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NETWORK ASSIMILATION METHODOLOGY AND SECTORIZATION OF WATER DISTRIBUTION SYSTEMS BY GRAPH MINING AND OPTIMIZATION ALGORITHM

Presentata da:

Lorenzo Carmelo Zingali

Supervisore:

Prof.ssa Cristiana Bragalli

Co-supervisore:

Prof. Michele Monaci

Coordinatore di Dottorato:

Prof. Alessandro Tugnoli

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Abstract

Water Distribution Networks (WDNs) play a vital importance rule in communities, ensuring well-being band supporting economic growth and productivity (Dunn and Wilkinson, 2013). Consequently, they are identified as critical infrastructures for which the identification of interventions priorities is a fundamental step. The growing of WDNs has not often been the result of an overall design, but has followed various upcoming needs due to new urbanizations and the need to connect new resources to compensate for the increase in water demand. Therefore, in addition to problems related to rapid development of the systems, it is necessary to deal with the aging of infrastructures which in some situations can cause high levels of water loss. In context of water scarcity due to the increase in water consumption and the impact on the availability of water resources caused by climate change, there is a consequent reduction in reliability. The need for greater investment then requires design choices will impact on the efficiency of management in the coming decades. This thesis proposes an algorithmic approach to address two related problems: (i) identify the fundamental asset of large WDNs in terms of main infrastructure; (ii) sectorize large WDNs into isolated sectors in order to respect the minimum service to be guaranteed to users. Two methodologies have been developed to meet these two objectives and subsequently they were integrated to guarantee an automatic process which allows to optimize the configuration of the sectorized network taking into account the needs to integrated in an overall vision the two problems (i) and (ii) considered. With regards to the problem (i), the concept of a subset of continuously connected pipes mainly dedicated to transport water from the sources to the pipes instead mainly dedicated to supply users is consolidated, but in large looped WDN the identification of this subset is not uniquely determined. A part of literature is indeed dedicated to the degree of importance of each pipeline, often measured on the impact in terms of hydraulic operation and satisfaction of water consumption due to an interruption of its flow. Identifying the main connections between water production, pro-

cessing and distribution sites can give a clearer comprehension of their structure, importance and criticality (Fortini et al., 2014). Graph theory is particularly suitable for the description of a WDS. Indeed, a Water Distribution Network could be represented as a Graph. The vertices of the Graph are all punctual elements of the WDN that are junctions (elements in which the water demand to be satisfied is allocated), and nodes with fixed value of hydraulic head that represent the water resources that supply the WDN or the internal tanks to it. The edges of the Graph are all linear elements of WDN,in details pipes, valves and pump stations. If more specific information is available, the Graph can also be weighted using a dimension (physical attribute) or a combination of physical and hydraulic attributes. The methodology introduces the concept of primary network to give an answer to the problem (i) with a dual approach, of connecting the main nodes of WDN in terms of hydraulic infrastructures (reservoirs, tanks, pumps stations) and identifying the paths with the minimal potential energy loss. This methodology is able to provide a result without necessarily using a hydraulic model, which is not always available to avoid that the primary network obtained may be affected by the current operational rules that could be not optimal. The primary network identified can be used to read infrastructural critical issues of the open WDNs for re-design purposes or as a base to design the sectorization of WDNs. The sectorization of WDN, also defined as water network partitioning in district meter areas (DMAs), has the purpose to improve water loss detection, pressure management and the protection from accidental and intentional contamination of water resources. Also it can represent an opportunity to re-design the layout and re-define the water management and operation of the new configuration of WDNs starting from the existing hydraulic infrastructure. The sectorization problem (ii) has been faced using optimization techniques by means the development of a new dedicated Tabu Search algorithm. In literature, the introduction of objective functions in the problem formulation has naturally led to use the optimization algorithms, mainly the heuristic algorithms, mainly the heuristic algorithms, in the proposed methodologies (Gilbert et al., 2017; Liu and Lansey, 2020; Mu et al., 2021) . The design criteria expressed by the objective functions require the assessment of hydraulic variables, thus also the hydraulic model is generally part of the appraches (Nardo et al., 2016; Zhang et al., 2019; Pesantez et al., 2019; Sharma et al., 2022), as in the methodology developed in this thesis. The algorithm was developed to be able to deal with real case studies of large WDNs. For this reason, in this thesis three new hydraulic models of the WDNs have been created in order to be able to test the capabilities of the algorithm on different and complex cases of which a deep knowledge has been acquired. Also

some models taken from the literature with a high complexity in terms of number of elements and management rules, were used to test the efficiency of the approach. The methodology set up to automatically identify the primary network deficits by adding new pipes to it in order to sectorize the WDN has given a good response for the complex case studies in which the high degree of loops formed during the expansion of the real WDN has in fact defined a transport system with multiple parallelisms of the pipelines.

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Chapter 1

Primary Network

1.1 Introduction

Water Distribution Networks (WDN) in densely populated areas are complex graphs whose development took place in successive stages without an overall vision. A key interpretation of water distribution network is that the diameter of WDNs a pipe is not an absolute measure of the current importance of the edge, but a relative one: in less populated rural areas, the most important pipes have smaller diameters, comparable with the secondary ones of the water distribution network in urban areas; similarly, design choices or changing conditions compared to the original design, can lead to discrepancies between diameter and the aspected flow rate. Furthermore, the process of expansion and interconnection has often led to having aqueducts that supply both urban and rural areas, therefore the relative importance of the edges appears difficult to refer to clusters based on geometric dimension alone. To guide the planning, design and management decisions, a graph-theory based algorithm was presented in Fortini et al. (2014) introducing the concept of primary network with the goal of making the operation of water distribution systems more "readable", in particular by improving the ability to highlight the paths of transfer of water resources from the network entry points to the most relevant areas of water consumption, namely to water demand centers. The applications of this key of reading may include the identification of components relevance inside a given network framework; the identification of vulnerable areas within infrastructure systems; the optimal re-design of the water distribution networks.

1.2 State of Art

In WDN, the concept of a subset of continuously connected pipes mainly dedicated to transport water from the sources to the pipes instead dedicated to supply users is consolidated, but in large looped WDN the identification of this subset is not uniquely determined. A part of literature is indeed dedicated to the degree of importance of each pipeline, often measured on the impact in terms of hydraulic operation and satisfaction of water consumption that an interruption of its flow could cause. Identifying the main connections between water production, processing and distribution sites can give a clearer comprehension of their structure, importance and criticality (Fortini et al., 2014). If in a completely open WDN, this distinction between pipes mainly dedicated to transport water and pipes instead dedicated to supply users has lost importance, it becomes a key aspect in a sectorization design. An approach to determine the pipes mainly dedicated to transport water is presented by Brentan et al. (2018a) in which they define the trunk main through a process based on the shortest-path concept derived from graph theory associated to the flow in each pipe. Several general criteria distinguish the trunk network from the distribution network, such as diameters, connections, and locations. In general, the connection to the trunk network is restricted to medium-diameter and large-diameter pipes. Ferrari et al. (2014) identify water transmission mains as the series of connected pipes having a diameter equal to or greater than a threshold used to extend and convey water between sources, such as storage facilities, external water supply networks, wells, springs. Thus, the distinction made in the definition of transmission mains and distribution mains is a function of the size of the water system itself. The concept of pipes mainly dedicated to transport water in the sectorization of WDN is also considered in Liu and Lansey (2020), in which the feed pipes are determined as first phase of a multiphase approach to design a defined number of sectors. Identification of the trunk network is not a trivial matter as it determines to some extent the final partition of WDN and thus the implementation of sectors costs and the hydraulic performance of the sectorized WDN (Zhang et al., 2019, 2021). These main pipes refers to the pipes that have large diameters and transport a large amount of water. Each branch pipe on the main pipes can be considered as a possible outset of the sectors in design and the water is supplied from the main pipes to sectors through the branch pipes (Zhang et al., 2019). In Diao et al. (2016), the WDS is decomposed into a twin-hierarchy pipeline structure consisting of backbone mains and community feeders.

The backbone mains refer to all the most critical paths forming the backbone network of the system. For instance, trunks connecting critical infrastructures, e.g., reservoirs, tanks, and pump stations, thus changes of any backbone mains will have significant impacts on the whole system's water supply (e.g., water demand supplied, pressure, energy consumption). Graph theory and standard graph metrics of betweenness centrality (Freeman, 1977) and connectivity were adapted to account for connectivity to supply points in the system by Giustolisi et al. (2019) and Chen et al. (2021). This approach to define pipeline criticality assessments can be used as a mirror reading in terms of importance of the pipes; this type of approach can be further refined if the hydraulic model is available (Meijer et al., 2021).

1.3 Definition of Primary Network

The approach developed in the Primary Network identification methodology is based on the hydraulic infrastructure analysis, thus not conditioned by the current operation rules that could be not optimal. The primary network identified with the methodology explained in this chapter wants to give a reading of the WDN beyond the rules with which it is managed. This perspective makes it possible to analyze the present infrastructure in terms of available pipelines without the conclusions being conditioned by operational choices which could also be non-optimal. As far as the contribution of numerical modeling is concerned, this can be found to be interesting only if the information for the construction of the model and its calibration are available and reliable, a condition which is not always achieved in practical applications. For the definition of the primary network it is first necessary to introduce the concept of primary nodes. Primary nodes are significant points elements of the water distribution network as reservoirs, tanks, pumping station, connections with others WDNs. The primary network is here defined as the portion of water distribution network that connects the main nodes (Reservoir, Tanks, Pump station, connections with others WDNs) and a proper fraction of consumption by means the minimum weighted path. Following the given definition, the methodology developed to find the primary network consists on the sum of two different algorithmic approaches:

- System approach, in which the primary nodes are connected
- Consumption approach, in which the asset that supply customers is identified

In both approaches the WDN is considered an indirect graph (Multigraph if self loops are present in the WDN). The weight attributed to the edges is an infrastructural weight, which can be also representative of the distributed head losses in each edge. In fact, the weight is obtained starting from the Darcy-Weisbach formula:

$$\Delta H = \frac{\lambda}{D} \cdot \frac{v^2}{2g} \cdot L = \frac{8\lambda}{g\pi^2} \cdot Q^2 \cdot \frac{L}{D^5} \tag{1.1}$$

where the friction factor λ can be calculated by Colebrook – White formula. The meaning of this weight indicates that to minimize energy dissipation to transfer a given flow rate, pipes with greater diameter must be chosen, also taking into account the length. Consequently, the infrastructural weight attributed to each pipe can be assumed equal to:

$$weight = \frac{8\lambda}{g\pi^2} \cdot \frac{L}{D^5} \tag{1.2}$$

If the information on the roughness of the pipes were not available or reliable, a homogeneous value of the roughness can be assumed for the whole network and therefore the weight is reduced to:

$$weight = \frac{L}{D^5} \tag{1.3}$$

Consequently, a path with a lower weight is more energy efficient than a path with a higher weight.

1.3.1 System Approach

A systemic reading of the WDN based on the hydraulic infrastructure, initially requires identifying the fundamental nodes, which are defined here as primary nodes. The points of vital importance for a WDN are first of all the resources or the nodes that supply the network, which in the hydraulic model are represented by the Resevoirs or by nodes with imposed head. Also of fundamental importance are all those tanks and pump stations which, due to their position or size, make possible to supply WDN. Finally, in certain WDNs, nodes can also be identified whose demand represents non-disconnectable consumption, for example water transfer nodes to other networks or customers of particular strategic importance for the city. According to an infrastructural approach, the primary network can be defined as the minimum cost tree that connects the identified primary nodes. This problem can be equated to a problem known in the literature as the Steiner tree problem (Ljubic, 2021). The Steiner Tree is an NP-hard problem. Given a weighted indirect graph G(N, E) and a subset $S \subseteq N$ the goal is to determine a minimum cost tree that must contain all the nodes in S. In this thesis to solve the Steiner Tree problem in a WDN the Leitner et al. (2018) algorithm was used. The weight assigned to each edge can be identified with regards to different criteria. Following the systemic reading of the WDN based on the hydraulic infrastructure, the weight given to the edges is the one defined in the equation 1.3. The result provided by the resolution of the Steiner Tree problem gives fundamental information: the identification of the minimum energy cost tree (from an infrastructural point of view) between the resources and the other primary nodes of the network. In fact, in WDNs where there are more resources and the need to manage their exploitation based on their availability, it is of fundamental importance to understand how they are connected. Therefore, identifying pipes with very small diameters in the minimum energy cost tree allows to identify the structural deficits of the network, and the real possibility of replacing one resource by increasing the contribution of the others. The primary network identified from a reading of the existing connections between the primary nodes does not provide a complete reading of the main assets of WDN. In fact, if for some reason the network has not been designed to have resources that communicate with each other through a network of significant diameter, the algorithm is able to highlight a structural deficiency, but not to identify which are the most important pipes for transporting the resource in the current configuration. Furthermore, if the WDN is supplied by gravity from a single resource (Reservoir) or has more than one resources close to each other from a topological point of view and well connected, no primary network can be identified (in the first case) or a small primary network is identified that connects the resources but is not able to identify the important asset for distribution. To solve the problem in this case it could be extended by adding to the subset of the nodes to be connected the nodes with a demand greater than an established demand. In this case there would be the risk that the primary network pass through nodes with a high demand but not necessarily significant, in fact there may be groups of nodes close and connected to each other (clusters) that are more significant in terms of total demand. For these reasons, an approach that takes into account the spatial distribution of water consumption in different way is needed.

1.3.2 Consumption Approach

The edge betweennes has found application in WDN (Giustolisi et al., 2019; Chen et al., 2021) for its ability to read the most important edges. The edge betweennes is a fundamental reading tool to understand which edges are most important to ensure the connectivity of the nodes in a graph, but in the case of a graph representing a WDN not all nodes have the same importance by function or for consumption. A classic application of edge betweenness in a WDN could be misleading for two reasons. The first is that the source nodes are treated like all other nodes, the second is that the nodes are not distinguished by the water demand. The first problem can be solved by calculating the edge betweenness only between the resources and the nodes (therefore not between node and node)((Chen et al., 2021)). To solve the second problem as well, an algorithm was developed that is able to take into account the importance of the various nodes in the network, in terms of consumption. The nodes in a WDN have different requests from each other, an application that attributed equal importance to the nodes would risk distorting the result. Obviously, any edge can be of fundamental importance to ensure total connectivity of the network, but in this case we want to prioritize the edges not according to the importance of guaranteeing the connection to the nodes but according to the importance of guaranteeing the connection with respect to the demand of the network. With the aim of approaching large real WDNs, the type of data and cartography must be considered. The presence of a node separating two edges in a cartography of a WDN can depend on many variables. In addition to every connection with another edge, there is certainly a node in every change of diameter and material in the pipes. They could be a node for the decision to break an edges given the presence of groups of users, in order to be able to attribute their demands to the node. Another reason is the presence of a valve which in a GIS could correspond to a node or two (as in the case of a hydraulic model) depending if valves are represented by a punctual or linear element. Therefore, in the cartography of a WDN, there could be clusters of nodes without large consumption and small groups of nodes with consistent consumption. In this case, in terms of connectivity to the nodes, more importance is given to the edges that connect the former to the resources than to the edges that connect the latter to the resources. For this reason, the Consumption approach algorithm (Algorithm 1) was developed which measures the centrality of the edges based on the demand of the nodes. This algorithm uses the complete graph of the WDN whose weight of edges is the infrastructural one (equation 1.3). In the graph, a "counter" attribute set equal to zero is defined for all the edges of the WDN graph. A node is considered and the shortest paths that connect it to the resources (Tank and Reservoir) and the corresponding weights of the paths found. Among the shortest paths, the shortest and therefore the closest resource is identified. All the edges that are part of this path are identified and the node demand value is added to their counter. This operation is repeated for each junction of the WDN. In this way, therefore, the most energetically convenient paths that connect the nodes to the resources are identified, weighing them according to the demand that they theoretically transport. It was evaluated in terms of results whether it could be more representative to choose all the shortest paths that connect the node to the resources and apply a counter increase to them. But it was considered that the analysis could be redundant with respect to the System approach 1.3.1, since the connection of the resources to each other and therefore of the node with all the resources is already guaranteed by the Steiner Tree.

1.3.3 Identification of Primary network

The last step allows the identification of Primary network. As regards the Consumption Approach is required to decide a probability value q and calculate the $q - quantile$ in the population of the counters found. The pipes considered to belong to the primary network are those that have a counter greater than the $q - quantile$. The primary network is constituted by the sum of the result obtained with the System approach and the result obtained with the Consumption approach (fixed at q-quantile). The primary network thus obtained by the analysis of the WDN according to the two approaches is therefore able to highlight on one side the most important pipes for connecting the main nodes and on the other for supplying the demand nodes. To be able to use the primary network not only as an interpretation of the existing infrastructure, but also as a basis for redesigning purpose, it may be useful to loop it.

1.3.4 Primary network expansion

For the terminal nodes of the network, i.e. those nodes that have only one primary incident edge, it is possible to search if there is any path that connects them that is more convenient in terms of weight than the one currently identified. To do this, the terminal nodes are connected to each other with the shortest paths (as it can be seen in Algorithm 2) and edges that do not already belong to the primary network are added.

Algorithm 1: Consumption approach

```
Input  :
         WDN Graph
         list of sources
Output:
         counted edges
initialization;
for each edge of WDN Graph do
    edge[counter] = 0;
end
for each junction of WDN Graph do
    read junction Demand;
    for each source of WDN graph do
        calculate shortest path (from junction to source);
        calculate shortest path weigth (from junction to source) ;
    end
    find minimum shortest path weigth;
    choose minimum shortest path;
    for each edge of minimum shortest path do
        edge[counter] = edge[counter] + junction Demand;
    end
end
```

Algorithm 2: Primary network expansion

```
Input  :
        WDN Graph
        primary network graph (sum of Steiner Tree and Consumption Approach)
Output:
        primary network looped
initialization;
define an empty terminal list;
for each node of primary network graph do
    find node degree;
    if degree==1 then
        add node at terminal list;
    end
end
if length of terminal list > 1 then
    calculate all combinations of length 2 of terminal nodes;
    for each combination do
        read first node of combination;
        read second node of combination;
        calculate shortest path (from first node to second node in WDN Graph);
        for each edge of shortest path do
            if edge is not in primary network then
                add in primary network;
            end
        end
    end
end
```

Chapter 2

Sectorization

2.1 Introduction

Water distribution networks (WDN) have often grown in disorderly way to respond to upcoming needs, without an overall design. So often it is of fundamental importance reorganize WDN layout to optimize the operation and management. For this reason, WDNs can be partitioned into sectors (in literature also named District Meter Areas). Sectors are defined as sub-network isolated from each other by means of disconnections already existing in the layout or by closing isolation valves; as result, this process determines defined hydraulic boundaries for the sectors. Also, each sector is supplied by one or more entry points in which the quantities of water entering and leaving the area are metered, along with other parameters, such as pressure. Managing a water network in smaller sectors can assist in achieving goals, such as controlling pressures, maintaining water quality and identifying leakages.A first criterion is to identify the sectors considering physical boundaries that are normally present within the WDN layout, as railroads, rivers, highways that interrupt the continuity of pipelines and reduce the degree of connection between pipes. Other criteria for the division of the network into sectors have been widely investigated, generally grouped into topological, hydraulic and economic.

2.2 State of the Art

The sectorization of WDN, also defined as water network partitioning in district meter areas (DMAs), has the purpose to improve water loss detection, pressure management and the protection from accidental and intentional contamination in a context of expansion of WDNs. The process of sectorization of WDNs can represent an opportunity to re-design the layout and re-define the water management and operation of the new configuration of WDNs starting from the existing hydraulic infrastructure. Gilbert et al. (2017) consider the sectorization of a large water distribution network into district metered areas (DMAs) and simultaneously optimize the rehabilitation of the network with new pipes, control valves, and storage tanks with a multistage approach. Designing configurations of WDN subdivided in sectors to meet management goals, such as pressure or demand uniformity, is challenging. Traditionally, WDN sectorization is conducted using a trial-and-error approach. Considerable efforts have been made by scientific research in development of procedures based on different assumptions for the identification of sectors. The approach to the sectorization follow in literature is generally divided in phases (Khoa Bui et al., 2020): (i) clusters identification, which focus on defining the optimal configuration of sectors; (ii) sectorization or boundaries optimization, which physically decompose the network by selecting pipes that connect the sector to decide if installing flow meters or gate valves and (iii) performance evaluation of the partitioned network (Bianchotti et al., 2021; N. Sharma et al., 2022). The last phase is highlighted by Palomero-González et al. (2021) to help the decision making regards to sectorized WDNs. The use of graph theory is widely applied (Alvisi and Franchini, 2014; Scarpa et al., 2016; Pesantez et al., 2019). In literature other approaches were applied as the community detection algorithms based on social network theory (Brentan et al., 2018b; Zhang et al., 2021; Sharma et al., 2022). The criteria for choosing of edges to close is made in order to assure the minimum pressure during the peak water demand, in some approach this concerns only non-zero demand nodes (Pesantez et al., 2019). Furthermore, other criteria can be introduced as to maximize the resilience of the entire systems (Alvisi and Franchini, 2014; Scarpa et al., 2016), also minimizing the coefficient of variation of demand similarity among sectors, as in Pesantez et al. (2019). The number of sectors can be assigned a priori (Alvisi and Franchini, 2014; Liu and Lansey, 2020; Castro-Gama et al., 2016). In Scarpa et al. (2016) consider a multisource condition and the design of sectors is driven by the areas of influence of each supply source for the WDN. Another criterion in the design of sectors of WDN concerns the reduction of background leakage, that coherently requires to optimize the pressure management by means the introduction of pressure reducing valves at the inlet points of hydraulically isolated sectors (Zhang et al., 2019, 2021). Clearly, pressure management requires creating isolated sectors by closing isolation valves and installing measuring instruments at only the few inlet points left open to supply each sector. A different perspective considers the creation of virtual sectors by installing bidirectional flow meters along the pipes that connect the sectors so as to allow the water balance with the closure by means of isolation valves of a few connections. The introduction of objective functions in the problem formulation has naturally led to use the optimization algorithms, mainly the heuristic algorithms, in the proposed methodologies (Gilbert et al., 2017; Liu and Lansey, 2020; Mu et al., 2021). The design criteria expressed by the objective functions require the assessment of hydraulic variables, thus also the hydraulic model is generally part of the proposed methodologies (Nardo et al., 2016; Zhang et al., 2019; Pesantez et al., 2019; Sharma et al., 2022). For WDN partitioning, Creaco et al. (2019) considers the fast-greedy partitioning algorithm (FGPA), based on the original formulation of modularity, to merge elementary parts of the WDN in sequential steps until the desired number of district metered areas is reached; furthermore optimization techniques were combined with FGPA to propose different merging combinations. The choice of the best suited sectorized configuration of WDN from a set of feasible alternative solutions based on the preference given to each objective can be sustained by means multiple attribute decision-making method (MADM) as in Sharma et al. (2022). In some approaches, human experience is also considered in the process for an engineering adjustment (Zhang et al., 2019). The applicability of the sectorization methodologies to real WDN requires to test them on large layout (Vasilic et al., 2020) . For highly constrained large WDNs, Pesantez et al. (2019) combine geospatial analysis with a hydraulic simulator to design sectors. The changes in the scenario of availability of water resources and water consumption or events within the hydraulic infrastructure as breaks, operational problems, water contamination, could require to revise the partitioning of the sectorized WDN. Giudicianni et al. (2020) propose a multiscale network layouts for a WDS based on Complex Networks Theory to automatically define the dynamic partitioning of WDSs to support further DMA aggregation/disaggregation operations using the resilience index (Todini, 2000) as a driver.

2.3 Problem Formulation

The methodology developed has the purpose of dividing the existing water distribution network into sectors isolated each other and supplied by a primary network. The methodology is founded on the idea of an overall design in which the determination of the primary network and of the sectors is developed by means a unique process. At the end of this design process, the isolated sectors will be supplied by the most promising pipelines already present in the WDN. At each phase, the part of the WDN to be sectorized is that obtained from the complete WDN by subtracting the primary network. The primary network is therefore excluded from the sectorization process having the role to transport the water to the sectors. In the Chapter 1 the methodology to identify the primary network has been proposed. The problem formulation to design isolated sectors is described in the following paragraphs. Some definitions necessary to understand the following formulation are given below:

- E is the set of edges of the WDN, and e is the generic element belonging to the set E ($e \in E$)
- N is the set of nodes of the network, and n is the generic element belonging to the set N ($n \in N$)
- R is the set of water storage (reservoir and tank) of the WDN ($R \subset N$), and r is the generic element belonging to the set R ($r \in R$)
- J is the set of junctions of the network ($J \subset N \setminus R$), and j is the generic element belonging to the set J ($j \in J$)
- E_P is the set of edges belonging to the primary network ($E_P \subset E$), and e_P is the generic element belonging to the set E_P ($e_P \in E_P$)
- N_P is the set of nodes of the primary network ($N_P \subset N$), and n_P is the generic element belonging to the set N_P ($n_P \in N_P$)

2.3.1 Variables

The variables can be grouped into the two infrastructural and hydraulic typologies.

- **Infrastructural variables:**

  $x(e) =$ status of edge e ($\forall e \in E \setminus E_P$) where $x(e) \in 0, 1$

  the status of edges that do not belong to the primary network can be open or closed.

- **Hydraulic variables:**

$Q(e) =$ flow in edge e $(\forall e \in E)$

$H(j) =$ hydraulic head of junction j $(j \in N \setminus R)$

$Q(e) =$ flow into or out of source nodes r $(r \in R \subset N)$

2.3.2 Constraints

2.3.2.1 Topological constraints

- **Numbers of supply edge:** the number of supply edge for each sector must equal be equal to or less than m, with $m \in \mathbb{N}$

$$\forall\, sector\ the\ number\ of\ supply\ edge\ e \in E \setminus E_p\ is\ less\ then\ m\ (\ with\ m\ \in\ \mathbb{N}\ ) \tag{2.1}$$

- **Connectivity:** The nodes must all be connected to the primary network, i.e. there must be at least one path that connects each node of sectors of WDN to a node of the primary network. This means that, as a consequence of the primary network definition (Paragraph 1.3), ensuring connectivity with a primary network node is consequently guaranteed that every node will be topologically connected to every water resource. This is also equivalent to saying that there can not be portions of the WDN disconnected from the water resources and therefore not supplied:

$$\begin{gathered} \forall\ j \in J\ exists\ path\ that\ connected\ j\ with\ a\ primary\ network\ node \\ or \\ \forall\ j \in J\ exists\ path\ that\ connected\ j\ with\ at\ least\ one\ source \end{gathered} \tag{2.2}$$

- **Isolation:** In case of only one supply edge is chosen (m=1), the isolation of sectors can be guaranteed by means this topological constraint. The sectors must have only one entrance so each sector will be connected to the primary network by one and only one supply edge, this constraint guarantees that the sectors are isolated:

$$\forall\ Sector\ S\ \exists!\ edege\ e\ that\ guarantee\ the\ connection\ with\ primary\ network \tag{2.3}$$

If the number of supply edges is higher (m>1), in order for the sectors to be isolated, the hydraulic isolation constraint must also be respected.

2.3.2.2 Hydraulic constraints

- **Hydraulic head bounds [Linear]** For each junction $j \in J$ it is imposed a minimum H_{min} :

$$H_{j,min} \leqslant H_j \qquad (\forall j \in J) \tag{2.4}$$

This constraint could also be written in terms of pressure at each junction:

$$p_{j,min} \leqslant p_j \qquad (\forall j \in J) \tag{2.5}$$

- **Flow bounds (dependent on cross-sectional area of pipe) [Smooth but nonconvex]:**

$$-\frac{\pi}{4} v_{max}(e) D^2(e) \leqslant Q(e) \leqslant \frac{\pi}{4} v_{max}(e) D^2(e) \qquad (\forall e \in E) \tag{2.6}$$

or the problem can be set considering a maximum velocity value for each edge.

- **Flow conservation [Linear]:**

$$\sum_{e \in \delta-(i)} Q(e) - \sum_{e \in \delta+(i)} Q(e) = dem \qquad ; \ (\forall i \in N \setminus S) \tag{2.7}$$

- **Energy conservation [Nonsmooth and nonconvex]:**

$$H_i - H_j = r(e) sgn(Q(e)) \cdot \mid Q(e) \mid^n \qquad (\forall e = (i,j) \in E) \tag{2.8}$$

- **Hydraulic Isolation:** Finally the hydraulic constraint to replace the constraint (2.3) is shown if a number of entrances per sector greater than one is allowed. In this case to guarantee that the sectors are isolated (therefore that part of the flow circulated in the sector can then circulate in the primary network) it is necessary to verify that the direction of the flow is only at the entrance to the sector.

$$all\ primary\ edges\ are\ supplied\ only\ from\ Sources\ or\ from\ another\ primary\ edge \tag{2.9}$$

consequently:

$$all\, sectors\, are\, supplied\, only\, by\, supply\, edges\, without\, return\, of\, water\, into\, primary\, network \tag{2.10}$$

In the case that sectors could have a number of supply edges greater than one and non-isolated sectors are accepted, the constraints expressed by 2.3 and by 2.9 are removed from the formulation of the problem.

2.3.3 Hydraulic objective functions

Among the many objectives that the sectorialization of a water distribution network can pursue, the search for greater uniformity of the pressure in each sector is particularly significant in a perspective of pressure control. Other aspects could assume greater importance depending on the application contexts. In this thesis work we have focused on the problem of equalizing the pressures within the sectors and an objective function has been defined to minimize the pressure difference within each sector. This objective leads to a sectorialization of the WDN optimized for the pressure management. To represent the pressure difference in a generic sector are chosen its median pressure and its minimum pressure. The intention is therefore to create sectors that could be also pressure management areas. For this reason, the median pressure is chosen because it is not conditioned by the maximum values that could be reduced locally and by the minimum pressure of the sector represented by means of the critical point in the case of a pressure reduction. It was decided to aggregate all the values of the sectors by calculating a weighted average, thus giving more weight to the pressure differences found in the sectors with greater network length. This choice actually allows each sector to contribute to the value of the target function according to its extension, but has the limit of not controlling the extension of the created sectors.

Minimum difference for pressure within sectors (Objective function)

$$pD = \frac{\sum_{s=1}^{t} \delta_{p,s}}{\sum_{s=1}^{t} L_s} \tag{2.11}$$

$$\delta_{p,s} = (median(p_s) - p_{min,s}) \cdot L_s \tag{2.12}$$

$where:$

t is total number of sectors

s is the generic sector

L_s the total length of edges of sector s

p_s all pressures in the junctions of generic sector s

$p_{min,s}$ is the minimum pressure of generic sector s

2.4 Algorithmic approach

2.4.1 Algorithm overview

The formulation of the problem for the sectorization of a network hydraulics, described in the previous paragraphs, required the implementation of an algorithm, the main structure of which is shown in the flowchart in Figure 2.1. The algorithm consists of five main stages:

- Problem input data acquisition phase: in this phase are acquired the WDN model, network elements identified as primary, maximum number of supply edges per sector (this aspect is configured as a constraint) and parameters required by the functions used by the algorithm (Paragraph 2.4.3).

- Construction of the graph to be sectorized: in this phase the WDN is treated as a graph and the portion of the network to be sectorized (Sectorization Graph) is identified by subtracting the primary network from the overall network (Paragraph 2.4.4).

- Pre-analysis: it is an optional phase and allows to orientate the sectorization process in an engineering sense, including defining if the Sectorization Graph should be considered globally or if some parts should be excluded (Paragraph 2.4.5).

- Sectorization Process: it is the key phase of the sectorization process, in which the starting solution found in the previous step is improved. From an algorithmic point of view, a tailored Tabu Search 2.4.6.1) for the formulation of the optimization problem is developed (Paragraph 2.4.6).

- Strengthening of the primary network: it is foreseen if with the initial primary network, the sectorization process is not able to find a solution that satisfies the constraints of the optimization problem (Paragraph 2.4.7).

2.4.2 Development environment

The methodology subsequently illustrated was developed in a Python environment, with the aid of the Pandas (pandas development team, 2020) package for DataFrame management, the wntr (Klise et al., 2017) package for reading the characteristics of the hydraulic model of the WDN and to be able to call the EPANET 2.2 hydraulic solver. The NetworkX package (Hagberg et al., 2008) has been used for the algorithms applied on the network graph.

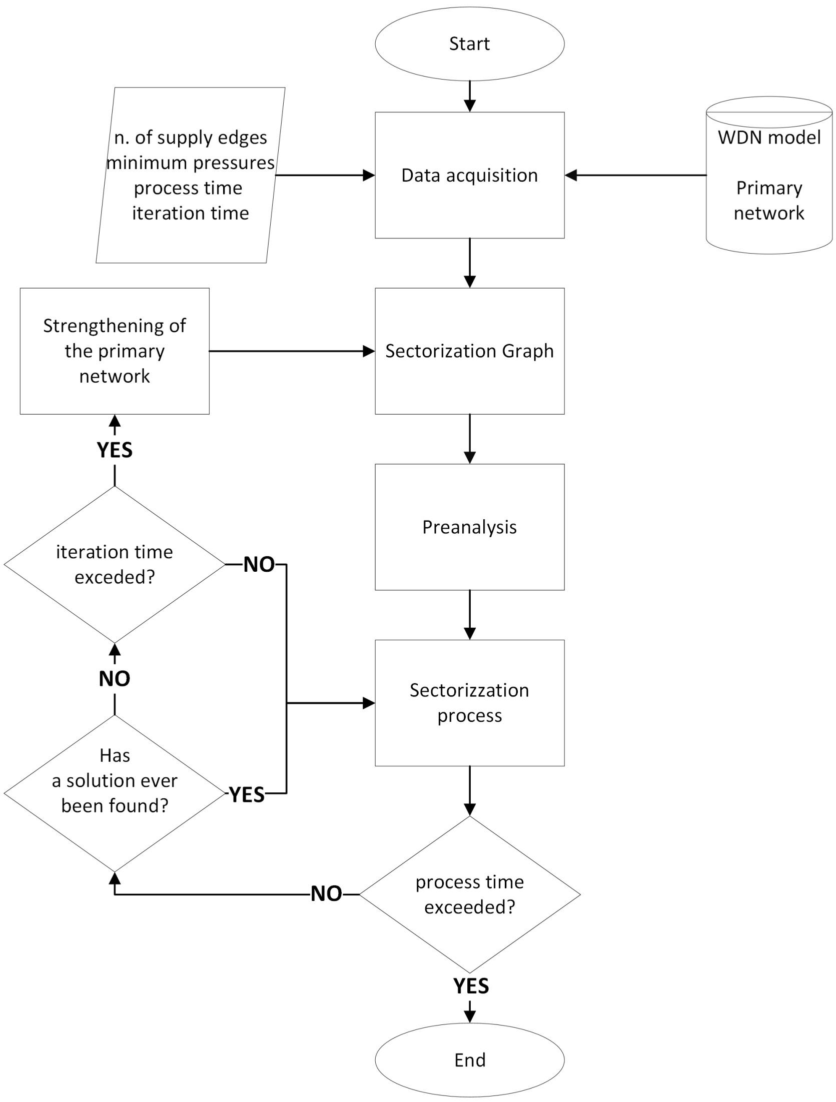

Figure 2.1: Flowchart of process

2.4.3 Problem input data acquisition

The process begins with the acquisition of the starting data for solving the sectorization problem:

- hydraulic model of WDN;
- primary network (nodes and edges set as primary);
- maximum number of supply edges for each sector or rather maximum number of edge that supply each sector (constraint 2.1);
- minimum pressures to be guaranteed in the nodes of WDN in the configuration divided into sectors and the related acceptable violation Δ ($\Delta >= 0$) (constraint 2.5).

