

DHgeN: Automated Generation of District Heating Network Layouts for feasibility studies

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Abstract

District Heating Networks (DHNs) are part of the solutions towards a low-carbon energy transition for space heating, making an efficient use of renewable or waste energy sources. In early-stage planning, their potential is often evaluated at the demand side, using large-scale building energy models. However, from the financial and energy efficiency standpoints, the actual potential is also depending on the development of the physical pipework connecting the supply heating station with the consumer substations. To this end, this work proposes a framework for the automated generation of a plausible network layout by solving a minimum spanning tree problem connecting the different stations and assigning a sizing peak power to each network element. Although fully adapted to data available in other contexts, we show here an application using Swiss open geodata, which allows for a quick analysis for any location in Switzerland with a few user inputs. The application in Broc (CH) shows a good match with the operating DHN in terms of piping linear length.

Keywords: district heating networks, Python module

1. Introduction

District Heating Networks (DHNs) are energy systems distributing heat generated in a central location to multiple building consumers using an insulated pipework. By the efficient use of local waste and renewable energy resources, also within cogeneration plants, district heating systems provide a viable solution to decarbonized heat supply to buildings.

Due to the long-term investment (Colmenar-Santos et al., 2017, chap. 3), DHNs require careful planning. Typical regional-scale potential assessments or early-stage viability studies (Bush and Bale, 2019; Gils et al., 2013) are commonly conducted by estimating heat density in a given region and hence selecting locations achieving a minimum threshold for DHN viability. Other studies focused on the potential allocation of demand and supply, in terms for example of excess industrial heat (Chambers et al., 2020) or geothermal energy (Li et al., 2022). However, the viability of a network is also depending on the necessary pipework to connect all consumer substations to the heating station(s) (Best et al., 2020).

Conceived as a flexible Python-based toolkit, DHgeN provides easy access to existing and new algorithms to generate a plausible network path and model the peak power of the network nodes and edges. Unlike existing optimization solutions (Best et al., 2020), it focuses on straightforward application of existing graph theory models from available geodata. Similarly to the work of Chambers (2020), it features a method for generating a network topology from open geodata, while focusing on the pipeline layout and with the goal of wrapping different models in a ready-to-use open-source Python module.

2. Methodology

The module consists of a simple building peak power demand adapted to the Swiss context (§2.1) as well as an implementations of algorithms for generating the layout (§2.2), in particular for solving the minimum spanning tree (Steiner tree) and minimum cost flow (Simplex model) problems. Thanks to the presence of open data in Switzerland, the generation can be done with only a few user inputs while using some basic assumptions.

2.1 Model of the peak power demand

The peak power demand P [W] of buildings is modeled as follows:

$$P = A \cdot \Delta T \cdot U \quad (\text{eq. 1})$$

where ΔT is the difference between the indoor T_{int} and outdoor temperature T_{out} [K], U is the standard envelope U-value ($\text{W}/\text{m}^2\text{K}$), and A is the building envelope area [m^2] calculated assuming a squared footprint and a 3-m floor height using the following equation:

$$A = 4\sqrt{\text{area}_{\text{footprint}}} \cdot 3 n_{\text{floors}} + 2 \text{area}_{\text{footprint}} \quad (\text{eq. 2})$$

In Switzerland, the $\text{area}_{\text{footprint}}$ and n_{floors} , the period of construction and geographic coordinates of each building can be automatically retrieved from the Swiss Federal Register of Buildings and Dwellings (RegBL) available through an open API (see Table 1). The envelope U-value is set using the calibrated wall U-value for typical Swiss buildings for different periods (Perez, 2014, p. 177) and Swiss Society of Engineers and Architects (SIA) Norm 380/1:2009 for the most recent values. The T_{int} and T_{out} can be set by the user, for example using standard values from the SIA. Depending on the building use, a power density of 1 to 3 $\text{W}/\text{m}^2_{\text{floor area}}$ is also considered, while internal loads, solar gains and window losses are neglected here.

