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# Least-Cost-Path and Closest Facility Analysis for Generating District Heating Networks on a Communal Level

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Keywords: Least-Cost-Path; Closest Facility, District Heating Network; Restructuring of Heat Infrastructure; Replication



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Article

# Least-Cost-Path and Closest Facility Analysis for generating District Heating Networks on a communal level

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**Abstract:** Due to an urgent need for reducing the fast progressing climate changes, a rapid, standardized and replicable solution for the infrastructure restructuring of heat demand coverage of buildings at district and city level must be developed. As more and more communities in Europe, especially in Germany, are obligated to have plans for coverage of heat demand, city planners, energy agencies seek a tool, which will help them to design the first drafts of heating network routes, which can supply whole districts and cities with renewable energy. ArcGIS Pro Tools like Least-Cost-Path-Analysis (LCPA) and Closest Facility (CF) allow to find the shortest and “cheapest” way between the heat source and heat consumers in the analyzed areas. Starting from the community level, through the district, county, voivodeship and whole country levels, the replication of the methods for generating district heating (DH) network infrastructure can be achieved. The proposed LCPA and CF based methods help to design the most suitable and efficient DH networks in the analyzed areas. As only few open-source data input, like street networks and building footprints are needed, the methods can be implemented in all communities of the country of Poland. In this paper one example of one community of Wroclaw county, called Siechnice and surroundings is presented.

**Keywords:** least-cost-path; closest facility; district heating network; restructuring of heat infrastructure; replication

## 1. Introduction

The expected need for far-reaching restructuring of the heat supply infrastructure poses great challenges for many municipalities and system operators. In particular, the question arises as to how the necessary supply infrastructure can be built intelligently. Furthermore, regarding the future-oriented manner with a high level of acceptance, how can it be integrated into the existing urban infrastructure, which has often grown over several generations. In this respect, covering the heat demand through District Heating (DH) networks has proven to be a good and effective solution [1]. The increasing heat consumption of the buildings and the connection of new neighborhoods to the heating network call for heating pipes to be installed in a way that minimizes their costs and preserve landscapes. A municipal heat supply with climate-friendly heating networks that are fed by renewable energies has many advantages: for the neighborhood, the municipality and the private households [2]. District heating is one of the best solutions for the decarbonization of the heat sector in urban areas [3].

The use of innovative system infrastructure enables an intelligent interaction of energy saving, efficiency increase and potential-optimized use of renewable energies. Unfortunately, there is as yet no solution approach for a consistent, systematic analysis of heat supply and demand and their linkage, taking into account the interaction with electricity generation. With reference to this unsolved problem of implementing sustainable heat supply and the current multi-criteria economic operational system problems (rising fuel costs, partly outdated technology, potential supply shortages because of the unstable political situation such as e.g. war in Ukraine, the aim of this study

was to develop a standardized method for the rapid and precise assessment of the potential of heating networks to plan a cost-efficient coverage of the existing heat demand.

Based on the demand for development resulting from the e.g. 2030 Agenda for Sustainable Development (targets: 7, 11, 12 and 13)<sup>1</sup>, the municipalities began to implement new climate protection and energy concepts, the integral element of which was a sustainable heat supply. In this context, Germany even went a bit further, where with the Amendment of Climate Protection Act (KSG BW), the state of Baden-Wuerttemberg gives all municipalities the opportunity to create and update a municipal heating plan. The large districts and cities must submit a heat plan by 31 Dec 2023 [4]. This amendment defines Municipal Heat Planning as a strategic planning process with the goal of climate-neutral heat supply by the year 2050. The preparation of municipal heat plans is part of this process. The central steps for the preparation of such a plan, regulated under § 7c paragraph 2 KSG BW [5] is the development of a scenario for covering the future heat demand with renewable energies to achieve a climate-neutral heat supply. This includes a spatially resolved description of the future supply structure required for this in 2050 with an interim target for 2030. This is achieved by identifying suitable areas for heat networks and individual supply. As the chief of the Climate Protection and Energy Baden-Wuerttemberg says: "Heating networks can provide system services for an integrated and sustainable energy system, which is why they are considered to play a central role in the transformation of the heat transition" [6]. So, due to the fact, Germany has 11.700 communities, which will all be obligated in the next future to have such plans, solving this target would be without having fast and wide applicable, automatic tools quite impossible. Therefore, the work done within this paper occurs to be very necessary and urgent with a view to fast coming radical changes in the energy policy. Also in Poland, the so called studies for spatial development – documents specifying the municipality spatial conditions are available and considers also, like in case of the Wroclaw City, the energy issues<sup>2</sup>, e.g. heating pipes available and potential areas for renewable energy supply.

