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HYDRAULIC AND CO-LOCATED PIPE CRITICALITIES IN THE REHABILITATION OF WATER DISTRIBUTION MAINS

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Abstract

Infrastructures in urban areas can have spatial and also functional correlation. Water distribution networks (WDNs) along with other infrastructures therefore constitute a complex and interlinked multi-utility system in cities. This brings up the risk of cascading failures to the different networks' elements; for example, a pipe failure could interrupt traffic in a main street, eventually leading to a road network failure. On the other hand, WDNs should be hydraulically robust so that the potable water is supplied to the customers with high reliability. Traditionally, there is a single perspective design approach for WDN rehabilitation and upgrade activities such as pipe replacement, duplicating, and lining, which does not consider the interlinked system in a city. This study aims to assess this issue in terms of an integrated asset management perspective with a multi-utility approach. For this purpose, beyond minimizing costs, two reliability indices will be defined to represent the reliability of a WDN against the hydraulic and multi-utility cascading failures. The hydraulic reliability represents the robustness of the network against the water pressure deficit, and cascading reliability represents the extent to which WDN elements are decoupled from other assets elements. Then, the rehabilitation problem is solved with the contribution of a nature-inspired optimization algorithm, the Non-Dominated Sorting Genetic Algorithm (NSGA-II), through a dynamic approach. In every decision of pipe rehabilitation action, the priority could be given to either the first or second reliability index. These two cases will be assessed and compared to examine the hydraulic and co-location pipe criticality roles in the decision-making for the upgrade of aged water distribution mains on a simplified real network located in the southwest Iran.

Keywords
Water distribution networks, Complex network, Cascading failures, Asset management perspective, Rehabilitation, Multi-objective optimization.

1 INTRODUCTION

Water distribution networks (WDNs) are considered complex infrastructures and their design, construction, and rehabilitation are very complicated and multi-criteria problems [1]. Together with the advancements in developing computer-based models, solving such complex problems through optimization algorithms has been the target of many researches over the past decades [2-7].

While pipe diameters have been the common decision variables in WDN optimization problems, there are many other practical considerations which could significantly impact on the construction cost of the output plans [8]. For example, WDNs change dynamically as time goes by and this deviates the optimum solutions due to the uncertainties in layout expansion, consumers' demand and budget allocation. Some authors have proposed phasing design and construction approaches to deal with this challenge [9-13].

Conflicts between WDN elements (pipes, valves, pumps and etc) and adjacent urban infrastructure systems (road, sewer, etc) increase the risk of cascading failures in the case of failure events [14, 15]. Hence, the renewal plans for WDNs should be organized in such a way that not only demanded water with desirable pressure is delivered to the consumers, but also the layout of WDNs should be dynamically re-designed to achieve decoupled WDNs from the elements of neighbour networks. On the other hand, there is not always enough budget to reach all the goals. In this regard, there are important questions as follows:

1- What is the trade-off between the hydraulic and decoupled reliability measures when an aged WDN must be rehabilitated?

2- How can an aged WDN be improved when there is a budget constraint?

This study attempts to respond to the abovementioned questions through a novel approach.

2 METHODOLOGY

To dynamically solve the rehabilitation problem of a WDN through an optimization algorithm, the design period with the planning horizon T is divided into p phases where every phase is Δt years long, as is shown in Figure 1.

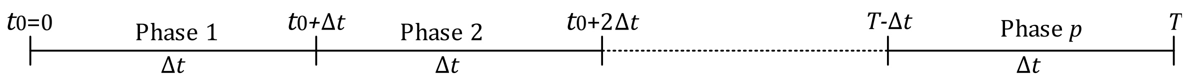

Figure 1. Design period in dynamic optimization of an aged WDN rehabilitation problem

Renewing the WDN starts from phase one. The WDN is simulated with the average of peak demand of consumers over the phases. The multi-objective optimization problem is solved in phase one generating some renewal plans. Based on the available budget or desired reliabilities, a renewal plan is selected and constructed in phase one. The network is updated at the beginning of phase two to repeat the optimization as done in the previous phase. This dynamic phase-by-phase rehabilitation continues till the phase p and gradually upgrades an aged WDN saving money and ending up a well status network [13]. This is a nonlinear, constrained, and integer-real optimization problem stochastically solved by the common nature-inspired approach, Non-Dominated Sorting Genetic Algorithm (NSGA-II) [16]. In the following sections, the decision variables, constraints and objectives of the optimization problem are explained.

