

Operational interventions in WDS to improve water quality: a comparison of multi-objective optimization formulations

Claudia Quintiliani¹, Oscar Marquez-Calvo², Leonardo Alfonso³, Cristiana Di Cristo⁴, Angelo Leopardi⁵, Giovanni de Marinis⁶

^{1, 4, 5, 6} University of Cassino and Southern Lazio, Cassino (Italy)

^{2, 3} UNESCO-IHE Institute for Water Education, Delft (The Netherlands)

¹c.quintiliani@unicas.it

ABSTRACT

Managing water quality in drinking water distribution systems is very important to guarantee consumers' health. Disinfection is used to reduce the risk of pathogenic contamination or microbial species proliferation. Chlorine is a disinfection substance that is traditionally used due to its effectiveness and low cost. However, the use of chlorine has related disinfection by-products, some of which can have carcinogenic effects on human health (e.g., trihalomethanes, THMs). In this context, the objective of this paper is to compare different multi-objective optimization problem formulations to improve the operational interventions of WDSs, in order to reduce the formation of THMs in the network. The analysis of two case studies shows that operating valves is more convenient than operating hydrants and pumps in most of the proposed formulations.

Keywords: Optimization, drinking water quality, operational interventions

1 INTRODUCTION

Water distribution systems (WDSs) are networks of pressurized pipes that transmit drinking water from a source to the demand nodes. A paramount purpose of the utilities designated to manage it, in addition to the delivery of a proper quantity of the resource, is the public health protection by ensuring safe drinking water to the population. This aim can be achieved by the disinfection of water through reactive chemical agents [1], mainly chlorine compounds, which have the ability to guarantee a residual concentration in the WDSs and thereby to prevent possible pathogenic contamination downstream the treatment plant.

However, the disinfection of drinking water is not enough to keep water quality standards until it is delivered. In order to improve its effectiveness, it is also necessary to keep the water age in the network under “optimal” values. Indeed, an excessive residence time of water in the network can affect its quality by facilitating the formation of chemical by-products (DBPs) such as trihalomethanes [2], whose exposure also through non-ingestion routes has potential health consequences [3], and by increasing the re-growth of microbial species escaped from the treatment. For these reasons, reducing the time required for the water to travel from the sources to the users' tap is strongly recommended. This can be achieved by controlling the flow velocities in the pipes, for instance, by finding the optimal operation of valves, pumps and hydrants in the analysed system, for a specific demand scenario.

The purpose of the present approach is to improve the water quality in a WDS by formulating and solving a multi-objective optimization problem, in a similar fashion as [4]. In particular, in this study different formulations of the two objective functions, both to be minimized, have been introduced and compared in order to find the most efficient combination. The operation of valves, pumps and hydrants are considered as decision variables. The optimizer used in the present work is AMGA2 [5], coupled with the EPANET Programmers Toolkit functions implemented in a C++

script to run the hydraulic/water quality simulation and to evaluate the objective functions. AMGA2 is based on the theory of genetic algorithms, so it is considered as an evolutionary algorithm. The proposed approach is applied to two example case studies.

2 METHODS

The proposed method for the minimization of the THMs in a WDS has three main components: the OPTIMISER, the EVALUATION of the objective functions, and the ENGINE modelling the water distribution network. These three components can be seen in Figure 1. The optimiser that we used is AMGA2 [5], which is a multi-objective evolutionary algorithm. A multi-objective evolutionary algorithm is required because we are minimizing two conflicting objectives: the THMs and the number of operations. The result of such optimization is a Pareto front with a set of optimum solutions where none of them can be said is better than any other one. It is job of the stakeholders to select one of these solutions, the solution that best fit their interests.