Results are bounded to recommended power-to-floor-area densities for non-labeled buildings (SuisseEnergie, 2016), i.e., a minimum of 25 $\text{MW}/\text{m}^2_{\text{floor area}}$ (i.e., for recent buildings) and a maximum of 80 $\text{MW}/\text{m}^2_{\text{floor area}}$ (i.e., for poorly insulated commercial buildings), in order to avoid outliers due to possibly incorrect input data.

2.2 Model of the network layout and power distribution

The process of generating the network is illustrated in Figure 2. The Python implementation is largely based on NetworkX (Hagberg et al., 2008, 2019) and GeoPandas (Jordahl et al., 2020) modules. An initial graph G is modeled as a regularly spaced grid, where the width and length of the cell nodes (by default 25 m) and rotation (by default 0°) can be set by the user. It is also possible to generate a custom tessellation instead of the regularly-spaced grid, but its implementation, using at the moment only input points from the (sub)stations data and a Voronoi diagram, is still basic.

In addition to the input (sub)stations, other geodata can be included in the module. If footprint data is added, the graph edges intersecting with the building footprints are removed from the initial graph G . If road data is added, a graph R is created from the vector paths, which are densified to the same resolution as G . The two graphs are connected by creating new nodes at their geometrical intersection resulting in graph G' .

The network G'' is then created by connecting all heating (sub)stations s to the closest edge ab . This is done, as illustrated in Figure 1a, by adding a new node x and new edge sx perpendicular to ab , splitting ab into two new edges ax and bx and removing the original edge ab .

The minimum spanning tree connecting all consumer (sub)stations s in graph G'' is computed solving a Steiner tree problem. This method is commonly used for optimizing electrical grids and has been already implemented in DHN layout optimization (Delmastro et al., 2016). In our implementation, G''

edges can be weighted by a parameter set by the user, where a value lower than 1 can be used to give a priority to a road (i.e., from original graph R) over other edges (e.g., from original graph G) which by default have a value of 1.

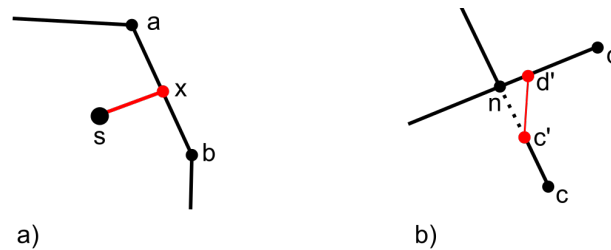


Figure 1 – Schematics of the main graph-processing algorithms: a) Connection of a substation s to the network
b) Transformation of a 4-degree node n into two 3-degree (T-junction) nodes n' and d'

In DHgeN, the user has the option to choose either Networkx's approximate Steiner tree model or a Steiner tree heuristics (Hušek et al., 2019). The latter model was developed in the framework of the PACE2018 Competition, where it obtained the 4th place in the track dedicated to heuristics with large tree width and high number of terminals (Bonnet and Sikora, 2019). It has been chosen for integration in DHgeN because of its complete documentation, easiness to compile, fitness to large graphs, and compatibility with the GPLv3 license.

In the final network, the degree of each graph node n is limited to a maximum value of 3, so as to accept only T-junctions. As illustrated in Figure 1b), this is ensured by creating a new node n' translated over one of outgoing edges, e.g., nd . The nd edge is then replaced by two edges nd' and $d'd$ and the original nc edge is replaced by the new edges $d'c'$ and $c'c$.

The resulting non-directional graph is transformed into a directional graph originating from the heating station, whose spatial location can be set by the user, resulting in a typical branched DHN. Finally, the peak power of each edge of the network is computed using NetworkX simplex network model, using as demand the substations power (calculated in §2.1) and as weight the edges' priority (i.e, edge length multiplied by edge weight).

