The Evaluation of Hydraulic Reliability Indices in Water Distribution Networks under Pipe Failure Condition

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Abstract

In this research, reliability indicators of water distribution networks were evaluated under pipe failure conditions. The case studies included two benchmark and one real-life water distribution networks in Iran with more hydraulic constraints. Some important reliability indicators were presented such as resilience index, network resilience, modified resilience index and minimum surplus head index. GANetXL was used to do one-objective and two-objective optimization of the previously mentioned water distribution networks in order to not only minimize the cost, but also maximize the reliability indicators. Moreover, the results of a statistical analysis for each pipe were used to determine the sensitive pipes that were of the most failure probability. GANetXL is an optimization tool in Excel environment and works based on Genetic Algorithm. GANetXL has the capability of being linked to EPANET (Hydraulic simulation software). The results obtained clearly showed that network resilience index was poor performance when compared with the other indexes under pipe failure conditions, especially in real-life networks that include small pipe diameters. It was also showed that if a water distribution network was optimized only in terms of cost, there would be an unacceptable pressure drop at some nodes in case of pipe failure.

Keywords: GANetXL, Optimization, Pipe Reliability, Resiliency, Water distribution Network

1. Introduction

Water distribution networks (WDNs) are designed to provide users with a minimum acceptable level of supply, in terms of pressure, availability, and water quality at all times under a range of operating conditions (Liserra, Maglionico et al. 2014, Eslami, Esmaeili et al. 2022). Nowadays, WDNs have become complex and need huge investments in construction and maintenance (Fujiwara and Khang 1990). As a result, there is an avid desire to improve their efficiency through minimizing their cost and maximizing their benefit (Alperovits and Shamir 1977).

Optimal WDN design is a computationally complex problem because of its non-linear nature and the constraints involved (Rouholamini, Wang et al. 2018). Therefore, finding the globally optimal solution is difficult if we use optimization methods as the non-linearity is significant. In the last decades, several researchers have broadly studied the design optimization problem of WDNs. The problems have been solved using linear, non-linear and various meta-heuristic methods. Linear and non-linear methods were predominantly used in the period 1960–1990(Jacoby 1968, Watanatada 1973, Alperovits and Shamir 1977, Quindry, Liebman et al. 1981, Lansey and Mays 1989, Fujiwara and Khang 1990). Linear methods applied to nonlinear problems have not resulted in optimal solutions. The non-linear methods did not necessarily yield a global optimum, and the final solution depended on the initial solution used as a starting point for the search procedure (Piratla 2016). In addition, the use of discrete variables, specific-size pipe diameters, limits the quality of the optimal solution obtained. These limitations led to the employment of meta-heuristics that use stochastic optimization methods.

Murphy and Simpson were the first researchers who used a simple Genetic Algorithm (GA) to optimally design water distribution systems. This model was applied to determine the least cost combination of pipe diameters and rehabilitation actions (Murphy and Simpson 1992). GA has been integrated with hydraulics simulator to optimize the solutions by many researchers (Simpson, Dandy et al. 1994, Simpson and Goldberg 1994, Savic and Walters 1997, Lippai, Heaney et al. 1999, Neelakantan, Suribabu et al. 2008). (Vasan and Simonovic 2010) recently applied a differential evolutionary algorithm (DE), an improved GA. The major difference between GA and DE is that GA relies on crossover, a mechanism of probabilistic exchange of information among solutions to create better solutions, while DE uses mutation as the primary search mechanism (Vasan and Simonovic 2010). DE uses a uniform crossover that can take child vector parameters from one parent more often than from the other one. It is said that GA most of the times succeed in finding the global optimum or at least arriving at somewhere very close to it. More importantly, GA is capable of handling discrete optimization (as pipe diameters are discrete) (Savic and Walters 1997).

Many other optimization algorithms have been used in the optimal design of water distribution systems (Tayfur 2017). (Loganathan, Greene et al. 1995) and (Cunha and Sousa 1999) applied simulated annealing for optimal design of water distribution systems. (Geem, Kim et al. 2002) developed a harmony search optimization approach to solve network design problems while (Eusuff and Lansey 2003) developed the shuffled frog leaping algorithm. (Maier, Simpson et al. 2003) applied the ant colony optimization approach and improved GA both in terms of computational efficiency and its ability to find nearly optimal solutions. (Baños, Gil et al. 2007) analyzed the performance of memetic algorithms for optimal design of looped water distribution systems and demonstrated that it works well for problems of large scale. (Mohan and Babu 2009) proposed to use a heuristic based approach called heuristics-based algorithm (HBA) to identify the least cost combination of pipe diameters. They demonstrated that the HBA is capable of identifying the least cost combination of pipe diameters with fewer numbers of evaluations. (Moghaddam, Alizadeh

70   et al. 2018) applied a Simple Modified Particle Swarm Optimization (SMPSO) to minimize the cost of water distribution networks. SMPSO then used a novel factor to decrease the inertia weight of the algorithm in proportion with simulation time to facilitate both global and local search. Literature review shows that stochastic models, particularly the GA types, give better results than linear and non-linear optimization models (Pandit and Crittenden 2012).

75   Objective function is important in optimizing the design of distribution systems. The main negative aspect of the single-objective constrained formulation is that it does not effectively set up a trade-off between cost and reliability/robustness of a design (Todini 2000). Reliability can be considered as the ability of providing an adequate supply under both usual and unusual conditions (Farmani, Savic et al. 2005), including demand uncertainty, pipe failure, etc. One of the most used reliability criteria is the concept of resilience index suggested by (Todini 2000),which

80   is a measure of the ability of the network to handle failures and is related indirectly to system reliability. Several suggestions were made to modify the resilience index introduced by Todini (Prasad and Park 2004, Farmani, Savic et al. 2005, Jayaram and Srinivasan 2008, Reca, Martinez et al. 2008, Raad, Sinske et al. 2010, Baños, Reca et al. 2011, Greco, Di Nardo et al. 2012, Pandit and Crittenden 2012).

       Subsequently, a genetic algorithm technique is used in this research as a part of GANetXL(Savić, Bicik et al. 2011). .