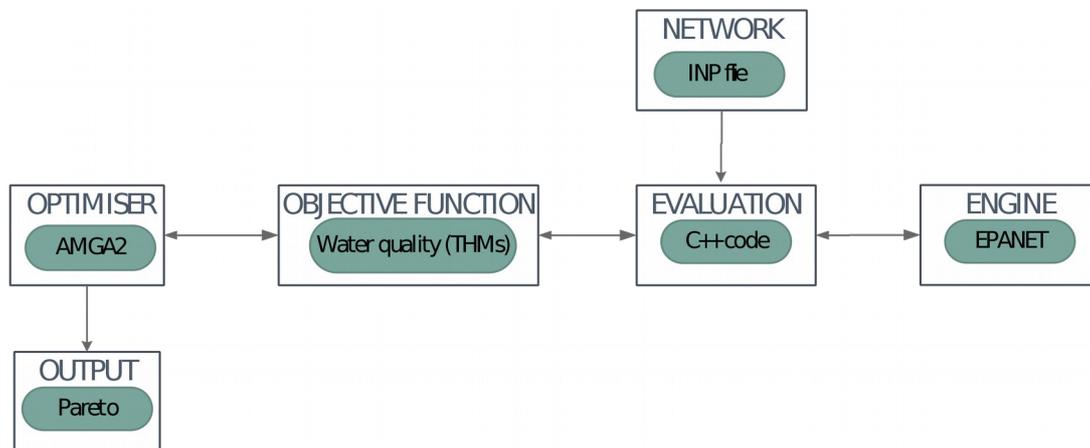


Figure 1 First level of abstraction of the components of the optimization

The component corresponding to the evaluation of the objective functions is carried out using C++ code that it is in charge of reading the combination of decision variables generated by the optimiser. This part is also responsible for the coordination of the operations requested to the engine to calculate the value of the objective functions. Finally, this component returns the value of these objective to be fed to the optimiser.

The component corresponding to the engine is EPANET [6]. This is a widely known software to model water distribution networks. The application programming interface (API) provided by this software is accessed by the evaluation component written in C++ code.

2.1 Water quality models

Different valid approaches have been presented in the literature to predict THMs concentration (e.g. [7], [8] and [9]). In this study, the equation (1), suggested in [10] and [11], has been used. In particular, it is based on numerical simulation results using kinetic models and allow to evaluate THMs formation trough chlorine consumption.

$$[THM_s] = [THM_s]_0 + D * ([Cl_2]_0 - [Cl_2]) \quad (1)$$

Where, $[THM_s]$ ($\mu\text{g/l}$) and $[Cl_2]$ (mg/l) are THMs and chlorine concentrations during time, $[THM_s]_0$ and $[Cl_2]_0$ are the initial THMs and chlorine concentrations, D ($\mu\text{g/mg}$) is the THMs yield coefficient.

In order to predict chlorine decay, the simple first order model has been used, as some authors [12] have demonstrated its good performances. Furthermore, it is assumed that chlorine is consumed only through a bulk reaction.

$$[Cl_2] = [Cl_2]_0 * e^{-k_b * t} \quad (2)$$

Where k_b (/h) is the bulk chlorine decay coefficient and t (s) is the time.

2.2 Multi-objective formulation problem

Objective functions

Two objective functions are considered in the formulation of the optimization problem, both to be minimized. In particular, as a first objective function (*Ob.F1*) the number of interventional operations (number of the decision variables with a modified status) or the volume flushed by hydrants have been used (3).

$$Ob.F1 = minimize \{(N.ops) \text{ or } (Vol)\} \quad (3)$$

The second objective function (*Ob.F2*) is the one that represent a global parameter of the water quality in the network and it has been defined through the evaluation of the maximum value of THMs, considering different formulations introduced and described in details in [12].

$$Ob.F2 = minimize \{max([THMs]_j), max(C_j^{THMs}), max(M_j^{THMs}), max(T_j^E), max(V_j^{c,n})\} \quad (4)$$

The parameters in Equation (4) represent, in order: the THMs time variable concentration ($\mu\text{g/l}$), the THMs average concentration, the mass of THMs delivered in each demand node when their concentration is above a required regulatory threshold, the exposure time (the time when the THMs concentration exceeds the limit value) and the normalized contaminated volume (it varies between 1, when all the water delivered is contaminated and 0, if the threshold is never exceed in that node). The last two parameters are considered in terms of the number of nodes with the maximum value of T_j^E (nn T_j^E) and of $V_j^{c,n}$ (nn $V_j^{c,n}$).

All the formulations have been evaluated by introducing a maximum THMs concentration fixed threshold and their formulation is deeply described in [13].

Decision variables

The formation of THMs can be controlled by changing the velocities in the network trough specific operations. In this study, valves, pumps and hydrants have been considered as decision variables. In particular, their status can assume the values 1/0, on the basis of the condition on/off for the pumps and open/close for the hydrants and the valves. In each of the experiments that will be presented in the following paragraphs, it has been supposed to turn on pumps and open the hydrants for a fixed number of hours during the simulation, while once the valves have been closed they keep the new status for the whole simulation time.

