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Rehabilitation of a Water Distribution System using Sequential Multi-Objective Optimization Models

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Abstract

Identification of optimal rehabilitation plan for a large water distribution system (WDS) with enormous amount of decision variables is a challenging task especially when no super computer facilities are available. This paper presents an initiative methodology for rehabilitation of WDS based on three sequential stages of multi-objective optimization models for gradually identifying the best-known Pareto front (PF). A two-objective optimization model is used in the first two stages where the objectives are to minimize costs of rehabilitated infrastructure and operational costs. The optimization model in the first stage applies to a skeletonized WDS. The PF obtained in stage 1 are further improved in stage 2 using the same two-objective optimization problem but for the full network. The third stage employs a three-objective optimization model by minimizing the cost of additional PRVs as the third objective. The suggested methodology was demonstrated through the application to the C-town WDS presented in the WDSA2014 conference. Results show that the efficiency of the suggested methodology to achieve the optimal solutions of a large WDS in a reasonable computational time. Results also suggest the

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minimum total costs will obtain once maximum leakage reduction is achieved due to maximum possible pipeline rehabilitation without enlarging the existing tanks.

Keywords: Water distribution system; Rehabilitation; Leakage; Infrastructure cost; Operation

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Introduction

Many researchers and practitioners developed various rehabilitation plans for water distribution system (WDS) in the past (Farmani et al. 2004). The commonly used objectives typically include a trade-off between minimizing total costs and improving WDS performance. This improvement can be envisaged in number of WDS performance metrics. An efficient rehabilitation plan should usually improve all performance metrics but different researchers have addressed specific performance metrics within a rehabilitation plan such as maximizing reliability (Kapelan et al. 2005; Fu et al. 2012) and resiliency (Farmani et al. 2005; Nafi and Kleiner 2009) minimizing leakage (Araujo et al. 2006; Fu et al. 2012) and failure risk (Giustolisi et al. 2006). Minimization of water losses through the pipe leakage is usually considered as the main aim for many rehabilitation plans due to considerable economic potential for saving potable water (Mahdavi et al. 2010; Giustolisi et al. 2015). Another economic intensive for reducing leakage is because of the increased operational cost as a result of additional energy consumed in pumps for supplying water loss (Colombo and Karney 2005). Pipe leakage in WDS can be classified as background (from joints and small cracks as invisible) and burst (visible/invisible) losses (Lambert 1994). The major factors for occurrence of these losses are typically due to high pressure and old pipelines (Giustolisi et al. 2008). The most commonly used rehabilitation techniques for reducing both types of water losses are pressure management and pipeline rehabilitation (Gomes et al. 2011). Pressure management can also be conducted in WDS using pressure control valves (PCVs) (Mahdavi et al. 2010) or pump scheduling (Price and Ostfeld 2014). The major challenge for PCVs is to identify the best site location and optimal scheduling of valve setting to keep the pressure head as minimum as possible while satisfying the minimum pressure required (Araujo et al. 2006). Identification of the most efficient rehabilitation techniques for a case is heavily dependent on the main characteristics of the network infrastructure and operation. Thus, an optimization algorithm may be required to find the optimal solutions using all potential rehabilitation techniques. This can be a tedious task and computationally expensive due to enormous feasible space of solutions (Fu et al. 2012).

Numerous researchers employed multi-objective optimization models especially multi-objective genetic algorithms for solving WDS rehabilitation problem (Farmani et al. 2005; Kapelan et al. 2005; Behzadian et al. 2009; Fu et al. 2012). However, employing such optimization models comprising a large number of decision variables (DVs) in a large WDS preferably requires a very fast or super computer. In a recently developed multi-objective optimization models, Fu et al. (2011) decreased the burden of complexity of WDS using global sensitivity analysis and thus reduce the number of DVs. This paper strives to achieve this aim by developing an initiative method to find optimal solutions of rehabilitation problem for a WDS with many DVs assuming that limited computer facilities is available. In order to tackle large WDS, the proposed method in this paper includes a number of sequential multi objective evolutionary algorithms to decrease the computational and thus gradually approach near optimal solutions. A brief overview of the problem description and further details of the suggested method will be described in the next section followed by the results and discussion section.

Problem description

The case study used here is C-Town WDS presented in the BBLAWN (Battle of Background Leakage Assessment for Water Networks) problem of the WDSA2014 conference (Giustolisi et al. 2014; Giustolisi et al. 2015). The main purpose of the problem is to control the background pipeline leakage and rehabilitation scheduling of the WDS by means of a number of rehabilitation techniques (i.e. pipeline rehabilitation, pump scheduling, tank and pump upgrading, pressure management by placing and setting pressure control valves and pipeline closing). The objective is to minimize three categories of annual costs incurred by (1) infrastructure rehabilitation including pipes, pumps and tanks upgrading; (2) WDS operation including water loss and energy consumed by pumps; (3) installation of PCVs.

