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An Automated Tool for Smart Water Network Partitioning

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Abstract Water Network Partitioning (WNP) represents the application of the “divide and conquer” paradigm to a Smart WAter Network (SWAN) that allows the improved application of techniques for water balance and pressure control. Indeed, these techniques can be applied with greater effectiveness by defining smaller permanent network parts, called District Meter Areas (DMAs), created by the insertion of gate valves and flow meters. The traditional criteria for the design of network DMAs are based on empirical suggestions (number of properties, length of pipes, etc.) and on approaches such as ‘trial and error’, even if used together with hydraulic simulation software. Nevertheless, these indications and procedures are very difficult to apply to large water supply systems because the insertion of gate valves modifies the original network layout and may considerably worsen the hydraulic performance of the water network. The proposed tool, based on some graph partitioning techniques, commonly applied in distributed computing, and on an original optimisation technique, allows the automatic design of a WNP comparing different possible layouts that are compliant with hydraulic performance. In this paper, the methodology was tested on a real case study using some performance indices to compare different WNPs. The proposed tool was developed in Phyton and integrates graph partitioning, hydraulic simulation techniques and a heuristic optimisation criterion. It allows the definition of DMAs with resulting performance indices that are very similar to the original network layout.

Keywords Water network partitioning · Graph theory · Smart water network · Sectorization · Water leakage

1 Introduction

The transfer of new Information and Communication Technologies (ICT) to different aspects of urban life has contributed to generating the notion of a Smart City, which was recently

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recognised in the scientific and technical international community (Chourabi et al. 2012) and is defined as a city where the use of ICT makes the use of “critical infrastructure components and services—which include city administration, education, healthcare, public safety, real estate, transportation and utilities—more intelligent, interconnected and efficient” (Washburn et al. 2010).

The development of new monitoring and control technologies and the recent increase of computational power for use by simulation software have changed the traditional approach to analysis, design and management of Water Distribution Systems (WDSs) from passive to more efficient actions (Lambert 2002). The low cost availability of new monitoring and management devices that can be controlled by a remote system allows the acceleration of the alignment of WDSs to other network utilities, such as electricity, gas, the Internet, etc. Then, the application of ICT devices to WDSs makes it possible to also introduce the new concept of a Smart WAter Network (SWAN) as a key subsystem of the Smart City.

Therefore, in this new perspective, the possibility of inserting remote control valves and flow meters in a WDS allows the implementation of the paradigm of “divide and conquer”, which implies dividing a large water network into *k* smaller subsystems to simplify and improve the management of the water supply system, as initially experienced in the UK (Water Authorities Association and Water Research Centre 1985) and, subsequently, in many other countries (Farley 2001; AWWA 2003; Morrison et al. 2007).

Indeed, partitioning the network into hydraulically independent subsystems or districts, called District Meter Areas (DMAs), can significantly improve water loss detection and pressure management (Wrc/WSA/WCA 1994; Lambert and Hirner 2000; AWWA 2003; Di Nardo and Di Natale 2011) and water safety (Grayman et al. 2009; Di Nardo et al. 2013a) in WDSs.

Permanent Water Network Partitioning (WNP) into different DMAs can be achieved by installing flow meters and boundary (or gate) valves in the network. Depending on the characteristics of the network, DMAs may be supplied by single or multiple feeds and may flow into adjacent DMAs or be self-contained. A technical-economic rule is to minimise the number of flow meters; if possible, the best condition would be to have a single inflow meter for each district to simplify the calculation of the synchronous water balance, as suggested in Di Nardo et al. (2012). Therefore, the fewer the number of flow meters, the easier and cheaper the calculation of the DMA water balance will be. This can be obtained by using boundary (or gate) valves to reduce the number of pipe connections according to hydraulic constraints and performance.

When water systems are already working, it is more difficult to set the number and dimension of districts, and in many cases, WNP may even worsen the hydraulic performance of water networks, especially node heads (Wrc/WSA/WCA 1994; Di Nardo and Di Natale 2011) and, consequently, water demands. WNP changes the hydraulic behaviour because, in principle, it is in conflict with the traditional design criteria of looped water networks that allow water systems to be more reliable under mechanical and hydraulic failure conditions (Mays 2000). The main design criterion is the pipe redundancy that markedly improves the network reliability, which can be significantly reduced by pipe closures, which is necessary to obtain permanent WNP, because it reduces the network reliability, especially during peak demands, diminishing the service level for users.

Water network partitioning may then alter the general and partial hydraulic performance of the water system; thus, the design of network districts should be done by experts and with the aid of simulation software, especially for extensive water supply system analysis, to compare different possible solutions.

Traditional network DMA design is based on empirical suggestions (number of properties, length of pipes, etc.) and on approaches such as “trial and error”, even if it is used in combination with hydraulic simulation software, as reported in some studies (Water Authorities Association and Water Research Centre 1985; Water Industry Research Ltd 1999; Butler 2000;

Twort et al. 2000). These indications and procedures are very difficult to apply to large water supply systems, and only recently have some techniques based on different approaches (graph theory, multi-agent, clustering and graph partitioning) been proposed to improve the design of water network partitioning.

