OPTIMAL DESIGN OF VIRTUAL DMA'S WITH GONDWANA

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Abstract

Dutch drinking water companies are interested in improving their knowledge about their distribution systems, including background leakage, valve statuses, demand patterns, among others. District metering is a technique that can be useful in achieving this goal. Dutch water companies do, however, not wish to alter the hydraulic performance of their systems, which leads to a preference for virtual district metered areas (DMAs).

In this contribution, the performance of virtual DMAs in detecting system changes in relation to DMA size is explored. The design of virtual DMAs is formulated as a constrained single-objective optimization problem. The objective consists of minimizing the DMA boundaries (as a surrogate for number of flow meters that are installed) that are necessary to identify changes of a certain magnitude in a single DMA.

The optimization problem is solved in Gondwana, a generic software platform for the optimization of drinking water distribution networks. Gondwana has been extended with new functionality in order to be able to design virtual DMAs. This new functionality is tested on a real-life network, with good results. A trade-off between the number of required flow meters and the DMA sensitivity to detect anomalies is characterized.

Keywords: optimization, DMA, design, real-life application

1 Introduction

Within a Drinking Water Distribution Network (DWDN), District Metered Areas (DMAs) are demarcated subsections with a flow meter or closed valve installed at each pipe that connects to the rest of the network. Together, the flow meters provide a DMA's water balance, which can be monitored to detect anomalies in water supply within the DMA. The first use of DMAs was aimed at the detection and quantification of water losses through leakage (UK Water Authorities Association, 1980). Since then, DMAs have also been applied to aid pressure control by outfitting each water meter-bearing pipe with a pressure reducing valve (Farley, 2001; Morrison, Tooms *et al.* 2007). Apart from these main applications, DMAs can have many other uses, such as the isolation of drinking water quality incidents (Di Nardo, Di Natale *et al.* 2013) or the identification of valves with an incorrect setting.

The Dutch drinking water companies are interested in applying DMAs to improve their knowledge about their DWDN, including background leakage, valve statuses and demand patterns. When introducing DMAs to an existing DWDN, physically separating subsections by closing valves allows for efficient determination of water balances with only a few flow meters. Such an approach, however, may change the hydraulic properties of the network, which may in turn affect the pressure gradients, water quality and the reliability of the network. The Dutch water companies do not wish to alter the hydraulic performance of their systems and therefore prefer to explore the possibilities of so called *virtual* DMAs (Di Nardo, Di Natale *et al.* 2012), which essentially are DMAs created exclusively through the installation of flow meters.

The Dutch water companies are interested in exploring the possibilities provided by virtual DMAs

Many different subdivisions are possible when organising a DWDN into virtual DMAs. Initial forays into DMA use in the Netherlands have led to a wide variety of configurations, with DMA sizes ranging from 3 to 459 km in pipe length and the number of connections per DMA ranging from 50 to 110000. Finding a configuration with optimal performance can be a convoluted exercise, as the performance depends on many factors, such as cost, the tangled hydraulics of a large looped system and, indeed, the intended use of the DMA. Numeric optimization software methods can be a powerful tool to aid in this complex task.

The goal of the present work is to illustrate the use of genetic optimization algorithms to design optimal DMA configurations. To this end, part of the existing DWDN of the Dutch village of Sittard was subdivided into DMAs using Gondwana, a generic software platform for the optimization of DWDN, recently developed at KWR (van Thienen and Vertommen, 2015). This demonstrates that drinking water utilities can employ optimization software methods to tune DMA configurations to their specific needs. In turn, this will allow drinking water utilities to obtain a greater understanding of their DWDN and to employ this understanding to improve network models, operational decisions, reduce losses and overall enhance reliability.

2 Optimization problem definition

Gondwana is built around the EPANET library (Rossman, 2000), used for hydraulic calculations, and the Inspyred library (Garrett, 2015), which provides metaheuristic optimization methods. The conceptual approach of the optimization process used by Gondwana is shown in figure 1A. Over a number of iterations, a population of possible candidates is graded up with respect to defined performance criteria. Every cycle starts with evaluating the performance of each candidate, with respect to which they are then sorted. The best performing candidates are kept while the rest is replaced with newly generated candidates that are based on partial modifications of the best solutions. The next iteration starts with the resulting population. The process repeats until a given convergence criterion is met, e.g. when no better solutions have been found for several generations or a user pre-defined number of function evaluations have been completed.