Although the effectiveness of local heating plans has been proven in many studies, their development for whole municipalities is complex and in operational practice only possible by applying a standardized and tailor-made methodology that has not been available so far. The method proposed in this paper tries to solve this problem by using a "standardized-replicable" method, which means that the same method can be used for different spatial levels. Starting from the community level, through the district, county and voivodeship levels, the generation of heating network infrastructure for the whole country of Poland by using the same replicable method can be achieved. Going one step further, it is also possible to try to replicate this method in other European countries in the future.

Techniques for the routing of power lines or heat pipes have evolved through the years, and today Geographic Information Systems (GIS) approaches allow designers to easily identify the most suitable routes [6]. However, a fast, suitable, practicable and especially standardized method for the generation of the first rough draft of potential district heating networks, in order to make it replicable at different spatial levels, is not yet efficiently developed until now. The methods developed within a German project [7] are mostly based on the ArcGIS route procedure, which is really time-consuming and rather manual. Therefore, there is a need for a more automated and faster but still reliable method, which can sufficiently estimate the length and position of the heating pipes as part of the strategic heating planning and before the execution planning. This should help in the further step to estimate the economic site of the district heating planning, by calculating heat distribution costs as a function of various parameters, such as the connection rate and the availability of local renewable energy sources.

As a response for the above mentioned need, the work done within this paper focuses on the development of a rapid and widely applicable tool for an automated planning process of district heating supply. This goal is to be achieved through the development of an innovative, GIS-based, transdisciplinary methodology for generating district heating networks by using available spatial

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<sup>1</sup> <https://www.un.org.pl/>,

<sup>2</sup> <https://gis.um.wroc.pl/imap/?locale=pl&gui=classic&sessionID=2776588>

analysis functions, like Least-Cost-Path-Analysis (LCPA) and Closest Facility (CF). Both of these tools allow finding the shortest and “cheapest” way between the heat source and heat consumers in the analyzed areas. The LCPA approach has been effectively used for routing of power lines to minimize environmental impacts [8], as well as human and technical related constraints [9]. Other notable applications include analysis of alternative highway routes [11], maritime movement [12, 13] or air traffic [14]. Often, Analytical Hierarchy Process based multicriteria analysis is employed to determine the weights of cost surfaces [11, 15, 16]. Whereas, a description and discussion of the least-cost path modeling concepts and algorithms have been presented in [17, 18, 19].

The methods described in this paper make it possible to generate district heating (DH) routes based on openly available data sources, like street networks and building footprints. The approach considers one important criterion to identify the most suitable route for the potential district heating network, which is the distance between the heat source and each of the heat consumers or the distance between the heat consumer and the closest heat consumer. However, other ones can be added if required. Firstly, LCPA is used to generate a Cost Distance Surface (CDS), which calculates the least accumulative cost distance for each cell from or to the least-cost source over a cost surface [20]. This raster effectively illustrates the cost distance from the heat source for each considered cell within it. Then, using this CDS, a most suitable route based on the street network is generated. The method was tested on one simple example area, and then implemented in one of the communities of Wroclaw county, called Siechnice and surroundings. As a result, a consistent DH network for the mentioned community was generated. As the DH network generated by using LCPA method has one important weak point, another method by using Closest Facility Tool was tested. Hereby, by using an iterative process the shortest route between each of the heat consumers and another closest heat consumer was additionally considered. As a result of this method a more efficient DH network was generated with the possibility of its replication for further communities, counties, voivodeships and finally for the whole country, in the study, Poland. The replication for other European countries is also possible to achieve in the next future, as the method is a very easy one (considers only the distance between heat source and heat consumers) and needs as input open-source data.

Additionally, the method presented in this paper gives a possibility for further optimizations and development within the project funded by the National Science Centre, Poland. The optimization can be based e. g. of the consideration of further criteria by generating the cost surface by using the LCPA method, e.g. slope of the terrain, or land-use value. The optimization of the CF method can be in order to reduce the time of proceeding the model.