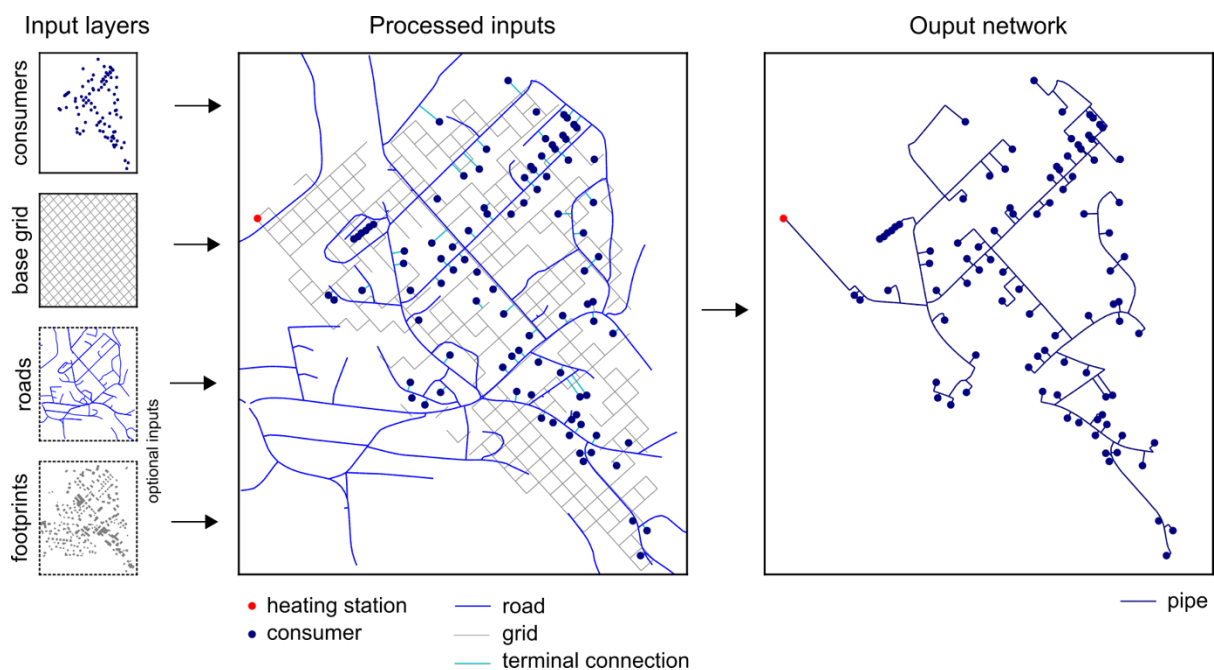


Figure 2 – Main datasets and processes involved to create the network layout.

3. Test-case application

We present here a test-case application in an area of the municipality of Broc (Switzerland) where a DHN is currently in operation. The online repository (see §4) contains also other examples of applications using either geodata from the GeoAdmin API available in Switzerland or a sample input file.

This section presents additional results comparing the modeled network in Broc with the data provided by the design engineering firm. The part using publicly-available data is reproducible using the scripts in the online repository

3.1 Presentation of the case study

In the data representing the status in 2019, the network in Broc is composed of 85 substations connected (or planned to be connected) to a heating station located at the north-west boundaries of the village. We delimit our analysis in the area bounded by this network, covering a surface of almost 500,000 m². It should be noted that not all buildings in the area are connected (or planned to be connected) to the DHN nor are listed in the Register of Buildings and Dwellings (RegBL) as such.

For the purposes of this study, we show the existing reference network R as well four modeled versions using as input layers:

1. The buildings classified in the RegBL as having access to the district heating network as of September 2022 (n=92) and connected by
 - a. A grid-based graph;
 - b. A grid-based graph including also the road network and excluding edges intersecting with the building footprints.
2. The substations coordinates as in the data available from the engineering company (n=85) connected through:
 - a. A grid-based graph as in 1a;
 - b. The same graph as in 2a, but including a road segment with its weight set to 10 to avoid crossing twice the railway lines. This variant is proposed to demonstrate how the user can add further constraints and is meant to have a layout that is more similar to R.

In all cases, a base graph formed by 25x25-m grid is used. This is rotated by 42°, so as to visually align with the main roads and produce more realistic results. In variants 1b and 2, the network also includes the road graph with a 0.5 weight.

For all variants, the peak power is modeled using data from the RegBL (see §2.1 and Table 1). In records with missing values default values of $n_{floors} = 2$ and $U = 1.35 \text{ W/m}^2 \text{ K}$ were used. It should be noted that these hypotheses are not necessarily aligned with those used in the design of the network R.

