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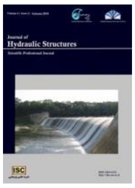

# Smart Pressure Management in Urban Water Distribution Networks for Firefighting

Saghar Ahmadian[1]
Adell Moradi Sabzkouhi[2]
Ali Haghighi[1]
Mohammad-Hadi Ranginkaman[3]

## Abstract

The rapid population growth and urban development have notably influenced the role of water distribution networks (WDNs) compared to the past. This issue encourages operators to adopt new smart tools to better system management. Such a smart system is expected to play an effective role in both crisis and normal services. For fire extinguishing services, a WDN needs to be well-equipped to supply the fire flow efficiently. In this sense, WDNs are required not only modern fire-fighting equipment but also a systematic program to satisfy the fire demand in the right place at the right time. This paper aims at introducing a pre-processing (not real-time) approach for smart pressure management using the regulation of control valves. The problem is formulated as a mathematical programing in which the reliability measure is maximized and the valve opening positions are decision variables. Using a self-adaptive Genetic Algorithm coupled with EPANET, the problem is solved. The proposed algorithm is applied to a case study from the literature and produces the optimum pattern for regulation of valves. Such results can be an appropriate guide for operators to practically maneuver valves in fire situation. The case study manifests that by applying the model the reliability of system can be increased up to 40.7%.

**Keywords:** Water Distribution Network, Fire Extinguishing, Smart Pressure Management, Reliability, Optimization.

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[1] Department of Civil Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran.
[2] Department of Water Engineering, Agricultural Sciences and Natural Resources University of Khuzestan,Iran. AdellMoradi@asnrukh.ac.ir **(Corresponding author)**
[3] ABNIROO Bandar Imam Petrochemical Co., Khuzestan, Iran.

## 1. Introduction

Water distribution networks (WDNs) have traditionally played a major role in suppling potable water with sufficient quantity and quality. In modern cities nowadays, urban development and modernization have caused the performance of WDNs to become more important and complicated. While the number of fire events has increased with the development of commercial areas, heavy traffic may reduce the chance of successful fire extinguishing activities. In such a condition, a reliable pipe network could effectively improve the performance of firefighting activities if its hydraulic features are well recognized and the components are properly operated in a crisis. In this regard, WDNs are required not only modern fire-fighting equipment but also sophisticated management of infrastructure to satisfy water demands for firefighting in the right place at the right time.

Smart pressure management of WDNs in fire events could be defined as the measures systematically forcing the system's dynamic elements to change their status in order to reliably supply fire flow for hydrants located around the site involved in fire. Such pressure management, at the same time, should maintain an acceptable and safe range of service pressure in other normal sites. In fact, the pressure management in WDNs for the control of fire, is somewhat similar to the pressure management for water loss control in terms of tools and methodology, but differs in terms of objective. Although, pressure management is not a new concept in WDNs operation, its components and the ways of implementation may be different based on the objectives and facilities.

This study aims at introducing a systematic pre-processing approach for optimally operating the control valves' maneuver in pipe networks for firefighting purposes. The model deals with smart pressure management using the regulation of valves as a function of the fire time and place. The method supposes that because of limitations in telemetric data acquisition and transmission system, the input data of nodal water demand is not real-time. On this basis, the problem is formulated as a mathematical programing in which the maximization of the fire node reliability is the objective function and the control valve settings in five different opening levels are the decision variables. Since the water consumption changes during a 24-hour period, a demand prediction model is required to incorporate the water consumption variations into the main model. Nonetheless, this study simply assumes that the network has nodal consumptions that are temporally varied but known as a diurnal demand pattern. Hence, for each junction at every time step, it is needed to successively solve the arisen single objective optimization problem to achieve the optimal operating of valves in all cases of the fire place and time.

## 2. Background

### 2.1. Pressure Management in WDNs

Pressure management (PM) in WDNs is mainly based on control of the pressure head as a means to restrict water leakage and losses [1-4]. There are, however, some other aspects regarding PM with different objectives. For instance, PM may be carried out for energy management [5], water consumption management [6], urban water rationing in the case of drought or natural disasters [7-10], uniformity in distribution of irrigation water on farms [11,12], etc. In the above-mentioned applications, PM is chiefly implemented using pressure reduction in order to manage the outflow from the network. On the other hand, in a few other applications, PM can also be applied to boost the local pressure in target zone(s) for special objectives such as releasing the unconventional contaminants from the network [13] or promoting the system's reliability for water supply in fire events. In the recent application, PM consists of measures taken to safely maximize the pressure head of the fire node, maintaining an acceptable level of reliability for normal junctions using the maneuver of control valves and/or the operation of pressure supply apparatus (pumps and drives). Although, this application of PM may require a short operational duration, it would greatly influence the reduction of human loss and financial cost.

PM is normally imposed on WDNs, by either pressure control devices, such as pressure reducing valves, PRVs,[2,6,14-17], throttle control valves, TCVs, [18], isolation valves [19], pressure supplying apparatus, such as constant or variable speed pumps [20], or a combination of valves and pumps [21]. The PM may be implemented simply based on the experiences in operating and/or simulation of the system [22] or exploiting state-of-the-art simulation-optimization techniques [19]. The complexity of a pipe network's operation in different situations leads to the use of advanced modeling techniques to conduct a reliable PM. For this purpose, the application of Artificial Intelligence in smart tools is very helpful [6,23].