With reference to the graph theory approach, only recently were some techniques specifically developed to address water network partitioning problems; Ostfeld and Shamir (1996) introduced the concept of a water network *backup subsystem* to define a subset of system links where a prescribed level of service is maintained when failure occurs. Tzatchkov et al. (2006) subsequently suggested an algorithm derived from graph theory to identify the independent supply sectors (or districts) of a network layout based on the *Last-In-First-Out (LIFO) stack approach*. More recently, Giustolisi and Savic (2010) described an algorithm for identifying the association between valves and "isolated segments" (or sectors) based on the use of the topological matrices of a network, whose topology is modified to account for the existence of the valve system, and on the use of a genetic algorithm for minimising the number of isolation valves and the maximum total undeliverable demand. A heuristic Design Support Methodology (DSM) was later proposed by Di Nardo and Di Natale (2011) for partitioning a water supply system in DMAs. This DSM, based on graph theory, the use of energy indices and research on minimum energy paths, which are computed from each reservoir to each node in a water network, allows the definition of the optimal districts. Another Decision Support System (DSS), which was proposed recently by Gomes et al. (2012a) and is based on graph theory concepts, some user-defined criteria and a simulated annealing algorithm, allows the identification of the optimal number and location of entry points and boundary valves and the determination of pipe reinforcement/replacement necessary to meet the velocity and pressure requirements. The proposed technique was also optimised for the implementation of pressure management (Gomes et al. 2012b). Both DSSs are not completely automatic, and some choices have to be made by the operators during the design process that show a strong heuristic approach, which could limit their use in water utilities. Recently, two techniques for water network sectorisation have been proposed, based on different heuristic optimal procedures: the first one used a Depth First Search algorithm (Di Nardo et al. 2013c), while the second one used the minimum Dissipated Power Paths (Di Nardo et al. 2013b), and both were coupled with a genetic algorithm.

Then, with reference to the second approach, Izquierdo et al. (2011) recently proposed an original procedure based on a multi-agent approach to define the DMAs of a water supply network in which each agent is a consumption node with a number of associated variables (elevation and demand are the most important) to obtain different WNP scenarios. A spectral clustering technique was proposed by Herrera et al. (2010) to partition a water supply network using dissimilarity matrices (transformed into weighted kernel matrices) obtained with graphical and vector information (pipes, demand nodes and water constraints).

Finally, graph partitioning techniques have been used for water network partitioning; specifically, Sempewo et al. (2008) and Tzatchkov et al. (2012) both proposed similar procedures for the optimal demarcation of water networks into zones based, respectively, on balancing length, demand or flow within zones and on the shortest paths from each water source to each network node computed by minimising the time water travels in the network pipes before being supplied. Nevertheless, neither methodology uses performance indices to compare different WNPs, nor do they provide information about hydraulic degeneration of the water system due to the insertion of gate valves.

In this paper, following the paradigm of "*divide and conquer*", an original approach for an automatic WNP of a smart water network is proposed based on some graph partitioning techniques commonly applied in distributed computing (Chevalier and Safro 2009) and on an energy approach that allows the identification of the optimal partitioning of a water network.

The proposed methodology is based on the likeness between a computational mesh network and a water supply network. More specifically, the similarity is between the design objectives of a parallel Computational Network Partitioning (CNP) and a water network partitioning, including the following:

a) workload balancing by partitioning tasks for a distributed computation in a CNP compared with flow balancing by partitioning of a WNP into different districts;
b) the minimisation of communications between partitions in a CNP that corresponds to the minimisation of pipe closures in a water network partitioning;
c) dimensioning and mapping of partitions on the computing elements of a CNP according to different features related to network topologies, bandwidths or computing power, which is similar to geographic mapping of nodes to water districts according to network topology or territorial boundaries.

The methodology was tested on a real Italian water supply network and was integrated into a tool that, given a number of DMAs, automatically identifies the best WNP by evaluating some performance indices.

2 Materials and Methods

Graph partitioning is a computer science technique that was developed to solve problems that require huge computational power, such as simulations based on finite element methods that require the distribution of a finite element mesh among different processors.

To improve performance, this distribution must be made according to two main rules: 1) an equal number of finite elements must be allocated to each processor to balance the workload; and 2) a minimum number of adjacent elements between processors has to be found to reduce communication overhead.

This problem can be compared to partitioning a computational mesh in k-ways or into k-processors that will each perform computational processes. The mesh is commonly schematised by a graph with vertices that correspond to individual computational processes (i.e., finite elements) and with links that correspond to their connections. Therefore, graph partitioning techniques were developed in computer science for the optimal allocation of a computational mesh in parallel or distributed computing architectures.

Consider a simple graph $G=(V, E)$, where V is the set of n vertices (or nodes) and E is the set of m edges (or links). A k-way graph partitioning problem consists of partitioning V vertices of G into k subsets, $D_1, D_2, \ldots, D_k$ such that $D_i \cap D_j=0$ for $i \neq j$, $|D_i|=n/k$ and $\cup_i D_i=V$.

Recently, some Multi Level Recursive Bisection (MLRB) algorithms have been proposed as highly effective methods of computing a k-way partitioning of a graph (Karypis and Kumar 1998a, b; Safro et al. 2010). MLRB techniques are essentially based on the following phases, which are schematically illustrated in Fig. 1 and synthetically described below: a) coarsening; b) partitioning; and c) uncoarsening (also with refinement).

The *coarsening* phase simplifies the original graph $G_0=(V_0, E_0)$ through a node aggregation that generates a sequence of smaller graphs $G_i=(V_i, E_i)$, each with fewer vertices such that $|V_i|<|V_{i-1}|$. Each graph G_{i+1}, obtained by the aggregation of the adjacent vertices of G_i that creates a new vertex v (also called a *multinode*), is called a *coarser graph*. In this way, the edge that connects adjacent vertices collapses; this idea was formally defined by Bui and Jones (1993) in terms of *matching* a graph. Figure 2 shows two types of matching: a) a

