doi: 10.2166/9781789062380_0237

Chapter 10

Innovative methods for optimal design of water network partitioning

Armando Di Nardo and Giovanni Francesco Santonastaso*

Department of Engineering, Università Della Campania 'Luigi Vanvitelli', Via Roma 29, 81031 Aversa (CE), Italy
**Corresponding author. E-mail: armando.dinardo@unicampania.it*

LEARNING OBJECTIVES

At the end of this chapter, you will be able to:

(1) Understand the main characteristics of Water Network Partitioning (WNP).
(2) Explain the advantages and drawbacks of WNP.
(3) Distinguish empirical and automatic approaches.
(4) Run a basic automatic procedure based on Python code.

10.1 INTRODUCTION

One of the most effective ways to reduce water distribution network (WDS) complexity is to apply the paradigm of 'divide and conquer' (Di Nardo *et al.*, 2014c), which exploits the property that complex systems can be better analyzed if it can be split into many sub-components.

This technique was proposed in England in the early 1980s (Water Authorities Association and Water Research Centre, 1985; Water Industry Research Ltd., 1999; Wrc/WSA/WCA Engineering and Operations Committee, 1994) and is now implemented in many countries. It consists of defining smaller water districts or sectors, defined as district meter area (DMA), obtained through the permanent insertion of boundary valves and flow meters along properly selected pipes. This can significantly improve management and maintenance, and, specifically, the water balance estimation for water leakage, pressures control, and water security from intentional contaminations (Di Nardo *et al.*, 2015a; Grayman *et al.*, 2009).

In Figure 10.1, a layout of permanent Water Network Partitioning (WNP) with three DMAs is shown, highlighting flow meters, gate valves, and district boundaries.

This technique, defined more recently in Di Nardo *et al.* (2013) as WNP, provides a series of interventions on the WDSs that require a careful economic planning by the managing authority; furthermore, it envisions the use of modern monitoring systems (remote control, etc.) which are generally becoming less expensive, and which, to be implemented, only await a new management policy. It is evident that having a network divided into smaller sub-regions makes it easier to study and manage the system (Di Nardo & Di Natale, 2011; Water Industry Research, 1999).

The definition of an optimal partitioning layout is a crucial and arduous problem. Nowadays it is possible to provide new opportunities to the traditional approach of analysis, design and management

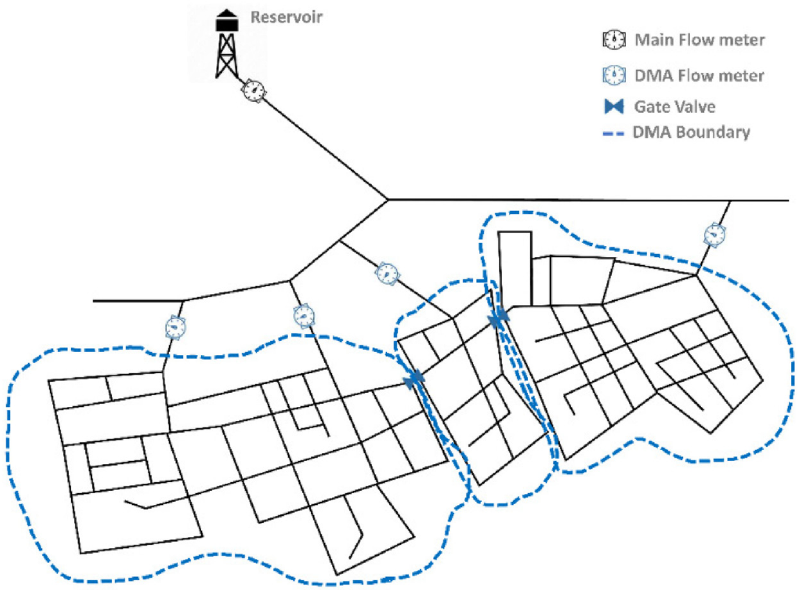

Figure 10.1 Scheme of a permanent Water Network Partitioning.

with the development of new monitoring and control technologies and with the recent growth of computational power used by simulation software. Therefore, WNP represents a crucial task not only for the technicians of the sector but also for the scientific community, because it modifies (and even challenges) some fundamental criteria followed in the design of water systems.

WNP contrasts with the traditional design criteria of the WDS with a high level of topological redundancy with many loops to have a more robust water system to face unforeseen changes in design conditions (such as pipe breaks or different distribution of water demand). Indeed, the introduction of the concept of permanent sub-districts and water sectors (Di Nardo *et al.*, 2015b) is in opposition to the traditional criterion followed in the field of the hydraulic constructions (Mays, 2000) designed with a multi-meshed network to improve its efficiency under different operating conditions. Network partitioning can indeed generate a hydraulic performance deterioration of the system (Di Nardo *et al.*, 2015b); in fact, when it is carried out in almost all cases on networks already designed and implemented using traditional design criteria, system efficiency can be partially and/or globally compromised. Indeed, the closure of some pipes with boundary valves can decrease, also significantly, the available hydraulic diameters of the whole network, with the increase of head loss and dissipated power and, consequently, worsening of the level of service for the users in terms of water pressure.

However, and conversely, the introduction of 'divide and conquer' for WDS design promotes innovation in management of water networks by introducing the concept of a Smart WAter Network (SWAN) as a key subsystem of the notion of Smart City (Di Nardo *et al.*, 2021).