## 2.2. Hydraulic Performance of WDNs

The desirability of a WDN's performance under normal and emergency conditions like fire extinguishing services, is mostly evaluated based on the concept of Reliability or its dependence measures. According to the literature, there are various measures related to the reliability of WDNs. Gulter [24] defined the term of reliability as the network's ability to supply the demand for water under failure conditions. A classic method for determining the reliability in WDNs [25] depends upon the scenario under which the system is assumed to fail. Such a complexity often makes the designers consider the reliability measures rather than the reliability itself. Some more practical measures include Redundancy [26, 27], Entropy [28], Available Surplus Pressure Head [29], Resiliency [30], Vulnerability [31], etc. Since the hydraulic performance of WDNs in fire events is associated more with the pressure head of the fire node, the present paper adopts and redefines the Available Surplus Pressure Head [29] as the measure of reliability of the system under a fire condition. Moreover, the methodology presented here accepts a minimum service pressure head,$(H_{min})_{S,}$, to be satisfied for other normal junctions during the fire control, considered in the constraints of the mathematical programming.

## 2.3. Optimization Approach in Pressure Management of WDNs

Optimization, especially the modern optimization techniques based on meta-heuristic algorithms provide powerful tools for the hydro-systems planners to explore the optimal scenario in design and operation phases based on desired objective function(s) under different types of constraints. The application of meta-heuristics in PM of pipe networks has mainly focused on leakage control and unaccounted-for water. Hindi & Hamam [23], Reis et al. [32], Savic & Walters [33], and Araujo et al. [1] scheduled for optimal location of valves to minimize the leakage. Nicolini & Zovatto [34] planned a pressure management model to lower the leakage by optimal location of control valves using a multi-objective optimization. The model optimized the installation positions as a function of the number of valves. Through the same research, Ali [18] simultaneously optimized the valves location and openings as a function of the number of valves. Comparing the two recent works, there was less effort at the simulation runs for the latter since it simultaneously assessed the valve optimal location and opening. Thereafter, putting the hydraulically more effective pipes forward as candidates of valve installation locations, Ali [18] shrank the decision search space. Creaco & Pezzinga [19] showed that the simultaneous consideration of the problems of pipe replacement and optimal control valve locations would be more successful in reducing leakage in pipe networks.

Using a hydraulic simulation model coupled with a self-adaptive Genetic Algorithm, the present study introduces a pre-processing pressure management framework to determine the optimum opening of TCVs in WDNs to maximize the pressure head at the fire node quickly and safely. As far as the literature review shows application of GAs for PM has not yet been used to boost local pressure for more reliable firefighting purposes. The performance of the proposed approach is investigated using a benchmark pipe-network from the literature and the results are discussed.

## 3. Governing Equations

The equations governing the hydraulics of water distribution networks, include the conservation of mass and energy in junctions and closed loops, respectively. The law of mass conservation in junctions' states:

$$\sum_{i=1}^{NP(j)} Q_{ij} - q_j = 0, \qquad for\ j = 1\ to\ NN - 1 \tag{1}$$

where $Q_{ij}$ represents the discharge in the pipe $ij$ connecting node $i$ to $j$, $NP(j)$ is the number of pipes connected to Node $j$, $q_j$ shows the demand flow in Node $j$, and $NN$ is the total number of nodes in the network. The law of energy conservation in the closed loop $l$ is as follows:

$$\sum_{j=1}^{np(l)} h_{lj} + \sum_{j=1}^{np(l)} Hv_{lj} - \sum_{j=1}^{np(l)} HP_{lj} = 0 \qquad for\ l\ = 1\ to\ NL \tag{2}$$

where $NL$ is the number of loops in the network, $np(l)$ is the number of pipes in Loop $l$, $h_{lj}$ represents the friction head loss in the $j^{th}$ pipe of Loop $l$, and $HP_{lj}$ and $Hv_{lj}$ are the rise and drop in the energy along the $j^{th}$ pipe of Loop $l$ due to pump and fittings (e.g. valve), respectively. The sign of $h_{lj}$ could be either positive or negative depending on whether the energy is dissipated or increased along Pipe $j$, clockwise around Loop $l$. These two sets of equations are linked to each other using proper friction and minor head loss equations to incorporate the resistance to the fluid flow. For friction head loss, the theoretical Darcy–Weisbach and empirical Hazen–Williams equations are two better-known formulas applied in computer models. However, the Hazen–Williams formula is more commonly used especially in the case of water distribution networks due to its simplicity. The Hazen–Williams equation is as follows:

$$h_l = \frac{\omega L Q^{\alpha}}{C^{\alpha} D^{\beta}} \tag{3}$$

where $L$, $D$, $Q$, and $C$, respectively, represent the length, diameter, discharge, and the Hazen–Williams coefficient of the pipe and $\alpha$, $\beta$, and $\omega$ are empirical coefficients being 1.852, 4.87, and 10.667 (in SI metric units), respectively. The minor head loss is generally taken into account using the following equation:

$$Hv = k\,{}^{v^2}\!/_{2g} \tag{4}$$

where $k$ is the valve or fitting head loss coefficient and ${}^{v^2}\!/_{2g}$ denotes the kinetic energy of the flow.

To analyze the hydraulics of a pipe network, Equations (1) and (2) along with Equation (3) and (4) form a system of nonlinear equations that must be solved to specify the unknowns, i.e. the nodal heads and flow in pipes. The present article exploits EPANET [35] hydraulic simulation model to analyze the WDNs.

## 4. Methodology

In this paper, the maximization of the reliability measure in a fire node is attained using a simulation-optimization framework to optimally maneuver the TCVs installed in the network. The setting of each TCV is the head loss coefficient, $k,$ which relates the head loss, $Hv,$ to the kinetic energy of flow passing through the valve, ${}^{v^2}\!/_{2g}$ , as expressed in Equation (4). Using the TCV’s regulation, the system determines how the flow in pipes should be distributed to attain optimum hydraulic performance in any given fire node. Under such conditions, the optimum reliability of the system guarantees that the fire flow, as a model input parameter considered to be 15 $lit/sec$ in this study, would be satisfied, while the system fulfils a minimum acceptable predefined service pressure for other normal junctions (not engaged in fire). The proposed method requires a 24-hour demand predicting input model, to load the demand for normal junctions, which is assumed to be known in this study. Using a SCADA system and its essentials, the proposed method is capable of incorporating a data collecting module and a hardware framework for real-time application. However, this study assumes that input demand data is not real time which leads to the post-processed output results.