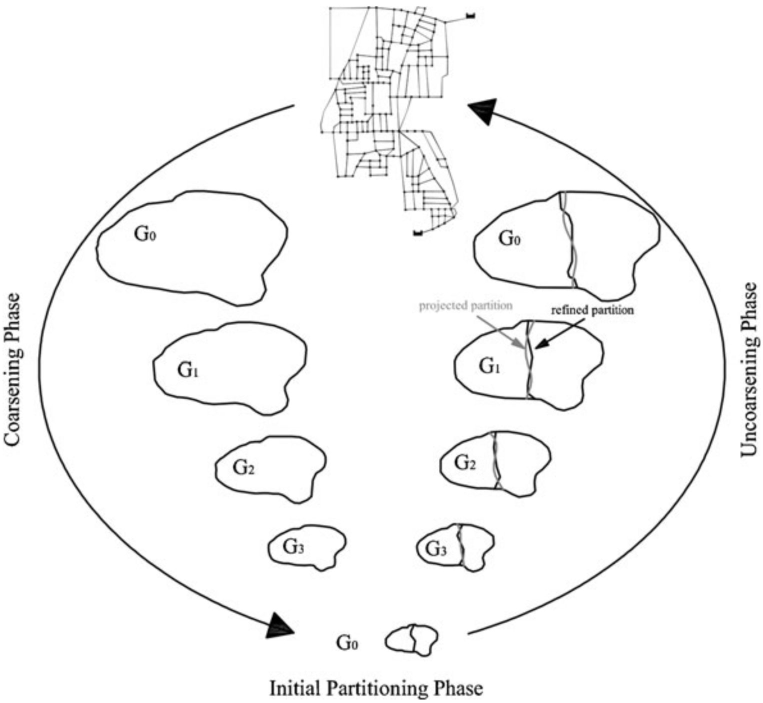

Fig. 1 Different phases of an MLRB graph partitioning algorithm

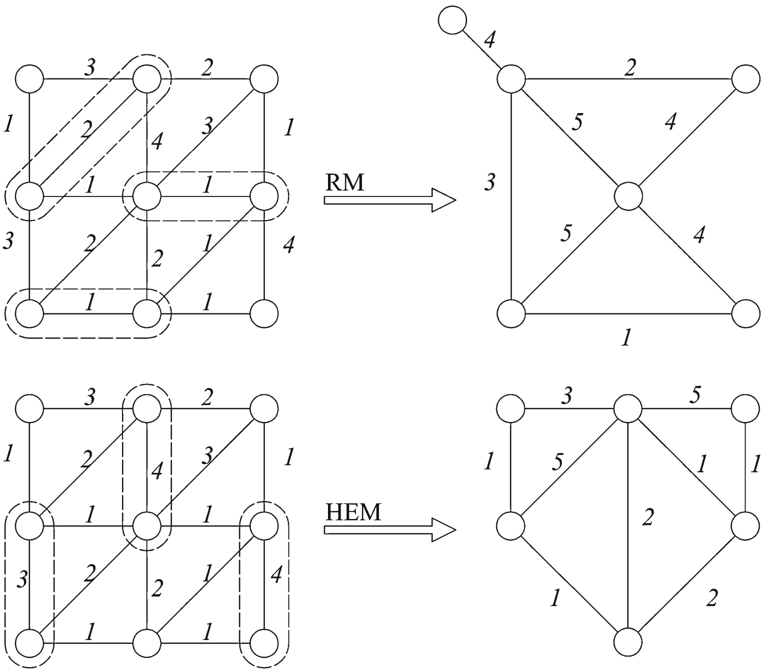

Fig. 2 Two different matching techniques: Random Matching (RM) and Heavy Edge Matching (HEM)

random matching (RM) along with the coarsened graph, that results from collapsing together vertices incident on every matched edge, and b) a heavy-edge matching (HEM) that tends to select edges with higher weights (Karypis and Kumar 1998a). Thus, the next level of a coarser graph G_{i+1} is constructed from G_i by finding a match of G_i and collapsing the matched vertices into multinodes. This phase is essential in order to reduce the dimensions, in terms of vertices and edges, of a graph and, consequently, to reduce the complexity of finding a k-way partitioning. The best node aggregation (or collapsing) technique (two of them are schematically illustrated in Fig. 2) is the one that best maintains the connectivity of the original graph (Karypis and Kumar 1998a).

The next phase of an MLRB technique is to find a k-way partitioning by recursive bisection. First, G_i is subdivided into 2-way partitions, and then each part is further subdivided into 2-way partitions or bisections. Thus, a k-way partition can be solved by performing a sequence of 2-way partitions. In this phase, an optimisation procedure must be used to obtain a partitioning with the minimum number of edges $N_{ec} = \sum_{i\in D_p \Rightarrow j\notin D_p} e_{ij}$ (with e_{ij} called the edge-cut that connects vertices in different partitions and with D_p being a generic subset with $1 \leq p \leq k$) and with a balance of the number of vertices n_p belonging to each subset, with the optimal limit condition of $n_p = n/k$.

In the cases where the vertices and edges have associated weights (weighted graph), respectively indicated with positive weight ϖ_i, with $i \in V$, and non-negative weight ε_{ij}, with $ij \in E$ and $\varepsilon_{ij}=0$ if $ij \notin E$, the goal is to partition the vertices into k disjoint subsets such that the sum of the edge-weights, whose incident vertices belong to different subsets $W_\varepsilon = \sum_{i\in D_p \Rightarrow j\notin D_p} \varepsilon_{ij}$, is minimised and the sums of the vertex-weights $W_\varpi = \sum\limits_{i\in D_p} \varpi_i$ in each D_p are the same.

Then, the Objective Function (OF) of a k-way graph partitioning can be formalised by *minimising* the number of edge-cuts e_{ij} or of associated weights ε_{ij}, expressed by the following relationship:

$$\mathrm{OF} = \min(N_{ec}) \;\; or \;\; \min(W_\varepsilon) \tag{1}$$

Equation (1) has to be obtained by balancing the number of vertices n_p or the associated weights ϖ_p for each subset. This constraint is achieved by *minimising* the *balance index* I_B:

$$\min\left(I_B = \frac{k \cdot \max\left(d_p\right)}{n}\right) \tag{2}$$

where max (d_p) can be the size of the largest subset n_p or the maximum weight ϖ_p obtained by the k-way partitioning algorithm.

