2: Energetic and economic results of the optimized topology for scenario 3; a CHP at 80°C and a mine system at 65°C.

Calculation times	
Scenario 1 (80°C / 80°C)	37 min 12 sec
Scenario 2 (80°C / 60°C)	68 min 3 sec
Scenario 3 (80°C / 65°C)	47 min 10 sec

Table 3: Calculation times for each of the three presented scenarios.

based preprocessing was introduced and coupled to a previously established non-linear heating network optimization framework. More specific, the potential pipe routing options were mapped out based on the existing street network and an accurate, realistic, representation of the building heat demand was obtained for both the residential sector and larger consumers. Coupling these databases resulted in a graph structure that links heat demand, production and trajectory to a specific geographic location.

This approach was applied for an urban area in the city of Waterschei, Belgium, and used to determine the optimal network topology for three scenarios. The injection temperature and heat cost for two considered heat producers was varied and shown to have an impact on the network topology (3 different layouts) and energetic (up to 10 percent variation in operational cost) and economic performance (up to 5 percent variation in total cost). More importantly, the ability to correctly resolve the consumer heating system efficiency was highlighted. The existence of large consumers in the outreach of the network necessitated a backbone connection to the high temperature production to ensure thermal comfort. As such and in contrast to intuition, the cheapest network solution does not utilize the cheapest heat production, i.e. the fine balance between heat losses and pumping costs favoured the high temperature source in this configuration. In reality, where a multitude of uncertainties are inherent to any district heating project, the impact on the topology is amplified, further underlining the need for an automated method that can flexibly take into account the full range of options and deliver accurate and fast results.

The application potential of the GIS based framework was further underlined via the short calculation times. All scenario's could be processed in roughly one hour or less, for a case comprised of 645 edges, 545 nodes (of which 323 are consumers) and 2 producers.

5. Outlook

The case study presented here was deliberately chosen to showcase the GIS supported optimization process with minimal variation on the input side and a limited number of consumers after mapping the heat demand on street level. Still, a similar application of automated optimization to district heating has not been performed at this level previously. The framework is currently applied to city-scale projects, and can include much more detail than presented here. A major benefit of the implemented adjoint based approach is that optimization does not scale with the number of variables. Instead, network optimization times depend mostly on the number of edges in the graph object and resulted in acceptable wall-times for geographical areas up to city level. In principle, any segment or node in the input graph can have exclusive properties assigned provided that there is a model or database to extract that information from. Combined with the option to freely (dis)connect to the network or to fulfill the heat demand via other technologies, this opens the door for truly accurate and realistic case studies and provides a major leap compared to the current state-of-the-art in DHN design. Future developments should focus on accurately feeding heating system characteristics (e.g. design conditions estimated from publicly available data) into the framework and introducing temporal aspects into the analysis.

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