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Optimization of district heating network design

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Abstract

Due to the relatively high investment costs of district heating networks, their optimal design is crucial for a high ROI. A software tool supporting decision makers and network planners to find the cost optimal network topology is introduced. Beside topology the tool also estimates diameters of the district heating pipes. The optimization is based on user defined cost data, geo-referenced input of supply and consumer nodes, all possible laying routes for the pipes and technical boundary conditions. Further constraints can be considered, e.g., the usage of an already existing network or possible obstacles, e.g., costly crossings of rivers or railroad tracks. The optimization usually leads to an unmeshed network. Meshes which are needed to guarantee uninterrupted service can only be enforced by the manually definition of existing pipes. To ensure an easy-to-use interface for geo-referenced data the tool is provided as a plugin for the geographic information system QGIS.

The optimization process consists of a combination of classical non-linear methods, minimal spanning tree calculations and evolutionary algorithms. It allows solution of the mentioned problem for one specific user defined design case. In addition to the geo-referenced topology of the network, the diameter of each pipe and the total investment costs, the result of the computation provides further technical specifications, e.g., mean flow velocities and pressure losses, in the considered case. So far, different scenarios can only be calculated separately.

With a short training period the tool is largely intuitive to use. It is currently used in university courses in order to understand the challenges involved in the planning and design process of district heating networks. It is also used in research projects and is continuing to be developed.

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1. Introduction

District heating is very well represented in metropolitan areas and makes a decisive contribution to the relief of the environment by reducing emissions. A significant expansion of the use of district heating could be achieved by opening up smaller areas with a low heat density or a smaller local area. In the case of district heating, the high investment cost share of the distribution generates a high base share of the fixed costs, which is very stable

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compared to the energy use. This cost consideration was previously a disadvantage compared to competing systems, but this changes with the increasing prices of fossil fuels.

Due to the number of the factors to be considered using district heating, there are reservations at the decision-making level, especially in the small output range. Because of the already mentioned relatively high network costs of district heating systems, it is necessary to optimize the networks with regard to their design parameters, in particular the pipe diameters and the routing (network topology). To enable municipalities and smaller planning offices to carry out a well-founded investigation and decision, there is still a lack of suitable aids. This is why the STEFaN[1] software tool was developed and made available to support the expansion of the use of district heating using existing and available systems. It serves as a planning tool and is intended to support a decision in favor of district heating supply. In addition, it can also be used to recalculate existing systems in operations.

The results to be gained with the help of the tool can be divided into three main types:

- The costs affecting values include the route topology and the diameter of all pipelines.
- The most important technical parameters such as pressure losses and mass flows are output for all pipes.
- Further derived values are, among others, the total and specific investment costs as well as the heat transport per meter of pipe length.

The tool presented is a further development of the STEFaN tool presented by Gnüchtel and Groß [1]. The improvements primarily concern a user-friendly implementation of network optimization as a plugin for the free open-source program QGIS, which serves as a geographical information system.

Further content expansions compared to the referenced version 1.0 concern, among others, the possibility of considering several heat producers per network as well as a factor for adapting the demand load, which enables the calculation of several design cases.

2. Physical and mathematical background

2.1. Graph theory

The hydraulic processes in heating networks are described with the help of graph theory. In graphs, nodes are visualized as points and edges as arrows connecting the nodes. In district heating networks, the edges correspond to the existing and possible routes. For the program, a route always consists of a supply and a return pipeline of the same size (or it is empty). Nodes connected to one edge can be both supply points (sources) and also demand points (sinks). The properties of a route (e.g., pipe diameter) change at nodes with two edges. Nodes with more than two edges are branch points.

2.2. Hydraulic calculations

The technical basis for the diameter and route optimization is hydraulic calculations. The pressure losses in the pipelines are primarily considered. They are mainly caused by the friction on the inner pipe wall and the internal friction of the heat transfer medium, which are taken into account by means of the pipe friction coefficient λ. Another contribution to the resulting pressure losses is caused by built-in elements (e.g., fittings, measuring devices, filters, valves, orifices, etc.), which are considered by means of the resistance factor ζ.

For a pipe of length l, diameter d, the density of water ρ and the flow velocity c, the pressure loss Δp can be calculated using Eq. (1).

$$\Delta p = \frac{\rho}{2} c^2 \left(\sum \zeta + \lambda \frac{l}{d} \right) \tag{1}$$

Distinct turbulent flow can be assumed in district heating systems. By suitable substitutions using the surface roughness of the pipe k, the pipes cross-sectional area and the mass flow through the pipe, Eq. (2) results.

$$\Delta p = \frac{0,88}{\pi^2 \rho} \cdot k^{0,25} (\alpha + 1) \cdot \dot{m}^2 \frac{l}{d^{5,25}} \tag{2}$$

The district heating network is represented by a coherent, finite and undirected graph. This graph can have multiple meshes. Each demand point must be connected to at least one path from the supply point.