Constraints

The operational interventions in the system have to satisfy the users' demand in terms of quantity and quality conditions. For this reason is mandatory to define constraints on pressure, that has to be

maintained in a fixed range (5), and on chlorine residual concentration on the consumption points (6).

$$Cl_{2j} \geq Cl_2^{min} \quad (5)$$

$$P_{min} \leq P_j \leq P_{max} \quad (6)$$

2.3 Description of the experiments

In order to solve the multi-objective optimization problem presented herein, different formulations of the objective functions were considered and compared to select the best performance. In addition, also other settings, such as the node base demands and the initial THMs concentration, have been modified from an experiment to another to improve the methodology.

As regards the experiment A, it has been applied only to the small network (Figure 2) in order to define which one of the formulations of THMs exposure was more efficient to solve the optimization problem. The experiments B, C and D have been done for both the case studies, but herein only the ones related to the Case study 2 will be illustrated (Table 1).

Table 1 Summary of the experiments

Experiment	Ob.F1	Ob.F2	Number of decision variables	Case of study
A	N.ops	[THMs] _j max, M _j ^{THMs} max, C _j ^{THMs} max, nn T _j ^E max, nn V _j ^{cn} max	7	1
B	N.ops	[THMs] _j max	18	2
C	Vol	[THMs] _j max	29	2
D	N.ops	M _j ^{THMs} max	92	2

In the case study 2 different decision variables have been used from one experiment to another. The criteria used to select the elements to be operated were related to considerations reading the velocities in the network and the diameter of the pipes. While for the case study 1 the number of decision variables is fixed for all the experiments.

The experiment C is characterized mainly by a different definition of the Ob.F1, passing from the number of operations to the total volume flushed in 6 hours by the hydrants, in order to check if solutions without the use of the hydrants are feasible. Furthermore, the node base demands have been reduced to prove how the velocities in the network can affect the results of the procedure.

We notice that without any intervention in the network (what it is defined as the initial status), the THMs are high during low user demand, generating a peak in the level of THMs. It is for that reason that in the experiment D we decided to try reducing the THMs by releasing water via the hydrants with a pattern that it is opposite to the pattern of the user demand. In addition, also the time length for the opening of the hydrants has been explored.

3 ANALYSIS AND RESULTS

3.1 Case studies and characteristics of the performed simulation

In Figure 2 the scheme of the simple case study [4] is presented. It consists of a network characterized by 25 demand nodes (all with the same base demand and constant demand pattern), one reservoir and 41 pipes (all with the same length and diameter). In this case study the elements

that can be operated are valves (from V1 to V5) and hydrants (H1 and H2), for 7 decision variables in total.

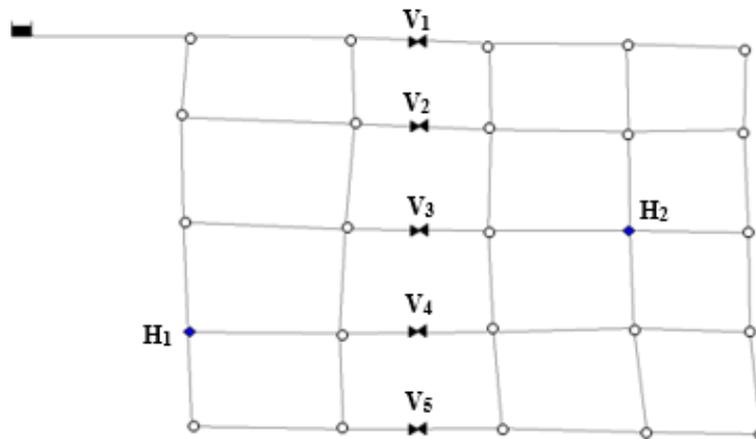


Figure 2 Scheme of the Case study 1

In case study 2, represented in Figure 3, water is supplied from 4 reservoirs, treated in the same treatment plant and therefore characterized by the same initial water quality. In this scheme there are 259 demand nodes and 373 pipes. The total number of decision variables is 92 (30 hydrants, 60 valves and 2 pump stations), even though in some of the experiments only few of them have been selected and considered to solve the optimization problem.