Traditionally, WNP was achieved basing on empirical suggestions, such as the number of customers or parcels, length of pipes or other geometric or topological criteria; while the hydraulic alteration due to the insertion of gate, or boundary, valves is tested with hydraulic simulation based on 'trial and error' methods. These semi-empirical approaches are not effective for large water networks with thousands of nodes and links because the number of possible layouts of water districts is huge and requires heuristic optimization approaches.

In the last 10 years, many authors proposed different procedures to obtain automatically optimal water network partitioning layouts (Bui *et al.*, 2020), based on two phases, called clustering and dividing, with a systematic approach based on different innovative algorithms such as *graph algorithms, multilevel partitioning, community structure, spectral clustering*, and so on. Also, performance indices can measure the reduction of water network resilience because the reduction of network pipes availability, due to insertion of gate valves, reduces the level of service and the capacity of the water network to face different design conditions, as widely reported in Di Nardo *et al.* (2013).

The authors of this chapter developed the first automatic tool, called SWANP© (Smart Water Network Partitioning and Protection), to define the optimal layouts of water districts and sectors that is presented in this work.

10.2 ADVANTAGES OF WNP

The optimal design of DMAs simplifies monitoring and maintenance, with reference to the problems that will be explained in the following sections. Specifically, the main advantages of a permanent WNP, obtained inserting both gate valves and flow meters, can be arranged as follows:

- water balance;
- water pressure management;
- water contamination protection.

Furthermore, the data collection by monitoring of each DMA (and not of the whole network) can provide to water utilities other several detailed information related to each single district, such as demand distributions, categories of users, break frequencies, pressure levels, water quality, and so on., that can improve management, quality and cost of service.

10.3 WATER BALANCE

The most important problem of WDS management is the obsolescence of pipes and hydraulic devices (gate valves, control valves, flow meters, etc.) that generate low hydraulic performance (insufficient pressures, reduced resources during summer, poor water quality, etc.) and, above all, high values of Non-Revenue Water (NRW) both real and apparent, as reported in Lambert and Hirner (2000).

As is well known, the United Nations devoted the year 2003 (United Nation, 2003) to the problem of water in the world, and to the areas of the planet affected by water scarcity, suggesting actions to minimize waste and optimize resources. A year before, the Organization for Economic Co-operation and Development (OECD) already focused attention on the waste of water resources for the major industrialized countries, estimating that water losses in urban water networks account for around 30% (for the 30 most industrialized countries), exceeding the optimal economic level of 10 and 20% (OEAD, 2002). The more recent estimation in some industrialized countries, such as Italy, indicate water losses of about 40% (ISTAT, 2021).

Evidently, water balance estimation is crucial to evaluate the efficiency of a WDS and to help management activities reduce water leakage. The estimation of water loss is achieved as follows using a simple mass continuity statement:

$$\text{Water losses} = \text{Water Inflow} - \text{Water Consumption} \tag{10.1}$$

The practical application of the water balance is a very complex problem, from scientific and technical perspectives and for economic and management reasons. Some practical problems are: (a) water inflow depends on accuracy of flow meters; (b) water consumption depends on the ability of water utility to measure all user consumptions; (c) difficulty to identify user consumption (civil, industrial, commercial, etc.), authorized or not; (d) some water consumption is not measured (such as public fountains, schools, hospitals, etc.); (e) all measures have to be synchronized (or reported at the same time interval).

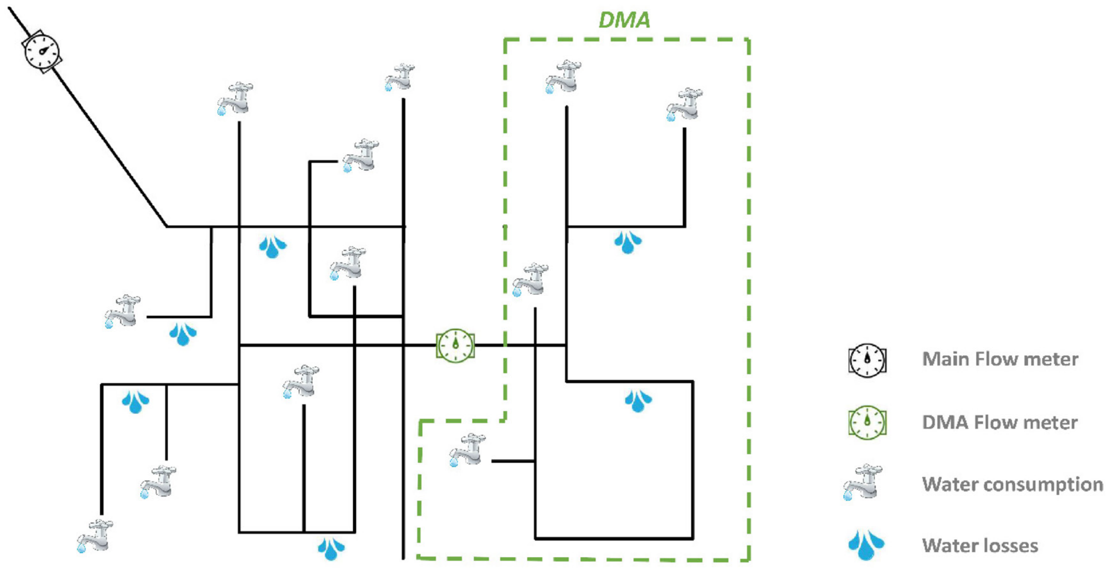

Figure 10.2 Water balance: Network vs DMA layout.

The correct application of the water balance estimation can also provide water utilities precious information about the percentage of real (or physical) losses, water really lost, apparent (or administrative) losses, and not billed water.