[1] STEFaN: Software zur Trassen-Erschließung Fernwärme für allgemeine freie Nutzung (Free to use software for district heating route development).

2.3. Optimization model

The general optimization task is structured in 4 levels from 0 to 3:

Level 0 concerns the heat generation and consumption. The technical features of the heat generator and the spatial position, specified by the geographic coordinates are prerequisites for optimizing the network. For the developed tool they are assumed as given. The required heat generation results from the expected heat demands of the consumers to be connected to the network for the stationary case, e.g., the design case, which is defined by the user. In addition, the geographical location of the demand and supply points as well as their load have to be defined.

Level 1 relates to the system parameters. The heat demand and, if applicable, the existing network are specified. The pressure level, the type of pressure maintenance and the system temperatures are determined in accordance with [2]. Based on the considered design case, the constraints for optimization are calculated in form of a stationary pressure calculation. The design mass flows and the available pressure difference are determined as the result.

Level 2 includes the topological optimization of the routing. The design mass flows and the pressure difference are specified, usually with specification of possible routes. This is usually a complex optimization problem. As a result, the structure of the network, the route as well as the design mass flow in each section are provided.

Level 3 is dedicated to the diameter optimization. The network structure and the routing are specified; the network is dimensioned by defining the diameter. This, too, is usually a high-dimensional optimization problem. As a result, the diameter and investment costs are determined for each section.

Optimization programs are not widespread for levels 2 and 3. Often routing and diameters are determined via an iterative approach, where they are "tried" and the usability is checked afterwards by hydraulic recalculation. In addition to the standard variant calculation, the presented tool also enables an optional combined consideration of levels 2 and 3 as a closed optimization problem where the diameter optimization (level 3) is included in the route optimization (level 2).

In the following some of the equations defining the resulting optimization problem are described. The objective function includes the costs of each new route to be built. The costs are included in the model in the form of Eq. (3) which is the share of costs for one pipe K_i:

$$K_i = \begin{cases} \left(a_{i,0} + a_{i,v} \cdot d_i^h\right) \cdot l_i + \sum_z \left(a_{i,0,obs} + a_{i,v,obs} \cdot d_i^h\right), & \text{pipe exists} \\ 0, & \text{pipe not existent} \end{cases} \tag{3}$$

The brackets of the first summand include the investment costs of the route per running meter as a complex price and must therefore be multiplied by the route length. In the second term, z obstacles can be included as direct costs depending on the diameter. The exponent h weights the diameter dependency of the costs. In the current program version, this exponent is set to 1. Thus, it is assumed that there is a linear relationship between cost and diameter of the pipe. The parameters $a_{i,0}$, $a_{i,v}$, $a_{i,0,obs}$ and $a_{i,v,obs}$ are input values.

In addition to the diameter d, other (auxiliary) variables are required to formulate the constraints of the optimization problem. This includes the mass flow $\dot{m}$ and the pressure loss Δp in the edges. Additional binary variables b_i are used for the detection of the discontinuity at $d_i = 0$, i.e., the distinction if a pipe exists or not. Several local and technical restrictions force the formulation of further constraints, e.g., as shown in equations Eqs. (2), (4) and (5).

Kirchhoff's first law is also known as the nodal theorem and describes the conservation of mass. The sum of all mass flows in a node is zero. Matrix A is known as the node-edge incidence matrix.

$$A \cdot \dot{m} = 0 \tag{4}$$

Kirchhoff's 2nd law is the theorem of meshes. It describes that the sum of all pressure losses along a mesh is zero. Matrix B is referred to as the mesh-branch incidence matrix.

$$B \cdot \Delta p = 0 \tag{5}$$

2.4. Mathematical methods

The diameter optimization for a fixed network topology and a design case is solved with methods of classic non-linear optimization (NLP), i.e., within the actual optimization core for the route optimization, the inner pipe diameter is continuously defined. The rounding to the specified standard diameter takes place internally in the program after the actual optimization.

The topological optimization uses well-known algorithms of graph theory. In a directed graph, the shortest paths can be calculated using the DIJKSTRA algorithm and the shortest networks (minimal spanning tree) can be calculated using the KRUSKAL algorithm. The topological optimization takes place by means of a combination of these two algorithms with modular use of the non-linear diameter optimization described above.