In addition, some parameters needed by the algorithm must be provided:

- maximum length of the Tabu list (this data is involved in the sectorization process);
- process time or maximum time available to the algorithm to find a solution;
- iteration time, less than or equal to the process time, maximum time available to find a sectorization solution for the current primary network; when the iteration time is overcome, if the process time is not up, the strengthening of the current primary network is performed and the process starts again with the new primary network up the end of the process time.

2.4.4 Sectorizzation Graph

In this phase the network to be sectorized, the Sectorization Graph, is identified. The methodology proposed to sectorize the WDN uses the corresponding graph and hydraulic model. The complete graph of the network (WDN Graph) is an indirect weighted graph. The weight assumed to each edge is given by the ratio of their length to the diameter raised to the fifth (L/D^5). Of course, if self loops are present in the WDN, the graph is an indirect-weighted multigraph (in this case the algorithm handles edges that have the same start and end node). The attribution of the weight to the edges is necessary to find a first solution, but not for all the other subsequent operations, consequently it does not enter as necessary data in the process of

Tabu Search. The first operation is to identify the portion of the WDN to be sectorized. As seen in the formulation of the problem (Paragraph 2.3), the edges of the primary network are not included in the process of finding closures leading to the construction of of isolated sectors. If the pipes already closed in the current configuration of the WDN must be keep, these edges will be subtracted from the overall graph as happens for the primary network. To obtain the Sectorization Graph, i.e. the graph which represents the portion of the network to be sectorized, from the WDN graph (Fig. 2.2 in 1) all the primary edges (Fig. 2.2 in 2) and all the primary nodes connected only to primary edges are eliminated (2.2 in 3). The remaining primary nodes are therefore primary nodes that have at least one non-primary incident edge (Fig. 2.2 in 3). The primary nodes left after this process are called "primary supply nodes". Once the primary supply nodes have been identified, all the potential supply edges for the sectors that will be identified are known (Fig. 2.2 in 4). Among the primary supply nodes, those having a degree of connection greater than one, which could serve districts unless they are closed in later stages, are identified 2.2 in 4). These nodes are replaced by as many dummy nodes as their connection degree (that is number of supply edges incident). Therefore, for example, if a primary supply node is connected to two supply edges, two dummy nodes will be created, if there are three supply edges incident to the primary supply node, there will be three dummy nodes. The process of replacing the nodes with a value of connection degree greater than one with dummy nodes is done for two purposes:

- The first purpose is to identify the connected components after the elimination of the primary network. The subtraction of the primary edges and nodes (Fig. 2.2 3) from the graph had in fact already determined one or more connected components, some of which will thus be further subdivided. This process identifies the subgraphs of a connected components that have in common only primary nodes and divides them. In this way the existing connected components will be further decomposed .

- The second aim concerns primary supply nodes whose replacement with dummy nodes does not produce any further decomposition of the connected components already found. This aim will be explained later and concerns the verification of the connection (Constrain 2.2) (i primary supply nodes vengono utilizzati nella ricerca locale del tabu search per verificare sia il vincolo del constrain sia il vincolo di numero massimi di ingressi per distretto)

Once the operations described have been completed, the graph obtained is the graph of the network to be sectorialized (Sectorialization Graph) (Fig. 2.2 5). In this graph we therefore identify the connected components that are indicated as "primary connected components". The process of sectorization further subdivides these connected components whenever possible. In order to be subdivided, a generic primary connected component must have a number of supply edges greater than one. If all the primary connected components obtained by subtracting the primary network have only one supply edge, a solution is already available without having to perform any edge closure. Instead, if sectors with more than one supply edge are accepted , it is necessary to check, through the hydraulic model, that the sectors are isolated consistently with the constraint 2.9.

In the following some fundamental definitions for understanding the subsequent steps of the methodology are given:

- WDN Graph: is the complete graph of the network. The graph is indirect and weighted. The edge weight was assumed equal to L/D^5.
- Sectorization Graph: graph of the portion of the network to be sectorized, all edges, that appertain to this graph (included supply edges), can assume the open or closed state (see Paragraph 2.3.1) during the next procedure. This graph can be composed of one or more connected components.
- Primary connected components: connected component belonging to Sectorization Graph, each component has at least one primary supply node and a supply edge which, in the complete WDN Graph and in the hydraulic model of the network, connects it to the primary network. The primary connected component is subject to a subsequent subdivision if it has a greater number of supply edges than those allowed for each sector.
- primary supply node: node appertain to the primary network and to one or more primary connected components. The primary supply nodes are all those primary nodes connected to edges not belonging to the primary network. As we have seen previously, if necessary, they are replaced with dummy nodes to which only one real node will correspond in the WDN graph and in the model. Indeed they are no longer the original nodes, they are primary nodes and dummy nodes which then effectively become primary supply nodes (all nodes in blue in Figure 2.2). These primary supply nodes indicate that the potential solution to the problem will have at most a number of sectors equal to them.
- supply edge: edges, belonging to the primary connected component, that have a primary

node as vertex. The supply edges connect the primary network and the primary connected components. These edges exchange the water resource between the primary network and the primary connected components and after the subsequent sectorization, they are the supply links of the sectors.

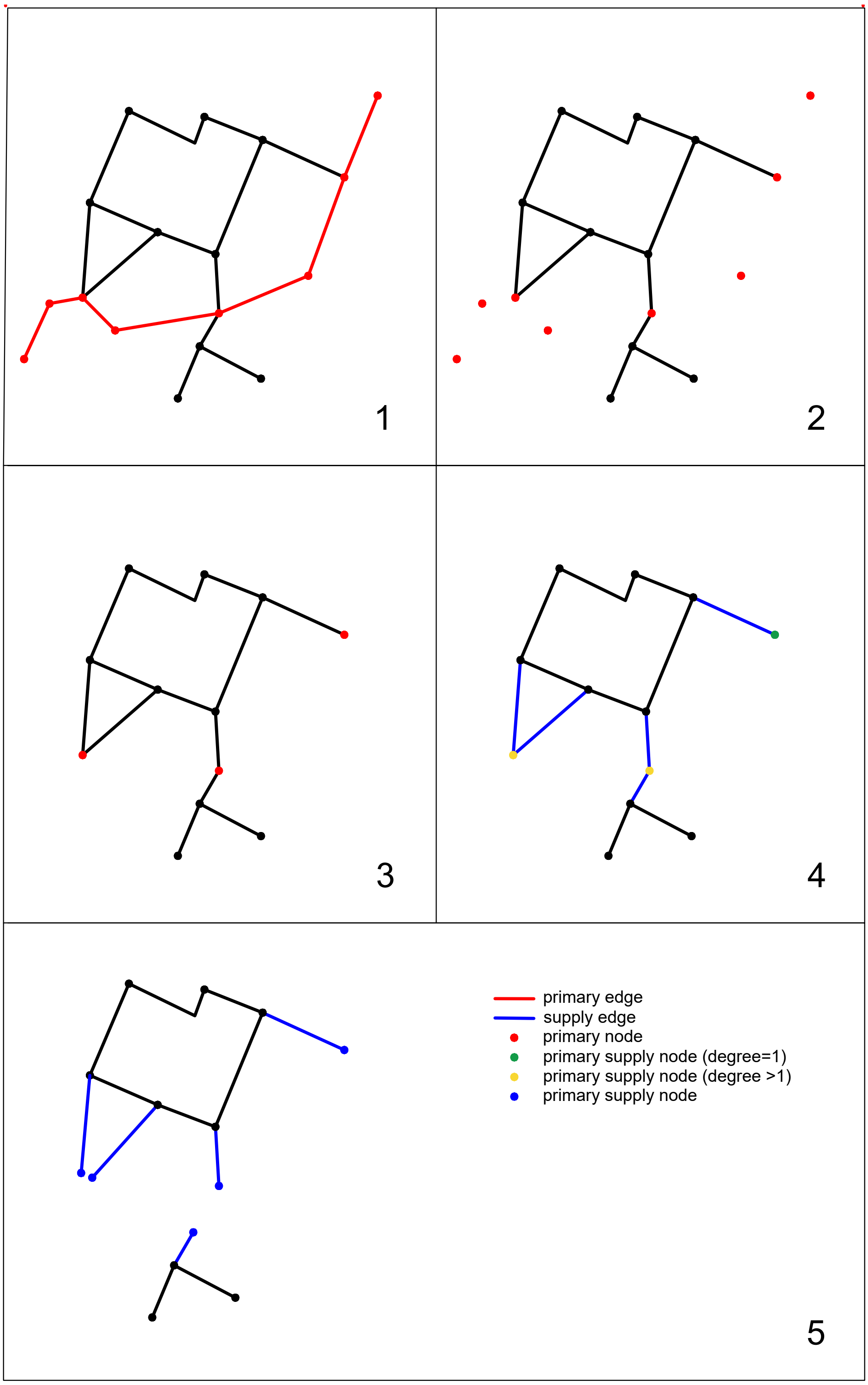

Figure 2.2: Steps to create Sectorization Graph. The WDN Graph is shown in 1, with the primary nodes and edges in red. The WDN graph without primary edges is shown in 2. In 3 the primary nodes with degree equal to 0 are eliminated. In 4 the primary nodes (in yellow) with degree greater than 1 are identified, in order to replace them with a number of dummy nodes equal to their degree. Finally in 5 the Sectorization Graph is shown, with its final primary supply nodes and edges 3

Algorithm 3: Sectorization Graph

```
Input  :
        Graph of WDN
        list of primary nodes
        list of primary edges
Output:
        SectorizationGraph
        list of primary supply nodes
        list of supply edges
        list of primary connected components
initialization;
SectorizationGraph = copy of WDN-Graph;
for each edge of SectorizationGraph do
    if edge in list of primary edges then
        delete edge from SectorizationGraph;
    end
end
create a empty list of primary supply nodes;
create a empty list of supply edges;
for each primary supply node of SectorizationGraph do
    calculate degree of primary supply node;
    if degree ==0 then
        delete primary supply node from SectorizationGraph;
    else if degree==1 then
        find edge connected to the node;
        add edge to list of supply edges;
        add primary supply node to list of primary supply nodes;
    else if degree>1 then
        find all edges connected to the node;
        for each connected edge do
            add edge to list of supply edges;
            create new primary supply node in SectorizationGraph;
            add new primary supply node to list of primary supply nodes;
            replace primary supply node in edge vertices with new primary supply node;
        end
        delete primary supply node from SectorizationGraph;
    end
end
identify connected components of SectorizzationGraph;
create a list of connected components ;
```

2.4.5 Pre-analysis

The execution of the pre-analysis of the primary connected components obtained with process explained in paragraph 2.4.4 is not mandatory. To obtain a complete sectorization of the

Sectorization Graph the pre-analysis must not be performed.To highlight the engineering applicability of the method, the possibility of directing the sectorization process illustrated below is presented. By analyzing the primary connected components, it is possible to evaluate which ones to exclude from the sectorization process and therefore not to subdivide them further. The attributes that can lead to exclude some primary connected components from further subdivision can be length, water consumption, number of customers. In this case the excluded connected component may be able to supply the primary network, the water that enter in this area will then be able to go back in the primary network. Another pre-analysis application, that can be useful in the case of an engineering approach to sectorization, is to decide that certain supply edges must be closed if, for example, they have a diameter smaller than established one. In this case they are deleted from the Sectorization Graph with the corresponding primary supply nodes.

2.4.6 Sectorizzation process

2.4.6.1 Tabu Search

As algorithmic approach to solve the Sectorization problem was used Tabu Search (Glover, 1989, 1990). Tabu search is a meta-heuristic technique used to solve multipurpose optimization problems. Among the innumerable applications in which it is used, it is very suitable for solving Graph optimization problems, including Graph Partitioning problems (Glover and Laguna, 1999). Tabu Search requires a local search procedure that must be tailored for the problem that the algorithm has to address. The Tabu Search local search procedure works like a local search procedure, in which the last solution found is not necessary better than the previous one. If no improving move is available, worsening moves can be accepted, in order to possibly reach a new point in which it can find better solutions around. To prevent the process from returning to the same local optimum, the Tabu list is used. The solutions previously explored by the algorithm are inserted in the Tabu list. In Fig.2.3 is shown the flowchart of the process. Initially, an initial solution is required and it is initialized as current solution. The candidate solutions are searched for in the neighbourhood of the current solution and they are compared with the previous explored solutions contained in the Tabu List (obviously at the first iteration of the process the list will be empty). The candidate solutions contained in the Tabu list are eliminated. Among remaining candidate solutions, the best one is chosen as solution and added to the Tabu list. If the stop criterion of the algorithm is not satisfied, this solution is initialized as the current solution, and the process goes on. The Tabu list can have a fixed length. In this case, when an element is added, if the list has reached the maximum length established, the oldest solution will be eliminated from the list. The stop criterion is chosen based on the problem being faced. Generally the algorithm stops after a defined time or low or no improvement in the best solution.

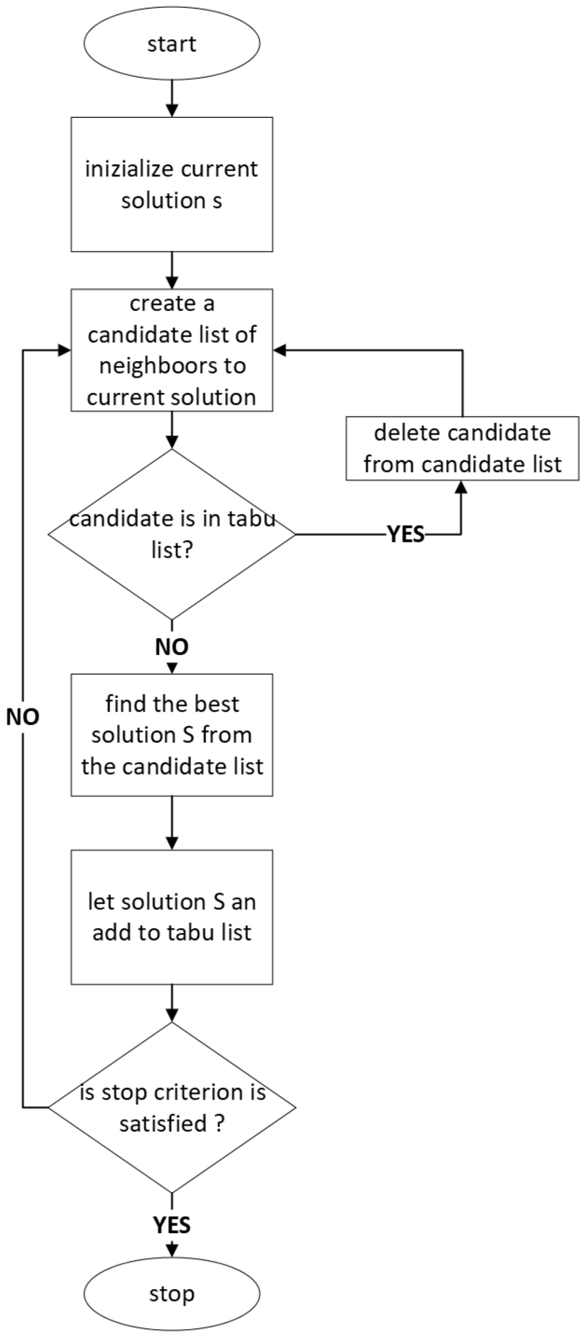

Figure 2.3: Tabu Search optimization algorithm flowchart

2.4.6.2 Problem formulation for Tabu Search

The implementation of the Tabu Search algorithm requires to consider the variables, constraints and objective listed in the paragraph 2.3with the goal to close only the edges belonging to the SectorizationGraph. The algorithm will be able to close only the edges belonging to the Sectorization Graph. For the hydraulic variables instead, the totality of the nodes and edges of the WDN is considered and not only those included in Sectorization Graph. The closures found during the optimization process are equivalent in the Sectorization Graph to delete the closed edges, and in the hydraulic model of the WDN to the closure of the relative pipes or valves. As a result, the primary connected components, once the edges have been eliminated, are devided into several connected components. The connected components that have only one node and no-edegs (in this case the node must be a primary supply node in order not to violate the connectivity constraint 2.2) are not sectors. In this case the primary edge or edges incident to the node have been closed. The constraint 2.2 of the problem, i.e. that the connectivity of each node towards the primary network is guaranteed, is equivalent to saying that each connected component must have at least one primary supply node. If in each sector there is only one entrance (only a supply edge), the hydraulic constraint of isolated sectors is also guaranteed. If more than one entrance has been allowed, with hydraulic simulation it must be verified that the flow is entering the sectors (Costraint 2.9). The constraint 2.4 is modeled in the problem as an objective function that calculate the pressure violation in the WDN nodes. The goal is to minimize this violation below a Δ ($\Delta \geq 0$) considered acceptable.

$$pV = \sum_{j \in N \setminus S} C_j^{pen} \cdot max(0, p_{j,min} - p_{min}) \tag{2.13}$$

where:

C_i^{pen} is the penalty if the minimum Pressure in j-th node is not respected. It could be different depending on the importance of the node). The cost could be one for all nodes or depend on the importance of the node

The second objective function 2.11 is hierarchically subsequent to the first, which indeed represents a contraint. The second objective is calculated only when the first is satisfied.

The respect of maximum velocity in the WDN is not modeled in this proposed solution; however, this constraint could be introduced in different ways. It could be used to exclude solutions found from time to time. But it was preferred to subsequently verify the satisfaction of this constraint or the extent of its non-satisfaction in the possible solution(s) found, so as not to further constrain the problem.

2.4.6.3 First solution

The Tabu Search algorithm needs an initial solution that in this problem consists first division into sectors of the Sectorization Graph. The initial solution must respect the constraints given in the problem formulation (Paragraph 2.4.6). To find the first solution it is assumed that each sector is supplied by only one edge. In this formulation it means that each connected component must contain only one primary supply node; in this way isolated sectors and only one entrance to each sector is guaranteed. It also is guaranteed that must not be parth of network not supplied by primary network. This is the only constraint of the problem because the respect of minimum pressure is modeled as a objective function 2.13. The algorithm that searches for a first solution has been written to respect the constraint of the problem and to try to find a solution that does not have a high cost of the objective function 2.13. The the algorithm starts from the Sectorization Graph and works on each of its primary connected component that have more than one primary supply node. The idea to try to contain the OBJ 1 2.13 of the solution is to consider the infrastructural energy weight (L/D^5). Initialized a primary connected component, the cost of all the shortest path from each primary supplied node (of the connected component) to the other nodes is calculated. A list is created for each supply node and each node is assigned to the closest primary node in the corresponding list. In the next step is considered each edge of the connected component, the edges which have the vertices (initial and final node) belonging to two different lists must be closed (in hydraulic model). The application of this algorithm (whose pseudocode is attached in Algorithm 4) ensures that every connected component found by the elimination of the edges of this solution has a primary node and that every generic node is supplied by the closest primary node from an energy point of view (considering only the infrastructure). The presented procedure to find the first solution can be computationally expensive especially if the primary connected components have many primary nodes and many internal nodes. The computational costs mainly due to the algorithm to find the shortest paths; in this proposal Dijkstra algorithm (Dijkstra, 1959) was used, in particular, a version of this algorithm (Eppstein, 1994), developed in Python. This version allows to calculate all the shortest paths from a source to different targets. A possible alternative to the previously exposed process is to closed all supply pipes in each primary connected components, except the one with the largest diameter. Naturally in this case the calculation time is shifted from first solution to the Tabu Search procedure. It is therefore necessary to evaluate whether it is actually convenient from the point of view of global computational cost. In fact in this case a solution with high value of objective function 2.13 (OBJ 1) is almost certainly obtained. To facilitate a faster improvement of the objective function by Tabu Search, the pipes closed with the algorithm are sorted according to the following procedure. The simulator is called up and the impact of the closures (first solution) found is evaluate in terms of objective function by means a single period simulation. As already seen previously, the graph is used to search for closures and to identify candidate sectors. In this case, therefore, the edges listed in this solution are eliminated from the reference graph for the sectorization process and the connected components are evaluated. These connected components that will have more than one node (of course the isolated nodes obtained after the elimination of the links of first solution will not be identified as sectors, a case that can only concern the primary supply nodes if the algorithm has directly closed a supply edge). The OBJ 1 (2.13) of the solution found is calculated. If it is satisfied, identified the sectors, OBJ 2 (2.11) is also calculated. The sectors are identified as components connected with at least two nodes (beyond the primary supply nodes) of the Sectorization Graph from which the edges of the first solution have been eliminated. If the OBJ 1 (2.13) of the network is not satisfied,the value of the OBJ 1 2.13 in each individual sector is calculated and the sectors are sorted from the one with the highest cost to the one with the lowest cost. Closures identifying sector boundaries are sorted in the same order as the sectors.For each sector, the pipes that isolate it from the others (the closed ones) are identified and sorted by diameter in descending order. If OBJ 1 (2.13) is satisfied, the same operation is executed with OBJ 2 (2.11). If more than one edge divides one sector from another, the edges are reordered according to the diameter size from largest to smallest. In this way, Tabu Search initially works on the worst points of the first solution network in terms of constraint point of view (OBJ 1 2.13) or in terms of a performance point of view (OBJ 2 2.11). This sorting is used to initially search a greater margins for improvement of the solution. Similarly for pipes, Tabu Search before considers the pipes with larger diameters whose closure is usually less desirable from head loss point of view. Calculated OBJ 1 (2.13) for all WDN, if it is greater than delta OBJ 1 (2.13) is initialized as best OBJ 1 (2.13). If OBJ 1 (2.13) is less than Δ, the OBJ 2 (2.11) is calculated and initialized as best OBJ 2 (2.11). The first solution and the best cost are the starting points for the local search of the Tabu Search.

Algorithm 4: First Solution

```
Input  :
        Sectorization Graph
        list of primary nodes
        list of primary edges
Output:
        first solution (list of closed pipes)
initialization;
create a first solution list;
for each primary connected component of SectorizationGraph do
    identify primary supply nodes of connected component;
    if primary supply nodes >1 then
        identify nodes of connected component;
        identify edges of connected component;
        create a empty DataFrame(index = primary supply nodes, coloumn names =
          nodes);
        for each primary node of connected component do
            for each node of connected component do
                calculated shortest path weigth (from primary supply node to node);
                add the weigth to DataFrame(primary supply node, node);
            end
        end
        create an array formed by minimum values of columns of DataFrame;
        create sector node list;
        for each primary supply node of connected components do
            nodes attribution = DataFrame(primary supply node, :)== array;
            nodes name list = coloumn names of nodes attribution(nodes attribution ==
              True);
            add nodes name list to sector node list;
        end
        for each edge of connected components do
            identify vertices of edge;
            if vertex 1 and vertex 2 in any nodes name list then
                add edge at first solution;
            end
        end
    end
end
```

2.4.6.4 Tailored Tabu Search algorithm

The Tabu Search uses the first solution as the current solution during the first iteration. Cost 1 of the first solution is initialized as best cost, if instead it is satisfied (OBJ 1 $< \Delta$) OBJ 2 is initialized as best cost. The local search procedure is applied edge by edge. Given the current solution, its edges are initialized one by one, the candidate solutions are found by replacing that edge with combinations of edges adjacent to it. The neighborood thus found is compared with the tabu list, eliminating candidate solutions already present in it. The next step is to evaluate the candidate solutions with the objective function(s) (depending on whether the condition of OBJ 1 (2.13) is satisfied or not). If the cost of one of them is lower than the initialized best cost, this candidate solution is initialized as the current solution, its cost as the best cost, and the process restarts. If instead the cost is higher, the next edge of the current solution is considered, until a lower cost than the best cost initialized is calculated. If no cost lower than the best cost is found after having explored all the candidate solutions of the edges of the current solution, the candidate solution with the lowest cost among those calculated is initialized as current solution. In this way, the local search procedure does not find and evaluate all the candidate solutions belonging to the neighbourhood of the current solution, but it stops when it finds a better one and starts again. This choice is made with the aim of being able to face problems starting from solution with a very high OBJ 1 (2.13) compared WDNs of a certain size represents the bottleneck of the algorithm. Consequently, we proceed to accepting a better solution immediately without waiting a lower cost solution generated from another pipe in current solution. In this way, OBJ 1 (2.13) will initially decrease more rapidly. The various phases of the Tabu Search, tailored to solve the sectorization problem of a WDN, are explained in the following paragraphs.

2.4.6.5 Find neighborood

Given the list of closed edges (current solution), the first edge is initialized. The necessary information of the edge for this step are:

- the vertices of edge referred to as "backward node" and "forward node";
- the connected components of Sectorizzation Graph (see Paragarph 2.4.4) to which the edge belongs. This datum is not changed throughout the process, to limit some operations performed on the graph only to the part on which affects, saving in computational cost.

The edge initialized by the current solution is deleted from list of closed edges, in fact it must be open. If the number of maximum supply edges per sector is greater than 1 (m > 1 in Constraint 2.1), this is already a combination to be processed. If, on the other hand, m = 1, only the subsequent combinations will be created, not considering the opening as a possible combination. Find the edges incident to the forward node excluding the initialized edge. If any of these edges are present in the current solution, delete them from this one. At this point all the possible combinations $C_{n,k}$ of the identified edges are considered. The possible combinations $C_{n,k}$ are given by the formula:

$$C_{n,k} = \frac{n!}{k!(n-k)!} \tag{2.14}$$

where is it:

n is the number of elements contained in the list of adjacent edges to the start node which will be as seen at node degree minus 1;

k is the cardinality of the subset of elements of n to be grouped to obtain all the possible combinations k varies from 1 (each combination obtained requires the closure of only one edge at a time) up to the number of identified edges (all the identified edges are closed).

Figure 2.4 shows the degree of nodes belonging to some literature WDNs. As it can be seen in most cases, except for some outlier degree of the nodes, the degree is contained within the value of 4, which as seen above would mean 3 edges (one edge is not considered because it is the one to open). Thus the enumeration of all combinations is possible without usually a large computational cost. For each combination obtained, (including that of an open edge with no adjacent closures in the case n>1), two fundamental operations must be carried out before it can be considered a candidate solution. The first is to verify that the new combination of edges closures does not isolate some nodes (Constraint 2.2) and that each generated sector has no more than m (numbers of supply edges) (Constraint 2.1). In the proposed solution this means that each connected component identified after edge elimination in the possible candidate solution must have at least a primary node (Constraint 2.2) and that this must be less than m (Constraint 2.1). Furthermore, given the presence of only one supply edge, the constraint of isolated sectors is also respected. This operation can be performed only in the primary connected component to which the initialized pipe belongs. Therefore all the edges of the current solution that belong to the primary connected component (except the initialized edge) and the new combination are considered. It is useless to verify the respect of constraints in the other primary connected components as the new combination has no effect on them. If the possible combination examined respects the constraints, the second fundamental operation is to verify that there are no useless closures, i.e. closures of edges that do not identify any connected component. In fact, the new candidate solution is obtained by moving the border of the sector, and this operation can make some closures present in the candidate solution (resulting from the current solution) useless (as it can be seen in the Fig. 2.5). These internal sector closures must be identified and removed from the candidate solution. The verification of useless closures has been developed in the code, verifying that in the candidate solution list there are no edges whose vertices belong to the same sector, identified by the forward node (or by the backward node). In fact, an edge that has both vertices in the same sector is not a boundary edge and therefore can be open. Chooses performed for the forward node that result in a forward list of candidate solutions must also be performed for the backward node in order to obtain a backward list of candidate solutions. If the list of candidate solutions (sum of the two lists) is empty (no candidate solutions satisfying the constraints have been found) the next pipe of the current

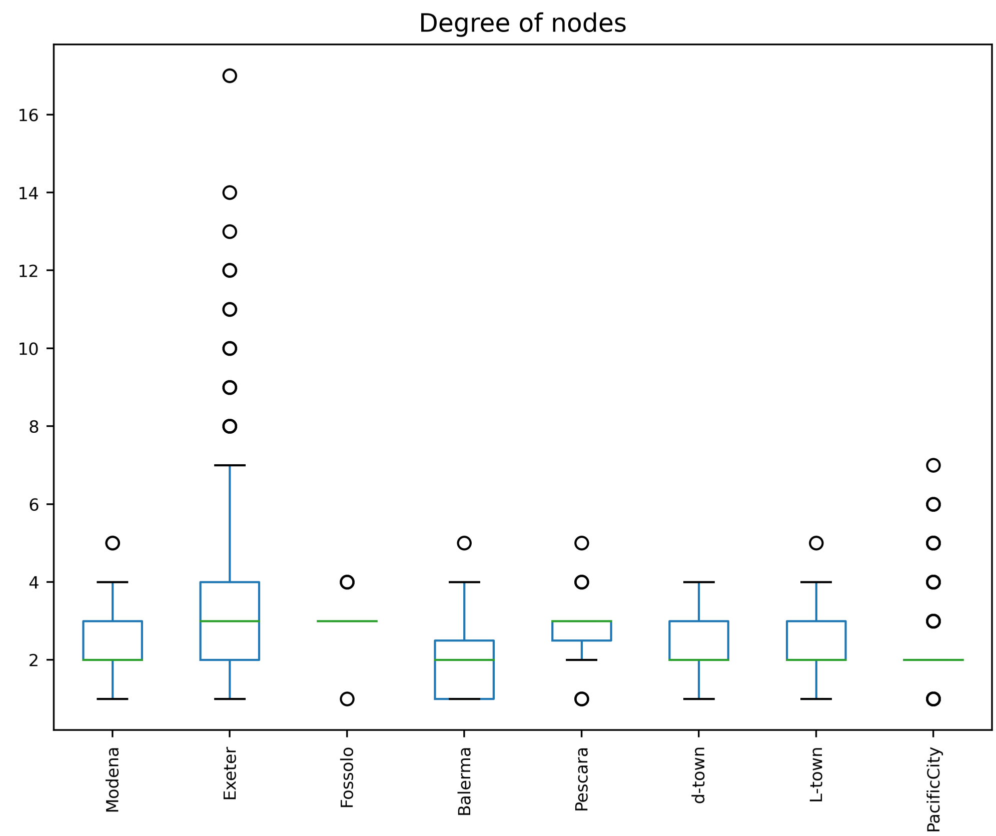

Figure 2.4: Degree of nodes nodes for literature WDNs

solution is initialized. If candidate solutions have been found, they are compared with the Tabu list.

2.4.6.6 Comparison of candidate solutions with Tabu list

At this point the list of candidate solutions is compared with the Tabu list to eliminate the previously explored ones, which have been stored in this list. The remaining candidate solutions are then evaluated.

2.4.6.7 Evaluation of candidate solutions

The candidate solutions that have not already been explored, therefore do not belong to the Tabu list, are processed through hydraulic simulation. If the number of supply per sector is set equal to 1 ($m = 1$) it is the case in which the sectors will certainly be isolated, therefore there is no candidate solution to be eliminated because it does not respect the Constraint 2.9. If, on

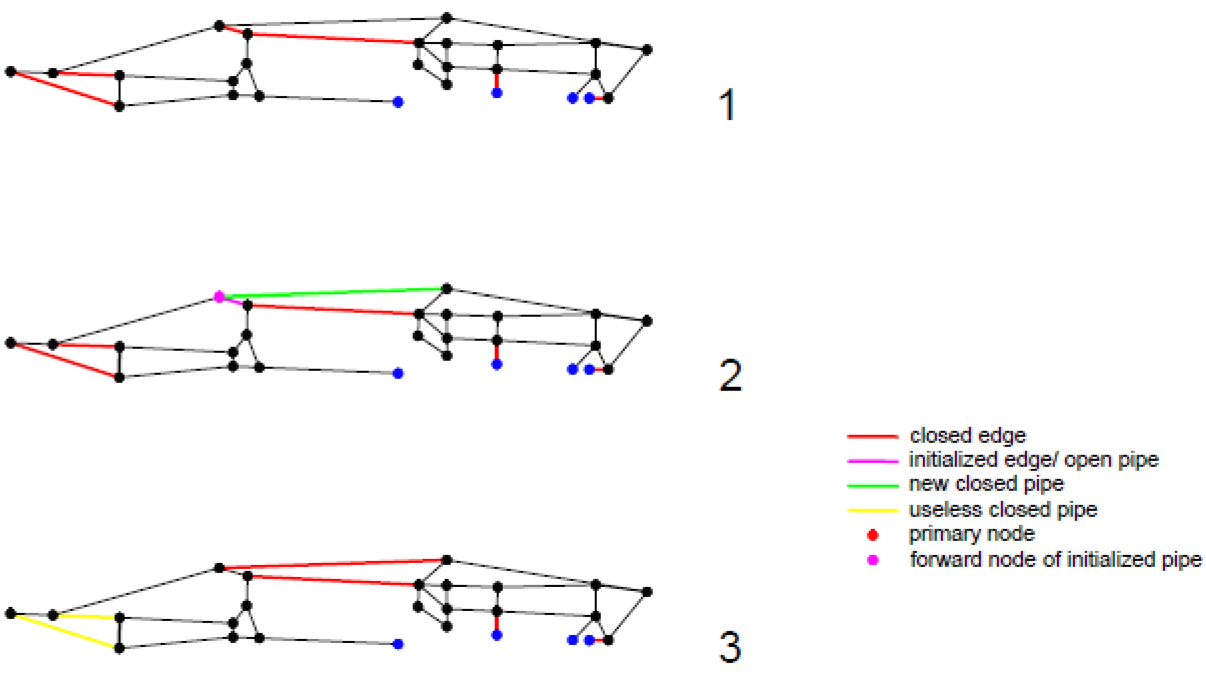

Figure 2.5: Steps of candidate solution search process. The current solution is shown in 1. The initialized pipe and its forward node is shown in 2 in magenda with new closed pipe (to replace the initialized pipe that is opened) in green. Finally in 3 the closures maken useless due the new closure are shown.

the other hand, a number of permitted supply edges greater than 1 ($m > 1$) has been set, it must be verified that the sectors are isolated using the results of the hydraulic simulation. The candidate solutions are eliminated if the flow direction in one of the supply edges is opposite to the direction that going from the primary node to the other node of the supply edge. In fact, it would fall back to the case of a primary network supplied by water from a sector (violation of the constraint 2.9). For the candidate solutions that respect the Isolation Constraint 2.9), the next step is the calculation of the value of the objective functions. There are therefore two objective functions, the second (2.11) is calculated if OBJ 1 is satisfied. If any of the candidate solutions has a value lower than the minimum value of the objective function found up to that moment (best OBJ 1, if it has not yet been satisfied or best OBJ 2 if a OBJ $1 < \Delta$ has already been found), this candidate solution becomes the current solution, otherwise the next pipe of the current solution is initialized. If all the edges of the current solution have been initialized, and the neighborhood has been completely explored without finding a solution with a lower cost than the best cost, a pejorative move is accepted compared to that of the previous iteration. Therefore, among all the candidate solutions, the one with the lowest value of the objective function (in any case greater than the best cost) is initialized as the current solution. Before restarting the process the current solution is stored in Tabu List. If a maximum length of memorizable solutions has been assigned to the Tabu list, the size of the Tabu list is checked. If it exceeds the desired one, the oldest element of Tabu list is deleted.