## 2. Materials and Methods

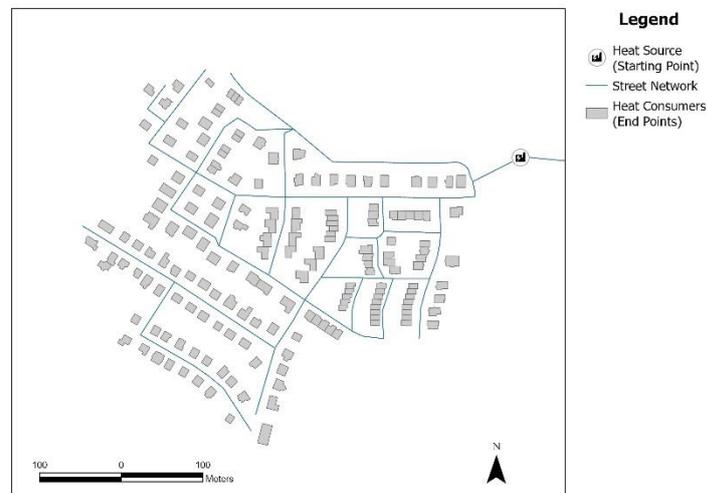
### Materials

Taking into account the target of generating a district heating network in a rapid, automatic and reliable manner, the following general criteria seen in the Table 1 were considered:

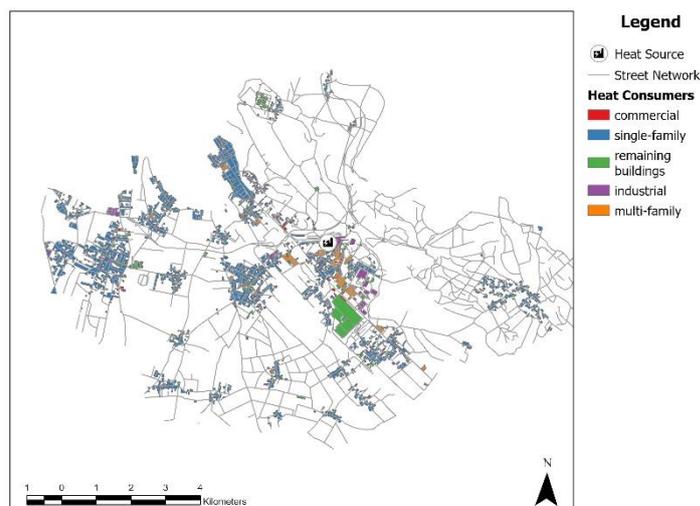
**Table 1.** General criteria considered in the development of the methodology.

Criteria	Test Area + Case study Area
Data Input	Street network
	Building footprints
	Location heat source
Heat flux	Distribution along the reliable street network
	Direction from the starting point (heat source) to the endpoints (buildings as heat consumers)

The data material (building footprints, street network) were taken from the available open-source data<sup>3</sup> for one example test area and a case study area, the community of Siechnice and its surroundings. The location of the heat source was put as a reliable point location. All data shown in Figure 1 and Figure 2 will be used for the development and testing of the methodology.



**Figure 1.** Data material used for the methodology (Test Area).



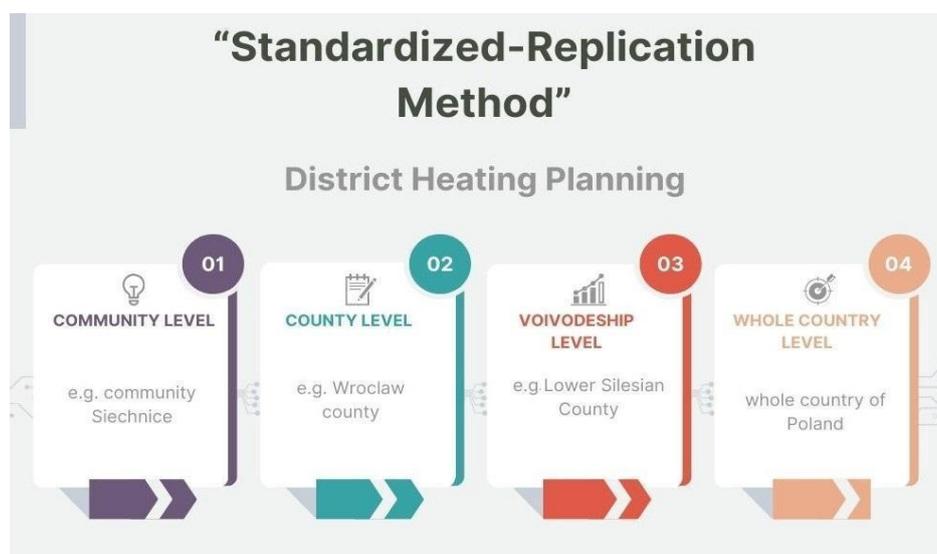
**Figure 2.** Data material used for the methodology (Case study area – Community of Siechnice).

