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A validated method to assess the network length and the heat distribution costs of potential district heating systems in Italy

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ABSTRACT

The evaluation of the district heating network investment costs requires the knowledge of its topology. However, when assessing district heating potential, the topology is not known a priori and a simulation is required. One method for modelling future heat networks involves the use of Minimum Spanning Tree, from the graph theory. In this work, the MST is used together with real networks lengths to elaborate an updated equation describing the effective width in correlation with the number of building ratio instead of plot ratio. The reason motivating the use of simulated networks lies in the goal of analysing sparse areas where there's a general lack of data. In this study, the census cells vertexes and local roads layout are used as inputs for the application of the MST in order to simulate DH network layouts in areas where DH is not present. The method has been validated by running simulations in areas where DH is already present, allowing the comparison of the respective lengths. The validation shows a variable but systematic overestimation of the simulated lengths. The study of the error has brought to the definition of a correlation between accuracy of results and the share of buildings with centralized heating systems suitable for DH connection. The updated version of the effective width confirms the exponential tendency and gives higher results for Italian cities then for Scandinavian ones, showing an important impact of the city structure in the curve. The city of Milano is finally used as a case study to show the effects of using the updated effective width curve.

Keywords

District heating;
Effective width;
GIS;
Validation;
Minimum spanning tree.

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1 Introduction

The diffusion of DH in European countries has been recognized as a beneficial technological development for the decarbonisation of the energy sector and as an enabler of energy efficiency at urban level [1], [2]. For this reason, the EU member states are asked by the Energy Efficiency Directive 2012/27/UE to provide a potential diffusion estimation of this technology in their countries [3]. One of the main driving forces of DH is its ability in recovering renewable [4] or waste heat [5],[6] with benefits from the environmental and economic point of view on the energy system. These beneficial effects are even greater in case of fourth generation DH systems, 4GDH, [7] that can accept a wider range of low temperature excess heat and renewable sources thanks to lower temperatures, greater efficiencies and reduced costs [8]. In addition to these aspects, in future national energy systems that see a significant increase of the renewable energies' share, DH can play a major role in the integration between energy sectors, enabling the balance of fluctuating renewable energies' overproduction also thanks to heat storages [9]. Therefore, a broader diffusion of DH could facilitate the realisation of smart energy systems towards decarbonisation, with a sustainable and economic use of waste sources and renewables [9].

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Abbreviations

DH	District Heating
Err	Error
GIS	Geographical Information System
MST	Minimum Spanning Tree
CHP	Combined Heat and Power
MSE	Minimum Square Error

Symbols

A	Area [m^2]
C	Cost [€]
d	Pipe diameter [m]
e	Plot ratio
k	Correction factor
L	Network trench length [m]
p	Number of people
Q	Heat [MWh]
w	Effective width [m]
x	Share of buildings with centralized heating system

Nevertheless, the economic sustainability of DH systems depends not only on their energy sources and storages [10] a but also on the combination of these ones with infrastructural distribution costs, being the latter the main additional cost in comparison with individual alternative heating systems [11]. The assessment of DH distribution costs is of fundamental importance to guarantee the proper estimation of DH diffusion potential, especially in low density areas [12] or in future energy scenarios characterized by lower energy demanding buildings [7]. In fact, it is in these areas of low density demand that DH profitability is mostly questioned because of the high infrastructural investment costs compared to high density areas [13]. It is especially in low density areas that 4GDH systems, fed by cheap waste heat recovery and renewables, have proven to be an economic and environmental sustainable solution [14] with great potential in future energy scenarios [15]. Nevertheless, even if their application is increasing [14], 4GDHs do not represent the majority of existing DH cases and so it can be stated that available data about these systems and about sparse areas DH systems in general do not represent a significant statistical database. Much more empirical information about distribution costs and network length estimation can be found regarding high temperature DH. This is one of the reasons that has motivated this research, with the aim of finding a way to better estimate DH network costs, through its topology, at national level for the assessment of potential development of DH, especially in low density areas.

1.1. DH distribution network - simulation and cost estimation

In literature it is possible to find various studies aimed at investigating the profitability of DH depending on the distribution costs. In [12] the challenges of distributing heat in sparse areas are addressed from a business perspective. The result of this study is a model for the analysis of low density DH systems and for the determination of boundaries for favorable conditions for their expansions. In [16] the authors present a method for low density energy DH system design, testing different pipe sizing methods, substation types, and network layouts. The same topic is developed in [17], in which the profitability of DH systems is investigated in a specific area by considering different heat demand densities and different grid lengths. The focus of the work is the analysis of the heat losses in the outer branches of a grid, in which the required capacity of the pipes, and therefore their size, is mainly determined by the need for domestic hot water, heavily impacting in low space heat demand buildings.

From these studies, it clearly emerges that DH distribution costs are a crucial component of final costs when assessing DH feasibility. The evaluation of the investment costs of a DH network requires the knowledge of its geometry in terms of topology, length and diameter size [18]. However, when assessing the sustainability of DH potential expansion on the territory, the topology is not known a priori and this adds uncertainty in the investments [19]. In literature it is possible to find two main approaches to address the problem of estimating network topology, and therefore costs, which are influenced by the size of the application level: small scale, such as city or single district network, and large scale, such as region or country. Addressing the first group, the distribution costs are commonly approached by a detailed simulation and sizing of the DH network topology in city level feasibility applications, in which the specific DH network is sized and its topology is simulated. Starting from buildings or aggregated heat demand, the network is sized by the use of algorithms [20], [21], or softwares, such as OPTIT [22],[23] or Comsof Heat [24], [25], commonly based on optimisation techniques, which use heat demand georeferenced data as inputs.

In [20] a methodology to spatially assess the integration of DH networks in urban energy systems is developed by using several algorithms such as clustering, Delaunay triangulation and Minimum Spanning Tree. In [25] a plug-in for GIS applications is developed based on Comsof Heat. The GIS framework and open data maps such as OpenStreetMap [26] are commonly used for this type of analyses.

In [27] a suitability map for DH is elaborated through a spatial smoothing method based on fuzzy algorithms which considers the influence of nearby objects. Starting from heat demand models based on the typology of buildings, the theoretical pipe lengths are calculated using the length of the streets, based on OpenStreetMap data, plus the distance between the streets and demand points. In [28], the presented GIS model consists of several Python scripts written for ESRI's ArcMap software [29] to simulate network topologies and costs.

The second category includes all the cases in which the feasibility of DH is studied at a wider territorial scale, like an assessment of the potential diffusion of the technology at regional [30], national [31], [32], [33] or international level [34], [35]. In these cases, the problem of estimating distribution costs is mostly addressed correlating infrastructural costs to widely available territorial data sets such as number of buildings, heat density, demographic data and other urbanistic parameters.

While in [30] the distribution costs are considered indirectly through indicators and weighting criteria on heat densities, in national studies like [31] for Denmark, [32] for Austria and [33] for France, the estimation of DH distribution network length is estimated by the use of the effective width parameter [36], [34].

1.2. The effective width

The effective width is a parameter that has been defined to relate the length of a DH network to the land area in which it is located, allowing the estimation of trench lengths, and therefore distribution costs, by knowing urbanistic parameters such as land area and building area. The effective width is in fact expressed as an empirical correlation curve that supports the estimation of network length using public available demographic and urbanistic data as inputs. The effective width has been presented by Persson and Werner in [34] where it is expressed as an exponential correlation of the plot ratio, namely the ratio between the built area and the total land area of the analysed territory and it has been extensively used in the framework of the Heat Roadmap Europe project to estimate distribution costs and DH potential for European member states. While in [32] and [33], the effective width is calculated through the correlation presented in [34], in [31] an adaptation of the curve to the Danish context is presented by the authors that have developed a method for assessing the costs of supplying Danish buildings by DH: data from the DH company in Aarhus have been there used to find a specific effective width for the Danish context.

After further researches and refinements of the model during the years, in [35] the effective width curve has been elaborated as a linear function since, according to the authors, the exponential curve tends to overestimate the effective width in sparse areas with few buildings therefore underestimating distribution costs.

Due to the uncertainty of the effective width curve in low density areas and because of the correlation of this parameter with the urban characteristic of the analysed territory, which can be very heterogeneous in different states, the objective of the work presented in this paper is to update the effective width curve to better adapt the correlation to the Italian context by the use of real Italian networks data. In addition to this aspect, one of the purpose of this work is to give a special attention to the analysis of the effective width curve in low density areas. Because of the few statistical sample of input data, additional synthetic networks data are simulated by the use of the Minimum Spanning Tree in low density areas and they are therefore used to build the updated correlation of the effective width.

