Use of urban space types for the planning of cross-sectoral energy infrastructures

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Abstract: Various quarter approaches are repeatedly presented that enable the planning of energy infrastructures, but inhomogeneous building structures within a quarter are not considered in detail. Therefore, an automated method is presented in this paper that uses urban space types to automatically subdivide a quarter into different levels of consideration. This approach makes it possible to assess whether certain types of urban areas have greater potential for a "centralized" heat supply concept than others. This method can be used, for example, to analyze different technologies for heat supply in terms of technical and economic framework conditions within a specific urban space type.

Keywords: quarter approach, cross-sectoral planning, urban space types

1 Introduction

In order to solve the current problems of the German energy transition and achieve the greenhouse gas reduction targets by the year 2045, the transformation of the electricity, gas and heating sectors is an important starting point. To this end, a quarter approach is repeatedly taken up in various studies [1-3] and is taken into account in particular by political initiatives such as municipal heat planning [4-5] or in the amendment of the German “Gebäudeenergiegesetz” [6]. However, most studies only differentiate between building types such as “multi-family house” or “single-family house” [2]. In addition, only the cases "holistically centralized" or "holistically decentralized" are considered for the construction of the energy infrastructure of the entire quarter or no specific procedure is provided on how to design a corresponding analysis for a given quarter [1-3]. Various approaches based on the analysis of grid cells or urban districts using geographic information systems have also been presented in the literature. However, these analysis approaches do not take into account the inhomogeneity in terms of building typology or the consideration of different energy infrastructures within the grid cells or city districts [7].

This article therefore presents a method that groups buildings in a quarter on the basis of urban space types (UST). In addition, the linear heat density is used to estimate whether an UST has greater potential for a centralized or decentralized heat supply concept.

2 Methodology

2.1 Definition of urban space types

UST is the term used in this paper for units similar to urban morphology and is based on the UST presented in [8]. The different UST are shown in Table 1. The UST 9 and UST 10 separated in [8] are not used in the following procedure, but are combined as non-residential buildings (NRB) to form the type NRB. This type is established as a separate UST, as a specific consideration is made for NRB. This is due to the fact that inhomogeneous electricity or heating requirements must be taken into account for NRB depending on their functional characteristics [9]. For example, a restaurant has strongly divergent electricity or heating requirements and different requirements for the energy infrastructure in relation to a production facility.

Table 1: Definition of the various Urban space types (own representation according to [8])

Urban space types with predominantly residential use	
UST 1	Small-scale, detached residential development
UST 2	Terraced house development
UST 3	Ribbon development
UST 4	Large-scale residential development
UST 5	Perimeter block development
Urban space types with predominantly mixed use	
UST 6	Village development
UST 7	Historic old town development
UST 8	City center development
Urban space type with predominantly commercial and industrial use	
NRB	Non-residential buildings

Using the approach, which is presented in [8], a quarter can be subdivided into different levels of consideration (several blocks, sections and parcels with buildings) in terms of urban development. Figure 1 shows schematically how the individual levels of consideration are defined in the context of this paper. The lowest level of consideration is the building level. This only includes individual buildings, which are analyzed further in the subsequent procedure.

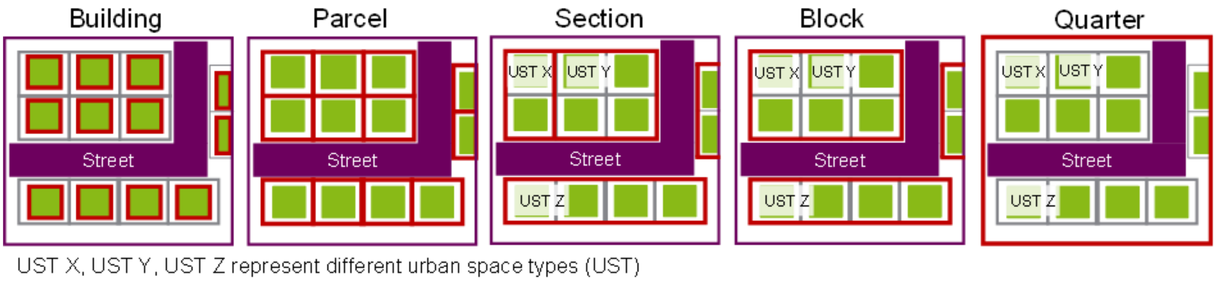

Figure 1: Schematic representation of the different levels of consideration (own representation according to [8])