In order to improve the optimization results of the processes mentioned for the combined optimization of levels 2 and 3 generic methods are used.

2.5. Geographic information systems

Geographical information systems (GIS) combine geographical data with factual information (attributes) and are essential for working with the program. Performing a topological optimization requires the input of geo-referenced data. In previous program versions, this input was inconvenient, as both the preparation of the input parameters and the post-processing of the results were carried out using separate software.

To simplify the workflow, the current version of the route and diameter optimization is designed as a plugin for the open-source program [3]. Thus, all processing steps are united in one tool.

3. Workflow based on a sample network

3.1. Sample network

In the following, the workflow will be presented using the exemplary calculation of a fictitious heating network. The sample network consists of 27 demand points and 1 supply point. A river to be crossed serves as an obstacle. The workflow typically can be divided into several steps.

3.2. Step 1: Geographical input data

First layers with geo-referenced information (nodes for producers and consumers as well as edges for existing and possible routes) are created in QGIS:

- Choice of a geo-referenced background image for orientation in the terrain. One source for geo-referenced map material is, for example the free geodatabase QpenStreetMap.[2]
- Definition of supply and demand points with given attributes (e.g., heat demand).
- Route preselection: Input of possible routes and assignment of attributes (e.g., already existing pipes, laying type, maximal diameter).

Fig. 1 shows this pre-processing step. The demand and supply nodes are added in form of vector layers of geometry type point. One layer contains all demand points (marked in orange) and also the supply point (red). The possible routes can be added in form of a vector layer with the geometry type line shown in orange dashed lines. The river is illustrated in form of a blue dashed line.

3.3. Step 2: Non-geographical input data

The next step is providing and processing of the non-geographical data. Default values for this data are defined in two separate ASCII files and are automatically imported during the network calculation. It is recommended to enter all known project-specific information individually, especially case specific technical data and cost data. The above-mentioned files can either be edited by a standard text editor or using the QGIS plugin. This plugin simplifies the modification of general network information, e.g., system temperatures or economic data.

Fig. 2 shows the input mask for editing the project and cost data. There are 5 categories to choose from: Number ('Anzahl'), Optimization ('Optimierung'), Individual costs ('Einzelkosten'), System parameters ('Systemparameter') and Routes ('Trassen'). The left side of Fig. 2 shows the input of the type and number of heat generators, consumers,

[2] https://www.openstreetmap.org

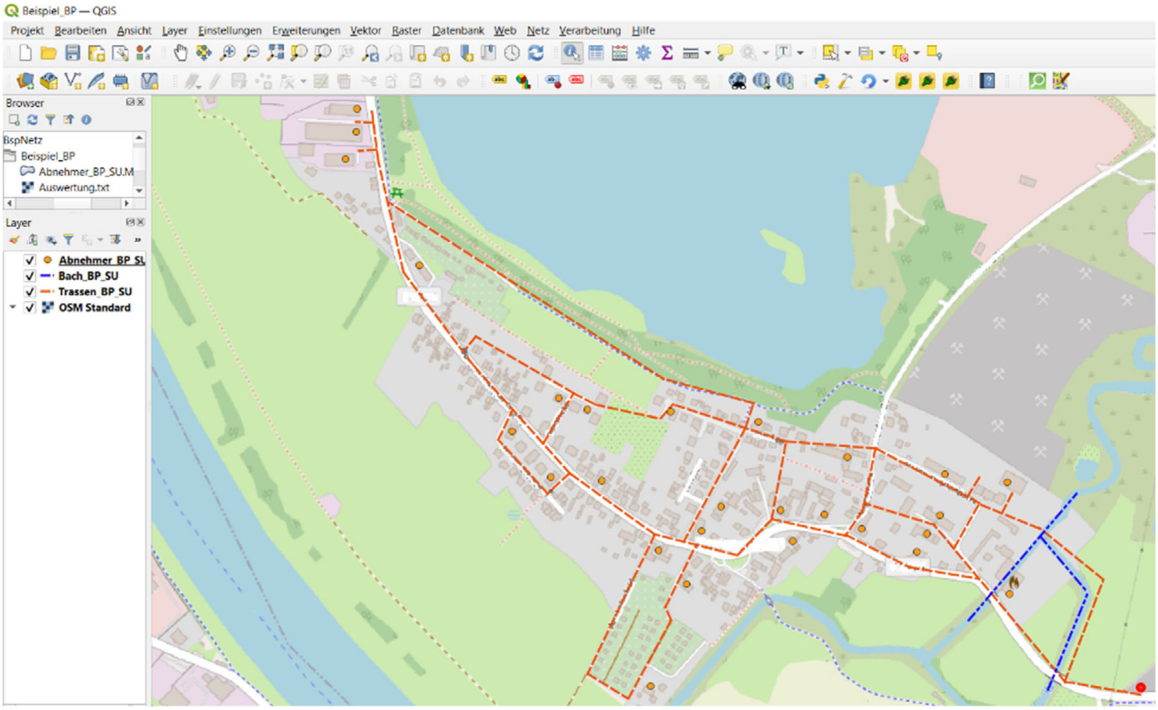

Fig. 1. Geographical data in QGIS. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