## Methods

In order to achieve the replicability of the proposed method, the following scheme, as seen in Figure 3, was developed. Using this scheme, a progressive replication of the method for generating heating network pipes can be possible to achieve in a very easy manner. Starting from the community level and implementing the method tested on a test area in one community of Siechnice and surroundings, a possibility for its replication for further communities in the Wroclaw county is given. Further on, after the estimation of heating pipes in each community of a Wroclaw County the County level would be covered, and then the same with the replication to the Voivodeship level (all counties of e.g. Lower Silesian Voivodeship will cover the whole mentioned Voivodeship). Finally, having

<sup>3</sup> Geoportal.gov.pl

district heating networks generated for all voivodeships of Poland, the whole country would be covered with the potential district heating networks.



**Figure 3.** Scheme of "standardized-replication" method of District Heating Planning.

#### *Least-Cost-Path Method*

The method uses the Least-Cost-Path-Analysis (LCPA) tool, implemented in the software ArcGIS Pro<sup>4</sup>, to generate the shortest route between the heat source and each of the heat consumers. The methodology uses a two-step approach, which are the streets as the first step and the buildings (heat consumers) as the second one. The method described below, was firstly tested on an example Test Area, in order to implement it in a real case study area (community of Siechnice and surroundings) later on.

**Step 1, considers the streets:** In the first step, a buffer zone of 2 m was generated around the street network of the analyzed test area. Secondly, a polygon of the streets must be transferred into a raster format in order to be able to perform the next steps. In the third step a Cost Distance tool was used, which calculated the least accumulative cost distance for each cell from or to the least-cost source over a cost surface. This raster effectively illustrates the cost distance from the heat source for each considered cell within it.

**Step 2, considers the buildings:** Firstly, a tool Feature to Point was used to generate the centroids of each of the buildings. Next, a tool called Snap was involved using a parameter of distance set as high to make sure that each of the buildings is dropped on the nearest street available.

As a final result, a Cost Path was generated, which represents a targeted district heating network. Here, a tool called Cost Path as Polyline was used in order to do this. The input data for this tool was as follows:

- Raster of feature destination data (Result of Step 2),
- Input Cost Distance (result of Step 1),
- Backlink Raster (from Step 1),
- Path Type (Best Cell), matched to each point representing a building (Version 1)

Since the idea was that the lines are not stratified to each point of the building, but only generally run the network to all endpoints (so that there aren't as many network endpoints as there are buildings), a further step of selecting only the network endpoints was needed (Path line Version 2).

In the final step, again the tool called "Cost Path to Polyline" was used, but this time the layer, which represents only the endpoints (shown in the Figure 6) was used as input. This resulted in a simplified network, which does not consist of such many endpoints as before. The following steps

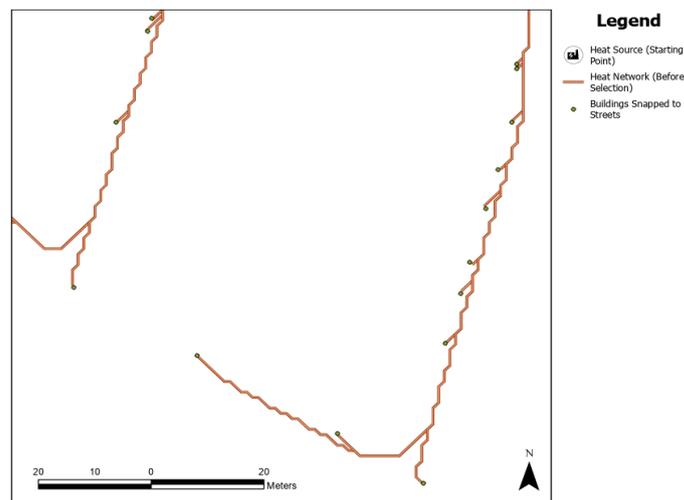
<sup>4</sup> <https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/creating-the-least-cost-path.htm>



### 3. Results

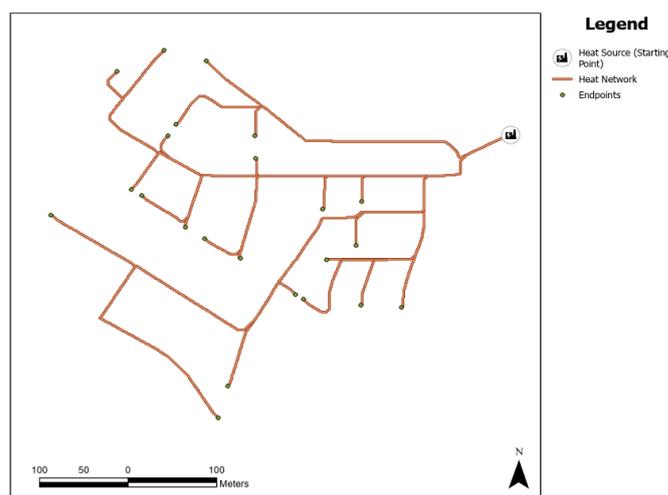
#### 3.1. Least Cost Path Analysis for the Test Area

As mentioned in the chapter methodology, the development of the method for generating heating networks on the basis of street networks happened in a few steps. The first one involved matching the path line to each point (centroid) representing a building. Figure 6 provides a close-up view of a part of the network's branches to reveal its real structure.