At the second level of consideration, the individual buildings are assigned to a specific parcel. Overall, the term "parcel" cannot be equated with the term "plot of land", as a building can also be located on several plots of land. In this case, it is a developed parcel if one or more buildings are located on it. It should also be noted that one or more buildings cannot be located on several parcels. Other parcels are characterized by a different land use category, such as forest, meadow or roads or public transport routes. Homogeneous, structurally identical areas are summarized in the section. It therefore consists of the sub-units of properties with their buildings that have the same UST. The section is bounded by neighboring sections with different UST or by public transport routes. Several sections are represented within a block. The block is bounded by public traffic routes or the quarter boundary. The last and most comprehensive level is the quarter level, i.e., the entire area for which a cross-sectoral energy infrastructure is to be planned.

2.2 Methodological approach

The schematic methodical procedure is illustrated in Figure 2 using an abstracted quarter. This entire procedure is automated and implemented with the Python library Geopandas [10]. The individual rectangles represent the respective parcels, which represent the entire quarter.

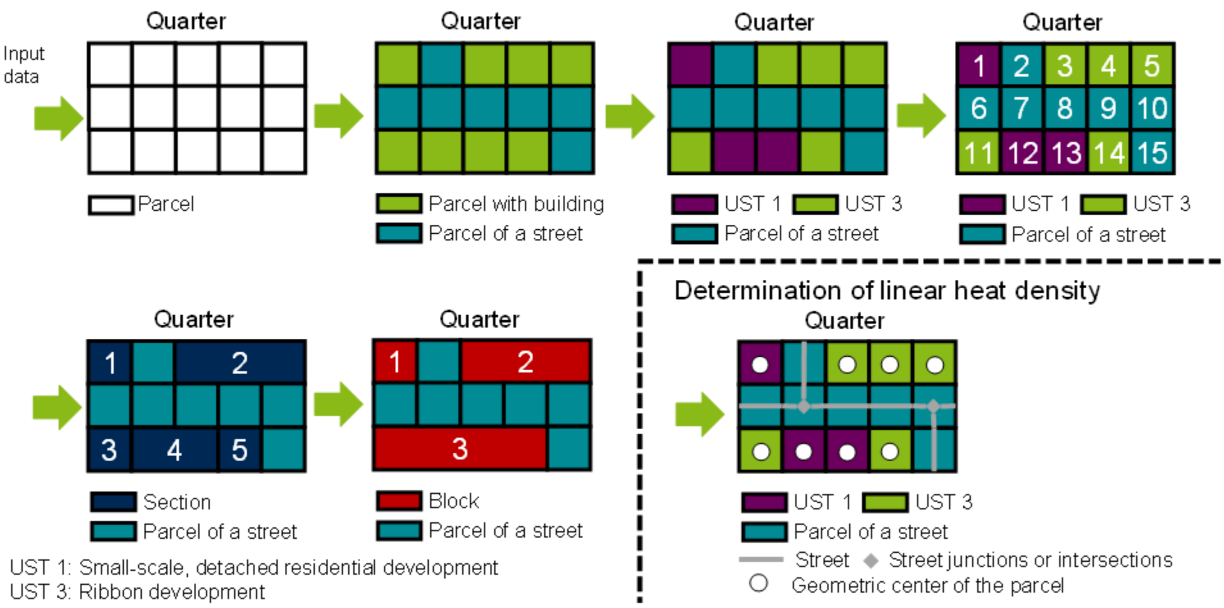

Figure 2: Schematic representation of the methodological approach

On the one hand, the geometries of the buildings, plots of the land and streets that are located within the quarter under consideration are required as input data. On the other hand, building parameters such as the building category (residential, mixed-use or non-residential) are specified. The building height is also taken into account by the input parameters. In the next step, the building geometries are assigned to the individual parcels. These building geometries are shown in green in Figure 2. The other parcels represent the street structure in this abstracted quarter and are shown in turquoise. In a further step, five real parameters are determined based on [5] in order to assign the individual parcels to a specific UST. For example, two different UST occur in this abstracted quarter (UST 1 and UST 3).