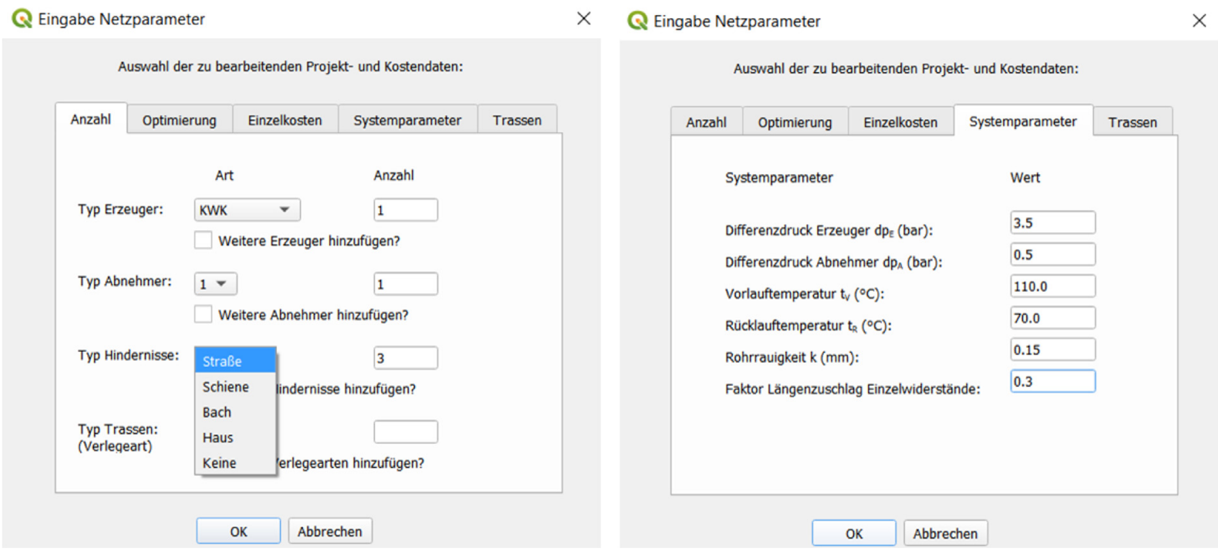

Fig. 2. Editing general network information and system parameters.

obstacles and routes (laying type). Obstacles can be, for example, crossing highways, railroads, houses or rivers. It is possible to edit the information of the selected components, e.g., investment costs, in the input mask of individual costs or to use the pre-set default values.

Similarly, the right menu in Fig. 2 shows the input mask for the system parameters. The pressure differences at the heat generator and the consumers, the flow and return temperatures of the network, the pipe surface roughness and a factor for the length addition of the individual resistances can be specified at this point.

3.4. Step 3: Network optimization

After pre-processing, the calculation of the optimal network topology can be started. Fig. 3 shows how to start the optimization via the QGIS plugin.

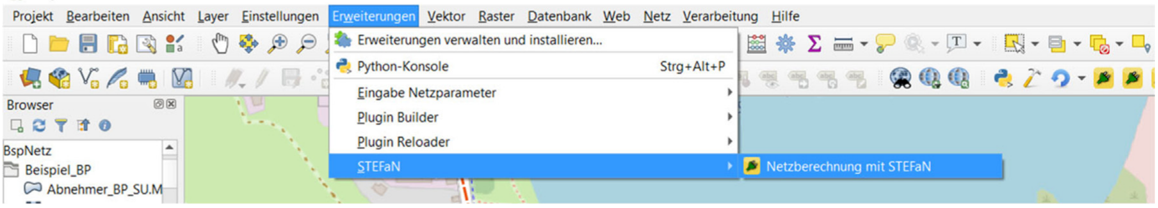

Fig. 3. Start network optimization.

After importing the previously defined input data, the program creates the network topology of the possible routes. Gaps in the connection points between multiple pipes are eliminated automatically to form a connected graph. The radius of capture can be set individually. To further simplify the input of geographical data, nodes, e.g., the defined demand points, are automatically connected to the predefined network if they are located within this radius of capture and are not directly connected to the network already. After that, the optimization of routes and diameters is performed automatically by the use of previously described mathematical methods.