85   GANetXL is used as the optimization tool in this research. GANetXL has been developed by the Center for Water System of University of Exeter as an add-on in Microsoft Excel (Miri and Afshar 2014, Peirovi, Moghaddam et al. 2020). It is a common optimization tool with spreadsheet-based interface for solving both single-objective and multi-objective optimization problems (Savić, Bicik et al. 2011). The primary advantage of GANetXL is its capability of easy integration with EPANET via Visual Basic. GANetXL incorporates GA for single-objective and NSGA-II for

90   multi-objective optimizations (Deb, Pratap et al. 2002). In addition, it has the capability to apply penalty functions. GANetXL is well suited for solving multi-objective optimization problems (Mala-Jetmarova, Barton et al. 2014). There are a few applications of GANetXL in water systems, which include the development of a model for optimal management of groundwater contamination (Farmani, Savic et al. 2005, Farmani, Henriksen et al. 2009) and multi-objective optimization of water distribution systems (Piratla and Ariaratnam 2012, Mala-Jetmarova, Barton et al. 2015,

95   Piratla 2016). GANetXL is used to optimize two benchmark networks from literature (Two-loop and Hanoi water networks) in two different conditions including single-objective (cost) and two-objective (cost and reliability criteria) optimizations. Afterwards, the solutions obtained, as well as the performance of the proposed Resilience Index, Network Resilience, Modified Resilience Index and Minimum Surplus Head Index are discussed. Finally, as the results obtained for the benchmark networks are satisfactory, GANetXL is used to design a real-life water network in

100   Iran in which there are more hydraulic constraints compared with the benchmark networks Thus, it is necessary to mention that quality issues were not addressed in this paper.

2. Material and Methods

2.1 Optimization Model for WDN Design

In this paper, WDNs were optimized with pipe diameters as decision variables. Cost was considered as the objective function that must be minimized [Eq. (1)] and the reliability criteria were modeled in the form of a two-objective function [Eq. (2)].

$$Min\ f_1 = \sum_{i=1}^{N} c_i D_i \times l_i \tag{1}$$

$$Max\ f_2 = Reliability\ factor \tag{2}$$

Where f_1 is network cost, f_2 is network reliability, c_i is cost for unit length of pipe with diameter, D_i length l_i and N is pipe numbers in the network.

3. Constraints

The constraints to the optimization problem were as follows:

1) Explicit system constraints such as conservation of mass of flow, conservation of energy and conservation of mass of constituent, which all were controlled by water network simulator software, EPANET (Rossman 2000, Mala-Jetmarova, Barton et al. 2015).

2) Implicit bound constraints, which include choosing pipe diameters from a commercially available set of discrete pipe sizes [Eq. (3)], minimum and maximum pressure at load nodes [Eq. (4)], minimum and maximum velocity in pipes [Eq. (5)].

$$D_i \in \{CD_k\} \quad \forall i \qquad k = 1,2,3, \dots, nc \tag{3}$$

$$H_j^{min} \leq H_j \leq H_j^{max}, \qquad j = 1,2, \dots, nd \tag{4}$$

$$V_i^{min} \leq V_i \leq V_i^{max}, \qquad i = 1,2, \dots, np \tag{5}$$

where D_i = diameter of pipe i; CD_k = kth commercially available pipe size; nc = number of available pipe sizes; H_j = hydraulic-head available at node j; H_j^{min} = minimum hydraulic-head required at node j; H_j^{max} = maximum hydraulic-head at node j; nd = number of demand nodes; V_i^{min} = minimum velocity required at pipe i and V_i^{max} = maximum velocity at pipe i; np = number of pipes.

2.2 Reliability Indicators

A range of reliability criteria has been introduced to different degrees of complexity. Usually, these criteria give some suggestion of the ability of a WDN to handle changing conditions and are straightforward to analyze so are practical for optimization studies that compare the performance of network design. This section presents the definition of the key criteria and their derivatives as well as the advantages and disadvantages of them.

2.3.1 Resilience Index (I_r)

Todini's resilience index is a popular surrogate measure within the WDN research field. It considers surplus hydraulic power as a proportion of available hydraulic power. The resilience index, I_r, is measured in the continuous range of [0-1] (for feasible solutions of $H_j^{min} \leq H_j$) and is formulated as below (Todini 2000):

$$I_r = \frac{\sum_{j=1}^{nn} q_j (H_j - H_j^{min})}{\sum_{k=1}^{nr} Q_k H_k + \sum_{i=1}^{np} P_i/\gamma - \sum_{j=1}^{nn} q_j H_j^{min}} \tag{6}$$

140   Where nn is the number of supply and demand nodes; nr is the set of supply nodes (reservoir/emptying tanks); np denotes the number of pumps; H_j is the available head at supply node j; H_j^{min} represents the required head at supply node j; q_j is the demand at node j; Q_k is the supply at input node k; H_k is representative of head associated with the input node k; P_i is the power of pump i; and finally γ is the specific weight of water. Maximization of the resilience index improves the ability of a pipeline network in encountering failure conditions.

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2.3.2 Network Resilience (I_n)

Prasad and Park (2004) introduced another reliability measure called network resilience (I_n), which incorporates the effects of both surplus power and reliable loops. Reliable loops can be ensured if the pipes connected to the same node do not vary greatly in diameter. If $D_{1j}, D_{2j}, ..., D_{npj}$ (where $D_{1j} \geq D_{2j} \geq \cdots \geq D_{npj}$) are the diameters of the np pipes

150   connected to node j, then uniformity of that node is given by Eq. 7,

$$C_j = \frac{\sum_{i=1}^{np} D_{ij}}{np \times \max D_{ij}} \tag{7}$$

where npj is the number of pipes connected to node j. The value of $C_j = 1$ if the diameter of the pipes connected to the same node are the same; and $C_j < 1$ if the pipes connected to a node have different diameters. For nodes connected to only one pipe, the value of C_j is taken to be one.

155    $$I_n = \frac{\sum_{j=1}^{nn} C_j q_j (H_j - H_j^{min})}{\sum_{k=1}^{nr} Q_k H_k + \sum_{i=1}^{np} P_i/\gamma - \sum_{j=1}^{nn} q_j H_j^{min}} \tag{8}$$

Theoretically, the value of network resilience may vary between 0 and 1. However, for real-world systems it never attains a value of 1, since imposing the same diameter to all pipes in a network need not always provide a Pareto-optimal solution in Cost-I_n space, as I_n is a measure of the combined effect of surplus power and nodal uniformity.

160   ### 2.3.3 Modified Resilience Index (MRI)

Jayaram and Srinivasan(Jayaram and Srinivasan 2008) proposed a modified resilience index (MRI), which theoretically overcomes the drawback of Todini's resilience index when evaluating networks with multiple sources. In contrast to Todini's resilience index, the value of the modified resilience index is directly proportional to the total surplus power at the demand nodes. Eq. (9) describes MRI, which only considers the solutions with pressures equal

165   to or higher than that required in all nodes. While Todini's I_r and Prasad's I_n take values up to a maximum of 1, Jayaram's MRI can be greater than 1(Baños, Reca et al. 2011).

$$MRI = \frac{\sum_{j=1}^{nn} q_j H_j - H_j^{min}}{\sum_{j=1}^{nn} q_j H_j^{min}} \tag{9}$$

2.3.4 Minimum Surplus Head Index (I_m)

In a WDN, minimum surplus head, I_m, is defined as the lowest nodal pressure difference between the minimum

170   required and observed pressure, formulated as

$$I_m = min\{H_j - H_j^{min}\} \qquad j = 1,2, ..., nn \tag{10}$$

Maximization of the available surplus head at the most depressed node to some extent improves the reliability of a network (Prasad and Park 2004).