2.1 Optimization Decision Variables for Rehabilitation of WDN Problem

Every deteriorated pipe in a WDN should be reclaimed and rehabilitated over its life span to supply potable water continuously to the customers. In this regard, there are some pipe rehabilitation and upgrade techniques such as replacement, duplicating, repairing and etc. The suitable strategy depends on the desired targets requested by water utility managers. In the current study, the client requests a low-cost rehabilitation program making the network decoupled from adjacent infrastructures (in line with the objective of decreasing the risk of cascading failures under hazard-based circumstances) and hydraulically robust overcoming pressure deficit due to the increase in demands, pipe bursts, aging and leakages. Hence the decision variables are defined in the optimization algorithm as follows:

$$r_i \in \{0,1,2,3\}, i = 1: n_{ps} \quad (1)$$

$$d_i \in \{D_{c,min}, \ldots, D_{c,max}\}, i = 1: n_{ps} \quad (2)$$

where, r_i is rehabilitation indicator actions for pipe i which could get integer numbers between 0 to 3 explained in Table 1, n_{ps} is the number of pipe sites which are already occupied by the pipes giving services to the customers, d_i is the pipe i diameter belonging to the set of commercial diameters which are real values changing from $D_{c,min}$ (the minimum available commercial diameter in the market) to $D_{c,max}$ (the maximum available commercial diameter in the market).

Table 1. Decisions for the upgrade of an aged water distribution network

Decision ID	Action Indicator	Explanation
1	$r_i = 0$	The old pipe is removed from site i
2	$r_i = 1$	The old pipe is kept in site i to continue its service
3	$r_i = 2$	The old pipe is replaced with the new pipe which has d_i diameter
4	$r_i = 3$	The old pipe gets a parallel pipe with d_i diameter

The first decision contributes to make the network robust against interconnectivity with adjacent networks. The second decision contributes to save rehabilitation costs. Here, the main assumption is neglecting the pipe maintenance and operating cost. The third and fourth decisions are for improving the hydraulic aspect of the network.

2.2 Optimization Constraints for Rehabilitation of WDN Problem

The hydraulic simulation of WDN is carried out by EPANET 2.2 and therefore the physical constraints of the pipe network hydraulics, i.e., the conservation of mass and energy, are automatically satisfied in the simulation model. Moreover, every solution is feasible as long as it keeps the piezometric pressure head of network's nodes above the minimum pressure service, Equation (3), below which the demand of the node is not satisfied [17]. In Equation (3), H_j is the pressure head at node j, H_{min-s} is minimum service pressure head and n_n is the number of demand nodes in WDN layout.

$$H_j \geq H_{min-s}, j = 1: n_n \quad (3)$$

There are some practical and decision constraints for rehabilitation actions. The first decision cannot be applied to the pipes playing the main role in supplying the water demands of associated node. For this, first, the graph analysis of WDN layout is carried out to recognize the shortest path (where the edge weights are the Euclidean length) from a source to a demand node of the network's graph. Those pipes which belong to the shortest path set are marked as critical sites.

Once the decisions two or three is constructed for the pipe i in phase $k, k = 1: p$, repeating the mentioned decisions is avoided in the following phases, phases $k + 1, k + 2, \ldots, p$. These decisions constraints are due to the fact that a multiple pipe replacement is not economical and laying numerous parallel pipes beside each other is practically infeasible.

As being clear, there is a trade-off between choosing the decision variables in terms of reaching the main objectives of the current rehabilitation problem. For example, while removing a pipe could make a decoupled WDN for an element in a site, it could worsen the hydraulic reliability of the network; or laying parallel pipes increase the hydraulic capacity of the network, but it makes the rehabilitation program expensive and increases the risk of cascading failures. In this regard, two scenarios are considered for laying parallel pipes in this study (Figure 2).

