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Development of a Methodology for Heating Network Planning to be Considered in Electricity Network Planning

A Cross-Sectoral Approach for Greenfield Planning

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Abstract. The transformation of heating supply is critical to achieve climate neutrality by 2045. In 2024, new regulations specify climate-neutral heating solutions for new quarters. Heating networks are a viable option for meeting these requirements. This contribution presents an automated methodology for heating network planning in new quarters. The entire process is completed within a few seconds to minutes per optimization level, enabling an iterative approach between heating network planning and energy-based optimization. This method can be applied to both small and large quarters and provides essential data for electricity network planning, particularly regarding economic efficiency and the number of consumers served by alternative decentralized solutions.

Keywords: Cross-Sectoral Planning, Heating Networks, Greenfield Planning

1. Introduction

The transformation of heating supply is essential to achieve climate neutrality by 2045. Heating buildings and providing hot water have the greatest share of ultimate energy demand in Germany [1]. Since 2024, new requirements for a climate-neutral heating supply must be met for new quarters. These were set out in the Building Energy Act [2]. Heating networks are one possible option for meeting these requirements. An overview of the current use of heating networks is given in [3]. There, it is described how the successful future use of heating networks requires cross-sectoral planning of electricity, heating and gas networks. Without this planning approach, synergies between electricity, heating and gas networks are not used. Cross sectoral planning of electricity, heating and gas networks in quarters has already been examined in various examples. In [4], a planning approach of electricity and gas networks is discussed. An algorithm for the optimal positioning and dimensioning of power-to-gas plants to reduce the need for expansion in electricity and gas networks is presented as well. There are also algorithms that enable the optimal dimension of electricity, heating and gas networks by minimizing operating and investment costs [5]. It shows that there are already many approaches to cross-sectoral planning of electricity, heating and gas networks. Nevertheless, the coordination of these networks is often not considered in new quarters. In new quarters, cross sectoral planning of electricity and heating networks is particularly important. This is due to the fact that natural gas is increasingly being replaced by heating pumps and heating networks [1]. For these reasons, a methodology for automated planning of heating networks in new quarters is presented in this contribution. It also explains how the results obtained are used for electricity planning.

2. Methodology

The methodology for planning heating networks is a part of a cross-sectoral approach for greenfield planning. Hence, even though the planning of heating and electricity networks occurs sequentially in the underlying methodology, parallels in the individual methods and direct dependencies of the results exist, which can also be further expanded to an approach for simultaneous cross-sector planning. For example, the same complete knot-edge-model is used for planning heating and electricity networks. The complete knot-edge-model contains all potential connection lines for each connection area and network service areas or on the street structure. Examples of connection areas are buildings or parking lots. Network service areas are useful for positioning heating sources for the heating network on them. In the cross-sectoral approach, planning of heating network is completed first, on which the electricity network planning is based. Because each connection area requires a connection to electricity network, e.g., for household loads, the share of the quarters heating supply that is supplied via heating or electricity networks is analyzed. The methodology of the entire cross-sectoral planning process is shown in Figure 1.

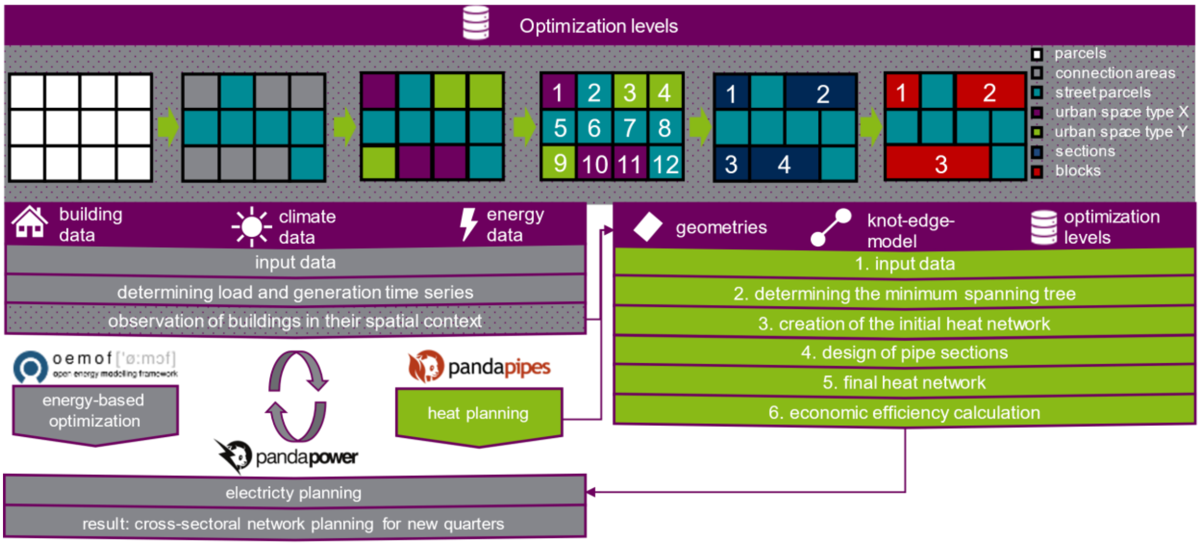

Figure 1. *Schematic representation of the methodological approach to cross-sectoral planning*