Finally, Fig. 1 represents the *uncoarsening* phase, which typically consists of two steps: a) a projection from the coarser graph G_m back to the original graph G_0 by going through the graphs G_{m-1}, G_{m-2}, . . ., G_1 (*uncoarsening*) assigning the matched vertex of the previous level G_m to each multi-node v of G_{i+1} and b) a local optimisation of the partition (*refinement*).

The second step is very important for improving the partition; indeed, even if the partitioning of G_i is at a local minimum, the projected partitioning of G_{i-1} may not be at a local minimum. Hence, it may still be possible to improve the projected partitioning of G_{i-1} using local refinement heuristic algorithms (Kernighan and Lin 1970; Fiduccia and Mattheyses 1982; Hendrickson and Leland 1993), thus decreasing the edge-cuts (or total weights) by moving a vertex from one partition to another and maintaining compliance with the constraint of relationship (2).

A water supply network can be easily represented by a graph in the form $G=(V, E)$ in which V corresponds to n nodes and E corresponds to m pipes of a water system.

The proposed methodology, which is illustrated for each step in the flow chart of Fig. 3, has been implemented in an original tool developed by the authors that integrates METIS (Karypis and Kumar 1998c), EPANET2 (Rossman 2000) and a heuristic optimisation procedure in a unique Phyton framework.

Starting from the network model as an input (with node water demand distribution Q_i, with $i=1..n$; source heads H_s, with $s=1..r$ reservoir; pipe length L_{ij} and node elevations z_i), the pipe flow q_{ij}, node heads h_i and head loss ΔH_{ij} for each pipe can be calculated by a Demand Driven Approach (DDA) (Rossman 2000) or by a Pressure Driven Approach (PDA) (Giustolisi et al. 2008). Then, after the hydraulic simulation (step a) has been carried out in the peak demand condition (Di Nardo and Di Natale 2011), and once the number k of DMAs of the water network has been chosen (step c), a MLRB technique can be applied to find a k-way partitioning.

To obtain the best results, the methodology can be performed with different weights ϖ_i for the vertices and ε_{ij} for the links using the geometric and hydraulic properties of the network, specifically pipe flow, dissipated power or diameters for the edges and water demand for the vertices (steps b1-b3).

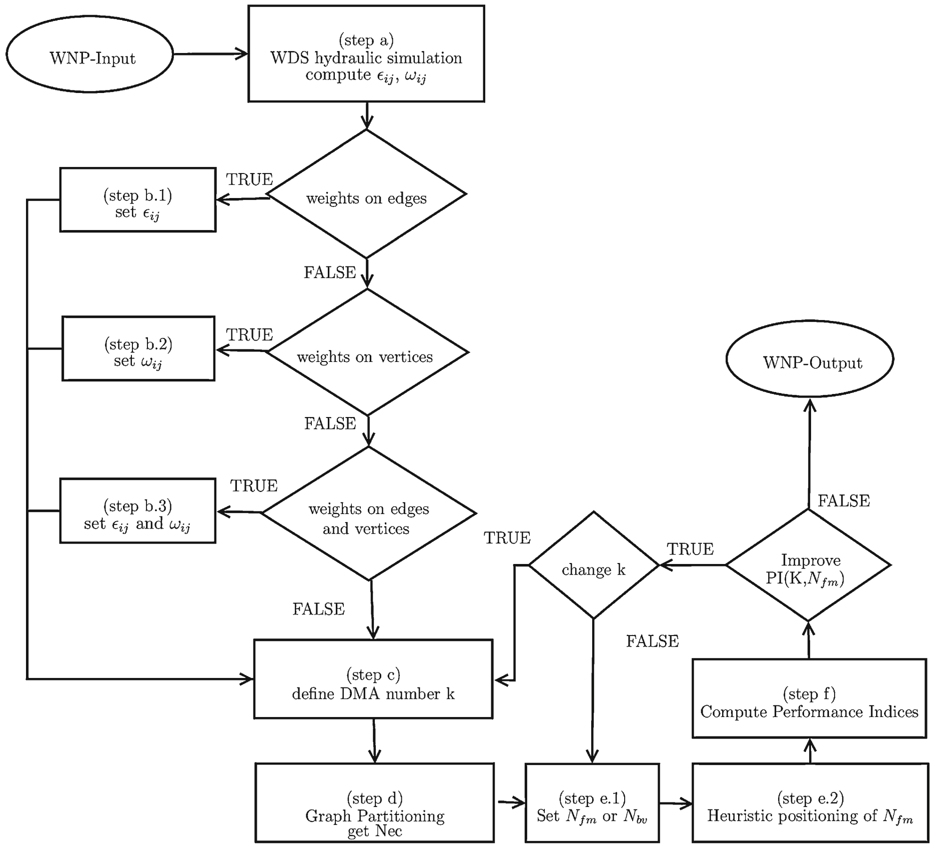

Fig. 3 Flow chart of automatic tool for WNP

Then, once the set N_{ec} of the edge-cuts (or *boundary pipes*) is obtained that is compliant with relationship (1), it is necessary to choose how many and which of these boundary pipes must be closed with N_{bv} gate valves or, equivalently, must be used for installing N_{fm}=(N_{ec}-N_{bv}) flow meters (step e1). In other words, for k assigned districts, after finding the possible positions e_{ij} for the flow meters and boundary valves by a graph partitioning technique (step d) and choosing the number of N_{fm} and N_{bv}, it is necessary to define which pipes have to be closed between all of the possible combinations of WNP layouts N_c expressed by the binomial coefficient

$$N_c = \binom{N_{ec}}{N_{fm}} \tag{3}$$

Therefore, once the number of flow meters N_{fm} was fixed, an optimisation technique was developed to find the best solution of which pipes to insert gate valves into by minimising the following Objective Function:

$$\min\left(P_D = \sum_{j=1}^{m} P_{Dj}\right) \tag{4}$$

where P_D is the total dissipated power of the network and P_{Dj} is the dissipated power in each j-th pipe (or edge). This phase was achieved by a novel heuristic procedure carried out with a Genetic Algorithm (GA) (Goldberg 1989) developed by the authors. The GA allows the determination of the optimal position of each flow meter in the network by inserting gate valves in the pipes that belong to the *edge-cut* set. Specifically, the minimisation of Eq. (4) was carried out with the help of the Genetic Toolbox of MATLAB©.