2.3 GANetXL

In this paper GANetXL is employed in two steps: in the first step for single-objective optimization based on GA and the second step for two-objective optimization based on NSGA-II. GA and NSGA-II parameters such as population size, the number of generations, selection method, crossover and mutation operators, crossover and mutation probability and the type of algorithm were tested and reasonably well-performing parameters selected for final optimization runs (see supplementary data).

4. Results and Discussion

Three example applications were studied: the Two-loop (Alperovits and Shamir 1977), Hanoi (Fujiwara and Khang 1990) ,which are the benchmark networks, as well as a real-life case study in Iran.

3.1 Example 1: The Two - loop network

The Two-loop network was originally presented by (Alperovits and Shamir 1977). The network consists of 7 nodes and 8 pipes with two loops, and is fed by gravity from a reservoir with a 210 m fixed head. The minimum pressure head requirement of the other nodes is 30 m above the nodal elevations.

In the first step, as a result of single-objective optimization of the Two-loop network using GA technique in GANetXL, the minimum cost obtained 419000$ with 35000 number of function evaluations (NFEs) which is the same to minimum costs obtained by GA (Savic and Walters 1997), Simulated Annealing (SA) (Cunha and Sousa 1999), Shuffled frog leaping Algorithm (SFLA) (Eusuff and Lansey 2003), Harmony Search (HS) (Geem 2009)and Scatter search (SS)(Lin, Liu et al. 2007) with 250000, 25000, 11323, 5000 and 3215 NFEs, respectively.

As a result, minimum cost was 419000$ for one-objective optimization of this network using GANetXL after 1000 generations that was equal with minimum costs obtained by GA, Simulated Annealing (SA), Shuffled frog leaping Algorithm (SFLA) Harmony Search (HS) and Scatter search (SS).

In the second step, figure 1 (a-d) shows the obtained Pareto front for two-objective optimization of two-loop network using NSGA-II in GANetXL considering I_r, I_n, MRI and I_m as the second objective function, respectively. All of the solutions in this Pareto front were feasible (and all the network constraints are satisfied). As it is observed the cost changes in the range of $[0.424 \times 10^6 - 4.400 \times 10^6]$ $ and I_r, I_n, MRI and I_m criteria change in the ranges [0.338-0.903], [0.287-0.903], [0.040-0.107] and [0.122-12.856], respectively. The range of numbers presented is based on the minimum and maximum values of the solutions presented in the graphs. The lowest and the highest point on the Pareto front in each of the charts were the criteria for deriving the range of reliability indices and the cost range. In the cost range of $[0.424 \times 10^6 - 1 \times 10^6]$$, Cost-I_n Pareto front shows more and varied solutions, in comparison to other graphs. However, with increase in cost, non-dominated solutions decreases and the current continuity in Pareto front disappears while Cost-I_r (Fig 1.a) and Cost-MRI (Fig 1.c) Pareto fronts have better performance. In Cost-I_m (Fig 1.d) graph the variety of obtained solutions in the lower and upper bound of Pareto front is lower than other graphs.

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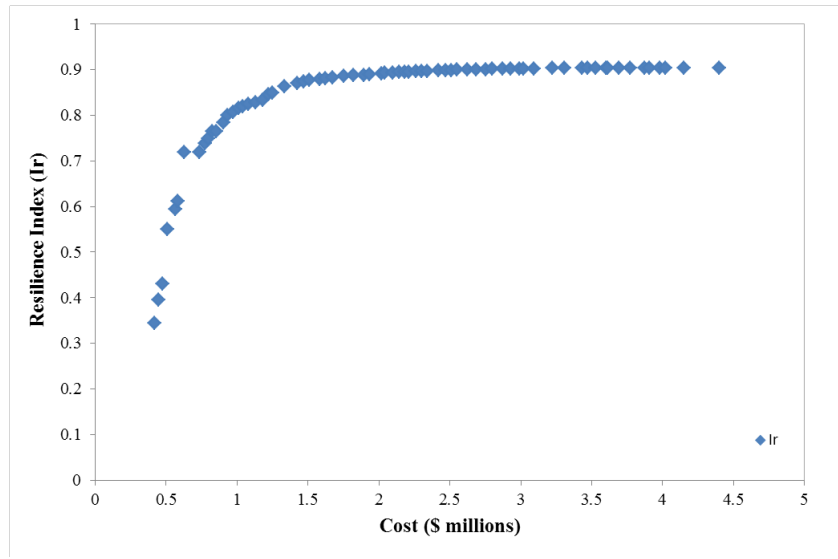
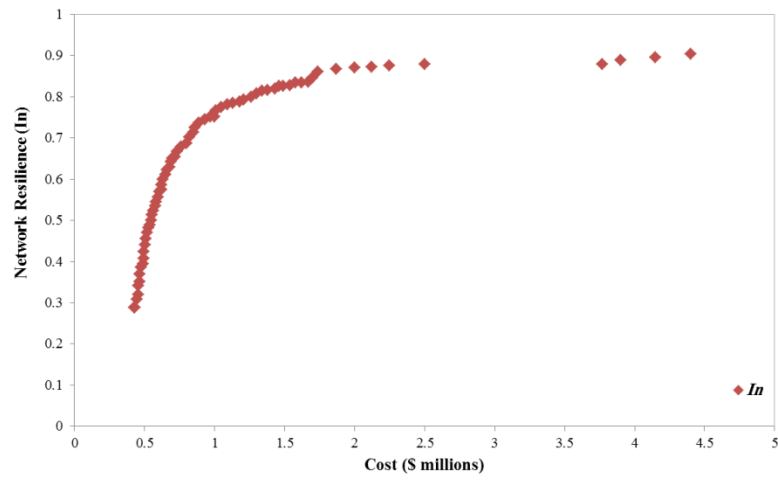
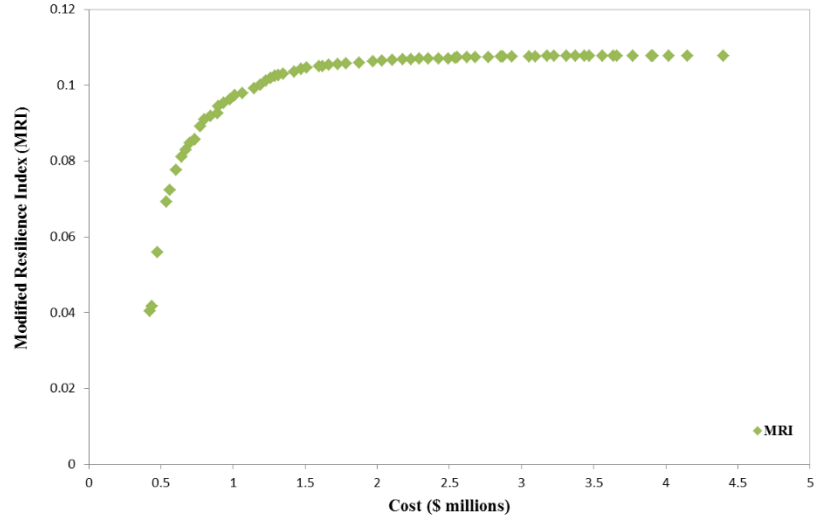