To form a section, a neighbor analysis is carried out. For this purpose, all neighbors of the respective parcels are determined. If the individual parcels geometries touch, they are neighbors. If this is not the case, the respective parcel is not considered a neighbor. The corresponding identity numbers of the various parcels are shown in Figure 2 with a white number. For example, the neighbors of parcel 13 are determined as parcels 7, 8, 9, 12 and 14. Once the neighbors of a parcel and their associated UST have been determined, the sections and blocks are formed. To form the sections, the previously determined neighbors are checked to see whether they have the same UST. For other parcels to be combined with parcel 13 to form a section, they must also have UST 1. If the neighboring parcels under consideration do not have the same UST or the neighboring parcels are roads, then these parcels are not combined into one section. However, if the neighboring parcels have the same UST, these parcels are combined into one section. In this example, parcel 1 is therefore section 1, parcels 3, 4 and 5 are section 2, parcel 11 is section 3, parcels 12 and 13 are section 4 and parcel 14 is section 5. These sections are shown in dark blue in Figure 2.

In contrast to the section, no distinction is made as to whether the parcels have the same UST when forming the blocks; instead, all parcels that are bordered by a road or the quarter boundary and do not contain a NRB are grouped together to form a block. The blocks are shown in red in Figure 2.

Once the buildings have been analyzed in their spatial context, the next step is to determine the linear heat density in order to estimate which parcels, sections or blocks are particularly suitable for a central heat supply, e.g., via a local or district heating network. The linear heat density is defined and calculated as the heat demand of all buildings in relation to the nearest street section length. To determine the linear heat density, the street geometries are first required and divided into individual street sections. These are shown as gray lines in Figure 2. A street section is the part of a street bounded by street junctions or intersections, including the adjacent buildings. The junctions or intersections are marked with a gray diamond. In a subsequent step, the geometric centers or centroids of the parcels are determined. These can be recognized by a white circle with a black outline. To determine the linear heat density, the shortest routes to the various street sections are first determined. The heat demand of a parcel or the building on it is now assigned to the street section closest to the geometric center of the parcel. If several parcels are assigned to a street geometry, their heat requirements must be added together and divided by the length of the street section. If only one parcel is assigned to a street geometry, only its heat requirement is to be divided by the length of the street section.

3 Application of the method to an example quarter

The method described above was tested for validation on five quarters, all of which have a different composition of different building typologies. For better understanding, the method is explained below using an example quarter (quarter 1) in Figure 3. Quarter 1 has 16 buildings (shown in green) and 18 parcels (shown in grey). Thirteen buildings are residential, two are non-residential and one is a mixed-use building. A mixed-use building is one in which, for example, there is a store in the lower part of the building and apartments in the upper part.

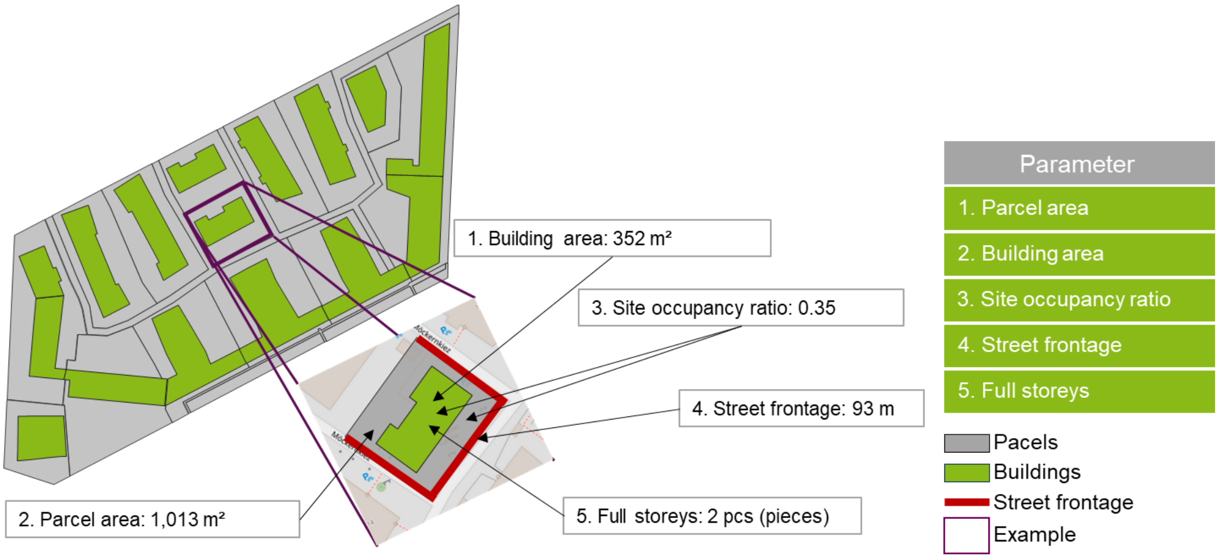

Figure 3: Illustration of an example quarter (quarter 1) and the real parameters of a parcel