In particular, each individual of genetic algorithm is composed of a sequence of chromosomes corresponding to the number of pipes belonging to the set N_{ec}. Each chromosome assumes a value of 1 if a gate valve will be inserted in the j-th pipe; otherwise, the value is 0 if a flow meter will be inserted. The GA was carried out for n=30 generations with a population composed of 100 individuals with a crossover percentage equal to P_{cross}=80 % and a mutation rate equal to P_{mut}=2 %.

Therefore, after defining the optimal positions of flow meters (or the complementary positions of gate valves) (step e.2), it is possible to compute (step f) the Performance Indices (PI). Three categories of PIs have been used to test different sectorisation layouts using both a Demand Driven Approach and a Pressure Driven Approach: a) *energy indices*, measured by the resilience index I_r (Todini 2000), based on the comparison between the dissipated power and the maximum power necessary to satisfy the node demand constraints, and the resilience deviation index I_{rd}, proposed by Di Nardo and Di Natale (2011) and Di Nardo et al. 2013d), based on the comparison among the resilience indices of the original and sectorised networks; b) *pressure indices*, traditionally measured by mean node pressure h_{mean}, maximum node pressure h_{max}, minimum node pressure h_{min} and standard deviation pressure h_{sd}; and c) the *flow deficit index* computed only for the PDA approach because in the DDA approach, it is obviously always equal to 1.00:

$$I_{fd} = \frac{\sum_{i=1}^{n} \alpha_i Q_i}{\sum_{i=1}^{n} Q_i} \begin{cases} Q_{a,i} > \ Q_i \Rightarrow \alpha_i = \ 1 \\ 0 \le Q_{a,1} \le Q_1 \Rightarrow \alpha_i = \dfrac{Q_{a,i}}{Q_i} \end{cases} \tag{5}$$

where $Q_{a,i}$ represents the actual demand delivered in the PDA approach.

In this way, as illustrated in the flow chart in Fig. 3, by iteratively changing the number of k DMAs or reducing the number of flow meters N_{fm}, a WNP can be chosen according to the desired level of service for the users.

3 Case Study

To validate the proposed approach, the tool was applied to a real water system already used by the authors in other studies, the Villaricca network (Di Nardo and Di Natale 2012), with 30,000 inhabitants in a densely populated area north of Napoli (Italy). The Original Water Network (OWN) has, with a demand driven approach, h_{mean}=36.54 m, h_{max}=45.94 m, h_{min}=25.12 m and h_{sd}=3.68 m and a low resilience index I_r=0.369 while, with a pressure driven approach, h_{mean}=36.58 m, h_{max}=45.95 m, h_{min}=26.56 m, h_{sd}=3.64 m, I_r=0.376 and I_{fd}=0.997.

The network was modelled using EPANET2, as reported in Fig. 4a, and the main hydraulic characteristics are reported in Table 1.

Both networks have low values of the resilience index, which shows a "low availability" of the water system to be partitioned or, in other words, to change its original layout by the insertion of gate valves without a decrease in hydraulic performance. This idea may be expressed by robustness, i.e., the capability of a system to maintain given performance levels in the presence of unfavourable variations in operating conditions (e.g., closure or bursting of a pipe, etc.). Because the resilience can be used as a proxy for measuring robustness (Greco et al. 2012), i.e., the higher is the value of I_r of a network, the larger the capability of the water system to accommodate a change of the network layout, it is possible to consider that the Villaricca network has low robustness and low inclination to be sectioned. Therefore, for these case studies, it is more difficult to find a water network partitioning compatible with hydraulic performance with only the use of traditional approaches based on empirical suggestions and only simulation techniques.

A preliminary analysis carried out with both the DDA and PDA approaches was finalised to find the best effective weights to use in the MLRB algorithm for graph partitioning a water system. Then, some WNPs for the case study were obtained considering different combinations of weights of edges (ε_{ij}) and of both edges and vertices (ε_{ij}, ϖ_i), which were identified with labels from VA1 to VD3.

4 Results

The simulation results are reported in Tables 2, 3, 4 and 5 in which the number of districts k, the number of edge cuts N_{ec}, the number of flow meters N_{fm}, the number of the boundary valves N_{bv}, the number of nodes n_d for each DMA, the values of balance index I_B and all performance indices illustrated in the previous section are reported.

A preliminary analysis for Villaricca was carried out with the same choice of k=5 DMAs, and the same number N_{fm}=6 of flow meters for each combination of weights was used to obtain a water network partitioning. In the 2nd column of Table 2, the simulation results of WNP VA1 (performed with a DDA approach), obtained with graph partitioning without any weights, are listed. In this first case, the resilience index, although lower than the value of I_r for the OWN before partitioning, has a small relative deviation equal to I_{rd}=10.03 %. Then, the node number for each water district is practically balanced with I_B=1.02; indeed, each DMA includes 38, 39 or 40 nodes. In this case, without weights for the vertices, the balance index I_B is computed only with the maximum size of the largest subset n_p=40 of DMA 2, as indicated in (2).