(a)

(b)

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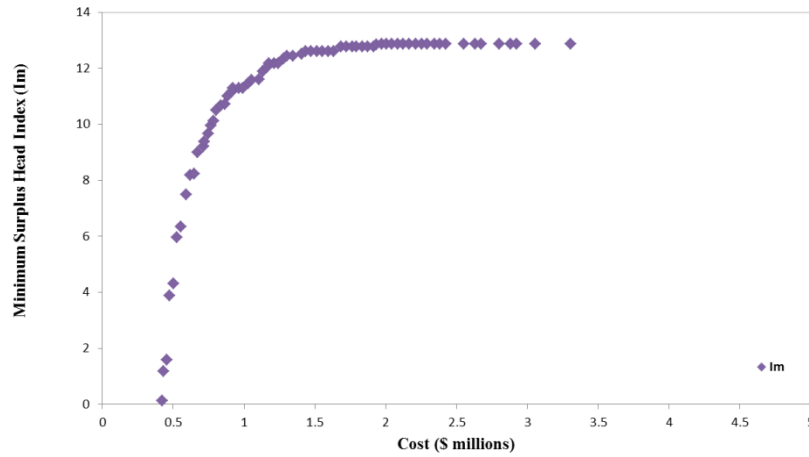

(d)

Fig 1. Pareto front of two-objective function optimization of the Two-loop network, (a) Cost-I_r, (b) Cost-I_n, (c) Cost-*MRI*, (d) Cost-I_m

Figure 2 shows the surplus pressure of the minimum pressure head requirement in the nodes of Two-loop network for solutions with maximum reliability criteria and minimum cost. As it is observed, the surplus pressure of the nodes in the solutions with minimum cost was lower than the solutions of maximum reliability criteria (I_r, I_n, *MRI* and I_m). Also, the design based on single-objective function (minimum cost), surplus pressure was closer to the minimum allowed pressure in nodes 3, 6, and 7, showing that these nodes were the critical nodes of the network. As a result, if the two-loop network was designed only based on minimum cost, in critical periods such as pipe failures, there would be problems issues at these nodes.

Reliability evaluation should be analyzed under all feasible extreme conditions. Failure of multiple pipes as well as the failure of the reservoir connection line during a firefighting event and/or power or pumping station failures should

be evaluated simultaneously. Although an infinite number of failure scenarios were likely, the probability of simultaneous failures in multiple pipes was too low (Tabesh, Tanyimboh et al. 2001). Pipe failures independency can be assumed (Su, Mays et al. 1987) and any likely dependency will be negative. For example, if a pipe failure occurs in the network, the pressure will decrease, and consequently the probability of another pipe failure will decrease as well. However, in case the system is a large-scale WDN, the influence of pressure might not be significant. Other pipe failure reasons, such as damages or traffic loadings, may lead to pipe failures that are completely independent events (Shafiqul Islam, Sadiq et al. 2013).

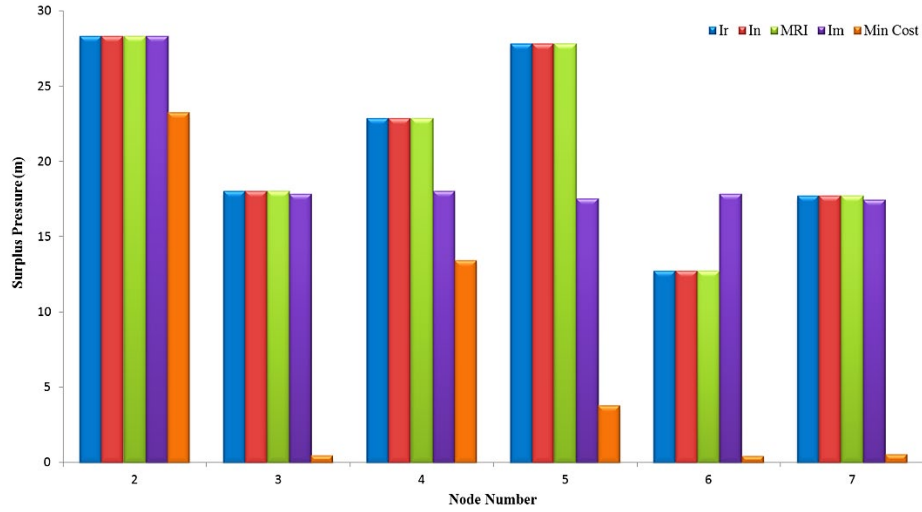
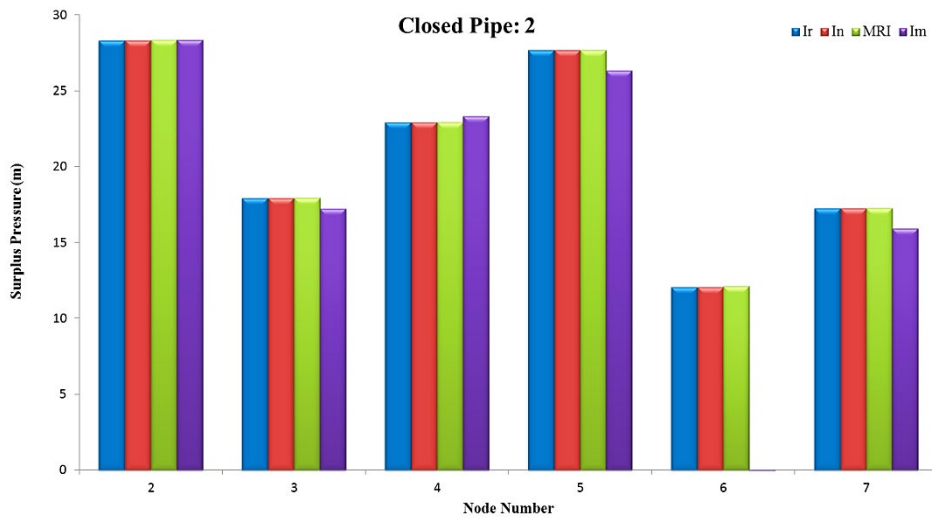
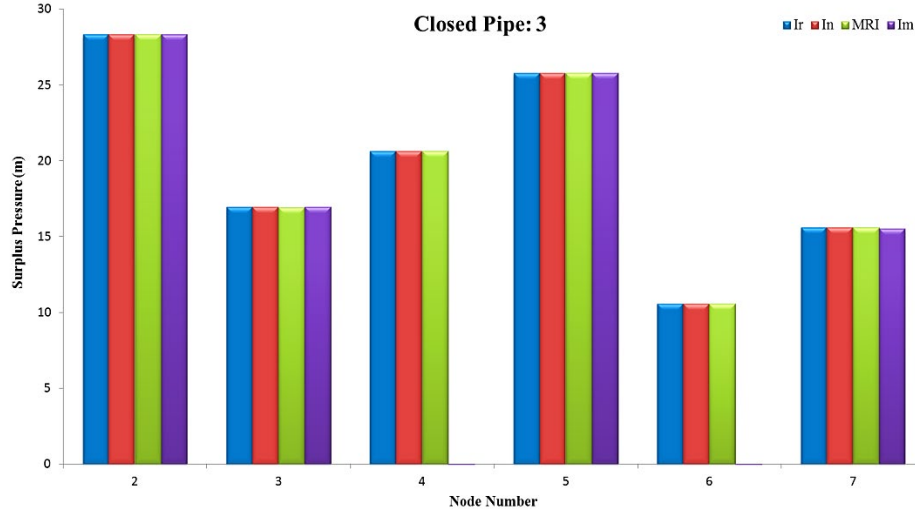