2.4.7 Strengthening of the primary network

Mainly in relationship to the WDNs framework, in same case, the procedure previously illustrated could not give satisfying results. If in the current best solution OBJ 1 calculated by the objective function 2.13 is greater than the deficit Δ considered acceptable, different strategies can be adopted to try to decrease its value. The Paragraph 2.4.5 illustrated the possibility of avoiding the subdivision of connected components using a filter. The connected components with low rate of the total length of the edges with a greater number of supply edges can be studied in depth. In the case that these connected components have a length-weighted mean diameter of the pipes comparable to the diameter of the primary pipes to which they are connected, they can be considered self loops of the primary network. The choice not to further sectorize these components could useful for redistributing the flow when these components will not be isolated.

In this case the non-sectorized connected component becomes an integral part of the primary network and it can locally, where it works as a self self loop, contributes to decrease the head-loss. Therefore, non-sectorisation could in this case have a positive effect for the achievement of OBJ 1. Another adoptable strategy is to allow sectors with more than one supply edge. In cases where some areas seem to have an infrastructural deficit for which a division that guarantees non-violation of the minimum pressure is difficult, more drastic solutions can be adopted, i.e. completely excluding them from the sectorisation process or creating non-isolated sectors. The strategy illustrated in this paragraph starts from the assumption instead of not changing the constraint on the number of inlet points in each sector. In this case, if an acceptable solution cannot be found, the primary network must be reviewed. In fact, it is possible that in some parts the primary network is infrastructurally lacking to achieve the required objective, i.e. ensure a minimum pressure to all nodes of the WDN. It is necessary to identify the primary network portions to be strengthened and proceed with their infrastructural strengthening. Assuming that the problem does not allow the variation of diameters of the primary network, its reinforcement can be done by extending it. For this goal, a methodology has been developed. Portions of the network are iteratively added to the primary network. The procedure can be divided into two phases:

- identify identify the problems presented by the current best solution by the developed Tabu Search algorithm;
- research phase of the edges to add to the primary network for its strengthening.

2.4.7.1 Identify problems of the current best solution found

The procedure starts with the analysis of the best solution (in terms of OBJ 1) found by Tabu Search.A hydraulic simulation is performed after having applied to layout of WDN the closures set for the edges (pipes or valves) present in the solution. First, the relative pressures are considered and the nodes that do not satisfy the minimum pressures assigned are considered. These nodes can belong to the primary network and to the sectors. If the node is primary, it is chosen, if it is not primary, the primary supply nodes (not dummies but real) of the primary connected component of the Sectorization Graph to which it belongs are chosen instead. The nodes chosen in this way are all primary nodes and are considered representative of the structural inefficiency of the primary network. The next step is to identify the infrastructural inefficiencies of the primary network. Primary network edges that supply the nodes at issue must be identified. For this reason, a Digraph is obtained from the hydraulic model simulation results, executed at the beginning of the procedure. The direction of the edges of the Di-graph is the same as that of the flows. The edges needed in this step are only the primary ones. For this reason, all non-primary elements (edges and nodes) can be removed from the Digraph. Therefore, a graph of the primary network oriented with the flow directions determined by the Tabu Search better solution is obtained. On this Di-graf, Sedgewick algorithm 2001 is applied to find all possible paths from the water storage (Reservoir and Tank) to the chosen primary nodes (those that do not satisfy the p_{min} and those primary supply nodes representing the primary connected components where there are nodes that do not satisfy the p_{min}). This operation therefore makes it possible to identify which are the primary network edges which are currently supplying the nodes with low pressure. For these edges a headloss analysis (in terms of headloss per unit length obtained by the hydraulic model) is performed. The headloss values must be critically evaluated to identify the edges with high headloss. If the procedure is automatic, a quantile must be identified to establish which pipes have high headloss. A length filter can also be established to prevent very high headloss on short pipes from invalidating the statistical analysis. Therefore, all those pipes of the primary network that exceed the headloss value considered as too high are identified.

2.4.7.2 Research new links to add at primary network

As last step, the primary network must be expanded by finding an alternative to the identified edges. Starting from the graph of WDN (indirect graph with weighted edges L/D^5) weight is added to the primary edges that exceed the established headloss. The shortest paths from the water storage (Reservoir and Tanks) to the critical primary nodes in terms of pressure are calculated on this reweighed graph. The new weight has been added so that the shortest paths avoid edges that have a high headloss in order to create loops for those edges that redistribute the flow rate by lowering their headloss. The weight must be chosen to find alternative diameter edges, if it is accepted any path in replacement of those edges just add a greater weight than the maximum weigth. The shortest paths can again choose from primary edges or new edges. These new edges are added to the primary network. The procedure for sectorizing the WDN can then restart by repeating the steps: it starts again from the identification of the Sectorization Graph, the search for the first solution and subsequently the Tabu search application.

Chapter 3

Demand Model

3.1 Introduction

This chapter is dedicated to the model developed to obtain the water demand curves (Demand patterns) starting from monitoring data of WDN and other context information. Subsequently, the Demand patterns were used within the numerical models to describe a temporal variation of water demand consistent with the daily flow balance of the WDNs. The implemented methodology was applied to the construction of the numerical model of the original case studies presented in this thesis. Depending on the different different situations, the monitoring system can provide more or less information, but compared to the past, the evolution of measuring instruments and communication systems and the lowering of their cost allows greater availability of online flow and pressure data. On the monitoring side of water consumption, the presence of smart meters in large users or in particular users also allows to know in detail the trend of consumption during the day. These data can be associated with the knowledge of georeferenced traditional meters linked to the annual water consumption database of the different type of users.

3.2 Development environment

The various steps described in the following paragraphs have been implemented in MATLAB, in particular the EPANET-MATLAB Toolkit (Eliades et al., 2016) is used to read, modify a hydraulic model, perform hydraulic simulations and read the results, which allows the interface with EPANET 2.2.

3.3 Data

In order to apply the methodology it is necessary to identify in a WDN the zones in which it is possible to estimate a flow balance through flow measurements. The necessary initial data are:

- Map of the WDN (usually available in GIS) with the relative information (such as length, year of installation useful for attributing the roughness to the pipes, elevations).
- Database of georeferenced traditional meters linked to the annual water consumption database of the different type of users. The meters can be associated with criteria of proximity to network nodes. The water consumption volume is used for billing by the Water Utility and it is usually read on a six-monthly or annual basis. For each user, the annual volume consumed can be transformed into an annual average flow that corresponds to the Base Demand (BD) in the hydraulic model. Users in databases are also characterized by their type of consumption (e.g. domestic, industrial, agricultural, firefighting).
- Temporal series of flow measure taken on the boundary within is assessed the flow balance; also measure of flow and level at the tanks could be necessary to take into account in the flow balance the water storage within the tanks of the considered WDN.
- Customer consumption of users monitored in the same period or any consumption curves obtained from studies carried out for the same typology of users in other periods or for users of similar typology.
- Number of housing units or resident population in the areas where the flow balance is closed. Depending on the type of consumption database, this data is not always available (e.g. a appartament block consumption can be registered as one) and must be obtained by crossing census data. In the absence of this data or of the resident population data, water losses are estimated by annual water balance.
- The pressure data, within the area, fundamental in the calibration phase of the hydraulic model, can also be useful for the construction of the demand model for the part dedicated to the temporal variation of the water loss.

3.4 Flow balance

The first operation to derive the demand patterns for water consumption and water losses concerns the identification of the boundary within which it is possible to evaluate the flow balance, which could be the entire WDN or sub-zones of it. For purposes related to the hydraulic model, the flow balance is not necessarily annual as for the IWA (International Water Association) water balance (Alegre et al., 2000), but it is necessary to move from the concept of annual water balance to the concept of flow balance for the same period on which the numerical analysis will be performed. Once an area has been defined in which it is possible to perform a flow balance, by measuring the incoming and outgoing flows, it is possible to set the balance equation which allows at any moment to determine the sum of the total flow required by the users not directly monitored with smart meters and total water loss

The flow balance is then given by:

$$Q_{area}(t) = Q_{in}(t) - Q_{out}(t) - Q_{c.m.}(t) \tag{3.1}$$

where is it:

Q_{in} is the inlet flow at time t measured at the inlet points located on the flow balance assessment boundary

Q_{out} is the outflow at time t measured at the inlet points located on the flow balance assessment boundary

Q_{cm} is the flow of users monitored at time t, and/or the sum of the flow of all users to which a known pattern can be attributed. In this case for the j-th user, it is given at time t by the product of his pattern and his base demand:

$$Q_{c.m.j}(t) = pattern_j(t) \cdot BD_j \tag{3.2}$$

3.5 Water Losses Assestment and distribution

In the flow balance 3.1, it is possible to identify the time step in which the flow is minimum, that for zones in which the domestic users are dominant and the water losses have values that are not too high, corresponds to the Minimum Night Flow (MNF). Once the flow $Q_{area}(t_{MNF})$

has been identified, assuming the night consumption of the users, the value of the Water Losses can be obtained:

$$Q_L(t_{MNF}) = Q_{area}(t_{MNF}) - Q_c(t_{MNF}) \tag{3.3}$$

where:

$Q_L(t_{MNF})$ is the water losses assumed at the moment of MNF

$Q_c(t_{MNF})$ is the assumed consumption at the moment of MNF

The assessment of the night water consumption of an area starts from the analysis of the presence of night-time water-demanding users different from the domestic one. For the part relating to night-time consumption by residential users, the night water consumption is calculated by multiplying the number of residential units and the night consumption per residential unit. Although the availability of information from smart meters could change perspectives, due to the lack of direct measurements, night-time consumption per housing unit is generally assumed in the literature, the first value proposed was 1.7 $l/property/h$ (WRc, 1994). However, there are other estimates of this consumption, in fact other studies have produced higher average unit consumption values, 2.69 $l/housing\,units/h$ (Bragalli et al., 2019). There are other correlations linking the value of night consumption to the population in the area (McKenzie and Langenhoven, 1999). Once the water losses in t_{MNF} have been estimated, it is inserted into the model as a demand to the nodes. The water losses value assigned to each junction as demand BL_j is assumed equal to the semi-length belonging to the node multiplied by the water losses per units of length value:

$$BL_j = \frac{L_j}{2} \cdot \frac{Q_L(t_{MNF})}{L_{tot}} \tag{3.4}$$

where is it:

L_j is the total length of the edges incident to the node

L_{tot} is the total length of the pipes in the area

3.6 Demand pattern

Calculated the water losses in t_{MNF} with equation 3.3, the water losses (during the period of flow balance can be considered constant throughout the period or a pattern that represents the variation can be calculated. In the second case it is necessary to identify a representative measure of pressure in the considered area. The water losses at each time can be found using a simplified equation of the FAVAD (Fixed and Variable Area Discharge) (García et al., 2008):

$$Q_L(t) = Q_L(t_{MNF}) \cdot \left(\frac{P_{ref}(t)}{P_{ref}(t_{MNF})} \right)^n \tag{3.5}$$

where:

$Q_L(t)$ is the lost flow at the time t

$P_{ref}(t)$ is the pressure of the reference measuring point

$P_{ref}(t_{MNF})$ the pressure at time t_{MNF}, usually if there are no-night pressure reduction policies, is also the maximum pressure recorded

n is the pressure coefficient which depends on the material of the pipes

Found values of loss, it is possible to proceed with the calculation of the pattern to be assigned to BL_j:

$$pattern_{Losses}(t) = \frac{Q_L(t)}{\sum_j BL_j} \tag{3.6}$$

Having estimated the lost flow, the demand $Q_D(t)$ can be obtained by subtracting the lost flow calculated in equation 3.5 from the flow Q_{area}:

$$Q_D(t) = Q_{area}(t) - Q_L(t) \tag{3.7}$$

The value of $Q_D(t)$ represents the total value of billed metered users excluding those to which it was possible to attribute a pattern or measurement in the period. The pattern to apply to the BD_j is found from the following formula:

$$pattern_{Consumption}(t) = \frac{Q_D(t)}{\sum_j BD_j} \tag{3.8}$$

The pattern thus found can be divided into two components:

- a coefficient representative of the flow requested by users in the period T of measurements analysed:

$$coeff.seasonal = \frac{mean(Q_D(t))}{\sum_j BD_j} \tag{3.9}$$

- a pattern indicative of the variation of the flow in the sampling interval ΔT compared to average flow for the period:

$$pattern_{\Delta T}(t) = \frac{Q_D(t)}{mean(Q_D(t))} \tag{3.10}$$

Therefore, all the elements necessary for the construction of a mathematical model of a WDN were found.

3.7 Water Losses and pressure relationship

As seen in Paragraph 3.5 the estimate of water losses are made in the t_{MNF}, therefore certain pressures in the nodes correspond to this estimate. If the hydraulic model is well-calibrated, i.e. numerically stable and credible from the point of view of network flow and pressures, the water losses can be transformed from demand to pressure-dependent demand. In this case the nodes must be considered as emitters only as regards the water losses, instead the water consumption defined by means the Base Demand remains assigned. The lost flow is expressed by:

$$q_j = \alpha_j \cdot P_j^n \tag{3.11}$$

where is it:

α_j is the discharge coefficient of j-th node

n is the exponent which depends on the material of the pipes

P_j is the pressure value

The first step is the estimation of the emitter coefficients of the nodes. The estimate made at the time of MNF t_{MNF} for each node, with the operations seen previously in the Paragraph 3.5, is considered a reliable estimate of the lost flows. At this time, the BL_j was estimated and from the calibrated model the Pj are known in each node. Consequently, given a representative n depending on the materials of the pipes present in the network (Kabaasha et al., 2020), the value of the emitter coefficient can be calculated for each node:

$$\alpha_j = \frac{BL_j}{P_j^n(t_{MNF})} \tag{3.12}$$

where:

BL_j is the loss of the j-th node at the instant of MNF and as previously seen it depends on

n is the pressure coefficient which depends on the material of the pipes

P_j is the pressure value calculated in the calibrated hydraulic model, where the water losses were modeled as a demands, at time t_{MNF}

Once the value of the discharge coefficients has been calculated, an extended simulation can be performed for the entire calibration period (the same as the time series for which the flow measurements were analysed). The flow balance 3.7 must be respected. By substituting the sum of q_j to Q_L, the flow balance becomes:

$$Q_D(t) = Q_{area}(t) - \sum_j q_j(t) = Q_{area,t} - \sum_j \alpha_j \cdot P_j^n(t) \tag{3.13}$$

The variation in the representation of the water losses which, as can be seen from equation 3.14, depends in each time of simulation on the pressure at nodes (once the values of α for each node and of n have been fixed). The Q_{area} is imposed because it derives from the flow measurements in and out of the area, the latter including customers with known patterns. And the value of α was calculated at the moment of t_{MNF}, whose $Q_D(t)$ must be re-calibrated on the basis of pressure trend. The calibration operation of the new demand pattern occurs recursively. Having identified the value of the discharge coefficients, a long-term simulation is launched and the difference between the flow rate $Q_{area}(t)$ obtained from the measurements and the flow rate which is actually calculated from the model, which is made up of the sum of user flow rates and lost flow rates:

$$\Delta Q(t) = Q_{area}(t) - pattern_{Consumption}(t) \cdot \sum_j BD_j + \sum_j \alpha_j \cdot P_j^n(t) \tag{3.14}$$

Difference that can be positive or negative depending on whether the water losses has been underestimated or overestimated. Subsequently $\Delta pattern_{consumption}(t)$ can be computed:

$$\Delta pattern_{consumption} = \frac{\Delta Q(t)}{\sum_j BD_j} \tag{3.15}$$

Once the $\Delta pattern_{consumption}$ has been calculated, it must be added to the $pattern_{consumption}(t)$ of the simulation in progress, so the new pattern is given by:

$$pattern_{consumption,i+1} = \Delta pattern_{consumption} + pattern_{consumption,i} \tag{3.16}$$

The operation is carried out for all the time instants of the simulation and is repeated until the difference between the measured flow rate $Q_{area}(t)$ and that calculated from the model $pattern_{Consumption}(t) \cdot \sum_j BD_j + \sum_j \alpha_j \cdot P_j^n(t)$ is less than a set limit. If in the same model there are several areas in which the flow balance is estimated, the pattern calibration operation must be done simultaneously for all the areas, given that the variations of one area could influence the results of the other.

Chapter 4

New extended real water distribution network models

4.1 Introduction

In this thesis work three new real case studies are presented, not from literature. The networks presented are Tyrrhenian Town, Adriatic Town and Extended Modena. Each one of these case studies has particularities that distinguish it from the others, both from the point of view of network characteristics and from a modeling detail point of view. The development of the hydraulic models of these three networks was necessary to have three real case studies of significant dimensions with different specificities that could serve to validate the methodologies proposed in the previous chapters both as regards the research of the primary network and as regards the division into sectors. These case studies present complexity of the networks that were important in the development of the algorithm, permitting the implementation of suitable methodologies to be able to deal with large real case studies, even very different from each other.

4.2 Tyrrhenian Town

4.2.1 Description

The modeled portion of the Tyrrhenian Town network serves a population of approximately 21690 inhabitants. The network is divided into nine sectors (in Figure 4.1) for which the number of housing units is known, having made an estimate by overlapping the area of the sectors on the census sections of ISTAT (Istituto Nazionale di Statistica). The Table 4.1 shows the estimate of housing units per sector.

Table 4.1: Housing units per sector

Parameter	Value
Sector A	2651
Sector B	2303
Sector C	4218
Sector D	2831
Sector E	674
Sector F	1796
Sector G	2372
Sector H	2480
Sector I	2354

The model contains 3016 nodes and 3122 links, in detail in the table 4.2 the different types present. The five Reservoirs of the hydraulic model represent one the inlet point of the network with known pressure measurement, in blue in Figure 4.2, the other 4, in yellow in Figure 4.2, are the wells present in the WDN. The Tank of the network is represented in red in Figure 4.2. The nodes in green in Figure 4.2 represent the exchange nodes with other portions of other networks (with measured flow), supplied by this WDN. In the model there are ten pumps, four connected to the wells, five in the main pumping station of the WDN which has the capacity to supply the whole system including the Tank by pumping the water coming from the Reservoir in blue in Figure 4.2. These pumps are never all in operation at the same time, but they are switched on based on water consumption, influenced by the season. The other pump supplies Sector A (in Figure 4.1) during consumption peak. The elevation of the nodes varies from the minimum share of 0 m to the maximum share of 98.38 m. The Base Demands is calculated starting from the database of the annual water consumption of the users.

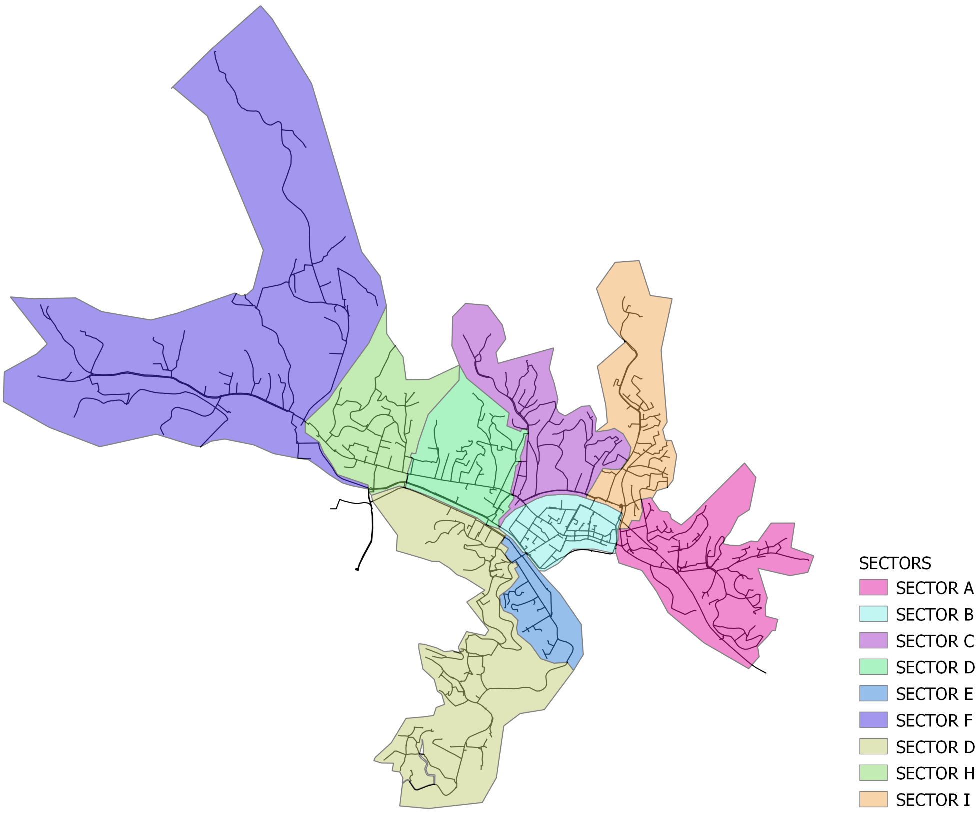

Figure 4.1: Tyrrhenian Town actual sectorization

Table 4.2: Tyrrhenian Town model data

Nodes	N^o
Junctions	3010
Reservoirs	5
Tanks	1

Links	N^o
Pipes	2285
Pumps	10
Valves	827

4.2.2 Flow Balance

The flow balance in the various sectors is estimated with the methodology described in Chapter 3. The Flow Balance is made in each sector starting from the input and output flow data of a summer day with a time step of 5 minutes. Within the model there are several hotel users to which a known pattern is attributed. The pattern is obtained starting from the analysis of the consumption data of nine hotels monitored with a half-hour time step by smart meters. Once the $Qarea$ is calculated, the $Q_L(t_{MNF})$ is calculated. Data on the number of housing

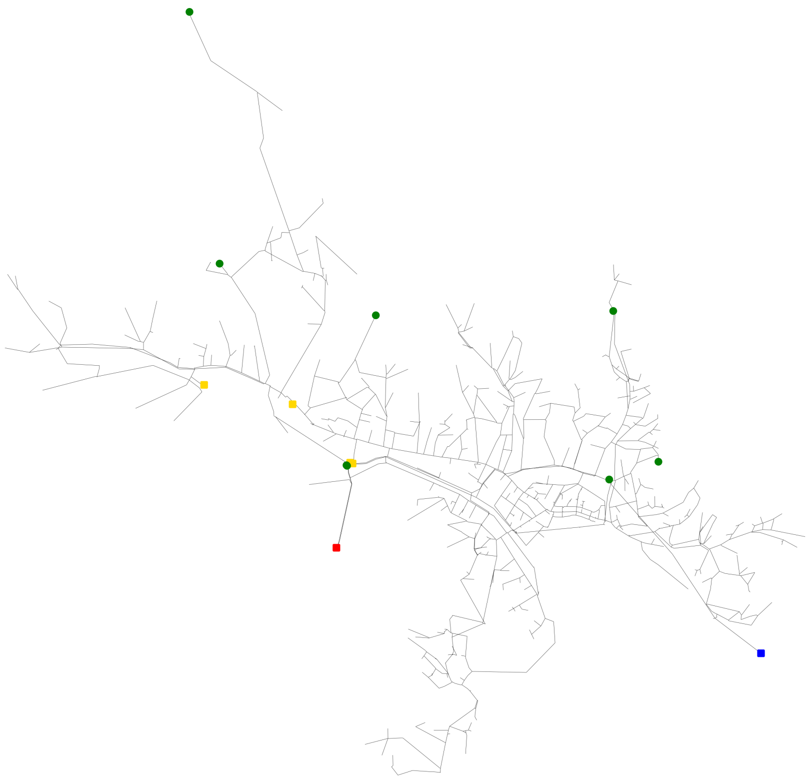

Figure 4.2: Tyrrhenian Town layout

units in 4.1 are used to estimate the leakage in the sectors. As regards the hourly consumption per housing unit, it is analyzed how it impacts on the water losses estimate. The table 4.3 shows the night-time consumption values per unit found by Bragalli et al. (2019) in a study made on some users located in different WDN sectors comparable in size to Tyrrhenian Town. As can be seen from the Figures 4.3 and 4.4, the estimate of water losses and the daily coefficient varies greatly depending on the choice of consumption in the night-time minimum hour attributed to the housing unit The value of 2.91 l/h.u./h, weighted average based on the number of housing units of the values recorded in the various sectors (Bragalli et al., 2019), was assumed in the construction of the WDN hydraulic model, as night-time consumption per housing unit. Once the $Q_L(t_{MNF})$ is found for each sector, the BL_j is assigned to the nodes of each sector as explained in Paragraph 3.6.

Table 4.3: Domestic consumption (l/hu/h) during the t_{MNF} (Bragalli et al., 2019)

Sectors	**Value (l/h.u./h)**
Sector M	1.40
Sector N	1.87
Sector O	2.49
Sector P	1.40
Sector Q	2.62
Sector R	2.94
Sector S	4.56
Sector T	5.15
Literature value (WRc, 1994)	1.70

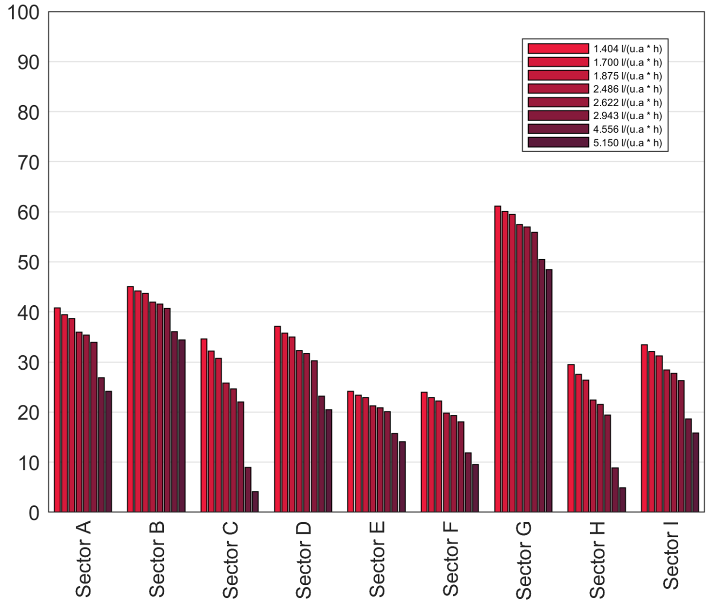

Figure 4.3: Variation of the water losses estimated

The pattern of water losses was set to 1 considering the water losses constant and equal to that calculated in the t_{MNF}. Once the model was calibrated, the procedure for modeling the pressure dependent loss was applied, thus recalibrating the Consumption Patterns. The recalibrated demand patterns have a higher value than the initial ones, this because by setting the water losses equal to that of t_{MNF} throughout the day, the loss tends to be overestimated, since the pressures in the network are lower when consumption is greater. The two sectors Sector B and Sector E are an exception, where a timed pressure reduction policy is applied (day-time and night-time regulation), in this case as can be seen from the figures 4.15 and 4.18 the recalibrated demand pattern is lower than the initially attributed pattern during the day, this

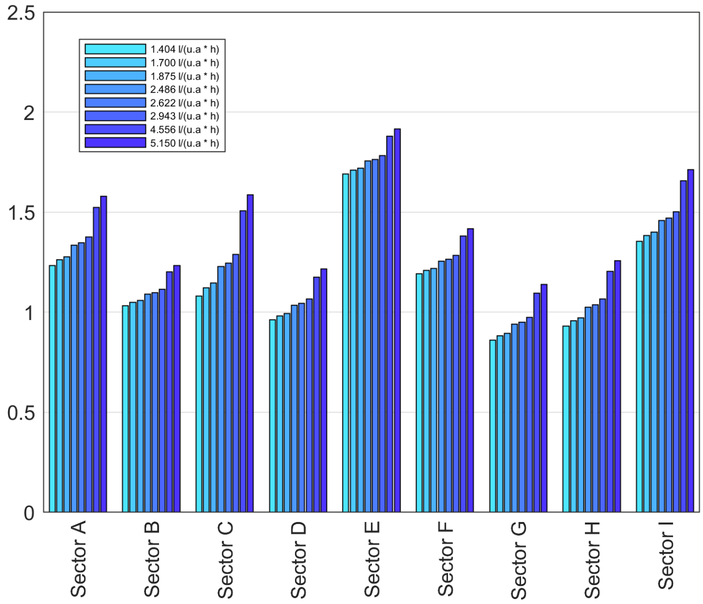

Figure 4.4: Variation of seasonal coefficient estimated

is because, being the pressure regulated via PRV, it has its highest values during the day when the applied pressure reduction is lower, so as not to risk compromising the service towards users, as a result, day-time losses are greater than night-time losses (Figures 4.6 and 4.9).