3.5. Step 4: Evaluation

The optimization leads to several possible routings for the network with associated pipe diameters. Fig. 4 shows an exemplary comparison of two possible variants of the sample network. The line width corresponds to the diameter of the pipes. The total network length and annualized investment costs in both cases are given in the figure. The cost calculation was carried out on the basis of an interest rate of 6% over a lifetime of 25 years. Variant 1 is the cost optimal solution for this example.

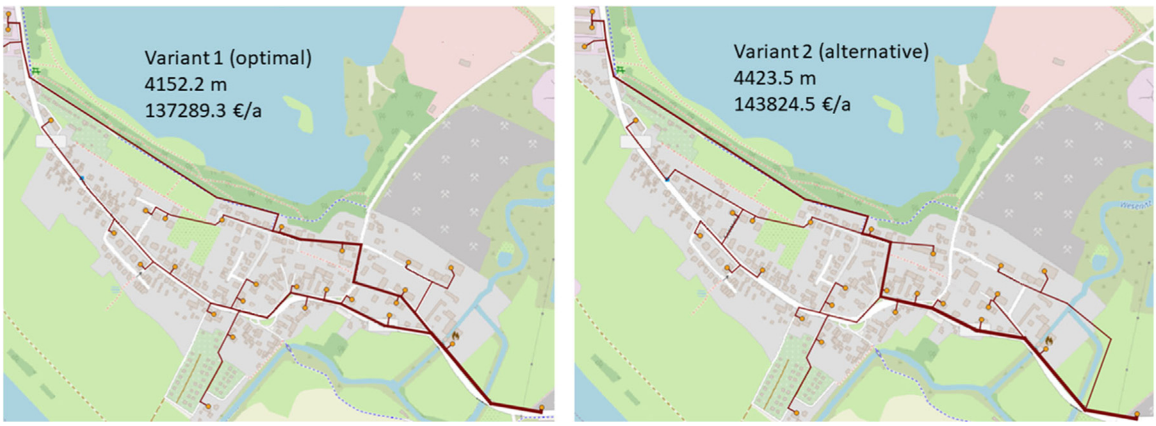

Fig. 4. Optimization results for 2 variants in comparison.

Table 1 shows several resulting values of some of the single pipes from variant 1.

Each pipe has a consecutive number and is defined by a start and end node. Some of the resulting values are, for example:

Table 1. Resulting values for variant 1.

Pipe	Start node	End node	Length in m	Inner diameter in mm	Mass flux in kg/s	Pressure loss in bar	Cost in €/a
1	1	79	10.7	69.7	2.411	0.01118	415.20
2	31	26	17.3	28.5	0.149	0.00572	538.20
3	31	101	5.5	53.9	0.863	0.00590	199.40
4	40	43	75.9	41.9	0.685	0.12568	2557.00
5	54	65	39.9	36.0	0.327	0.03073	1300.20
6	47	53	68.3	28.5	0.119	0.01449	2128.40
7	46	58	25.7	28.5	0.060	0.00136	800.70
8	30	80	156.4	69.7	2.411	0.16381	6083.80
9	34	82	41.6	53.9	0.804	0.04315	1493.30
10	62	16	19.2	28.5	0.119	0.00408	599.00

- the length of the pipe (in m),
- the optimal inner diameter of the pipe (in mm),
- the mass flux (in kg/s) and the pressure loss in the pipe (in bar),
- the annualized costs for pipe installation (in €/a).

Further results for the optimal variant, e.g., total net length, maximum heat load, annual costs, investment cost etc., are summarized as illustrated in Fig. 5.

Fig. 5. Evaluation of sample network.

4. Conclusion and outlook

A tool for the optimization of district heating network designs was developed as a plugin for QGIS. Following to a brief introduction of the methodology, the user-friendly operation is demonstrated based on an example. The resulting cost-optimal district heating network and an alternative variant are shown. The tool is currently used for university teaching and in research projects.

In order to expand the possible areas of application of the program, the following further developments are intended. At the moment, STEFaN can only calculate radial distribution systems. In a subsequent version, the calculation of meshed networks, the inclusion of the heat loss within the optimization process and the parallel computation of several design cases are considered as important. Furthermore, interfaces to other tools will be implemented. For example, the forecast of heat load profiles by the tool FreePlan [4] could be combined with the network optimization. It is also possible to use the result of the STEFaN tool as an input for the dynamic district heating simulation in TRNSYS-TUD ([5] as a further development of [6]).

Declaration of competing interest

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

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