Fig 2. Surplus pressure of nodes in two-loop network for solutions of maximum reliability criteria and minimum cost

In this paper, to evaluate reliability of the candidate solutions of maximum I_r, I_n, MRI and I_m criteria, the nodal pressures had been investigated under pipe failure conditions.

(a)

(b)

3.2 Example 2: The Hanoi network

The Hanoi network in Vietnam, first presented by Fujiwara and Khang, was a new design as all new pipes were to be selected. The network consists of 32 nodes and 34 pipes organized in three loops. The system was gravity fed by a single reservoir. The network details were given in (Fujiwara and Khang 1990). The minimum required pressure head for all nodes was 30 m and the elevation for all nodes is zero. There were six available pipe diameters to be selected for each new pipe and the pipe cost per meter for the six available pipe diameters had been listed in previous studies (Atiquzzaman and Liong 2004, Zecchin, Simpson et al. 2006, Savić, Bicik et al. 2011, Pant and Snasel 2021).

In the first step, as a result of single-objective optimization, GA method in GANetXL obtained a minimum cost of 6.097×10^6\$ with 100000 NFEs for this network while in the previous researches the methods of GA(Savic and Walters 1997), Ant Colony Optimization (ACO)(Zecchin, Simpson et al. 2006), and Shuffled Complex Evolution (SCE) Atiquzzaman and Liong (Atiquzzaman and Liong 2004)reported costs of 6.195, 6.134 and 6.22 million\$ with 1000000, 25402 and 85571 NFEs, respectively.

In the second step, figure 3. (a-d) shows non-dominated solutions of Hanoi network which calculated by NSGA-II considering minimum cost versus maximum reliability criteria and all of the solutions in the Pareto front was feasible. As it was observed in figure 4 minimum values of I_r, I_n, MRI and I_m are 0.228, 0.256, 0.555 and 0.090 and maximum values were 0.353, 0.353, 0.825 and 19.916, respectively. Cost values change in a range of $[6.251 \times 10^6 - 10.791 \times 10^6]$\$ for Cost-I_r and in $[6.584 \times 10^6 - 10.969 \times 10^6]$\$ Cost-I_n space that the increase in Cost-I_n to Cost-I_r is due C_j factor in formula [Eq. (8)] which cause uniformity diameters in the design phase. In this example monotony and variety of represented solutions were observed in all Pareto fronts, the reason could be found in the increase of the network size and possible solutions for network design.

(a)

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(b)

(c)

(d)