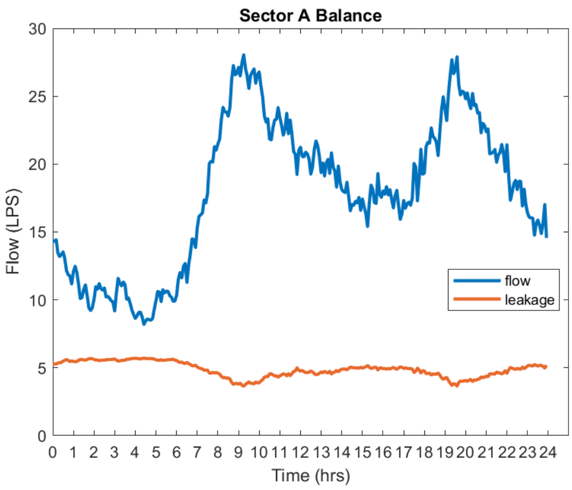

Figure 4.5: Flow Balance Sector A

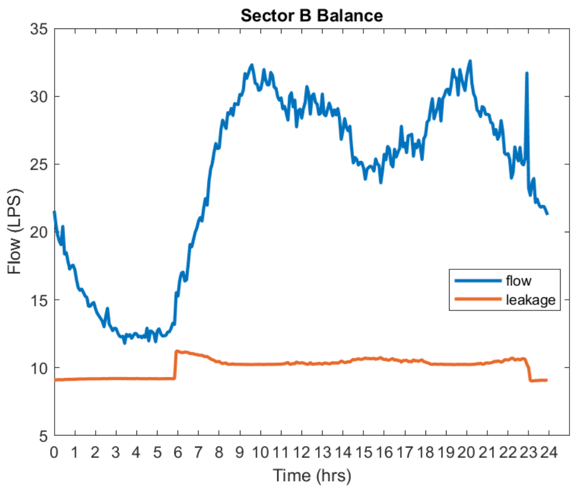

Figure 4.6: Flow Balance Sector B

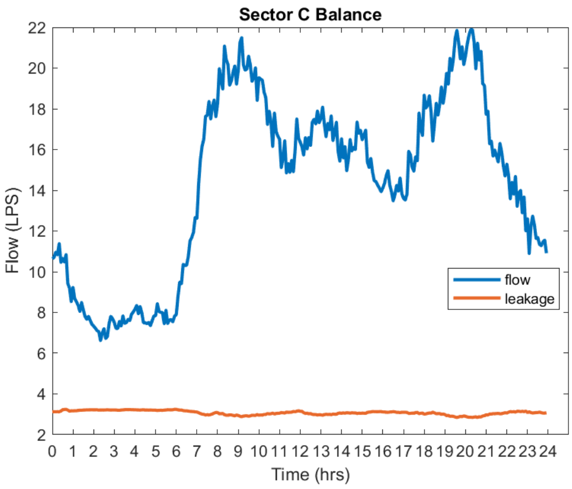

Figure 4.7: Flow Balance Sector C

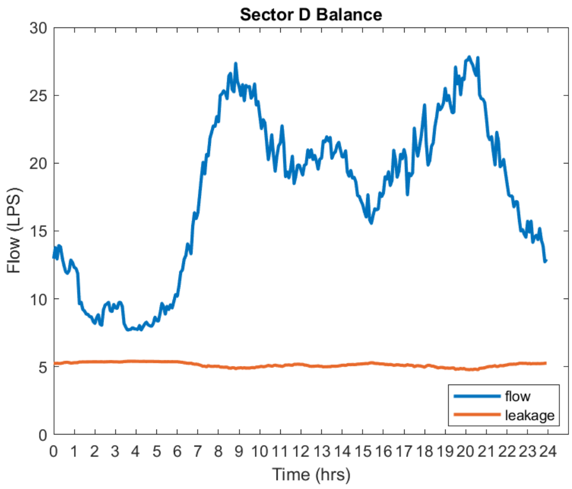

Figure 4.8: Flow Balance Sector D

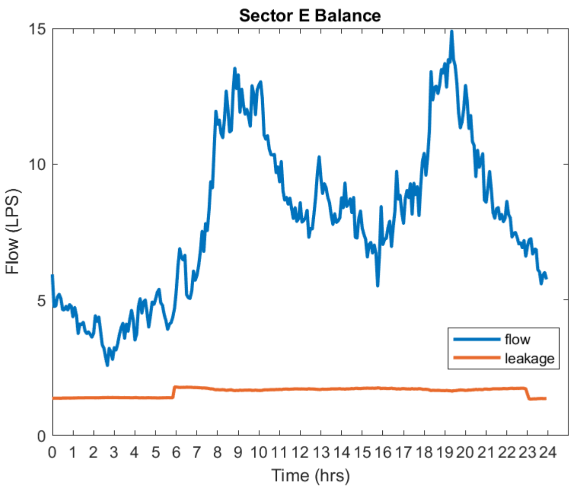

Figure 4.9: Flow Balance Sector E

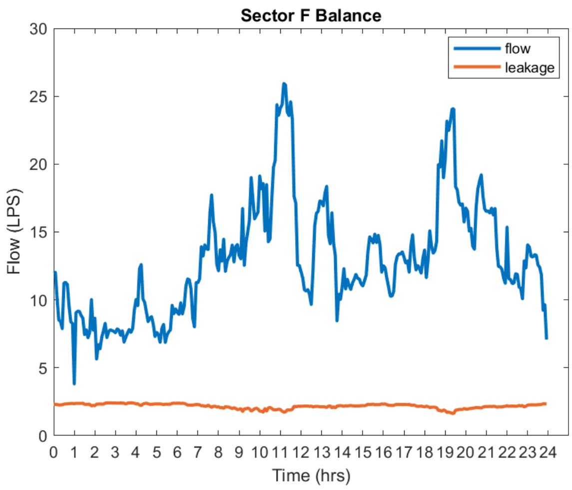

Figure 4.10: Flow Balance Sector F

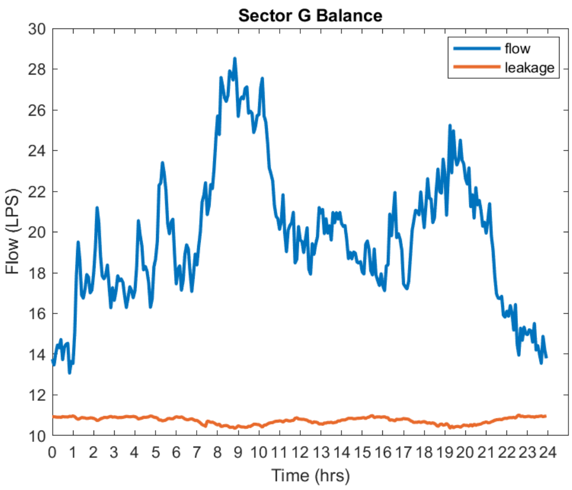

Figure 4.11: Flow Balance Sector G

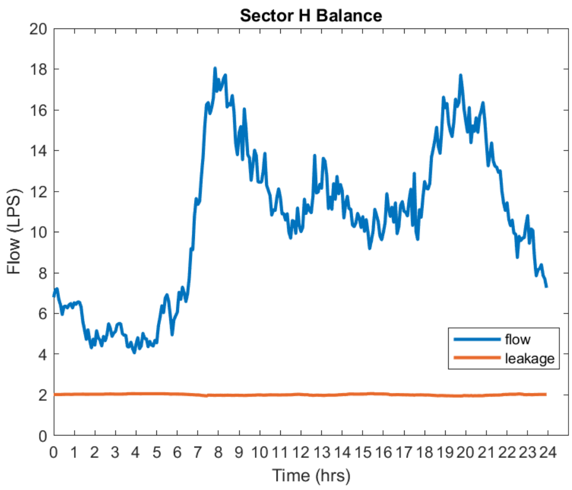

Figure 4.12: Flow Balance Sector H

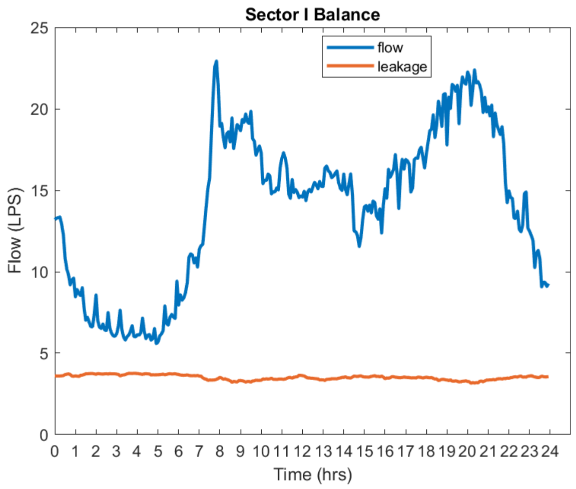

Figure 4.13: Flow Balance Sector I

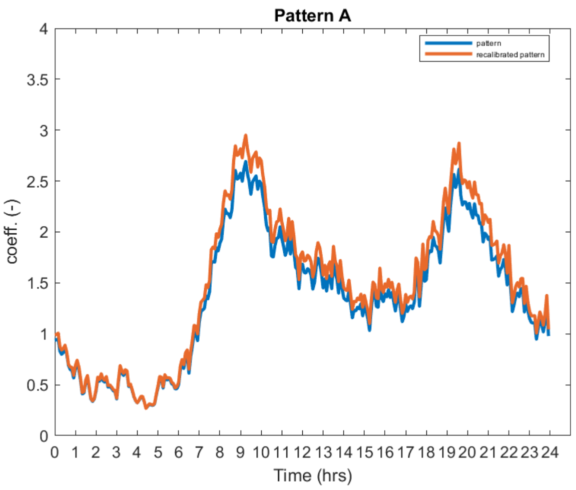

Figure 4.14: Demand Pattern Sector A

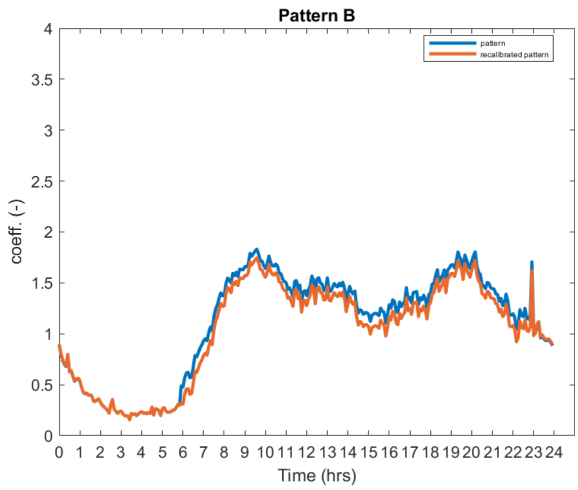

Figure 4.15: Demand Pattern Sector B

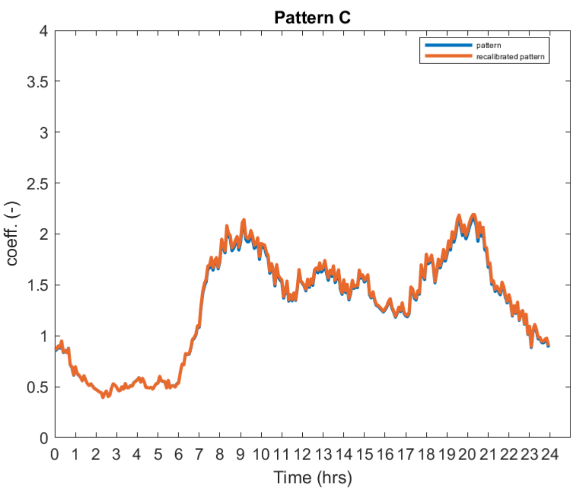

Figure 4.16: Demand Pattern Sector C

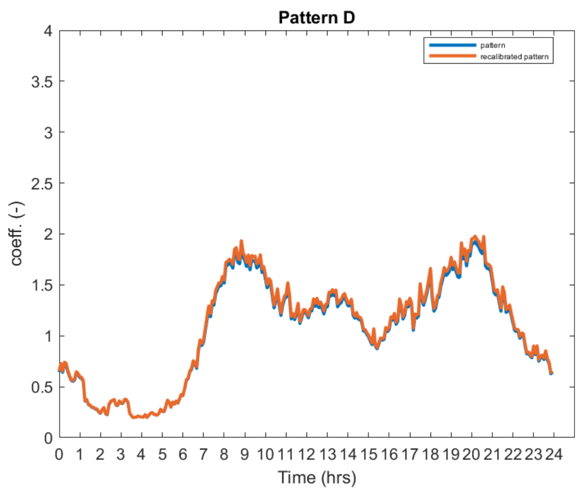

Figure 4.17: Demand Pattern Sector D

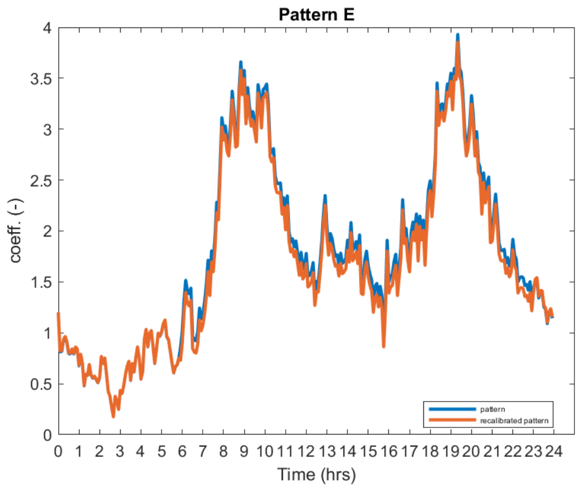

Figure 4.18: Demand Pattern Sector E

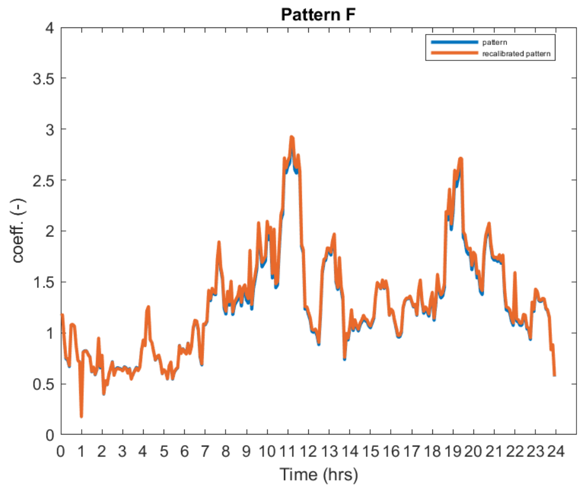

Figure 4.19: Demand Pattern Sector F

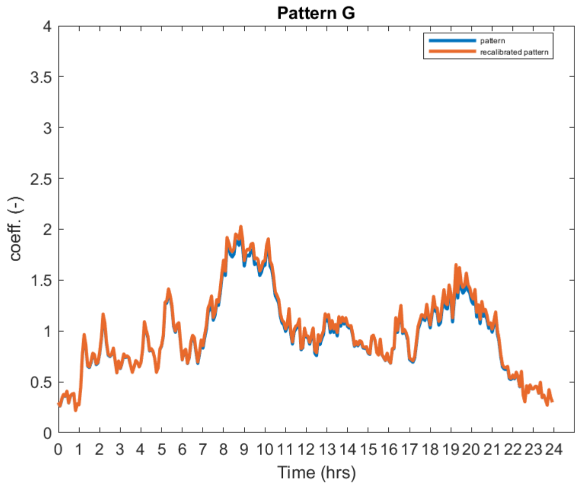

Figure 4.20: Demand Pattern Sector G

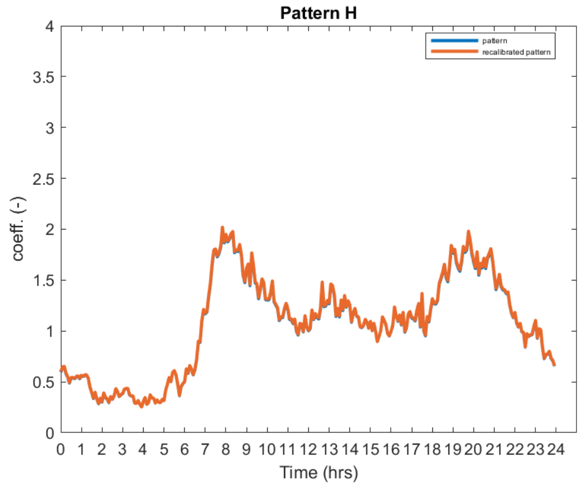

Figure 4.21: Demand Pattern Sector H

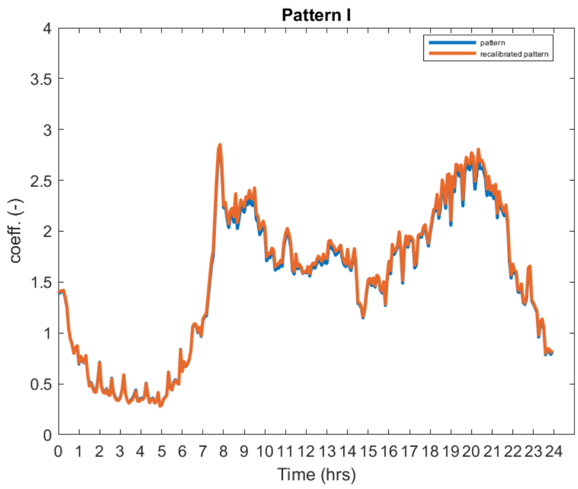

Figure 4.22: Demand Pattern Sector I

4.3 Adriatic Town

4.3.1 Description

The Adriatic Town WDN is a non-sectorised network, the modeled portion of the network supplies 38495 housing units. The model contains 14752 nodes and 15306 links, in detail in Table 4.4 the different types are present. The Reservoir of the model, in blue in the Figure 4.27, supplies the city of Adriatic Town, the level in the reservoir is measured and consequently it has been used as a boundary condition of the model. There are three tanks present in the network (in red in Figure 4.27), and they too are monitored so the levels and the incoming and outgoing flow rates are known. The green nodes in Figure 4.27 represent the exchange nodes with other portions of the network (with measured flow rate), supplied by this WDN. In the modeled portion of the network there are no pumping systems, the system is totally gravity supplied. The elevation of the nodes varies from the minimum elevation equal to 5.08 m to the maximum elevation equal to 121.55 m. The Demand at nodes is derived from the database of billed users.

Table 4.4: Adriatic Town model data

Nodes	N^o
Junctions	14748
Reservoirs	1
Tanks	3

Links	N^o
Pipes	12568
Pumps	0
Valves	2738

4.3.2 Flow Balance

In the set up of the hydraulic model of the network it was possible to make the balance on the whole network. Knowing the flow introduced into the network (in blue in the Figure 4.24) the outgoing flow rates that supply other portions of neighboring networks (nodes in green) and knowing the inflow and outflow of the Tanks. One week of data was available with a time step of 15 minutes. This made it possible to use the methodology described in Paragraph 3.6 to be able to estimate the leakage at nodes and the pattern of losses assuming a minimum night-time consumption per housing unit equal to 2.91 l/h.u./h., was applied the simplified FAVAD (García

Figure 4.23: Adriatic Town layout

et al., 2008) having available a reference measurement for the pressure inside the network so as to be able to obtain a law of variation of the water loss shown in Figure 4.26 that has permitted to calculate the demand pattern of users, shown instead in Figure 4.25.

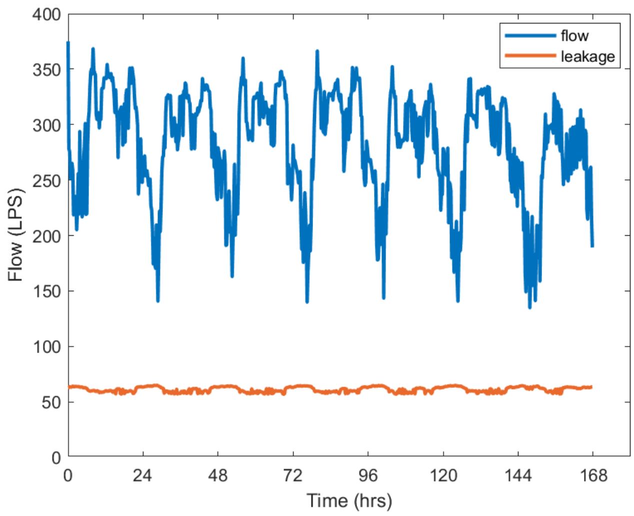

Figure 4.24: Adriatic Town Flow balance

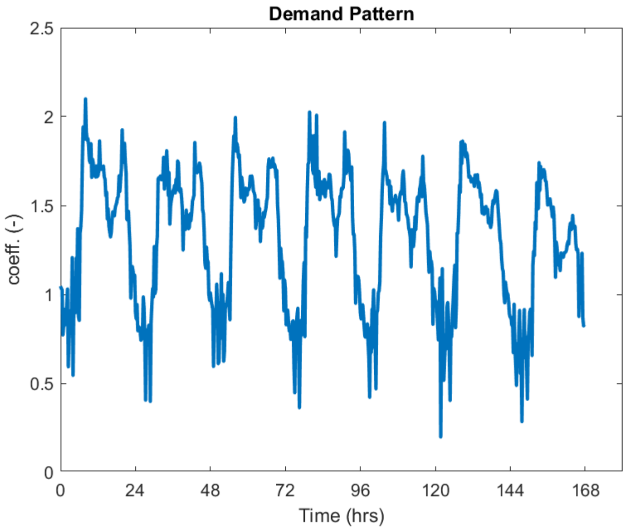

Figure 4.25: Adriatic Town Demand pattern

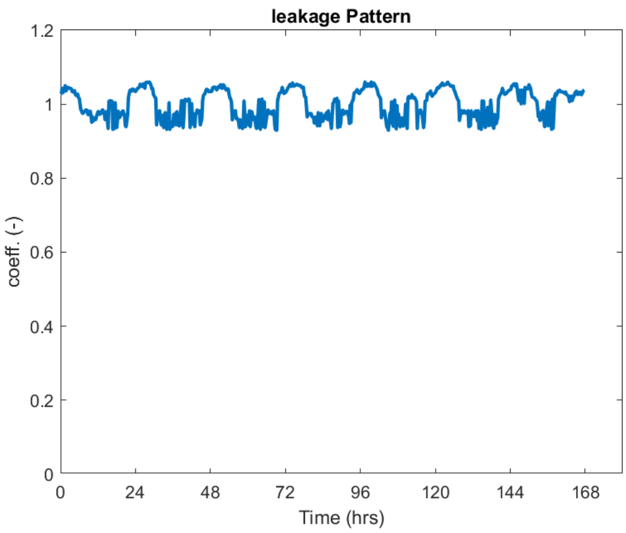

Figure 4.26: Adriatic Town leakage pattern

4.4 Extended Modena

Extended Modena network is a network calibrated for a single period simulation corresponding to the moment of maximum consumption. This network is an extended version of the Modena network well known in the literature (Bragalli et al., 2012). Extended Modena has 3321 nodes and 4312 edges. The reservoirs are shown in blue and the tanks in red.

Table 4.5: Extended model data

Nodes	N^o
Junctions	3321
Reservoirs	7
Tanks	3

Links	N^o
Pipes	4312
Pumps	0
Valves	0

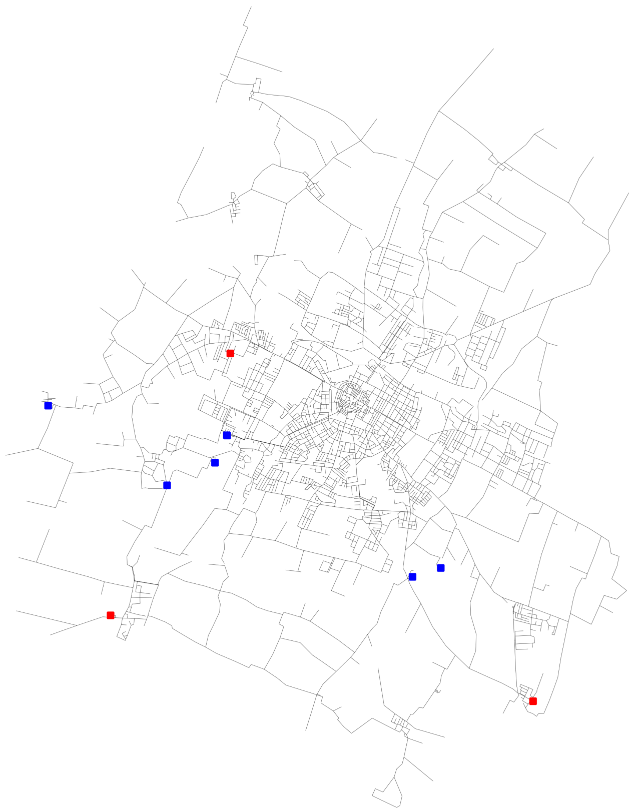

Figure 4.27: Modena layout

Chapter 5

Primary Network Results

5.1 Introduction

This chapter shows the results obtained on the networks of Balerma (Reca and Martínez, 2006), KY 2 (Jolly et al., 2014), BWSN 2 (Ostfeld et al., 2008), Adriatic Town (Paragraph 4.3), Extended Modena (Paragraph 4.4) and Tyrrhenian Town (Paragraph 4.2) by applying the methodology for the research of the primary network (as proposed in Chapter 1). While the System Approach in this procedure has one and only one result, it is in fact the minimum cost Steiner Tree that connects the nodes considered main (Reservoirs, Tanks, Pump stations, connection with other WDN), the network that derives from the Consumption Approach is obtained with a discretionary choice, depending on the filter that is applied to the results, which could also be different depending on the case study. In the results, a primary network is proposed, obtained from the sum of the Steiner Tree and the pipes with quantile of order greater than 0.90. The strengthening of the primary network has also been applied so that it can be the starting point for an isolated sectorization of the WDN (as proposed in Chapter 2). Also in this case the results can be different depending on the edges chosen with the Consumption approach (Paragraph 1.3.2).

5.2 Balerma

The Balerma network (Reca and Martínez, 2006) is a model of an irrigation district, located in Balerma (Spain). Te model contains a total of 443 junctions, supply by 4 sources nodes (Reservoirs) and 454 pipes. The layout of the network is shown in Figure 5.1. The results of the two approaches to identify the primary network are shown in the figure 5.1 and in the Figure 5.2. The final Primary Network shown in the Figure 5.3 is the sum of the System Approach and of the pipes that have q0.9 in Consumption approach. The connectiones of terminal nodes (the nodes of primary network with degree node equal to 1 respect primary edges) found are highlighted in green.

Figure 5.1: Balerma Steiner Tree

Figure 5.2: Balerma Consumption approach

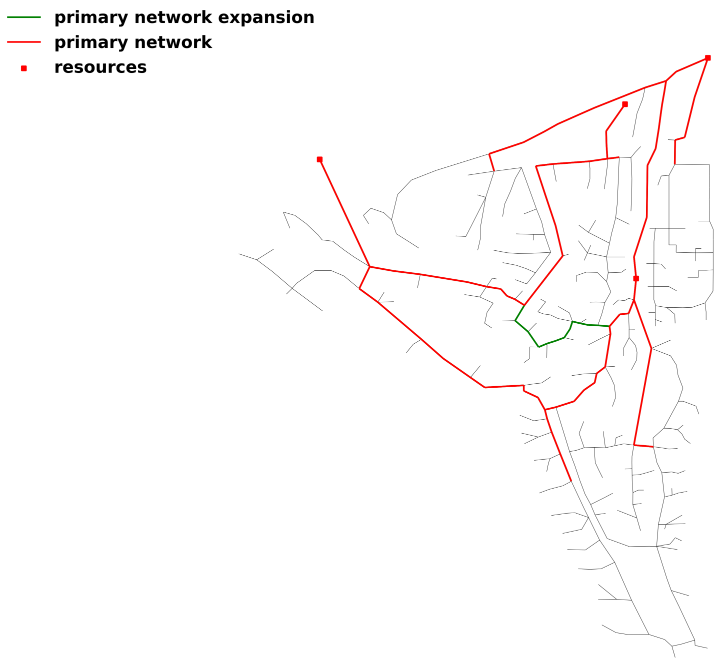

Figure 5.3: Balerma primary network

5.3 KY 2

The KY 2 network (Jolly et al., 2014) is a grid system in Kentucky with 815 nodes, 1125 edges the following assets: 3 Tanks, 1 Pump. The results of the two approaches to identify the primary network are shown in the figure 5.4 and in the Figure 5.5. The final Primary Network shown in the Figure 5.6 is the sum of the System Approach and of the pipes that have q0.9 in Consumption approach. The connectiones of terminal nodes (the nodes of primary network with degree node equal to 1 respect primary edges) found are highlighted in green.

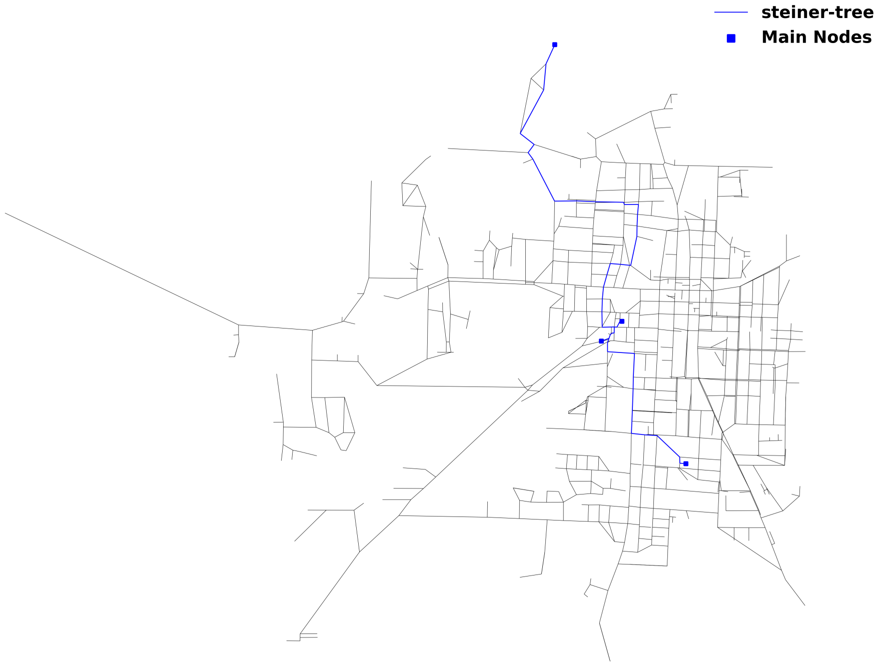

Figure 5.4: KY 2 Steiner Tree

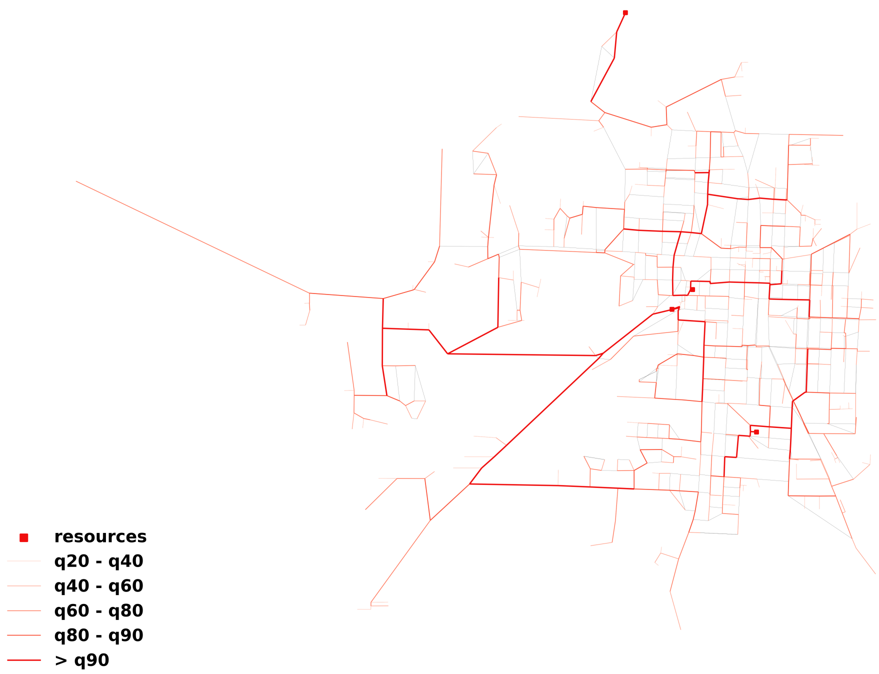

Figure 5.5: KY 2 Consumption approach

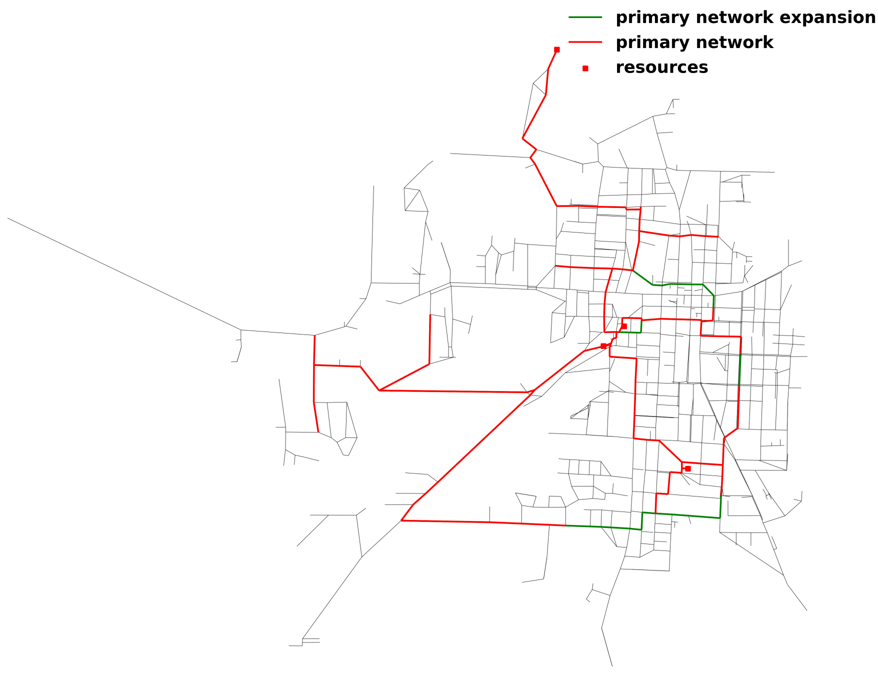

Figure 5.6: KY 2 Primary network

5.4 BWSN 2

The BWSN Network 2 (Ostfeld et al., 2008) is a model of real network, it contains 12523 nodes, 2 reservoirss, 2 tanks, 14822 pipes, 4 pumps, 5 valves, and is subject to 5 variable demand patterns. The model has an input node from which a flow of 195 l/s enters. This node is considered as a source in the System Aproach and in the Consumption Approach. In the Steiner Tree problem the pump nodes are considered terminal. Figures 5.7, 5.8, 5.9 show the results.