Table 1 – Extract of some records from a RegBL query run using the functions provided in DHgeN. The description of the fields and their keys can be found here: <https://www.housing-stat.ch/fr/help/42.html> (in German, French and Italian). The API documentation is available here: <https://api3.geo.admin.ch>

egid (unique identifier)	geometry	gklas (use)	gastw (n. of floors)	gbaup (construction period)	garea (footprint area in m ²)	genh1 (heating source)
1509806	POINT (2573843.9 1161849.4)	1110	2	8016	97	7501
504110198	POINT (2574202.6 1161870)	1276	N/A	8011	140	N/A
1509810	POINT (2573952.2 1161852.4)	1122	7	8015	252	7530
1509812	POINT (2574008 1161873)	1122	4	8014	492	7580

3.2 Results

The resulting layout solutions and the reference network are compared in Table 2 and Figure 3.

Since the number and location of the heating stations is slightly different for variants 1 compared to R, a fair comparison can be drawn only between variants 2a with R.

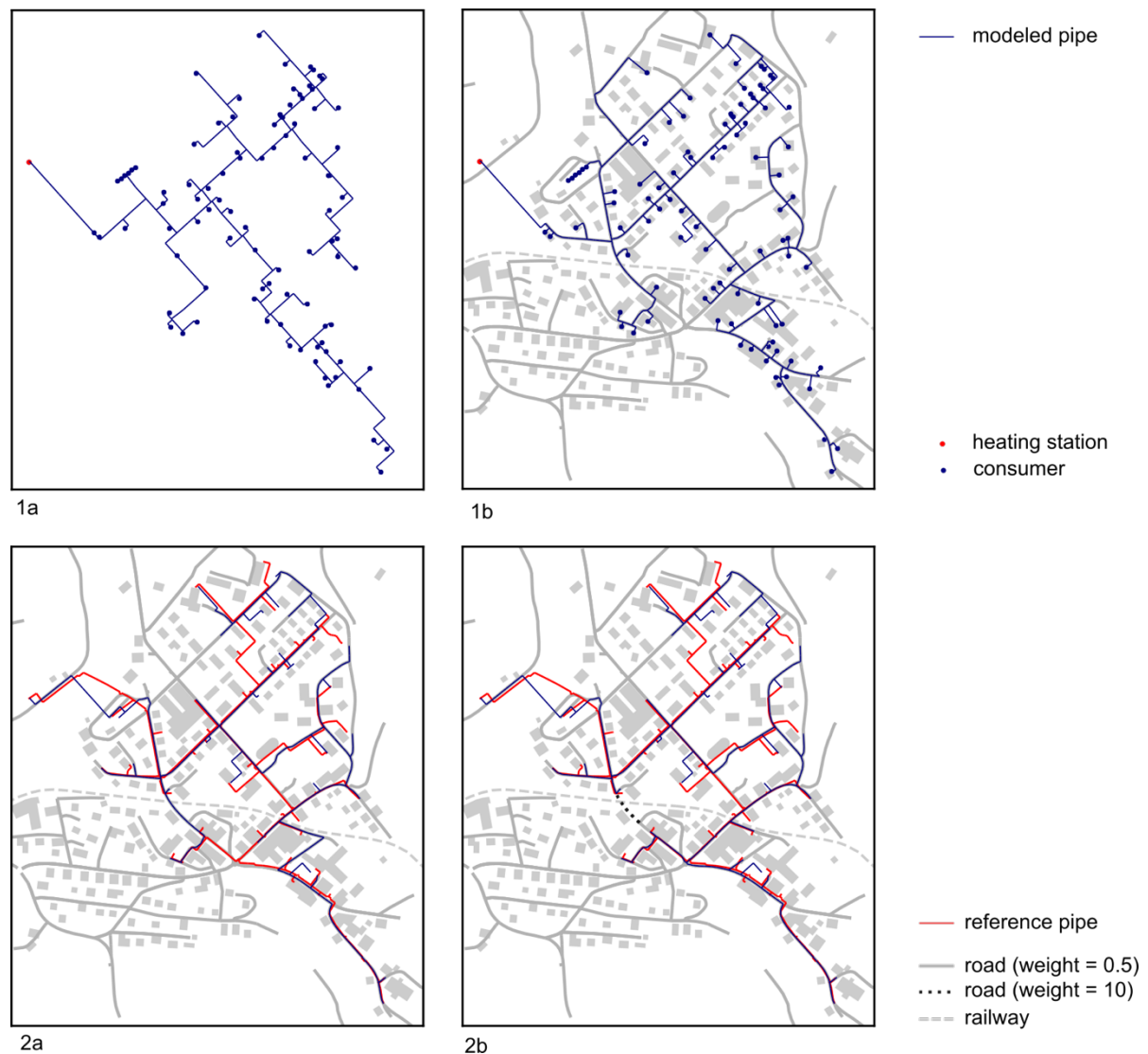


Fig. 3: Comparison of the paths generated by the algorithm. Layouts 2a and 2b are also compared to the actual path of the reference DHN: please note that the substations and their closest pipes are not shown here due to confidentiality. Layout 2b includes a custom weight = 10 for a road segment to avoid an additional crossing of the railway (drawn in the map, but not part of the inputs).

The length of the modeled networks present similar figures, while the cumulative power is underestimated compared to the reference. The length difference (+4%) between cases 2 and R seems negligible, both for expected power losses and costs due to longer piping. The modeled layouts look plausible, while in some cases differ from the reference one, particularly in the north-east area where more road options are possible. In terms of peak power of the substations (-20% of the reference), the figure can be considered a good estimate, before a safety margin at the heat exchanger level is added, as it was likely the case for the reference.