1.3. The Minimum Spanning Tree algorithm-MST

A commonly used technique coming from the graph theory to estimate all kind of network's paths is the Minimum Spanning Tree. The MST can be found in a wide set of application, such as [37], [38], [39], but it is also applied to DH projects to assess the most efficient network topology to connect buildings in a specific area of study. In [21] the MST is applied among other techniques in a project related to the evaluation of the profitability of the integration of geothermal resource for direct heat supply to a DH systems in the city of Lausanne, Switzerland.

A similar approach has been used also in [40], in which the main network is generated through the MST algorithm as the graph that represents the shortest connection for all buildings along the streets. The lengths of the house connections to the main grid are then estimated by spatially disaggregating the obtained graph based on topological relations. In [19], instead, a combination of empirical data and optimisation algorithm is used to assess DH development at city level: while the effective width is used to estimate distribution network costs inside clusters of heat demand, the MST algorithm is used to simulate transmission networks to connect the previously identified district clusters. In [41] the same approach of [40] is used to assess the length of the network and the size of the pipes in order to properly estimate the cost of distribution, connection and transport network including roads layout.

Other applications of the MST algorithm can be found, moreover, in other contexts than DH related to energy planning. For example, in [42] the MST has been used in the framework of developing a version of the Hamburg "Heat Demand Cadastre" as much complete and significant as possible, while ensuring data protection requirements. A parallel work from the same authors [43] presents a decision support tool based on energy planning including linear heat density calculated applying graph theory to streets layout and buildings GIS information.

1.4. Motivation of this work

In this work the MST method is used in a large scale application in order to refine the existing correlation of the effective width curve to the national context of application; the novelty lies in using a simulation approach which is usually used for small scale, single network detailed applications, to generate a statistical database, simulating a multiplicity of networks in order to generate an easy to use correlation to be readily applied in large scale territorial applications.

In fact, the MST algorithm is applied here on a GIS environment to simulate DH network topologies in a number of areas without DH presence with a statistical purpose. This allows not to limit the input database to existing DH only areas, but to explore also areas without DH, with different urbanistic parameters. Another different aspect of the analysis with respect to other works using MST in the DH field is the application of the algorithm to national census tracts database instead of single buildings. This has been motivated by two main reasons: one is the computational effort of the algorithm application to single buildings which is much more intense in particular in large scale applications. In fact, in each census tracts the buildings are in the hundreds, while the vertices of the shapes are usually less than ten. The second is due to the fact that the final goal of the analysis developed in this work is aimed at assessing the feasibility of DH systems including also the share of buildings with centralized heating system suitable for DH connection, that means considering also that not all the buildings are technically ready for DH connection the way they are built. If this aspect has not been possible to be considered at single building level, it has been possible to include it at district level.

The use of MST applied to census tracts in this work has been first tested in Italian areas with the presence of DH and then the results have been compared with the related real networks' paths length highlighting some promising results.

The validated approach has been finally applied in several other areas without DH systems in order to increase the statistical data sampling of DH systems' length in relation to surface areas, composed originally only by the existing network lengths. This enlarged database of existing and synthetic DH networks has been used to generate an updated version of the effective width curve contextualized to Italian cities urban characteristics.

A particular attention has been given to areas in which there is a scarce data availability and where the effective width curves lacks more on reliability, namely the sparse areas. In fact, as stated in [44] the correlation between the plot ratio and effective width tends to be weak especially in these areas.

Since very few works regarding the analysis of the effective width correlation can be found in literature, this paper has the purpose to give a contribution to the research in this field.

The result of the work is an updated effective width curve based on building ratio instead of plot ratio, due to the frequent data lack regarding building surfaces which do not belong to residential sector. The investigation's aim is to explore if the obtained curve is meaningful/reliable and if the correlation available in literature and based on northern European DH networks is representative for other contexts, in this case the Italian networks.

If the use of the MST allows the direct calculation of the network length, the use of the effective width correlation seems contradictory. In reality, the two tools are complementary: the use of the MST on a large scale is computationally burdensome, requiring numerous steps of integration with different geographical layers. A simple correlation based on few data makes the effective width correlation an easy energy planning and policy supporting tool for high level and large scale analyses that still need a realistic and plausible evaluation. The MST can be therefore consistently used for consequent more detailed analysis at local level.

The framework of this project is a broader project funded by the Italian DH association AIRU which has as main focus the estimation of national renewable district heating potential in Italy [45].

Within the wider framework of the project aimed at estimating the potential of DH in Italy, the MST is therefore used as a statistical instrument for the determination of the effective width, so that a representative correlation between demographic/urbanistic parameters and the length of the network can be applied on the entire Italian territory. The determination of a new curve has been driven by the intent to develop a correlation representative of the Italian territory and by the desire to better investigate the profitability/potential of DH in sparse areas.

2. Methodology and Research Steps

As previously mentioned, the present work framework is a broader project focused on the assessment of the potential diffusion of DH in Italy in which one of the main challenges is represented by the estimation of the network investment costs in areas of expansions. This work aims at finding a way to estimate the lengths of DH networks in areas where they are not present and starting only from the topography of the area of interest.

The final goal is the formulation of a rapid and easy to use equation applicable to the entire national territory, expressed as a correlation between two parameters: the effective width w, which is the ratio of the area served by a network and its length, and a urbanistic parameter that is the building ratio n_b, namely the ratio of total buildings, residential and tertiary, over the total land area.

The research articulates in the following steps:

1. Use of the Minimum Spanning Tree algorithm to simulate DH network topologies starting from national census GIS database.
2. Validation of the MST algorithm by comparison with real DH networks lengths.
3. Application of MST to create synthetic DH networks in areas without DH and low density of buildings.
4. Reformulation of the effective width curve using simulated and existing networks lengths and consequent calculation of linear heat density.
5. Application to a case study.

Starting from the input database, the national census data, in step 1 the MST algorithm is applied to the vertices of the shape areas of the census tracts to simulate DH network lengths in QGIS software. The following step 2 is the comparison of the resulting network path lengths from MST algorithm to real networks' ones: as foreseen the path and topology are not exactly the same, being the real installations driven by several practical aspects and barriers. Nevertheless, a comparison in network lengths is performed and a general overestimation of MST simulations is detected, so that a corrective factor depending on the share of buildings with centralized heating system suitable for DH connection in the areas is estimated to shorten the difference between simulated and real network lengths. The validated MST approach is then applied in step 3 in several areas without DH, which are chosen to be significantly different from the ones analysed in the previous steps, privileging low density areas. The purpose of step 3 is therefore to increase the sampling of network data onto which building the effective width curve in low density areas which is performed in step 4. Here, the new effective width curve, based on the previously built data, is analysed in the way it impacts the calculation of the linear heat density. Finally, the method is applied to a case study, the city of Milano, and the difference in results between the effective width original curve and the updated one is presented.

2.1 Input data

In this work, the data coming from national census has been used. Istat [46], the Italian National Institute of Statistics, provides some of the territorial data necessary for the development of the correlations shown in the methodology. The census tract is the minimum territorial unit of the census survey and it corresponds in most of the cases to a city block and it is used by Istat in relation to socio-economic data. For this work, it has been possible to obtain data on the number of residential and tertiary buildings, type and number of building heating systems, on residential floor area and total land areas by census tracts. Unfortunately for this analysis, census tracts have irregular shapes, which give an additional difficulty in finding a specific correlation, because they are mainly bordered by city streets which do not follow a regular grid. An example of the census areas grid definition can be seen in Figure 2.1.

Together with the census data, also network topologies coming from existing DH systems have been used. Three DH utilities have provided the GIS shapefiles of their networks. The analysed systems are eight and located in five cities. They are sometimes located in different part of the city and divided in smallest tracts, as shown in the Figure 2.1, enough to be considered as independent heat distribution networks.

Figure 2.1: District heating network in different areas of one of the analysed cities.

2.1.1. Estimation of DH length through MST algorithm

The previously mentioned DH networks are used as a starting point to be compared with the related synthetic networks simulated by the MST method.

The MST method is applied in the areas in which DH is already present to simulate the network and to validate the method, being the estimation of DH length L_{DH} the purpose of MST application.

The MST is an algorithm with the aim of joining several points arranged in space with the shortest possible length, named L_{MST}, simulating in this way the purpose of a DH provider of minimizing the length of pipes necessary to connect as many buildings as possible in a given geographical area.

From a mathematical point of view, given an undirected, connected and weighted graph $G = (N, E)$ of N nodes and E edges and assuming that length $L = (u, v)$ is a weight function for G, a MST for G is a set of edges such that:

$$L_{MST} = \min_{MST \in S} \sum_{(u,v) \in MST} L(u,v) \quad [\text{m}] \qquad (2.1)$$

Where S is the set of all trees spanning G.