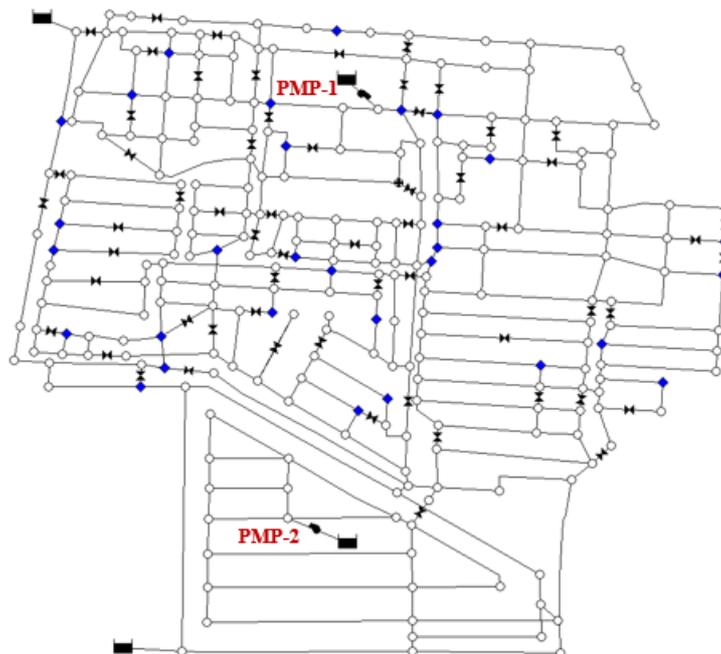


Figure 3 Scheme of the Case study 2

In the initial condition of both case studies, the objective functions are evaluated considering all the valves open (status set to 1) and all pumps and hydrants closed (status set to 0). The hydraulic and water quality simulations are performed using the EPANET 2 Toolkit functionalities. The total simulation time is three days in order to let the network models reach the steady conditions. Regarding the time of the operational interventions, pumps and hydrants are open

for few hours while the valves remain closed until the end of the analysis, due to the issue that opening hydrants and pumps implies high costs for water utilities, related to the loss of treated resource and the consume of energy.

The water supplied is supposed to be disinfected through sodium hypochlorite, injected with a constant dosage in the reservoirs.

3.2 Results

Table 2 (a) and (b) summarizes the results obtained by the experiment A, where all the formulations of the exposure of the users to THMs were explored using the case study 1. In particular, in Table 2 (a) the status of the decision variables for the six solutions (from “a” to “f”) is represented; while Table 2 (b) shows the value of Ob.F1 and Ob.F2.

Table 2(a) Results of the experiment A

Solution	Element ID						
	V7	V5	V4	V3	V2	H2	H1
a	1	1	1	1	1	0	0
b	1	1	1	1	1	1	0
c	1	0	1	1	1	0	1
d	1	1	1	0	1	1	1
e	0	1	1	0	1	0	1
f	0	1	0	0	1	0	1

Table 2(b) Results of the experiment A

Solution	Ob.F1	Ob.F2				
	N.ops	[THMs] _j max (µg/l)	M _j ^{THMs} max (µg)	C _j ^{THMs} max (µg/l)	nn T _j ^E max	nn V _j ^{cn} max
a	0	40.14	645749	39.95	10	10
b	1	34.42	398937	34.23	9	9
c	2	33.41	354862	33.21	7	7
d	3	/	/	/	5	5
e	3	33.16	344382	32.97	/	/
f	4	32.31	305683	32.08	/	/

In general, all the analysed formulations can be considered as efficient objective functions for the proposed multi-objective optimization problem, as they allow to get an improvement of water quality in the network. In particular, the maximum value of THMs in terms of average and instantaneous concentration moves from an initial condition of 39.9 and of 40.14 (µg/l), respectively, to 32 (µg/l). Also in terms of mass the improvement obtained is significant. In the other hand, according to the results of the experiment, the exposure time (T_j^E) and the normalized contaminated volume (V_j^{cn}) are totally equivalent.

Based on the results obtained in the experiment A, it has been chosen to run the other experiments considering two formulations of the Ob.F2: the instantaneous concentration ([THMs]_j), whose high

values can be considered an evidence of a likely dangerous exposure, and the mass (M_j^{THMs}), which gives information on the amount of users involved.