Variant 1a presents the shortest path, while, unsurprisingly, it is largely unfeasible because of the absence of constraints. Nonetheless, it could be still used as a design-support tool to select the best paths in a given area, especially when vector roads data and or building footprints are not available. In variants 1b, 2a and 2b, similar characteristics can be seen. In general, it can be noted that in some large lots,

longer paths are needed to connect to the substation consumers. These include some unrealistic U and T-shaped paths (see Figure 3, variant 1b), which are due to the underlying grid.

In both variants 1b and 2b, in order to supply some consumers south of the railway lines, the algorithm selects a road crossing the railway line. It is interesting to note how this crossing was instead avoided in the actual design path, probably for construction complexity and costs. In this sense, setting a custom weight as in variant 2b helps avoid this crossing. In general, if some roads are to be avoided or preferred for specific reasons, setting custom weights would help further customize the layout.

Based on the peak power of the consumer substations, DHgeN also attributes the power of each pipe segment as well as an estimated nominal diameter (DN). Figure 4 shows the peak power for both consumers and pipes for variant 1b. We argue that these values can be used as a first estimate to pre-size the pipework and anticipate hence the main construction works.

Tab. 1: Comparison of some relevant figures of the actual and modeled networks.

Variants	Reference network	Modeled networks			
	R	1a	1b	2a	2b
Data source	Private database	Public API (RegBL)	Public API (RegBL)	Private database	Private database
Additional data from public APIs		-	Footprints and roads	Footprints and roads	Footprints and roads (with custom weight)
Length of supply pipework	3861 m	3598 m (-7%)	4371 m (+13%)	3999 m (+4%)	4005 m (+4%)
Number of pipes	563	303	553	542	546
Cumulative peak power of the substations	3.06 MW	2.63 MW (-14 %)		2.43 MW (-20%)	
Number of substations	85	92		85	