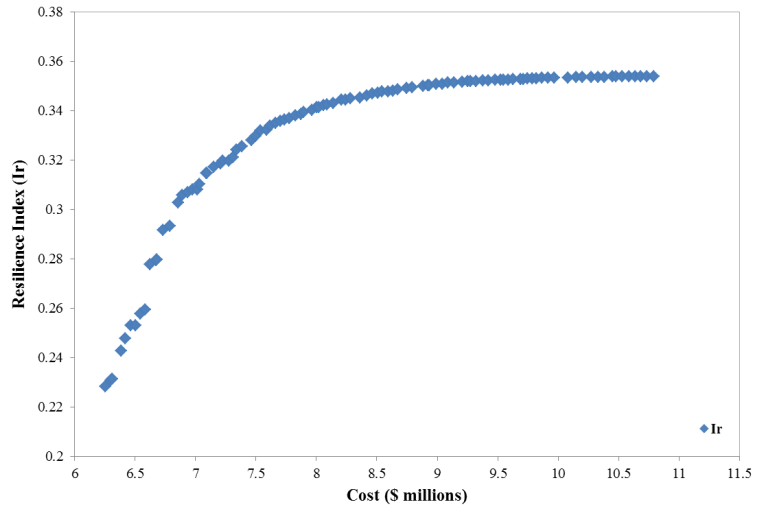
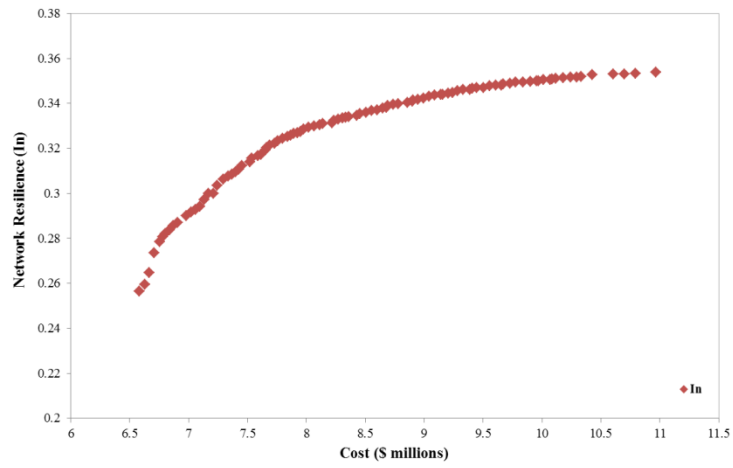
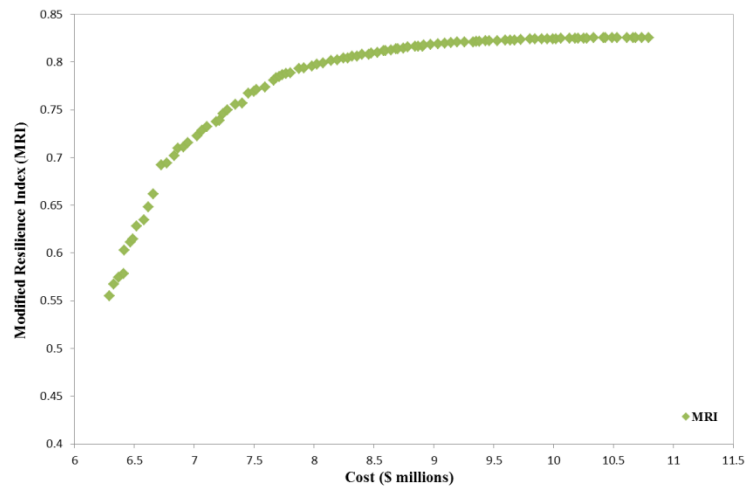
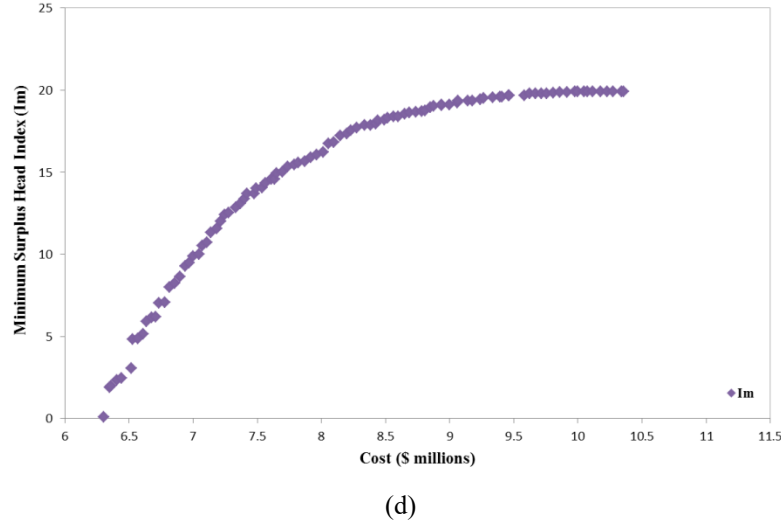



Fig 3. Pareto front of two-objective function optimization of the Hanoi network, (a) Cost-I_r, (b) Cost-I_n, (c) Cost-MRI, (d) Cost-I_m

Figure 5 shows the surplus pressure in comparison with minimum allowed pressure in the nodes of the Hanoi network for solutions of maximum reliability criteria and minimum cost. In the cost-based optimization, surplus pressure in nodes No. 13, 30 and 31 is less than 1 m which shows that these nodes were the most critical ones of this network. I_r, I_n and MRI criteria have similar performance for all the nodes, but I_m criterion determinates more surplus pressure for most of the nodes than other criteria in this network unlike the two-loop network.

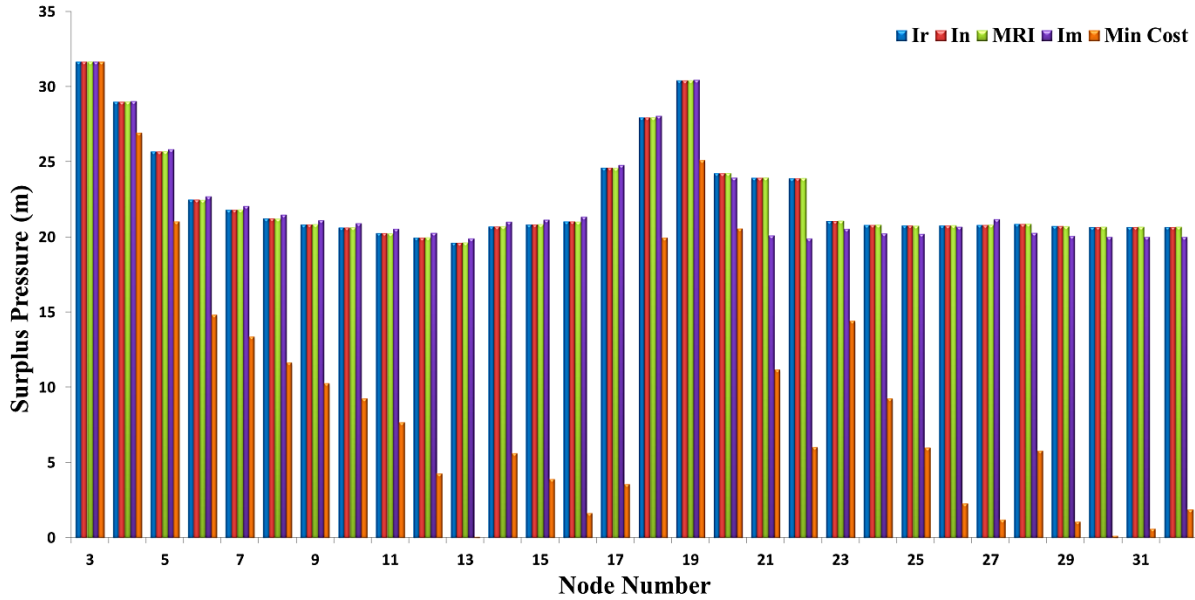



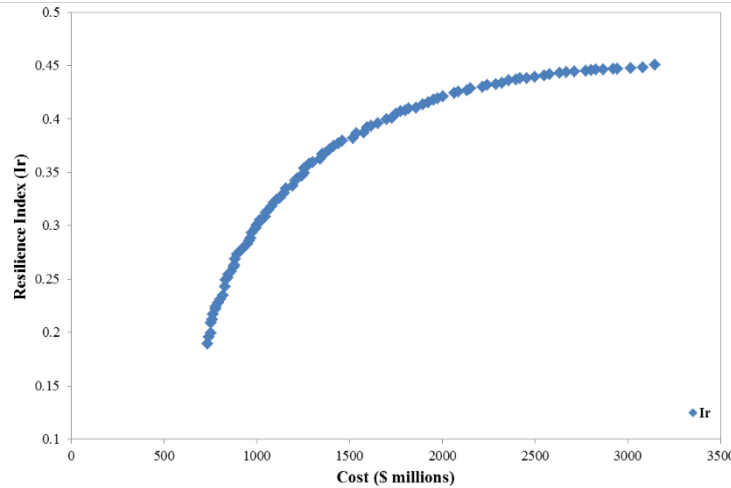
Fig4. Nodal surplus pressure of Hanoi network for solutions of maximum reliability criteria and minimum cost

