Divide and conquer partitioning techniques for smart water networks

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Abstract

Inserting remote control valves in a water distribution system allows the implementation of the “divide and conquer” paradigm that consists in dividing a large network into smaller subsystems, also called water network partitioning (WNP), for applying water balance, pressure control and water quality protection. Some heuristic procedures, based on different techniques (graph theory, clustering, graph partitioning, etc.), have been proposed recently for finding optimal WNP solutions. The authors developed a software, named SWANP (Smart WAter Network Partitioning), that allows to find automatically the optimal partitioning layout. In this paper, a first comparison is presented between SWANP and other procedures.

Keywords: Water network partitioning, District meter areas, graph theory, water leakage, smart water networks

1. Introduction

The development of new monitoring and control technologies and the recent growth of computational power used by simulation software have changed the traditional approach to analysis, design and management of Water Distribution Systems (WDS), from passive to smart actions, allowing the transformation of urban WDS in Smart WAter Networks (SWANs).

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1877-7058 © 2014 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the Organizing Committee of WDSA 2014.
This new approach, based on the use of control devices and Hydroinformatric techniques, allowed to division of water networks in subsystems implementing the paradigm of “divide and conquer” in SWANs [1]. This approach, defined also as Water Network Partitioning (WNP), allows improving the management of water distribution systems with reference to some important issues as water balance [2, 3], water pressure management [4] and water quality protection [5, 6]. WNP can be applied with greater effectiveness defining smaller permanent network subsystems, called District Meter Areas (DMAs) obtained by the insertion of gate valves and flow meters. The traditional criteria for the design of network DMAs are based on empirical suggestions (such as recommended number of properties or length of pipes per district, etc.) and on ‘trial and error’ approaches used with hydraulic simulation software [7]. Nevertheless these indications, the procedures are very difficult to apply to large water supply systems because the insertion of gate valves modifies the original network layout and may worsen the hydraulic performance of the water network. Indeed WNP changes the hydraulic performance [1] because it is in conflict with the traditional design criteria of pipe redundancy that markedly improves the network reliability, which can be significantly reduced by pipe closures, which are necessary to obtain permanent DMA.

In the last years different procedures have been proposed in the literature (a review is given in [1] and [8]) for finding an optimal network partitioning based on breadth and depth first search [8, 9, 10, 11, 12, 13], multilevel partitioning [1, 4], community structure [14], clustering [9, 15] and multi-agent [16, 17, 18]. Iterative procedures [10, 14] or genetic algorithms [1, 18] have been proposed for placement of flow meters and boundary valves. The effort of this preliminary study was to compare three procedures, based on different approaches, with another one, recently implemented by the authors in the SWANP software [19].

2. Water network partitioning

The procedures tested are based on different approaches 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). The general aim of the partitioning phase of each of the procedures is to minimize the number $N_{vc}$ of edge-cuts (links between the districts) with a constraint on the number of nodes that belong to each district. If the edges and vertices of the graph are weighted, the goal becomes to minimize the sum of associated weights on the edge-cuts and to balance the sum of node weights for each districts. The selection of edge cuts in which to insert boundary valves $N_{bv}$ or flow meters $N_{fm}$ is not provided by each procedure because, in some cases, the gate valves are then inserted in all edge pipes defining a Water Network Sectorization (WNS), as defined in [12].

The four techniques compared in this paper are synthetically described in the sections below but, for a detailed description of each algorithm, it is evidently necessary to refer to the papers in which they have been published.

2.1. Multi-agent simulation

The Multi Agent Simulation (MAS) framework, proposed by Hajebi et al. [17], is a two-step algorithm to solve the partitioning of the WDS into DMAs. The first step uses a k-means graph clustering algorithm [20] to partition the network geographically into a prefixed number of cluster or districts. The $k$-means algorithm is an unsupervised learning method for discovering cluster and cluster centers in a set of unlabeled data. It begins with choosing at random $k$-objects which represent, at first run, the cluster centers; then it assigns all the remaining objects to the nearest cluster centers. The process is repeated until convergence or after a finite numbers of trials. The second step applies a multi-agent system negotiation [17] to adjust the boundary nodes. The negotiation considers the difference of the elevation of the boundary nodes with the neighboring clusters. If the elevation is closer to that of the other cluster than to its current one, the boundary node is assigned to that cluster and the negotiation starts again for the new network arrangement. All boundary nodes are affected in a random sequence. The process stops when the total number of changes is less than a predetermined threshold number of changes. As reported in [17], the MAS is an heuristic algorithm and the optimal results for different runs may be different. This procedure, once found the optimal water network partitioning, does not provide a specific algorithm for the selection of pipes in which to insert flow meters or boundary valves.
2.2. Hybrid graph partitioning

The Hybrid Graph Partitioning (HGP) proposed by Ferrari et al. [10] combines two graph theory algorithms: the Kernighan-Lin (KL) [21] and the depth first search [22]. Specifically, the Kernighan-Lin is a bisection algorithm that divides a weighted graph with 2n nodes into two subsets, each of size n, minimizing the sum of its weights. It can be extended to the more general case of k-way partitioning by recursive bisection. The Depth First Search algorithm traverses the graph by visiting sequentially neighbor vertices, and is applied in order to verify the connectedness of the network each time in the bisection. Once found the optimal water network partitioning, HGP uses iterative procedures for the selection of pipes to be closed.

