SWANP: software for automatic Smart WAter Network Partitioning

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Abstract: The application of Information and Communication Technology in different assets of urban life has contributed to generating the notion of Smart City in which Smart WAter Network (SWAN) can be assumed as subsystems. The possibility of inserting remote control valves and flow meters in a WDS allows the implementation of the paradigm of “divide and conquer”, that consists into divide a large water network into k smaller subsystems, in order to simplify and improve the management and protection of SWAN. Traditional approaches for water network partitioning, based on empirical guiding principles (such as the maximum number of properties or total length of pipes in a district) combined with trial-and-error procedures, are not able to divide large water networks without a significant decrease of the hydraulic performance. Only recently in the scientific literature some approaches, essentially based on graph theory and partitioning techniques with Multi Level Recursive Bisection, have been proposed. This paper presents the SWANP (Smart WAter Network Partitioning) software that allows to achieve automatically a water network partitioning based on a novel multilevel algorithm based on bisection, genetic algorithm and original heuristic optimization approach based on energetic objective functions. Simulation results, carried out on real water network, confirms the effectiveness of the software that finds system partitioning in compliance with the level of service for the users. The SWANP software, developed in Python v2.7.6 language, includes some performance indices used to compare different water network partition layouts and provides to the operators a Decision Support System to choose the better solution.

Keywords: smart water network; network partitioning; graph theory; divide et conquer; network optimization

1 INTRODUCTION

Water Network Partitioning (WNP) represents the application of the paradigm of “divide and conquer” to a Smart WAter Network (SWAN) that allows improving the application of techniques for water balance and pressure control (Wrc/WSA/WCA Engineering and Operations Committee, 1994; AWWA, 2003; Di Nardo and Di Natale, 2011) and protection from contamination (Graymann et al. 2009; Di Nardo et al., 2013a and 2014a). These techniques can be applied with greater effectiveness defining smaller permanent network parts, called District Meter Area (DMA), obtained by the insertion of gate valves and flow meters.

The partition of a water supply network is very difficult because the insertion of gate valves in the pipes can decrease hydraulic performance reducing its topologic (network loops) and energetic (diameter sections) redundancy (Mays, 2000). The traditional criteria (Water Authorities Association and Water Research Centre, 1985; Water Industry Research Ltd, 1999; Butler, 2000) 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 number of possible partitioning is huge (Di Nardo and Di Natale, 2012).

Recently, in the scientific literature, some different procedures have been proposed based on different approaches: spectral clustering (Herrera et al., 2010); graph theory (Sharma and Swamee, 2005; Tzatchkov et al., 2006; Di Nardo and Di Natale, 2011; Gomes et al., 2012; Alvisi and Franchini, 2013; Di Nardo et al., 2013b, c), multi-agent (Izquierdo et al., 2011, Di Nardo et al., 2014b); community detection (Diao et al., 2013).
SWANP software is based on graph partitioning approach proposed more recently in Di Nardo et al. (2013d) that showed the best results comparing different techniques on real case study. The proposed tool has been developed in Python v2.7.6 language and integrates graph partitioning, hydraulic simulation and heuristic optimization criteria. SWANP allows to define DMAs with performance indices very close to the values computed for the network original layout.

2 SWANP SOFTWARE

In SWANP, the water network is assimilated to 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), and denoting by positive weight $\sigma_i$ with $i \in V$, and non-negative weight $\epsilon_{ij}$ with $ij \in E$ and $\epsilon_{ii} = 0$ if $ij \notin E$, a $k$-way graph partitioning problem consists in partitioning $V$ vertices of $G$ into $k$ subsets, $D_1$, $D_2$, $\ldots$, $D_k$ such that $D_i \cap D_j = \emptyset$ for $i \neq j$, $|D_i| = n/k$ and $\bigcup_i D_i = V$.