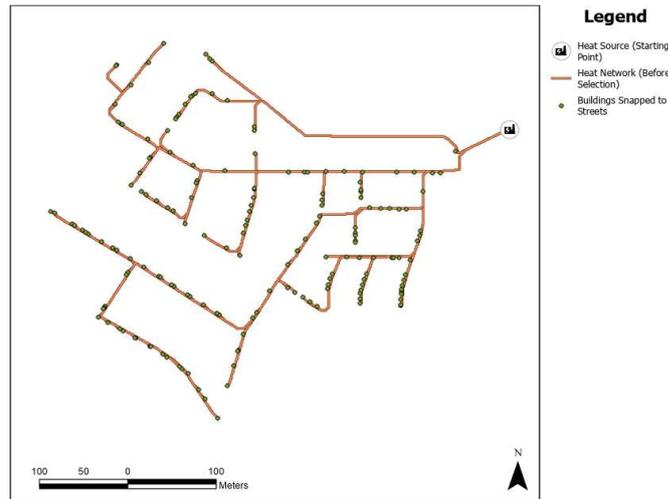
**Figure 6.** Selection of network branches for the test area.

In the next step this path line Version 1 was optimized in order to run the network considering all network endpoints a path line Version 1 was generated. Figure 7 depicts the outcome of the automated analysis steps in the test area.



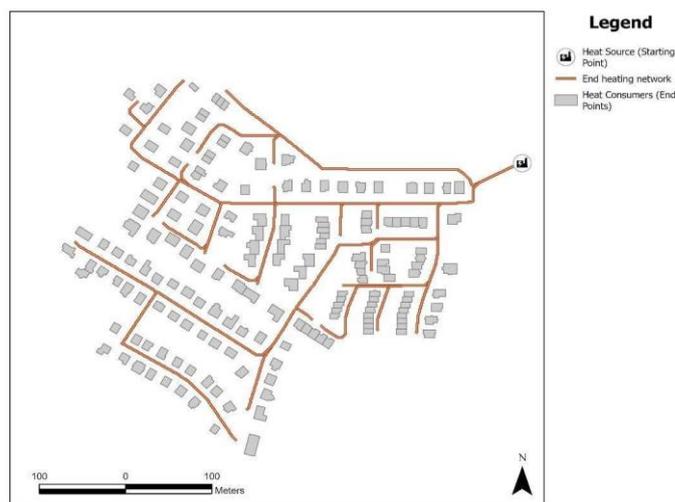
**Figure 7.** Simplified network for the test area: a) Version 1.

In order to prevent branching out to each of the buildings and obtain only a generalized network structure, it was necessary to select the edge buildings for analysis and repeat it. The result is shown in Figure 8.



**Figure 8.** End network for the test area: Version 2.

Figure 9 shows the final result of the proposed LCPA. The result is the generated district heating network for the small analyzed test area.



**Figure 9.** End heating network generated for the Test Area.

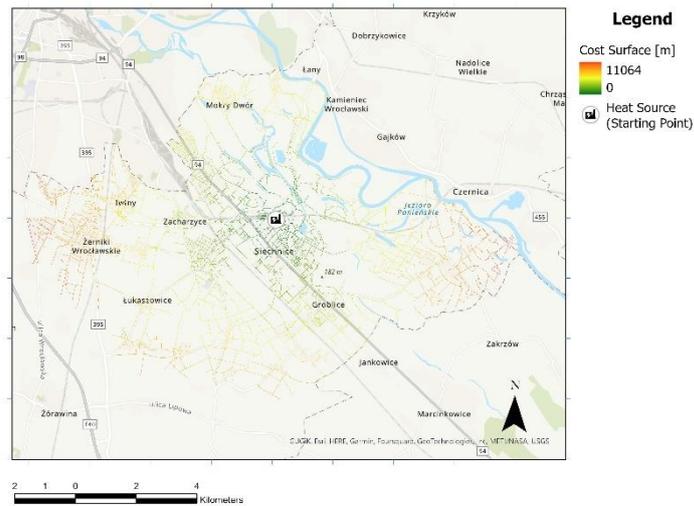
Looking at the heating network generated for the Test Area, we can observe that it was generated appropriately, considering the most important criteria, such as:

- the heating network should be distributed along the real street network route,
- the heating network should follow the path from the Starting Point (heat source) into each of the End Points (heat consumers),
- the heating network should not have closing spaces like e.g. circle or rectangle spaces; it should map out the shape of a tree.