Here the MST is applied to the graph in which the nodes N are the vertices of the census tracts' shapes and the edges E are limited to the borders of the shape areas lying in the streets layout, being the latter derived from OpenStreetMap. The MST shall simulate the network layout connecting all the buildings inside the census tracts. In a situation of full connection rate of buildings to DH, the MST would have been applied to single buildings. Since not all the buildings are ready for a connection, e.g. it is very common in Italy not having centralized heating systems in multiple dwellings buildings, and considering that information on types of heating system is not available for single buildings, but statistically on the census tracts, the MST is applied to all the vertices of the shape areas so to simulate that a connection to single buildings is possible from all the points of the perimeter. In this way, the aim is to reproduce the connection of DH to all the vertices of the district and so potentially to all the buildings, but without incurring in the certain overestimation of considering all the buildings connected. This method brings anyway to a general overestimation of the network lengths in comparison with real ones, which has been found to be related to the share of buildings suitable for DH connection. For this reason, the obtained L_{MST} is reduced by a correction factor depending on the share of buildings with centralized heating system in the census tracts as shown in the following.

The MST is applied by using the MST plugin in QGIS software [47]. The calculation procedure follows three steps [48].

In the first step the Delaunay triangulation is used to obtain the edges of the graph connecting the input vertices constituting the nodes, the second step is to determine the weights of the edges through the Euclidean distances. Since these distances do not follow the real paths of DH network, the roads, the distances are calculated over the border of census tracts through the streets. Finally, new weights are determined for each edge computing the distance passing through the streets. The last step consists in the application of the Kruskal's algorithm that calculates the shortest path to connect all the census vertices.

2.1.2. Validation

For each analysed network, the results of the simulated networks lengths L_{MST} are compared to real network lengths L_{DH}. A general systematic overestimation is detected as previously mentioned so that a correction factor k depending on the share of buildings suitable for DH connection x_{DH} is applied as shown by Eq. (2.2) in order to minimize the difference between simulated L_{MST} and real length L_{DH}. The error in fact is inversely proportional to the share of buildings with a centralized heating system: the highest is the connection rate, the lower is the error.

$$L_{DH} = L_{MST} \cdot k(x_{DH}) \qquad \text{[m]} \qquad (2.2)$$

The share of buildings suitable for DH connection X_{DH} is calculated starting from the information provided by Istat on the heating system serving buildings: the available data are the number, n_h and type, centralized or individual, of heating systems serving each building. The fraction of potentially connectable building is therefore calculated as the fraction of the overall civil sector demand (residential and tertiary) with a heating system suitable to be substituted by DH substation without the need to retrofit the internal distribution heating system: centralized heating system for multifamily buildings and single houses. The calculation is therefore done as:

$$x_{DH} = \frac{n_{h,centralized} + n_{h,single\ houses}}{n_{h,tot}} \qquad [\%] \qquad (2.3)$$

2.2. Effective width and linear heat density

After the validation of the use of MST to estimate trench length of potential new DH networks, the method is used to build an updated version of the effective width curve contextualized to Italian cities characteristics.

The aim of this step is the calculation of linear heat density, Q_s/L [MWh/m] [49], namely the ratio between the sold heat Q_s and the pipe trench length L, which is the key parameter when assessing DH investment costs. The expression of linear heat density has a function of the effective width and urbanistic parameter has been formulated by Persson and Werner [34]:

$$Q_S/L = q_b \cdot e \cdot w(e) \qquad \text{[MWh/m]} \qquad (2.4)$$

Where $q_b = Q/A_b$ [MWh/m^2] is the specific building heat demand over building area, $e = A_b/A_l$ is the plot ratio and $w = A_l/L$ is the effective width curve. A first expression of w, the Eq. (2.5), has been presented in [34] as an exponential correlation of the plot ratio, while a recent adaptation in a linear form, Eq.(2.6), has been presented in [50].

$$w = 61.8 \cdot e^{-0.15} \qquad \text{[m]} \qquad (2.5)$$

$$0 < e < 0.4; w = 137.5 \cdot e + 5; e > 0.4; w = 60 \qquad \text{[m]} \; (2.6)$$

In this work linear heat density and effective width are estimated with a different formulation of the equation correlating them which has been formulated according to data availability. In fact, in national census database the information on total building surfaces are available for residential buildings only, while for tertiary sectors the only known information regards the number of buildings. Even referring the information available on public database such as OpenStreetMap, only footprints data are available while no information on height nor number of floors can be found. The use of the sole residential buildings data would bring to a general underestimation of DH potential in areas with an important energy demand due to tertiary sectors, such as city centres and business and commercial districts, if linear heat density was calculated according to Eq. (2.5) because of the lack of data about tertiary buildings area surfaces. A common way to include tertiary sector heat demand, in case of lack of data, consists in allocating the energy needs of the sector to residential cells by increasing residential heat demand of a certain percentage (e.g. 40%). However, this would compromise the linear heat density estimation, because the tertiary sector generally resides in different geographic areas.

Therefore, equations (2.5) and (2.6) have been re-elaborated in order to correlate linear heat density and effective width to the number of buildings, that is a data available in national census database both for residential and tertiary sector, differently from building surfaces. As previously mentioned, besides the characteristics of the used national database, OpenStreetMap provide this information for all the areas mapped by the website [51]. This is possible provided that the overall energy need for the census tract Q is known and calculated a priori. Here Q has been calculated by specific surface energy need Q_{res} for residential buildings, while specific energy Q_{ter} per person employed p_{ter} has been used for the tertiary sector in a concurrent work in the same project framework presented in [52]. See Eq. (2.7).

$$Q = q_{res} \cdot A_{res} + q_{ter} \cdot p_{ter} \qquad \text{[MWh]} \qquad (2.7)$$

This new approach is here proposed also to investigate the impact of this change in variable, namely number of buildings instead of building surface.

$$\frac{Q_S}{L} = q_l \cdot w(n_b) \qquad \text{[MWh/m]} \qquad (2.8)$$

Where $q_l = Q/A_l$ [MWh/m^2] is the heat demand over the total land area A_l and $w(n_b)$ is the effective width of Eq. (2.9). It is expressed as a function of the number of building ratio n_b, namely the ratio of number of total buildings, residential and tertiary, over the total land area.

$$w(n_b) = z \cdot n_b^{\,y} \qquad \text{[m]} \qquad (2.9)$$

The elaboration of w and Q_S/L curve has been performed thanks to data of Q_S and L coming from the analysed Italian DH networks. In this context the MST has been used to increase, with simulated data, the statistical samples of data onto which the curve could be formulated and to investigate the w expression in the tract of the curve where it has shown to give less reliable results: in sparse areas. The validated MST method has been applied to several districts with low n_b.

Thanks to the analysis of the available Italian data, the new formulation of the effective width curve $w(n_b)$ confirms the exponential nature of the correlation and the application of MST has helped in the estimation of parameter z and y presented in the following chapter.

3. Application of MST and Analysis of Real DH Networks

In this chapter the MST is applied to the real networks of the five analysed cities and the results are used to validate the methodology. MST is then used to simulate new networks to build a specific effective width curve for Italian cities.

3.1. MST vs real network

The MST has been applied at first in areas were DH is already present. The borders of the Istat census tracts have been used as input of the MST to simulate the networks.

Geographical areas with greater population densities and with a greater number of buildings tend to have smaller census tracts, and sometimes corresponding to the buildings themselves, while areas of different use (e.g. agricultural) tend to be larger.

This makes it possible to describe in greater detail the DH network in densely populated areas, and to simulate the lack of pipes in large areas where there is a low number of homes, and consequently where the need for heating is lower.

To give a greater statistical detail to the study, all the census tracts that contain district heating networks belonging to the same city have been divided into groups; based on their geographical distribution, their presence in the territory, and the number of residential buildings in their vicinity, as recorded by Istat, as shown in Figure 3.1. From the eight analysed networks, 50 subsections and therefore groups of census tracts have been defined for the analysis. Figure 3.1 shows 3 of these tracts grouping with 3 different colours.

With the aim of simulating DH networks, the MST method is applied to the vertices of census tracts; the edges that coincides with the roads of the areas under consideration falling into at least one of the groups, have been filtered. This filter on census tracts has been applied by overlapping the census GIS map to road networks, downloaded from OpenStreetMap [26].

Once the filter has been applied, only the edges of the census tracts that fall within the groups selected for each city is available for the MST, coinciding with the roads that cross these areas. Figure 3.2 shows this filter.

The MST algorithm is applied only to the edges of the census tracts that fall within the groups selected for each city and that coincide with the roads that cross these areas as shown in *Figure 3.3*. The MSTs, calculated once for each group, connect the vertices of the edges of the selected census tracts with segments whose total length is the shortest possible; and it is compared with the total length of the starting district heating networks, as shown in Figure 3.4.