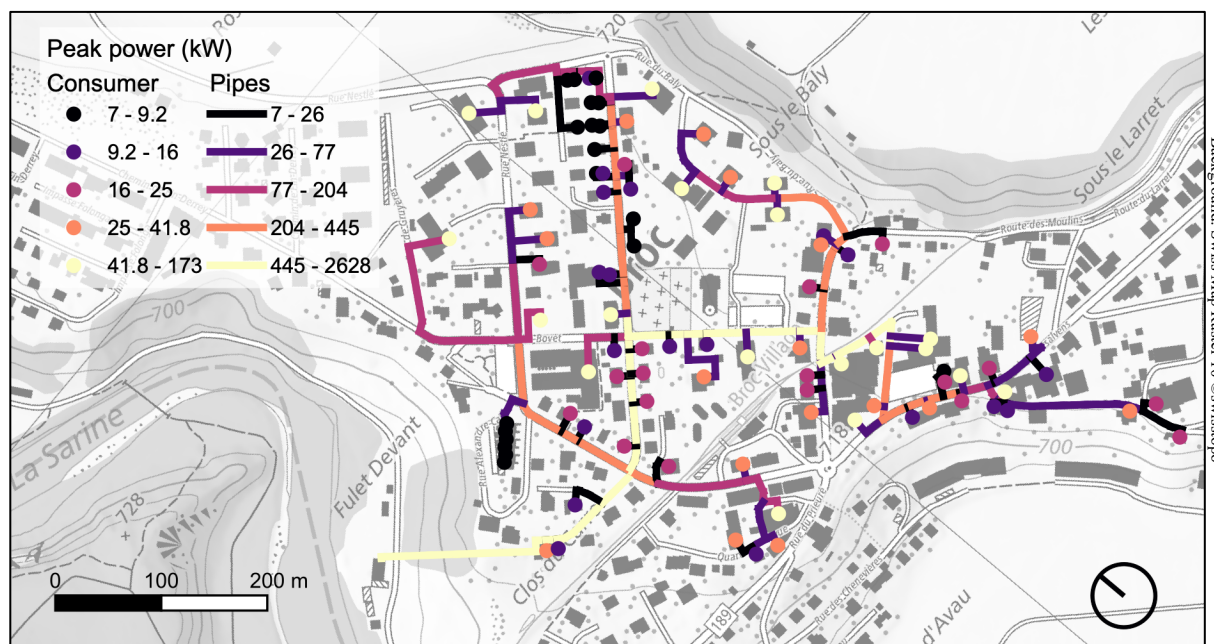


Figure 4 – Generated layout and power flow for variant 1b.

4. Software development and release

DHgeN is developed in Python using open-source libraries and is distributed under the GPLv3 license. It can be installed using pip. A Docker file is provided to allow for reproducibility and unit testing.

The source code is available at the following Git repository: <https://www.github.com/idiap/dhgen>. Any contribution is welcome using issues and merge requests.

5. Conclusion

This paper has given an overview of the DHgeN Python module at its current development stage (September 2022). DHgeN is released as open-source software under the GPLv3 license.

By using this tool, the user can test different planning scenarios, notably for choosing the optimal location of the heating station, minimizing the length of the pipework and/or the DN of the pipes.

The output of the models was compared to the layout of an existing DHN showing fairly realistic modeled layouts, only slightly longer than the reference one (+4%), i.e., a network partially planned and partially in operation designed by a local engineering firm. Based on these results, we argue that the proposed module can be used as a design-support tool to draft a DHN layout in the context of feasibility studies. The proposed layout can be then adjusted, also by setting custom parameters in the tool itself, to reach a further design phase.

Expected on-going and future development will be conducted along the following paths:

- Integration of further goals/constraints, also using an iterative approach. This, for example, would allow for the integration of further constraints (e.g., avoiding intersections) in the terminal connection from the main pipe network to the consumer substation;
- Improvement of the load model and interface to other tools for hydraulic/thermal simulation (CitySim, pyDHN);
- Integrating further geodata in the algorithm (fiber optics networks, railway lines, rivers);
- Creation of a user interface, either as web-application or as QGIS plugin.

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Additional datasets were retrieved using the GeoAdmin API: the layers *ch.swisstopo.swisstlm3d-strassen* (roads) and *ch.swisstopo.vec25-gebaeude* (footprints) of the Swiss Federal Office of Topography (Swisstopo), the layer *ch.bfs.gebaeude_wohnungs_register* (Swiss Federal Register of Buildings and Dwellings - RegBL) of the Swiss Federal Office of Statistics (SFS), and the layer *ch.bav.schienennetz* (railway) from the Swiss Federal Office of Transport (FOT). Further documentation on GeoAdmin can be found at <https://api3.geo.admin.ch> as well as in the DHgeN repository <https://www.github.com/idiap/dhgen>.