2.3. Water spectral clusters

The core of the Water Spectral Clusters (WSC), proposed by Herrera et al. [15] is a semi-supervised clustering algorithm. The starting point is building the affinity matrix for the WDS by assuming water demand as node weights and pipes diameter as edge weights. Then, other dissimilarity matrices, using different inputs and constraints about the water supply system, can also be built. In particular, other possible inputs are: geographic information of nodes, distance between nodes and node elevation, while a constraint is that each DMA is supplied by one or more water sources. Once defined the matrices of input information, they are transformed into a kernel matrix [23], which represents a synthesis of the WDS information data. Thus, starting from the information arranged in the kernel matrix, it is possible to apply the spectral clustering algorithm with the minimization of a Min Cut objective function in order to partition the WDS into the required number of DMAs. Also this procedure, once found the optimal water network partitioning, does not provide a specific algorithm for the selection of pipes to be closed.

2.4. SWANP

The Smart WAter Network Partitioning (SWANP) software is based on a Multi Level Recursive Bisection (MLRB) algorithm [24]. The authors proposed an original procedure [1] adjusting the traditional phases of a MLRB: a) coarsening; b) partitioning; c) uncoarsening; d) refinement with swapping. The k-way partition is recursively solved by performing a sequence of 2-way partitions (or bisections). Once defined, for each recursive bisection, in one go, all the boundary pipes, the MLRB optimizes the edge-cuts (refinement) moving a vertex from one partition to another (swapping) in compliance with the goals (minimization of the edge-cuts or associated weights) and constraints (balancing of the nodes or associated weights). Once defined by the MLRB procedure the links between districts (or the set of boundary pipes), a special Genetic Algorithm (GA) allows to choose heuristically the location of flow meters and gate valves. In addition, SWANP includes some performance indices to compare different layouts and to provide to operators a Decision Support System for choosing the best layout in compliance with the goal of WNP.

3. Results

The comparison between each procedure and SWANP was carried out using the same water network and the same number of DMA proposed in the original paper of each author. Then, the graph partitioning phase was achieved with SWANP using weights on pipes and nodes different from those used in the other procedures. Only pressure indices were computed to measure performance of WNP because no other information was provided for the case studies that would allow to compute other indices of SWANP (e.g., resilience, resilience deviation, etc., as reported in [25]). Because the information of each procedure and case study is not complete, the operative strategy of this first attempt to compare different techniques is based on the following: the SWANP software was tested on the same network used by the other authors comparing with the results provided in their studies.

In Table 1, the first comparison refers to the MAS procedure, as proposed by Hajebi et al. [17], on the Net3 network. In the first four columns the characteristics of network partitioning are reported, respectively: the number...
of DMA $k$, the number of nodes belonging to each DMA, and the number of boundary valves $N_{bv}$ and flow meters $N_{fm}$ (with $N_{ec}=N_{bv}+N_{fm}$). The comparison shows that the MAS procedure allowed to obtain, for that case study, a number of edge cuts $N_{ec}=5$ significantly lower than the one obtained with SWANP ($N_{ec}=15$) with node weights equal to “node elevation” and pipe weights equal to “water flow”.

In the Fig. 1, the best water network partitioning with $k=3$ DMAs, obtained by the SWANP software, is reported indicating the location of flow meters and boundary valves.

Although the MAS procedure does not provide the selection of boundary pipes, in this work the heuristic algorithm proposed in [1] was used for this aim; in this way, fixing $N_{fm}=2$ was found as the optimal number of flow meters and the alteration of hydraulic performance can be computed with pressure indices. In particular, because in this case the number of $N_{ec}$ obtained with MAS is small, it was possible to compute all combination of the location of $N_{bv}$ and $N_{fm}$. The performance indices show an interesting result, as reported in the last three columns of Table 1. It is expected that a solution with lower number of edge-cuts would provide lower alteration of hydraulic performance because the number of closed valves is lower, for a fixed number of flow meters. All pressure indices obtained by the SWANP solution nevertheless are higher than those obtained with the MAS procedure, and also higher than those of the original network. This singular result is certainly due to the presence of pump systems in the network that change the available power but also to the non-linearity of the problem and indicates that not only the minimization of edge cuts but also their location is a crucial aspect of water network partitioning. Anyway, comparing the results obtained by the MAS procedure with the original values of pressure indices of the network, it is evident that the MAS procedure is very effective and it is worth to test it on larger water networks, as already done for the SWANP software.