It is possible to schedule the above stated nonlinear problem as a continuous or a discrete mathematical programing problem. In the continuous form, the valves’ head loss coefficients ($k$) are taken into account as real number decision variables whose values could vary from near zero, i.e. fully open to infinity, i.e. fully closed. This form of representation of decision variables seems to make the decision space too large. In this regard, the primary tests in the present study demonstrated that the final results of continuous optimization were not promising (see results of the illustrative example). In the latter form, however, the continuous opening-head loss curve of TCVs (available from the valve manufacturer) is cut over some discrete levels. In this study, we have adopted the opening-head loss curve of TCVs reported by Kang and Lansey [13], shown in Fig. 1, and considered five discrete levels for head loss coefficients, including $k \approx 0$, i.e. fully open; $k = 320$, i.e. ${}^3\!/_4$ open; $k = 1270$, i.e. ${}^1\!/_2$ open; $k = 8300$, i.e. ${}^1\!/_4$ open; and $k = 10^6$, i.e. fully closed.

### 4.1. Mathematical Formulation

#### 4.1.1. Objective Function

The objective function for the above stated problem is the reliability measure based on the Surplus Pressure Head concept introduced by Walski and Gessler [29]. While the proposed classic method of calculating surplus pressure head [29] evaluates the reliability index throughout the network, we exclusively redefine it here to conceptually calculate the same measure, but only for the node engaged in fire as follows:

$$IS_t^j = H_{j,t}^j - H'^j_{j,t} \tag{5}$$

where $IS_t^j$ represents the surplus pressure head in a fire flow load condition for the fire node $j$ at any given fire time $t = 1\ to\ 24hr$, and $H_{j,t}^j$ and $H'^j_{j,t}$ are the pressure head in a fire flow load condition for fire node $j$ at time $t$, respectively with and without the TCVs' maneuver. In this article for all parametric terms, the letters in superscript point out the node engaged in fire. It is evident that maximizing $IS_t^j$ provides an optimal hydraulic condition to deliver fire flow with the highest level of reliability.

### 4.1.2. Decision Variables

Fig. 1 shows the variation of head loss coefficient as a function of TCVs' opening [13]. In the discrete form of the mathematical formulation of the above nonlinear problem, the decision variables are TCVs' head loss coefficients each has five alternatives to choose from including: $k \approx 0$, i.e. fully open; $k = 320$, i.e. $^3/_4$open; $k = 1270$, i.e. $^1/_2$open; $k = 8300$, i.e. $^1/_4$open; and $k = 10^6$, i.e. fully closed. Based on these assumptions, if the fire would have taken place in node $j$ at time $t$, each decision vector $K_t^j$ is:

$$K_t^j = \left[k_{1,t}^j, k_{2,t}^j, \dots, k_{i,t}^j, \dots, k_{NV,t}^j\right] \quad \text{for } j = 1\ to\ NN\ \&\ t = 1\ to\ 24\ hr \tag{6}$$

where $k_{i,t}^j$ is the head loss coefficient of Valve $i$ for the case of fire Node $j$ and fire Time $t$, $NN$ is the number of junctions and $NV$ is the number of TCVs. As the head loss coefficients are already converted into five different discrete values, each component of $K_t^j$ is picked up from the set$\{0, 320, 1270, 8300, 10^6\}$.

### 4.1.3. Constraints

There are two types of constraints in this mathematical programming problem. The first one is associated with the governing equations of mass balance in junctions and energy balance in closed loops as discussed in Section 3. These constraints are systematically handled by the simulation model, EPANET. The second type of constraint relates to the hydraulic performance of the network during fire extinguishing services. In the present study, we have considered two performance criteria; the minimum service pressure head, $(H_{min})_{S,}$ in all normal junctions (junctions not engaged in fire) and the maximum allowable pressure head, $H_{max}$. In fact, $(H_{min})_S$ guarantees that during fire control measures, the nodal reliability in other $NN - 1$ normal junctions would not be lowered to a minimum acceptable pressure defined by the user. The first performance constraint not only satisfies a minimum level of hydraulic desirability for the whole network but also validates the application of demand driven analysis approach. While $(H_{min})_S$ limits the lower bound of pressure head of the network, $H_{max}$, controls the upper allowable pressure head so that the model does not produce any nodal pressure exceeding the maximum tolerable limit of the network's components. On this basis, the performance constraints for a fire event in any given node $j$ at time $t$ are as follows:

$$H_{i,t}^{j} \geq (H_{min})_S \qquad for\ i = 1\ to\ NN \tag{7}$$

$$H_{i,t}^{j} \leq H_{max} \qquad for\ i = 1\ to\ NN \tag{8}$$

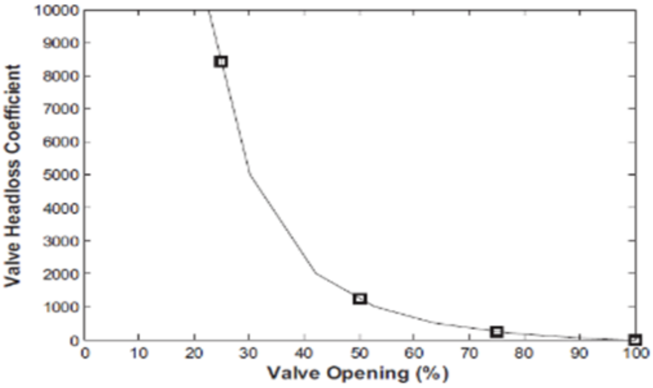

**Figure 1.Throttle control valve head loss coefficient as a function of valve opening (Kang and Lansey, 2010).**

Finally, the mathematical formulation for maximization of surplus pressure head of fire node $j$ at time $t$ is:

$$Maximize\ IS_t^j = \varphi\left(K_t^j\right)$$
$$K_t^j = \left[k_{1,t}^j, k_{2,t}^j, \dots, k_{i,t}^j, \dots, k_{NV,t}^j\right]$$
$$\text{Subject to:} \tag{9}$$
$$H_{i,t}^{j} \geq (H_{min})_S \qquad for\ i = 1\ to\ NN$$
$$H_{i,t}^{j} \leq H_{max} \qquad for\ i = 1\ to\ NN$$

where $\varphi$ is the hydraulic simulation model, EPANET, which calculates the objective function, $IS_t^j$,against each candid solution, $K_t^j$.

## 4.2. Simulation-Optimization Framework

The conceptual model presented in Fig. 2 was used to solve the above mathematical programming problem. As seen in this figure, the main framework includes simulation and optimization boxes. First, the hydraulic simulation model is developed in EPANET based on the configuration and technical data, and then normal demands at probable fire time are loaded based on a nodal demand forecasting model. In the optimization box, a discrete single-objective optimization Genetic Algorithm is developed in MATLAB 2011b environment and connected to the simulation model. Then, an initial population consisting head loss coefficients of TCVs is generated. This population matrix is transferred to the simulation model box to evaluate the objective function,$IS_t^j$, and the violation of performance constraints. Prior to the individuals' assessment, depending on the time $(t)$ and place $(j)$ of the fire event, the demand in the fire node increases to satisfy the required fire flow, $q_f$. Afterwards, the population returns to the GA box. In the GA box, based on the values of objective functions and violations, the individuals' ranking is updated and the GA's operators are imposed to reproduce the next generation. This new population is then resent to the simulation box for assessment. The above process continues until the convergence is met and the best setting for each TCV is achieved. After execution of the model alternatively against all possible fire nodes $j = \ to\ NN$ and fire time t=1 to 24 (i.e. $NN \times 24$ iterative optimization runs), a data base (e.g. as a cross-reference table) of the optimum openings of TCVs to any possible single fire event in nodes $j$ $(j = 1\ to\ NN)$ at times $t$ $(t = 1\ to\ 24)$ is provided to use in emergency fire condition.

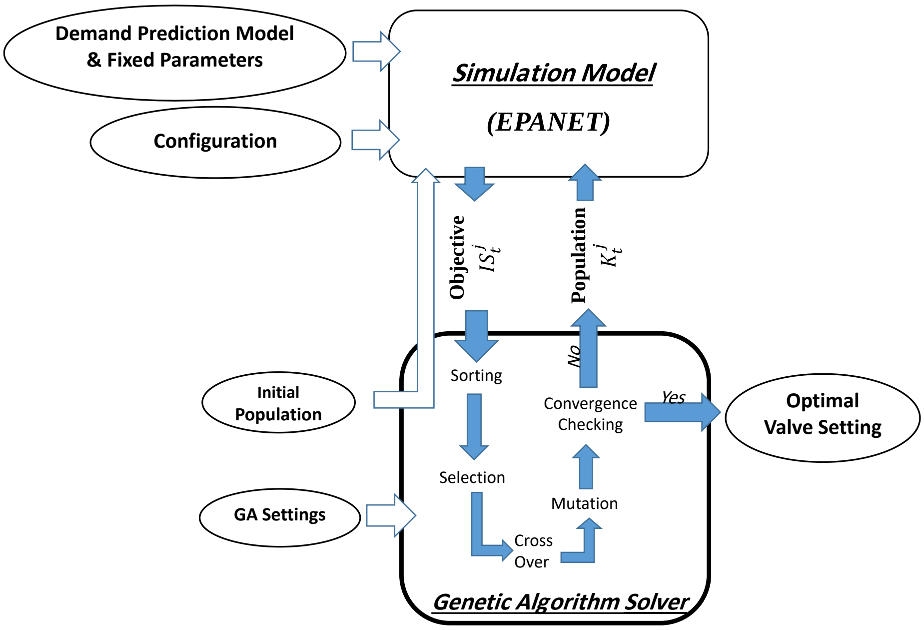

**Figure 2.Simulation-optimization conceptual framework**

## 4.3. Constraint Handling

As discussed in Section 4.1, in this study the scheduling of optimal regulation of TCVs in the case of fire extinguishing services, consists of physical or hydraulic constraints automatically handled by the simulation solver, and performance constraints controlling the pressure head of normal junctions to meet the minimum service pressure head, $(H_{min})_S$, and the maximum allowable pressure head, $H_{max}$, during the firefighting activities. Since the two above performance constraints have the same dimension, the total violation for each decision vector would be the sum of violations of each performance constraint in all junctions as follows:

$$V_t^j = \sum_{i=1}^{NN} Max(0, [(H_{min})_S - H_{i,t}^j]) + \sum_{i=1}^{NN} Max\left(0, \left[H_{max} - H_{i,t}^j\right]\right) \tag{10}$$

where $V_t^j$ is the total violation of the decision vector in the case of fire node $j$ and fire time $t$. The recent combined violation is self-adaptively handled using a tournament selection operator in GA. This selection operator, picks up the parents from the mating pool based on comparing both the objective function and the violation of chromosomes being candid for cross-over. In this regard, if the chromosomes $x$ and $y$ are candid to select, the winner will be:

- $x$ if $x$ is feasible and $y$ is infeasible
- $x$ if $x$ and $y$ both are infeasible and $(V_t^j)_x < (V_t^j)_y$
- $x$ if $x$ and $y$ both are feasible and $(IS_t^j)_x > (IS_t^j)_y$

While handling the constraints using the common approach based on the penalty function concept, usually suffers from many restrictions related to the penalty factor [36,37], the approach applied here, adaptively handles the constraints making the convergence much faster in the optimization process.