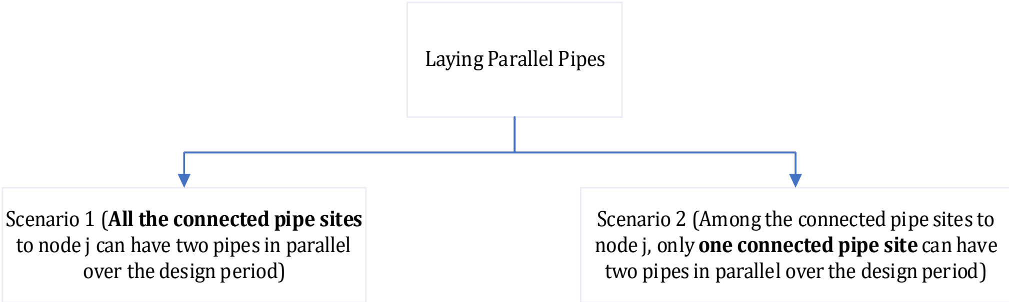

Figure 2. Laying parallel pipe scenarios for rehabilitation of WDN

While scenario one is more in favor of making a hydraulically robust network, scenario two is more in favor of making a decoupled network. Scenario two refers to constraints for laying parallel pipes in the decision-making process of optimization algorithm; Equation (4) represents the mentioned constraint, where $pp_{i,j}$ refers to the existence of a parallel pipe to associated node j in site i (the parallel pipe is defined as the new pipe laid beside the old pipe in site i). $pp_{i,j}$ gets binary values such that if there is a parallel pipe, $pp_{i,j} = 1$; otherwise, $pp_{i,j} = 0$.

$$\sum_{i=1}^{n_{ps}} pp_{i,j} \leq 1 \qquad (4)$$

There are some controls for laying parallel pipes in Scenario two. To explain the controls, first some graph and hydraulic-based indices should be introduced as follows:

- **Node j degree (D_{n_j}):** the number of pipes connected to node j represents the degree of the node j (Equation (5)), where $p_{i,j}$ refers to the existence of single pipe in site i and it gets binary values as done for $pp_{i,j}$. The nodes with the highest node degree could refer to a hub where crowded sites in urban areas including hospitals and administration offices are located.

$$D_{n_j} = \sum_{i=1}^{n_{ps}} pp_{i,j} + \sum_{i=1}^{n_{ps}} p_{i,j} \qquad (5)$$

- **Pipe i co-located degree (D_{Co-p_i}):** every pipe i in WDN can have a correlation with the adjacent networks' elements; for example, pipe i under a street and beside a sewer conduit has co-located degree of two. Equation (6) mathematically explains how this degree is calculated where $e_{z_i}$and n_z represent the site i adjacent element in network z and the total number of neighbour infrastructure systems, respectively.

$$D_{Co-p_i} = \sum_{z=1}^{n_z} e_{z_i} \tag{6}$$

- **Demand Edge betweenness centrality ($\mathbf{EBC_Q}$):** the number of times edge i (pipe i) is a part of the shortest paths between all node pairs j and the source node is known as the source edge betweenness centrality (EBC). This metric was modified by [18], referred to as demand EBC (EBC_Q). The EBC_Q of a pipe i finds the shortest path connecting the reservoir (source node S) and all demand node j, and adds the demand Q_j to the EBC_Q of all pipes located in that shortest path. $\mathrm{EBC}_Q(i)$ is formulated as follows(to know more about this index, please refer to [18]).

$$\mathrm{EBC}_Q(i) = \sum_{j=1}^{n_n} shortest\ path_{S,j}(i) \cdot Q_j \tag{7}$$

Considering the introduced indices, EBC_Q and D_{Co-p_i} represent the hydraulic and co-located criticality of a pipe. The algorithm of scenario two is shown in Figure 3. In short, if node j is a hub, the associated pipes cannot be strengthened by parallel pipes. If there is a decision for laying parallel pipes for the nodes which have a degree smaller than hub nodes, the priority of laying a parallel pipe is for the pipe site with the lowest co-located degree; if the co-located degrees are the same for all connected pipes to node j, the pipe with the highest EBC_Q gets a parallel pipe.

After upgrading the network in phase k, some updates for the status of the sites are necessary. If the pipe i has been removed, its site cannot be occupied with new pipe till the last phase unless the layout of adjacent networks has been changed in favor of decreasing the site i co-located degree. If the pipe site i has gotten a parallel pipe, this site is not among the critical sites anymore and there could be the option of removing the pipe. Moreover, it should be checked if there has become a hub (the nodes with the highest degree) to not receive a parallel pipe over the next subsequent phases.

