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The evaluation of hydraulic reliability indices in water distribution networks under pipe failure conditions

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Table S1. Optimum GA and NSGA-II values for the three case studies in this paper

Parameter	**Parameter values or method selected**	
	Two-loop Network	**Hanoi and Real- life Network**
Algorithm (Only in single-objective mode)	Generalation	**Generational Elitist**
Population size	70	**100**
Number of generations	1000	**1000**
Selection Method	Roulette	**Tourenmate**
Crossover operator	Simple one point	Simple one point
Mutation operator	Simple by gene	Simple
Crossover probability	0.8	**0.95**
Mutation rate	0.01	**0.7**
Adaptive mutation	Yes	**Yes**

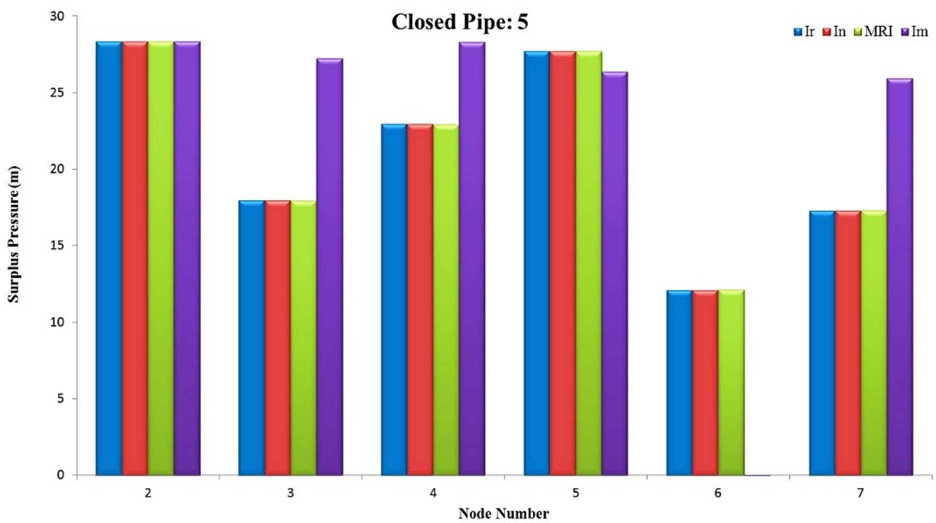
These parameters are presented in Table S1 for three example networks, which are described in the following sections. The crossover and mutation types are described in details in CWS (2011). The presented parameters are the main components of the genetic algorithm and must be set before running the algorithm. Sensitivity analysis by during the execution of different iterations of GA and NSGA-II algorithms has been performed to determine the optimal values of these parameters.

Table S2 presents the statistical parameters of each pipe in two-loop network under different runs of single-objective optimizations when the objective function is to minimize cost. This table helps the designers to recognize critical and sensitive pipes that have the most probability of failure in the network. For example, maximum and minimum diameters that are allocated to pipe 1 in different runs of GANetXL are 24 and 18 inches, respectively.

Table S2. Statistical parameters for diameters obtained for each pipe of two-loop network

Pipe numbers	Maximum (mm)	Minimum (mm)	Average (mm)	ST. DEV	Variance	C.V.
1	609.6	457.2	459.35	17.96	322.52	0.04
2	304.8	152.4	248.28	26.35	694.18	0.11
3	457.2	406.4	452.91	14.13	199.65	0.03
4	254	101.6	208.21	41.03	1683.23	0.20
5	609.6	406.4	469.36	37.62	1414.97	0.08
6	508	101.6	251.85	57.47	3302.97	0.23
7	558.8	76.2	217.87	63.47	4028.38	0.29
8	304.8	25.4	68.69	58.51	3423.79	0.85

According to Table S2, pipe numbers 2, 3 and 5 that have minimum standard deviations and variation coefficients are chosen for failure analysis. Pipe 1 belongs to a water transmission line from the reservoir to the network that is important during network operation. If a failure is considered in this pipe, then the network will be unreliable. That is why this pipe is not taken into account for failure analysis. Figure S1 shows the performance of solutions with maximum reliability criteria under the failure of pipes 2, 3 and 5.