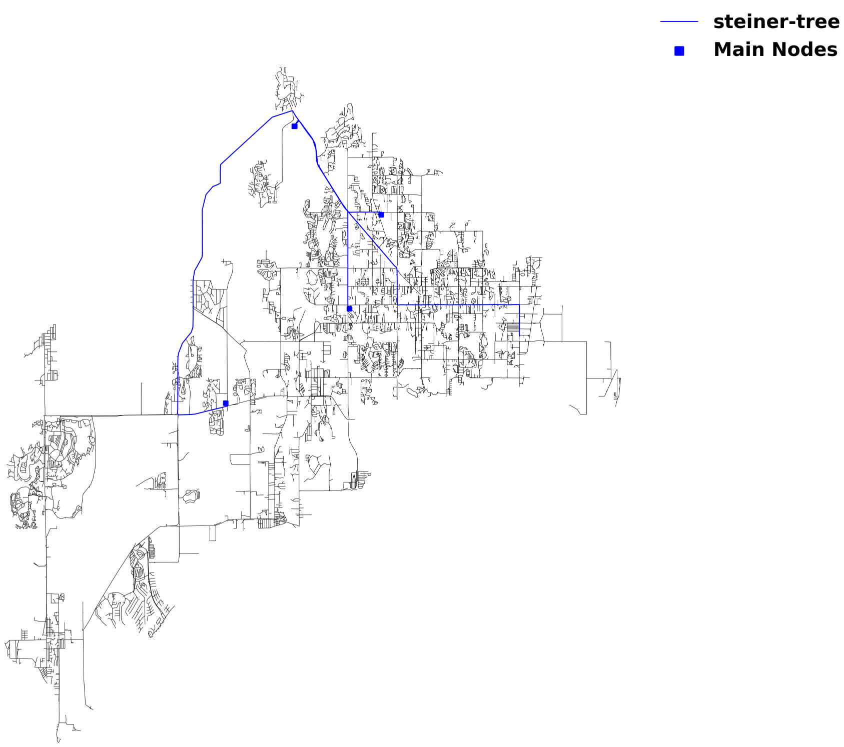

Figure 5.7: BWSN 2 Steiner tree

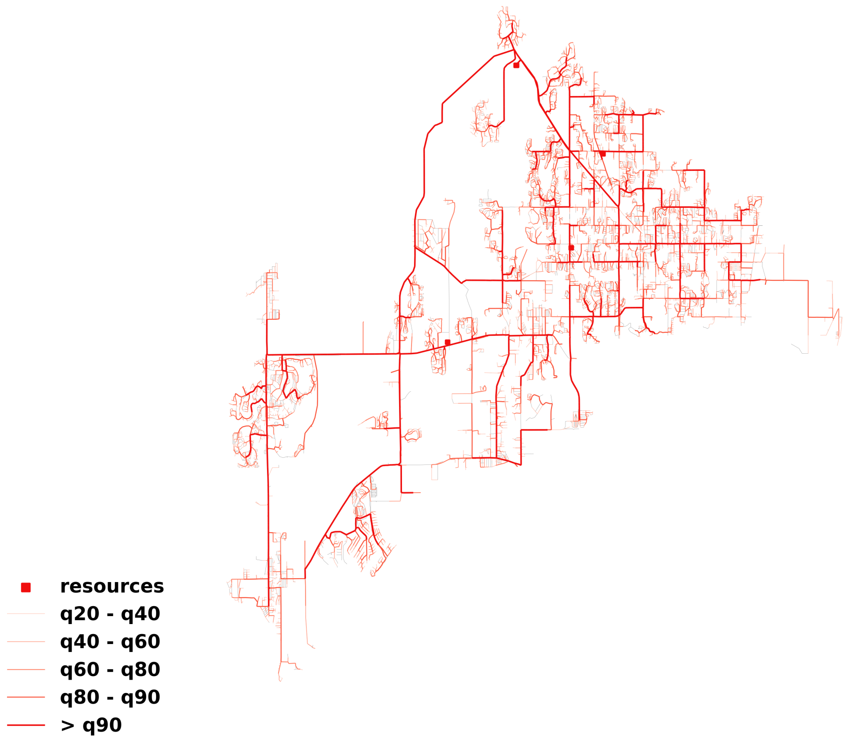

Figure 5.8: BWSN 2 Consumption approach

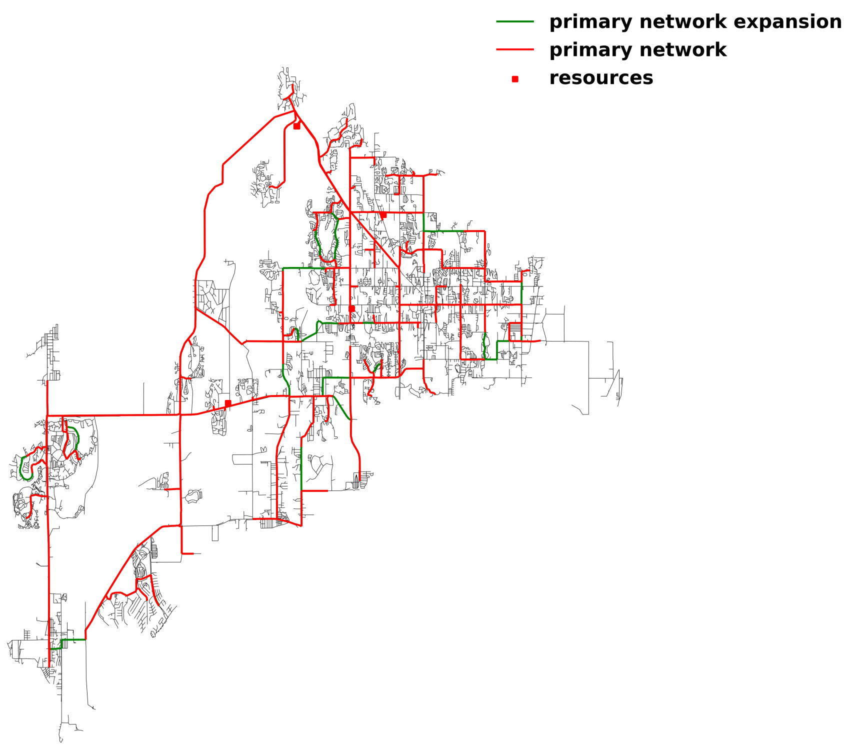

Figure 5.9: BWSN 2 primary network

5.5 Adriatic Town

Adriatic Town is supplied by gravity from a single resource (Reservoir) that is close and well connected to the other three Tanks from a topological point of view. Thus, the small primary network is identified with the System Approach exclusively (1.3.1). This highlights that, in this case study, i) the Steiner tree is not able to identify the important asset for the distribution and ii) the Consumption Approach is of fundamental importance to identify what are the most important pipes within the network. The resulting primary network, shown in Figure 5.12 represents the union of the Steiner Tree (Figure 5.10) and the q90 network (Consumption Approach Figure 5.11) with the application of the loop search which resulted in the addition of the edges represented in green in the figure.

Figure 5.10: Adriatic Town Steiner tree

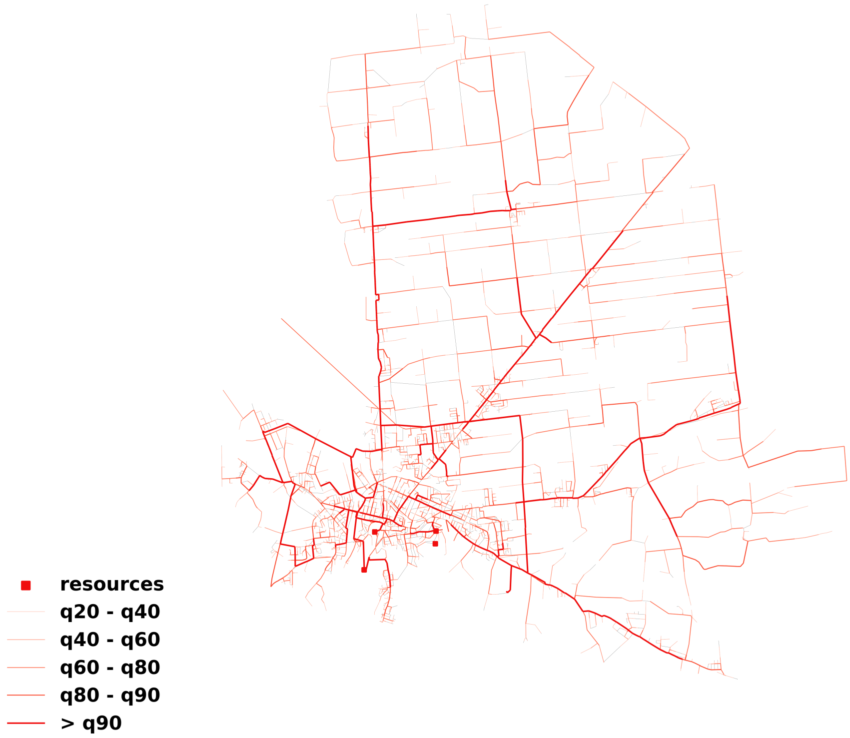

Figure 5.11: Adriatic Town Consumption approach

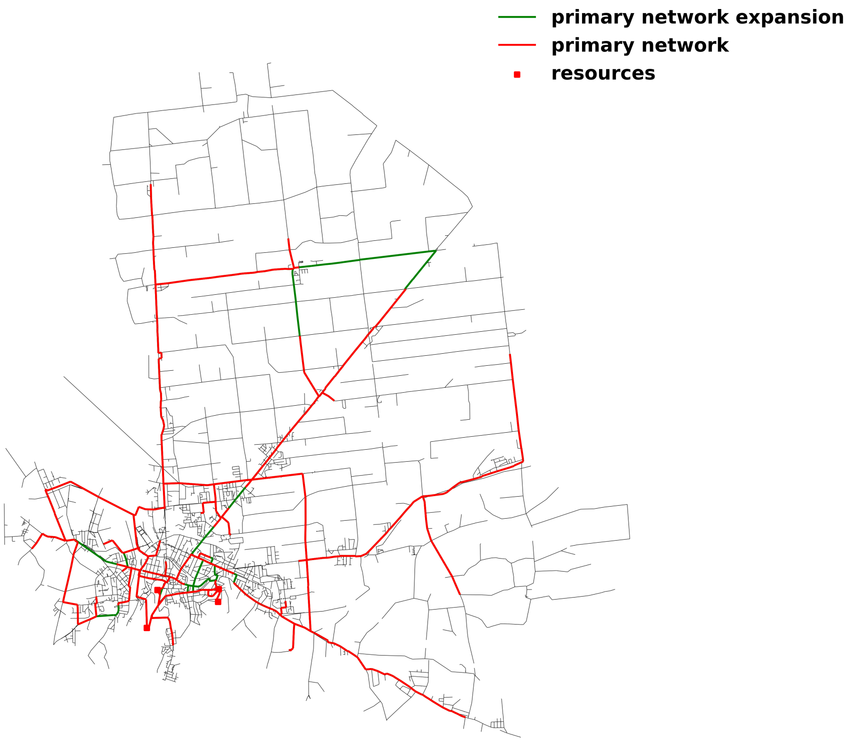

Figure 5.12: Adriatic Town primary network

5.6 Extended Modena

The Extended Modena network is described in chapter 5 paragraph. The result of the System approach (Figure 5.13) is obtained considering the 5 Reservoirs, the Tank and the pump stations nodes as terminals of the steiner tree. In this case, the result of the System Approach appears to be well extended, given the quite uniform distribution of the Main Nodes within the network. In Figure 5.15, that is the sum of System Approach (Figure 5.13) and Consumption Approach (quantile 0.9, in Figure 5.14).

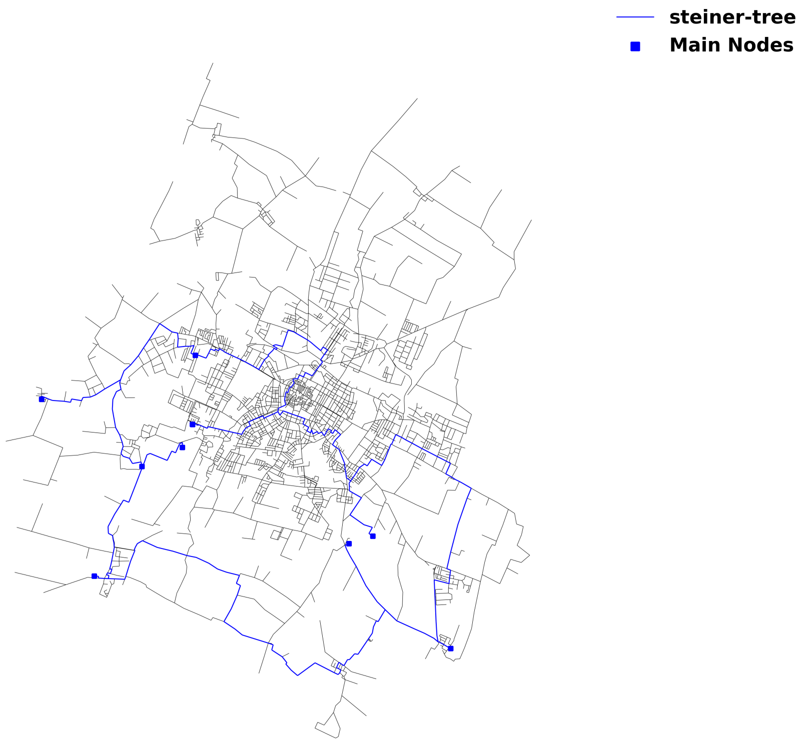

Figure 5.13: Extended Modena Steiner Tree

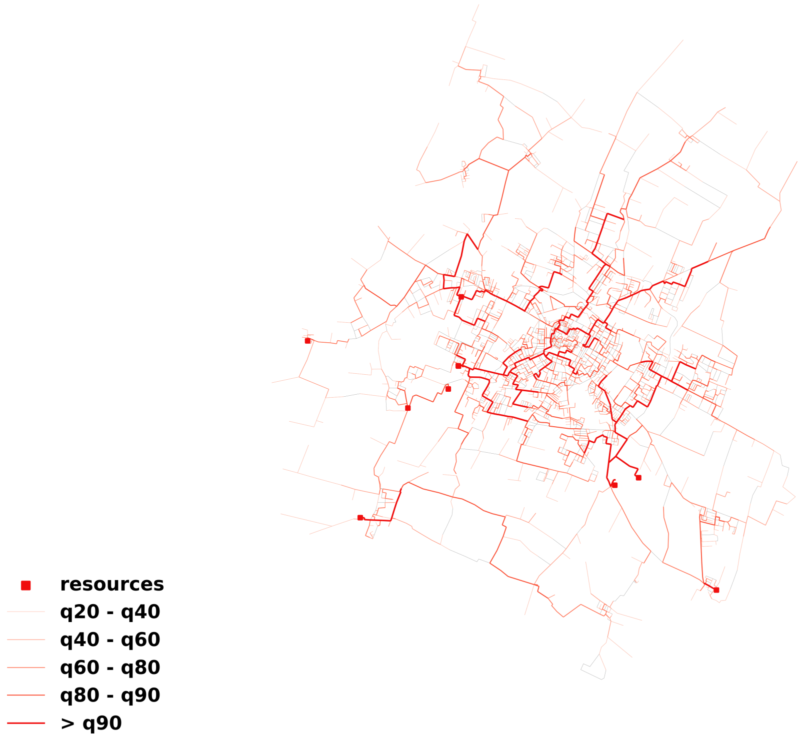

Figure 5.14: Extended Modena Consumption approach

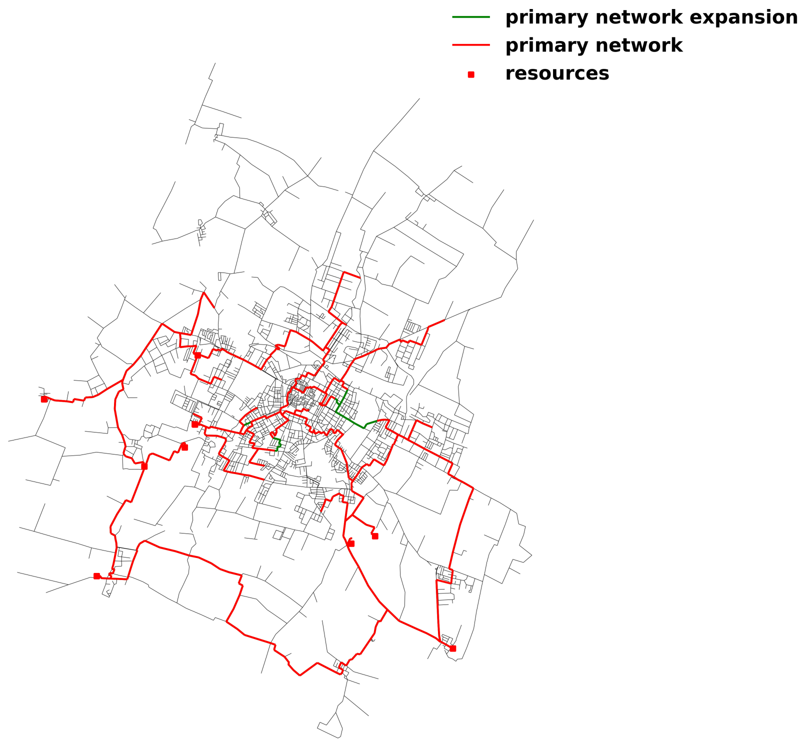

Figure 5.15: Extended Modena primary network

5.7 Tyrrhenian Town

The Tyrrhenian Town network is described in chapter 5 paragraph. The result of the System approach (Figure 5.16) is obtained considering the 5 Reservoirs, the Tank and the pump stations nodes as terminals of the steiner tree. In Figure 5.18, that is the sum of System Approach (Figure 5.16) and Consumption Approach (quantile 0.9, in Figure 5.17), it can be seen that there are no paths between the terminal nodes of the primary network that are minimum than those already included in the primary network.

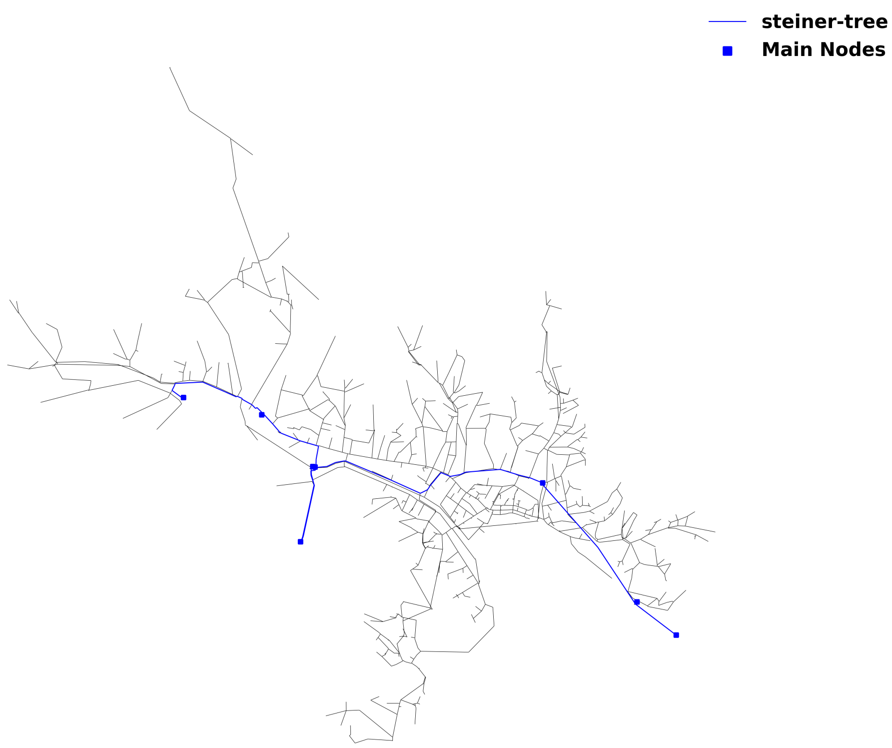

Figure 5.16: Tyrrhenian Town Steiner Tree

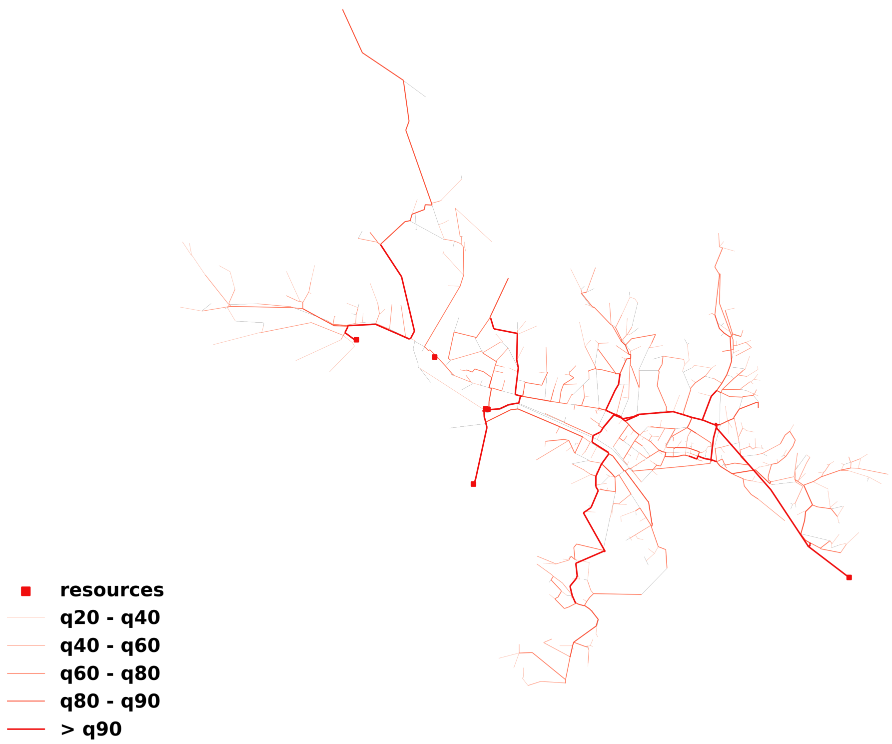

Figure 5.17: Tyrrhenian Town Consumption approach

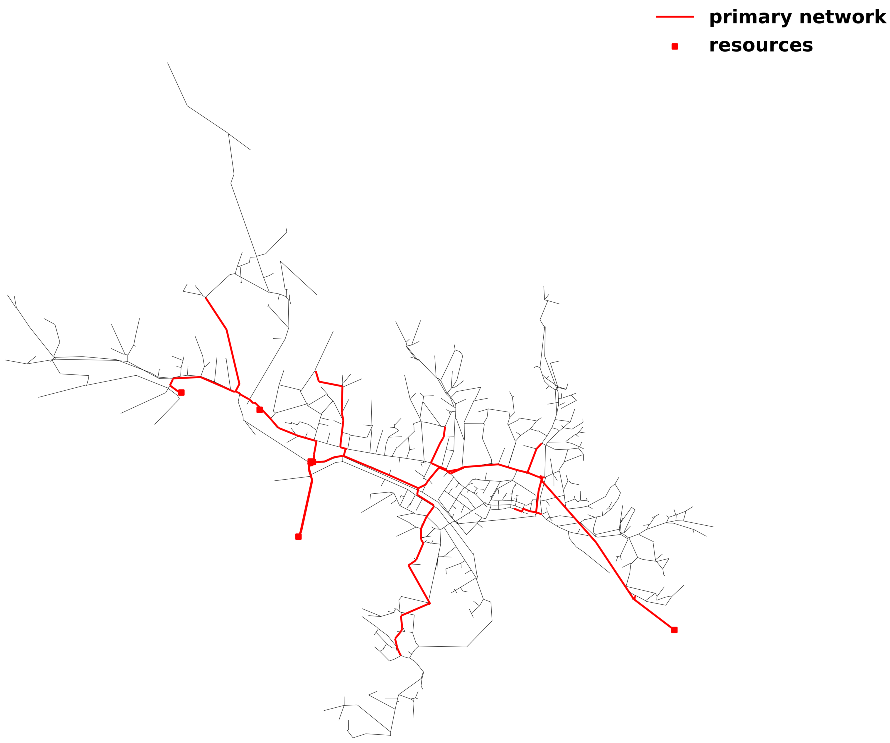

Figure 5.18: Tyrrhenian Town primary network

Chapter 6

Sectorization Result

6.1 Introduction

This chapter presents the results of the methodology for sectorizing the network based on the primary network identified as described in Chapter 1 and presented in Chapter 5 and on the part that concerns the sectorization of WDN as presented in Chapter 2. The scenario assumed for the application of the overall methodology corresponds to the peak water demand thus to be addressed the problem in the most complex moment to maintain the minimum required pressures.The primary networks found allowed in the case studies of Balerma (Reca and Martínez, 2006), KY 2 (Jolly et al., 2014), BWSN 2 (Ostfeld et al., 2008) and Adriatic Town (Paragraph 4.3) to obtain a solution with an acceptable violation Δ of OBJ 1, set at most to 1 m. As regards the last two networks proposed Extended Modena (Paragraph 4.4) and Tyrrhenian Town (Paragraph 4.2), it was necessary to apply the methodology for the Strengthening of the primary network (Paragraph 2.4.7), in fact initially a result is not found that satisfied the Δ imposed for OBJ 1. However, the procedure was done automatically without a pre-analysis that imposes filters on the non-sectorization of some connected primary components.

6.2 Balerma

The WDN of Balerma (Reca and Martínez, 2006) has been sectorized both in sectors with a single supply pipe and in isolated sectors with the possibility of two supply pipes. In both cases the p_{min} at the nodes have been set equal to 20 meters or equal to the value they have in the open network if it is less than 20 m. The Δ for which OBJ 1 is considered satisfied is set equal to 0. The resolution time given as a stop criterion is equal to 200 seconds in both cases.

6.2.1 Balerma with one supply pipe for each sector

The results obtained in the case of only one entry per sector of WDN are reported below. Subtracting the primary network in red in Figure 6.1 we obtain the primary connected components. In Figure 6.1 are shown in green the primary connected components that already satisfy the condition of a single supply edge. These components are already automatically considered as sectors and no closures are applied to them. For the WDN of Balerma the condition set for OBJ 1 is already satisfied by the initial solution, consequently OBJ 2 is calculated starting from the first iteration of the process and is minimized by the Tabu Search algorithm as shown in Figure 6.2. The best result in terms of OBJ 2 is reached after 96 seconds and is equal to 7.10 m. The sectors corresponding to the best solution are presented in Figure 6.3.

Figure 6.1: Balerma primary connected components filtered if they have only one primary supply edge

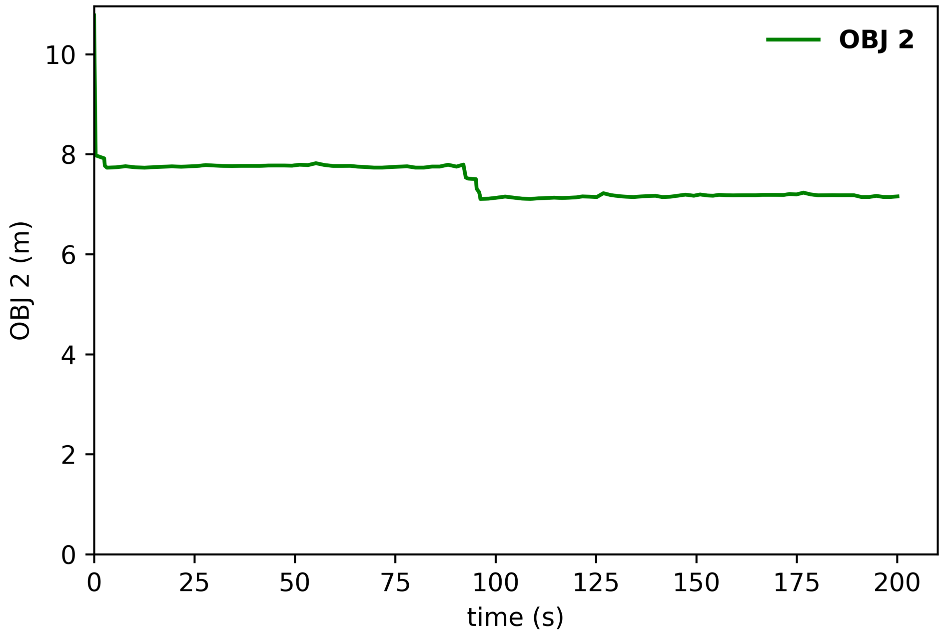

Figure 6.2: Balerma: OBJ 2 results during Tabu Search

Table 6.1: Balerma: Results of second process iteration

iter.	**OBJ 1 (m)**	**OBJ 2 (m)**	N^o **closed edges**	**time (s)**
initial solution	0	10.77	7	0
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
53**	0	7.10	7	96.2
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.

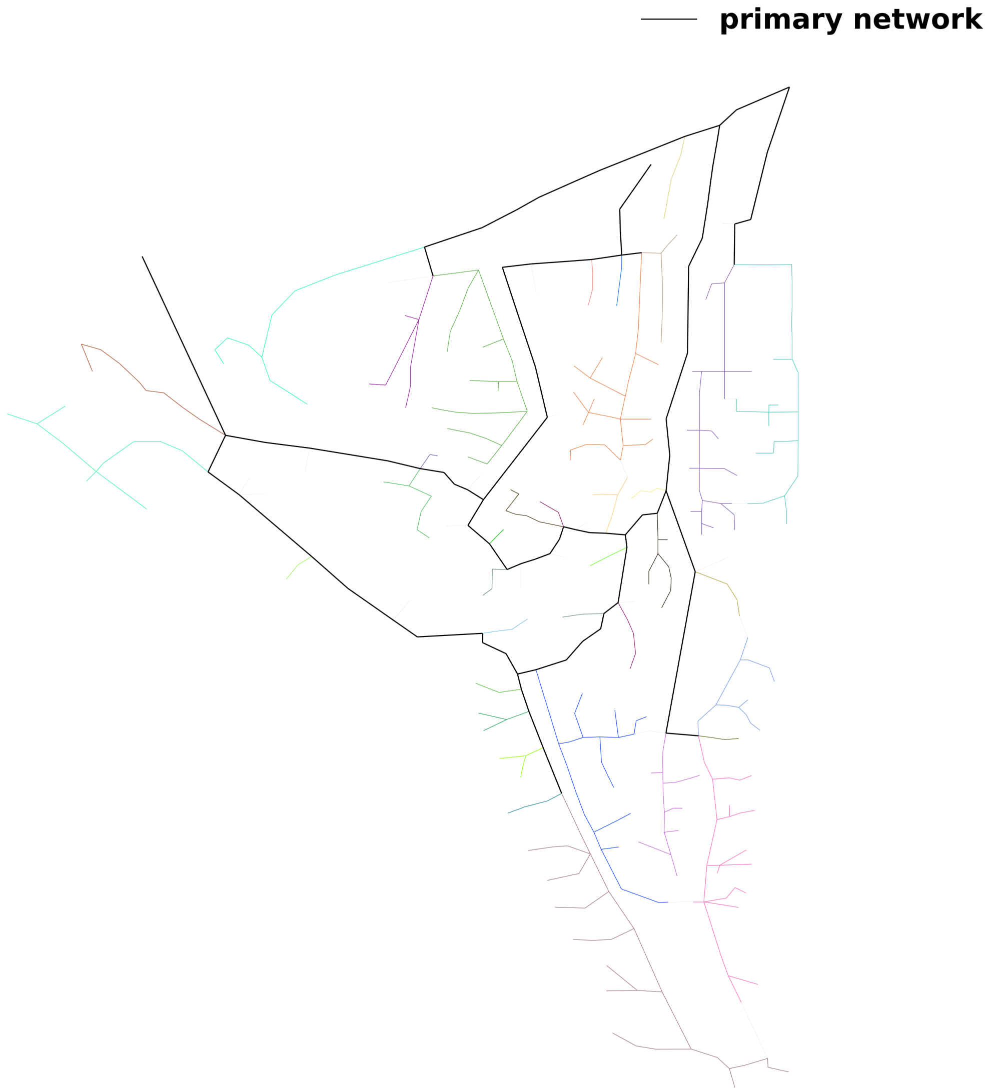

Figure 6.3: Balerma sectors

6.2.2 Balerma with one or two supply pipes for each sector

In this case the algorithm has the possibility of accepting sectors with two inlet points, while maintaining the constraint of isolated sectors. In the Figure 6.4 the primary connected components that have one or two supply edges are shown in green. On the latter, the algorithm for the first solution operates by imposing the closures necessary to divide them into two connected components. For this reason, the first solution is the same as in the previous case. Starting from this solution, however, the algorithm will evolve being able to find solutions with sectors supplied by means one or two primary supply edges. As it can be seen from the comparison of the Table 6.1 and 6.2, the algorithm obtains a result in terms of OBJ 2 (in red) equal to the one previously found by making one closure less. Figure 6.6 shows the sectors corresponding to the best solution.

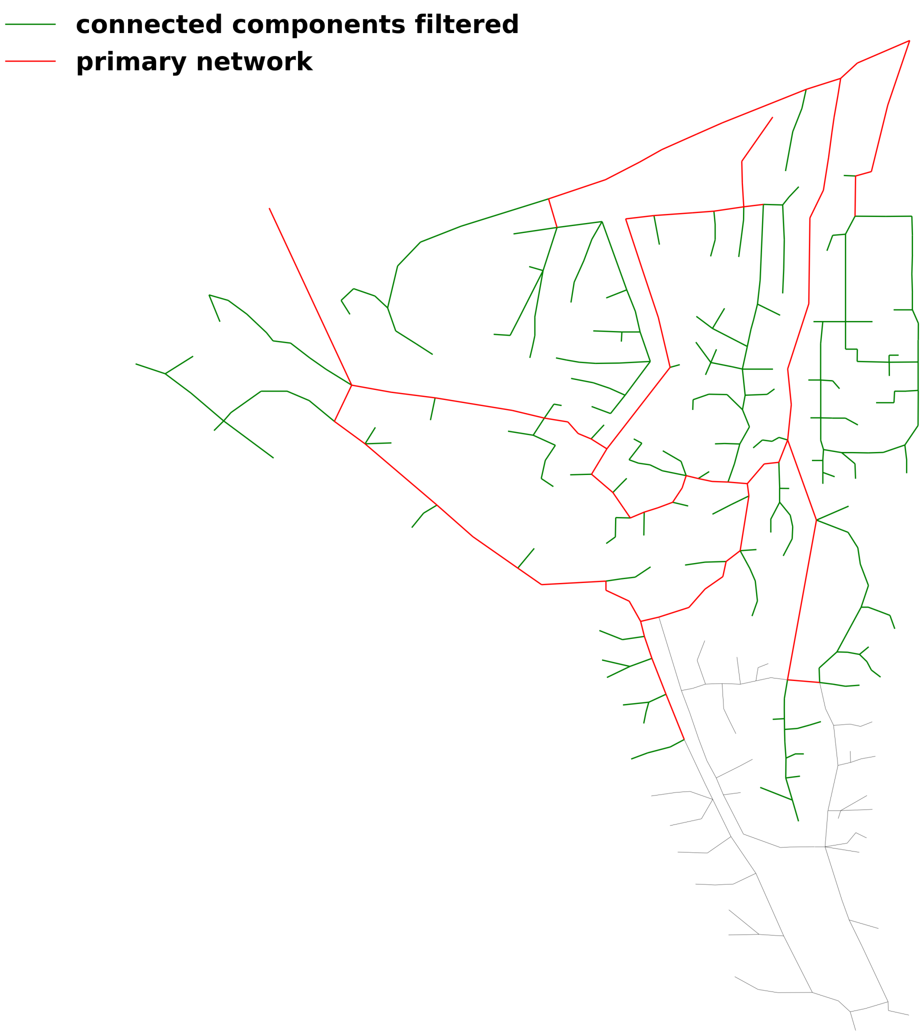

Figure 6.4: Balerma primary connected components filtered if they have one or two primary supply edges

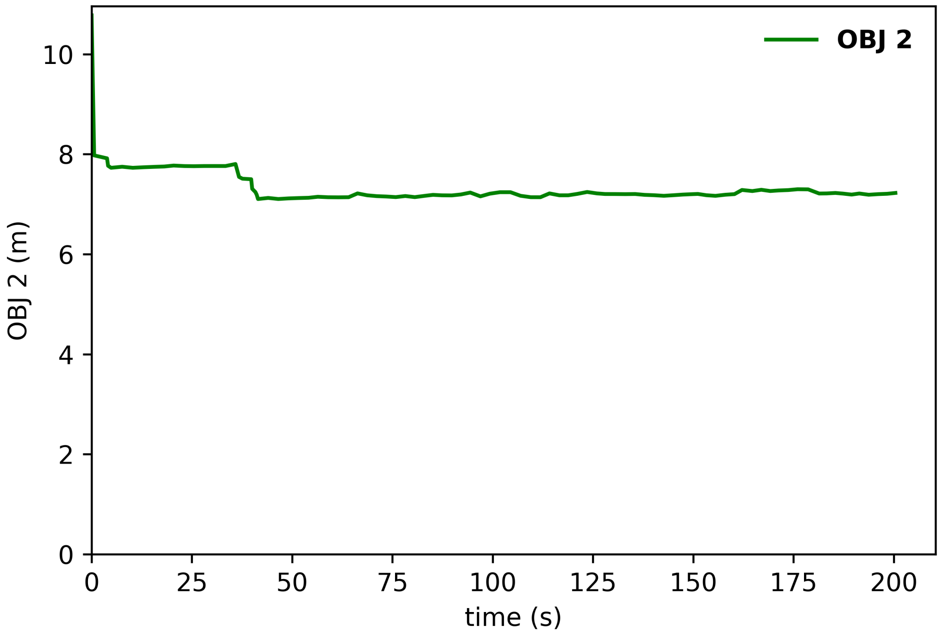

Figure 6.5: Balerma: OBJ 2 results during Tabu Search

Table 6.2: Balerma: Results Tabu Search

iter.	OBJ 1 (m)	OBJ 2 (m)	N^o closed edges	time (s)
initial solution	0	10.77	7	0
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
23**	0	7.10	6	41.5
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.