This method enables a bottom-up-approach up to entire quarter level. The iterative approach between an energy-based optimization and the heating network planning is used to check whether a centralized or decentralized heating concept is preferred. In doing so, the energy-based optimization determines which technology and which network – heating or electricity network – should be used for the heating supply. Subsequently, the heating network is planned in order to precisely determine the costs of a possible central heating concept and to incorporate these results back into the energy-based optimization. In this way, the decision on whether a centralized heating concept (i.e., planning of both a heating and electricity network) or a decentralized heating concept (i.e., planning of an electricity network only) is suitable can also be supported for specific spatially related sub-areas of the new quarters. The green boxes in Figure 1 are described in more detail in this contribution.

2.1 Input Data

The first step is to determine the heating requirements of the new quarter. For this purpose, load time series for building heating and providing hot water of the connection areas created on the basis of detailed input data of buildings, climate and energy (see Figure 1). The potential for heating sources in the network service areas is determined as well. This method is described in [6]. In the following step, buildings are considered in their spatial context, using the method presented in [7] by analyzing urban space types. This method is shown in Figure 1 with the gray-purple dotted background. The aim of this step is to identify optimization levels consisting of spatially related connection areas (section, block, quarter) for which a supply via a heating network is being considered. At each optimization level, it is checked whether, in addition to the connection areas, there are also network service areas for the installation of heating sources in the considered area. This analysis determines whether a district or local heating network is possible. District heating networks, as defined in this contribution, enable the supply of large areas over long distances, for example using combined heat and power, plants and are integrated into the quarter via a peripheral point. Local, heating networks supply buildings with heating from a heating source on a network service area within the quarter. The difference between the individual optimization levels is shown in Figure 2.

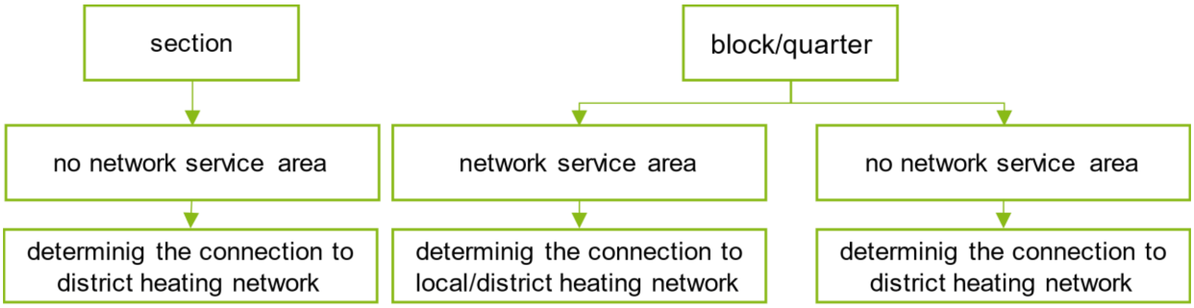

Figure 2. *Illustration of how a decision made whether a local or district heating network is planned depending on the optimization level*

It shows that a network service area must be available within the new quarter, when a local heating network is planned. If a network service area is available in the new quarter, the heating source can be integrated directly on site. However, if there is no network service area in the quarter, a connection is only possible via a peripheral point, which requires the expansion of an existing district heating network. It is clear that a local heating network cannot be planned at the optimization level of a section. Within a section, a network service area and a connection area (e.g. building) never overlap. The case distinction for the local and district heating connection is shown in Figure 3 using the optimization level of a block for an exemplary new quarter.

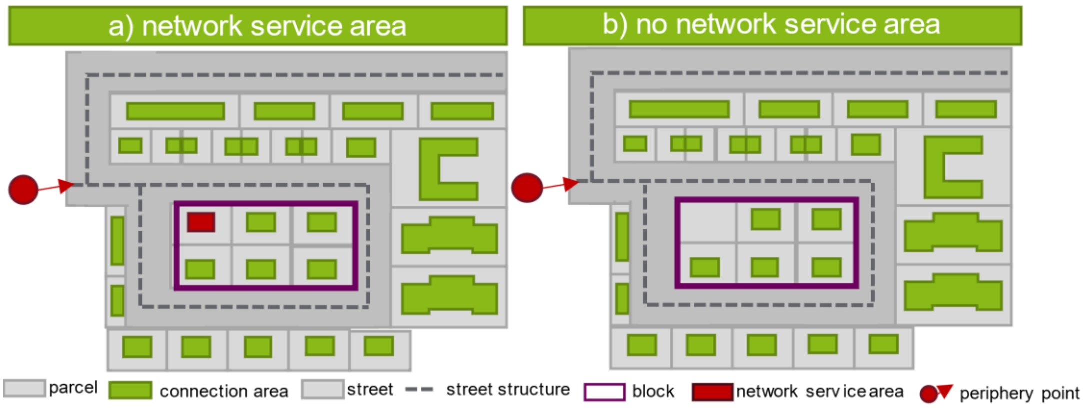

Figure 3. *Possible cases at block for determining the local a district heating connection*

The connection areas are marked in green. The block in view/consideration is marked in purple. The peripheral point that serves as the connection point to an existing district heating network is shown as a red point with an arrow. A network-relevant area within the block is also marked in red. In the following Figures, case a) demonstrates the procedure when a network service area exists within the block, while case b) illustrates the approach when no network service area is within the block.