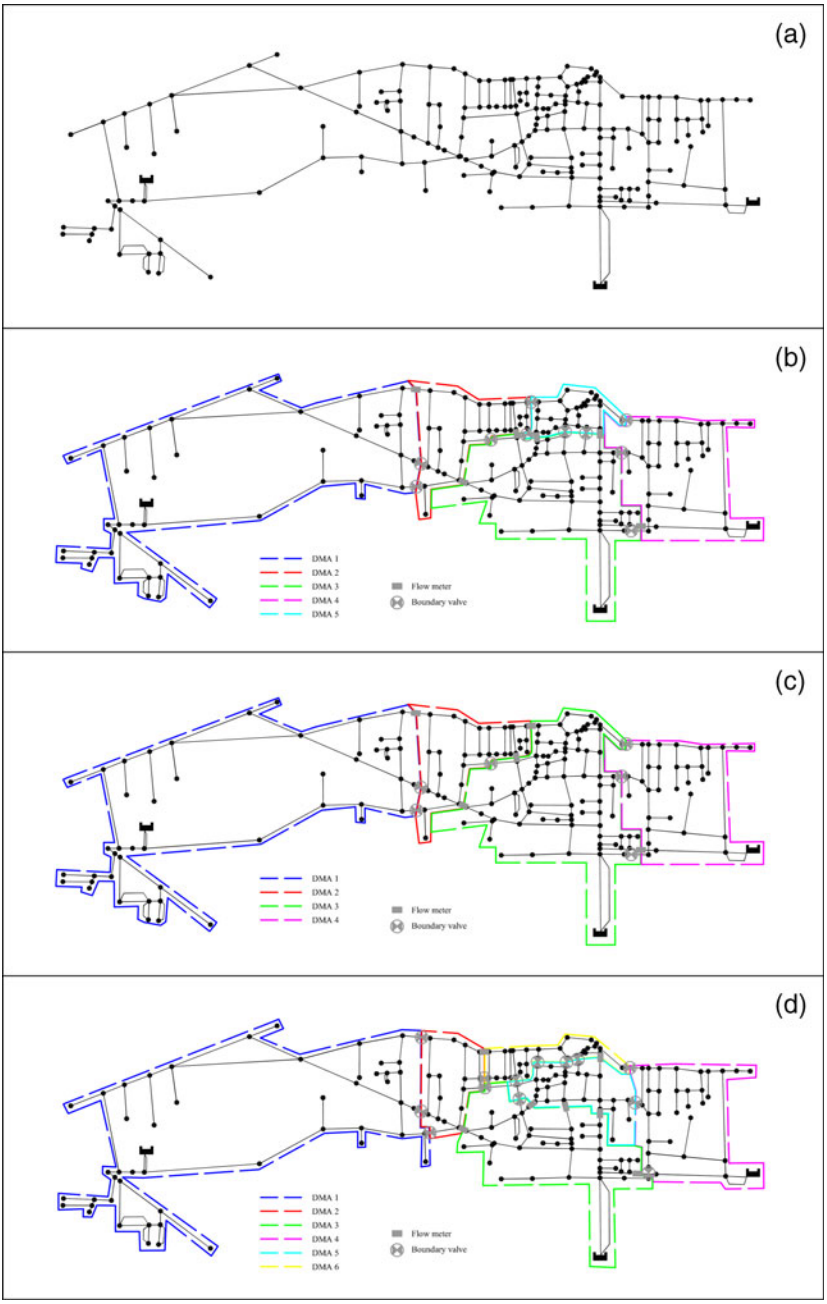

Fig. 4 Villaricca Original Water Network (OWN) and Water Network Partitioning (WNP) for 4 DMAs (VF1), 5 DMAs (VD2) and 6 DMAs (VE2)

Table 1 Main characteristics of hydraulic networks

Number of nodes, N	199
Number of links, N_L	249
Number of reservoirs, N_R	3
Hydraulic head of reservoirs [m]	155.0; 156.0; 156.0
Total pipes length, L_{TOT} [km]	36.0
Minimum ground elevation, z_{MIN} [m]	103.8
Maximum ground elevation z_{MAX} [m]	122.0
Pipes materials	Cast iron and steel
Pipes diameters [mm]	80; 90; 100; 110; 150; 200; 300
Peak demand, Q [m^3/s]	0.208
Design pressure head, h^* [m]	30
Network resilience, I_r	0.369 (DDA) and 0.376 (PDA)

This first encouraging result was significantly improved by using the edge weights, as shown in the 3rd, 4th and 5th columns of Table 2, which report the simulation results for different edge weights ε_{ij}, equal to the pipe flow q_{ij} (VB1), the dissipated power $q_{ij}{\cdot}\Delta H_{ij}$ (VB2) and the pipe diameter D_{ij} (VB3), respectively.

The best performance indices corresponded to the simulation with the edge weights equal to the dissipated power with an excellent value of I_{rd} equal to 6.78 % and with a balance index I_B=1.28 (as reported in Table 3) that indicates a different number of nodes for each DMA.