Following the EPANET format, a DWDN in Gondwana is essentially represented as a collection of nodes connected by links, where links represent pipes and nodes represent various water sources or sinks, such as reservoirs or household connections. A particular DMA configuration is defined as a collection of connected node clusters, with the links between two clusters representing the pipes with flow meters installed that mark the DMA boundaries (see Figure 1B). During the optimization process, new candidates are constructed from candidates with high performance through the random occurrence of 3 mechanisms: node exchange, DMA splitting and DMA merging, as illustrated in Figure 1C.

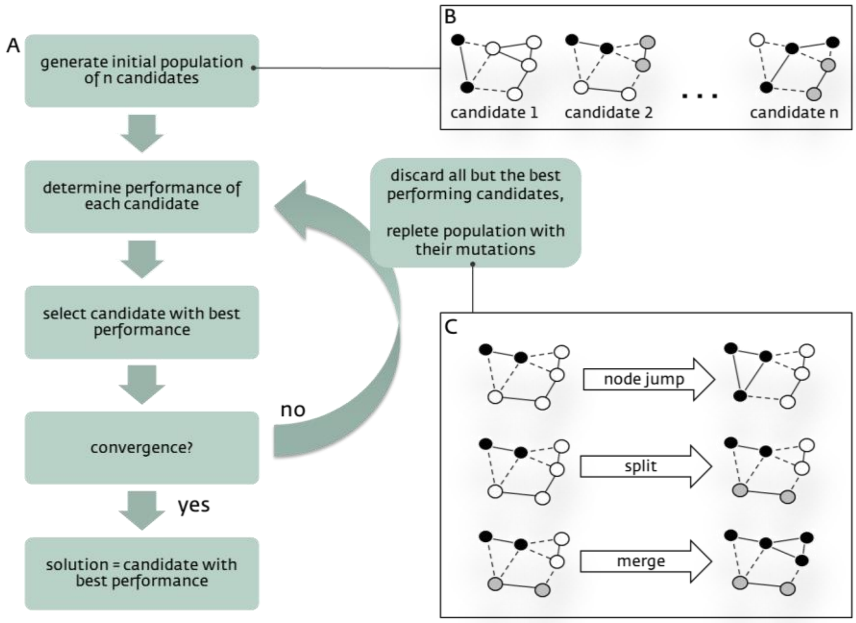


Figure 1 A. flowchart of the steps followed by the optimization platform Gondwana. B. schematic example of DMA configurations as handled by Gondwana. Node color indicates the individual DMA, defined as clusters of connected nodes. The dashed lines correspond to the pipes outfitted with flow meters that define the boundaries of the DMAs.

Following the wishes of the Dutch drinking water companies, two performance criteria are defined. Firstly the cost of a configuration is to be minimized so that resources are spent as efficiently as possible. The cost of a given DMA configuration is mostly determined by the number and size of flow meters that need to be bought, installed and operated. Within the structure of Gondwana, the objective function for cost, O_{cost}, is defined and evaluated according to Eq.(1):

$$O_{cost} = n_{boundary}, \quad (1)$$

with $n_{boundary}$ the number of boundary links between node clusters, representing the number of flow meters required for its realization. This is in fact a simplified surrogate for the cost, where it is assumed that all valves have the same costs. A more thorough approach should also consider the valve diameters.

Secondly, since the DMAs are intended to enhance momentary knowledge of the DWDN, the desired sensitivity of individual DMA's water balances to irregular flow situations is predefined by the user. To achieve this, it is assumed that a DMA's ability to reveal the occurrence of anomalies scales with the size of its total demand. The rationale behind this is that a disturbance can only be identified from the water balance when it is bigger than a regular fluctuation in water demand and that the size of regular fluctuations scales with the regular average demand. Within the structure of Gondwana, the constraint for sensitivity, $C_{sensitivity}$, is therefore defined and evaluated according to Eq. (2):

$$C_{sensitivity} = c \cdot (Q_{in} - Q_{out}), \quad (2)$$

with Q_{in} and Q_{out} the total flow into and out of a DMA, respectively and c a factor representing the relative size of fluctuations in regular demand patterns. This way, $C_{sensitivity}$ is an effective measure for the smallest irregular situation that can be detected.