Once all the MSTs are calculated using the algorithm, the results of MST length L_{MST} have been compared to real network lengths L_{DH}. The correspondence of results is analysed through the calculation of percentage errors for each group of census areas as defined by Eq. (3.1).

$$Err_{MST} = \frac{L_{DH} - L_{MST}}{L_{DH}} \qquad [\%] \qquad (3.1)$$

The errors have a wide range from -10 to 350% as shown by Figure 3.5.

In the few works [40][41][43] found in literature, in which the simulated networks are compared to existing ones, it is common to find a general overestimation around 5-10% in cases in which the MST is applied to single buildings locations, with a lower error in main DH grids and higher error in sparse areas, such as 3% and 13% respectively in [43]. The reasons of higher

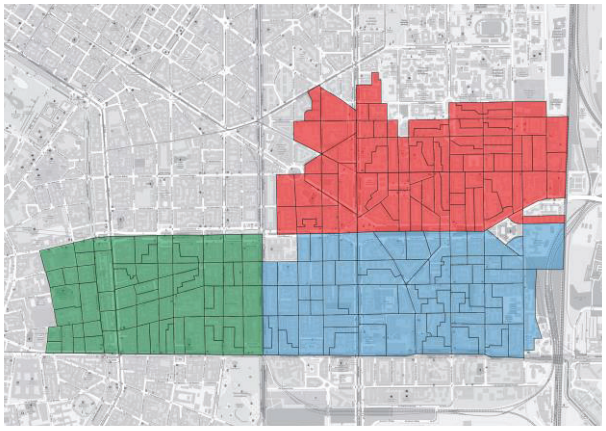

Figure 3.1: Census tracts.

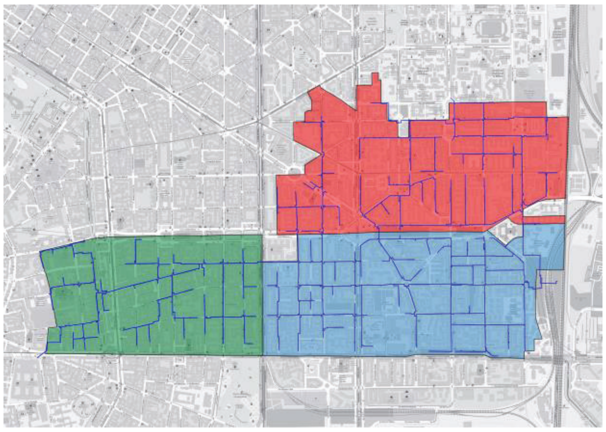

Figure 3.2: Existing district heating network and groups.

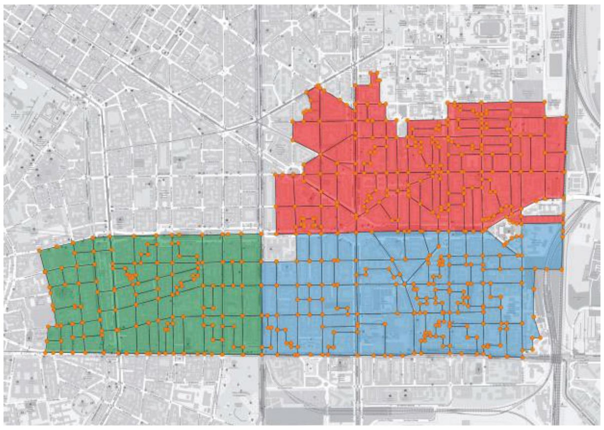

Figure 3.3: Vertices of the census tracts to be connected with the Minimum Spanning Tree.

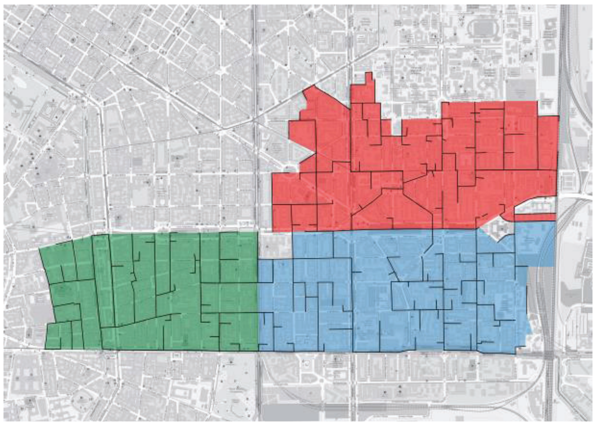

Figure 3.4: Minimum Spanning Tree (MST).

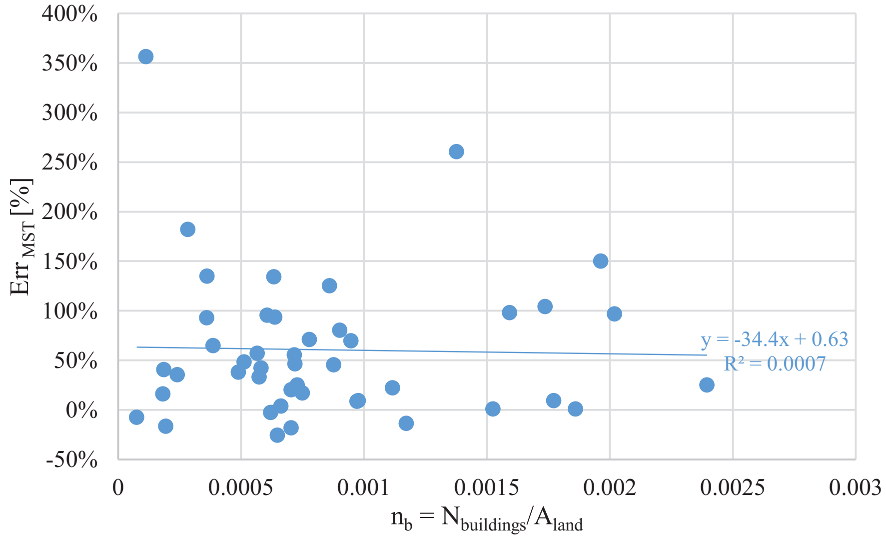

Figure 3.5 Regression line between MST Error and building ratio.

overestimation here can be explained by the fact that, since the input nodes of the MST are represented by the vertices of the census tracts, which are much more disperse than the single buildings, this choice results in the simulation of bigger distances. Nevertheless, the vertexes of the census tracts have proven to provide better results than single buildings used as inputs in the analysed networks, as better shown and analysed in the following. Several variables dependent on the territory have been taken into consideration to allow the identification of a link between the error in length results and these variables such as number of buildings, total floor area or plot ratio, but none of them have revealed any particular correlation: as an example, Figure 3.5 shows the errors related to the building ratio, confirming the lack of particular relation.

The reason of this overestimation has been therefore searched in the share of buildings which have a centralized heating system suitable for DH connection.

Since in Italy not all the buildings have a heating system ready for a connection to DH, a correlation with the potential connection, defined by (2.3), and the error of the MST simulation has been identified and is shown in Figure 3.6.

The picture shows the MST tested in its application to census tracts vertexes in blue and to single buildings inside the census tracts in green in one of the analysed city.

As can be seen a linear correlation can be identified between the error and x_{DH} showing that, regardless the actual number of buildings, where the potential connection rate of buildings to DH is higher, the results are more precise while the inverse happens in areas with low potential connection rate. The error shows also to be higher in the application to single buildings, confirming the choice of using census cells vertexes as MST inputs.

The analysis extended to all the cities census tracts considered in this work is presented in Figure 3.7. The points are more dispersed so that the linear regression correlation is less fitting, even if, considering the linear regression by single cities, the fitting is better as shown by Figure 3.8.

It's worth noticing that samples 1 and 3 have been neglected in Figure 3.8 and in the definition of the correlation since the networks shapefiles of these samples included also some substations connection pipes inside buildings, making them not comparable.