### 3.2.1. Case Study Area – Community of Siechnice and surroundings

#### Cost Distance Surface (CDS)

As mentioned in the previous chapter, the methodology generates in the first step a Cost Distance Surface (CDS), which calculates the least accumulative cost distance for each cell from or to the least-cost source over a cost surface. In Figure 10 a CDS for the Community of Siechnice and surroundings is shown.

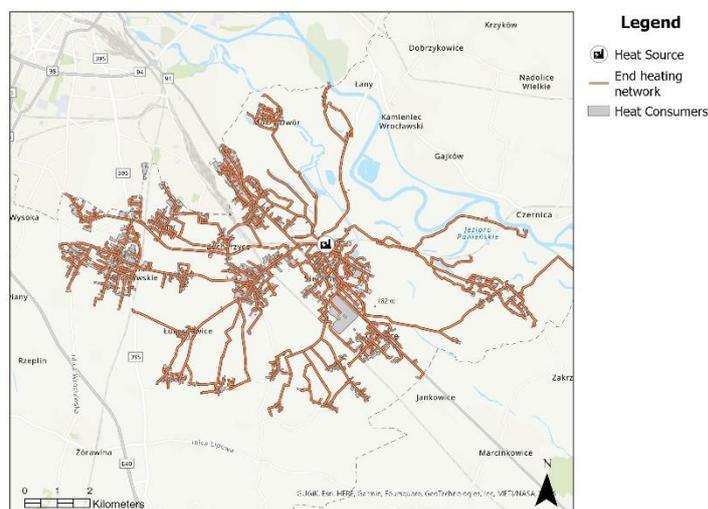


**Figure 10.** Cost Distance Surface (CDS) for the case study area of Siechnice and surroundings.

The raster shown above illustrates effectively the cost distance from the heat source (Starting Point) for each considered cell within it considering only the distance in [m] from the heat source to each cell of the street network.

#### Generated Heating Network

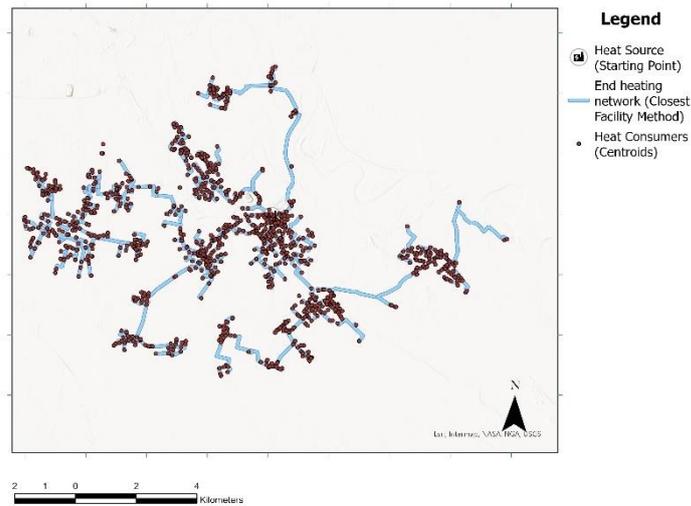
The next steps of generating the heating network on the basis of the CDS are described in detail and visualized using the example of the Test Area in the previous chapters of this paper. For the case study area – the community of Siechnice and surroundings, only the final result, which is the generated district heating network, is shown in Figure 11.



**Figure 11.** End heating network for the case study area, the community Siechnice and surroundings generated using LCPA method.

### 3.2. Closest Facility Analysis

Following the LCPA method, an additional method by using Closest Facility Analysis was developed. The final result coming from this method is shown in Figure 12.