3 Case study

As a case study, part of the existing DWDN of the Dutch village Sittard was divided into DMAs using Gondwana. The network has a total length of 10.8 km and has 1000 connections, including connections to a school, a residential building with 32 apartments and a care farm for mental patients. The network is fed by a single reservoir and has a mean total demand of 15 m^3/h. The DWDN was represented by an EPANET model consisting of 497 nodes, 474 links and 1 reservoir (Agudelo-Vera and Blokker, 2014). The network is displayed in Figure 2, including two of the resulting DMA configurations.

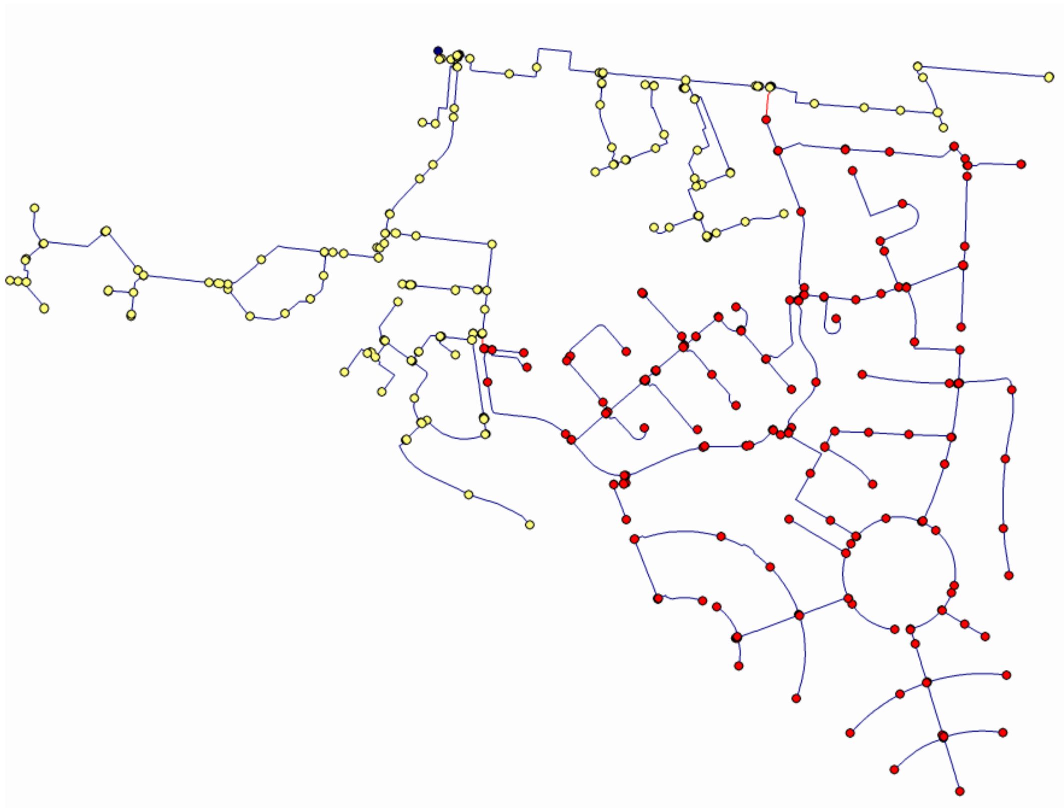
Maximizing DMA sensitivity (i.e., minimizing $C_{sensitivity}$) essentially favors subdivision into more, smaller DMAs. Since this typically results in the occurrence of more boundary links, minimizing both $C_{sensitivity}$ and O_{costs} constitutes a tradeoff between cost and sensitivity to anomalies. This tradeoff is investigated for the network according to the following approach:

- The minimization of O_{costs} is defined as the objective for optimization.
- $C_{sensitivity}$ is defined to be constrained below a chosen value, V. This means that emerging candidates that do not meet this requirement are rejected and replaced with new mutations regardless of their performance in terms of O_{cost}. A value of 0.1 was chosen for c in $O_{sensitivity}$. Based on the variation of water demand within DWDN and the accuracy of flow meters, more appropriate values can be chosen for c.
- The DMA configuration is optimized several times, each time for a different V.