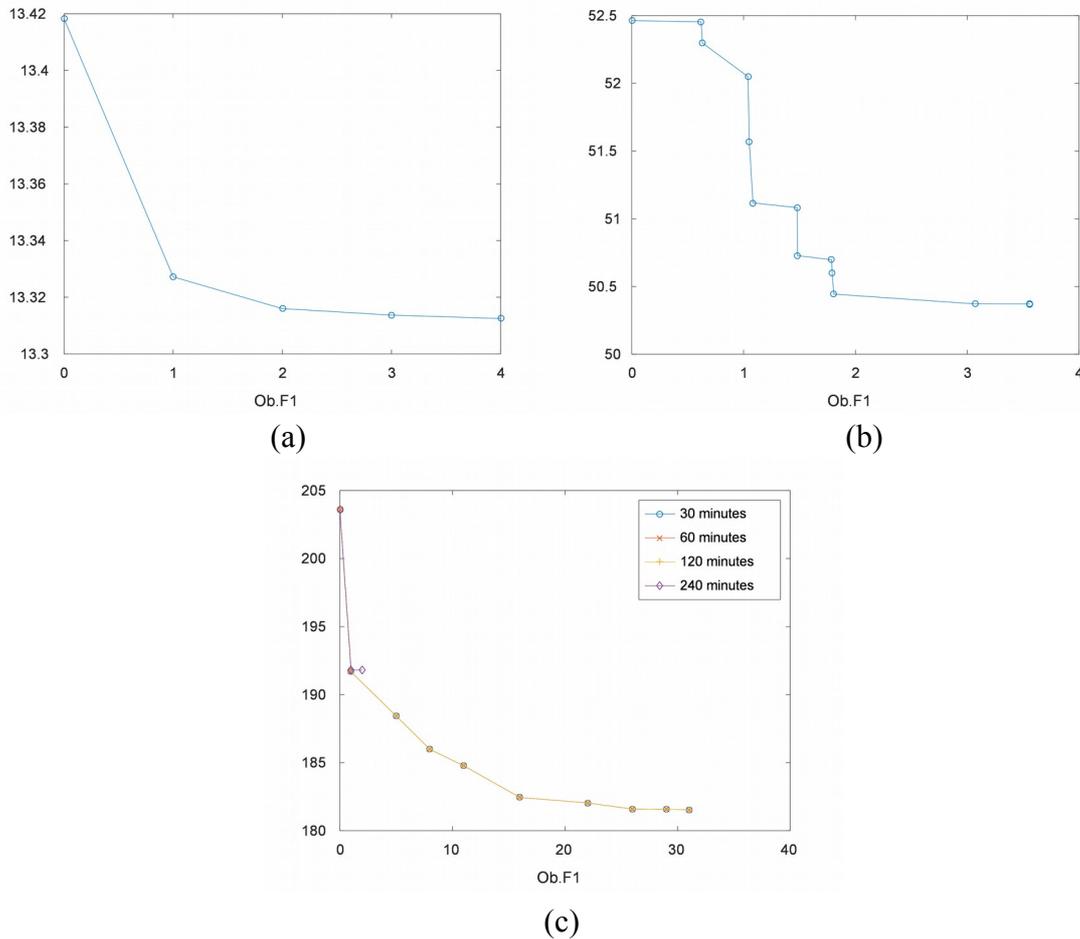


Figure 4 Results of the experiments B, C and D

From the Figure 4(a), related to the experiment B, we can see that the biggest reduction of THMs is after 1 operation, the rest of the operations make a marginal reduction of THMs. Nevertheless, it is evident that the optimization cannot improve much the situation of the network because the reduction of THMs is 0.11 $\mu\text{g/l}$ even after 4 operations.

As regards the experiment C, the results illustrated in Figure 4(b) show that it is possible to improve the water quality also without the use of hydrants and pumps; indeed, from an initial value of 63.8 $\mu\text{g/l}$ of THMs, through the operation of 9 valves the final maximum value is 52.5 $\mu\text{g/l}$. Furthermore, it is also clear that the influence of the velocities in the network (and so the demands) is significant for the good performance of the proposed methodology. In the experiment D we see that there is an improvement by opening the hydrants following a pattern that it is the opposite to the pattern of the user demand as can be seeing in the Figure 4(c). We saw that the peak of THMs had a time span of 4 hours, so that our next question was: Is it necessary to open the hydrants during those 4 hours. We tried with 4 time spans: 30, 60, 120, and 240 minutes. All of them coinciding with the beginning of the peak of THMs. We found exactly the same Pareto front for the durations of 30, 60, and 120 minutes. And unexpectedly we saw that opening the hydrant during 240 minutes (4 hours), it is no so good as opening it for less time, because the optimization just found basically one operation to reduce the number of THMs (with two operations the improvement is very marginal, as it can be seeing in the Figure 4(c)).

4 CONCLUSIONS

A comparison of different multi-objective optimization problem formulations to improve the operational interventions of WDS was presented. The comparison was framed having the goal of reducing the formation of THMs in the networks. The analysis of two case studies shows that operating valves is generally more convenient than operating hydrants and pumps.

In general, the deterioration of water quality is related to the increasing of the residence time of water in the network. For this reason, current research is focused in using water age as a simpler parameter globally representative of the quality in WDSs, for the formulation of an optimization problem similar to the one presented herein.

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