The correlation between the error and the x_{DH} identified in Figure 3.7 is therefore used to define Err_{MST} in defining the correction factor k in (3.2)

$$k(x_{DH}) = \frac{1}{1+Err_{MST}(x_{DH})} \tag{3.2}$$

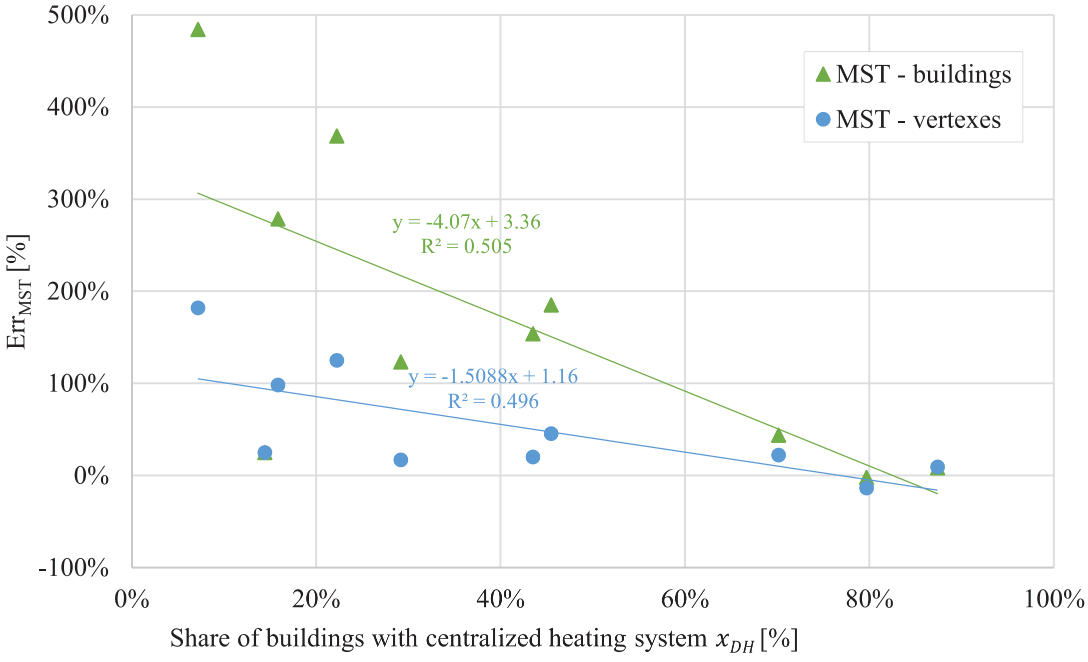

Figure 3.6 Correlation of MST Errors and share of buildings with centralized heating system in case of MST applied to census vertexes and buildings.

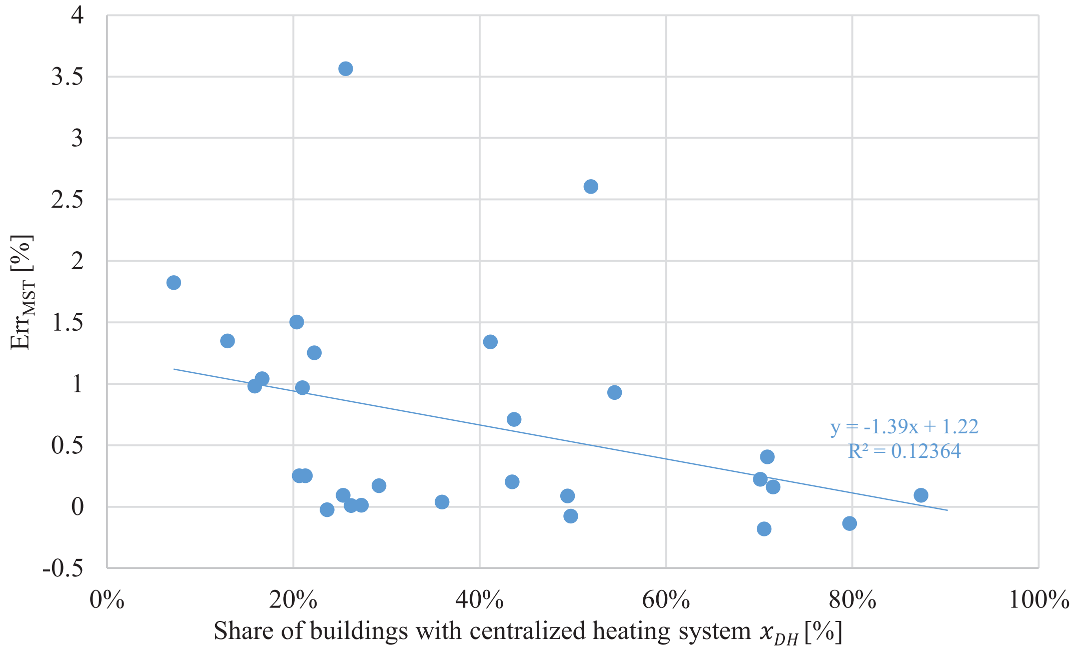

Figure 3.7 Correlation of MST Errors and share of buildings with centralized heating system in all the entire networks' database

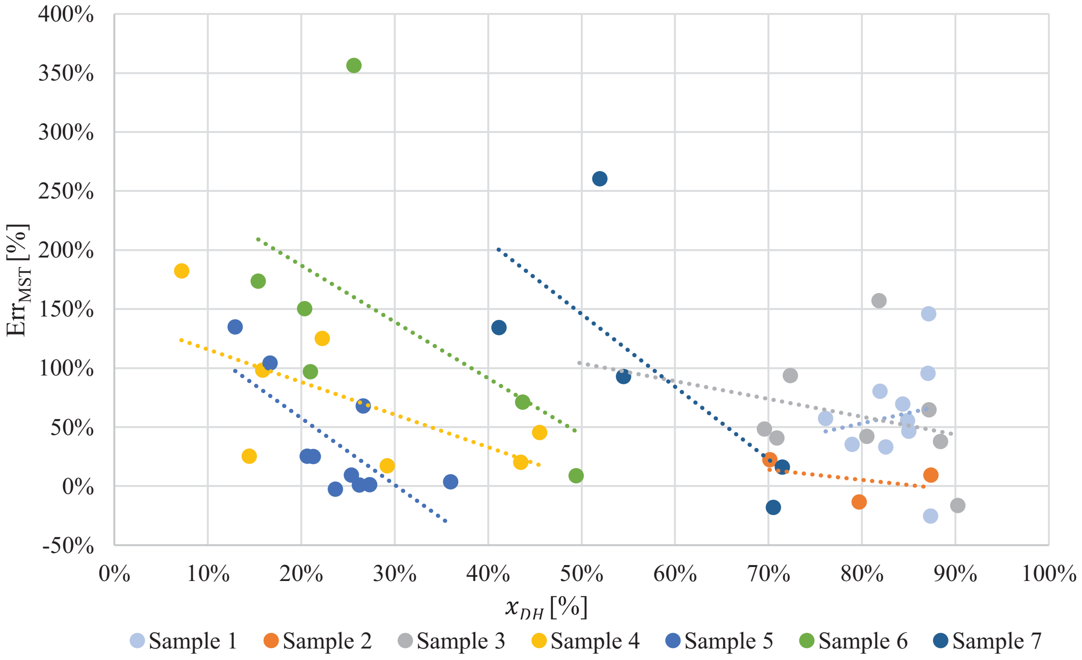

Figure 3.8 Correlations of MST Errors and potential share of buildings with centralized heating system considering single networks separately.

3.2. Effective width and linear heat density

After having validated the MST method, the results of simulated networks are used together with input data to build the effective width. The results of the effective width on the analysed census areas are presented in Figure 3.9.

In blue the figure shows the results of the application of the effective width curve presented in references [50] and [35], in black the effective width calculated as the ratio of land area and real length of the analysed networks and in orange the results of the application of MST, all of them as a function of the ratio of number of buildings on total land area.

Two preliminary consideration stands out. The first is that the Italian DH network shows bigger w than

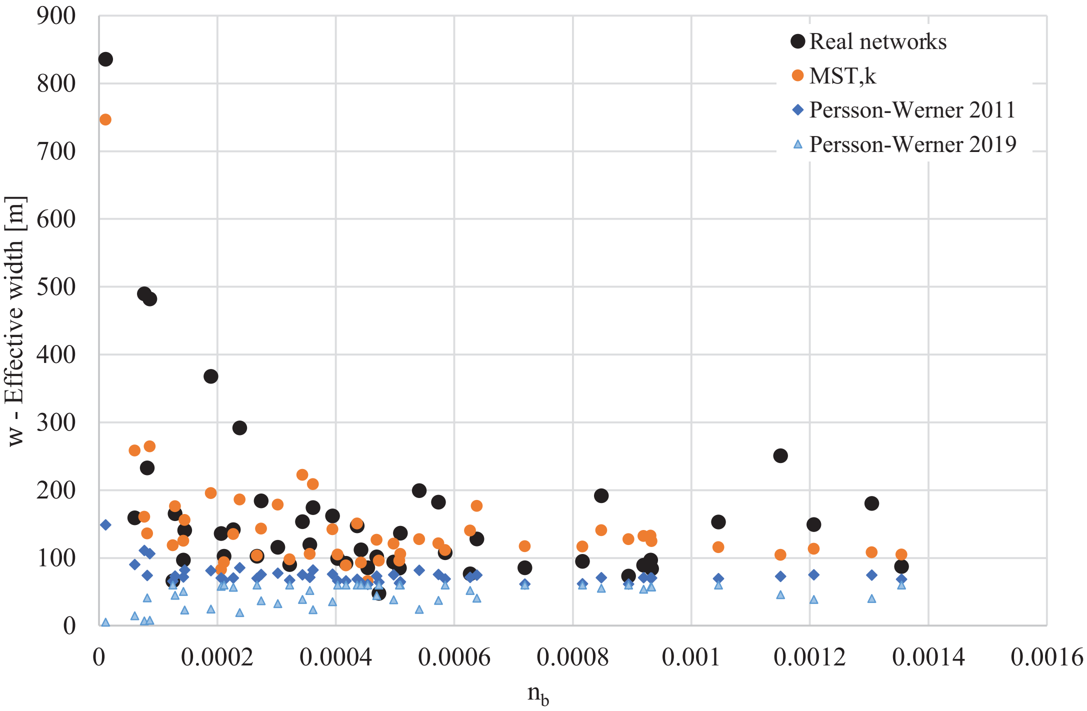

Figure 3.9: Effective width as a function of n_b calculated with real data, MST and according to Persson-Werner correlations [9] [7].