Furthermore, the water balance and evaluation of network integrity presupposes the exact definition of the different components of the volumes to estimate the water losses and to compare water networks of different systems in other locations. More than technical and scientific problems to correctly estimate the water balance, there have been difficulties related to the drafting of an international 'standard terminology'. So, the International Water Association (IWA) proposed a fundamental contribution (Lambert & Hirner, 2000) to define water balance components and compare the performance of the systems using evaluation indices equal for all countries (Lambert *et al.*, 1999).

Theoretically, we can carry out a water balance on the entire distribution network, but this operation is not very useful because it does not provide detailed information on which parts of the water network can be affected by higher leakage levels; so a DMA water balance is significantly better, as represented in Figure 10.2, allowing a more thorough investigation and monitoring of each district and supporting water utilities to prioritize the choice of economic investments for operations of water losses detection.

Therefore, the application of a *divide and conquer* approach with WNP optimal design allows the easier application of some methodologies for the water balance estimation developed in England (UK Water Industry, 1999; Wrc/WSA/WCA, 1994) such as minimum night flow (MNF) and minimum flow consumption (MFC).

10.4 WATER PRESSURE MANAGEMENT

Another advantage of WNP is to significantly facilitate the application of water pressure management to reduce water leakage.

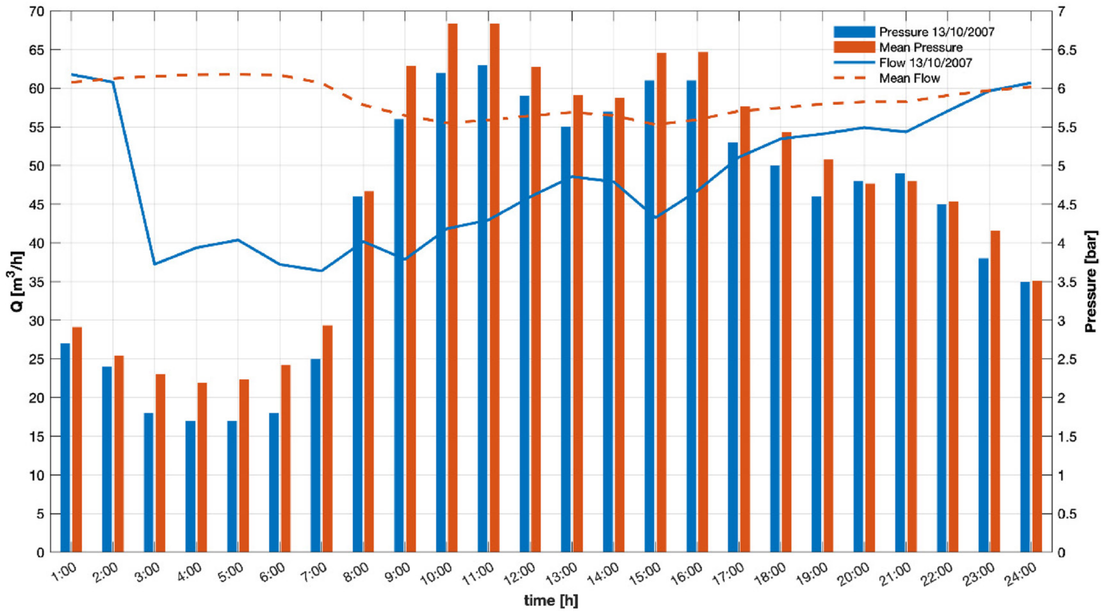

Figure 10.3 Flows reduction through pressure management.

As is known, water leakage Q^{Leakage} in the pipelines increases with increasing pressures P according to the relation (Khaled *et al.*, 1992; Lambert, 2000):

$$Q^{\text{Leakage}} = cP^{\gamma} \tag{10.2}$$

in which the values of the coefficients c and γ depend on the pipelines characteristics and the type of leak, while P (pressure or pressure head) is expressed in meters of water head.

Therefore, it is evident from Equation (10).(2) that the placement of pressure reducing valves (PRV) can bring about decreases in network water loss, as reported in Figure 10.3. The pressure reduction inevitably decreases the network hydraulic efficiency and the insertion of pressure regulation valves downstream to network reservoirs or sources can also reduce hydraulic performance of the whole water system using the same pressure control of all pipes. Therefore, a subdivision of the water network in some permanent DMAs can help the application of water pressure management inserting different PRVs upstream of each DMA and reducing water pressure for water saving. Also, it can help preserve the hydraulic performances of the system, guaranteeing the minimum level for the users in each DMA. In other terms, WNP also allows adjustment of the pressure values in each DMAs, considering the different needs of the urban areas (Alonso *et al.*, 2000).

10.5 WATER CONTAMINATION PROTECTION

Recent applications of water network partitioning have also shown interesting benefits with respect to protecting water systems from intentional contamination according to the dual-use value criteria (Di Nardo *et al.*, 2015a; Grayman *et al.*, 2009). Indeed, WNP has some primary aims ('main-use value'), related to water balance, pressure management, leakage reductions, and so on., and a secondary aim (or 'dual-use value') that consists of providing water protection from accidental or intentional contaminations. In this manner, the water distribution system protection obtained with WNP is