### Table 1. Comparison between WNP obtained with MAS and SWANP for the Net3 original network

<table>
<thead>
<tr>
<th>Network/WNP</th>
<th>$k$</th>
<th>DMA1 nodes</th>
<th>DMA2 nodes</th>
<th>DMA3 nodes</th>
<th>$N_{bv}$</th>
<th>$N_{fm}$</th>
<th>$h_{max}$ [m]</th>
<th>$h_{min}$ [m]</th>
<th>$h_{max}$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>41.73</td>
<td>4.19</td>
<td>92.45</td>
</tr>
<tr>
<td>MAS</td>
<td>3</td>
<td>38</td>
<td>24</td>
<td>30</td>
<td>3</td>
<td>2</td>
<td>41.87</td>
<td>4.21</td>
<td>92.54</td>
</tr>
<tr>
<td>SWANP</td>
<td>3</td>
<td>38</td>
<td>14</td>
<td>40</td>
<td>13</td>
<td>2</td>
<td>44.66</td>
<td>5.03</td>
<td>95.63</td>
</tr>
</tbody>
</table>

![Fig. 2. DMAs of Net3 network by SWANP.](image)
In the Table 2, the second comparison refers to the HGP procedure, proposed by Ferrari et al. [10] for a water network partitioning of Anytown network in \( k=2 \) DMAs. In this case, the SWANP software provides a number of edge cuts slightly lower than HGP (\( N_{\text{bv}}=9 \) vs \( N_{\text{bv}}=11 \)) after the partitioning phase with only node weight equal to “water demand”. Then, unlike the MAS procedure, the HGP procedure does include an iterative tool for selection of the location of flow meters and boundary valves. In order to simplify the comparison, in this case, the heuristic procedure to select the location of boundary valves and flow meters did not use but the performance indices obtained using the same number \( N_{\text{fm}}=3 \) and location of flow meters and inserted all gate valves in the other edge cuts. As reported in Table 2, the solution obtained with the SWANP is clearly better than HGP in terms of hydraulic performance with pressure indices practically equal to the original network and with a value of \( h_{\text{min}}=30.02 \) m almost twice the one obtained with HGP (\( h_{\text{min}}=16.10 \) m). Anyway, the HGP procedure provided a good value of \( h_{\text{mean}}=65.62 \) m compared with the value of original network (\( h_{\text{mean}}=68.57 \) m); also in this case the pressure values were affected by the presence of pump systems.

In Table 2, the last comparison between SWANP and the WSC procedure, proposed by Herrera et al. [15] for the real water network of Celaya in Mexico, is reported. It is worth to highlight that the WSC procedure [15] is proposed specifically for Water Network Sectorization (WNS) and not for water network partitioning. In other terms, the goal of the procedure is to find isolated district (or \( i \)-DMA, as defined in [12, 26]), each one supplied from one or more sources, inserting gate valves in each edge cuts. Then the partitioning algorithm should find a solution

\[
\begin{array}{ccccccc}
\text{Partitioning characteristics} & k & \text{DMA1 nodes} & \text{DMA2 nodes} & N_{\text{bv}} & N_{\text{fm}} & h_{\text{mean}}[\text{m}] & h_{\text{min}}[\text{m}] & h_{\text{max}}[\text{m}] \\
\hline
\text{Anytown} & - & - & - & - & - & 68.57 & 30.12 & 170.23 \\
\text{HGP} & 2 & 7 & 10 & 8 & 3 & 65.62 & 16.10 & 170.58 \\
\text{SWANP} & 2 & 8 & 9 & 6 & 3 & 70.00 & 30.02 & 170.41 \\
\end{array}
\]

In this case, a lower value of \( N_{\text{bv}}=9 \) obtained with SWANP was sufficient to obtain a better WNP, compared to the HGP procedure. It is reasonable to think that the use of heuristic optimization procedure in SWANP can find an even better solution. Finally, it is worth to test also the HGP procedure on larger water networks. In the Fig. 2, the best water network partitioning with \( k=2 \) DMA, obtained by the SWANP software, is reported indicating the location of flow meters and boundary valves.