(c)

Fig S1. Surplus pressure of nodes in two-loop network for solution with maximum reliability criteria under failure of pipes No. (a) 2, (b) 3 and (c) 5

Figure 1 shows that, nodeNo. 6 encounters with a serious pressure loss with failure in pipe No. 2, 3 and 5 in represented solutions by $I_m$criterion. In represented solutions based on I_r,$I_n$and $MRI$for all the pipes of the network the diameter was 609.6 mm while in the obtained solution with maximum I_m, the diameter of pipes No. 4 and 6 was 25.4 mm and other pipes were 609.6 mm. Consequently, $I_m$criterion is of lower performance than any other criterion under pipe failure condition.

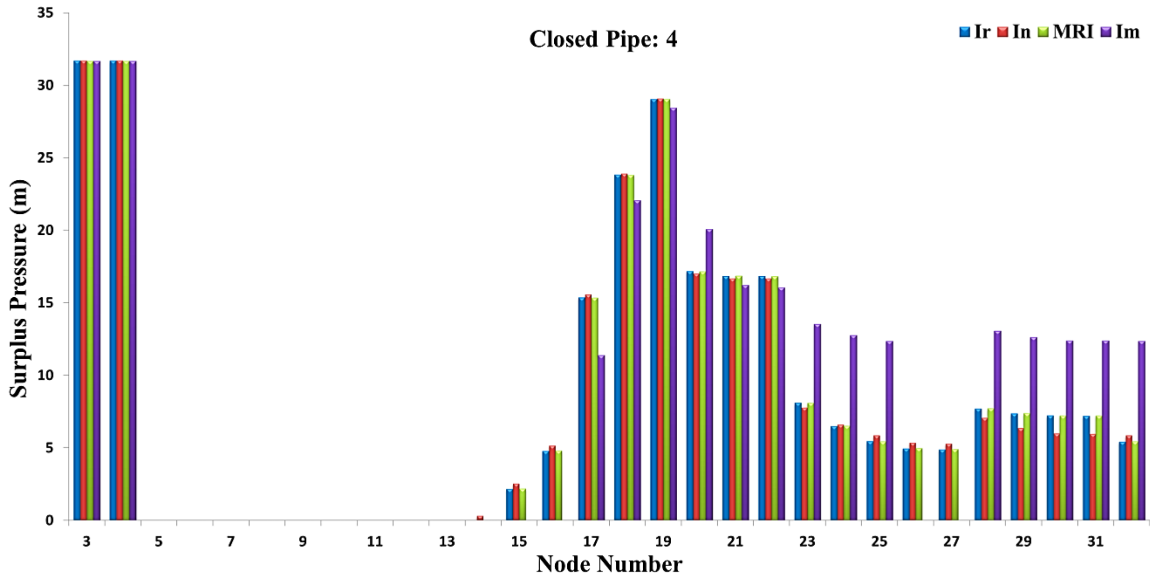
Table S3 shows the statistical parameters for each pipe of Hanoi network due to different runs of single-objective optimizations by GANetXL. According to this table, Pipes No. 4, 5, 6 and 20 that have standard deviation and variation coefficient equal to zero have been chosen for reliability evaluation when there is a failure in the network.

Table S3. Statistical parameters for diameters obtained for each pipe of Hanoi network