Figure 4 shows the relevant parts of the complete knot-edge-model in the quarter. For a local and a district heating network, considering the following cases: a) with a defined network service area and b) without a defined network service area. The potential connection lines in the block are shown in red. The connection areas to be supplied are shown in purple. Street points for determining a minimum spanning tree (MST) are also shown in red, while those that are irrelevant for the connection for the areas to be supplied are gray. Connection lines and connections points that are irrelevant are marked green.

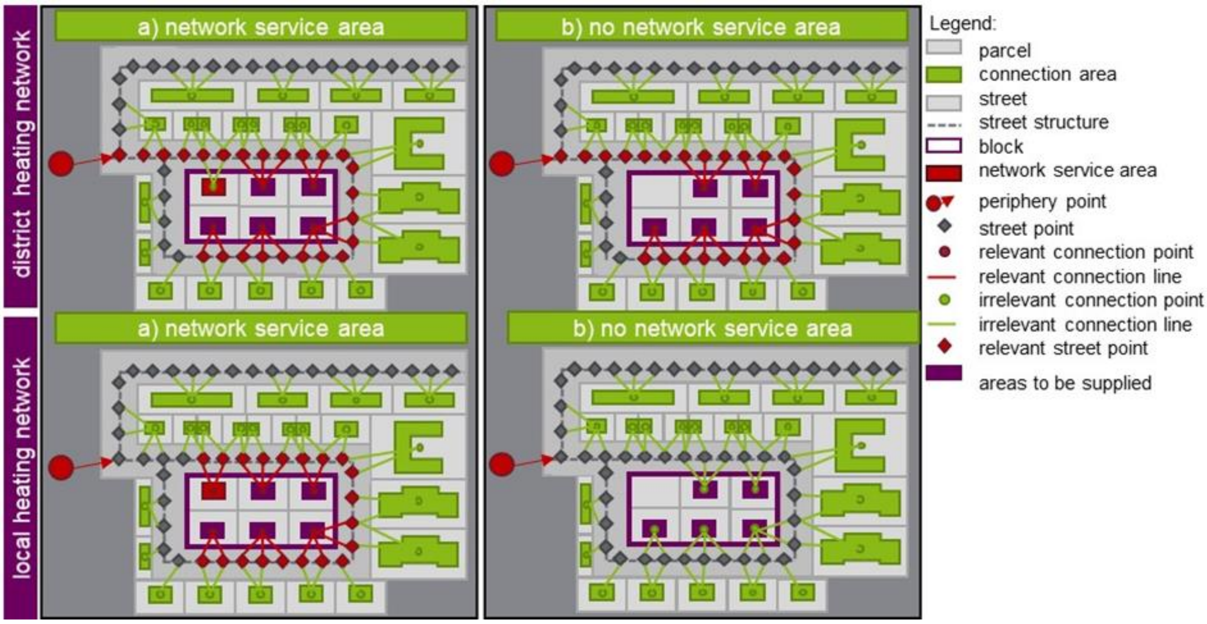

Figure 4. *Visualization of the complete knot-edge-model for district and local heating networks on block level*

2.2 Determining the Minimum Spanning Tree

In the second step of the heating network planning, the MST is determined following a further developed variant of the Steiner Tree algorithm based on [8] in order to define the optimal trench structure for the relevant connection areas. This takes into account whether a network service area is available in order to adapt the structure. In determining the MST, the optimal trench structure is derived for the connection areas to be considered at the optimization level and depending on whether a network service area is available. This calculates the optimal MST to connect all potential connection points of an optimization layer in the street structure. The connection areas of the buildings are then connected to the MST via the optimal path. In doing so, redundant and longer connections are gradually removed. This ensures that the trench structure for each optimization level is optimal in terms of length based on the complete knot-edge-model. This method is shown in Figure 5. The MST (red) connects all the connection areas to be supplied with a minimal overall length and forms the basic structure of the initial heating network.