Various real parameters are determined for each parcel on which one or more buildings are located. These real parameters are used to assign an UST to each parcel. The following parameters are taken into account in the analysis: the building floor area in m², the parcel size in m², the site occupancy ratio and the length of the street frontage in m as well as the number of full storeys in pieces (pcs) The values determined for the real parameters are shown for one parcel, which is shown enlarged again in Figure 3. The black arrows for the real parameters 1, 2 and, 5 point to the levels of consideration (building or parcel) that must be taken into account in order to determine the respective real parameters of the parcel. Both levels of consideration (building and parcel) are used to determine the real parameter 3, as the site occupancy ratio indicates the relationship between the building floor area and the parcel area. For the real parameter 4, it must first be determined on which street sections the respective parcels are located.

In the next step, the length of the parcel directly adjacent to one or more street sections is determined. If the parcel is located on several street sections, the street frontage is the sum of the lengths that a parcel is directly adjacent to several street sections, e. g. this parcel has a parcel area of 1,013 m², a residential building with a building floor area of 352 m² and a site occupancy ratio of 0.35 as well as two full storeys. In addition, this parcel has a street frontage of 93 m.

To ensure that the highlighted parcel in this example and all other parcels within quarter 1 are assigned to an UST, the quantile values of the various parameters for the respective UST from [5] must be taken into account. These quantile values were therefore used to derive the respective characteristic distribution functions for the associated UST, which are shown in Figure 4. To assign an UST to the individual parcels, the real parameters of the parcel are compared with the distributions of the respective parameters of the various UST. The deviations are calculated based on the deviation between the real value of the parcel and the mean value of the distribution. To take into account the different spreading of the different distributions, the previously calculated deviation is divided by the standard deviation of the different distributions. The total deviation from the eight UST is calculated by adding up the individual deviations of the various distributions for each UST. The UST with the lowest total deviation is assigned to a parcel. This procedure is carried out for all parcels on which one or more residential or mixed-use buildings are located. On parcels on which one or more NRB are located, the UST NRB is assigned directly.