The simulation results reported in the 6th column of Table 2 were achieved considering only vertex weights equal to Q_i (VC1); they essentially confirm the same results obtained without any weight with a worsening of the balance index to 1.09. In the cases with weights assigned to vertices, the index I_B is computed with a maximum weight ϖ_p equal to $\sum_{i\in D_p} Q_i$, as indicated in (2). The weight on the vertex can be very useful for the operators when they are interested in having districts with the same total water demand and not simply with the

Table 2 Characteristics of a WNP with 5 DMAs obtained with different edge and vertex weights

	No weight	Edge weights ε_{ij}			Vertex edge ω_i	Edge and weights ε_{ij} and ω_i		
	–	q_{ij}	$q_{ij}{\cdot}\Delta H_{ij}$	D_{ij}	Q_i	Q_i AND q_{ij}	Q_i AND $q_{ij}{\cdot}\Delta H_{ij}$	Q_i AND D_{ij}
WNP	VA1	VB1	VB2	VB3	VC1	VD1	VD2	VD3
k	5							
n_1	38	31	29	37	47	49	48	47
n_2	40	47	50	40	33	50	32	35
n_3	39	35	43	40	40	35	29	33
n_4	40	46	45	46	33	39	54	43
n_5	39	37	29	33	43	23	33	38
N_{ec}	16	22	24	18	17	19	16	18
N_{fm}	6	6	6	6	6	6	6	6
N_{bv}	10	16	18	12	11	13	10	12
I_B	1.02	1.20	1.28	1.17	1.09	1.12	1.43	1.02

Table 3 Comparison of DDA and PDA performance indices of a WNP with 5 DMAs

WNP	VA1	VB1	VB2	VB3	VC1	VD1	VD2	VD3
a) DDA simulation results (Ir=0.369)								
I_r	0.332	0.256	0.344	0.258	0.328	0.132	0.363	0.262
I_{rd} [%]	10.03	30.73	6.78	30.08	10.89	64.20	1.38	28.94
h_{min} [m]	21.89	7.83	24.12	23.80	24.69	20.55	25.18	21.67
h_{mean} [m]	36.09	29.30	36.28	34.94	35.86	32.70	36.52	35.31
h_{max} [m]	47.36	45.38	47.80	45.02	46.05	44.34	46.70	45.03
h_{sd} [m]	4.19	10.79	4.44	4.87	4.09	6.78	3.87	3.95
b) PDA simulation results (Ir=0.376)								
I_r	0.349	0.145	0.357	0.273	0.339	0.196	0.371	0.273
I_{rd} [%]	7.25	61.31	5.04	27.43	9.95	47.91	1.29	27.46
I_{fd}	0.995	0.954	0.997	0.994	0.996	0.981	0.997	0.995
h_{min} [m]	24.77	17.38	26.57	25.70	26.32	23.04	26.64	23.59
h_{mean} [m]	36.19	32.06	36.27	35.07	35.94	33.54	36.56	35.39
h_{max} [m]	47.36	45.62	46.69	45.02	46.07	44.35	46.69	45.04
h_{sd} [m]	4.07	7.68	3.79	4.78	4.03	5.94	3.83	3.91

same number of nodes. This balance constraint can be very helpful for water utilities in searching for leaks because using the weight Q_i would make it possible to compare DMAs that provide the same total water demand to the users.

Finally, in the 7th, 8th and 9th columns of Table 2, the simulation results obtained considering different pair of values of ε_{ij} and ϖ_i are reported. In these cases, excellent results can be observed for the coupled weights, dissipated power $q_{ij}\cdot\Delta H_{ij}$ and water demand Q_i (VD2); indeed, as reported in Table 3, the index of resilience deviations I_{rd}=1.38 % was significantly lower than the result obtained with only edge weight $q_{ij}\cdot\Delta H_{ij}$ (I_{rd}=6.78 %).

Table 4 Characteristics of WNPs with 4 and 6 DMAs obtained with different edge and vertex weights

	Edge weights ε_{ij}		Edge and weights ε_{ij} and ω_i	
	$q_{ij}\cdot\Delta H_{ij}$		Q_i *AND* $q_{ij}\cdot\Delta H_{ij}$	
WNP	VE1	VE2	VF1	VF2
k	4	6	4	6
n_1	56	29	48	25
n_2	46	41	32	39
n_3	65	30	83	32
n_4	29	30	33	35
n_5	–	50	–	36
n_6	–	16	–	29
N_{ec}	17	20	11	24
N_{fm}	5	7	5	7
N_{bv}	12	13	6	17
I_B	1.33	1.53	1.75	1.14

Table 5 Comparison of DDA and PDA performance indices of WNPs with 4 and 6 DMAs

WNP	VE1	VE2	VF1	VF2
a) DDA simulation results (Ir=0.369)				
I_r	0.350	0.339	0.364	0.293
I_{rd} [%]	5.18	8.18	1.25	20.68
h_{min} [m]	24.63	27.96	25.19	23.60
h_{mean} [m]	36.31	36.18	36.53	35.48
h_{max} [m]	46.85	47.22	46.70	47.79
h_{sd} [m]	4.02	4.29	3.88	5.09
b) PDA simulation results (Ir=0.376)				
I_r	0.359	0.341	0.372	0.317
I_{rd} [%]	4.49	9.23	1.17	15.63
I_{fd}	0.996	0.998	0.997	0.992
h_{min} [m]	26.24	28.18	26.64	24.96
h_{mean} [m]	36.37	36.19	36.58	35.73
h_{max} [m]	46.85	47.22	46.69	47.80
h_{sd} [m]	3.96	4.28	3.83	4.84

From Table 3, it can be observed that half of the WNPs have a change in the resilience index of less than 11 %, including the WNPs with large numbers of boundary valves up to N_{bv}=18. These good results are also confirmed by the pressure performance indices h_{mean}, h_{max}, h_{min} and h_{sd}, which have values slightly lower than the original pressure values, as reported in Table 3.

Therefore, for the case study of the Villaricca network, the proposed methodology allows the operator to very quickly find the WNPs that are compatible with the level of service for the users, even with network layouts that change significantly from the original layout of the water system.