## 5. Illustrative Example

### 5.1. Network's configuration and components

To evaluate the performance of the proposed model, it is applied to Anytown pipe network, a benchmark water distribution system from the literature as shown in Fig. 3 [38] with some minor modification to its hydraulic components. The distribution system consists of two reservoirs, three pumps, 33 pipes, and 16 consumption nodes, all exposed to potential fire risks. A check valve installed on Pipe 33 prevents backflow from the network into Reservoir 19. The data of pipes and junctions are given in Tables 1 and 2, and the reservoirs' and pumps' details are presented in Tables 3 and 4. It is assumed that corresponding to each pipe, there exists a TCV with a known head loss coefficient opening relationship as shown in Fig.1 [13]. In this study, five discrete valve settings are allowed including fully closed, ¼ open, ½ open, ¾ open, and fully opened.

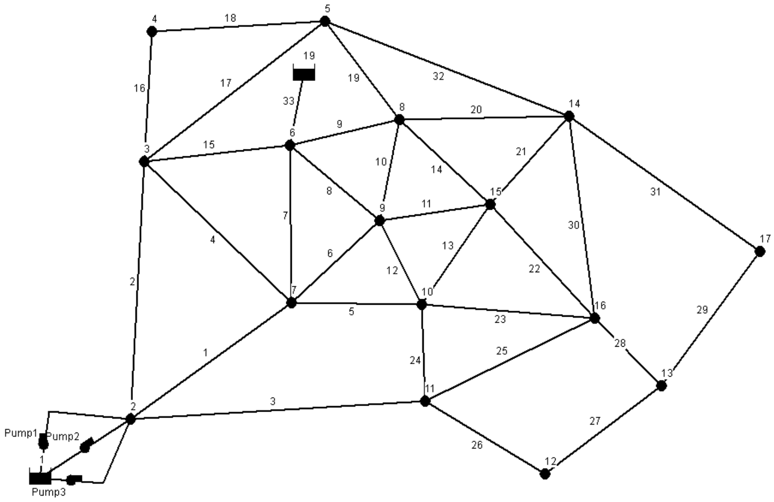

Figure 3. Anytown pipe network layout

**Table 1. Anytown network pipe data**

| Pipe No. | Upstream node | Downstream node | Length (m) | Diameter (mm) | HW roughness coefficient | Pipe No. | Upstream node | Downstream node | Length (m) | Diameter (mm) | HW roughness coefficient |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 2 | 7 | 3657 | 406 | 120 | **18** | 4 | 5 | 1830 | 254 | 120 |
| **2** | 2 | 3 | 3657 | 406 | 120 | **19** | 5 | 8 | 1830 | 254 | 120 |
| **3** | 2 | 11 | 3657 | 406 | 120 | **20** | 8 | 14 | 1830 | 254 | 130 |
| **4** | 3 | 7 | 2743 | 305 | 70 | **21** | 14 | 15 | 1830 | 203 | 130 |
| **5** | 7 | 10 | 1830 | 305 | 120 | **22** | 15 | 16 | 1830 | 203 | 90 |
| **6** | 7 | 9 | 1830 | 254 | 70 | **23** | 10 | 16 | 1830 | 305 | 90 |
| **7** | 7 | 6 | 1830 | 305 | 70 | **24** | 10 | 11 | 1830 | 203 | 90 |
| **8** | 6 | 9 | 1830 | 254 | 70 | **25** | 11 | 16 | 1830 | 254 | 90 |
| **9** | 6 | 8 | 1830 | 305 | 70 | **26** | 11 | 12 | 1830 | 203 | 90 |
| **10** | 8 | 9 | 1830 | 254 | 70 | **27** | 12 | 13 | 1830 | 203 | 130 |
| **11** | 9 | 15 | 1830 | 254 | 70 | **28** | 13 | 16 | 1830 | 254 | 130 |
| **12** | 9 | 10 | 1830 | 254 | 70 | **29** | 13 | 17 | 1830 | 203 | 130 |
| **13** | 10 | 15 | 1830 | 305 | 70 | **30** | 14 | 16 | 1830 | 203 | 130 |
| **14** | 8 | 15 | 1830 | 254 | 90 | **31** | 14 | 17 | 3656 | 203 | 130 |
| **15** | 3 | 6 | 1830 | 254 | 120 | **32** | 5 | 14 | 3656 | 203 | 130 |
| **16** | 3 | 4 | 1830 | 254 | 120 | **33** | 18 | 6 | 30.5 | 305 | 110 |
| **17** | 3 | 5 | 2743 | 254 | 120 | | | | | | |

**Table 2. Anytown network node data**

| Node No. | Elevation (m) | Demand (L/s) |
|---|---|---|
| 2 | 6.23 | 31.51 |
| 3 | 15.24 | 12.52 |
| 4 | 15.24 | 12.52 |
| 5 | 15.24 | 31.51 |
| 6 | 15.24 | 50.9 |
| 7 | 15.24 | 31.51 |
| 8 | 15.24 | 31.51 |
| 9 | 15.24 | 63.83 |
| 10 | 15.24 | 12.52 |
| 11 | 15.24 | 12.52 |
| 12 | 36.6 | 31.51 |
| 13 | 36.6 | 12.52 |
| 14 | 24.4 | 12.52 |
| 15 | 36.6 | 12.52 |
| 16 | 36.6 | 31.51 |
| 17 | 36.6 | 12.52 |