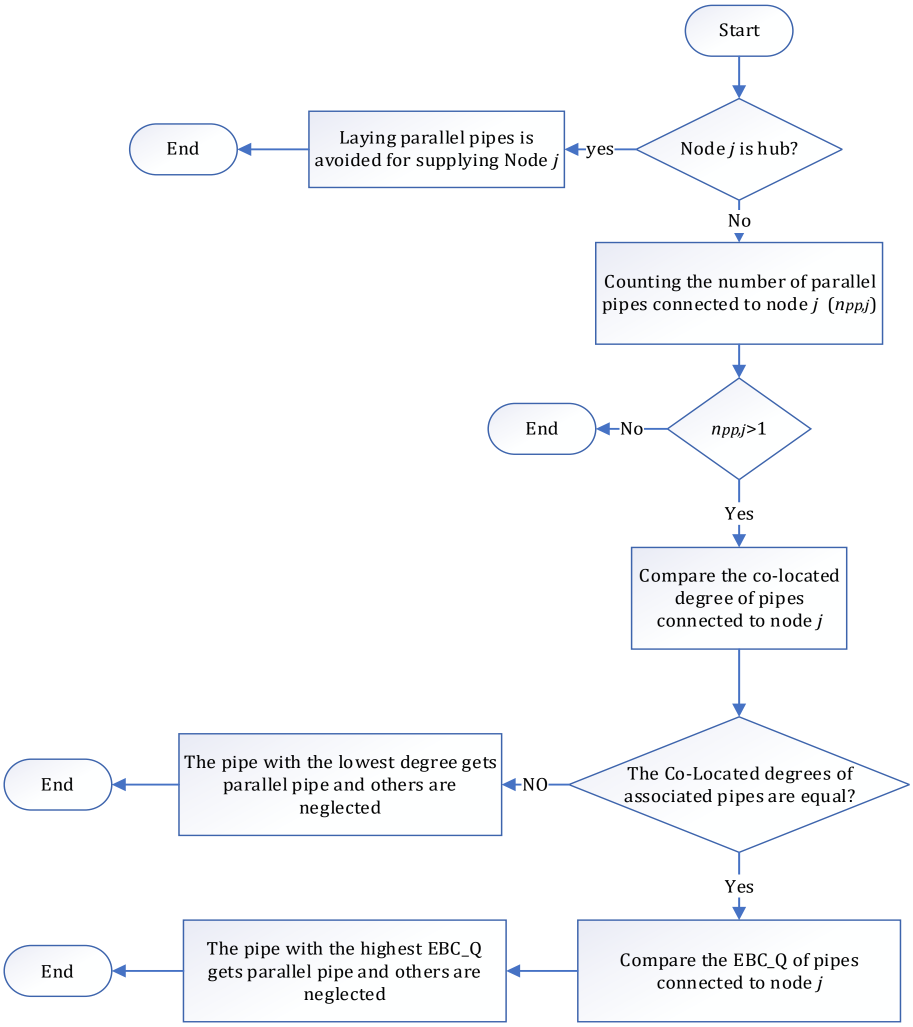

Figure 3. The decision-making algorithm of laying parallel pipes in scenario 2 for rehabilitation of WDN

2.3 Optimization Objectives for Rehabilitation of WDN Problem

The current multi-objective optimization problem is formulated with three objectives as follows:

$$\text{Minimize } (Cost_k(\Gamma_k(r,d)), -Rel_{\text{hyr},k}, -Rel_{\text{dec},k}) \tag{8}$$

where, $Cost_k$ is the rehabilitation cost of upgrade program Γ, indicating the budget of upgrading the network at the beginning of phase k, and evaluated by Equation (9):

$$Cost_k(\Gamma(r,d)) = \sum_{i=1}^{n_{ps}} c_i L_i \tag{9}$$

Where c_i is the unit cost of the commercial diameter size assigned to the pipe with a length L_i. Hydraulic reliability is the second objective of optimization calculated by a hybrid index which is the combination of two indices in hydraulically weak and robust conditions [13]. The first one is the frequency index of counting the number of demand nodes with water pressure above desirable pressure calculated by Equation (10):

$$Rel1_{hyd,k} = 1 - \frac{\sum_{i=k}^{p}\sum_{j=1}^{n_n} max\,(0, -sign(H_{ij} - H_{\mathrm{des}}))}{n_n(p-k+1)} \tag{10}$$

where $Rel1_{hyd,k}$ represents the first frequency hydraulic reliability of the network in phase k, and H_{ij} actual head at node j in phase i, where i changes from k to p, and H_{des} is desirable pressure. The second part of the hybrid reliably is the resilience index introduced by [19] and then improved by [20]:

$$Rel2_{hyd,k} = \frac{\sum_{i=k}^{n}\left(\frac{\sum_{j=1}^{n_n} C_{ij} \times q_{ij}\,(H_{ij} - H_{des})}{[\sum_{l=1}^{nr_i} Qr_{il} \times Hr_{il} + \sum_{m=1}^{pn_i}(\frac{P_{im}}{\gamma})] - \sum_{j=1}^{n_n} q_{ij}H_{des}}\right)}{(p-k+1)} \tag{11}$$

where q_{ij} is the design demand at node j at the end of phase i, nr_i is the number of reservoirs in phase i, Qr_{il} and Hr_{il} are respectively the discharge from and head at reservoir l in phase i, pn_i is the number of pumps in phase i and P_{im} is the power of pump m at the end of phase i. Also, C_{ij} is a weighting coefficient associated with the uniformity of the diameter of pipes connected to node j in phase i as follows:

$$C_{ij} = \frac{\sum_{r=1}^{np_{ij}} D_r}{np_{ij} \times max\{D_r\}} \tag{12}$$

where np_{ij} and $max\{D_r\}$ are respectively the number of pipes and the maximum pipe diameter size connected to node j in phase i. According to the above equation, $C_{ij} = 1$ if only one pipe is connected to node j or all pipes connected to that node have the same diameters and, $C_{ij} < 1$ if pipes connected to node j have different diameters.

In each phase k the two mentioned indexes are calculated and final hydraulic reliability would be as follows:

$$Rel_{hyr,k} = \begin{cases} Rel1_{hyr,k} & Rel1_{hyr,k} < 1 \\ 1 + Rel2_{hyr,k} & Rel1_{hyr,k} = 1 \end{cases} \tag{13}$$

Using the hybrid reliability index (Equation (13)) the upgrade program becomes more flexible and manageable so that the system can be gradually upgraded from a weak state ($Rel1 < 1$) to a normal state ($Rel1 \approx 1$) and then to a robust state ($Rel2 > 1$) depending on the money invested for the project and the reliability expected. Hence the value of $Rel_{hyr,k}$ changes between 0 and 2.

The third objective refers to the decoupled reliability (Equation (14)) of WDN showing how much the rehabilitation plan can make a decoupled network in phase k.

$$Rel_{\mathrm{dec},k} = 1 - mean(Avg(D_{Co-p_{i,k}})) \tag{14}$$

where $Avg(D_{Co-p_{i,k}})$ calculates the average correlation for the pipe i in phase k meaning that for a network correlated with two adjacent networks (for example road and sewer), if a pipe element is correlated with only a road element, the average correlation for the pipe is 0.5. After calculation of the average correlation in every site i, the mean value of $Avg(D_{Co-p_{i,k}})$ gives an overall view about the decoupled status of WDN where its values change between 1 and 0.

3 APPLICATION

3.1 Case Study

To investigate the proposed approach, an aged water WDN, Baghmalek network (Figure 4), located in the southwest of Iran is considered for upgrading. The network has 90 pipe sites and 72 consumption nodes and is fed by one reservoir (node 1) located at the highest elevation of the region. The network is more than 30 years old and its current hydraulic performance turns out to be in an urgent need for rehabilitation and upgrading. It is assumed that the network only has correlations with sewer and road networks. The multiplex system is conceptualized in Figure 4 representing the correlations and the network configuration. The full information about the network can be found in [13] and is available upon request.

The network is first analysed for the existing conditions in year zero. Currently, the hydraulic performance of the WDN is weak and only 36% of the consumption nodes meet the desirable pressure of 18 m required for the network according to the national regulations (Rel1=36%). Also, the correlation of WDN with the adjacent infrastructures is about 63% and therefore the decoupled reliability is about 37%. Hence, the hydraulic and decoupled reliabilities of the network should be improved through upgrade actions. There are some main assumptions for upgrading the current network as follows:

- A 25-year design period is considered for upgrading the network (T=25)
- During the design period, the network has no extension in plan. The network layout is fixed with time.
- A list of polyethylene pipes containing 14 diameter sizes as shown in Table 2 is used for upgrading the network.
- For all new pipes, the Hazen–Williams coefficient in year zero is 130. Also, the Hazen–Williams coefficients are supposed to change linearly with time with a reduction rate of -0.6% yearly.
- The installation of a parallel pipe is more difficult and expensive than replacing a new pipe. To take this issue into account the unit cost of parallel pipes is increased by 20%.
- The network consumption is supposed to change with time linearly. The annual rate of consumption increase is estimated with 0.0332 l/s/year.
- The design period is divided into 5 construction phases, 5-year periods