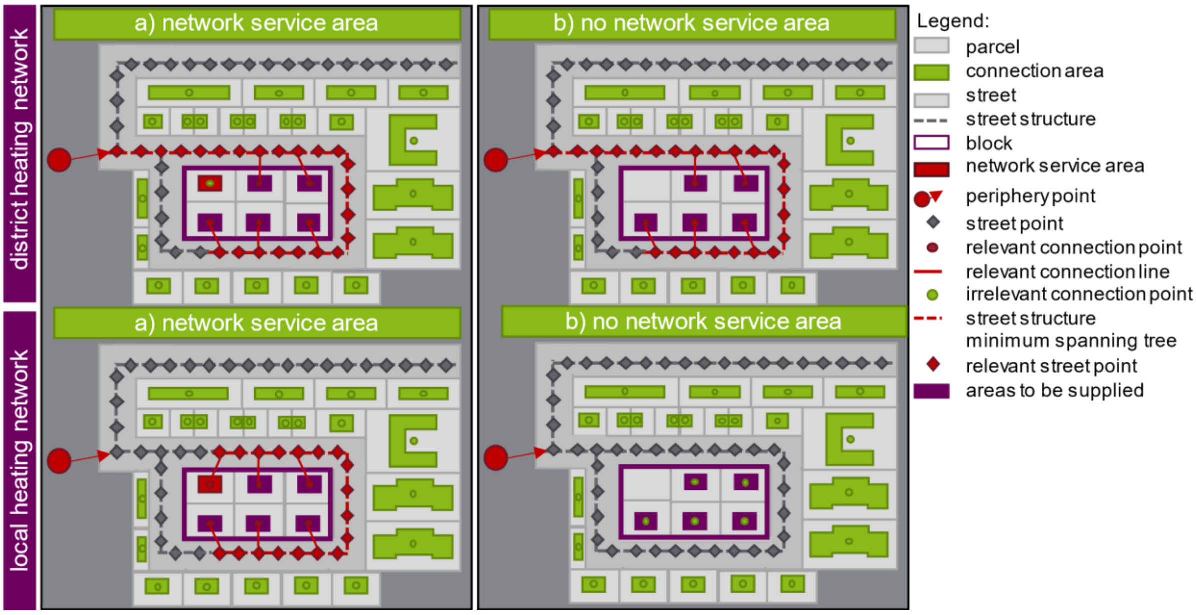

Figure 5. *Visualization of the minimum spanning tree for district and local heating networks on block level*

2.3 Creation of the Initial Heating Network

Next, the initial heating network is created requiring the selection of a suitable software for the planning of the heating networks. There a numerous established software products such as STANET [9] that are specialized in the calculation of heating and electricity networks. However, such examples are not publicly available. Publicly available tools such as DHNX [10] and pandapipes [11] also offer comprehensive functions for heating network planning. In this contribution, pandapipes is chosen. It can be linked to pandapower [12], which is already used for electricity network planning, thus supporting cross-sectoral planning. In pandapipes, the initial heating network is created based on the structure of the optimal MST. The initial heating networks are shown in Figure 6.

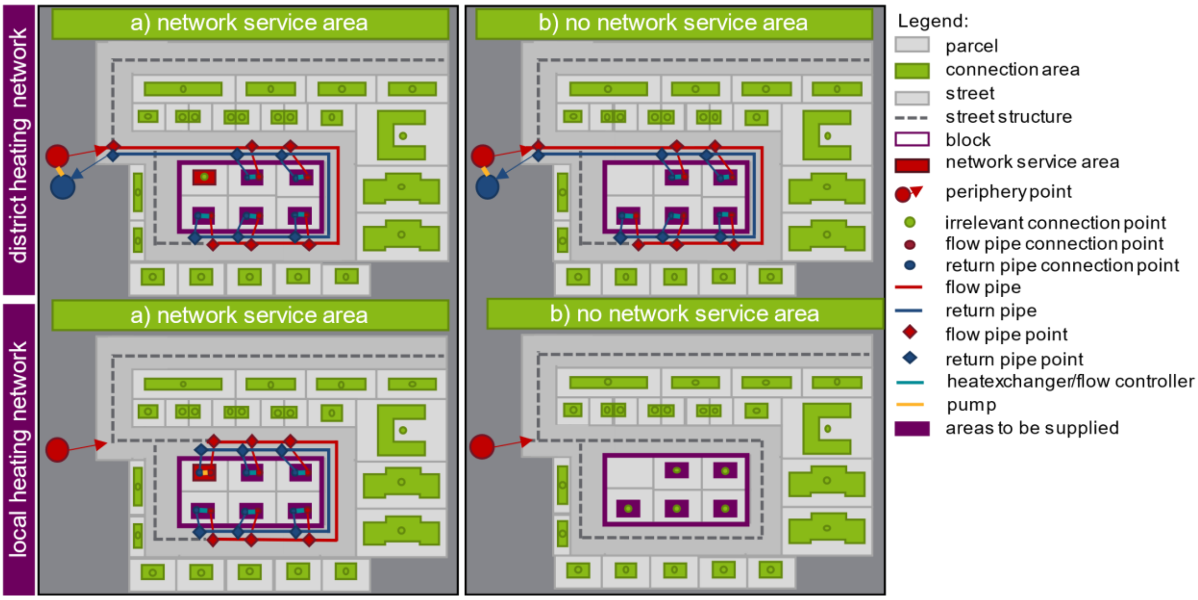

Figure 6. *Visualization of the initial heating networks for district and local heating networks on block level*

This includes flow pipes (red) and return pipes (blue), heating exchangers (turquoise), mass flow controllers (turquoise) and a central circulation pump (orange), which here represents the heating source. A flow and a corresponding return are created for the nodes and edges of the MST. The return is slightly offset from the flow. This is necessary in order to place the heat exchanger and the flow controllers between the flow and return pipes.