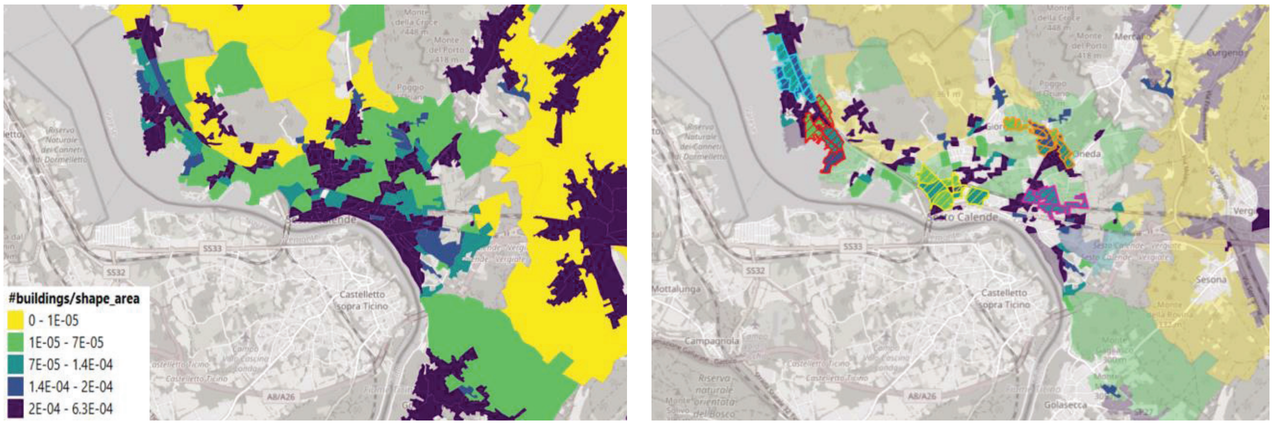

Figure 3.10. a: Extraction of GIS visualisation of n_b in sparse areas per census tract.
b: In coloured border the areas selected for the application of MST.

Scandinavian ones: in fact, even if the two curves by Persson and Werner are applied on the only available residential buildings surface data, they result in generally lower value of w.

The asymptotic tendency of Scandinavian w tends to 60 m while the Italian one approaches to 100 m.

The second is that, as expected, networks data collected are all related to moderate or high-density areas. This has motivated the application of MST in area with low density, thus in areas with number of buildings per land area, n_b, in the range of $n_b < 2 \cdot 10^{-4}$.

A map of n_b in the Lombardia region, the region in which all the analysed networks belong, has been produced by selecting these areas and a sample is presented in Figure 3.10.a. The areas in yellow and in green depict the census tracts with the least number of buildings and with the lowest values of n_b, as it can be seen in the legend of the map.

Nevertheless, most of the yellow and green areas have been excluded from the analysis since they tend to present total land area value of greater order of magnitude, being therefore unfairly comparable to already available data. A threshold of $1{\cdot}10^5$ m^2 of land area size has been therefore applied. The census tracts exceeding this value are represented in transparency in Figure 3.10.b, together with five areas selected among the remaining census tracts for the application of MST.

The effective width synthetic points resulting by the application of MST in 26 low density analysed areas are presented in red in Figure 3.11. The addition of these simulated points increases the sample of analysis from 50 to 75.

The results of effective width based on MST confirm the decreasing tendency of the *w* curve, in accordance with the first expression presented by Persson and Werner in 2011. An error analysis applied to three ten-

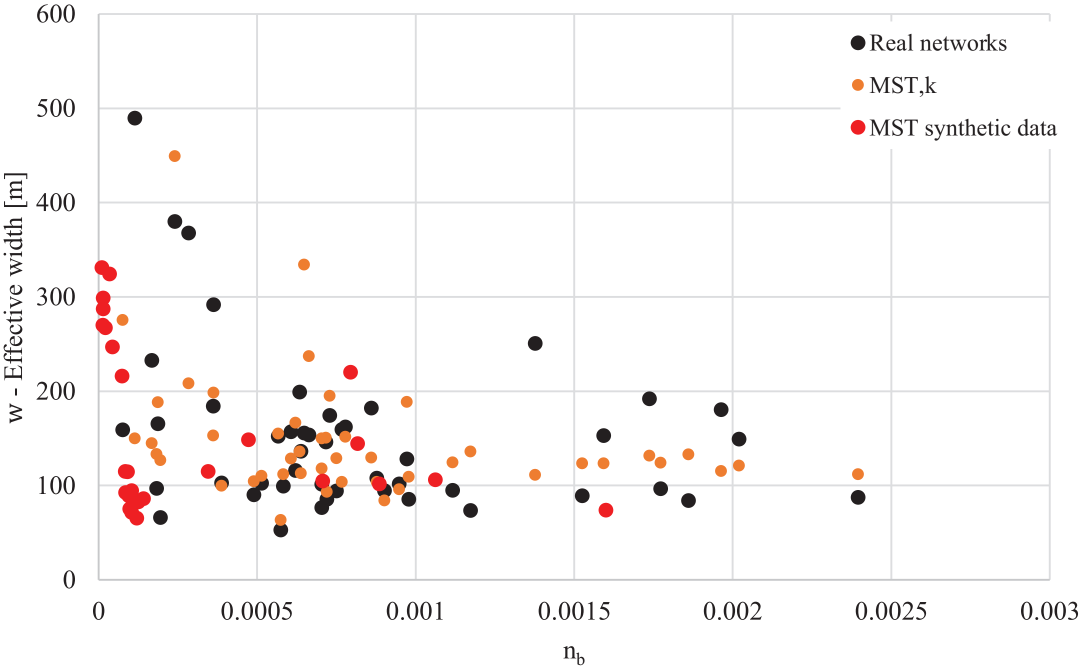

Figure 3.11: Effective width samples integrated with synthetic data in low density areas (in red).

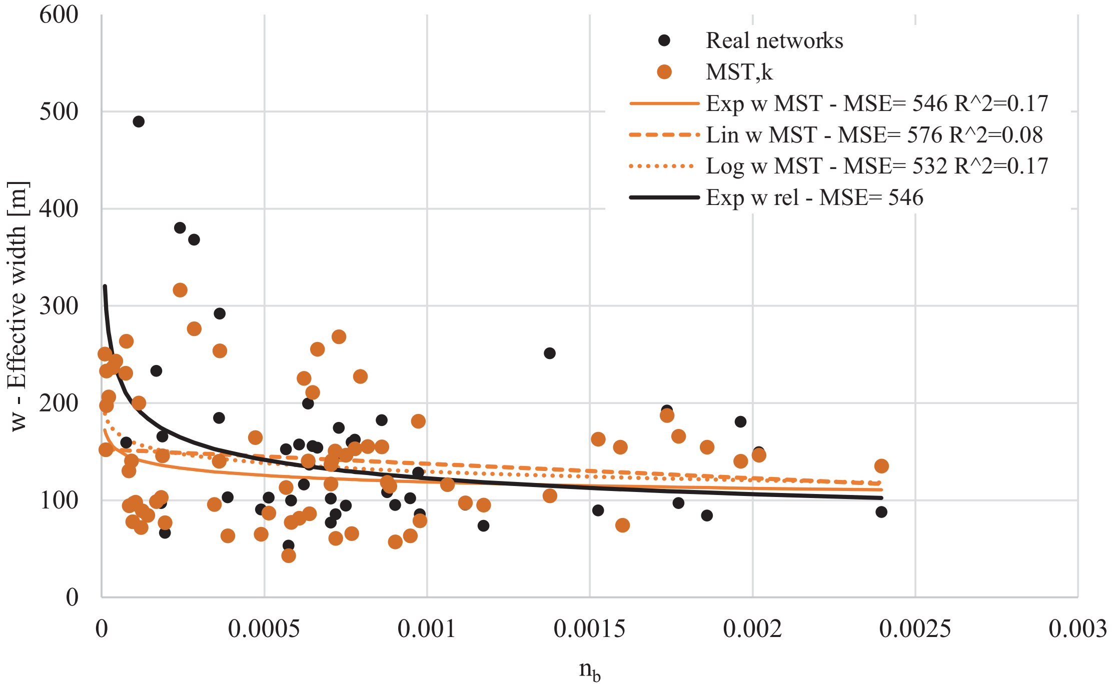

Figure 3.12: Effective width tendencies – exponential, linear and logarithmic - and their related Mean Square Errors.