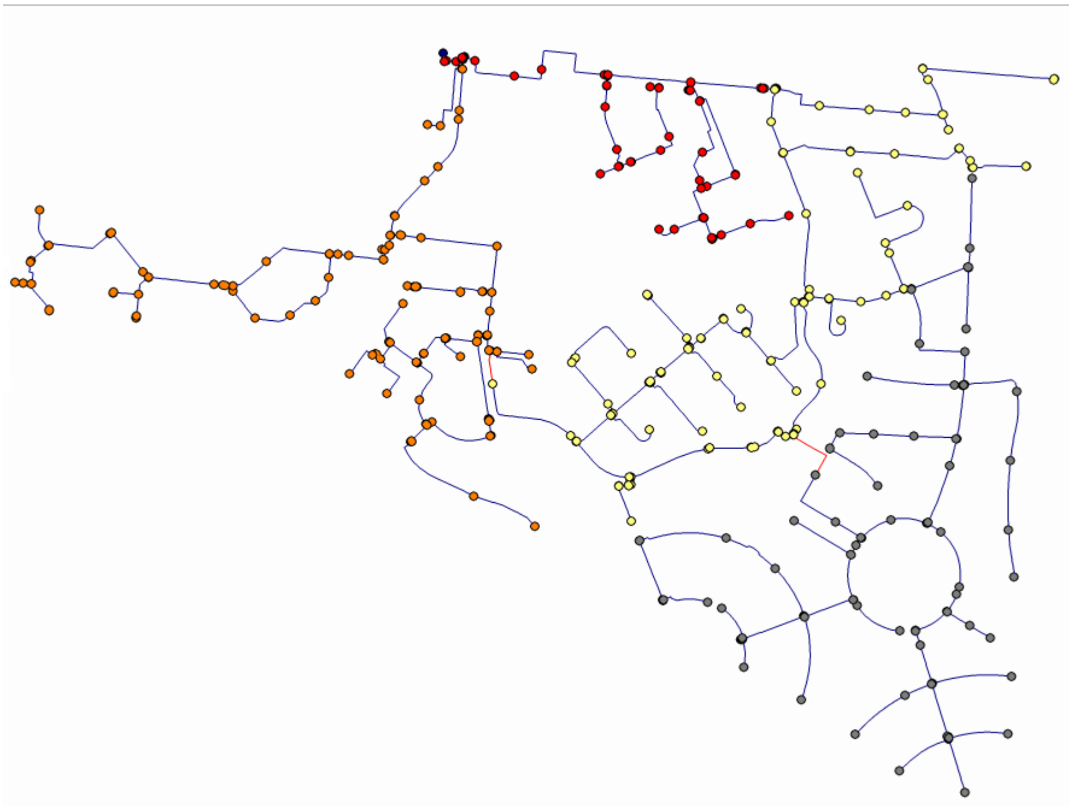
Minimizing costs for several minimum sensitivities in this way provides drinking water utilities with insight in the possibilities for trade-off and gives the best solution for any tradeoff that is ultimately chosen.

4 Results

The optimization process results in a specific DMA configuration for each predefined sensitivity level V. Figure 2 illustrates two examples of the subdivision of the Sittard network in DMAs, which are able to detect anomalies of 0.8 m^3/h and 0.4 m^3/h, respectively.



(A)



(B)

Figure 2. Representation in Gondwana of the examined part of Sittard's DWDN. Node color indicates DMA membership as a result of optimization sequences in which O_{cost} *was minimized while* $C_{sensitivity}$ *was constrained to remain below either 0.8 m*^{3}*/h (A) or 0.4 m*^{3}*/h (B). The DMA boundary links (where flow meters are located) are colored in red. Due to the scale of the figure, not all boundary links are visible.*

Figure 2 shows that, in order to detect anomalies of 0.8m^3/h it is necessary to subdivide the Sittard network into two DMAs, using three flow meters in the process. In order to detect irregularities of 0.4 m^3/h, it is necessary to install six flow meters, creating a total of four DMAs. As expected, to detect smaller anomalies it is necessary to install more flow meters, subdividing the network into smaller DMAs. The relation between the required number of meters and the sensitivity to detect anomalies is further investigated in Figure 3. The obtained trade-off curve allows water utilities to make a reasoned decision about DMA size, and the corresponding minimum required number of flow meters, that best fits their requirements and expectations in terms of detection of anomalies or desired level of detail in measurements.