- The correlation of a water pipe with a street (road element) is assumed if the water pipe is located under or in the 3-meter distance from the margin of the street.
- The correlation of a water pipe with a sewer network element is assumed if they are located in 3-meter radius distance from the axis line of each other (this assumption comes from the possible cascade failure in earthquake circumstances)

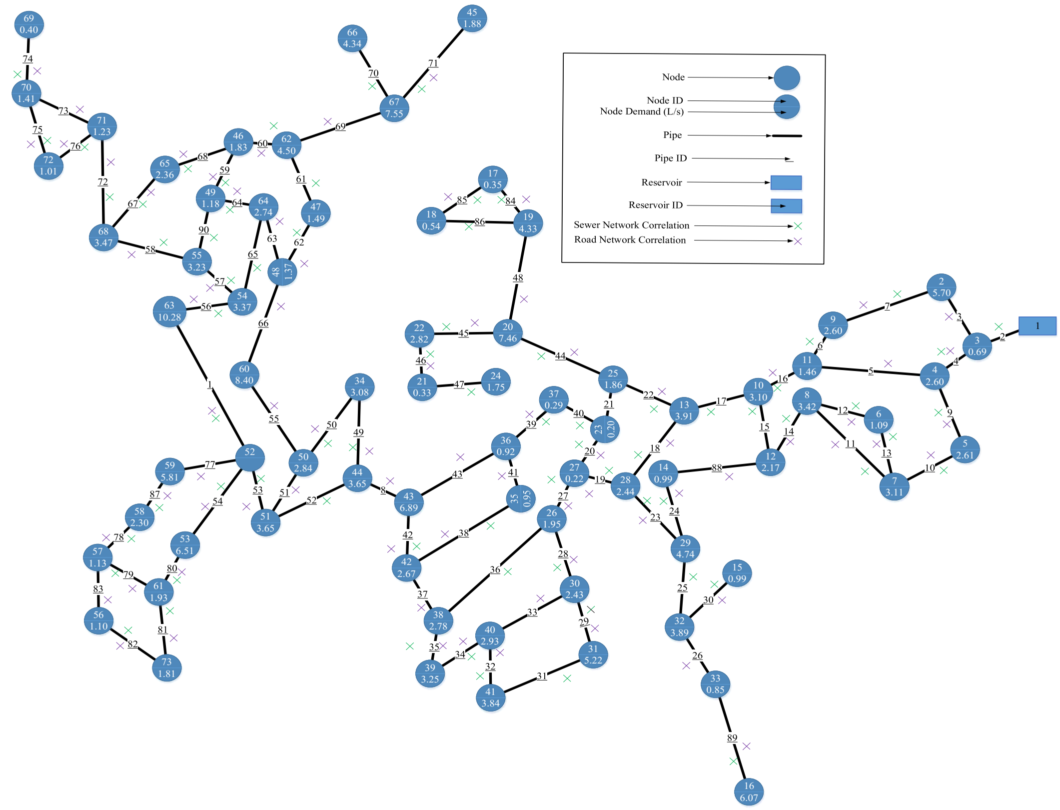

Figure 4. Baghmalek WDN and correlation with adjacent networks' elements in year 0

Table 2. Commercial polyethylene pipes with their unit construction cost in year zero, D_C: Commercial diameter, D: Internal diameter

D_C(mm)	*D* (mm)	*Unit cost (Rials/m)*
63	53.60	163473.90
75	63.80	192204.30
90	76.60	232484.70
110	93.80	300636.10
125	106.60	374078.20
160	136.40	543685.60
200	170.60	769448.30
250	213.20	1147234.00
315	268.20	1752000.00

400	341.20	2734489.00
450	383.89	3455312.00
630	537.50	6466257.00
710	605.77	8102474.00
800	682.58	10187126.00

3.2 Optimization Results

The Pareto fronts obtained from the multi objective optimization are shown in Figure 5. The left side Pareto fronts (Figure 5-(a)) refer to the rehabilitation programs of Scenario 1, while the right-side Pareto fronts (Figure 5-(b)) indicate the rehabilitation programs of Scenario 2.

As being clear, the Pareto fronts show a serious trade-off between objectives. The higher budget investment in the rehabilitation of WDN, the higher improvement in the hydraulic aspect of the network, and the higher values of hydraulic reliability, the lower values of decoupled reliability.