**Table 3. Anytown reservoir data**

| Reservoir ID | Description | Elevation (m) |
|---|---|---|
| 1 | Reservoir | 3.04 |
| 19 | Reservoir | 77.7 |

**Table 4. Anytown pump data**

| Pump No. | Upstream node | Downstream node | QH curve | |
|---|---|---|---|---|
| | | | Q (l/s) | H (m) |
| 1 | 1 | 2 | 0 | 91.4 |
| | | | 252.5 | 82.3 |
| | | | 504.7 | 55.2 |
| 2 | 1 | 2 | Same as above | |
| 3 | 1 | 2 | Same as above | |

## 5.2. Modeling Assumptions

The following assumptions are made in this case study:

a. To model Anytown WDN in its normal load condition, the diurnal demand pattern illustrated in Fig. 4 is supposed to be established in all demand nodes. It should be noted that the proposed model is able to be incorporated in an online data measuring and demand prediction system for real-time operation.

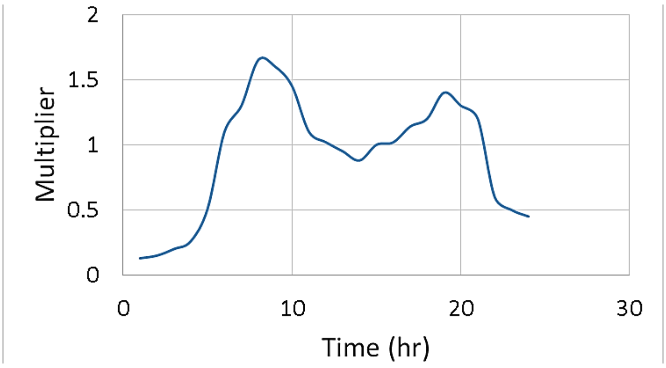

**Figure 4. Hypothetical diurnal demand pattern for Anytown network.**

b. The demand driven analysis (DDA) approach is acceptable to simulate hydraulics of the pipe network. This presumption will be automatically satisfied since the performance constraint of the minimum service pressure head, $(H_{min})_S$, does not permit any pressure deficit to happen for normal junctions during fire extinguishing service.

c. It is supposed that a TCV is installed on each pipe of the system, meaning that the problem consists of 33 decision variables, i.e. 33 head loss coefficient of TCVs each having five options for opening.

d. The minimum service pressure head, $(H_{min})_S = 10\ m$, and the maximum allowable pressure head, $H_{max} = 90\ m$, in all normal junctions are taken into account in this case study.

e. It is assumed that there is a single-fire event with one-hour duration happening in the network. The quantity of this single-fire flow, $q_f$, is assumed to be equal to $15\ lps$.

## 5.3. GA Parameters Calibration

To efficiently utilize any meta-hueristic optimization technique, it is better to tune the parameters of optimization since the algorithm performance in terms of both, reliability and efficiency, significantly improves with appropriate selection of the parameters' values. Hence, the parameters of the standard Genetic Algorithm that include population size, cross-over rate, and mutation rate were determined using a post-execution performance analysis. For this purpose, by taking each parameter variable over its conventional interval and keeping the others fixed at their typical valuves, a limited number of primary optimization runs with only 20 generations, were done to relatively improve a few objective functions, $IS_t^j$. Then, the average relative improvement of $IS_t^j$ with respect to $H'^j_{j,t}$, (the pressure head in the fire demand load condition for fire node $j$ at time $t$, without TCVs' maneuver), was then calculated. Finally, the optimum value for each parameter as the one with the best performance was got. Based on this process, population size, cross-over rate, and mutation rate were set as 50, 1 and 0.05, respectively.

## 5.4. Applying the Model

The proposed model with the above mentioned presumptions and tuned GA parameters was iteratively applied to all demand nodes (as the potential area of fire) for each hour of the day in Anytown pipe network. Since the network has 16 consumption nodes, $16 \times 24 = 384$ separate optimization runs were done to pre- processingly achieve the optimum valves' setting for all $t$ and $j$, i.e. the time and the junction of a probabale single-fire event. For each optimization run, the inputs include $(H_{min})_S$, $H_{max}$, $q_f$, and GA settings. To determine the peak hourly demands, based on $t$, all nodal base demands multiplied by the multiplier taken from Fig. 4. Next, according to $j$, the peak hourly demand of the node $j$ was added by $q_f = 15\,lps$. For this emergency load condition, the simulation-optimization model was then recalled to search the optimum TCVs' settings.

## 5.5. Results

### 5.5.1. Discrete vs. Continuous Optimization Results

As discussed in Section 4, TCV head loss coefficients (i.e. decision variables of the problem) could be taken as both continuous and discrete values. Since the most effective way of representing the decision variables was not already clear, we preferred to primarily compare the results of both approaches for a limited number of objective functions. As an example, Fig. 5 shows the results of $IS_t^j$ improvement trend as a function of the generation number, wherein the fire starts around Node 6 at Time 14. The figure indicates that the performance of discrete optimization in terms of both, accuracy and efficiency, is much better than continuous optimization. While the continuous GA results in $3.42\,m$ increase in pressure head of the fire node, during the same number of generations, discrete GA leads to a $5.39\,m$ promotion in surplus pressure head. Hence, for all nodes at all times, the discrete module of the proposed algorithm was preferred to produce the optimum TCVs' maneuver schedule.