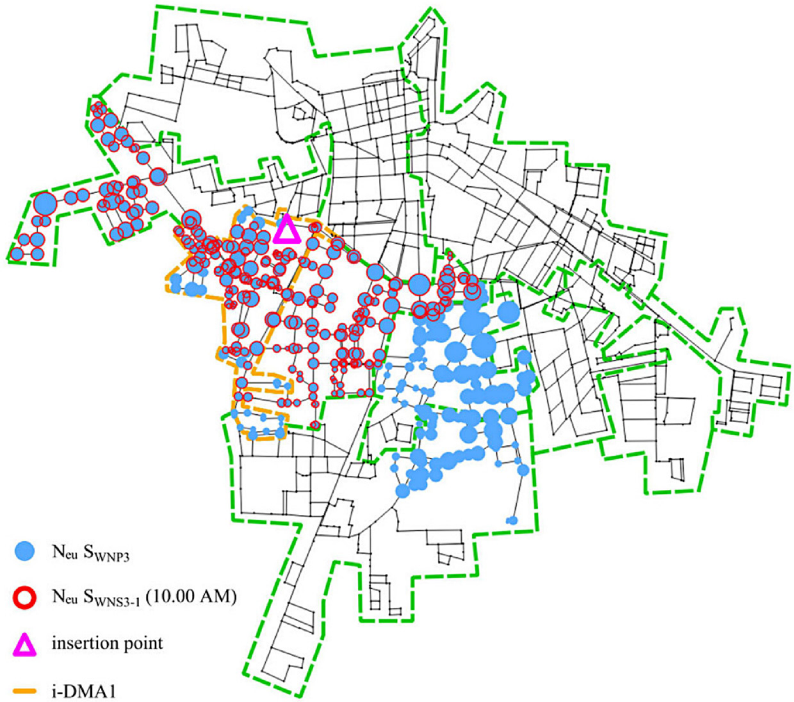

Figure 10.4 Simulation results of risk mitigation from terroristic attack of Matamoros water distribution network (Di Nardo *et al.*, 2015a).

capable of a likely return on investment because evidently only a small portion of the system lifetime will be spent on network protection while the majority of the system lifetime will be spent on the day-to-day management of achieving the main goals, as illustrated in Di Nardo *et al.* (2015a).

The authors investigated how WNP can reduce the risk of user contamination and limit the effects of a malicious (terroristic) act on water distribution systems. Specifically, Di Nardo *et al.* (2015a) showed that an optimal design of permanent DMAs can reduce exposures due to terrorist contamination with cyanide. This is done by closing all gate valves and quickly sectorizing the attacked district. The analysis was carried out on a real water distribution network comparing different sectorization scenarios and the simulation results showing the effectiveness of an early warning system coupled with WNP to significantly reduce the contamination risk for users.

In Figure 10.4, a simulation on the Matamoros network is reported, in which the triangle indicates the insertion point of contamination attack, light gray being the isolated DMA (i-DMA) after contamination alarm, and the dot is the exposed user without isolating district and the circle is with isolating actions. The effectiveness of WNP with isolation is clear: the number of exposed users, proportional to circle dimension, are significantly lower. More details can be found in Di Nardo *et al.* (2015a).

10.5.1 Clustering and dividing

As anticipated, the main problem of WNP is represented by the perturbation on the water distribution system due to pipe closing. Indeed, the insertion of gate valves can also significantly reduce the water network performance in terms of alternative paths of flows in case of pipe breaks (decrease of topological redundancy) and nodal water pressures (decrease of energy redundancy).

Physical (or permanent) district metering gives more opportunities than virtual districting metering, which uses only flow meters for water balance without closing the pipe (Di Nardo *et al.*, 2018). The permanent definition of DMA allows to simplify the monitoring and managing of WDS and to optimize and simplify water pressure management for leakage reduction thanks to insertion of district pressure regulation valves (PRV). In addition, physical district metering can also be used to protect water networks from accidental or intentional contamination, implementing a dual-use approach (Di Nardo *et al.*, 2015a).

On the other hand, this methodology is complicated to achieve because, by intervening in a physical way on the system (with closing pipes by gate valves), it is necessary to verify the variations of the system with respect to the initial conditions through hydraulic simulation and calibration techniques (Di Nardo & Di Natale, 2011).

The main outcomes that can be achieved through permanent WNP optimal design include (but are not limited to): (a) minimize the alteration of hydraulic performance (b) minimize the number of flow meters (the best management condition occurs when a single meter is installed for each district) in order to simplify the computation of water balance (Twort *et al.*, 2000).

The literature offers empirical suggestions for water network partitioning based on DMAs characteristics (number of users, pipes length, etc.) (Water Industry Research, 1999); or 'trial and error' approaches used with hydraulic simulation software (Di Nardo *et al.*, 2013). However, these suggestions and approaches are very difficult to apply to large water supply systems. In the last 10 years, many optimization techniques have been proposed, based on graph and network theory, that have significantly improved water network partitioning.

Several suggestions about DMA size can be found in the technical literature, that propose to include:

- 1000–3000 properties (Water Authorities Association and Water Research Centre, 1985);
- 2500–12 500 inhabitants with 5–30 km of water network (Butler, 2000);
- a number of properties up to 1000 (small DMA) and 3000 (medium DMA) and 5000 (large DMA) (as recommended by the UK Water Industry Research).

These guidelines cannot be easily extended to large water supply systems since they are based on empirical considerations, and sometimes on a small number of case studies.

Different optimization methods allow to define automatic procedures for water network partitioning (or sectorization) (Bui *et al.*, 2020). Generally, the procedures are divided into the two phases discussed below (Di Nardo *et al.*, 2016d; Perelman *et al.*, 2015).

10.5.1.1 Phase 1

Clustering is aimed at defining the shape and the dimensions of the network subsets in order to minimize the number of connections (or other characteristics like diameter, length, conductance, etc.) balancing the number of nodes (or other characteristics like flow, pressure, etc.) for each district.