2.4 Design of Pipe Sections and Final Heating network

In the step "design of pipe sections", the pipe segments for the flow and return pipes are dimensioned. The maximum flow velocity and the specific pressure loss are used as criteria for the design of the individual pipe sections. The algorithm used for this is shown in Figure 7 and is based on predefined input parameters such as the material to be used and the pipe insulation. These parameters limit the selection of available standard types. For example, plastic jacket pipes are available in nominal diameters (DN) from 20 up to 600. The process of defining these input parameters is highlighted in purple, while the process of dimensioning each individual pipe is shown in green. In the first step, all pipes of the initial heating network are initially sized to the smallest possible DN. Each pipe is then checked individually, with the current average flow velocity and the specific pressure loss of the respective pipe being analyzed. If the average flow velocity exceeds the specified maximum value or if the specific pressure loss is above the maximum permissible value, the pipe must be adjusted accordingly. If an adjustment is required, the steps shown in turquoise are taken. If the average flow velocity or the specific pressure loss is too high, the standard type is adjusted to the next larger available dimension. If, on the other hand, the flow velocity and the pressure loss are below the maximum permissible values, it is checked whether a smaller DN is possible. This procedure is repeated for each pipe until no further adjustments are necessary.

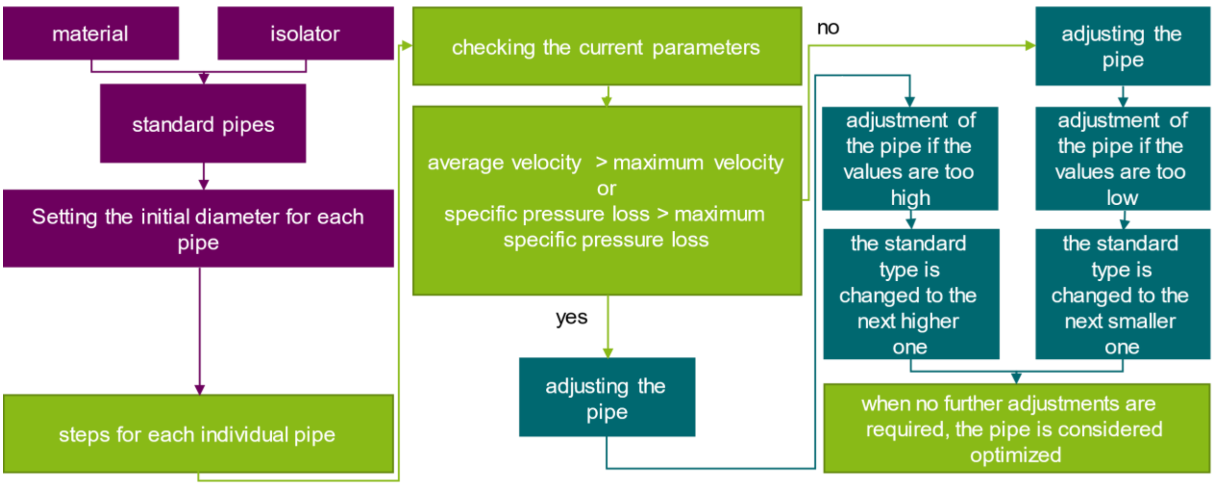

Figure 7. *Schematic overview of the algorithm for designing the pipes*

After the entire initial heating network has passed through this algorithm, the result is the final heating network.

2.5 Economic Efficiency Calculation

After the design of the heating network, a profitability calculation is carried out to determine the maximum costs for a decentralized heating supply based on an electricity network. For this profitability calculation, the following costs for pipes and trenches for plastic jacket pipes are used [13]. The costs for greenfield is used. All costs are shown in Table 1. For pipes with a DN of exactly 250, the total costs for DN 250 are applied directly. A linear approximation is used for DN, such as DN 175 and DN 225, because no explicit values are listed. This approximation is also used for all pipes that exceed a DN of 250.

Table 1. *Specific costs for piping, trench and plastic jacket pipes with insulation class Series 2 for underground installation [13]*

Nominal diameter in mm	Pipe costs in €/m	Trench costs (greenfield) in €/m	Total costs in €/m
20	226	83	308
25	231	83	313
32	257	83	340
40	272	83	355
50	293	107	400
65	335	107	442
80	376	124	500
100	504	140	645
125	640	157	798
150	791	165	956
200	960	182	1,141
250	1,363	207	1,569

3. Results

In the following, the explained methodology is applied to two quarters. For these new quarters, the investment costs are analyzed. In addition, the calculating time required for the design of the heating networks is examined. Finally, the various heating networks of the individual optimization levels are evaluated.

3.1 Exemplary Quarter 1

Initially, the proposed methodology is applied to a new quarter in Berlin, Germany, consisting of 14 buildings, 12 of which are apartment buildings. One building is a mixed-use building that contains both residential and non-residential areas. In addition, there is a building that represents a purely non-residential building. For this quarter the six steps of heating network planning are examined. However, since there are no network service areas and also no potential peripheral point to an existing district heating network, it is assumed that a fixed connection area serves as a heating source. The structure of the quarter is shown in Figure 8. At the lowest level (basis a) and b)) in Figure 8, the buildings to be supplied are shown in light gray and a connection area used as heating source is shown in red.