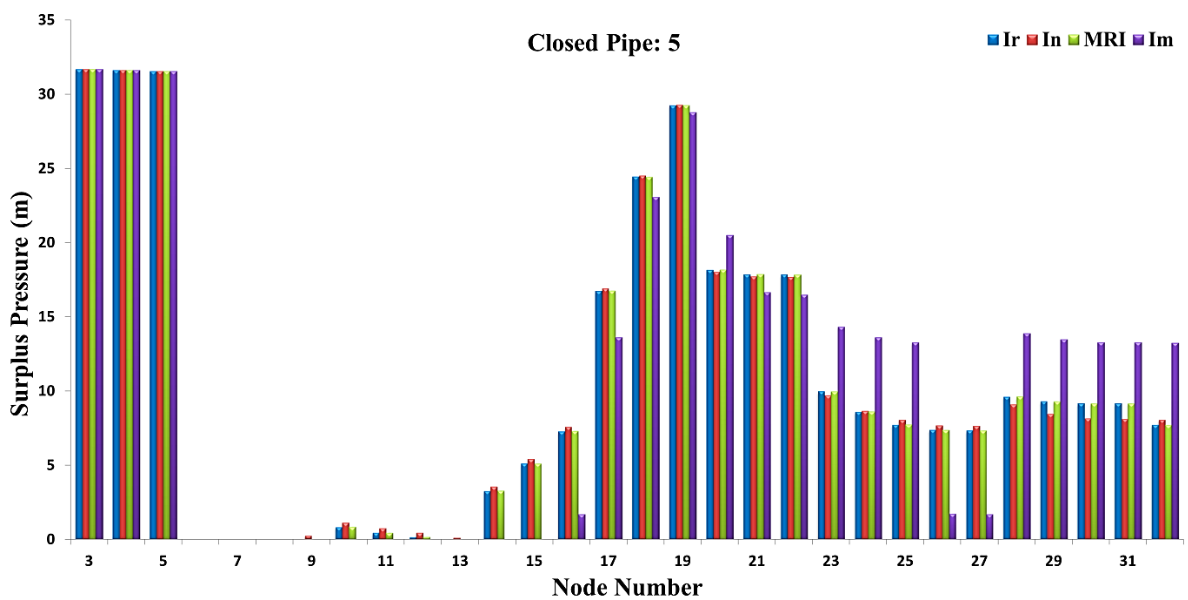
Pipe numbers	**Maximum (mm)**	**Minimum (mm)**	**Average (mm)**	**ST. DEV**	**Variance**	**C.V.**
1	1016	762	1005.84	49.77	2477.41	0.05
2	1016	762	1010.92	35.56	1264.51	0.04
3	1016	508	1005.84	61.38	3767.73	0.06
4	1016	1016	1016	**0**	0	**0**
5	1016	1016	1016	**0**	0	**0**
6	1016	1016	1016	**0**	0	**0**

7	1016	762	1013.46	25.27	638.71	0.02
8	1016	762	1005.84	49.77	2477.41	0.05
9	1016	508	1008.38	56.28	3167.74	0.06
10	1016	508	889	136.78	18709.64	0.15
11	762	304.8	608.584	47.64	2269.93	0.08
12	762	508	611.124	31.69	1004.13	0.05
13	1016	406.4	495.808	67.82	4599.73	0.14
14	1016	304.8	477.52	107.52	11561.27	0.23
15	762	304.8	387.604	146.47	21453.12	0.38
16	1016	304.8	341.376	110.85	12287.98	0.32
17	508	406.4	447.04	49.77	2477.41	0.11
18	1016	508	662.432	137.61	18937.77	0.21
19	762	406.4	511.048	43.59	1900.38	0.09
20	1016	1016	1016	**0**	0	**0**
21	1016	406.4	510.032	53.72	2886.19	0.11
22	1016	304.8	399.288	210.32	44233.20	0.53
23	1016	762	1013.46	25.27	638.71	0.02
24	1016	609.6	824.484	120.18	14444.10	0.15
25	1016	609.6	850.392	126.00	15877.13	0.15
26	1016	406.4	541.528	117.66	13843.59	0.22
27	1016	304.8	414.528	220.58	48656.42	0.53
28	1016	304.8	369.824	135.95	18481.51	0.37
29	1016	304.8	504.952	102.06	10416.50	0.20
30	609.6	304.8	446.024	64.09	4107.35	0.14
31	609.6	304.8	346.456	78.82	6213.15	0.23
32	1016	304.8	799.592	263.14	69244.76	0.33
33	1016	304.8	491.236	163.36	26686.66	0.33

34	762	406.4	514.604	40.42	1633.80	0.08



(a)



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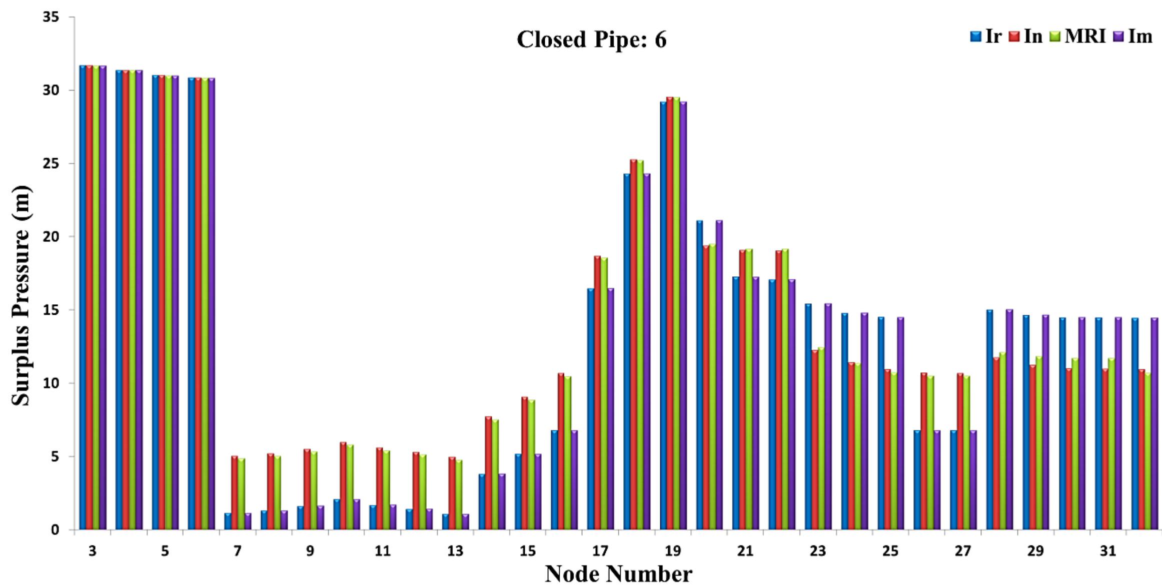