As shown in Figure 10.5, with reference to a simple network clustered in two subnetworks (highlighted in red and blue colors in three different ways) shows the importance of clustering, minimizing the number N_b of boundaries and balancing the nodes. In Figure 10.5a, there are only three links (or boundaries) between two subnetworks but this solution is not well balanced with six red nodes and 12 blue nodes. Figure 10.5b shows a perfect balanced scheme with nine nodes both for blue and red nodes but a significantly higher number (seven) of boundaries. Finally, in Figure 10.5c shows the best clustering with a perfect balance of nodes (nine) and the minimum number of boundaries (three).

Therefore, the example shows that already with a very small network, different clustering layouts are possible. In a large water network, the problem to find the optimal solution in terms of minimization of elements between the clusters (links or boundaries) and of balancing of nodes or other characteristics in a way that the similarity (or the density) in each cluster is maximized (as number of nodes, length of pipes or flow delivered, etc.) is an NP-hard problem (Fortunato, 2010).

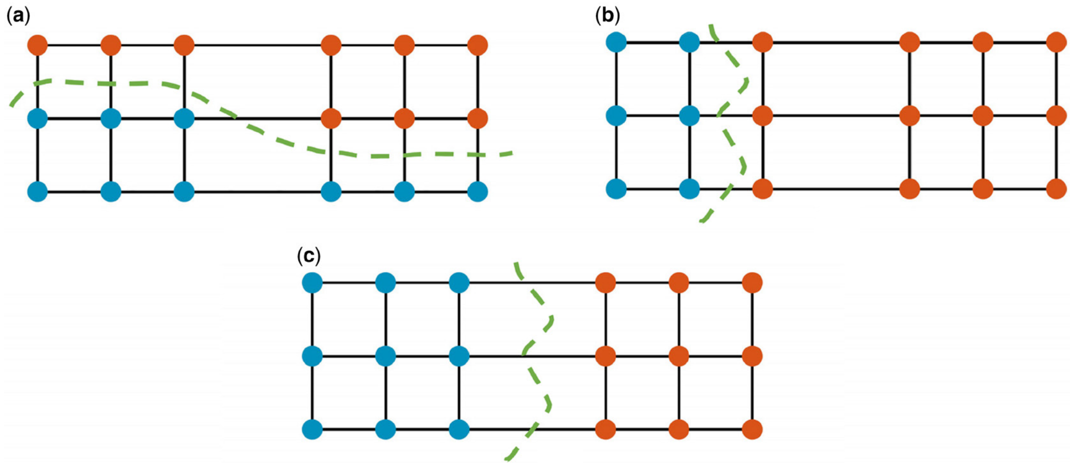

Figure 10.5 An example of possible clustering of a small network.

10.5.1.2 Phase 2

Dividing is aimed at physically partitioning the network by selecting boundaries (pipes) in which to insert flow meters or gate valves, as reported in Figure 10.6.

In the case of a small network, such as that represented in Figure 10.6, this phase, once the number N_{fm} of flow meters is fixed, can be carried out with the need of hydraulic software, permutatively, inserting the number of boundary valves $N_{bv} = (N_b – N_{fm})$, minimizing the alteration of hydraulic performance of water distribution network due to the closure of some pipes with the insertion of boundary valves between clusters. In the dividing phase, for large water networks, this problem is very complex and it is impossible to test all permutations of the possible positioning of flow meters and boundary valves in links between clusters.

This problem is an NP-hard problem (Bodlaender *et al.*, 2010) and it requires heuristic algorithms to find optimal solutions (Tindell *et al.*, 1992). In other terms, once all the N_b boundary pipes between clusters have been defined, those that can be closed must be chosen among all the possible combinations N_C of water network partitioning layouts, expressed by the following binomial coefficient:

$$N_C = \binom{N_b}{N_{fm}} = \frac{N_b!}{N_{fm}!(N_b - N_{fm})!} \tag{10.3}$$

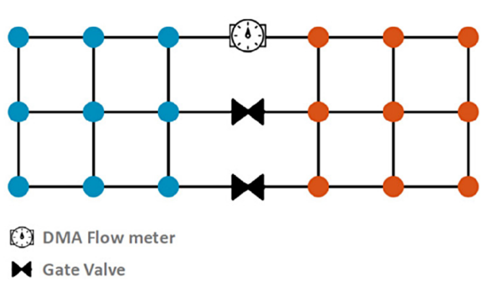

Figure 10.6 An example of possible dividing of a small network.

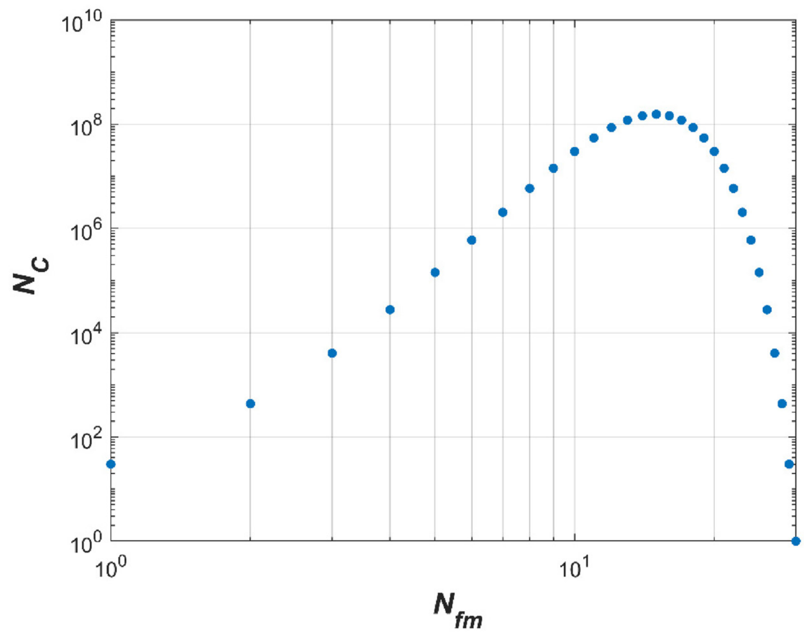

Figure 10.7 Number N_C of possible dividing layout of WNP for a small network changing N_b.