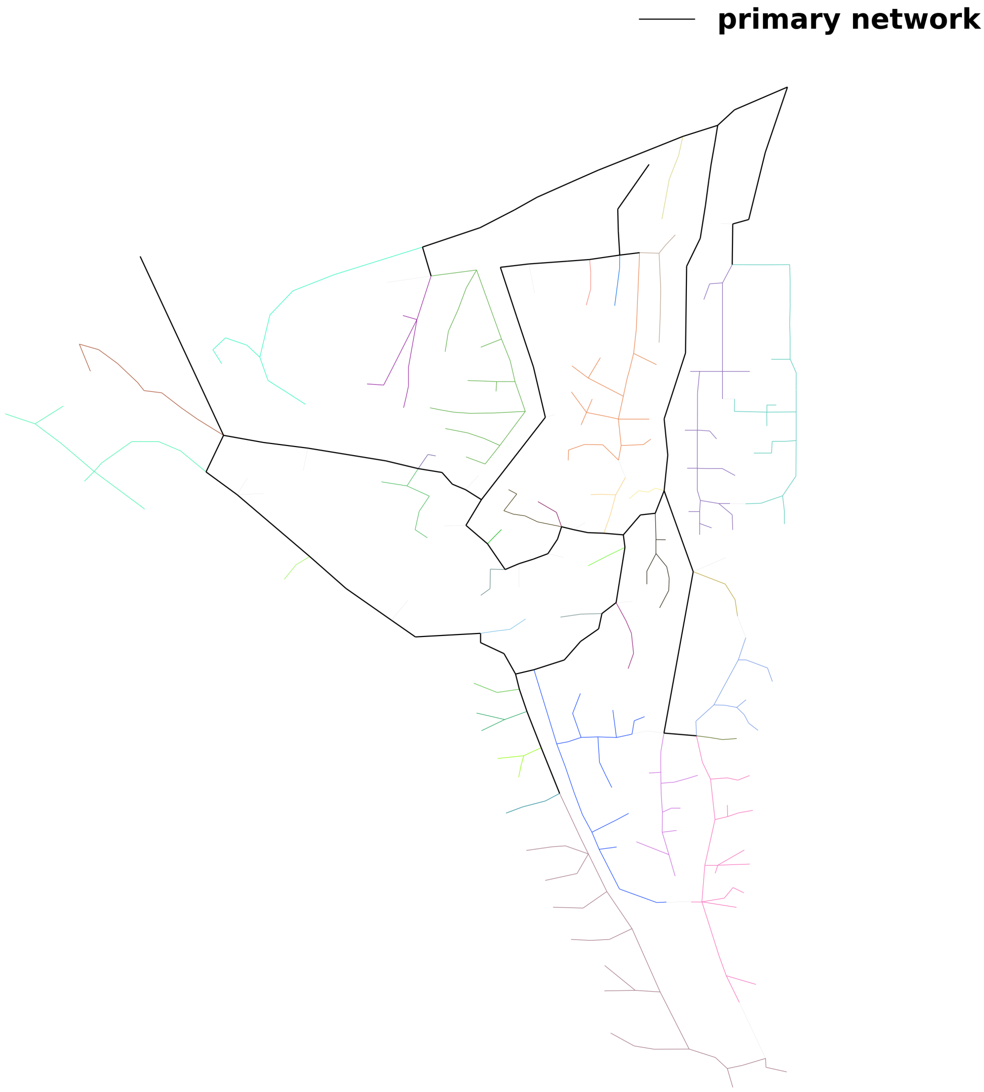

Figure 6.6: Balerma sectors

6.3 KY 2

The model of the KY 2 network (Jolly et al., 2014) is an extended period model, with in total 24 time step and an interval of time equal to 1 h. The algorithm evaluates the results for the calculation of OBJ 1 and OBJ 2 at time step equal to 20, that corresponds to the moment of maximum consumption. The number of inlet points per sector is set equal to 1. The violation Δ for OBJ 1 has been set equal to 0. The stop criterion used is that the algorithm stops after 1 h. The results are shown in Figure 6.7 and summerozed in Table 6.3 . Initially there is a worsening of OBJ 2, which then improves again reaching the minimum value of 1.90 m as reported in Table 6.3. Figure 6.8 shows the different sectors corresponding to the best configuration obtained.

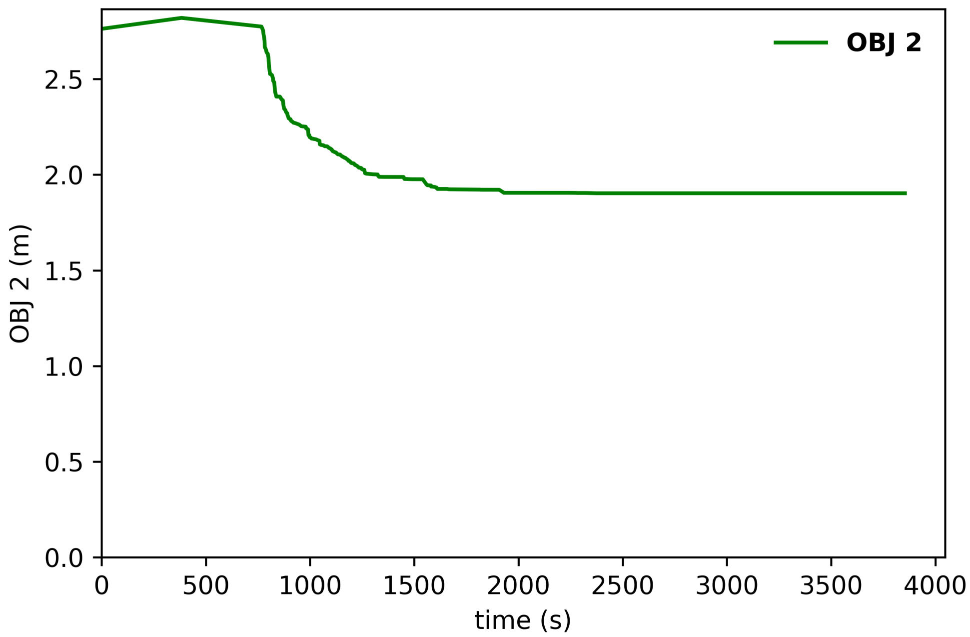

Figure 6.7: KY 2: OBJ 2 results during Tabu Search

Table 6.3: KY 2: Results of Tabu Search

iter.	OBJ 1 (m)	OBJ 2 (m)	N^o closed edges	time (s)
initial solution	0	2.76	234	0
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
164**	0	1.90	244	2383
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.

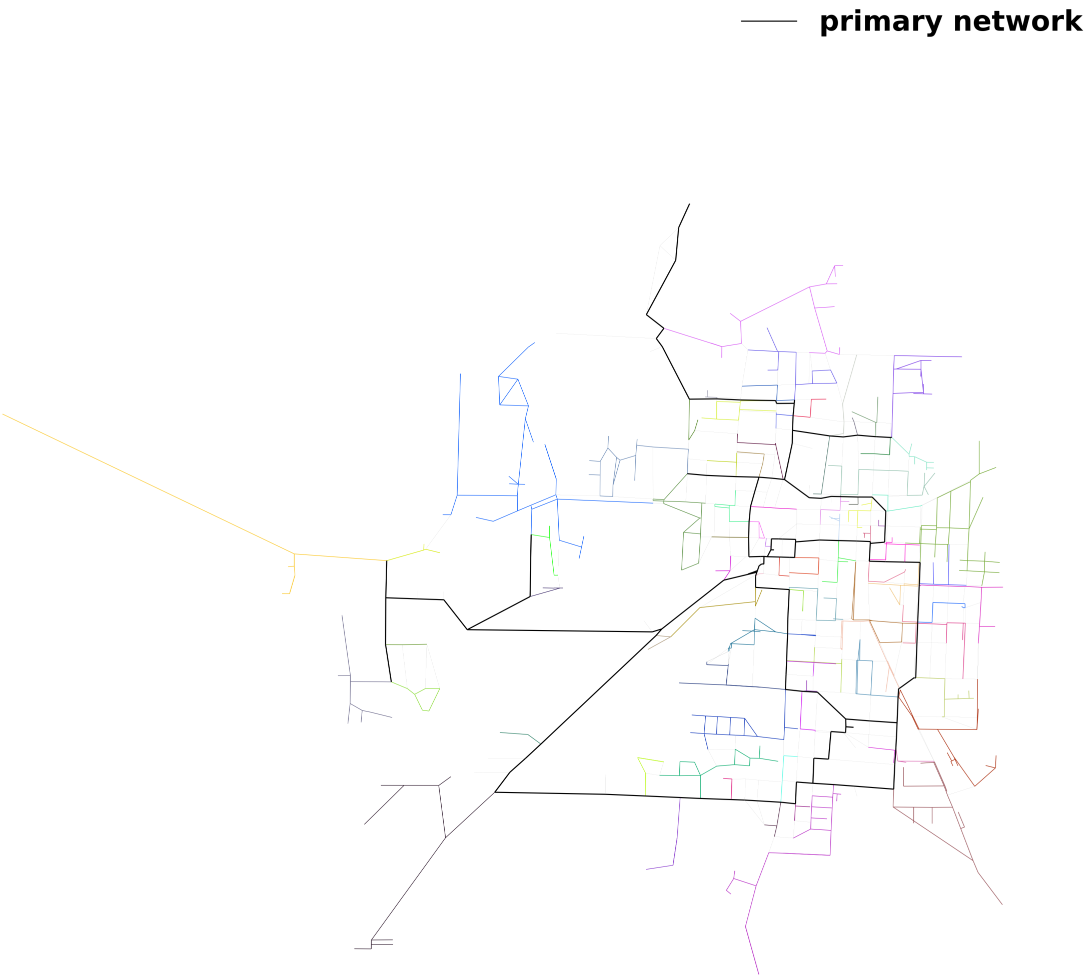

Figure 6.8: KY 2 sectors

6.4 BSNW 2

The BSNW network is sectorized by not applying any modification either to the configuration or to the rules of the WDN. The simulation performed during the search for the solution is an extended period simulation equal to 30 h with a time step of 1 h. The results that guide the objective functions OBJ 1 and OBJ 2 are those of the 30^{th} hour, corresponding to the moment of the maximum consumption. The number of supply pipes per sector has been set equal to 1. The stop criterion of the algorithm is the maximum calculation time equal to 24 h. The p_{min} have been set equal to 20 m and the violation Δ for which OBJ 1 was imposed equal to 1 m; this value was reached after 5688 seconds (Figure 6.9). The best value for OBJ 2 is 2.47 m (Table 6.4), as shown in Figure 6.10. Figure 6.11 shows the sectors corresponding to the best solution that minimizes OBJ 2.

Table 6.4: BWSN 2: Results of Tabu Search

iter.	**OBJ 1 (m)**	**OBJ 2 (m)**	N^o **closed edges**	**time (s)**
initial solution	484.3	nan	816	0
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
924	0.96	3.9	681	5688
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
1932**	0.99	2.47	711	75230
.	.	.	.	.
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.	.	.	.	.

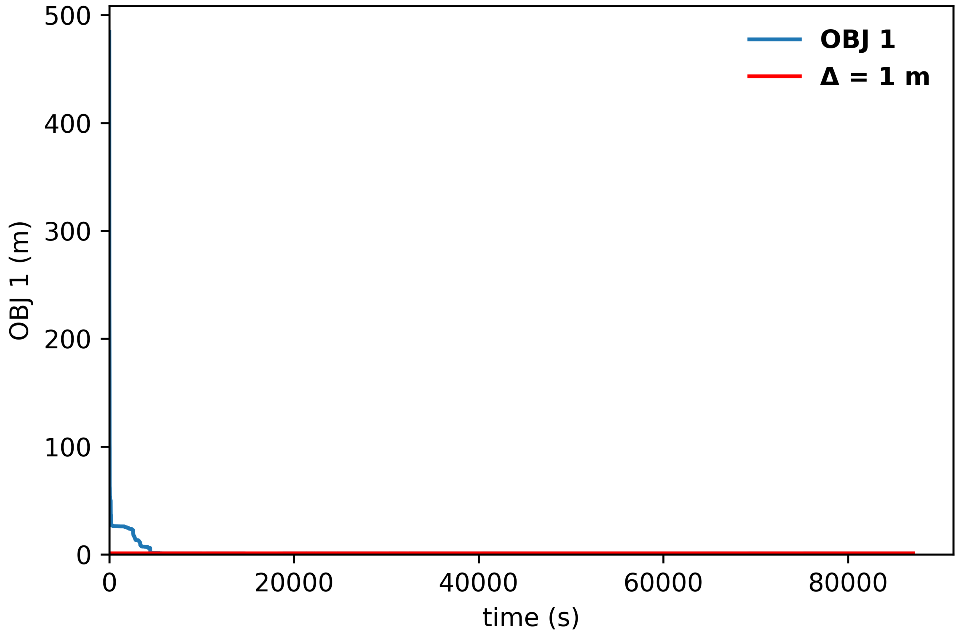

Figure 6.9: BSNW 2: OBJ 1 results.

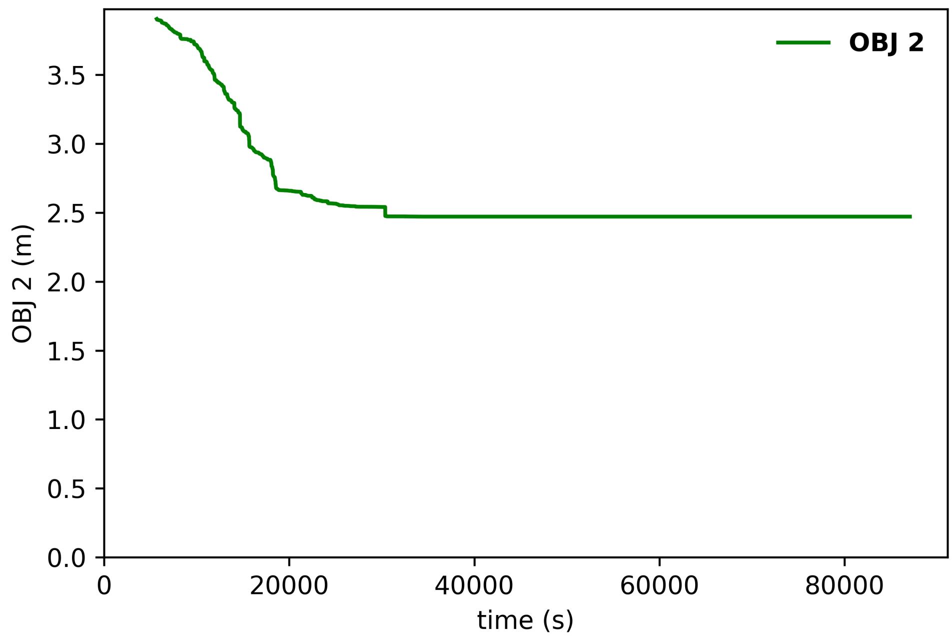

Figure 6.10: BSNW 2: OBJ 2 results

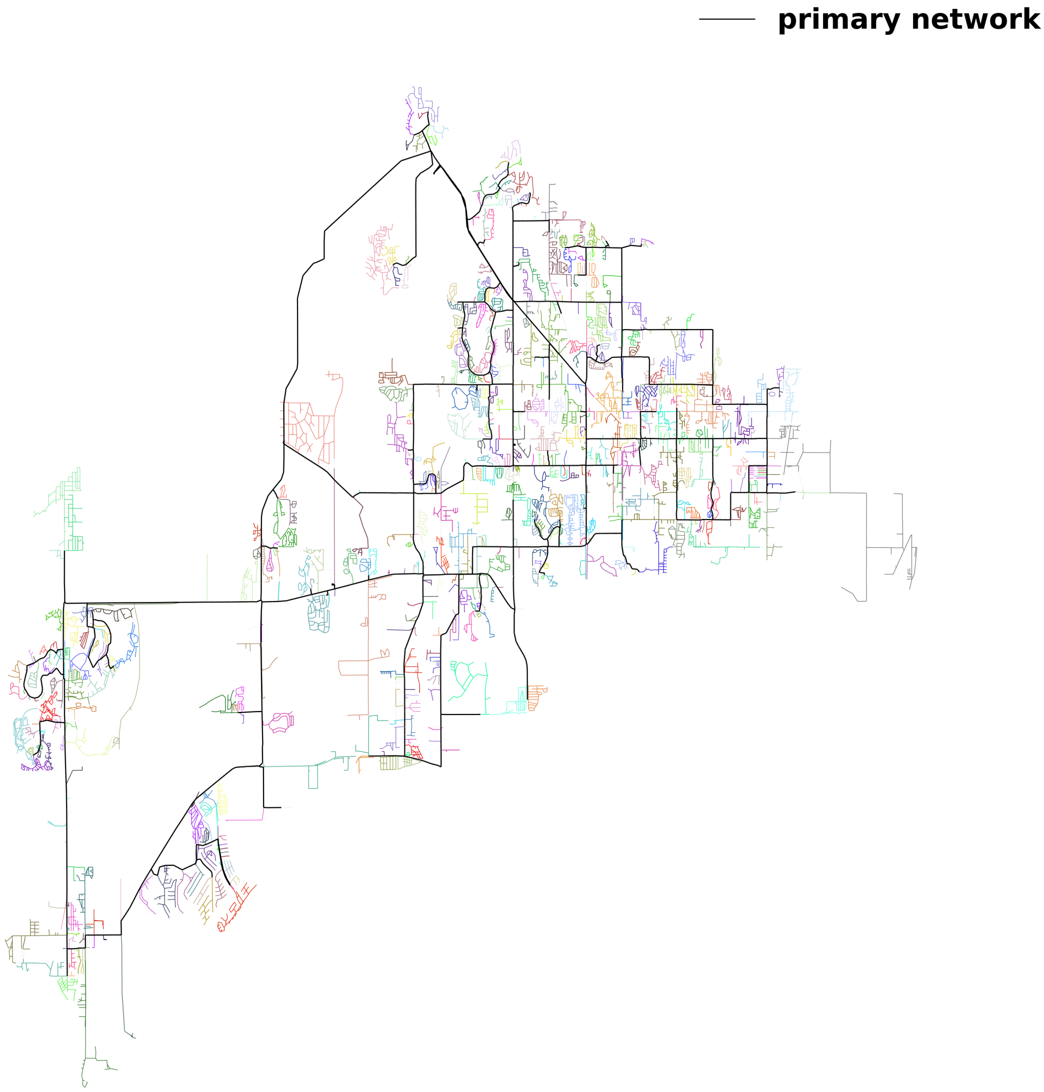

Figure 6.11: BWSN 2 sectors

6.5 Adriatic Town

In the case of Adriatic Town network, a single period model is used corresponding to the maximum consumption scenario. The situation is the most disadvantageous from a hydraulic point of view, in fact, in addition to being the maximum consumption, the tanks have been considered at a level such as to be supplied. Also in this case study the p_{min} is set equal to 20 meters except for nodes with a value of less than 20 m in open network, in this case p_{min} was assumed equal to their current pressure condition. The violation Δ for which OBJ 1 has been set equal to 1 m. The algorithm satisfies this value after 32991 seconds (Table 6.5). For subsequent iterations the value of OBJ 1 is always satisfied (Figure 6.12) and consequently, the algorithm started to minimize OBJ 2 up to the value of 4.39 m (Figure 6.13). The results of the optimization process are summarized in Table 6.5. Finally, the Figure 6.14 shows the sectors corresponding to the best OBJ 2 solution found (in red in Table 6.5).

Table 6.5: Adriatic Town: Results of Tabu Search

iter.	**OBJ 1 (m)**	**OBJ 2 (m)**	N^o **closed edges**	**time (s)**
initial solution	79646.4	nan	397	0
.	.	.	.	.
.	.	.	.	.
3699	0.75	5.13	336	32991
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
4332**	0.97	4.39	351	43333

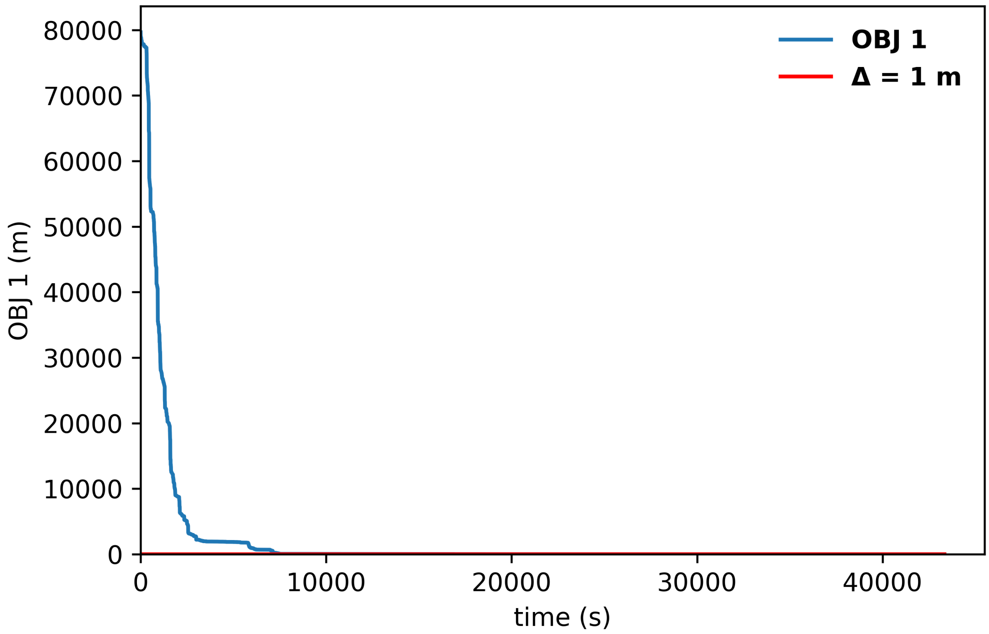

Figure 6.12: Adriatic Town: OBJ 1 results.

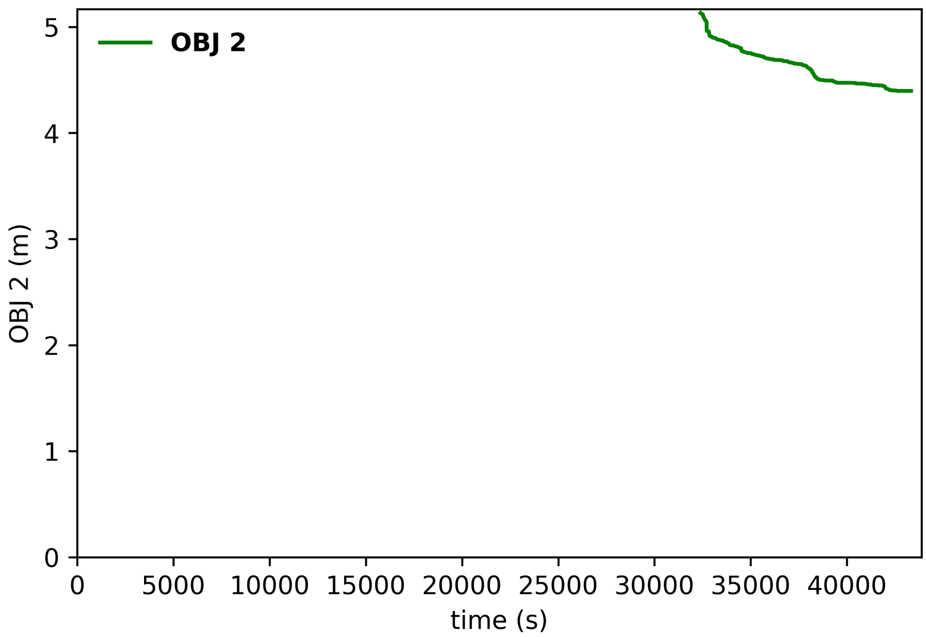

Figure 6.13: Adriatic Town: OBJ 2 results

Figure 6.14: Adriatic Town sectors

6.6 Extended Modena

The Extended Modena network is sectorized starting from the primary network shown in the Figure 6.15. The Extended Modena model is a single period model at the moment of maximum consumption. In solving the sectorization problem of Extended Modena, it is shown the possibility of the proposed methodology to iteratively expand the primary network during the optimization process if a solution that satisfies OBJ 1 is not found at the first step. The stop criterion set in this case is that the search for the solution stops anyway after $1:30\ h$ from the beginning of the search (for a given primary network) or that it can stop already after an hour if the relative average decrease of the OBJ 1 value of the last ten solutions found is less than 10^{-5} . Once the stop criterion has been reached, the algorithm expands the primary network (see paragraph 2.4.7) and restarts in search of a solution that satisfies OBJ 1. The process time limit for the whole process has been set equal to 8 h, after which the search for the solution stops regardless of the results found. The number of supply pipes per sector was set equal to 1. p_{min} for each node was fixed equal to 20 m or to the value calculated by means of hydraulic simulation with the network completely open for the nodes in which the pressure resultedess than 20 m. The violation Δ of OBJ 1 was set equal to 1 m, once this value is reached, the algorithm proceeds with the calculation of OBJ 2, and from this moment on considering having satisfied the violation Δ, it no longer proceeds with the enlargement of the primary network. As regards the order of the quantile for the statistical analysis on headloss (see Paragraph 2.4.7.1), it was set at 0.85.

6.6.1 First iteration

Subtracting the primary network (in red in Figure 6.15) the primary connected components are identified. In Figure 6.15 the connected components that satisfy the number of supply edges per sector are shown in green and therefore no closure is performed on them. Once a first solution has been found, the algorithm proceeds with the Tabu Search to find a result that satisfies the violation Δ of OBJ 1. During the first iteration, the algorithm, as shown in the Figure 6.16, was not able to find any solution lower than Δ.

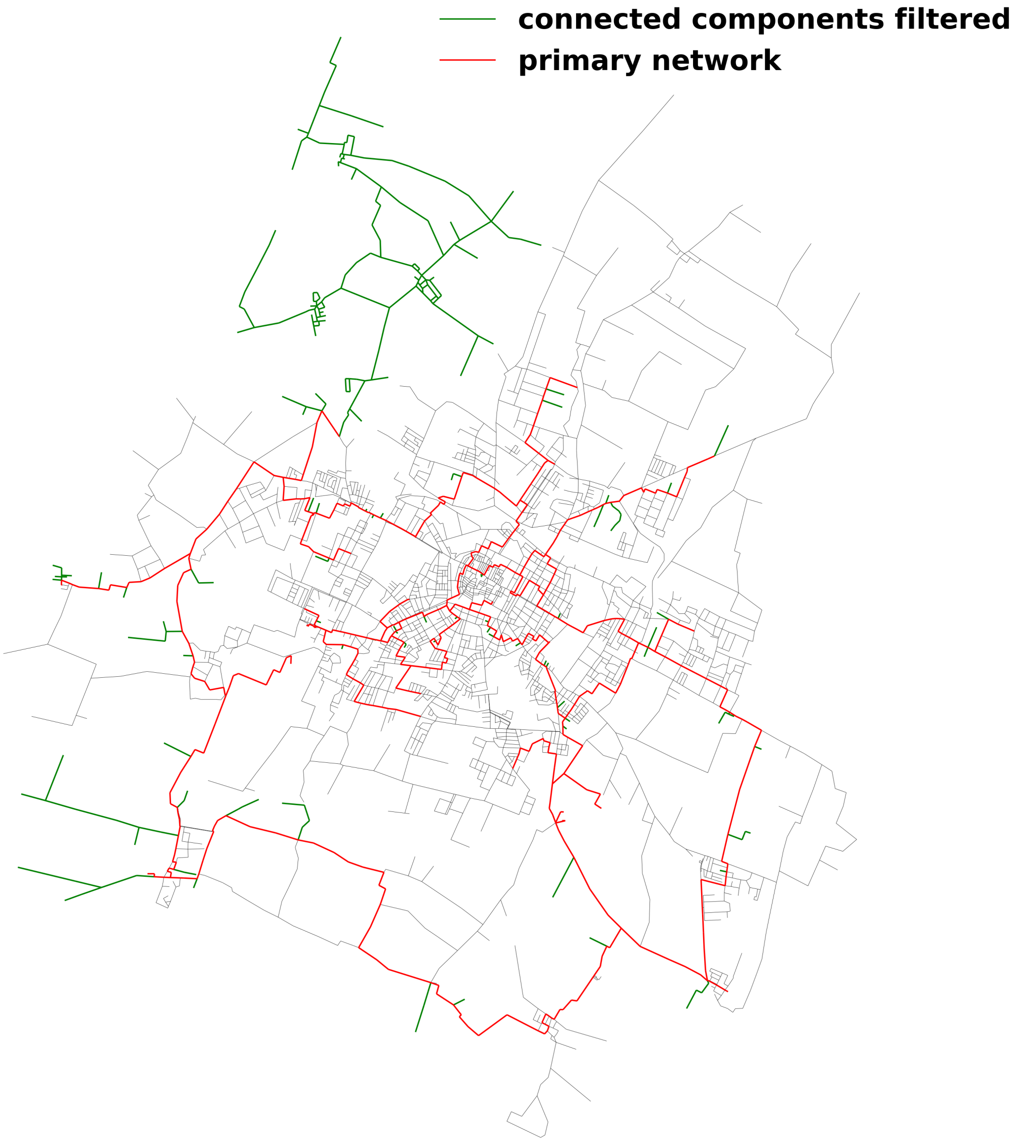

Figure 6.15: Extended Modena primary connected components filtered with only one primary supply edge

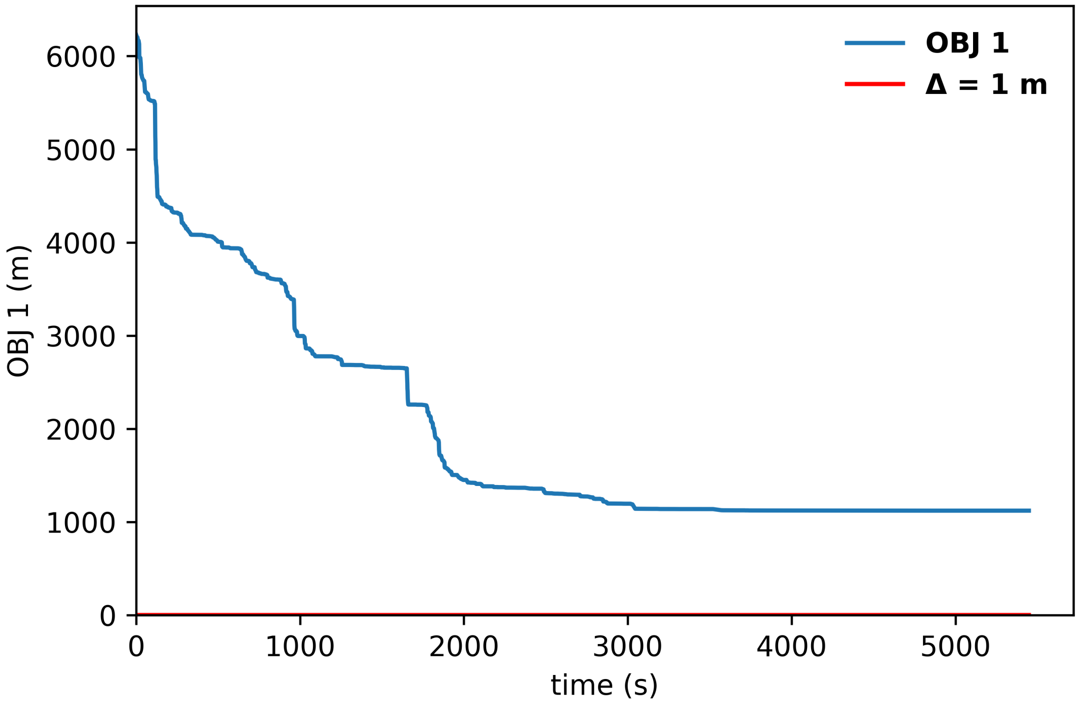

Figure 6.16: Extended Modena: OBJ 1 results during first iteration

The subsequently step is the analysis of the best solution found (the one with the lower OBJ 1 value obtained during the first iteration) to read the structural inefficiencies of the primary network. Once the solution closures of the edges corresponding to the current best solution found were applied a hydraulic simulation is performed, and the results are analysed to extend the primary network: pressures, flow directions and pipe headloss. First of all, the nodes in which the p_{min} initially set is not satisfied are identified (Figure 6.17). The subset of these nodes that are primary nodes or primary nodes of primary connected components which do not satisfy p_{min} was listed (Figure 6.18).