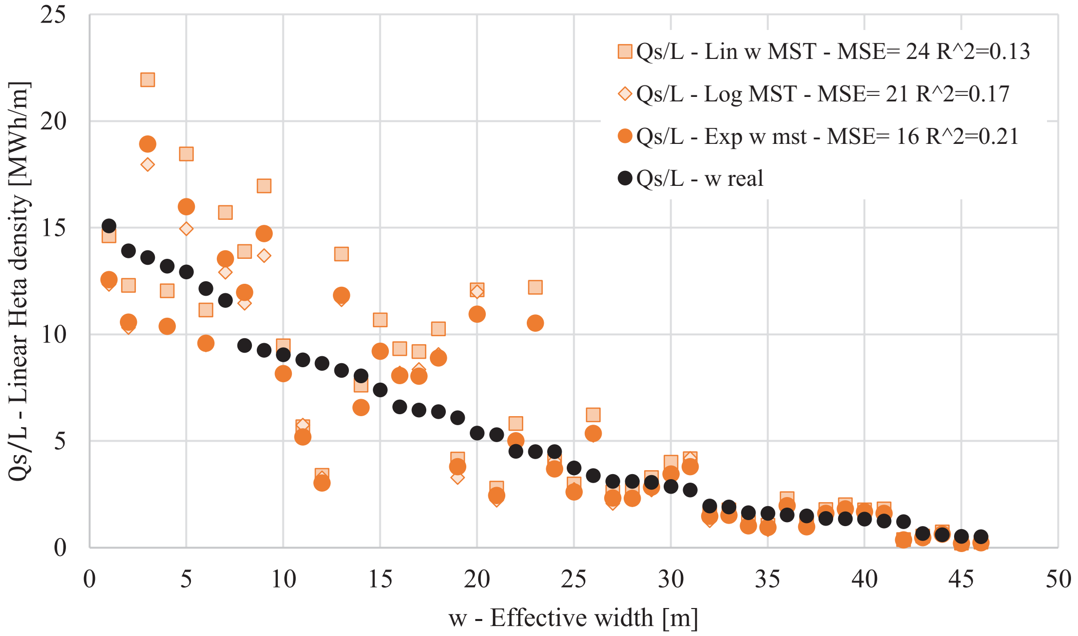

Figure 3.13: Linear heat densities calculated according to different effective width correlations and their MSE.

dencies, linear, logarithmic and exponential has been performed showing that logarithmic and exponential correlations have the smallest errors. Nevertheless, the exponential correlation seems more suitable to the asymptotic tendency on the x-axis.

In order to confirm this, the effective width impact on linear heat density has been analysed.

Figure 3.13 shows the results of linear heat density calculated with the Eq. (2.9) according to the correlations presented in Figure 3.12. The linear correlation implies the highest mean square errors (MSE), while the exponential is the correlation of effective width which minimizes the MSE on linear heat density.

The linear heat density results confirm that the exponential correlation is the one which produces closer results to real data one. The exponential correlation is represented by Eq. (3.3), being the one with the smallest error.

$$w = 50.25 \cdot n_b^{-0.127} \qquad [\text{m}] \qquad (3.3)$$

4. Application of the method and results

The correlation in Eq. (3.3), derived with the described methodology, has been applied to the city of Milan as a case study to show the impact of the use of the existing effective width correlation and the updated one on DH distribution costs. The results are presented here, in comparison with the ones obtained by applying the reference effective width curve of Eq. (2.5).

The starting point of the analysis is the map, shown in Figure 4.1, of the heating needs for the civil sector, residential and tertiary, in Milano. The maps in Figure 4.1 have been created based on the heating need data retrieved from the concurrent work “A transparent assessment of retrofit potential in Italy based on open data” presented at the 6th International Conference on Smart Energy Systems [52].

The picture clearly shows the geographical mismatch of the heating needs in these two sectors and better motivate the necessity of using both residential and tertiary sector data, that has brought to the formulation of a new effective width curve. Indeed, as already explained in paragraph 2.2, since in national census database only residential buildings’ surfaces are available, the availability of input data brought to formulate a different effective width curve, where the number of buildings is used instead of the buildings’ surface.

Observing the picture below, it can be understood that the use of the plot ratio referring to simple residential buildings would have brought to an underestimation of the linear heat density (and hence of the DH potential) in the areas where there is an important energy demand due to tertiary sectors: mainly in the city centre, but also in business and commercial districts in the surroundings.

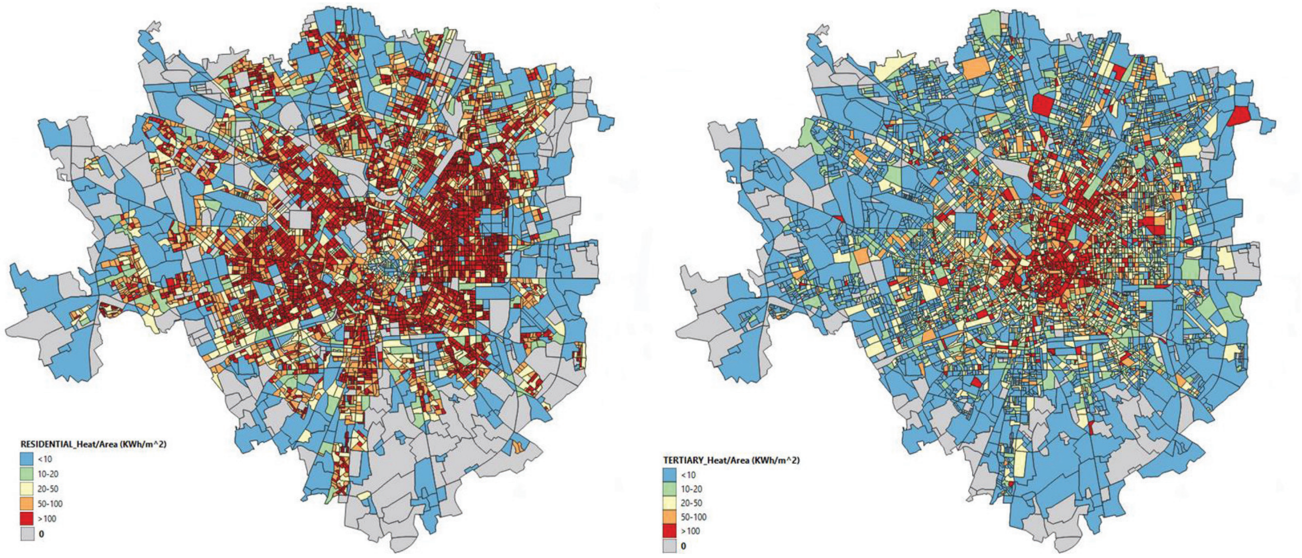

Figure 4.1 Residential and tertiary sector heat demand over total land area.