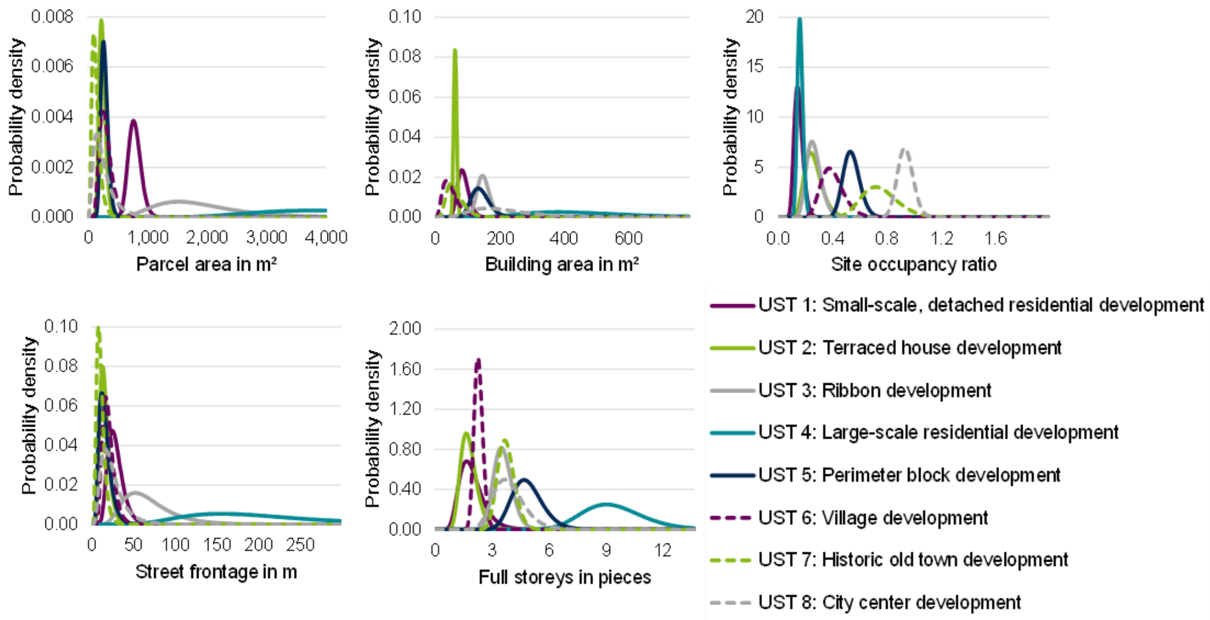

Figure 4: Illustration of the various distribution functions of the respective urban space types and parameters

Figure 5 shows the allocation of the individual UST to the 18 parcels. The calculated deviations of the real values from the mean values of the various distribution functions for three parcels are shown as examples. The sample quarter 1 is characterized by UST 3 and UST 4 as well as NRB. UST 3 shows the smallest deviation for parcel X, as well as for parcel Y. In contrast, UST 4 shows the smallest deviation for parcel Z.

Figure 5: Assignment of the various urban space types to the respective parcels for quarter 1

In particular, it can be seen that UST 2 and UST 7 show the greatest deviation for all three parcels. This is due in particular to the fact that the building floor area, the parcel area and the street frontage deviate significantly from the real parameters. This is because UST 2 and UST 7 are characterized by a small parcel area and a small street frontage [8].

The formation of sections and blocks for quarter 1 is shown in Figure 6. In the case of sections, those parcels with the same UST are grouped together. When forming blocks, the parcels that are enclosed by a street or the quarter 1 boundary and are residential and mixed-use buildings are grouped together. When merging the geometries, the associated information on which parcels or buildings are assigned to a section or block is taken into account at each consideration level. This makes it possible to access the data of the underlying consideration level from each consideration level and to consider the data within the presented bottom-up approach at any point in time.