in which, already with a small network with 30 boundary pipes (N_b) and only 10 flow meters (N_{fm}), the number of all possible water partitioning layout, N_C, reaches about 3×10^7, as reported in Figure 10.7.

It is important to emphasize that even for a small water supply network and for a small number k of DMAs, N_C can be such a large number that it is often computationally impossible to investigate the entire solution space.

Therefore, it is clear that both the phases of clustering and dividing require us to define a permanent water network partitioning, and cannot be achieved using a traditional approach based on empirical suggestions or hydraulic simulation based on 'trial and error' methods if an effective optimal solution is needed. Indeed, these empirical or semi-empirical approaches are not effective for large water networks and require automatic procedures, which will be explained in the following section.

10.5.2 Innovative methods for optimal WNP design

As anticipated, traditional approaches for WNP cannot find the optimal design of DMAs for large water distribution networks. In this section, we introduce some innovative methods based on different algorithms, often developed in other disciplines for different classes of problems.

With reference to the clustering phase, the main methods proposed in the literature (Di Nardo *et al.*, 2018) to obtain a WNP are based on the following techniques:

(1) *graph algorithms* (Jacobs & Goulter, 1989; Savic & Walters, 1995; Tzatchkov *et al.*, 2006) starting from the representation of the water network as a simple weighted graph considering $G = (V, E)$, where V is the set of n vertices (or nodes) and E is the set of m edges (or pipes). Subsequently, the network is defined by a $n \times n$ connectivity matrix A and the matrix of weights W *n by n* (matrix of the intensity of the connections between nodes). Then, the application of different techniques of graph theory, in particular related to the search for minimum paths

(with or without the use of weights on links and nodes), allows us to obtain groupings of nodes on which it is then possible to apply the next dividing phase. Through these techniques it is possible to quickly identify the districts in the subsequent dividing phase and to guarantee a minimum service level compatible with original network reliability (Di Nardo & Di Natale, 2011; Di Nardo *et al*., 2014a). The 'least important' or 'most redundant' sections are identified and, at the same time, the number of sections on which it is needed to insert gate valves and/or meters is reduced.

(2) *multilevel partitioning* (Di Nardo *et al*., 2015c) that starts from techniques implemented in informatics tools allows us to automatically obtain water network clustering, minimizing the number of links between districts. In fact, for simulations that need huge computational power like, for example, simulations based on finite element methods, parallel computation can be used. In this case, it is necessary to distribute the finite element mesh among different processors. This distribution, to improve performance, must be made according to two main rules: (1) an equal number of finite elements has to be allocated to each processor for balancing the workload; (2) a minimum number of adjacent elements between processors has to be found for reducing communication overhead. This problem can be assimilated to partitioning of a computational mesh in a k-way or in k-processors that will perform each computational process. The mesh is commonly schematized by a graph with vertices corresponding to individual computational processes (e.g., finite elements) and with links corresponding to their connections. Starting from this schematization of the mesh, partitioning techniques of a graph in k-way were developed in Computer Science for the optimal allocation of a computational mesh in parallel or distributed computing architectures. The proposed methodology is based on the similarity between a calculation mesh and a water distribution network, in particular on the analogy between the districts design criteria and those of parallel computing system, in other words: the balancing of the load of calculation to be assigned to different processors can be compared with the balancing of the number of nodes (or the flow rates) to be assigned to each water district, and the minimization of the connection elements between two processors corresponds to the minimization of the pipe closures.

(3) *community structure*, is a bottom-up hierarchical algorithm based on the measure of network density to define clusters. These algorithms identify sub graphs in an iterative manner, aggregating nodes time by time and then the groups of nodes, minimizing the density between groups and maximizing the density within each group. Density therefore becomes a measure of the quality of the clustering process, where for density it means the number of connections between nodes. Modularity and centrality of segments are generally used as metrics for measuring density (Di Nardo *et al*., 2015c; Newman, 2004).

(4) *spectral approach*, developed in the last few years (Di Nardo *et al*., 2016a; Herrera *et al*., 2010) starts from considering the network as a simple graph $G=(V,E)$, where V is the set of n vertices vi (or nodes) and E is the set of m edges. Subsequently, it defined the matrix of connectivity A $n \times n$ and the matrix of weights W $n \times n$ (matrix of the intensity of the connections between nodes). In this case, methodologies and algorithms of complex networks theory are adopted (Boccaletti *et al*., 2006), assuming water distribution networks as complex systems, constituted by thousands of elementary units (nodes and stretches), connected to form meshes (loop), and strongly geographically bound (Boccaletti *et al*., 2006). Starting from the adjacency matrix A, it defined the diagonal matrix of the degrees D $n \times n$ (matrix of the degree of connection of each single node), and therefore the Laplacian matrix of the graph $L=D–A$, whose spectrum defines important characteristics of the network. In detail, if k is the number of clusters in which the network has to be divided, the first k eigenvectors of the Laplacian define a new representation of the nodes that facilitates the identification of the subsets (Fiedler, 1973). It is shown that

the obtained clustering layout minimizes the number of boundary (or infra-clusters) pipes and simultaneously balances the number of nodes for each clusters (or the sum of the weights if the graph is weighed).

