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A graph theoretical sectorization approach for energy reduction in water distribution networks

M.E. Castro-Gama[a]*, Q. Pan[a], A. Jonoski[a], D. Solomatine[a].

[a]UNESCO-IHE, Institute for Water Education, Westvest 7, 2611AX, Delft, The Netherlands.

Abstract

Most water supply utilities in the world need to deal with daily operations of their systems while at the same time they are required to increase their efficiency. One way to increase the efficiency of the system is to divide the water distribution network into smaller subsystems called sectors. This article presents a new sectorization approach, which has been developed as part of the European FP7 research project ICeWater, focused on increasing energy efficiency. The approach is based on the combination of graph theory and multi-objective optimization applied to the system of Milan (Italy). Most existing approaches for sectorization deal with gravity sources. The methodology presented here has been applied to a system with 26 pump stations, which is an innovation and a step forward for other utilities facing similar challenges. The application of sectorization to the network of Milan has the advantage of allowing to fix the number of sectors and enabling the exploration of multiple scenarios of system operation.

Keywords: Sectorization, graphs, water distribution networks, Milan

1. Introduction

In the past, many researchers have proposed solutions to Single Objective Optimization (SOO) and Multi-Objective Optimization problems (MOO) formulated for reducing energy consumption in Water Distribution Networks (WDN), such as, for example, pump scheduling problems. However, in most cases the number of decision

* Corresponding author. Tel.: +31-6-8281-4926.
E-mail address: m.castrogama@unesco-ihe.org

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variables used for optimization is low as compared to the number of decision variables required in real systems [1, 2].

Nomenclature

$\boldsymbol{A_{pn}}$	incidency matrix of the Global Gradient Algorithm
$\boldsymbol{D}$	degree matrix of a graph
DMA	District Metering Areas
$\boldsymbol{E_x}$	a set of graph edges
$\boldsymbol{G_x}$	a graph containing a set of vertex $(\boldsymbol{V_x})$ and a set of edges $(\boldsymbol{E_x})$
$\boldsymbol{k}$	number of sectors
$\boldsymbol{L}$	Lapacian matrix of a graph
MOO	Multi-Objective Optimization problems
$\boldsymbol{n}$	number of subsectors
$\boldsymbol{n_c}$	number of configurations of sectorization to be generated for a particular number of sectors $\boldsymbol{k}$
$\boldsymbol{n_{eig}}$	number of non-zero eigenvalues of matrix $\boldsymbol{L}$
$\boldsymbol{n_n}$	is the number of nodes, tanks and reservoirs in a network
$\boldsymbol{n_p}$	number of pipes, valves and pumps in a network
$\boldsymbol{r}$	number of remaining subsectors for allocation
$\boldsymbol{S_k}$	A sectorization configuration with $\boldsymbol{k}$ sectors.
$\boldsymbol{s_i}$	a subsector of a list of $\boldsymbol{n}$ available
SOO	Single Objective Optimization
WNP	Water Network Partitioning
WNS	Water Network Sectorization
WNSeg	Water Network Segmentation
WDN	Water Distribution Networks
$\boldsymbol{V_x}$	a set of graph vertices

It is necessary to find new ways to approach the problem of energy minimization for real networks of large size. Such approaches include: Water Network Partitioning (WNP) which corresponds to dividing a network into a number of district metering areas (DMA) [3, 4]; Water Network Segmentation (WNSeg) [5, 6], in which the goal is to identify locations for pressure regulating valves; Water Network Sectorization (WNS) when a part of a WDN, named 'sector' is supplied only by a single source and the DMAs are completely isolated [7].

All of the approaches mentioned above are intended for application with gravity sources, and in small to medium size WDNs. For that reason these approaches are not suitable for most large WDNs.

In the case of Milan, the system has a total of 26 pumping stations. The system contains 103 booster pumps, 41 tanks, 143,684 junctions, 113,784 pipes and 35,338 valves. Currently the system is operated as a single Pressure Management Zone (one large sector), which leads to excessive energy use, bringing costs to the utility of nearly €16m per year [8]. Recently, several different methodologies have been applied for pump scheduling in a subsector of Milan known as Abbiategrasso [9] and a WNS approach was proposed for the northern area of Milan [10]. In another approach, a WNS of the full system of Milan was proposed [11], making the boundaries between isolated subsectors part of the optimization process, but lacking the possibility to fix the number of sectors required.

One of the main problems with sectorization approaches is that the number of sectors can not be fixed as desired. The only attainable way to overcome this is to pose a constraint to the number of sectors or partitions and include this in the MOO. This is a known issue even for most complicated approaches using modularity analysis for WNSeg of WDN [6, 7].

The approach presented here allows us to deal with two main issues of WNS: 1) the sources of each sector created can be pump stations and not only gravity sources, 2) the number of possible sectors can be fixed for a particular problem setup.

The methodology is applied to the case of Milan WDN. The new sectorization approach enables splitting of the network in such a way that a large WDN can be converted in a set of smaller isolated networks of a manageable size.