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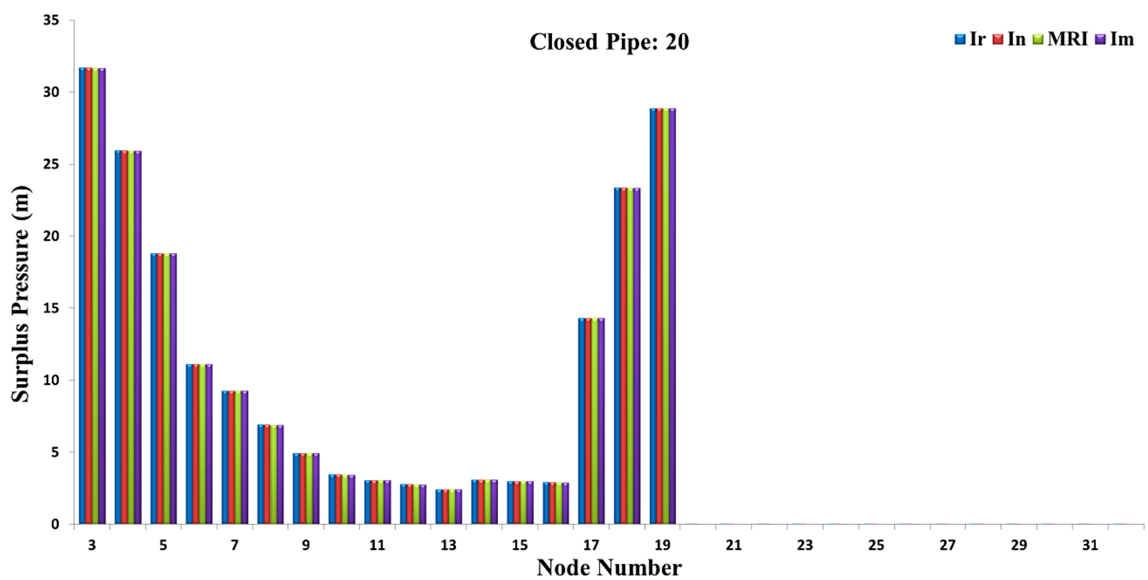


(d)

Fig S2. Surplus pressure of Hanoi network nodes for solutions of maximum reliability criteria when pipes No. (a) 4, (b) 5, (c) 6 and (d) 20 are lost due to failure

The results of figure S2 (a) and (b) shows that by failure in pipes No. 4 and 5 the surplus pressure in most of the nodes for solutions of maximum $I_m$criterion is more than solutions with maximum I_r, $I_n$and MRI. In effect of pipes No. 4 and 5 failures, nodes reactions to pressure changes are similar because these two pipes are along. However, due to failure in pipe No. 6, none of the nodes of the network meet lack of pressure and the figure S2 (c) shows that the solutions with maximum $I_n$and MRIcriteria have more capability to supply pressure in most of the networks. In figureS

2 (d) there is no significant difference in represented solutions with reliability criteria values. The nodes with no values in the graph are those that have negative pressures.

