Multi-objective Optimization of Sensor Placement to Detect Contamination in Water Distribution Networks

Margarida Dolores
INESC Coimbra
Rua Antero de Quental 199
3000-033 Coimbra, Portugal
+351239851040
margarida.dolores@gmail.com

Carlos Henggeler Antunes
DEEC, Polo 2, University of Coimbra, 3030-290 Coimbra, and INESC Coimbra, R. Antero de Quental 199; 3000-033 Coimbra, Portugal
+351239796259
ch@deec.uc.pt

ABSTRACT
The water distribution network (WDN) is the most vulnerable part of a water system due to the large number of access points, requiring a reliable monitoring and surveillance system to timely detect contamination events. A multi-objective evolutionary approach to determine the location of sensors in a WDN is presented, to minimize the potential consequences of contamination events. The objective functions are the expected time of detection, the expected population affected prior to detection, the expected consumption of contaminated water prior to detection, and the detection likelihood. A set of non-dominated solutions is obtained offering further information for practical decision making.

Categories and Subject Descriptors
I.2.8 [**Computing Methodologies**]: Artificial Intelligence – *problem solving, control methods, and search.*

Keywords
Water distribution networks; sensor placement; contamination; multi-objective evolutionary algorithm.

1. INTRODUCTION
The contamination of water infrastructures affects people in general and the local economy, being a concern of governments, regulators, and water management entities. The water distribution network (WDN) is the most vulnerable part in a water supply system, due to the large number of multiple and unprotected access points, being extremely difficult to timely detect contamination events without a trustworthy monitoring and surveillance system. The location of the sensors in a WDN is an essential issue for implementing an effective and reliable contamination warning system. The number of sensors in a WDN is generally limited due to budgetary and technical feasibility reasons, and their location should minimize the potential consequences of a contamination event on public health.

The Battle of the Water Sensor Networks (BWSN) developed a framework of rules to compare sensor placement strategies [1]. This paper presents a multi-objective evolutionary approach based on NSGA-II to determine the location of sensors in a WDN considering as objective functions the expected time of detection, the expected population affected prior to detection, the expected consumption of contaminated water prior to detection, and the detection likelihood.

GECCO'15 Companion, July 11-15, 2015, Madrid, Spain
ACM 978-1-4503-3488-4/15/07.
http://dx.doi.org/10.1145/2739482.2764639

2. A SENSOR NETWORK PLACEMENT APPROACH BASED ON NSGA-II
2.1 Objective Functions
To allow the comparison of different optimization methods, the BWSN defined a base case and three derivative cases. In the base case (case A), the contamination event occurs in any node of the network, with an injection flow of 125 l/h of contaminant and a concentration of 230 g/l during two hours. Each event occurs in a single node of the network and begins at any time with equal probability. It is assumed that the contaminant is stable after the injection and the sensors instantly detect any contaminant concentration and the corrective actions are taken without delay to eliminate further exposure [1]. To simulate the effect of a contamination event the EPANET 2.0 software was used [2], which allows static and dynamic hydraulic simulations and water quality assessment in a drinking WDN, operating over an extended period of time.

The four objective functions (OF) to evaluate (the sensor network placement) solutions are the following, in which “expected” refers to the expected value over the assumed probability distribution of contamination events.

- **Expected time of detection (Min Z_1):** the time needed to detect the contaminant by a sensor network after the occurrence of an event.
- **Expected population affected prior to detection (Min Z_2):** the expected population affected is a function of the ingestion of the contaminant mass and the population served by each node in the WDN.
- **Expected consumption of contaminated water prior to detection (Min Z_3):** expected value of consumption of water with a concentration of contaminant above a specified threshold until the detection of the event.
- **Detection likelihood (Max Z_4):** ratio of the number of events that are detected by the sensors with respect to the total number of simulated events.

The solution search procedure is based on NSGA-II [3] to characterize the non-dominated front, and it was implemented using Matlab, EPANET Programmer’s Toolkit and EPANET Matlab Toolkit [4].

2.2 Solution encoding and operators

A solution consists in a set of sensor locations and is encoded as a vector of integers representing the index of the nodes in the WDN model, taking into account the technical feasibility of deployment.

The search in the solution space follows the structure of the WDN. A mutated solution is obtained by randomly selecting the sensor to be changed and the adjacent node to be used (guaranteeing that no more than one sensor can be placed at each node). The best results for the crossover operator were obtained using a uniform crossover in which the genes from each parent that are passed to each offspring are determined by a random mask (0-1 pattern).

3. CASE STUDIES

Two case studies were analyzed: a small network (1) with 129 junctions, 1 source, 2 tanks and 168 pipes, and a bigger network (2) with 12,523 junctions, 2 sources, 2 tanks and 14,822 pipes. Possible contamination events occur at all nodes, at all possible time steps during 24 hours, one event at a time. The total simulation time was 96 hours. Two experiments were conducted, one to place 5 sensors (N1A5 problem) and another one to place 20 sensors (N1A20 problem).