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7. References

- Best, R.E., Rezazadeh Kalehbasti, P., Lepech, M.D., 2020. A novel approach to district heating and cooling network design based on life cycle cost optimization. *Energy* 194, 116837. <https://doi.org/10.1016/j.energy.2019.116837>
- Bonnet, É., Sikora, F., 2019. The PACE 2018 Parameterized Algorithms and Computational Experiments Challenge: The Third Iteration. Presented at the 13th International Symposium on Parameterized and Exact Computation (IPEC 2018). <https://doi.org/10.4230/LIPICS.IPEC.2018.26>
- Bush, R.E., Bale, C.S.E., 2019. Energy planning tools for low carbon transitions: an example of a multicriteria spatial planning tool for district heating. *J. Environ. Plan. Manag.* 62, 2186–2209. <https://doi.org/10.1080/09640568.2018.1536605>
- Chambers, J., 2020. Computationally scalable geospatial network and routing analysis through multi-level spatial clustering. *MethodsX* 7, 101072. <https://doi.org/10.1016/j.mex.2020.101072>
- Chambers, J., Zuberi, S., Jibrán, M., Narula, K., Patel, M.K., 2020. Spatiotemporal analysis of industrial excess heat supply for district heat networks in Switzerland. *Energy* 192, 116705. <https://doi.org/10.1016/j.energy.2019.116705>
- Colmenar-Santos, A., Borge-Díez, D., Rosales-Asensio, E., 2017. *District Heating and Cooling Networks in the European Union*. Springer International Publishing, Cham. <https://doi.org/10.1007/978-3-319-57952-8>
- Delmastro, C., Mutani, G., Schranz, L., 2016. The evaluation of buildings energy consumption and the optimization of district heating networks: a GIS-based model. *Int. J. Energy Environ. Eng.* 7, 343–351. <https://doi.org/10.1007/s40095-015-0161-5>
- Gils, H.C., Cofala, J., Wagner, F., Schöpp, W., 2013. GIS-based assessment of the district heating potential in the USA. *Energy* 58, 318–329. <https://doi.org/10.1016/j.energy.2013.06.028>
- Hagberg, A.A., Schult, D.A., Swart, P.J., 2019. *networkx/networkx*. NetworkX: Python software for complex networks.
- Hagberg, A.A., Schult, D.A., Swart, P.J., 2008. Exploring Network Structure, Dynamics, and Function using NetworkX, in: Varoquaux, G., Vaught, T., Millman, J. (Eds.), *Proceedings of the 7th Python in Science Conference*. Pasadena, CA USA, pp. 11–15.
- Hušek, R., Toufar, T., Knop, D., Masařík, T., Eiben, E., 2019. *SteinerTreeHeuristics*.
- Jordahl, K., Bossche, J.V. den, Fleischmann, M., Wasserman, J., McBride, J., Gerard, J., Tratner, J., Perry, M., Badaracco, A.G., Farmer, C., Hjelle, G.A., Snow, A.D., Cochran, M., Gillies, S., Culbertson, L., Bartos, M., Eubank, N., maxalbert, Bilogur, A., Rey, S., Ren, C., Arribas-Bel, D., Wasser, L., Wolf, L.J., Journois, M., Wilson, J., Greenhall, A., Holdgraf, C., Filipe, Leblanc, F., 2020. *geopandas/geopandas: v0.8.1*. Zenodo. <https://doi.org/10.5281/zenodo.3946761>
- Li, X., Walch, A., Yilmaz, S., Patel, M., Chambers, J., 2022. Optimal spatial resource allocation in networks: Application to district heating and cooling. *Comput. Ind. Eng.* 171, 108448. <https://doi.org/10.1016/j.cie.2022.108448>
- Perez, D., 2014. *A framework to model and simulate the disaggregated energy flows supplying buildings in urban areas (PhD thesis)*. Ecole polytechnique fédérale de Lausanne.
- SuisseEnergie (Ed.), 2016. *Détermination de la puissance du générateur de chaleur*.