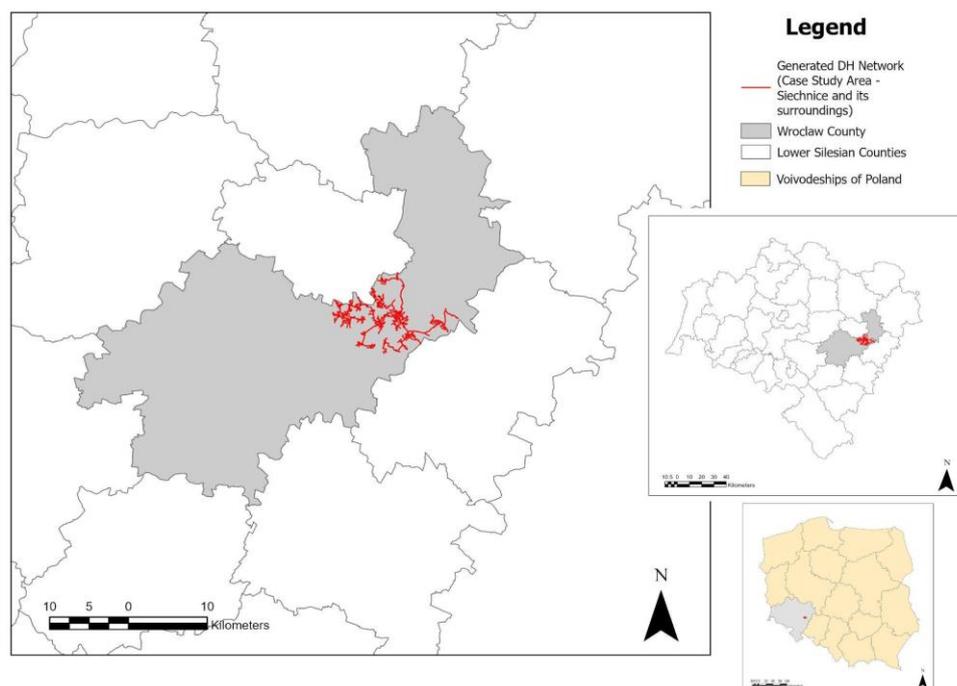


**Figure 12.** End heating network for the case study area, the community Siechnice and surroundings generated using Closest-Facility method.

Analyzing the result of Closest Facility method, shown in the figure above, we can observe a better, more efficient (less heating pipes as in case of Figure 11) DH network generated.

### 3.3. Replication on different communal levels

One of the main important targets of the proposed method is the achievement of its replicability on higher levels than the community level. In Figure 3, the scheme of the replication procedure proposed in this paper, was shown. Following this scheme, the for the case study area (community of Siechnice and surroundings) generated heating network should be implemented in other communities of Wroclaw County. Figure 13 presents the area of the whole Wroclaw County, showing also the generated district heating network for the case study community of Siechnice and surroundings. We can see that the generated heating network for the community of Siechnice and surroundings is only a small part of the whole county. Therefore, the target in the further work would be the implementation of the method in other communities in order to cover the whole Wroclaw county.



**Figure 13.** DH network in the community of Siechnice and surroundings as part of Wrocław County.

Further on, we can see a good potential for replicating the proposed method in further counties of the whole Lower Silesian Voivodeship as well as for the whole country of Poland.

#### 4. Discussion

In order to achieve the EU's ambitious energy efficiency targets<sup>5</sup>, like the reduction of greenhouse gas emissions by at least 55% (compared to 1990) until 2030, more and more countries are and will be obligated to develop appropriate strategies. Six different strategies have been recently proposed by EU energy system in the European Commission's report, Energy Roadmap 2050 [22]. None of these strategies involve large-scale implementation of district heating in order to achieve the 80% reduction in annual greenhouse gas emissions in 2050 [24], even if this occurs to be one of the main effective ways to achieve the EU targets. Expanding district heating help to utilize local renewable resources more effectively, as e.g. the Dutch examples show [23].

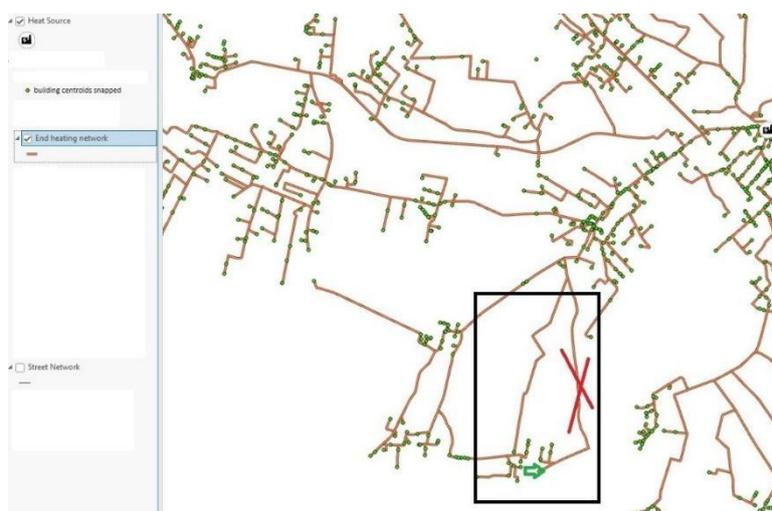
Therefore, some countries, like Denmark, Germany follows this way and introduce regulations, which will help to fasten the process of decarbonization via district heating systems. Germany, as one of the leaders in this topic, obligates all its communities to have heating plans for coverage of heat demand by 2050, like described in the chapter introduction. The strategy and methods to achieve this target is not solved until now, and there is a urgent need for doing this in a rapid and efficient manner. Although the previous works, especially through our German neighbors, shows that the generation of potential heating networks by using GIS methodology is possible and gives reliable results, there is still a great potential for the optimization of these techniques and methods. The investigations carried out within this study indicate that automatization of this process with reliable results is possible in a very easy and fast manner, as the proposed method is based on a very few input data.