After obtaining a diverse and well-populated non-dominated front using NSGA-II, a strategy to identify a good compromise solution having in mind its practical implementation consisted in assessing the tradeoffs of selected solutions to unveil regions in which improving a given OF would lead to a rapid worsening of the remaining OF. The marked solutions in Fig. 1 are possible compromise solutions minimizing a distance to the ideal solution using two different metrics: the Chebyshev (G), i.e. minimizing the maximum "discomfort" of not obtaining the best in all dimensions of evaluation, and the Euclidean distance (H).

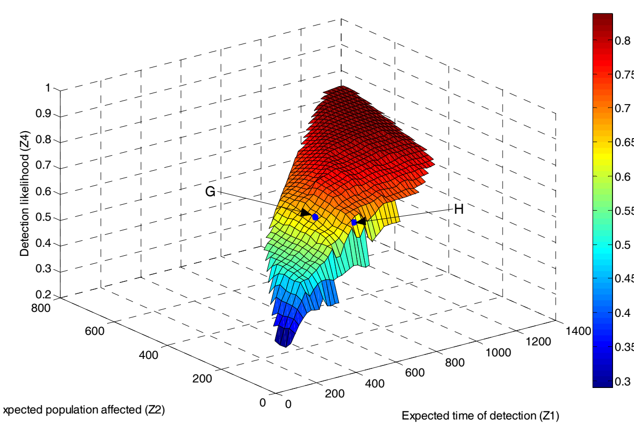

Figure 1. Non-dominated front for the N1A5 problem

Then to focus the scope of the search only solutions with values higher than 0.75 to Z_4 for problem N1A5 and 0.85 for problem N1A20 (Fig. 2) were considered. This reflects a learning process about the non-dominated solution set, thus enabling to reduce the search space by establishing "reservation" levels (i.e., OF values below which solutions are not acceptable). The analysis of the reduced fronts allowed spotting solutions where further improvement of Z_4 would lead to a significant degrading of the other OF. The identification of these solutions resulted from the visible presence of an almost vertical facet of the three-dimensional front, close to the minimum values of Z_1 and Z_2, leading to the choice of solutions close to the top of the facet. I and J are possible compromise solutions (e.g., J: Z_1=342 min., Z_2=91 persons, Z_3=988 gal., Z_4=87.01). The solution selected for placing 5 sensors is a subset of the solution obtained for placing 20 sensors in the same network, as displayed in Fig. 3.

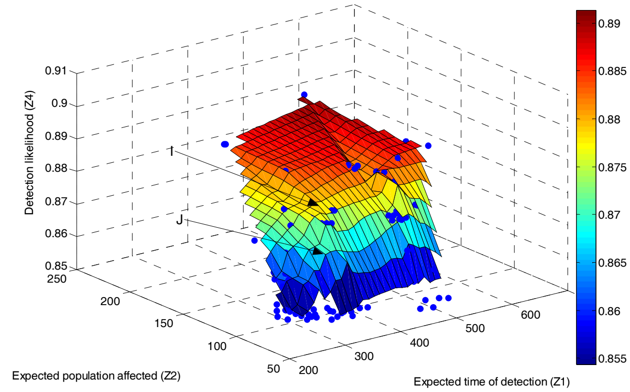

Figure 2. Subset of the non-dominated front with Z_4>0.85 displaying possible compromise solutions (N1A20 problem)

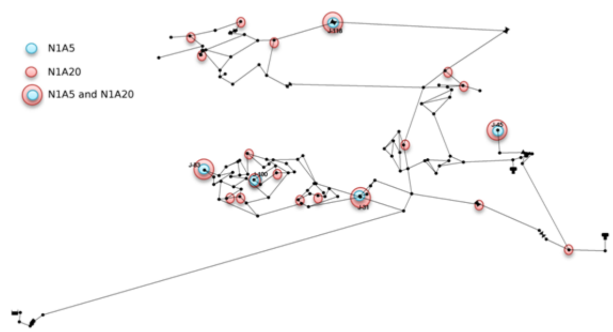

Figure 3. Solutions for 5 and 20 sensors (N1A5 and N1A20)

4. ACKNOWLEDGMENTS

This work has been partially supported by QREN Mais Centro Project EMSURE (CENTRO 07 0224 FEDER 002004) and FCT project grant UID/MULTI/00308/2013.

5. REFERENCES

[1] Ostfeld, A., et al. 2008.The Battle of the Water Sensor Networks (BWSN): a design challenge for engineers and algorithms. *J. Water Resour. Plan. Manag*. 134, 6 (Dec. 2008), 556–568.

[2] Rossman, L. 2000. EPANET 2 Users Manual. Environmental Protection Agency.

[3] Deb, K., Pratap, A., Agarwal, S., and Meyarivan, T. 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Trans. Evol. Comput*. 6, 2 (Apr. 2002) 182–197.

[4] Elíades, D. 2009. EPANET MATLAB Toolkit. http://www.mathworks.com/matlabcentral/fileexchange/25100-epanet-matlab-toolkit