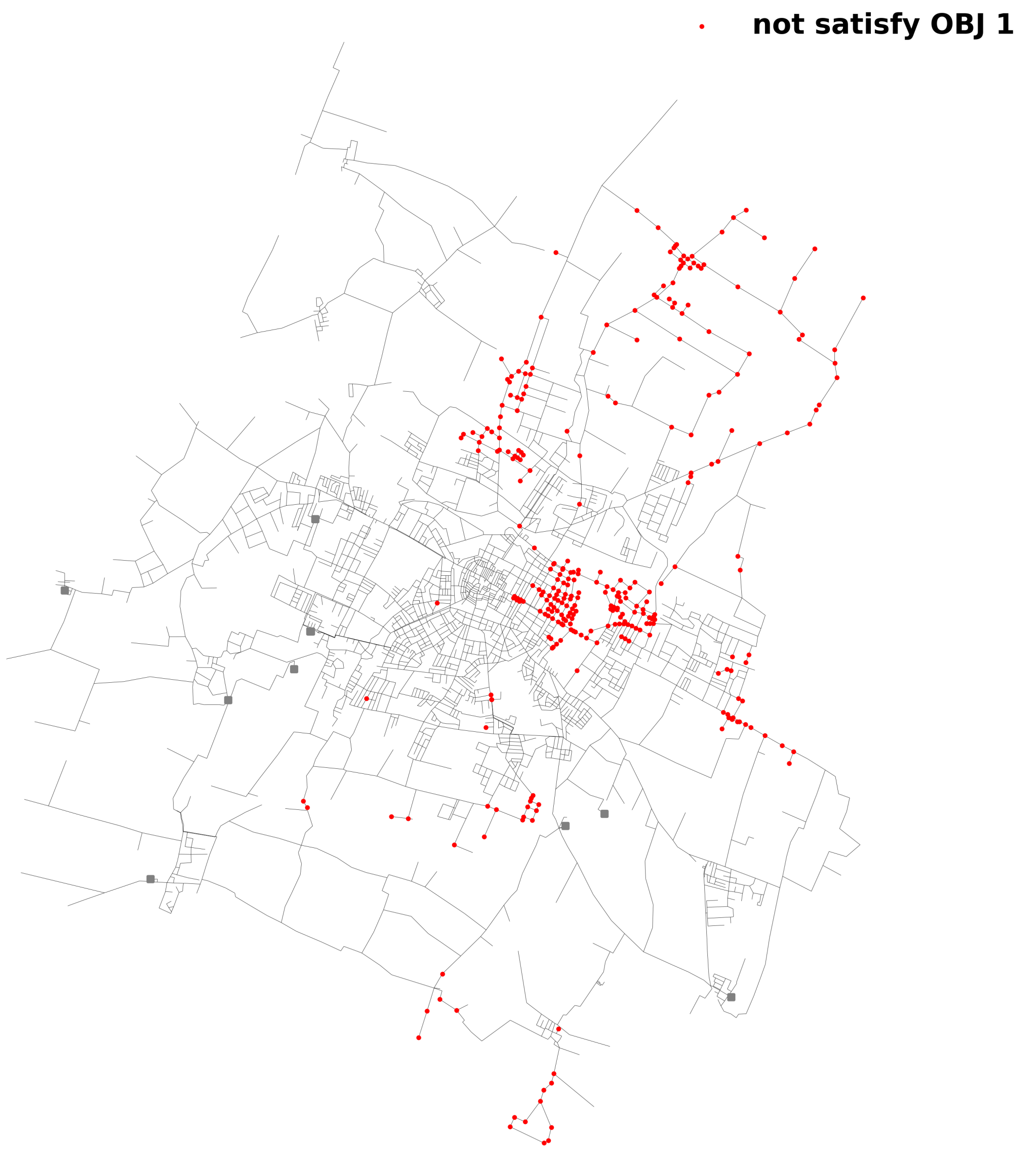

Figure 6.17: Extended Modena:Nodes that don't respect minimum pressure

Figure 6.18: Extended Modena: selected primary nodes

Once the digraph has been created with the edges oriented like the directions of the flows calculated with the hydraulic simulation, all the paths are identified with the Sedgewick (2001) algorithm, and consequently the water resources that supply the selected primary nodes (blue dots in Figure 6.19). The overall results are shown in Figure 6.19. An analysis of the headloss of the edges identified in the previous step (in red in Figure 6.19) is performed and the edges of the primary network whose headloss exceeds the quantile of order 0.85 (given established at the beginning of the process). A weight is given to the filtered edges (which is added to the weight L/D^5) such as to make their choice not convenient unless another path exists.

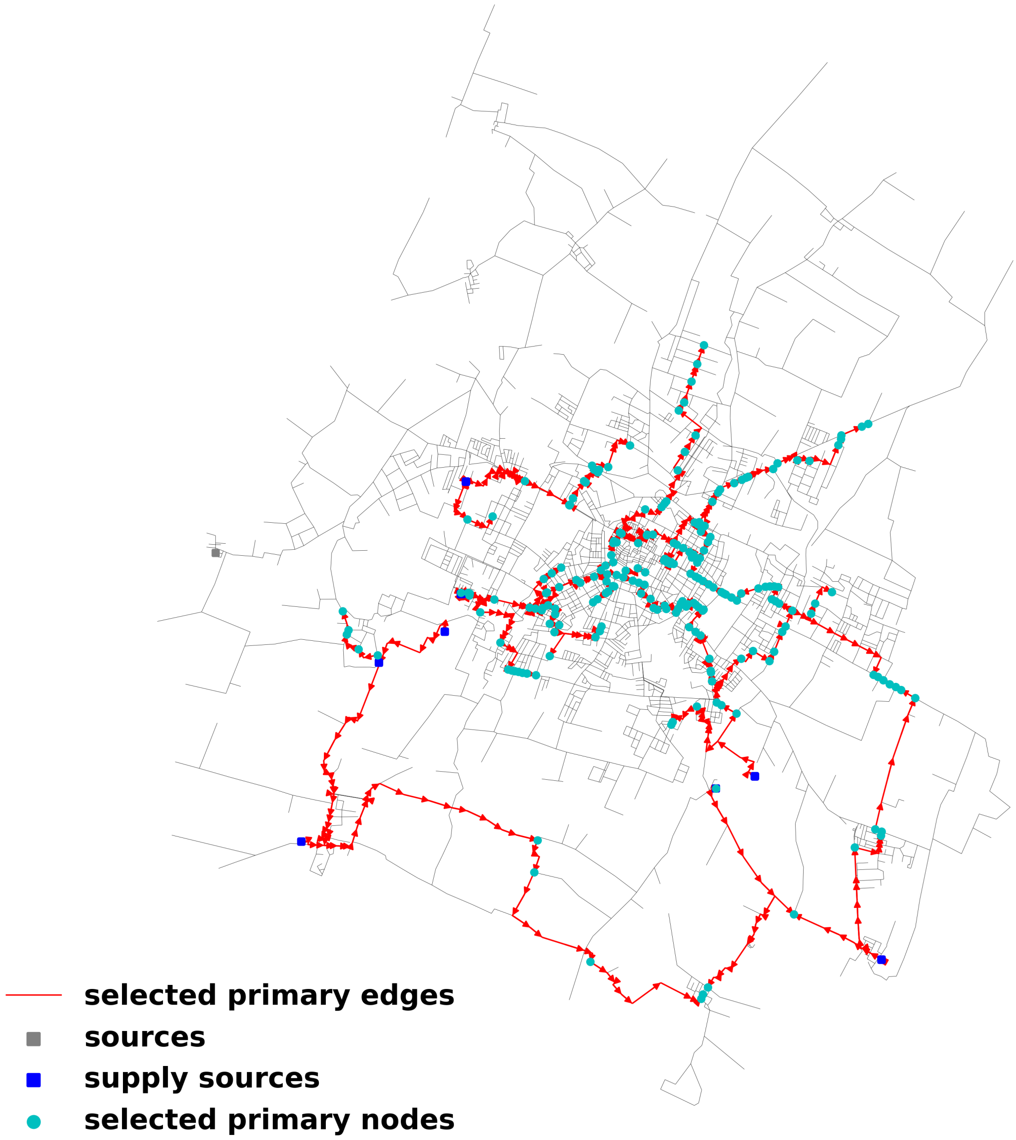

Figure 6.19: Extended Modena. Primary edges selected

Figure 6.20: Extended Modena. Primary edges filtered

Then on the indirect graph of the WDN, whose edge weight is L/D^5 except for the edges that have been reweighted, the shortest paths connecting the selected primary nodes to the network sources (Reservoirs and Tanks) are calculated. All those edges of the shortest paths that did not already belong to the primary network are then added to the primary network, shown in blue in Figure 6.21. The primary network thus identified becomes the basis for the second iteration (Figure 6.21). In Figure 6.22 the incidence of the diameter classes on the total length is represented, as it is possible to see the initial primary network is mainly composed of pipes with a diameter greater than 150 mm with many diameters exceeding 500 mm. It is interesting to note that although most of the network length was added (in blue), pipes with a diameter greater than 150 mm were also added to the primary network of the second iteration (in magenta) which in the first process to find the primary network had not been considered. The presence of many diameters of significant dimensions ignored in the first phase highlights the presence in the real WDN of alternative paths comparable in terms of energy to those initially identified and which therefore, once inserted, act as self loops of the initial primary network, better distributing the flow and thus decreasing the headloss. The process restarts by subtracting the new primary network to identify the primary connected components, as shown in Figure 6.23, in which the primary connected components that satisfy the constraint of number of supply edges equal to 1 are highlighted in green. During the second iteration OBJ 1 was satisfied (Figure 6.24), therefore the algorithm tries to minimize the OBJ 2 (Figure 6.25).

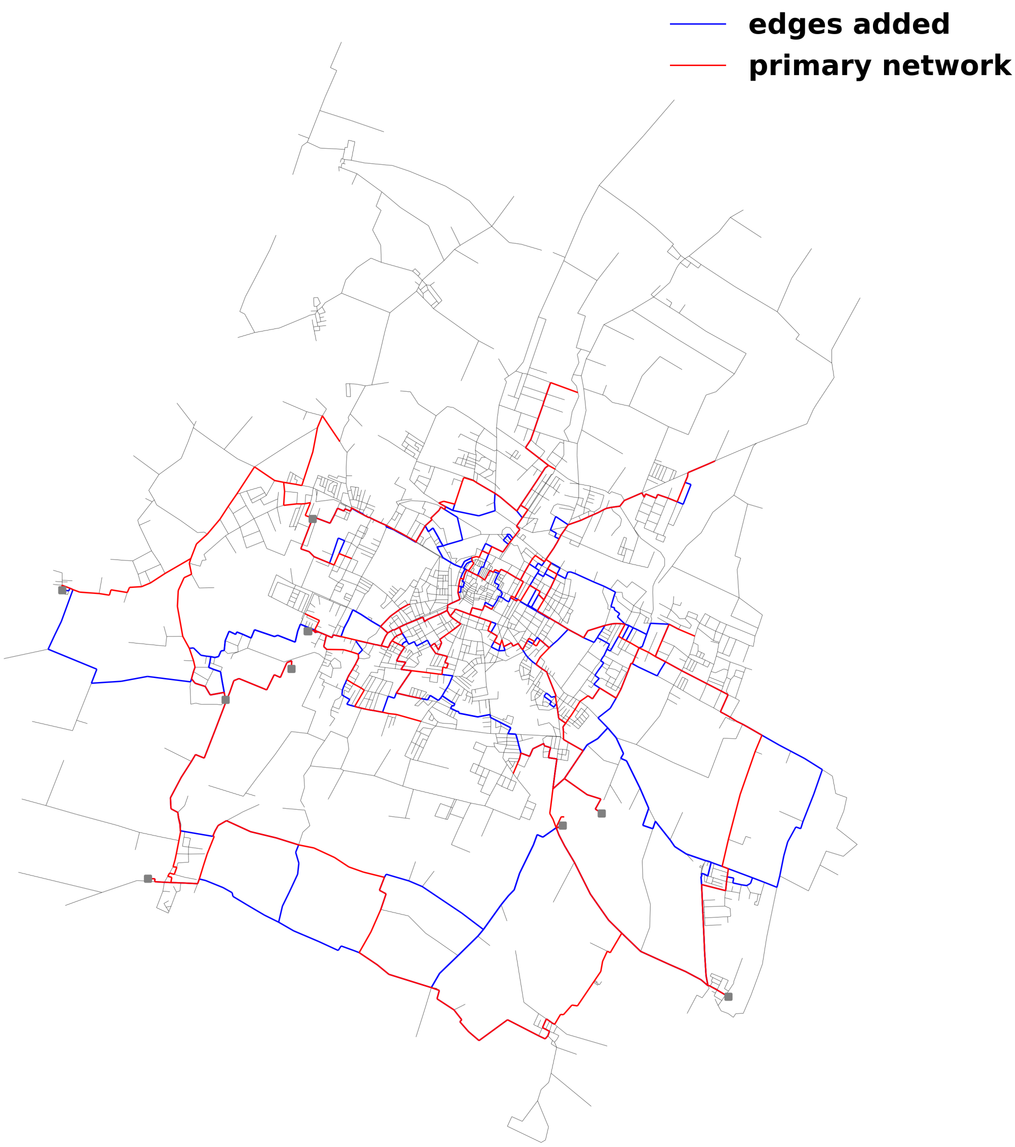

Figure 6.21: Extended Modena. Added edges to the primary network

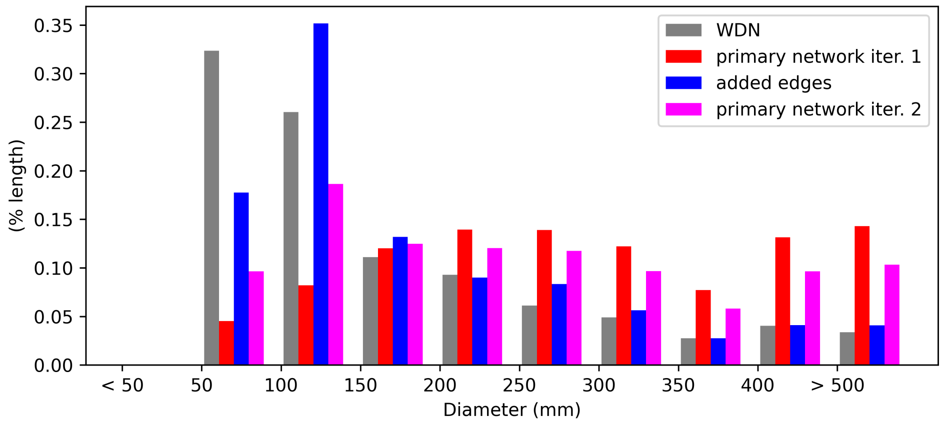

Figure 6.22: Extended Modena. Differences of the primary networks from the first to the second iteration process

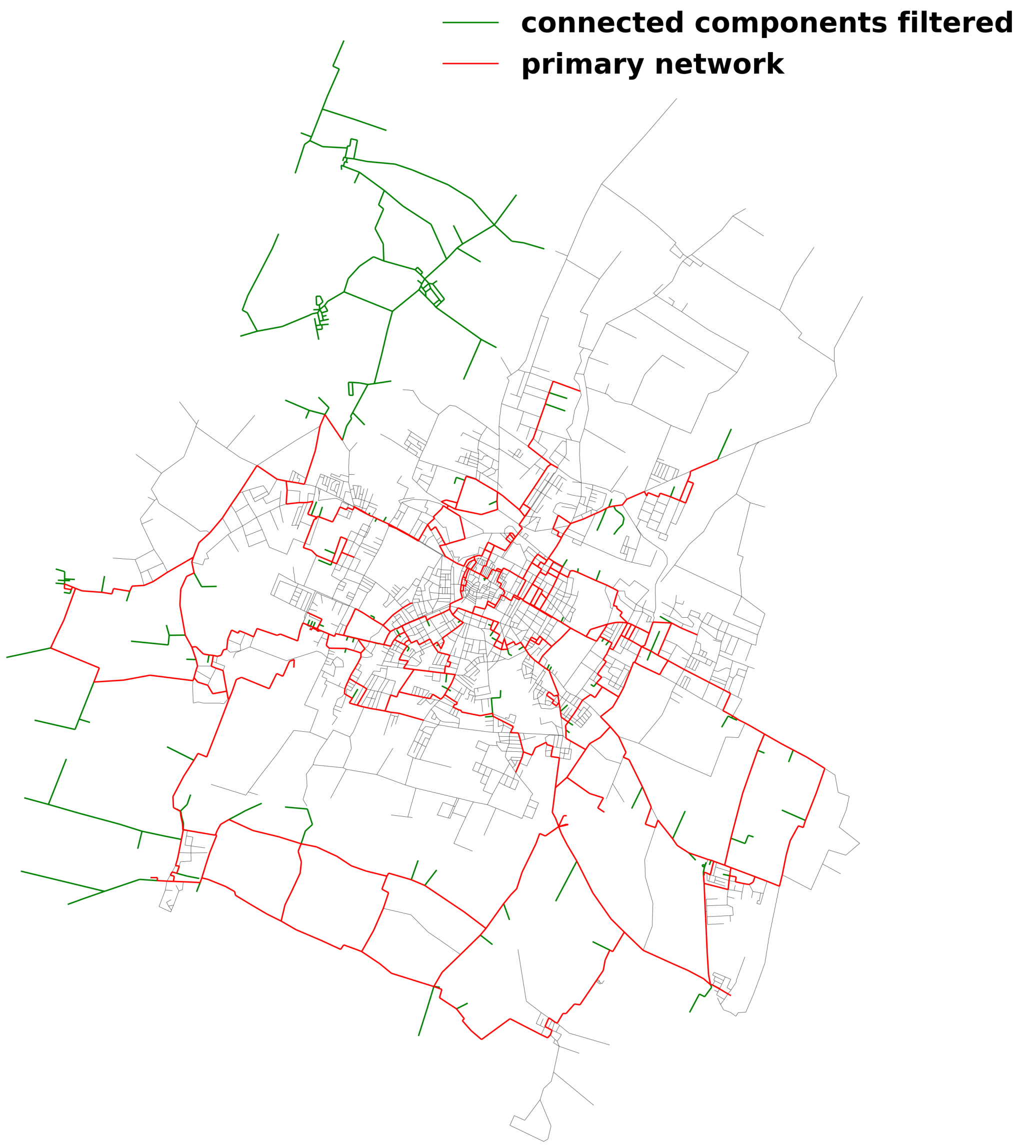

Figure 6.23: Extended Modena primary connected components filtered with only one primary supply edge

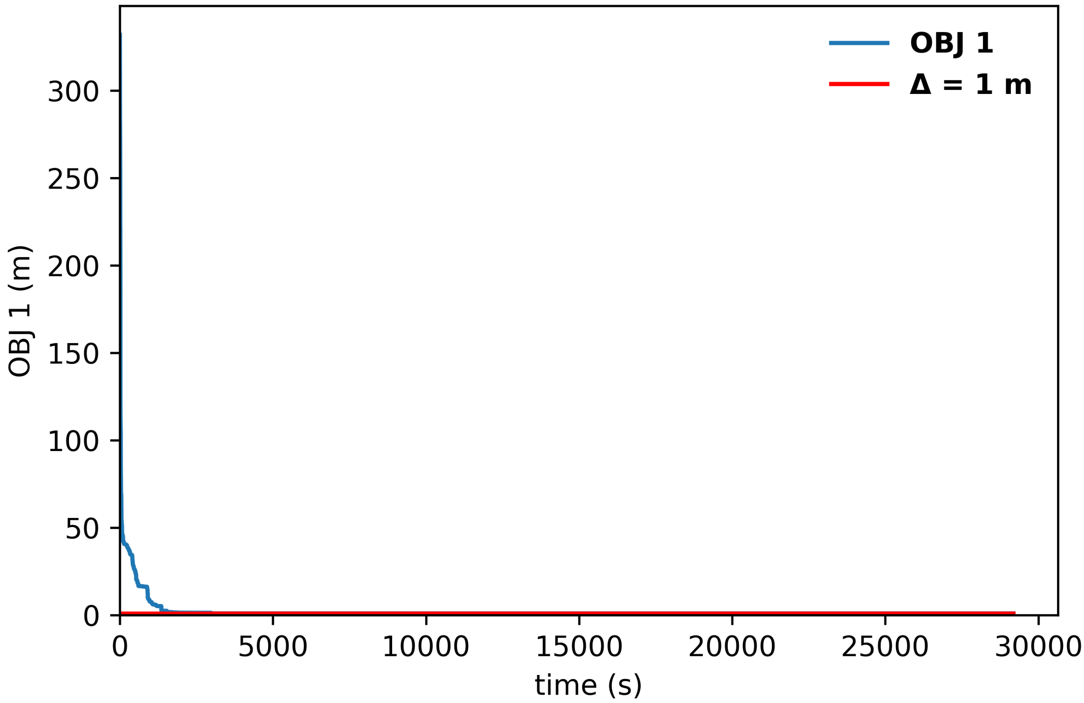

Figure 6.24: Extended Modena. OBJ 1 results during second iteration

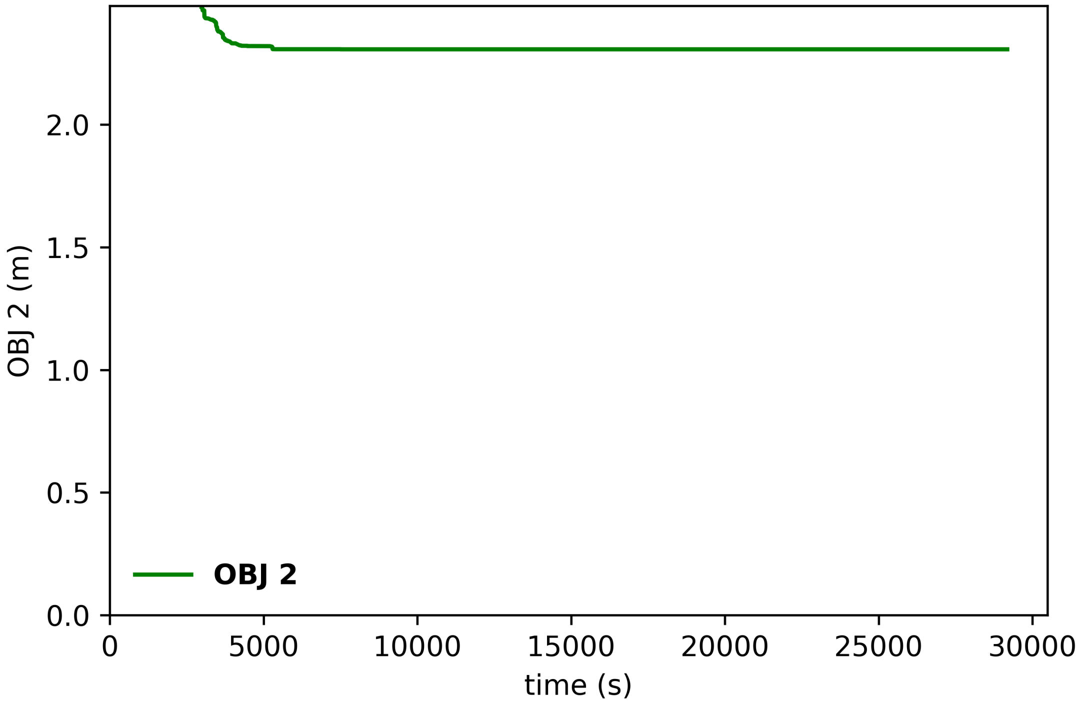

Figure 6.25: Extended Modena. OBJ 2 results during second iteration

6.6.2 Final result

In Figure 6.26 it is possible to see the sectorization resulting from the best configuration of closures in terms of OBJ 2 (Table 6.6).

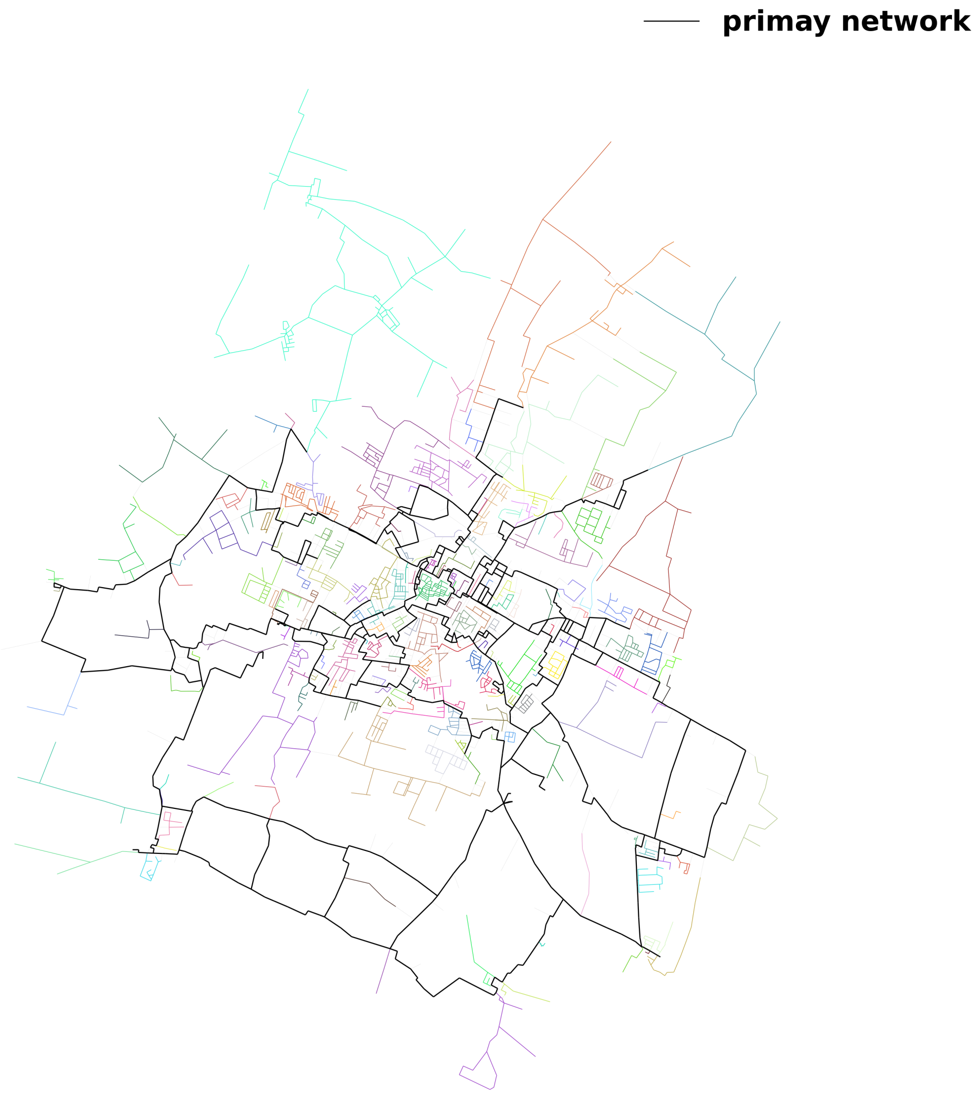

Figure 6.26: Extended Modena. OBJ 2 results during second iteration

Table 6.6: Extended Modena. Results of second process iteration

iter.	**OBJ 1 (m)**	**OBJ 2 (m)**	N^o **closed edges**	**time (s)**
initial solution	331.8	nan	633	0
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
857	0.99	2.47	586	3000
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
986**	0.99	2.30	575	5388
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.

6.7 Tyrrhenian Town

The Tyrrhenian Town network has been sectorized starting from the primary network shown in Figure 6.27. The Tyrrhenian Town model is read by the algorithm in the moment of maximum consumption starting from an extended time model of total duration of 24-hour with a time step of 5 minutes. The regulation of the pumps of the main pumping system has been left the same as for the 24 h model, for the other systems it has been possible to work at full speed (pump speed = 1). All the valves of the model were opened so that the algorithm works with the network completely open without constraints imposed by the current configuration of closures. The number of supply edges accepted per sector is 2, p_{min} for each node was set equal to 20 m or to the value calculated by means of hydraulic simulation with a completely open network if it was less than 20 m. The violation Δ of OBJ 1 has been set equal to 5 m; once this value is reached the algorithm proceeds with the calculation of OBJ 2: considering having satisfied the feasibility, it no longer proceeds with the enlargement of the primary network (paragraph 2.4.7.2). As regards the order of the accepted quantile by the statistical analysis on headloss, it was set at 0.90. The stop criterion of algorithm is that the search for the solution stops after 270 s from the beginning of the search (for a given primary network), otherwise it can already be stopped after 180 s if the average improvement of the solutions found in the last 10 iterations found was less than 10^{-5}. Once this condition has been overcome, the algorithm expands the primary network and restarts. The time limit set for the entire process has been set equal to 3 h, after which the search for the solution stops regardless of the results found.

6.7.1 First iteration

Subtracting the primary network, (Figure 6.27 line in red) the primary connected components are identified. In the Figure 6.27 the primary connected components that satisfy the number of supply edges per sector, i.e. less than or equal to two, are shown in green. In this case, however, if the supply edges of a primary connected component are equal to two, the algorithm for the search for an initial solution will divide them into two connected components. Coherently with the constraint of isolated sectors, if it is convenient for the achievement of OBJ 1 or to minimize OBJ 2 (however checking the constraint of isolated sector) the initially closed edges will be opened during the subsequently optimization phase with the Tabu Search algorithm. Once a first solution has been found, this solution is initialized as current solution of the Tabu Search to find a result that satisfies the violation Δ of OBJ 1, set in this case equal to 5 m. During the first iteration the Tabu Search algorithm, as seen in the Figure 6.28, cannot find any solution lower than the Δ given.

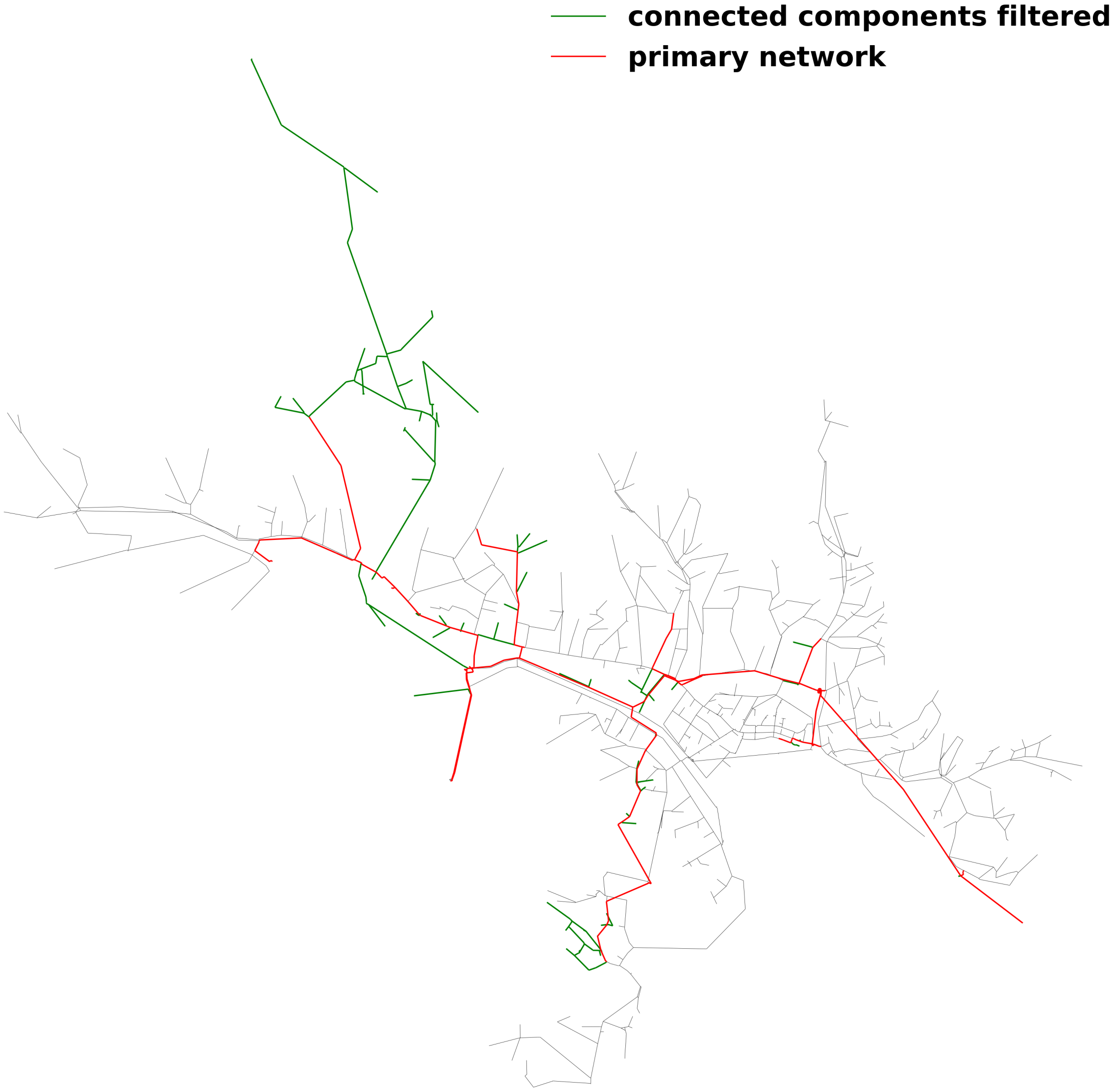

Figure 6.27: Tyrrhenian Town primary connected components filtered with only one primary supply edge

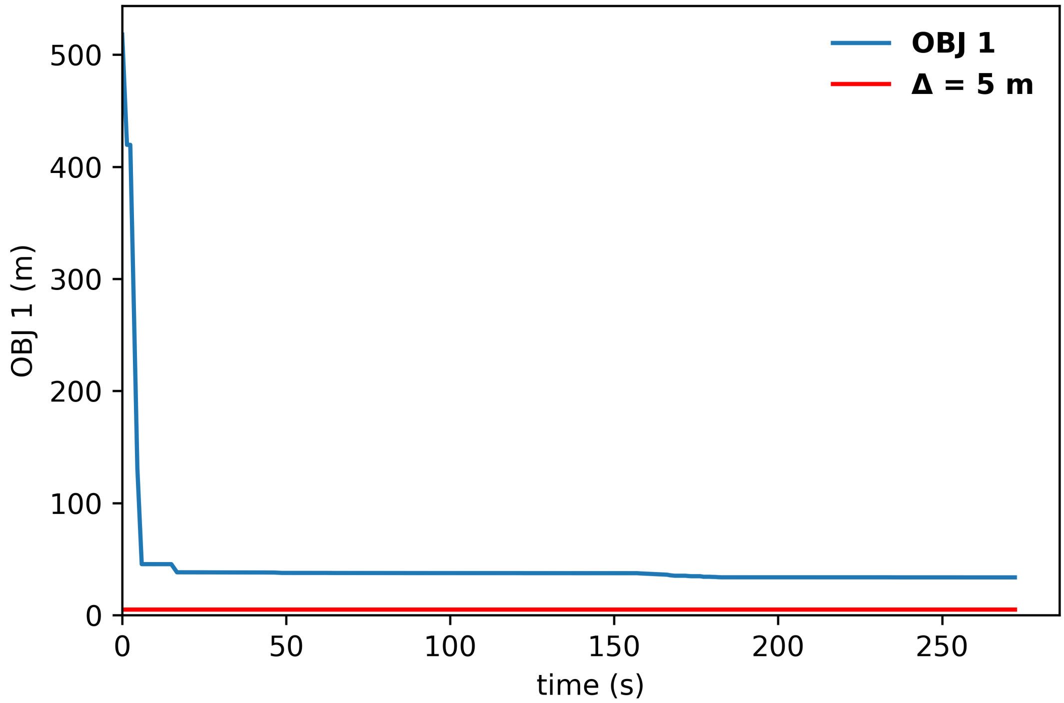

Figure 6.28: Tyrrhenian Town: OBJ 1 results during first iteration

The second step is the analysis of the best solution found (the one with the lower OBJ 1 value) to read the structural inefficiencies of the primary network. Once the closures of the edges of the solution have been applied, a hydraulic simulation is performed, and the results useful for enlarging the primary network (paragraph 2.4.7) are analysed, i.e. the pressures, the directions of the flows and the headloss of the pipes. First of all, nodes in which pmin initially set is not satisfied are identified (Figure 6.29). Also the primary nodes of the primary connected components to which the nodes that do not satisfy the pressure constraint belong are therefore identified. Consequently the nodes represented in Figure 6.30 are the primary nodes that do not satisfy the condition of p_{min}, or primary nodes of primary connected components in which there are nodes that do not respect p_{min}.