It is assumed that the policy in Phase 1 is improving both hydraulic and decoupled reliabilities of WDN to values around 0.93 and 0.47. The solutions with the mentioned desired reliabilities are selected from Pareto fronts. As observed, the rehabilitation program based on scenario two provides a cheaper price than the one from Scenario 1. Hence, the low co-located degree priority-based strategy for laying parallel pipes not only makes the cost saving rehabilitation plans, but also improves the optimization performance in terms of efficiency.

It is assumed in Phase 2 that there is a limitation in budget allocation and the WDN client can only invest 1.50 $\times 10^{10}$ Rials for rehabilitating of Baghmalek network. As being clear, while Scenario 1 provides solutions that make the WDN hydraulically resilient ($Rel1_{hyr,2} \geq 1$), Scenario 2 rehabilitations keep the hydraulic status of the network weak ($Rel1_{hyr,2} < 1$). On the other hand, decoupled reliability resulting from Scenario 2 is higher than the one related to Scenario 1 (0.46 vs 0.34).

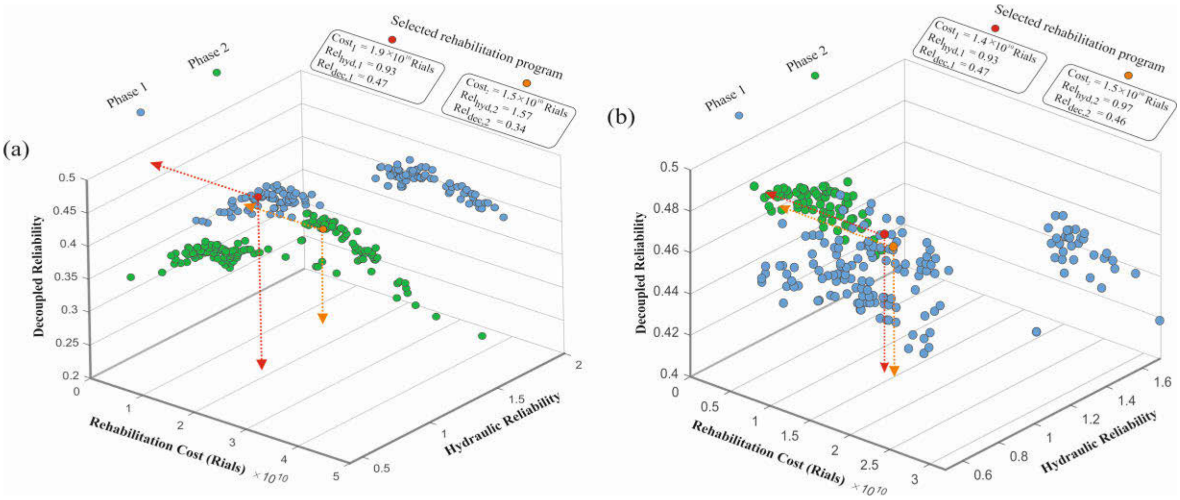

Figure 5. The three objectives Pareto fronts of rehabilitation programs for the WDN obtained by Scenarios 1 and 2 for two phases

Figure 6 shows the constructed rehabilitation plan in two phases obtained by Scenario 1 and 2 approaches which are Figures 6-a and 6-b respectively. As it can be seen, removing pipes can remove co-located degree and therefore significantly decreases the risk of cascade failures under events at the sites. For example, site 7 in Figure 6-b is removed in Scenario 2, and co-located degree becomes 0, while in Scenario 1, there is the replacement technique and no change in co-located degree in site 7. As seen, in the constructed plan of Scenario 2, there are no nodes with two connected parallel pipes whereas numerous are present in the Scenario 1 plan.

Another important consideration is recognition of hubs in every phase of rehabilitation. The hub for the Baghmalek network is node 52 with the degree four which is the highest degree. Hence, while node 52 gets higher degree in Scenario 1, it is avoided in Scenario 2. Moreover, in Scenario 2, some nodes reach degree four in phase 2 (for example node 43) and they cannot receive higher degrees by parallel pipes over the next phases unless the coming rehabilitation actions reduce the degree of the node (for example the pipe 43 could be removed).