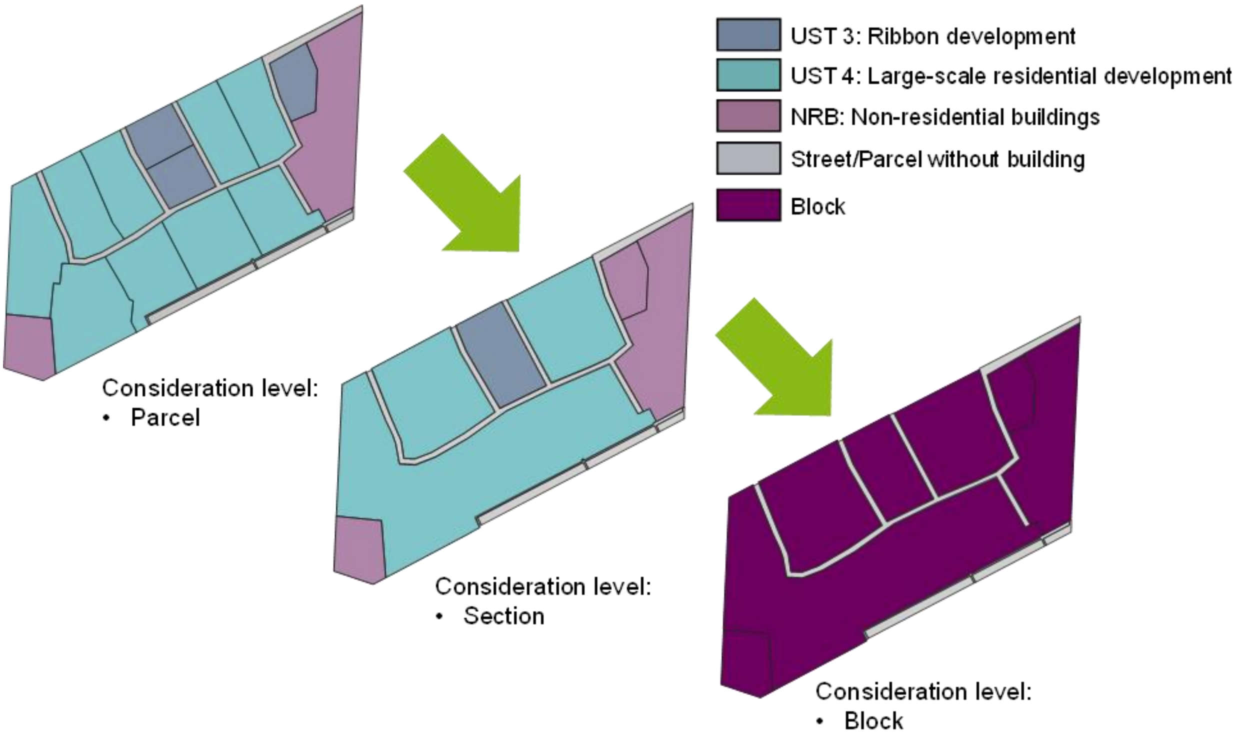

Figure 6: Illustration of the different levels of consideration for quarter 1

The method described in Section 2.2 is used to determine the absolute heat demand and the linear heat density. The results of this procedure are shown in Figure 7. It can be seen that some street sections are more suitable for a central heat supply concept than other street sections. For example, street sections 2, 3 or 12 in this application example are particularly suitable for a centralized heat supply concept. Street sections 4 and 7 are not assigned any heating requirements for the parcels, so these street sections have a linear heat density of 0 kWh/m · a. Street sections 5 and 6 are assigned a heat demand from various parcels, but the linear heat density is just below 2,000 kWh/m · a, which is mentioned in the literature as an economic guide value for the use of heating grids [11]. This value of 2,000 kWh/m · a is the linear heat density required for economical network operation before network losses. In [11], heat losses of 10 % are assumed, which leads to a linear heat density of 1,800 kWh/m· a. When looking at the example quarter 1, it becomes clear that a heating network can be economically installed in the street sections 3 and 12, in order to supply the parcels assigned to the street sections and the buildings on them.