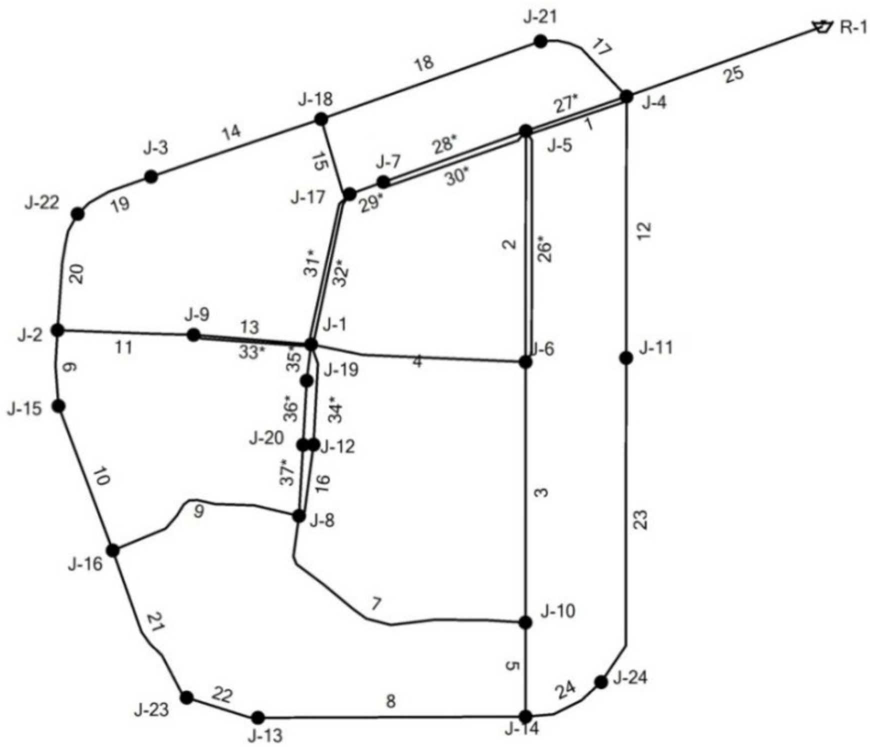


Fig S3. Layout of Real- life network

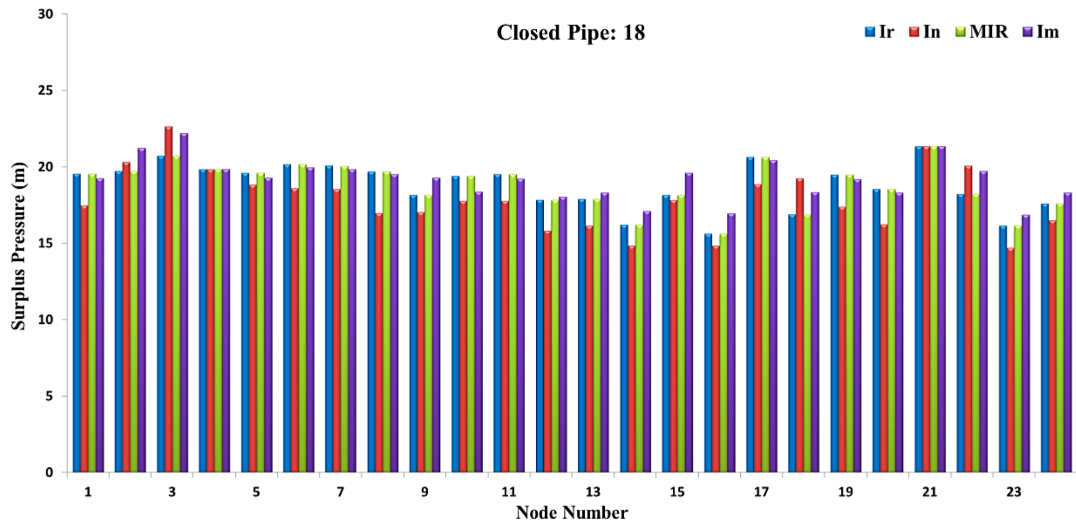
Table S4 presents statistical parameters for new pipes of Real- life Network in result of different runs by GANetXL when optimization approach is cost-based. According to this table pipes No. 18 and 21 were chosen to evaluate the performance of reliability criteria under failure condition because these pipes have less standard deviation and coefficient of variation than other pipes. Moreover, in this network the failure probability should be evaluated in the existing pipes because they have more lifetime in comparison to new pipes. There are different methods accessible to estimate the probability of pipe failure, repair time, and failure return periods. Interested readers should refer to Chapter 18 of Mays (2000). Subsequently, in this study, a random pipe failure has been created using a uniform distribution in the range of [26, 37], that is the pipe numbers for existing pipes (Shafiqul Islam, Sadiq et al. 2013) Finally, the failure of the pipes No. 27 and 34 was analyzed in the network.