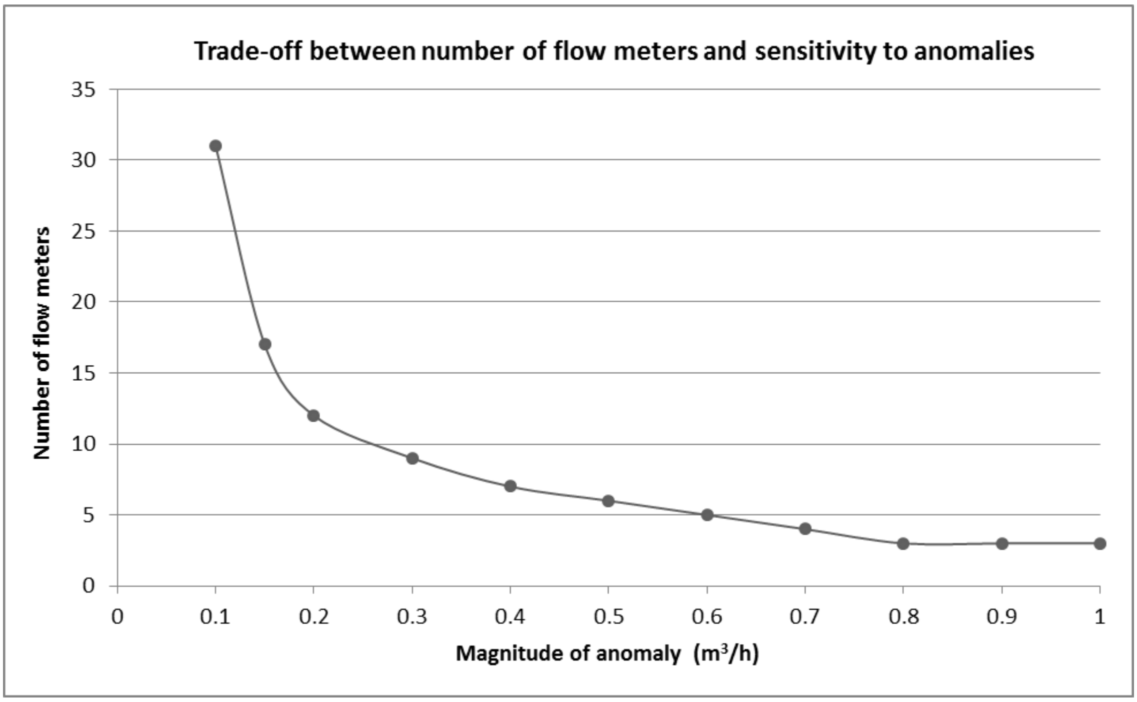


Figure 3. Trade-off between the number of flow meters required for an optimal DMA configuration and its sensitivity, expressed as the size of the smallest demand anomalies that can be distinguished from regular demand fluctuations.

5 Conclusions and future developments

Gondwana has been expanded with new functionality for the design of DMAs. The design objectives and constraints have been determined according to the requirements from Dutch water companies. The obtained results show that genetic algorithms are suitable to make optimal use of the inherent flexibility of virtual DMAs, despite their inherent complexity. The followed approach and the computation of a trade-off between number of flow meters and the DMA sensitivity to anomalies provides water utilities with useful information that may serve as a basis for grounded decisions about DMA size and optimal boundary locations.

Solving these problems with Gondwana also makes it easier to compute updated design solutions when new information becomes available: the optimization problem can easily be adapted to include changes in objectives, constraints or input demand scenarios, and then rerun.

In future developments real drinking water distribution networks with different sizes (10000 to 78000 pipes) will be considered in case-studies. The trade-off between the number of flow meters and DMA sensitivity will also be investigated for different values of the *c* factor. Appropriate values for the *c* factor can be explored taking into account the variability of demand and the type of demand uses in the network (residential, commercial or industrial). The objective function can also be further developed to consider not only the number of valves to be installed, but also their size.

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