In Table 3, the last comparison between SWANP and the WSC procedure, proposed by Herrera et al. [15] for the real water network of Celaya in Mexico, is reported. It is worth to highlight that the WSC procedure [15] is proposed specifically for Water Network Sectorization (WNS) and not for water network partitioning. In other terms, the goal of the procedure is to find isolated district (or \( i \)-DMA, as defined in [12, 26]), each one supplied from one or more sources, inserting gate valves in each edge cuts. Then the partitioning algorithm should find a solution
that, at same time, minimizes the number of $N_{ne}$ and the alteration of hydraulic performance of each i-DMA. Thus, no algorithm is required for the selection of the location of flow meters. In this case, reported in Table 3, the SWANP software provided a number of edge cuts significantly lower than WSC obtained with no weights on pipes and nodes: $N_{ne}=34$ by the WSC procedure and $N_{ne}=14$ by the SWANP software. In this case, the comparison is not very effective because the location of gate valves in the Celaya network provided from Herrera et al. [15] is not completely clear. Anyway, in order to provide a useful hint to further comparison, the same location of the $N_{fm}=4$ flow meters, and the same number $k=3$ of DMA were selected by SWANP, as illustrated in the Fig. 3.

Table 3. Comparison between WNP obtained with WSC and SWANP for Celaya original network

<table>
<thead>
<tr>
<th>Network/WNP</th>
<th>$K$</th>
<th>DMA1 nodes</th>
<th>DMA2 nodes</th>
<th>DMA3 nodes</th>
<th>$N_{ne}$</th>
<th>$N_{fm}$</th>
<th>$h_{mean}$ [m]</th>
<th>$h_{min}$ [m]</th>
<th>$h_{max}$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Celaya</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>--</td>
<td>--</td>
<td>10.55</td>
<td>--</td>
<td>14.70</td>
</tr>
<tr>
<td>WSC</td>
<td>3</td>
<td>122</td>
<td>84</td>
<td>127</td>
<td>34</td>
<td>4</td>
<td>4.86</td>
<td>2.89</td>
<td>14.22</td>
</tr>
<tr>
<td>SWANP</td>
<td>3</td>
<td>114</td>
<td>110</td>
<td>115</td>
<td>10</td>
<td>4</td>
<td>9.88</td>
<td>2.89</td>
<td>14.22</td>
</tr>
</tbody>
</table>

The performance indices, reported in Table 3, show a slight alteration of $h_{mean}$ and $h_{max}$ compared to the values of original network, from 10.55 to 9.88 m for $h_{mean}$, and from 14.70 to 14.22 m for $h_{max}$. A more significant worsening is observed for the value of $h_{min}$. It is 4.86 m for the original network, that shows a bad hydraulic performance also in some nodes of the original network, and goes to 2.89 m after partitioning (although by the SWANP the water pressure is under 4 m only at 20 network nodes).

![Fig. 3. DMAs of Celaya network by SWANP.](image)

Nevertheless, if the aim of Herrera et al. [15] was to design only a WNS, the simulation results obtained with SWANP are not comparable with their layout, as explained in [27]. The number of nodes and, consequently, the flow to assign to each source in a WNS depend on network topology and hydraulic characteristics and if the algorithms tries to respect the balance constraint, as instead happens in a WNP, hydraulic performance can be
significantly worsen. Indeed this constraint can be useful in a WNP because each DMA can be balanced in terms of nodes (or district flow) as it is not assigned to only one source but is connected with other districts, while it can be even negative in a WNS because it can generate layouts incompatible with the level of service [27].

4. Conclusion

In the last decade, some procedures for water network partitioning and sectorization have been proposed in the literature to overcome the empirical approaches followed by the operators to design district meter areas (DMAs) and isolated district meter areas (i-DMAs). In this study a preliminary comparison between three of these procedures and a software developed by the authors was achieved showing their effectiveness but also some critical issues as the following:

• the algorithms have to be tested on larger water networks; the authors suggest to identify a benchmark network with many loops, similar to a real water system, with a low value of resilience [28];

• the procedures should provide more details on each of their steps in order to allow a comparison; at this moment, it is practically impossible to compare each procedure on the same network because some information that is required is not available (e.g., in one case the model used, in other case the design pressure or details about the algorithm, etc.);

• the papers should provide a clear definition of their “divide and conquer” aims, possibly using the classification in Water Network Partitioning (WNS) and Water Network Sectorization (WNS);

• performance indices to compare the multi-objective optimization problem should be defined; in each of the tested procedures this aspect was completely neglected.

With reference to the specific results obtained in this study, the SWANP software showed better results with respect to the HGP and WSC procedures in terms of both hydraulic performance and minimization of the number of edge cuts, while the MAS procedure provided a better result only in terms of edge cuts. Then the SWANP software is arranged as a decision support system providing to operators partitioning and sectorization layouts that can be compared with the use of different performance indices.

Finally, it is worth to highlight that the research on the topic of water network partitioning can be considered advanced because the automatic procedures show a good ability to find the best solution, although the previous issues should be overcome in order to transfer the results to the water market.

References