Table S4. Statistical parameters for diameters obtained for each new pipe of Real- life network

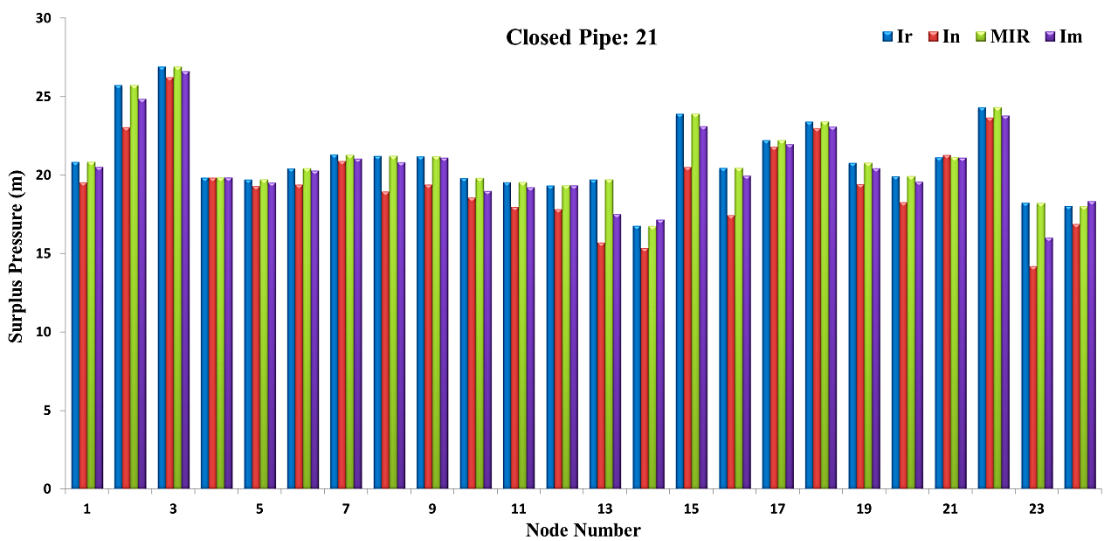
Pipe numbers	Maximum (mm)	Minimum (mm)	Average (mm)	ST. DEV	Variance	C.V.
1	213.2	76.6	125.86	21.14	446.99	0.17

2	170.6	76.6	83.30	16.06	257.93	0.19
3	238.8	76.6	140.96	23.97	574.42	0.17
4	302.8	76.6	93.83	25.70	660.65	0.27
5	213.2	76.6	94.09	20.03	401.31	0.21
6	302.8	76.6	112.86	37.87	1433.82	0.34
7	136.4	76.6	97.10	15.48	239.59	0.16
8	268.6	76.6	80.66	21.65	468.56	0.27
9	341.2	76.6	100.11	31.71	1005.72	0.32
10	341.2	76.6	97.53	42.00	1763.92	0.43
11	191.8	76.6	106.91	20.70	428.58	0.19
12	191.8	76.6	97.50	17.47	305.09	0.18
13	403.8	76.6	109.44	39.39	1551.55	0.36
14	213.2	76.6	117.36	29.38	863.00	0.25
15	238.8	76.6	113.80	34.39	1182.59	0.30
16	302.8	76.6	94.20	32.44	1052.59	0.34
17	238.8	76.6	122.40	43.05	1853.03	0.35
18	136.4	76.6	91.02	**11.28**	127.19	**0.12**
19	191.8	76.6	96.02	15.58	242.86	0.16
20	213.2	76.6	94.89	22.87	522.88	0.24
21	136.4	76.6	90.13	**10.38**	107.72	**0.12**
22	302.8	76.6	88.82	32.45	1052.68	0.37
23	268.6	76.6	88.20	31.13	968.85	0.35
24	170.6	76.6	93.74	17.64	311.19	0.19

The results of the investigations in figure S4 shows that only the failure in Pipe No. 18 can influence the pressure nodes. Consequently, this pipe is one of the most sensitive pipes in this network. However, reliability performance in the failure conditions is similar to no failure conditions in figure 7 (main paper). Finally, for this network that includes low diameter in existing pipes, I_n has 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 decreases due to the increase in head-loss in the pipes.