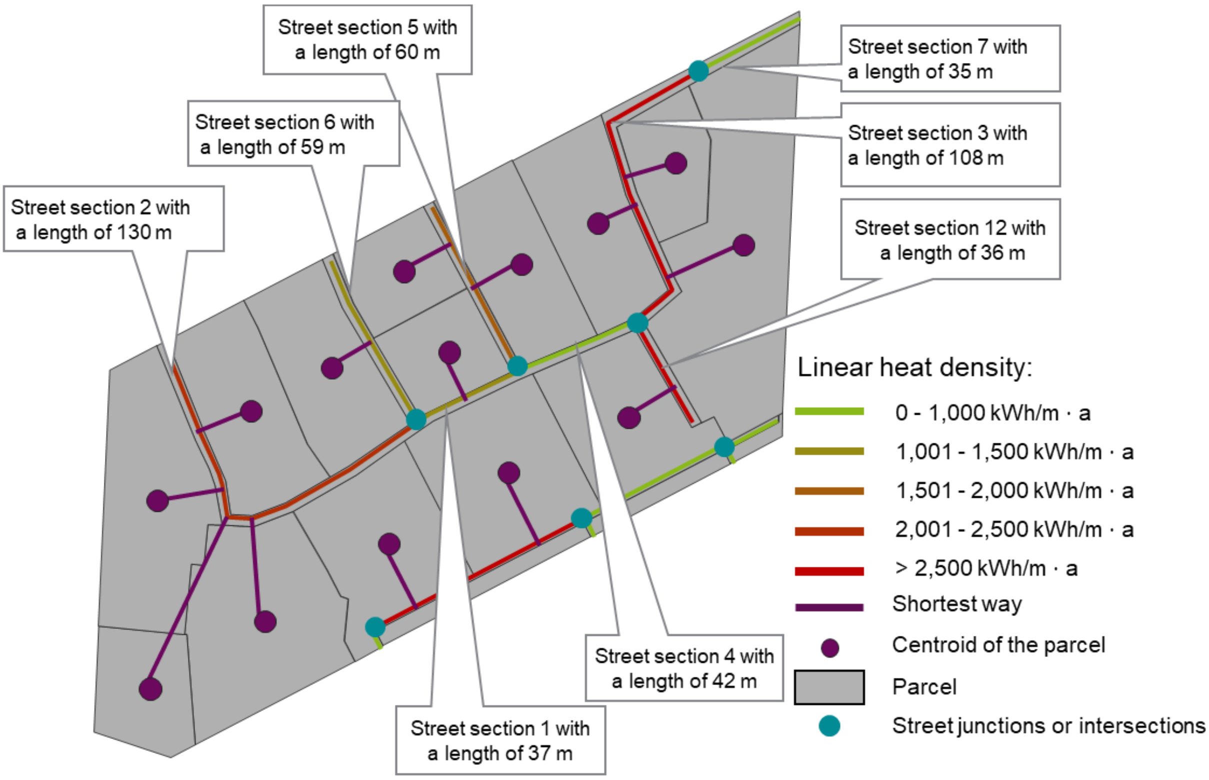

Figure 7: Exemplary illustration of the assignment of the centroids of the parcels to the street sections and the resulting linear heat densities for quarter 1

4 Results

Figure 8 shows the results of three further quarters. The allocation of the UST to the block level and the linear heat density determined are shown here.

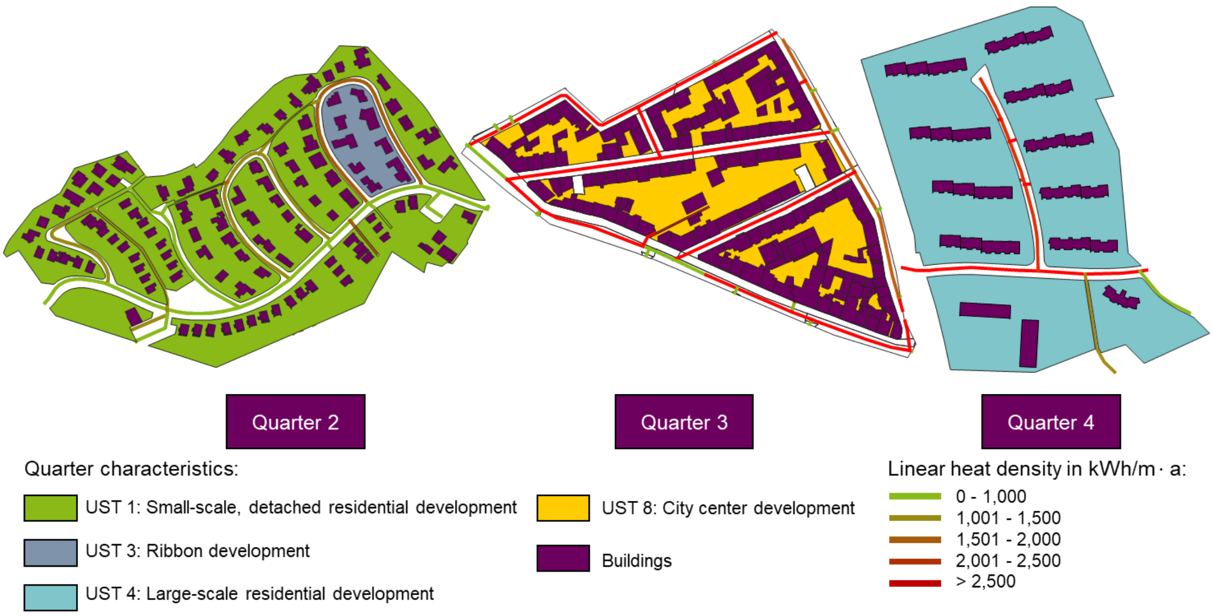

Figure 8: Representation of the urban space types that predominantly occurs at block level and the linear heat density for the quarter 2, quarter 3 and quarter 4

In quarter 2 it can be seen that the majority of the quarter is assigned to UST 1 and a small part is predominantly assigned to UST 3. The part assigned to UST 3 has a higher linear heat density compared to the area assigned to UST 1. It can be seen that quarter 3, which is predominantly assigned to UST 8, has a higher average linear heat density. Especially in comparison to quarter 2. In the third quarter (quarter 4), UST 4 in particular is represented. At this is a large-scale residential development, this quarter also has a higher linear heat density than, for example, quarter 2.

In the fourth quarter (quarter 5), which is shown in more detail in Figure 9 it is particularly clear that the approach presented here also assigns parcels wit buildings that are directly adjacent to each other to a suitable UST. UST 4 parcels are also represented in the north-eastern part of the quarter 5. In connection with these, a significantly higher linear heat density must also be taken into account. This example also shows that UST such as UST 1 or UST 4 generally have a larger parcel area and can therefore also be used for the possible use of heat pumps with geothermal probes, as there is more space for possible boreholes than with UST 2.