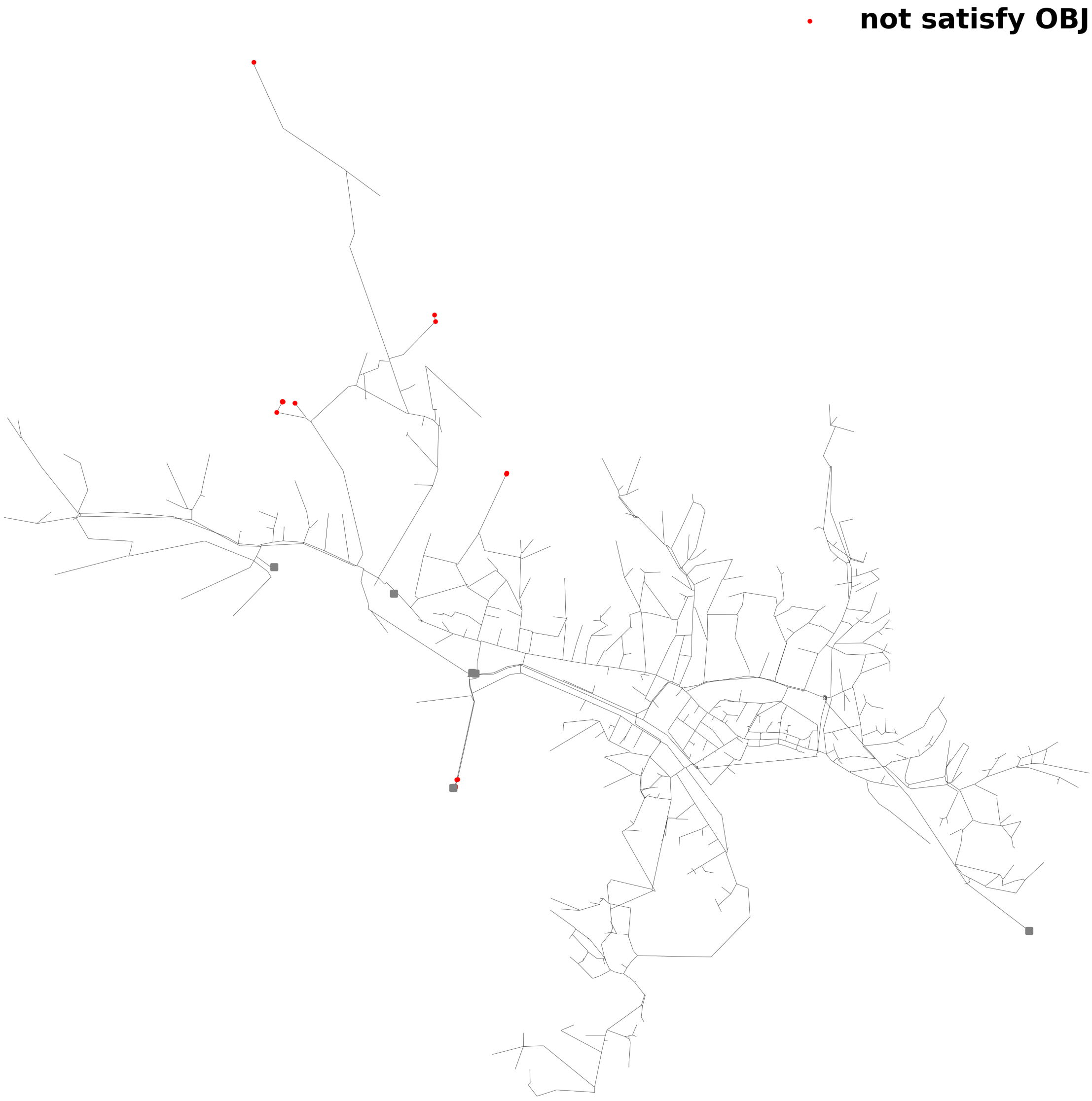

Figure 6.29: Tyrrhenian Town: Nodes that don't respect minimum pressure

Figure 6.30: Tyrrhenian Town. Primary nodes selected

Once the digraph has been created with the edges oriented like the directions of the flows calculated with the hydraulic simulation, all the paths are identified with the Sedgewick (2001) algorithm, and consequently the resources that supply the selected primary nodes. The results are shown in Figure 6.31.

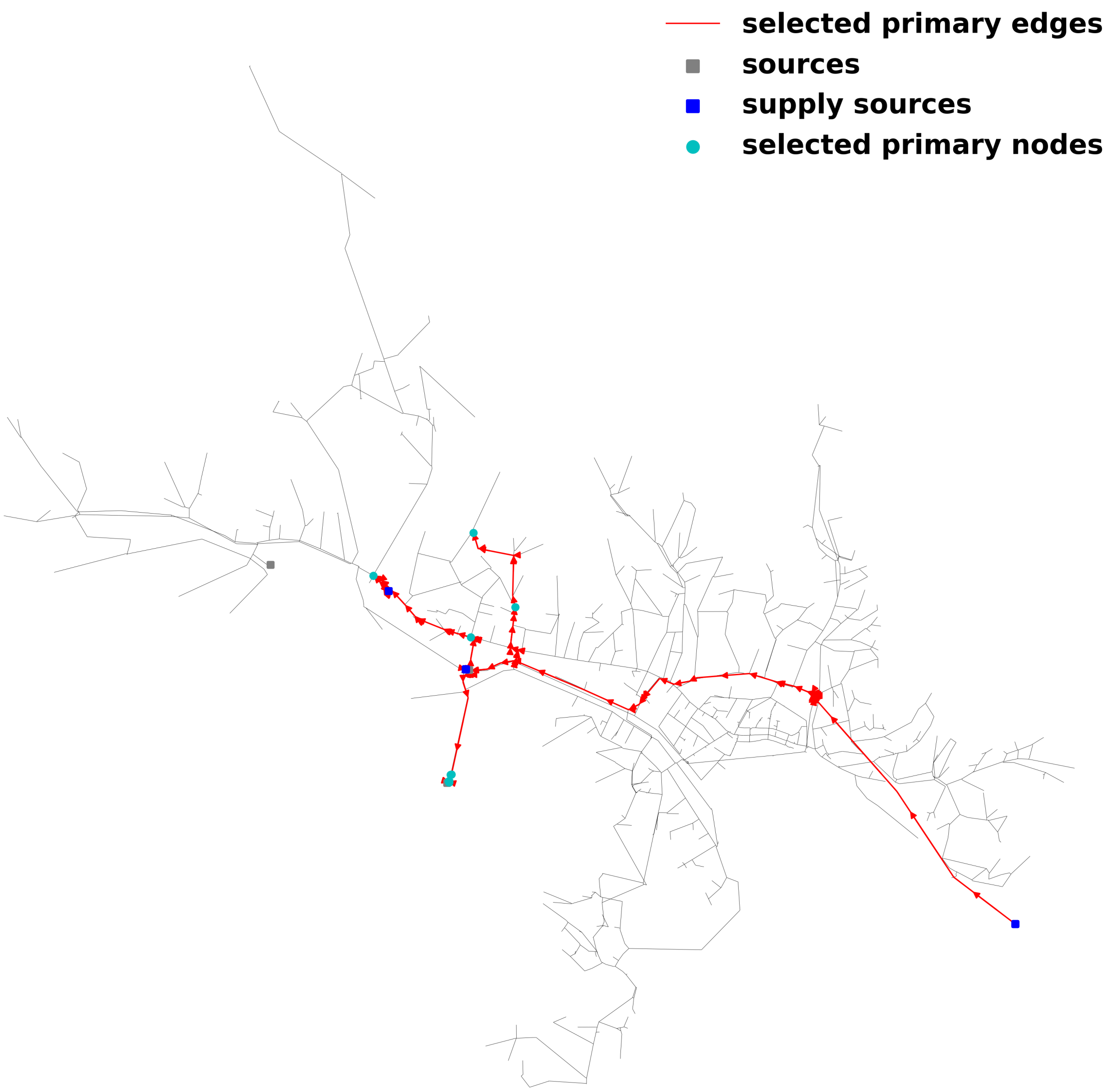

Figure 6.31: Tyrrhenian Town. Primary edges selected

An analysis of the headloss of the edges identified in the previous step is performed (in red in Figure 6.31) and the edges of the primary network whose headloss exceeds q90, the quantile of order 0.90 (assigned at the beginning of the process). A weight is given to the edges thus filtered (which is added to the weight L/D^5) such as to make their choice not convenient unless another path exists (Figure 6.32).

Figure 6.32: Tyrrhenian Town. Primary edges filtered

On the indirect graph of the WDN, whose branch weight is L/D^5 except for the edges which have been given a new weight, the shortest paths connecting the selected primary nodes to the network sources (Reservoirs and Tanks) they are calculated. All those edges of the shortest paths that did not already belong, in blue in Figure 6.33, are then added to the primary network. The primary network thus identified becomes the basis for the second iteration. Figure 6.34 shows the incidence of the diameter classes on the total length of the nets. As it is possible to see, the initial primary network is composed almost entirely of diameters greater than 100 mm. In this case, the expansion of the primary network takes place very locally by adding a self loop consisting of a diameter of 100 mm almost entirely (in blue in Figure 6.34). The reduced length of the added network means that, compared to its total length, the distribution of the diameter classes of the new primary network (in magenta in Figure 6.34) does not significantly alter with respect to the initial primary network (in red in Figures 6.34)

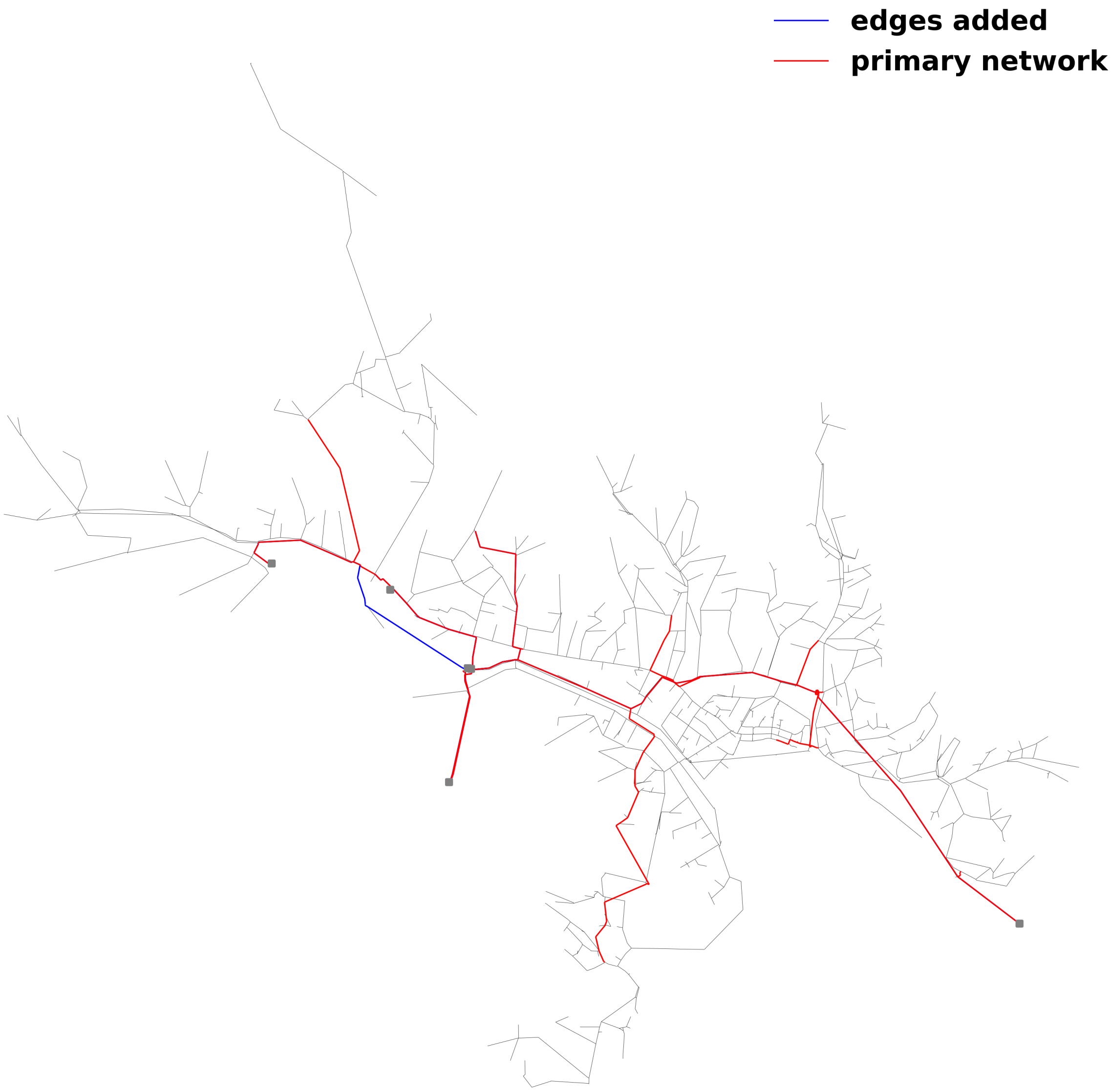

Figure 6.33: Tyrrhenian Town. Added edges to the primary network

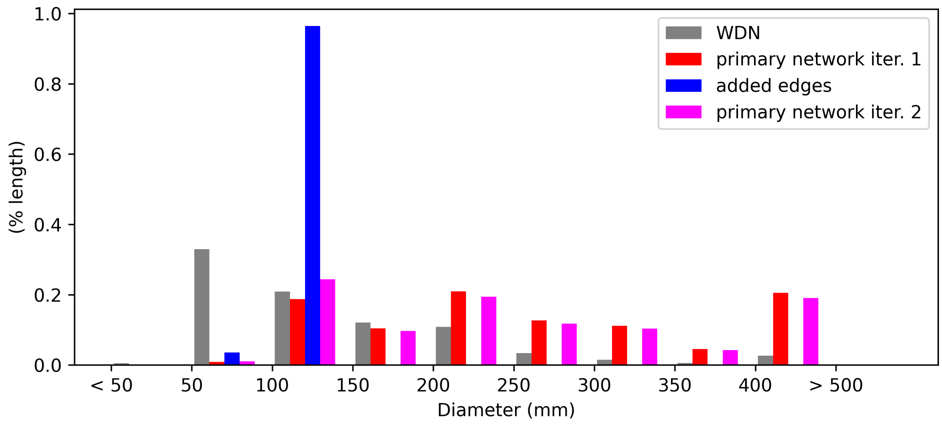

Figure 6.34: Tyrrhenian Town. Differences of the primary networks from the first to the second iteration process

6.7.2 Second iteration

The process restarts subtracting the new primary network to identify the primary connected components, as shown in Figure 6.35. The figure shows in green the primary connected components that satisfy the constraint of number of supply edges less than or equal to 2. The algorithm for finding the first solution subdivides the primary connected components with two supply edges with the necessary closures (to ensure that initially the sectors are isolated). During the second iteration of the process, OBJ 1 (6^{th} iteration Tabu Search) was satisfied (as shown in Figure 6.36). Subsequently the algorithm minimized OBJ 2 (Figure 6.37).

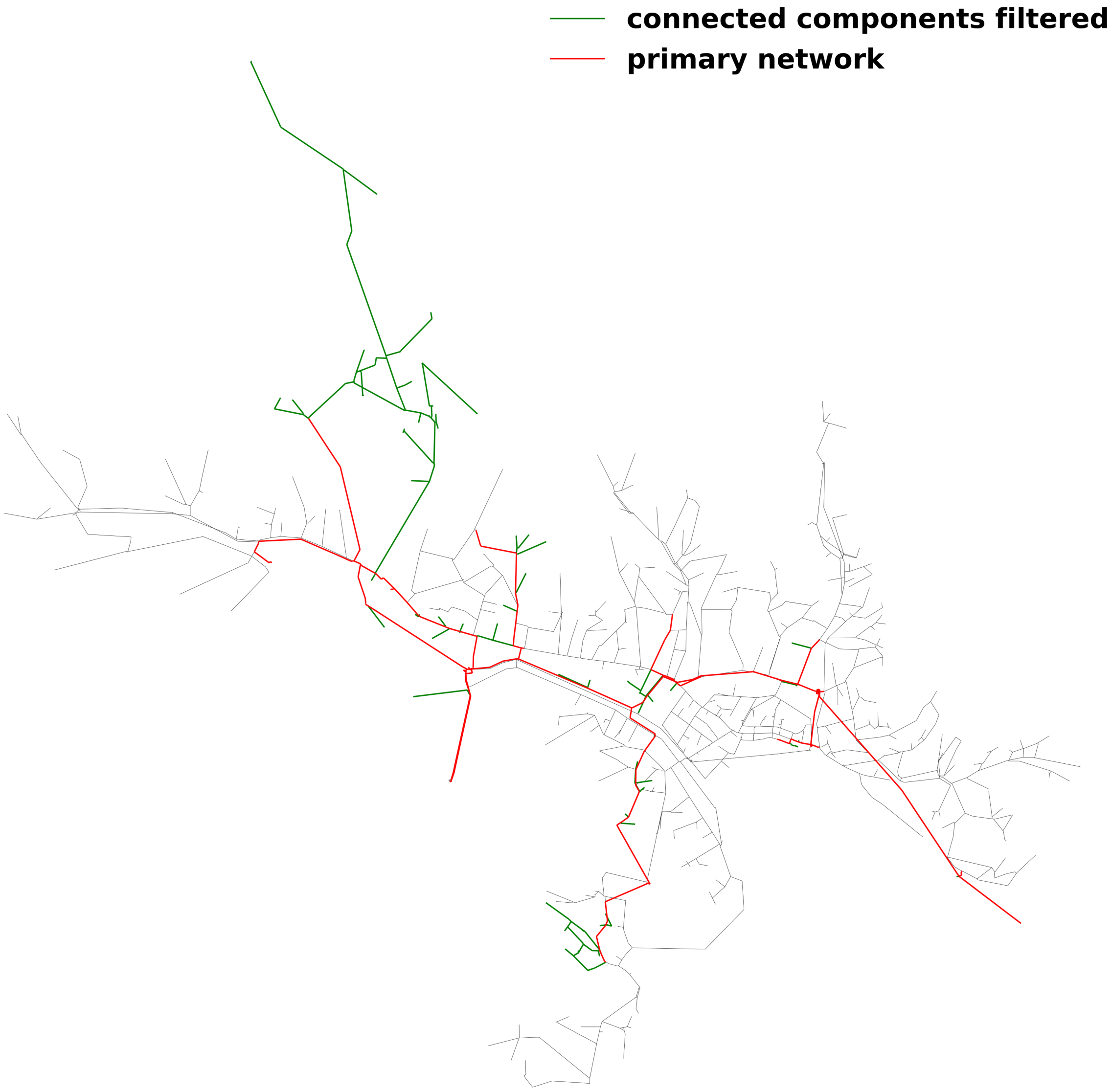

Figure 6.35: Tyrrhenian Town primary connected components filtered with only one primary supply edge

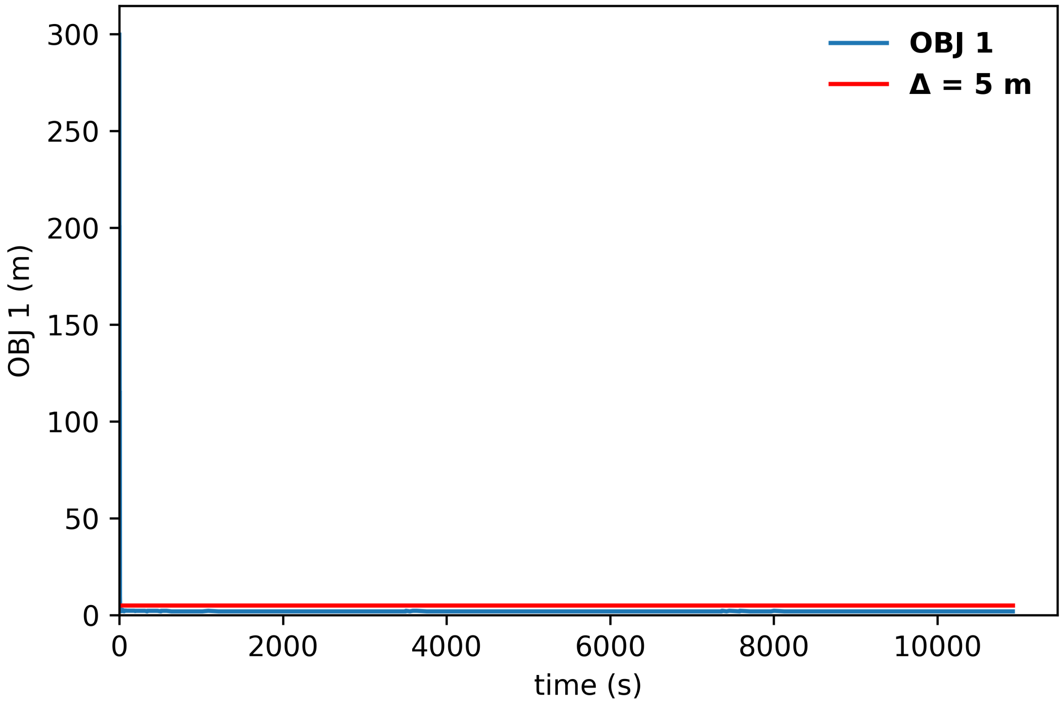

Figure 6.36: Tyrrhenian Town. OBJ 1 results during second iteration

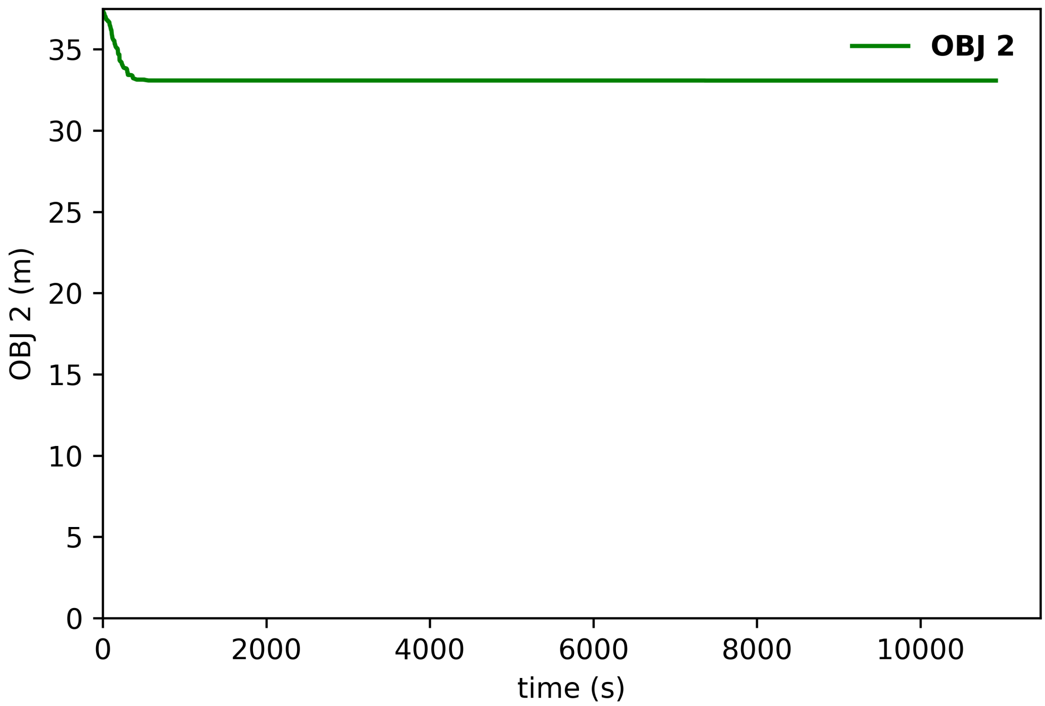

Figure 6.37: Tyrrhenian Town. OBJ 2 results during second iteration

6.7.3 Final result

In Figure 6.38 the sectorization resulting from the best configuration of closures in terms of OBJ 2 is shown; the numerical results of the optimization process are presented in Table 6.7.

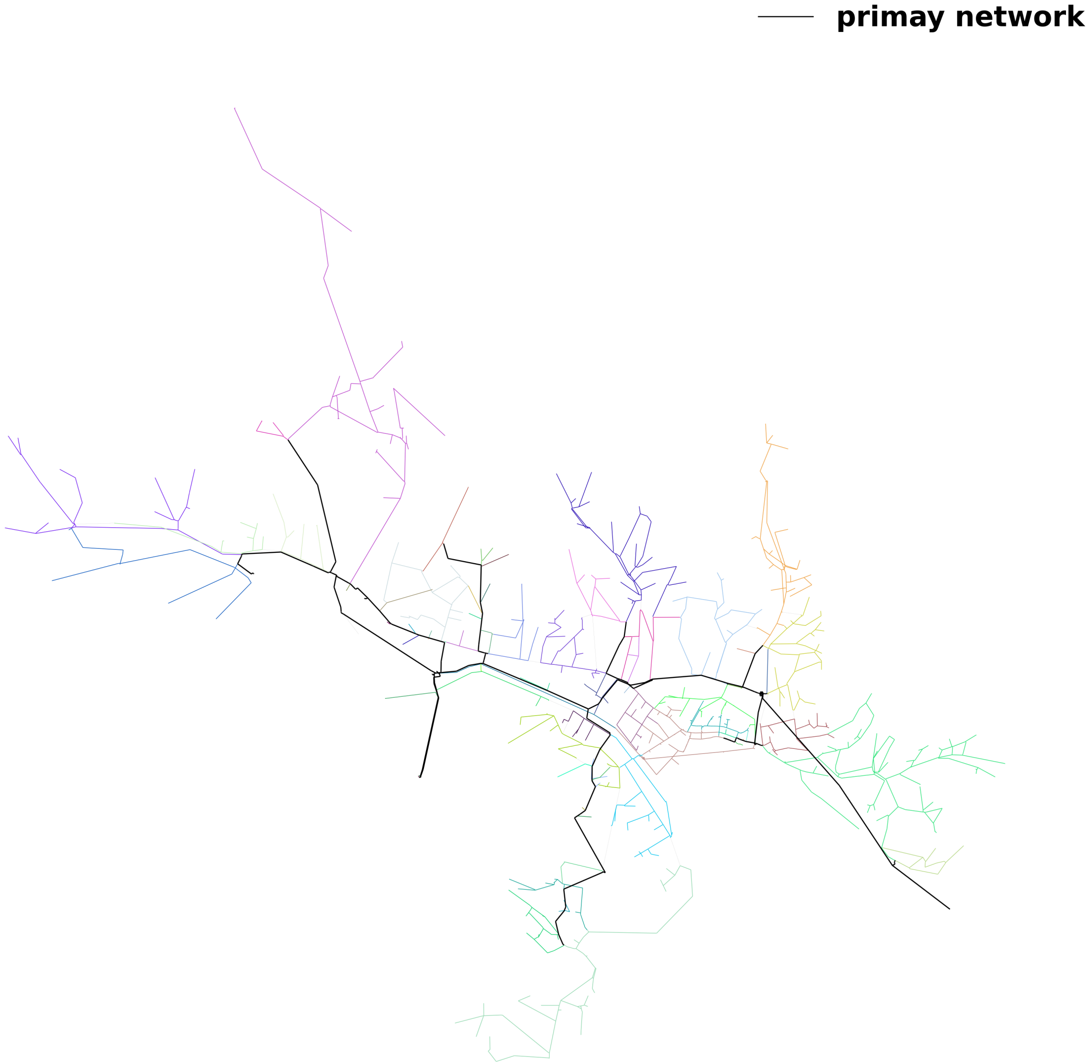

Figure 6.38: Tyrrhenian Town sectors

Table 6.7: Tyrrhenian Town. Results of second process iteration

iter.	**OBJ 1 (m)**	**OBJ 2 (m)**	N^o **closed edges**	**time (s)**
initial solution	299.7	nan	71	0
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
6	2.07	37.28	65	10.4
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
224**	2.22	33.08	64	5388
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.

Conclusions

This thesis proposes an algorithmic approach to find the solution of two related problems: (i) identify the fundamental asset of large WDNs in terms of main infrastructure; (ii)sectorize large WDNs into isolated sectors in order to respect the minimum service to be guaranteed to users. Two methodologies have been developed to meet these two objectives and subsequently they were integrated to guarantee an automatic process which allows to optimize the configuration of the sectorised network taking into account the needs to integrated in an overall vision the two problems (i) and (ii) considered. The methodology introduce the concept of primary network with a dual approach, of connecting the main nodes of the network and identifying the paths with the minimal potential energy loss. The methodology is able to provide a result without necessarily using a hydraulic model, which is not always available and which, in the presence of pumping stations or variable-level resources, may be affected by the regulations deriving from WDN operational rules. The primary network identified can be used to read infrastructural critical issues of the open WDNs for re-design purposes or as a base to design the sectorization of WDNs. The sectorization problem has been faced using optimization techniques by means the development of a new dedicated Tabu Search algorithm. The algorithm was developed to be able to deal with real case studies of large WDNs. For this reason, in this thesis three new hydraulic models of the WDNs have been created in order to be able to evaluate the capabilities and problems of the algorithm on different and complex cases of which a deep knowledge has been acquired. Also some models taken from the literature with a high complexity in terms of number of elements and management rules, were used to test the efficiency of the developed algorithms. The algorithm has been developed in the most elastic way possible so as to be able to adapt to the resolution of networks of different types with different objectives. In fact, it is possible to choose the number of supply edges of the sectors and to foresee the possibility that the sectors must be isolated or not. The results obtained up to this state of development of the algorithm focused on the implementation of a procedure capable of tackling problems (i) and (ii) for real WDNs of any complexity in terms of network extension, operational rules, duration of the hydraulic simulation analysis. The next step, not shown in the results, but in fact already implementable in the algorithm, will allow the insertion of engineering elements through a pre and post analysis. The sectorization process that curently takes place in many WDNs is often conditioned by factors that go beyond the advantages in terms of performance and therefore the solutions that optimize certain parameters. In this sense, the possibility has been foreseen of adapting the algorithm to a more engineering solution with a pre-analysis that can exclude areas from sectorization, or that can establish a priori not to consider some pipes. The results show the application to WDNs in which all pipes (except those of the primary network) are involved in the sectorization process. The results obtained are therefore those that optimize the two objective functions considered, the satisfaction of the pmin at the moment of maximum consumption and the homogeneity in terms of pressure within the sectors, which is the premise of subsequent analysis in terms of resilience and reliability. Instead, the second criteria introduces to the optimal pressure management. The flexibility of application therefore makes it applicable also for engineering solutions which must always then adapt to each WDN. The methodology set up to automatically identify the primary network deficits by adding new pipes to it in order to sectorize the WDN has given a good response in the complex case studies in which the high degree of loops formed during the expansion of the real WDN has in fact defined a transport system with multiple parallelisms of the pipelines.

Limits and future developments

The methodology of extending the primary network which has produced good results on several large WDNs considered in this thesis, highlights in certain WDNs the possibility to be improved. Infact if Steiner Tree algorithm is extremely efficient to find the shortest path it is not able to find alternative paths of similar cost. So this algorithm identifies initially the primary networks as branch networks, thus it is not possible to capture at the first step the self loops of points of the primary network unless reusing the same algorithms after having weighed more the edges already chosen. This also imposes the issue of calibrating the given weight and establishing a priori when a path is considered alternative. We therefore want to deepen the use of algorithms that already provide for the possibility of carrying out loops no longer given by the repetition of the same approach. This would also solve the problem of tanks having an inlet and outlet pipe automatically without forcing the process. Having developed large models of real

WDNs available with a view to responding to more engineering needs, we also want to vary the search for the neighborood in the Tabu Search so that it is only able to move between the valves, considering the already existing valves as the only edges that can be closed. The comparison with the results deriving from others existing methods should also be deepened so as to be able to effectively evaluate the efficiency of the algorithm with respect to those developed by other authors. Furthermore, having been able to support with acceptable calculation times within the search for the solution hydraulic simulations of extended period, we will proceed to consider other objective functions (for example to taken into account the water age) and to make the most of those already used by differentiating, for example, the search for a result that respects the pressure constraints which must therefore be evaluated in the hour of maximum consumption by the need to have homogeneous pressures in the same sector which can be evaluated at night when the possibility of applying pressure reduction policies and consequently of leakage is greater.

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