3.3 Example 3: The Real- life network

Real- life WDN is located in Iran and it had 37 pipes, 24 nodes and a reservoir with a 962 m fixed head (Fig 7). The design purpose of this network is municipal water supply of city and improving of the existing condition of the WDN (Moghaddam, Alizadeh et al. 2020). For this purpose, a series of pipes which had diameters more than 100 mm were

used for future conditions. For designing this network, polyethylene pipes (PE-80) with Hazen-Williams coefficient of 130 were used. The nodes and pipes characteristics were presented in (Moghaddam, Alizadeh et al. 2020). In the design of the network, nodes pressure and velocity constraints were between 14-60 m and 0.2-2 m/s, respectively (Department of Technical Affairs 2013). There were more constraints in this example than the other ones.

In the first step, as a result of single-objective optimization using GA in GANetXL, the minimum cost was estimated 7.54×10^8 Rials with 100000 NFEs which shows a cost decrease of 46.14% in comparison to the solution of the consultant company with 14×10^8 Rials (Rasekh, Afshar et al. 2010).

In the second step, the results of figure 5 (a-d) shows that the I_r, MRI, I_m criteria have better performance than I_n criterion for this network in terms of non-dominated solutions. All these three criteria have similar solutions of maximum and minimum cost in the Pareto front. All of the solutions in the Pareto front (figure 5) which obtained by NSGA-II is feasible and satisfied the velocity and pressure constraints.

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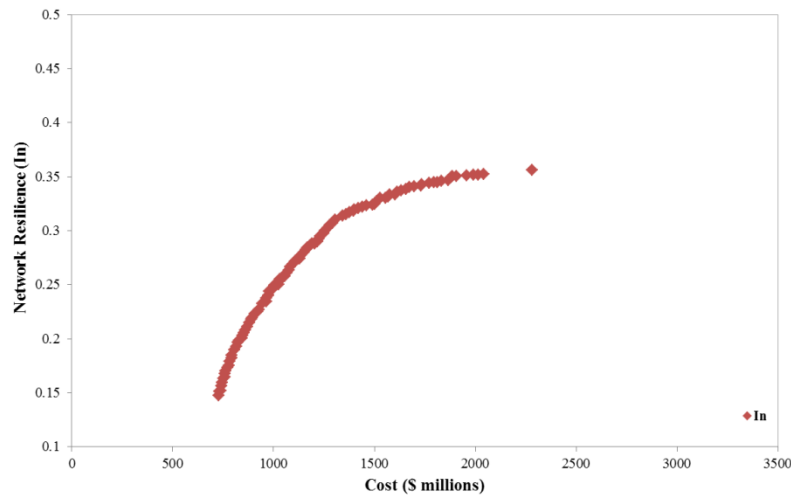
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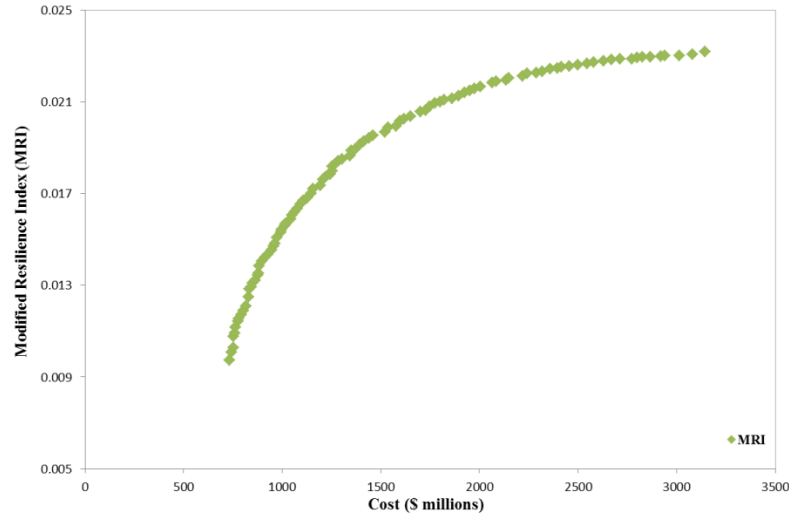
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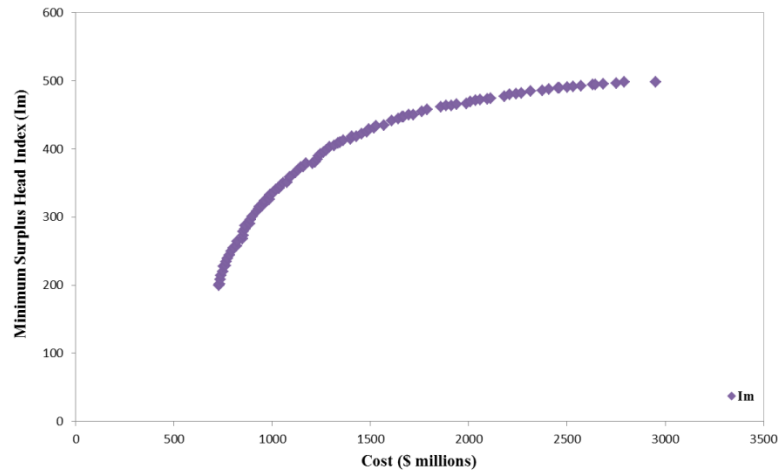
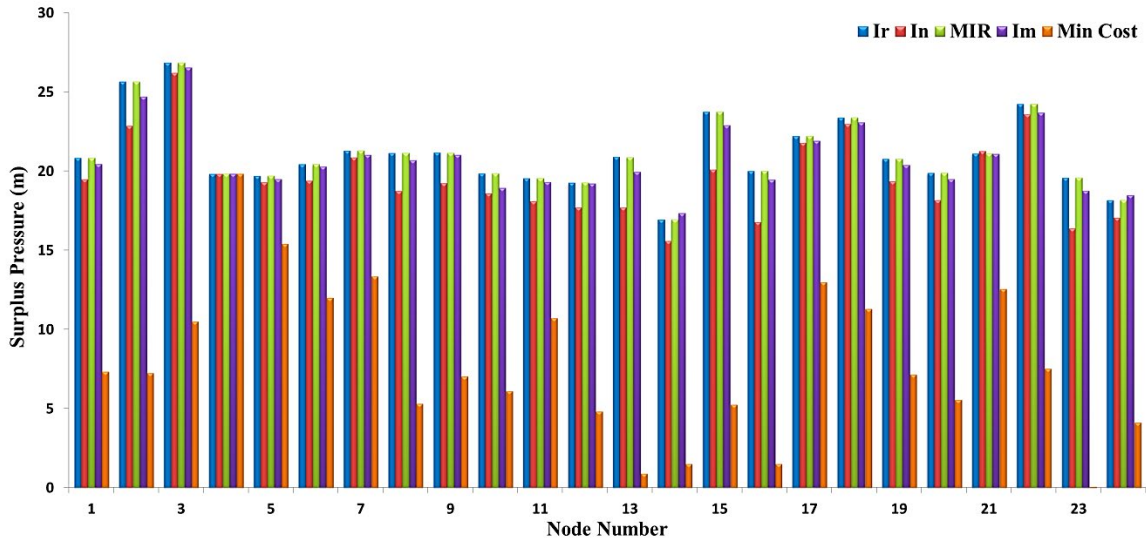