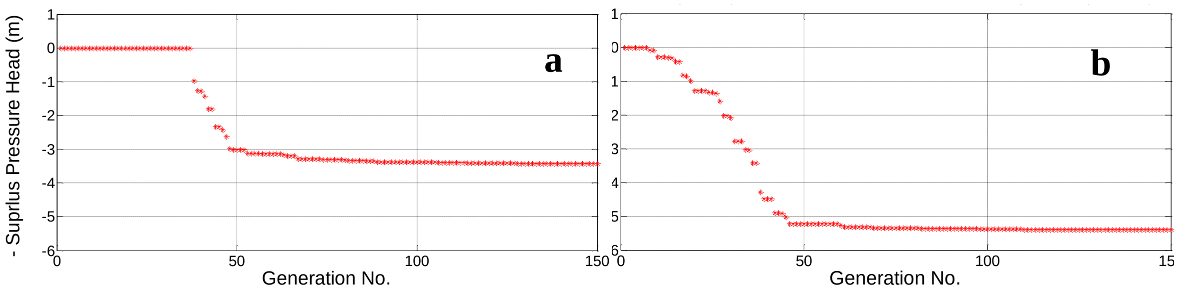

***Figure 5.*** ***$IS_t^j$ improvement trend as a function of generation for the case $j = 6$ and $t = 14$***
**a: Continuous GA, b: Discrete GA**

### 5.5.2. Surplus Pressure Head Results

The overall results show that the performance of the proposed algorithm to boost the surplus pressure head in fire nodes varies from 0 to 40.7% with an average of 10.7% (with respect to $H'^{j}_{j,t}$) based on the time and place of single-fire events. As an example, Table 5 shows the results of applying the proposed model to Node $j = 10$ while the fire starts at $t = 8$. As can be seen, for this condition, the maximum surplus pressure head reaches to $14.1m$ (27.5% with respect to $H'^{j}_{j,t}$). The optimal solution for TCVs' maneuver scheduling for $j = 10$ and $t = 8$ is represented in Table 6. The same results of optimum valve settings for all junctions at all possible fire time are available in request to interested readers.

The algorithm must not let the optimal maneuver of TCVs violate the performance constraints in emergency operation conditions, mathematically expressed through the Equations (7) and (8). Fig. 6 approves these criteria comparing the pressure of normal junctions (not engaged in fire) with $(H_{min})_S$ and $H_{max}$ while $\boldsymbol{j} = 10$ and $\boldsymbol{t} = 8$. It reveals that the model has successfully satisfied both the minimum service pressure head and the maximum allowable pressure head during fire control measures.

**Table 5. Parameters and results of the model for j = 10 and t = 8**

| **Fire time and place** | | | | | **GA parameters** | | |
|---|---|---|---|---|---|---|---|
| ***j*** | ***t*** | **Node *j* base demand (lps)** | **Hourly Peak Factor** | **Fire demand (*lps*)** | **Population size** | **Cross over rate** | **Mutation Rate** |
| 10 | 8 | 12.52 | 1.65 | 15 | 50 | 1 | 0.05 |
| **$(H_{min})_S$** | **$H_{max}$** | **$H'^{j}_{j,t}$ (m)** | **Max.$H^{j}_{j,t}$(m)** | **Max. $IS^{j}_{t}$ (m)** | **Max. $IS^{j}_{t}$ (%)** | **Total generations** | |
| 10 | 90 | 51.19 | 65.29 | 14.1 | 27.5 | 220 | |

**Table 6. TCVs' optimal setting (opening level% ) for t = 8 and j = 10**

| *TCV Number* | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| 100% | 100% | 100% | 0% | 100% | 25% | 0% | 100% | 100% | 75% | 0% | 0% | 0% | 100% | 75% | 100% | 100% |
| *TCV Number* | | | | | | | | | | | | | | | | |
| 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | |
| 100% | 100% | 100% | 75% | 75% | 0% | 0% | 100% | 100% | 100% | 100% | 50% | 75% | 100% | 100% | 100% | |

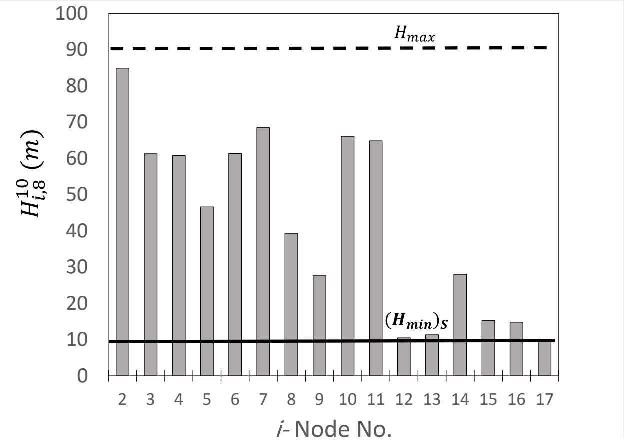

**Figure 6. Comparing $(H_{min})_S$ and $H_{max}$ with nodal pressure heads in Anytown network for j = 10 and t = 8**

## 5.5.3. Surplus Pressure Head Fluctuation

There are substantial fluctuations in surplus pressure head, $IS_t^j$, for any given fire node at different times of fire. For instance, Fig. 7 exibits the results of $H_{j,t}^{j}$ and $H_{j,t}^{\prime j}$ for $\boldsymbol{j} = 8$ and $\boldsymbol{t} = 1$ to 24. Since, the nodal demands vary during the day, the optimal $IS_t^j$ would vary as a function of the fire time. Based on this figure, $IS_t^8$ changes from $0.04\,m$ (0.05% relative to $H_{8,t}^{\prime 8}$) in $t = 1$, to $7.02\,m$ (14.5% relative to $H_{8,t}^{\prime 8}$) in $t = 8$. Comparsion of Fig. 4 and Fig. 7 proves that the more consumption the sysem has, the more surplus pressure head is achieved in fire node. It seems that for fire time corresponding to the lower demand hours of the day, the performance of TCVs to regulate the pressure is dramatically reduced. One of the main reason for this could be associated with inefficient performance of TCVs due to very small kinetic energy, ${}^{v^2}/_{2g}$, during low consumption hours. In fact, while the velocity is very low, for a wide range of head loss coefficient variations, the TCV's opening may not have a significant effect on the valve's energy dissipation and consequently, the hydraulics of the system. For peak consumption times, in contrast, small changes of the TCVs' opening have more impact on flow distribution in pipes and results in more effective pressure management measures.