2.1 Graph partitioning algorithms

The graph partitioning technique implemented in the SWANP software uses a multilevel procedure that combines different algorithms:

a) a Multi Level Recursive Bisection (MLRB) algorithm, originally proposed by Karypis and Kumar (1998) as a highly effective method for computing a $k$-way partitioning of a graph in Computer Science, especially in large-scale numerical simulations on parallel computers, that was adapted by the authors to obtain a water network partitioning. The MLRB algorithm, based on coarsening, partitioning and uncoarsening algorithms (Karypis and Kumar, 1998), allows to minimize the number of edge-cuts (or links between the districts) and to balance the number of nodes that belong to each district. The $k$-way partition is recursively solved by performing a sequence of 2-way partitions (or bisections).

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 goal is to partition the vertices into $k$ disjoint subsets $D_k$, such that the Objective Function 1 to minimize is equal to the sum of the number of edge-cut $e_i$ or of associated weights $\epsilon_{ij}$, whose incident vertices belong to different subsets:

$$OF1 = \left( N_{ec} = \sum_{i \in D_j \Rightarrow j \notin D_j} e_{ij} \right) \text{or} \left( W_e = \sum_{i \in D_j \Rightarrow j \notin D_j} \epsilon_{ij} \right)$$

(1)

The goal (1) has to be obtained balancing the number of vertices $n_p$ or the associated weights $\sigma_p$ for each subsets. This constraint is achieved by minimizing the balance index $I_B$:

$$Constraint = I_B = \frac{k \cdot \max(d_p)}{n}$$

(2)

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

The authors modified the MLRB algorithm to adapt the procedure to a water distribution system defining an oriented graph and suitable weights by hydraulic simulation (Di Nardo et al., 2013d).

b) a Genetic Algorithm (GA), proposed in Di Nardo et al. (2013d), to choice heuristically the positioning of flow meters and gate valves to define the best DMAs. The GA uses an energetic approach based on the power balance of a water network (Todini, 2000) defined as:

$$P_A = P_D + P_N$$

(3)

where
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\[
P_A = \gamma \sum_{i=1}^{r} q_i H_s \quad \text{is the Available Power (or total power)} \tag{4}
\]

\[
P_D = \gamma \sum_{j=1}^{m} q_j \Delta H_j \quad \text{is the Dissipated Power (or internal power)} \tag{5}
\]

\[
P_N = \gamma \sum_{i=1}^{n} Q_i H_i \quad \text{is the Node Power (or external power)} \tag{6}
\]

and \(q_s\) and \(H_s\) are the discharge and head relevant to each reservoir; \(\gamma\) is the specific weight of water; \(q_j\) and \(\Delta H_j\) are the flow and headloss for each network pipe; \(Q_i\) and \(H_i\) are the water demand and head at each network node.

Then the GA maximizes the following Objective Function 2:

\[
\text{OF2} = P_N \tag{7}
\]

The SWANP software, for each partitioning layout, computes some Performance Indices (PIs), to compare different layouts and to help the operators to choose the better solution as a Decision Support System. Specifically PIs, already proposed and tested in some studies, are: Resilience index, \(I_r\) (Todini, 2000), Resilience deviation index, \(I_{rd}\), Mean, \(h_{\text{mean}}\), Maximum, \(h_{\text{max}}\), and Min, \(h_{\text{min}}\), node pressure indices, and the Standard Deviation node pressure index, \(h_{\text{std}}\) (Di Nardo and Di Natale, 2011); Mean Pressure Surplus, \(MPS\), Mean Pressure Deficit, \(MPD\), Mean Squared Deviation from design Pressure, \(MSPD\) (Di Nardo and Di Natale, 2011).

### 2.2 Graphic User Interface (GUI)

SWANP is a Decision Support System that provides to the operators different solutions for water network partitioning in order to assess the optimal number of DMAs and the number of flow meters and boundary (or gate) valves to install. The SWANP software is developed using Phyton v2.7.6 programming language.

In this framework, two external DLLs were integrated: METIS (Karypis and Kumar, 1998), an open software used for a preliminary water network partitioning, and EPANET2 software (Rossman, 200) used for the hydraulic simulation.

The starting interface of SWANP is divided into four GUI sections: Network selection, Analysis Mode, Partitioning parameters and Optimization parameters.

![Figure 1. SWANP software GUI.](image)
In the Network Selection it is possible to provide the input file and choose the Partitioning Algorithm (in this first release, only METIS procedure is available but other partitioning algorithms are in progress); the input file is an EPANET2 file with a “.INP” extension.