With reference to the dividing phase, two different approaches are proposed in the literature:

(1) By selecting pipes for the insertion of flow meters or gate valves using recursive bisection procedure (Ferrari *et al*., 2014);
(2) Optimization technique (Di Nardo *et al*., 2016b) with the objective of identifying the optimal layout that minimises the economic investment and the hydraulic deterioration.

Specifically, once the number of N_b is found after the clustering phase, both methods aim to find the optimal N_C layout, which can reduce the number of flow meters N_{fm} or the number of boundary (gate) valves N_{bv}.

Usually, the optimization approaches adopted some performance indices (Di Nardo *et al*., 2015b), both in the objective functions chosen and after the optimization process, also to compare solutions providing to operators a wide perspective of the alteration caused by the closing pipes with gate valves and, consequently, the reduction of resilience, robustness, pressure, and so on. comparing different solutions, in terms of number of flow meters and gate valves inserted in the water network for each number of cluster selected.

For this reason, often a multi-objective optimization technique is preferred in order to take into account simultaneously different performance indices and installation and maintenance costs of devices (flow meters and boundary valves).

10.5.3 WNP with SWANP© software

After more than 15 years of research work on WNP and many international experiences of case studies, the authors thought that the time was ripe to collect all knowledge, algorithms and procedures to develop an automatic software which can automatically define the optimal layout of DMAs and provide to a flexible decision support system to water utilities to find different solutions in terms of number of districts, performance indices, compliance with the physical constraints, and so on.

Therefore, the authors have developed a software in Phyton (Di Nardo *et al*., 2014b, 2016c, 2020) in geographical information system (GIS) environment for the automatic clustering and dividing of a water distribution network. The software, called SWANP© (Smart Water Network Partitioning and Protection) and registered to Copyright Office Washington on March 10, 2019, implements different clustering algorithms and objective functions. It can carry out hydraulic simulation both in demand driven analysis (DDA) and pressure driven analysis (PDA), as well as water quality simulation to select the optimal positioning of quality detection devices to protect water systems from contamination.

SWANP© provides to the decision-maker different WNP layouts using topological, energy, hydraulic and protection performance indices.

In Figures 10.8 and 10.9, an example of the graphical user interface (GUI) of SWANP© is reported showing the results of both a clustering phase with four DMAs and a dividing phase with four flow meters and 11 gate valves for a small network in Italy.

10.5.4 Phyton code to design an optimal WNP

In this last paragraph, a Python code for students and operators to design an optimal water network partitioning is provided using a spectral method for the clustering phase and a multi-objective genetic algorithm for the dividing phase.

The code briefly gives some notes on the most important aspects (INPUT, OUTPUT, etc.) of the algorithms used. The readers can find more information in Di Nardo *et al.* (2013, 2016a).

```
def cluster_phase(path,network,n_dma):
  from epanettools import epanet2 as ep
  import numpy as np
  import os
  from sklearn.cluster import SpectralClustering
  """
  spectral approach (Jianbo Shi, Jitendra Malik 2000) to perform
  clustering phase
  input:
  network = Epanet input file of water distribution network (.inp)
  path = directory of WDS file
  n_dma = number of DMAs
  output:
  dma = labels that define cluster for each node
  boundarypipes = pipes between two different DMAs
  """
  #compute the adjacency matrix of water distribution network
  os.chdir(path)
  err = ep.ENopen(network,'net.rpt','') #opening Epanet network file
  err,n_node = ep.ENgetcount(ep.EN_NODECOUNT) #reading number of nodes
  err,n_link = ep.ENgetcount(ep.EN_LINKCOUNT) #reading number of links
  M = np.zeros((n_link,3), dtype = np.int) # array with index of link, start node and end node for each
  pipe

for i in range(0,n_link):
  err,startnode,endnode=ep.ENgetlinknodes(i + 1)
  M[i] [0]=i+1 # index of i-th pipe
  M[i] [1]=startnode # start node of i-th pipe
  M[i] [2]=endnode # end node of i-th pipe
ep.ENclose() #closing Epanet network file
A=np.zeros((n_node,n_node),dtype=np.int) # adjacency matrix of water network
for i in range(0,n_link):

  if A[M[i][1]-1][M[i][2]-1] == 0 and A[M[i][2]-1][M[i][1]-1] == 0:

  A[M[i][1]-1][M[i][2]-1]=1

  A[M[i][2]-1][M[i][1]-1]=1
clusters=SpectralClustering(n_clusters=n_dma,affinity = 'precomputed').fit(A) # spectral clustering
dma=clusters.labels_
```

(*Continued*)

```
boundarypipes=[]
for k in range(0,len(M)):

    cluster_node_i=dma[M[k][1]-1]
    cluster_node_j=dma[M[k][2]-1]

    if cluster_node_i != cluster_node_j:

        boundarypipes.append(k + 1)
return dma,boundarypipes
def dividing_phase(path,network,boundarypipes,design_pressure):
import numpy as np
from pymoo.model.problem import Problem
from pymoo.factory import get_algorithm, get_sampling, get_crossover, get_mutation
from pymoo.optimize import minimize
import matplotlib.pyplot as plt
from epanettools import epanet2 as ep
import os
"""
NSGAII algorithm to perform dividing phase
input:
network=Epanet input file of water distribution network (.inp)
path=directory of WDS file
boundarypipes=pipes between two different DMAs
output:
FO=values of computed objective function
flow_meters=array wiht optimal positioning of flow meter
(0 - closed pipe; 1 - opend pipe)
"""
os.chdir(path)
n_variables=len(boundarypipes) #number of variables
class MyProblem(Problem):
    def __init__(self):
        super().__init__(n_var=n_variables, n_obj=2, n_constr=1,
            xl=np.zeros(n_variables), xu=np.ones(n_variables),type_var=int)

    def _evaluate(self, x, out, *args, **kwargs):