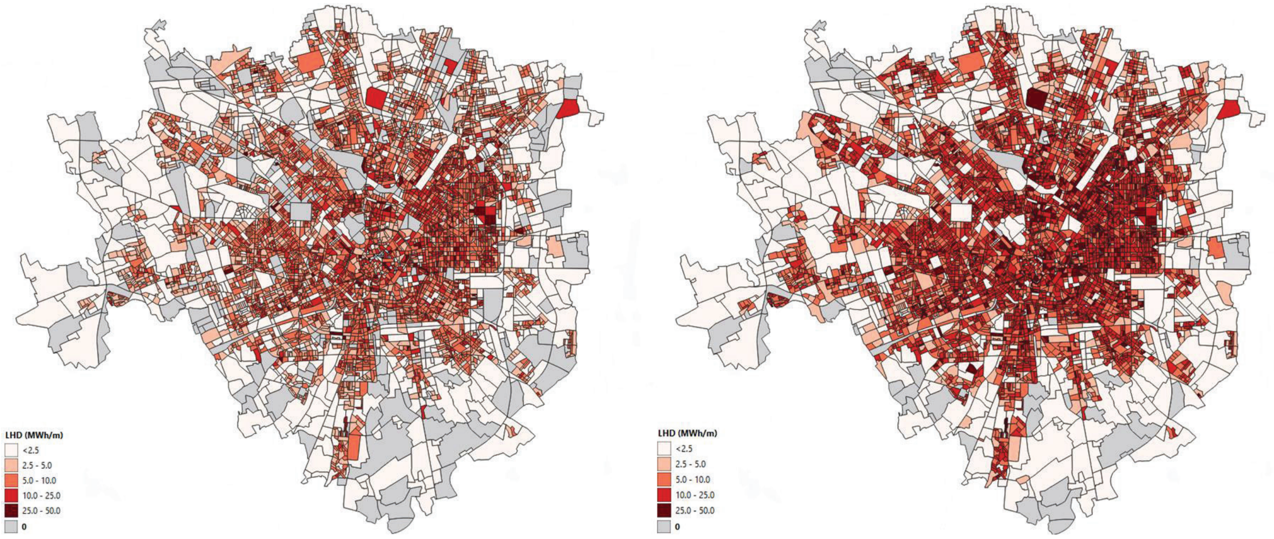

Figure 4.2: Linear heat density, calculated with the Eq. (2.4) on the left and with the Eq. (2.8) on the right.

Concerning the results derived by the application of the two different curves, the maps of the linear heat density in Figure 4.2 and of the distribution costs in Figure 4.3 are reported below. The maps on the left are obtained by applying the Eq. (2.5) and (2.4) from the reference approach developed by Persson et al. [34]; the maps on the right by applying Eq. (2.8) and (3.3) obtained with the methodology here illustrated.

By observing the Figure 4.2, it can be noted how the lower values of effective width as a function of the number of buildings (see Figure 3.9) translate in higher values of linear heat densities. It's worth high lightening that the linear heat density is calculated considering the share of buildings with centralized heating system calculated for every census tract.

According to the distribution capital cost model conceived in [38], higher values of linear heat density mean lower values of distribution capital costs: that is the main outcome displayed in the maps in Figure 4.3, obtained by applying the Eq. (4.1).

$$C_d = \frac{a*(C_1 + C_2 * d_a)}{\frac{Q_s}{L}} \qquad [€/MWh] \qquad (4.1)$$

where the other parameters have been assumed as:

Annuity	$a = 5\%$	[-]
Construction cost constant	$C_1 = 782$	[€/m]
Construction cost coefficient	$C_2 = 1878$	[€/m^2]

Pipe diameter

$$d_a = 0.0486 * \ln\left(Q_s / L\right) + 0.0007 \quad [\text{m}] \qquad (4.2)$$

The logarithmic relationship between linear heat density and average pipe diameter was established in [38]. For values of linear heat density below 0.42 MWh/m, pipe diameters of 0.02 m have been applied.

The effective width curve here revised with the aim to obtain more representative results for the Italian territory, even in sparse areas, leads to higher potential for DH expansion in the case study of Milan, with respect to the results that would have been obtained by using the Scandinavian reference curve. This difference is mostly due to the fact that by considering input data of both the residential and tertiary sectors, i.e. the number of buildings, lower values of the effective width are obtained and the underestimation of the linear heat density is avoided.

5. Discussion and conclusions

This work addresses the challenge of assessing DH network lengths in potential analysis of diffusion of DH in areas where this infrastructure is not already present.

The main outcome of this work involves the application of MST algorithm to estimate network topologies which has shown, under a certain determined margin of uncertainty, to be a good tool to support the simulation of network topologies.

Real networks' lengths coming from a sample of Italian DH systems have been used to validate the MST and to update the effective width curve available in literature to Italian cities.

All the analysed methods, namely the effective width and the Minimum Spanning Tree, have proved to be able to give answers to the research question of assessing network length in DH expansion areas even if with some weak points.

The first of this is related to the comparison of real network data used for the assessment of these methods: the shapefiles provided by utilities representing distribution pipes are not uniform since some of them includes transports or service pipes which bring to misleading validation results. Regarding input data, buildings database and heating system database often contains incomplete or outdated information or they cannot communicate because they are based on different information.

The MST is a very accurate method but if applied to these low quality input data, it could outcome in non-representative results. On the other side, the effective width is based on empirical information, that can

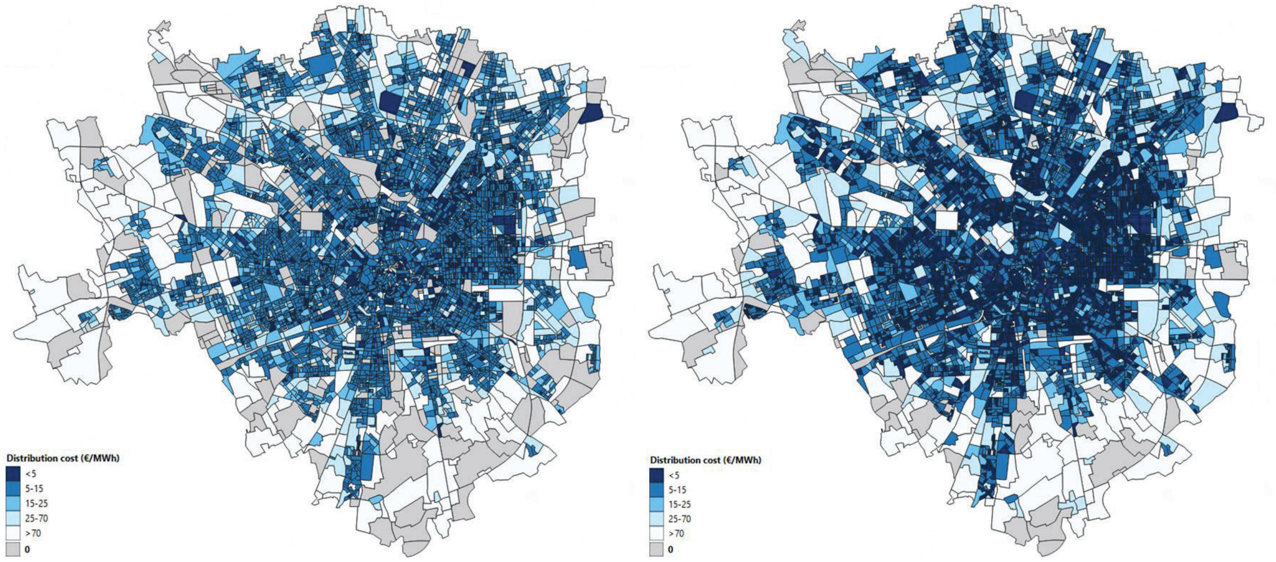

Figure 4.3: Distribution costs, calculated with the Eq.(4.1). Values obtained by using the linear heat density from Eq. (2.4) on the left, and from Eq. (2.8) on the right.

have low quality as well, but, even if less accurate in terms of methodology, it brings to more representative results.

The strength of the proposed methodology is to combine these two approaches to finally obtain an updated version of the effective width, which has the benefit of being a fast and easy correlation to be used at high level big scale planning analysis, that has been refined with the use of MST which is more used for detailed analysis.

In general, all the analysis performed on MST and effective width in comparison with real networks data have quite low R^2 values, because the sampling data is very sparse. Further researches are required with more data and based on uniform spatial units, such as regular grid cells instead of census areas, in order to have more comparable results.

A first observation that can be drawn from this work is that in comparing effective width results from Italian networks to the ones from Scandinavian countries, Italian cities shapes bring to general higher values of effective width. This means higher values of linear heat densities and therefore lower distribution costs and higher potential for the diffusion of district heating in the country. So an important outcome of this work is that different countries with different city shapes appear to require different correlations and therefore further research in this direction is required also to make the results more comparable (e.g. by using squared regular raster grids instead of irregular land shape areas).

An additional result of the analysis of the effective width in this work is that MST has helped in the increase of sampling of DH network by adding synthetic points of simulated networks in an area of the graph in which there is a general lack of data, which makes the results more uncertain: the area with low density buildings.

The analysed results helped in finding a suitable correlation from the effective width with more reliable results in low density areas. The analysed data seems to confirm the first version of the effective width curve, the exponential one, even if with different coefficients for the analysed areas in northern Italy.

The impact of the newly developed correlation on the calculation of linear heat density has been investigated highlighting the better correspondence of the heat distribution especially in areas with higher tertiary heat demand.

The findings of this work need nevertheless further analysis by widening the sample of analysed network and context. The research related to the estimation of network topology by territorial parameters is at the beginning but opens the doors to specific research paths in the direction of comparability of results and independence to the input data in order to increase the general validity and robustness.

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