In the Analysis Mode, the user can set two computation modality: Auto Mode and Manual Mode. In Auto Mode, SWANP offers automatically different solutions of possible water network partitioning; especially, starting from two DMAs, the software computes the maximum number of DMAs in compliance with the constraint imposed by the user (in this software release, the constraint is minimum pressure, $h_{min}$). For each partitioning obtained with a different number of DMAs, SWANP provides the best solution with a minimum number of flow meters.

While, in Manual Mode, the user can choose the number of DMAs and the number of the flow meters. The GUI section Partitioning parameters allows to choose some parameters for the network partitioning; the weights (Weights on pipes: none, flow, dissipated power, diameter, head loss and conductance and Weights on nodes: none and water demand) available both in Auto and in Manual Mode. In this GUI section is possible to define the constraint for the Auto Mode (the values of the minimum pressures) and the number of districts for Manual Mode.

The last GUI section Optimization parameters, available only in Manual Mode, allows the user to set the parameters of GA (Crossover Rate, Population Size, Mutation Rate, Generation Size and Number of the flow meters).

4 CASE STUDY

The case study is Parete (Di Nardo and Di Natale, 2012), located in a densely populated area in the South of Caserta (Italy), with 10,800 inhabitants. The original network, supplied from two sources, with a design pressure $h_i^* = 25$ m equal for each node, has the following indices computed with EPANET2 software: $l_i = 0.35$, $h_{mean} = 31.05$, $h_{max} = 50.47$ and $h_{min} = 21.36$, as reported in the Figure 2 that shows a SWANP screenshot.

The low value of resilience index indicates 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 (Greco et al., 2012). In this case the importance to have a DSS to help the operators in the partitioning design of the water network is clearly very useful.

The screenshot of Figure 2 illustrates the simulation results for the original network, for the whole partitioned network and for each DMAs.

In this paper, different layouts of WNP were achieved with SWANP by using Auto-Mode computation with diameters as weights on pipes and no weights on nodes (consequently the constraint (2) is only the balance of nodes for each DMA).

Figure 2. Performance Indices.

The results obtained with SWANP are illustrated in Figure 3, in which 6 network partitioning layouts, from k= 2 DMAs to k= 7 DMAs, are indicated with red square points that represent the values of Resilience index $I_r$. For each point illustrated in the Figure 3, also the minimum number of flow meters obtained by SWANP is highlighted. SWANP also allows to plot all other performance indices in the same format of the Figure 3.
As expected, the plot of Figure 3 shows that increasing the number of DMAs, the Resilience index worsens significantly and, in Auto mode, SWANP finds, automatically the maximum number of DMA, k=7, in compliance with minimum pressure equal to 15 m, with a minimum number of flow meters equal to \(N_{fm}=8\). Naturally, if the number of flow meters can increase, the hydraulic performance can improve consequently.

The analysis of Auto mode results, illustrated in the Figure 3, shows a good partitioning with \(k=5\) DMA; indeed the Resilience deviation index is equal to 17.14 and the Mean pressure index, \(h_{\text{mean}} = 25.8\) m, Min pressure, \(h_{\text{min}} = 18.84\) m (in DMA 2) are slightly lower than the original network values.

Simulation results were obtained with peak demand (at 8.00 am) but the software allows to compute also an Extended Period Simulation as showed in screenshot of Figure 2.

Finally, in the Figure 4, the water network partition of Parete with \(k=5\) DMA, achieved with Network visualization tool of SWANP, in which each node belong to the same DMA has the same colour, is illustrated.
4 CONCLUSION

The SWANP software provides to the operators and to the water utilities an effective tool to obtain different water network partitioning layouts. The software is arranged as a Decision Support System because it allows to compare different layouts using some performance indices.

The software, tested on real case study, allows with Auto mode to find automatically the best results minimizing the number of flow meters in compliance with the level of service of the water network.

The authors are working to improve the first release of the software by implementing other partitioning algorithms and a GIS (Geographic Information System) interface.

REFERENCES