Fig. 8 depicts $IS_t^j\%$ for all junctions in $t = 2, 9,$ and 14 as representative of low, peak, and mean consumption time of the day. As seen, the pattern of water consumption significantly affects the possibility of $IS_t^j$ improvement. While the average $IS_t^j$ (%) of all nodes for $t = 2$, i.e. the time with minimum water requirement, is about 0.14%, at the peak and mean consumption time, i.e. $t = 9$ and 14, it increases and reaches upto 17.1% and 14.6%, respectively. Through Fig. 8, the same trend is noticeable for all nodes except for 6, 7, 14, 15, and 16. For these nodes, despite more demand flow at $t = 9$ against $t = 14$, $IS_t^j$ (%) decreses as nodal consumptions increase. In other words, much more consumption for $t = 9$ against $t = 2$ makes a substantial difference between $IS_2^j$ and $IS_9^j$ for all fire nodes. Nonetheless, for $j = 6, 7, 14, 15, and\ 16$, the same trend is not seen at $t = 9$ vs. $t = 14$. It seems that, except for the demand variation, there must be other unknown factors (e.g. factors related to topology, network layout and configurations, tanks and reservoirs' location, etc.) affecting $IS_t^j$ variations. Such contradictions indicate that it is not simply possible to anticipate the hydraulic behavior of a WDN in a certain fire load condition even for small hypothetical cases like Anytown pipe-network. Therefore, the development of smart tools such as the model proposed in this article assists operators in having a better understanding and ability, especially in urban crises, to use the system's capacities in the most efficient way.

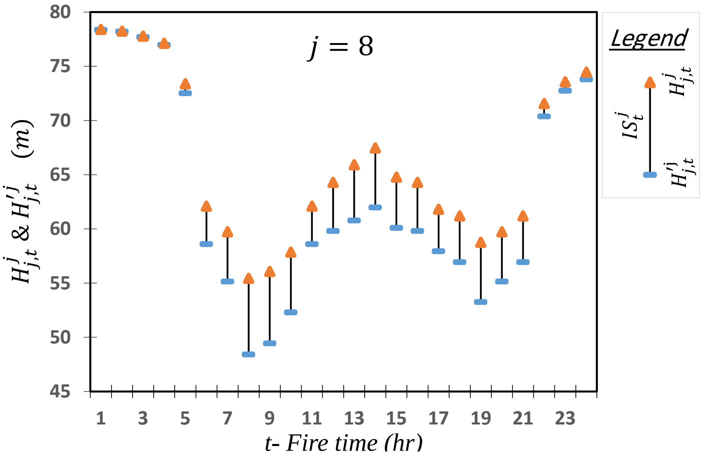

**Figure 7.** $IS_t^j$ ***fluctuation at different fire time for Node 8***

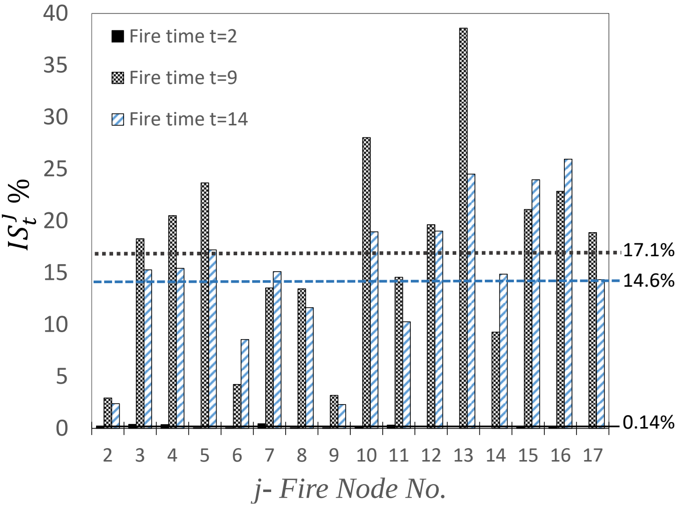

**Figure 8. Fluctuation of $IS_t^j$ for all nodes at the lowest, peak and mean consumption time of the day**

## 6. Conclusion

The smart operation of water infrastructure in emergency conditions of fire events could be very effective in improving the performance of the system to meet the fire flow. The complicated hydraulics of WDNs especially in pressure management measures, requires not only engineering judgements but also comprehensive analysis of the system to achieve the best status of hardware components. Hence, it is necessary to recognize in advance, the best operating condition of pumps and valves for different scenarios of a fire event. In this paper, based on a simulation-optimization model, the optimum operation pattern of TCVs for the maximum reliability of fire flow supply was explored. Applying the model on a small hypothetical pipe network revealed that based on the place and time of fire, the smart manuever of TCVs can boost surplus pressure head up to 40.7%. As per the case study, it is not possible to substantially improve the pressure head of the fire node at low consumption time of the day. In fact, while the velocity is very low, for a wide range of head loss coefficient variations, the TCV's opening may not have a significant effect on the valve's energy loss and hydraulics of the system. In the case of real pipe networks, it is simply not possible to anticipate the hydraulic behavior of a WDN in a certain fire load condition. Therefore, the development of smart tools such as the model proposed in this article assists operators in a better understanding and abillty, especially in urban crises, to utilize the system's capacities in the most efficient way.

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