In Table 3, the simulation results obtained with a PDA approach are reported; also in this case, the best values of PIs correspond to WNP VB2 (I_{rd}=5.04 %) and VD2 (I_{rd}=1.29 %) with a negligible deviation of I_{fd}=0.997, practically equal to the OWN, in both cases. This result shows that the proposed methodology is also very effective in a Pressure Driven Analysis, allowing a network partitioning that does not significantly reduce the node pressure, as also indicated by the pressure indices, which have values almost equal to those computed with a Demand Driven Analysis.

Similar considerations can be found for the simulation results reported in Tables 4 and 5, which have been carried out for different choices of the number of DMAs, with k=4 and k=6 (reported in the 2nd and 4th columns and the 3rd and 5th columns, respectively). In the case of 4 DMAs, the results are excellent with practically negligible changes in all performance indices for WNP VF1 with 4 DMAs (I_{rd}=1.25 %, h_{min}=25.19 m) and very good agreement for WNP VE2 with 6 DMAs (I_{rd}=8.18 %, h_{min}=27.96 m), as reported in Table 5.

In the case with k=6 DMAs, which is obviously a more significant alteration of the network layout with up to N_{bv}=17 boundary valves, the simulation results for a WNP obtained with a pair of weights (VF2) are discrete, with I_{rd}=20.68 % and h_{min}=23.60 m. These results, which are better in the case with only edge weights (VE2) than in the case with edge and vertex weights (VF2), can be explained by considering that, in increasing the number k of DMAs, the balance constraint (2) tends to strongly counteract the minimisation of the objective function (1).

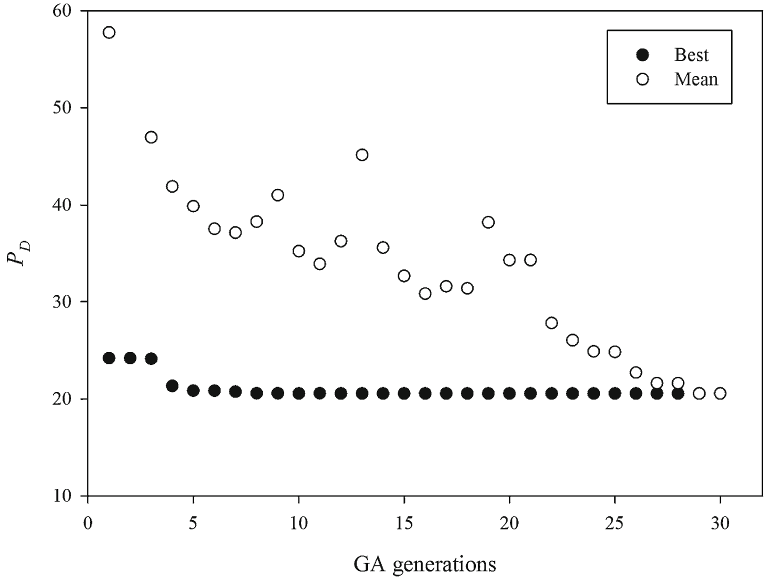

Fig. 5 Relationship between P_D^{bv} and number of GA generations for Villaricca WNPs with 5 DMAs

Indeed, in Table 4, it is possible to observe the inverse behaviour of the balance index, which is better in the 4th column with I_B=1.14 and worse in the 2nd column with I_B=1.53.

The analyses with 4 and 6 DMAs are also carried out with a PDA approach, as reported in Table 5; in this case, the simulation results are similar to the ones previously obtained with a DDA approach, with the best values of I_{rd}=1.17 % for 4 DMAs (VF1) and to I_{rd}=9.23 % for 6 DMAs (VE2), which is also confirmed by the I_{fd} index. The effectiveness of the methodology is also confirmed by comparing the results obtained by the authors here with a different methodology; indeed, in Di Nardo and Di Natale (2011), the best WNPs of Villaricca were I_{rd}=7.25 % (4 DMAs), I_{rd}=7.92 % (with 5 DMAs) and I_{rd}=13.21 % (6 DMAs), which are significantly worse than the results reported in the current study.

In contrast to the previous study's methodology, where some choices must be made by the operators during design process, this new methodology based on graph partitioning and heuristic procedure is completely automatic. Finally, the original network layout of Villaricca and the best WNPs obtained with the proposed methodology for k=4, 5 and 6 DMAs with I_{rd}= 1.25 % (VF1, Fig. 4b), I_{rd}=1.38 % (VD2, Fig. 4c) and I_{rd}=8.18 % (VE2, Fig. 4d), respectively, are reported in Fig. 4.

It is important to specify that the results shown in Tables 2, 3, 4 and 5 were obtained using the heuristic optimisation procedure based on GA, as previously explained. Specifically, the effectiveness of the proposed approach is shown in Fig. 5 with k=5 DMAs in which the best and main value of objective function for each generation is illustrated with a dot: it is possible to observe that, after 20–30 generations, the proposed GA is able to rapidly find a good solution.

5 Conclusions

A novel methodology that allows the definition of an optimal water network partitioning compatible with the level of service required by the users was presented. It is based on graph partitioning techniques, which are commonly applied for workload balancing in distributed computing, hydraulic simulation, which is frequently used in water resource management, and a heuristic optimisation approach that uses network energy considerations.

An original Phyton framework was developed to apply the described methodology to a real case study and to validate the effectiveness by using suitable performance indices. Simulations were performed, comparing different combinations of weights associated with the edges and vertices of a network graph in order to find the best weight conditions for use in the Multi Level Recursive Bisection algorithm. Then, the methodology was tested with different numbers of DMAs (from 4 to 6) to compare the effects of some WNPs on hydraulic performance.

The simulation results obtained for the real case study of the Villaricca network showed that the dissipated power is the best weight for the edges and the water demand is the best weight for the vertices. Excellent results were obtained using weights for both the edges and vertices.

The developed tool can easily be applied to large networks to support the design of a WNP that overcomes the traditional empirical approaches used by water utility companies.

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