The LCPA method tested and presented in this paper, shows very good results in case of small Test Area, generating the end heating network appropriately. Considering only this small example,

<sup>5</sup>[https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive\\_en](https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en)

it could be supposed that this method is good enough to reach the target of this work, which is the generation of potential heating networks in a very automatic manner on different spatial levels.

Going one step further, regarding the implementation of the methodology on higher spatial levels, we can observe on the basis of the example of one community of Wrocław county, which is Siechnice and its surroundings, that this method has one weak point. The weak point, shown in Figure 16, is due to the fact that the method presented in this paper generates some redundant (duplicate) heating pipes routes. This is caused by the fact that the method considers only the distance between heat source and end points (heat consumers) each time the heating pipe is generated.



**Figure 16.** A snap of the weak point of the LCPA method.

One example of the weak point is shown in Figure 16 in the black box, where two heating pipes were generated even if only one would be enough to connect all heat consumers placed in this area.

This weak point results finally in high cost when it comes to the realization of the potential heating network. Each time the heating pipe is generated it takes into consideration the distance between the heat source and the end point of the heat consumers, and not the shortest distance between the target not connected end point and the end point almost connected in case there is a street network available. This can be, however, easily addressed by adding another step in the algorithm, i.e. one that selects the shorter route between each considered pair of locations. In addition, the proposed method is scalable as other than distance costs can be added to generate the cost surface, namely slope of the terrain, land use, etc.

Summarizing, the LCPA based heating pipe routing method proposed in this paper, uses simple and nevertheless efficient and easily automated way to generate heating networks on the basis of very few input data, as they are the building footprints and the street network, which are available open-source for all communities in the European Union under the Inspire Directive [25]. In addition, volunteered geographic information (VGI) data sources such as the Open Street Map in case public data are not openly available.

Furthermore, this method is very fast, and therefore suitable for using it for the first general estimation of potential DH networks on different even higher (like, the whole voivodeship) levels.

In case, a more accurate and economically efficient generation of DH networks is needed, a better method was developed, which generates only as many heating pipes as needed. This method is based on an iterative process implemented in a Model Builder of ArcGIS Pro environment by using Closest Facility Tool. The only weak point of this method is that the iterative process causes high time-consuming performance of the model running.

Further future developments of this work will be focused on:

- 1) Analysis of open-source heat demand or even available heat consumption data of each of the heat consumers integrated in the DH network due to dimension of the generated heat pipelines of the DH networks.
- 2) Development of an additional option to generate the house connections between the main heat pipes and the heat consumers.
- 3) Enhancement of the model to perform the first cost-effective analysis on the basis of line density and effective width for district heating (example procedure in [21])  
Implementation of the model to fully automatically generate the potential DH networks at different spatial levels.

## 5. Conclusions

In this paper, a workflow for automatized and fast generation of DH networks on the basis of very few input data is proposed. The methodology considers reliable street networks and building footprints in order to draw potential heating networks in analyzed areas. The methodology was first verified on a very small test area, which enabled the proof that the model works appropriately. Then, the model was implemented in case study area of the Wroclaw County, the Siechnice commune and surroundings to assess if the implementation procedure on a wider scale than a small community is possible due to the target of achieving the replicability of this method on higher administrative division levels. A further and wider target is to transfer this methodology in other countries in Europe, especially in Germany, where an urgent need for such applications occurred due to achieving climate-neutrality regarding the heat supply.

The findings of this study can be summarized in the following points:

- A fast and accurate method on the basis of very few open-source data input is possible
- The DH networks generated are reliable, as they are based on real street networks
- The draw of the first potential DH networks on a smaller spatial levels is very appropriate: in case of higher spatial levels occurs a weak point due to the fact that some redundant (duplicate) heating pipes routes are generated.
- A solution to go around this weak point was found even if this method takes more time to run the model generating the DH networks.

Even if both methods have some restrictions they can both be used and implemented in the Municipal Heat Planning.

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