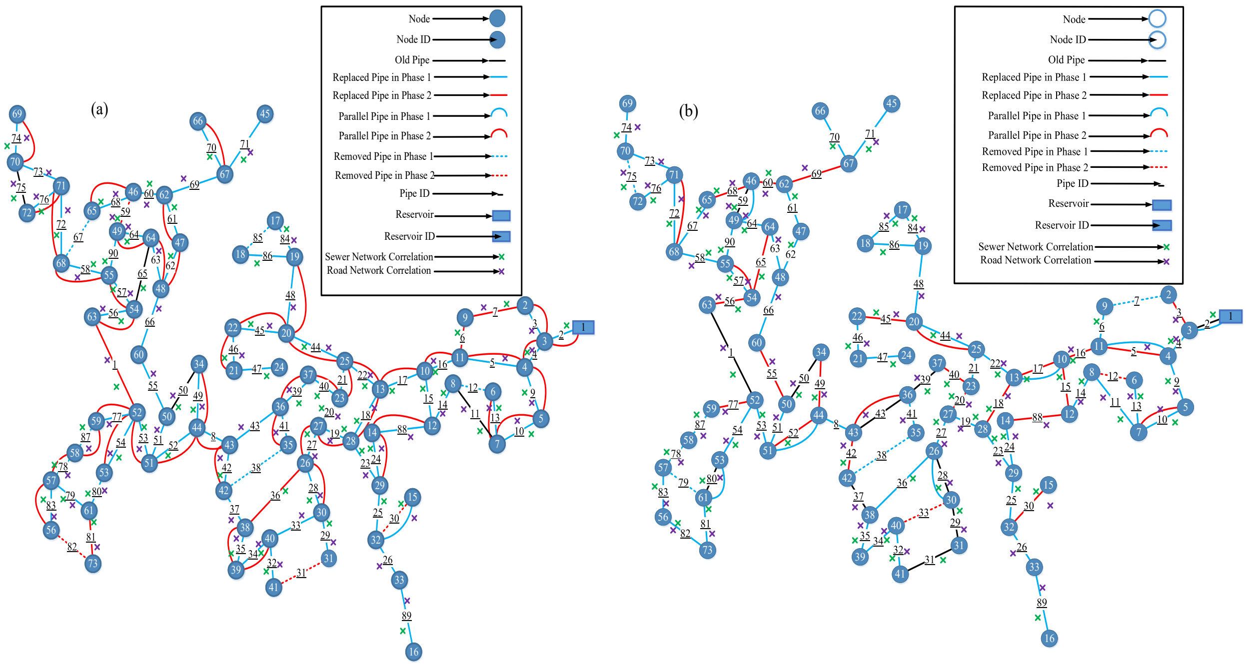

Figure 6. Constructed rehabilitation plan for Baghmalek WDN obtained by Scenario 1 and 2 approaches

4 SUMMARY AND CONCLUSIONS

Current study proposed a method for rehabilitation of aged water distribution mains when there are three conflicting objectives, minimizing rehabilitation cost, maximizing hydraulic reliability, and decoupled reliability showing the interconnectivity of WDN with adjacent networks (like road and sewer networks). In this method, the design period is divided into some intervals, and construction, as well as design of rehabilitation plans, are done phase by phase dynamically.

In every phase, multi-objective optimization problem with the mentioned objectives is solved where the decision variables are leaving the old pipe to continue its service, pipe replacement, laying parallel pipes and removing pipes.

Two Scenarios were defined for rehabilitation of the network. In Scenario 1, the node degree can be enhanced in every phase of rehabilitation by laying parallel pipes, while this can happen only one time over the design period in Scenario 2 where the hubs (nodes with the highest degree) are not allowed to receive a higher degree. In this regard, other locations are assessed in terms of co-located degree and demand edge betweenness centrality as co-located and hydraulic pipe criticalities. In every decision of enhancing the degree of nodes by parallel pipes, only the associated pipe with the lowest co-located criticality can get a pipe in parallel and if all the associated pipes have the same co-located criticality, the pipe with the highest demand edge betweenness centrality gets a parallel pipe.

The results showed that designing the rehabilitation programs in favour of asset managers could have negative impacts on the hydraulic performance of the WDN (Scenario 2). On the other hand, making hydraulically a resilient network by laying many parallel pipes (Scenario 1) results in a vulnerable network against cascading failure and is not desirable when there is the matter of budget constraints. This implies that the multi-utility rehabilitation planning is a highly complex task and should be synchronized with other asset rehabilitation and upgrade programs to save cost and obtain a better balance between decoupled and hydraulic reliability of WDN.

5 ACKNOWLEDGMENTS

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