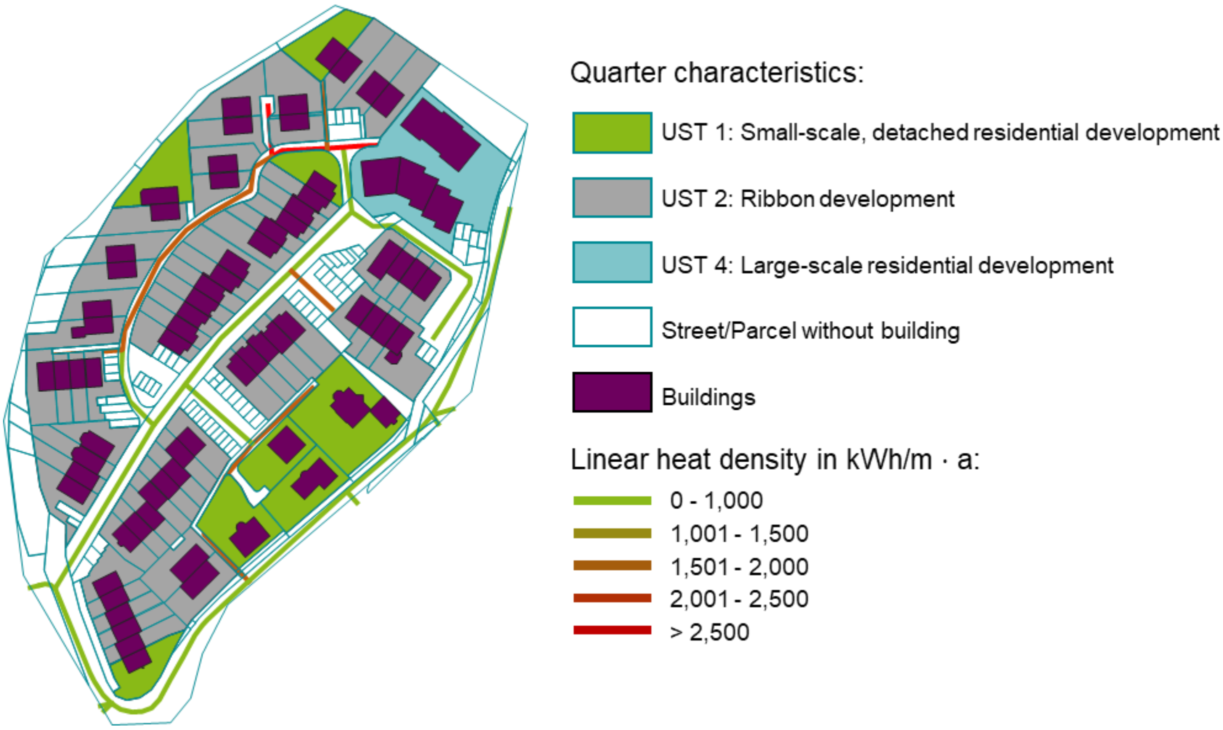

Figure 9: Representation of the urban space types at the consideration level parcel and the linear heat density for the quarter 5

Overall, it could be validated that certain UST have a higher linear heat density compared to others and thus a preselection could be made as to whether a centralized heat supply concept is more likely to be considered than a decentralized heat supply concept.

5 Conclusion

The grouping of buildings through the automated assignment of different UST within a quarter offers the possibility to take into account the different connection and load densities as well as linear heat densities per level of consideration and to compare centralized and decentralized heat supply concepts with each other. This approach allows different levels of consideration within a quarter to be evaluated separately or in conjunction with each other, either technically or economically. In addition, based on this targeted consideration of spatially connected buildings, operating resources to cover the heat supply can be determined and a cross-sectoral energy infrastructure can be planned. Particularly when looking at the linear heat density, areas within a quarter can be automatically determined which are suitable for central heat supply. Once these areas have been identified, the next step is to analyze the potential for using a combined heat and power plant or a large heat pump using a heat source such as lake or mine water. The approach presented here also offers the possibility of building an energy-based optimization on this and comparing the different levels of consideration (parcels, section and block) with each other, taking into account technical and economic parameters. In a further step, a sensitivity analysis should be carried out to check which parameters have which exact influence on the results presented.

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7 References

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