(a)



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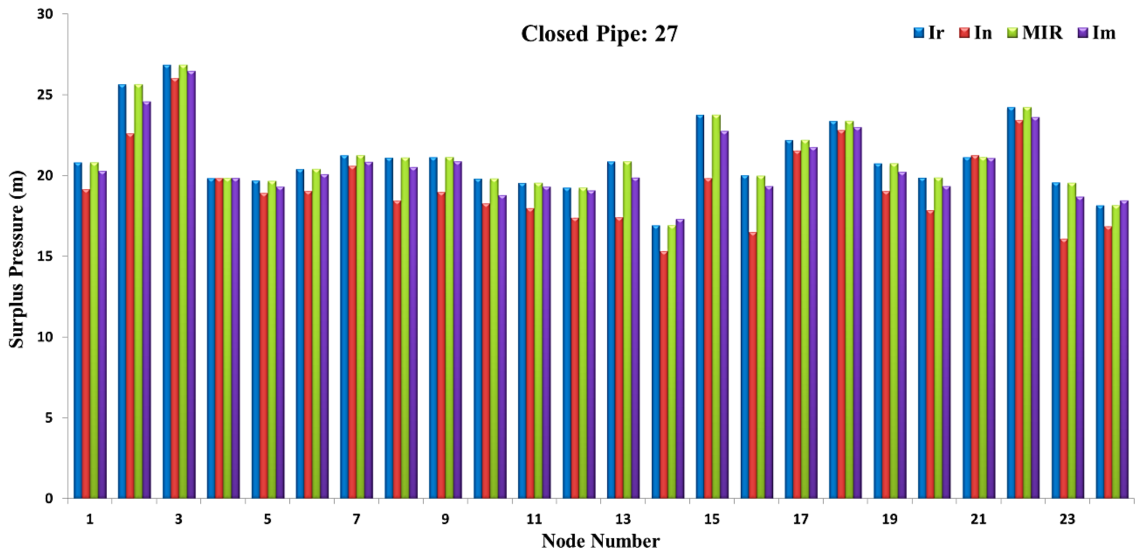

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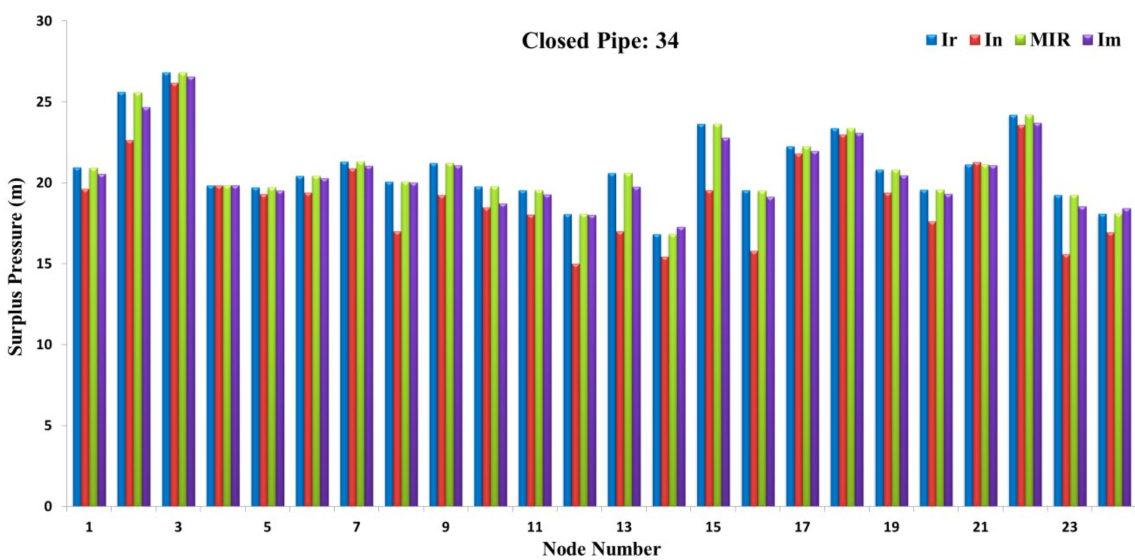

(d)

Fig S4. Surplus pressure of nodes in Real- life network for solutions of maximum reliability criteria under failure of pipes No. (a) 18, (b) 21, (c) 27 and (d) 34