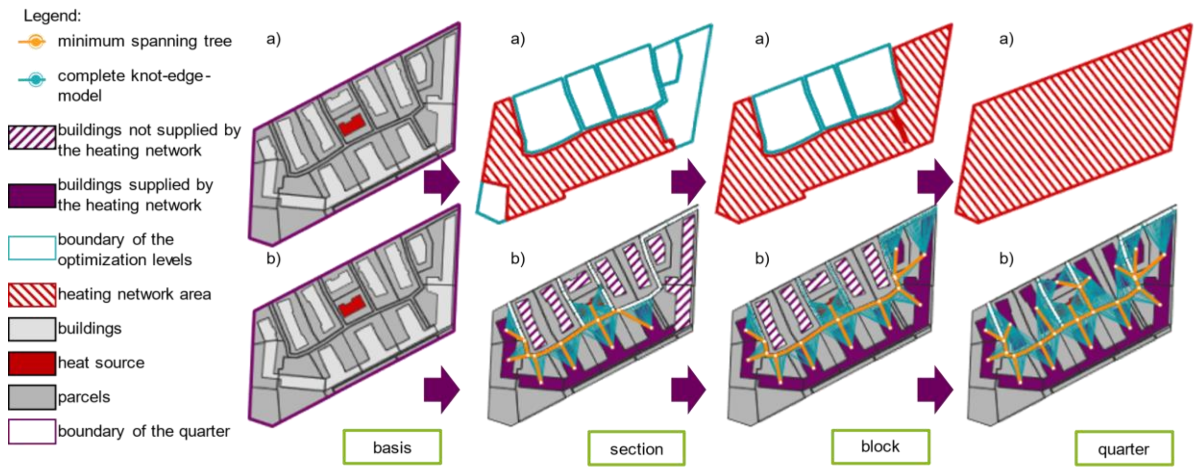

Figure 8. *Visualization of the optimization levels, the optimal trench structures and the complete knot-edge-model for a new exemplary quarter in Berlin*

The subdivision of the quarter into the different optimization levels is also shown in Figure 8. See the figures marked with an a). For the investigation of the different possible heating networks, three optimization levels are considered: the section level, the block level and the quarter level. A heating network is planned as an example at each of these optimization levels for the areas hatched in red. The course of the heating networks to be planned is shown in the Figure 8 with an b). The buildings supplied by a heating network are shown in purple. The complete knot-edge-model is shown with turquoise lines, while the MST determined on the basis of the complete knot-edge-model is shown with orange lines. It can be seen that the connection areas to be supplied are connected to each other via the shortest route.

Figure 9 shows the results of the automated pipe dimensioning for the three optimization levels. On average, pipes with a diameter of 0.063 m are used in the section, pipes with a diameter of 0.067 m in the block, and pipes with a diameter of 0.067 m in the quarter. The length of the heating network is 0.64 km for the section, 1.04 km for the block and 1.33 km for the quarter. The automated planning of the heating network takes 10.65 seconds for the section. 12.06 seconds for the block and 15.42 seconds for the entire quarter.

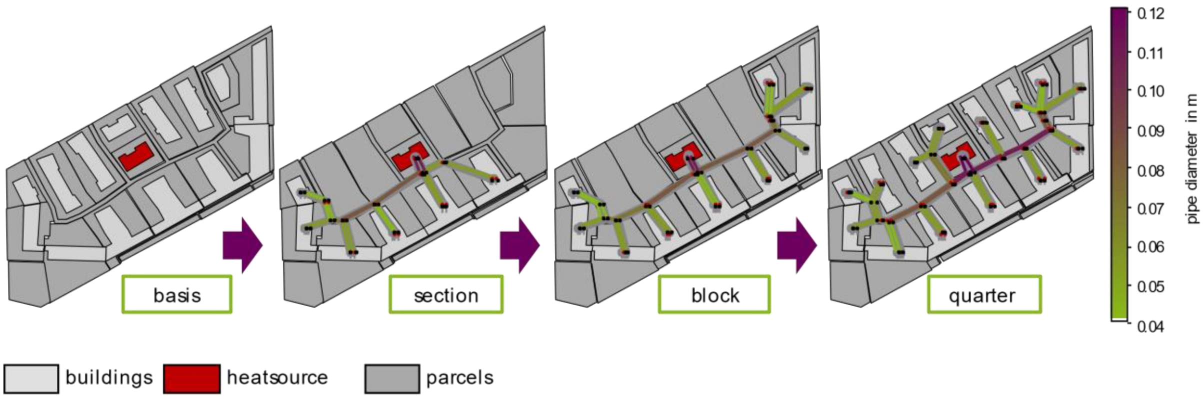

***Figure 9**. Determined pipe diameters fir the various optimization levels*

In addition, the investment costs for the pump, for the pipes including excavating a trench and house connections, i.e. the investment costs for the heating exchangers within the individual buildings, are calculated automatically. The investment costs for these components of the heating network are shown in Figure 10. The total investment costs for the heating network of the section, block and quarter are approximately 0.6 million €, 1.0 million € and 1.4 million € respectively. At all optimization levels, the investment costs for the pipes and trenches account for the largest share of the total investment costs. For a holistic view, investments costs for the heating source and operating costs must also be taken into account.