```

(*Continued*)

```
 ep.ENopen(network,'rete.rpt','') #opening Epanet network file

 err,n_node=ep.ENgetcount(ep.EN_NODECOUNT) #reading number of nodes

 err,n_link=ep.ENgetcount(ep.EN_LINKCOUNT) #reading number of pipes

 err,n_serb=ep.ENgetcount(ep.EN_RESERVOIR) #reading number of reservorir

dim_x=max(x.shape)
f1=np.zeros(dim_x)
f2=np.zeros(dim_x)
constraint=np.zeros(dim_x)
#chiusura dei tratti
for l in range(0,dim_x):

f1[l]=sum(x[l,:])
for k in range(0,len(boundarypipes)-1):
  err=ep.ENsetlinkvalue(boundarypipes[k],4,np.int(x[l][k]))


  err=ep.ENsolveH() #run hydraulic simulation

  pwr_node=np.zeros(n_node-n_serb, dtype=float)

  pressure=np.zeros(n_node-n_serb, dtype=float)


  pwr_node=np.zeros(n_node, dtype=float) #compute objective function 1 (number of flow meters)
  for k in range(0,n_node-n_serb):

  err,head=ep.ENgetnodevalue(k+1,ep.EN_HEAD)

  err,demand=ep.ENgetnodevalue(k+1,ep.EN_DEMAND)

  err,pressure[k]=ep.ENgetnodevalue(k+1,ep.EN_PRESSURE)
  pwr_node[k]=head*demand

f2[l]=-sum(pwr_node) #compute objective function 2 (node available power)
```

(*Continued*)

```
    constraint[l]=design_pressure-min(pressure)

    out["F"]=np.column_stack([f1, f2])

    out["G"]=constraint

    #chiusura epanet
    ep.ENclose()
problem=MyProblem()
method=get_algorithm("nsga2",
      pop_size=100,
      sampling=get_sampling("int_random"),
      crossover=get_crossover("int_sbx", prob=1.0, eta=3.0),
      mutation=get_mutation("int_pm", eta=3.0),
      eliminate_duplicates=True,
      )
res=minimize(problem,
      method,
      termination=('n_gen', 100),
      seed=1,
      save_history=True,
      disp=False)
res.F[:,1]=np.abs(res.F[:,1]) #print Objective Space
FO=res.F
flow_meters=res.X
plt.title("Objective Space")
plt.scatter(FO[:, 0], FO[:, 1])
plt.xlabel('FO1')
plt.ylabel('FO2')
plt.grid()
plt.show()
return FO,flow_meters
```

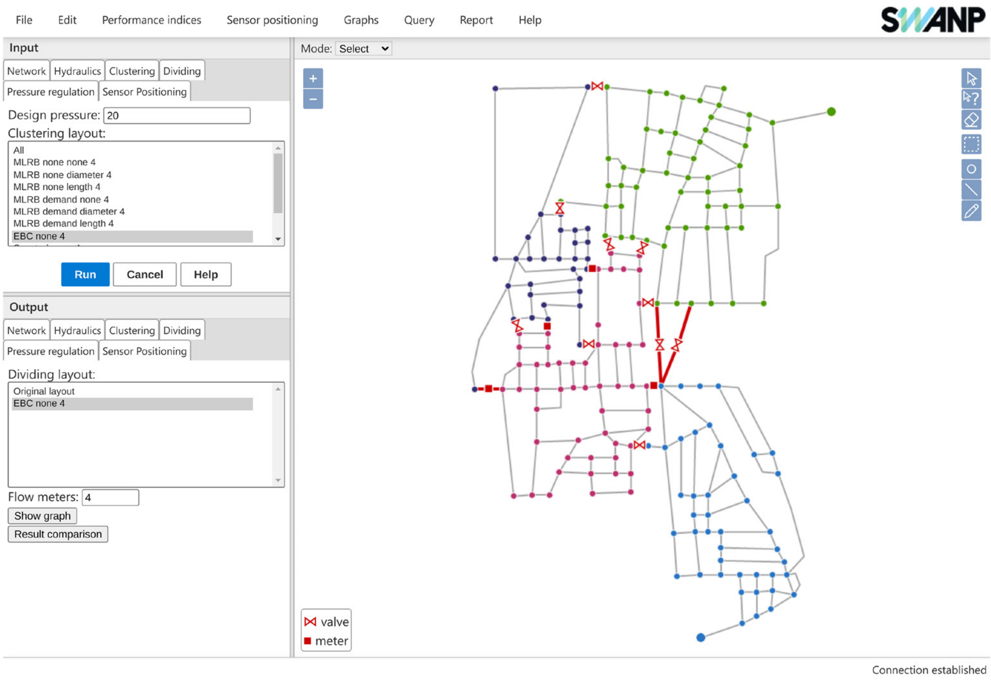

Figure 10.8 Clustering phase with SWANP©.

Figure 10.9 Dividing phase with SWANP©.

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