(d)

Fig 5. Pareto front of two-objective function optimization of the Real- life network, (a) Cost-I_r, (b) Cost-I_n, (c) Cost-MRI, (d) Cost-I_m

The results shown in figure 6 demonstrate that in the cost-based optimization, surplus pressure in the nodes number 13 and 23 is less than 1m that explains these nodes were the most critical ones in the network.I_r and MRI criteria have similar and more successful performance compared to I_m in terms of the surplus pressure for all the nodes in the network. I_n had less capability than other criteria to create surplus pressure in the network.

315   Fig 6. Surplus pressure of the real- life for solutions of maximum reliability criteria and minimum cost

The results of the investigations in figure S4 (see supplementary data) shows that only the failure in Pipe No. 18 can influence the pressure nodes. Consequently, this pipe was one of the most sensitive pipes in this network. However, reliability performance in the failure conditions was similar to no failure conditions in figure 7. Finally, for this

320   network that includes low diameter in existing pipes, I_n I_n had not a suitable performance because of making the uniformity in pipes connected to a node leads to the decrease of the diameter of new pipes. Thus, the capability of the surplus pressure decreased due to the increase in head-loss in the pipes.

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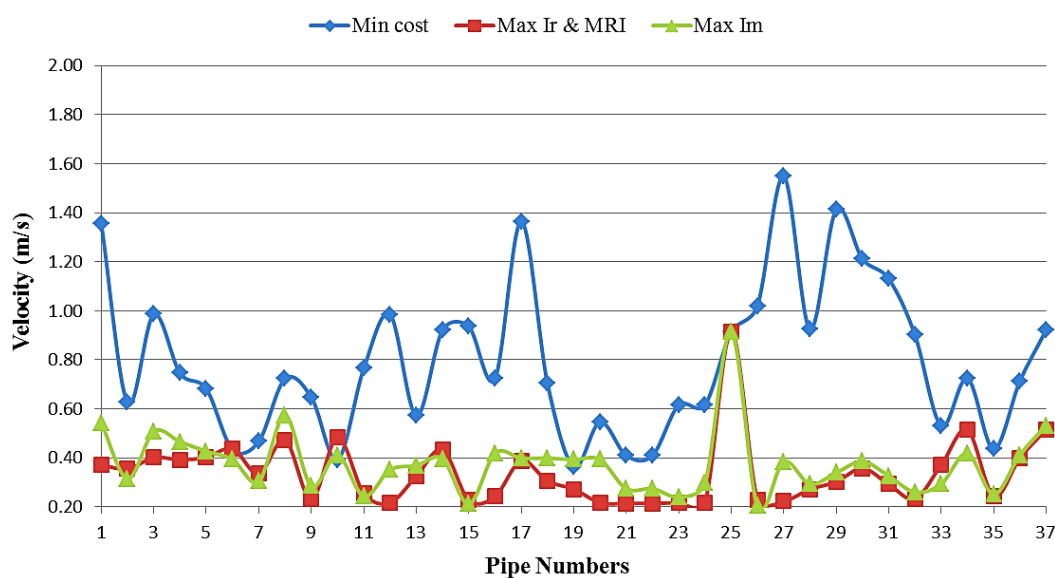
Fig 7. Velocity variations in pipes for the solutions of minimum cost and maximum I_r, MRI and I_m criteria

Figure 7 showed the velocity variations in the pipes for the solutions with minimum cost and maximum I_r, MRI and I_m criteria obtained using GA and NSGA-II in GANetXL. As it was observed, when the cost was the basis for the design and optimization of Real- life network, velocity variation was so high in the pipes. This can lead to some issues in the network. But in the presented solutions with maximum reliability criteria (I_r, MRI and I_m), velocity variations were not only low but almost uniform.

5. Conclusions

In this paper the performance of a few reliability criteria was evaluated when applying to a two benchmark (Two-loop and Hanoi) and one real-life (in Iran) networks. Both the existing pipes and hydraulic constraints were considered in the study in which GANetXL was used as the optimizer. The optimizations were performed taking into account two different objective functions including a cost and reliability.

The results of cost-oriented optimization showed that the solutions proposed by GANetXL for case study networks give solutions that are either less expensive than or as the same as the ones from literature. . In order to investigate the solutions with maximum values of I_r, I_n, MRI and I_m criteria and finding sensitive and important pipes with the most probability of failure in the network, statistical analysis of single-objective optimization was used. The results showed that I_r, MRI and I_m criteria have better performance than I_n under failure conditions, especially in real-life networks that include the existing pipes with small diameter and if a WDN was only optimized based on cost, it would be difficult to overcome losses in pipe failure conditions and pressure supply of nodes.

Competing interests: There is no conflict of interest.

Data Availability: All data and models generated or used during this study are proprietary and confidential in nature.

Author contribution: Conceptualization and data curation were done by A Moghaddam, formal analysis and methodology carried out by A Moghaddam, R Peirovi and H Rezaee, project administration was done by A Faridhosseini and R Peirovi, visualization and writing have prepared by A Naghi Ziaei, A Moghaddam and R Peirovi.

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