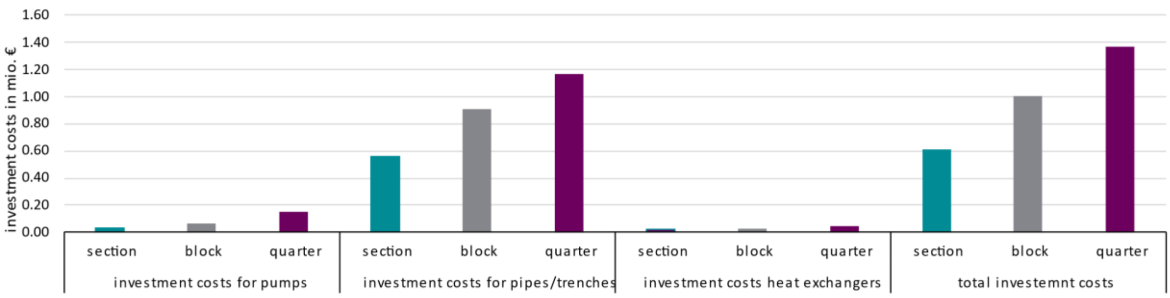

***Figure 10.** Investment costs of the heating networks for the optimization levels*

The results of the design of the heating network are integrated into an energy-based optimization. On this basis, a decision can be made as to whether a centralized or decentralized heating supply is more advantageous.

3.2 Exemplary Quarter 2

The second quarter is located in Hanau, Germany. It differs from the quarter in Berlin in particular in the number of buildings and the size of the quarter. A total of 469 residential buildings and 20 non-residential buildings in this quarter require heating. The residential buildings consist of 112 single-family houses, 270 terraced houses and 87 multi-family houses. The methodology described in Chapter 2 is applied to the analysis of this quarter, taking into account network services areas and a peripheral point. The structure of the quarter is shown in Figure 11. At the lowest level (basis), the buildings to be supplied are shown in gray. The subdivision of the quarter into the different optimization levels can also be seen in Figure 11. The optimization level of the section covers 106 sections, the block level covers 31 blocks and the quarter level covers the entire quarter. In total, there are 13 network service areas in the quarter, which are shown in red. For consideration and design of the district heating networks, the quarter can be connected to an existing district heating network in the south via a peripheral point (red point with arrow).

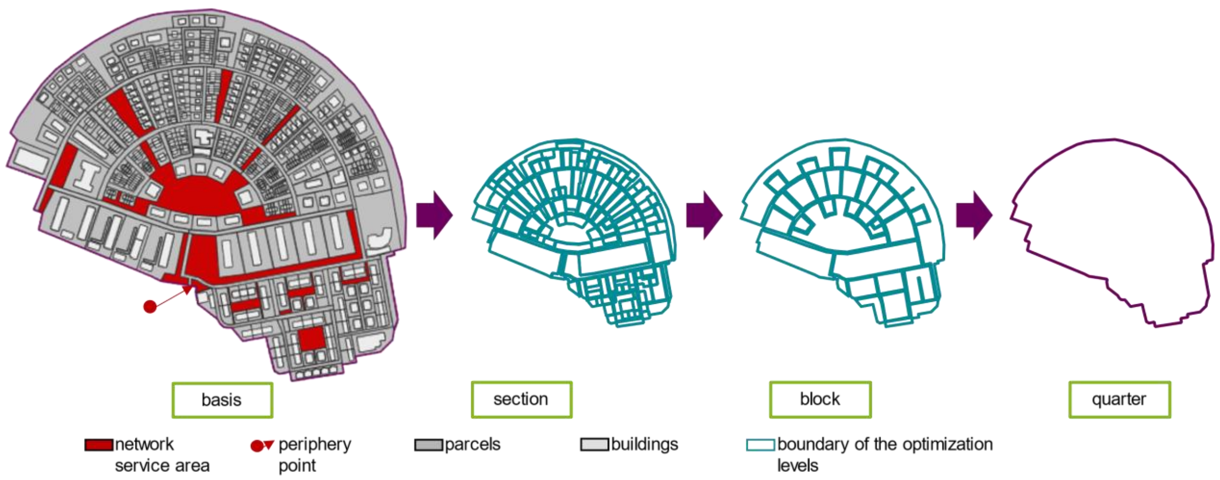

Figure 11. *Visualization of the optimization levels for a new exemplary quarter in Hanau*

Table 2 shows how many heating networks are included in the network planning depending on the optimization level and the type of heating networks (district heating/local heating). In addition, the ranges of the heating network lengths and the average pipe diameters are given. A total of 150 heating networks are planned. Of these, 137 heating networks are connected to a district heating network and 13 local heating networks have a network service area within the block.

***Table 2**. Planning of heating networks by optimization level and network type with information on network lengths and average pipe diameters*

Level of optimization (type of heating network)	Number of local heating networks	Range of heating network length in km	Range of average pipe diameter in m
section (district heating network)	105	0.32-2.19	0.02-0.05
block (district heating network)	13	0.22-8.42	0.02-0.05
block (local heating network)	31	0.078-3.83	0.02-0.05
quarter (district heating network)	1	28.01	0.06

Figure 12 shows the required computing times in minutes distinguishing between the time for determining the MST (in green), the time to design the final heating networks (in purple) and the total time (in turquoise). It can be seen that all six steps of the heating network planning take approximately 9 minutes for the optimization level section, approximately 11 minutes for the optimization level block and approximately 5 minutes for the optimization level of the full quarter. The pure determination of all MST takes approximately 5 minutes and the design of the heating network need approximately 5 minutes as well, at the optimization level section. At the optimization level block the determination of all MST takes approximately 7 minutes and the design of the heating network needs approximately 4 minutes. The determination of the MST requires under one minute for optimization level quarter and the design of the heating network requires about 5 minutes. Per section, approximately 3 seconds both to determine the MST and to plan the heating network. Per block, 9.84 seconds are required to determine the MST and 5.20 seconds to plan the heating network. The calculation of all optimization levels and their heating networks took about 25 minutes.

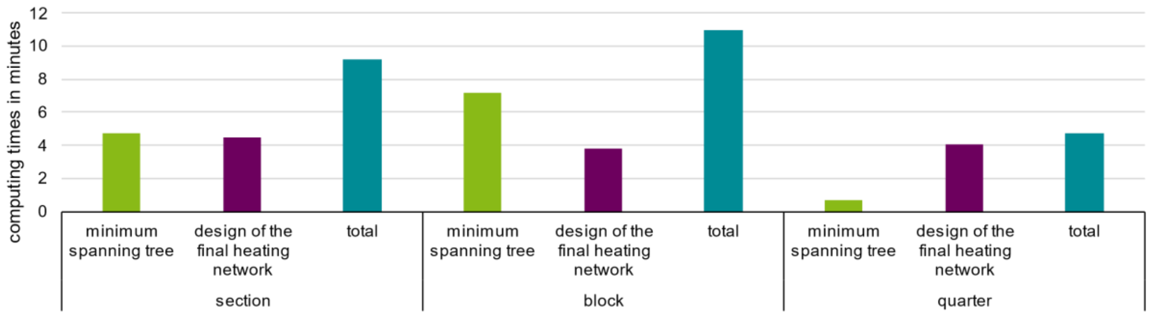

Figure 12. *Computing times for determining the minimum spanning trees and designing the heating networks*

Table 3 shows the ranges of investment costs according to the level of optimization and network type (district heating network or local heating network). It can be seen that some sections and blocks are identical, resulting in identical investment costs for the lower limit end of the range. It also shows that the investment costs increase significantly per heating network, when larger pipe dimensions have to be used to integrate more consumers via a central supply. The heating network costs at the various optimization levels range from around 63,000 € to over ten million €.

Table 3*. Planning of heating networks by optimization level and network type with information on network lengths and average pipe diameters*

Level of optimization (type of heating network)	**Range of investment costs for the pump in €**	**Range of pipe and trench investment costs in €**	**Range of heat exchanger investment costs in €**	**Range of total investment costs in €**
section (district heating network)	422-2,114	59,045-635,741	3,155-53,635	62,622 674,188
block(district heating network)	422-20,007	59,045-2,951,393	3,155-296,570	62,622-3,267,970
block(local heating network)	422-3,682	20,809-978,231	3,155-119,890	24,386-1,101,802
quarter(district heating network)	463,923	8,799,452	1,508,090	10,771,465

Similarly, to the exemplary quarter 1 the costs of the pipes and trench represent the largest share of the total investment costs. For example, for the optimization level of the full quarter, more than 75 % of the total investment costs of the heating network are attributable to the costs for pipes and trench.

4. Conclusion

In this contribution a methodology for automatically planning heating networks in context of an overarching cross-sector energy network planning approach has been presented. The heating network planning comprises six steps: 1. use of input data, 2. determination of the MST, 3. determination of the initial heating network, 4. automated design of the individual pipe sections of the heating network, 5. determination of the final heating network, 6. economic analysis of the final heating network. Some of these steps are also used for the planning of electricity networks. This enables cross-sector energy network planning. The entire heating network planning can be carried out within approximately five seconds to five minutes for one optimization level, enabling an iterative process between heating network planning and energy-based optimization. It has been demonstrated that the heating network planning presented here can be applied not only to small quarter but also to larger ones. The results of the heating network planning provide essential foundations for the electricity network planning, especially with regard to economic efficiency and the number of consumers to be supplied by alternative decentralized solutions. The pipe diameters are commonly by design of the methodology changed after each pipe section, so a limitation of the pipe diameters should be investigated in future work. In addition, the influence of different heating sources and their positioning should be investigated.

Data availability statement

The results presented in this contribution based on quantitative data such as publicly accessible geodata that was obtained during the practical implementation of the NeuPlan research project. The authors are available to provide further information and to answer any questions regarding the content of this data.

Underlying and related material

While this contribution is standalone, readers who want to gain a deeper understanding of the NeuPlan research project (funding number: 64.65.22.25-00007) are invited to read additional contributions. These resources explore various aspects of the project and provide a comprehensive overview of the research and results.

Author contributions

The primary author was responsible for the conceptualization, investigation, methodology, visualization, as well as the writing of the original draft and subsequent review and editing of the manuscript. The second and third author provided support for these activities. The fourth author was particularly involved in the acquisition of funding and as a scientific contact.

Competing interests

The authors declare that they have no competing interests.

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