The constraints of the WDS model are: (1) minimum pressure head of 20 meters at nodes with positive demand and positive pressure at nodes with no demand; (2) each tank needs to reach at least the same volume of water at the end of simulation period; (3) pumps and throttle control valves cannot be controlled by PLCs (e.g. by flow or time) and must be controlled by hydraulic conditions (e.g. tank elevation). Other main assumptions are: (1) only background leakage through pipes is used for calculation of water loss (Germanopoulos 1985; Giustolisi et al. 2008); (2) ; Pipe rehabilitation can be conducted by using either replacement or duplication of existing pipes; in the case of replacement, the background leakage reduces by 80%; (3) Any number of additional tanks and pumps are allowed but only in parallel to the existing ones; (4) Installing PRVs with variables pressure settings over time and closing any pipes without time scheduling are allowed in the network; (5) The hydraulic model needs to be simulated for one week and follows the pressure driven simulation approach. Further details of assumptions and formulations of the problem description can be found in Giustolisi et al. (2014).

Methodology

Due to the large size of the optimization problem and in the absence of super computer facilities, three sequential optimization models are proposed here for a large WDS rehabilitation problem. The methodology is based on a two-objective optimization problem for rehabilitation of an skeletonized WDS in the first stage to pick up some 'rough' optimal solutions without massive computational effort. The 'rough' solutions are tuned up in the second stage by restoring the trimmed network. The third stage accomplishes searching the solutions of the optimal rehabilitation problem by using a three-objective optimization model. All stages use non-dominated sorting genetic algorithm (NSGA-II) (Deb et al. 2002) as optimization model and EPANET (Rossman, 2000) as hydraulic simulation model.

In order to comply with pressure driven simulation model requested in the problem description, an iterative loop is employed to update nodal demands based on the pressure calculated from EPANET which is a demand driven simulation model. Each iteration involves solving EPANET based on the demand driven simulation model to calculate the nodal pressures. Then, Leakage as a nodal demand is then updated based on a function of the calculated pressures. The process of updating nodal demands (i.e. leakage values) continues until they finally converge into constant values. A maximum number of iterations are also considered if the convergence of leakage values cannot be obtained in a reasonably computational effort.

Decision Variables (DVs)

One of the distinguishing features of this optimization problem is the enormous number of DVs which are shown in 7 rehabilitation techniques in Table 1. Each rehabilitation technique is composed of one or more DV(s) which is briefly described here: (1) <u>Pipelines rehabilitation:</u>

each pipe can be rehabilitated by only one of three rehabilitation methods (duplication, replacement or 'do nothing') to make up one DV. Another DV is the pipe diameter among 12 commercial pipe sizes specified in the problem description. (2) Existing pump settings: the first DV specifies whether the pump is on or off. The other two DVs specify the pump scheduling options using minimum and maximum water level of the associated tank controlling the particular pump. (3) New pumps: in addition to the above three DVs of the existing pumps, new pumps have another DV which is the type of new pump being selected among 4 suggested pumps specified in the problem description. (4) New tanks (parallel additional tanks): the single DV for each new tank represents the volume of an 'equivalent' single tank in parallel with each existing tank. The 'equivalent' tank represents one or more additional tanks and thus its volume picks up a volume among 33 combinations of six standard tank volumes. Each combination of tank volume is made up of the least cost combination of the six standard tank volumes given in the problem description (Giustolisi et al. 2014). These 33 combinations cover all potential additional volumes from 500 to 10,000 m^3. For instance, the 'equivalent' single tank with 1000 m^3 volume is made of two 500 m^3 standard tanks with total annual cost of 28,040 €/year rather than one 1000 m^3 standard tank with 30,640 €/year cost. (5) Existing TCV (throttle control valve) settings: the first DV specifies valve status in three states: 'active' for operation, 'open' for not in operation (i.e. pipe without TCV) and 'closed' for blocking the pipe. The other two DVs specify the minimum and maximum water level of tank T2 controlling the only existing TCV in the network. (6) PRV settings: 31 potential locations were considered here for installing PRVs. These locations were selected based on a detailed examination of the network to control the pressure head of individual branch pipes or separate individual zones (Rahmani and Behzadian, 2014). The first DV represents the PRV status in three states: 'open' assumes no

PRV in the prospective potential location, ‘closed’ assumes closing a pipe without a PRV and ‘active’ is the only state assuming a PRV installed in the potential location. Selection of PRV size proportional with the mounted pipe (among 12 commercial pipe sizes) accounts for the second DV. Six other DVs of PRVs represent schedule of six pressure settings changing every four hours over a day. The pressure setting is assumed to be in a range between 0 and 60 meters. (7) Pipe closing: assuming a number of potential location at critical locations of the network, one DV is defined here with two choices of ‘open’ which means ‘do nothing’ and ‘close’ for closing pipe using isolation valve. 25 Potential locations for closing pipes were selected in the areas which can support functionality of PRVs more efficiently or change the network from looped to branched one to balance the pressure head in nodes (Rahmani and Behzadian, 2014). Overall, given the aforementioned DVs and the total number of potential components for rehabilitation, the size of search space in the C-Town WDS is equal to 1.76×10^{931}.

Stage #1

The skeletonized network was used in the first stage to speed up achieving some near optimal solutions by trimming all the branch pipes. Critical head losses from the trimmed pipes were added up to the minimum pressure of the remained nodes where the pipes were trimmed in order to ensure the minimum pressure would be satisfied after restoring the trimmed pipes. By skeletonizing the WDS, 146 pipes and 145 junctions were trimmed from the model. Therefore, 286 pipes (i.e. ~37,800 meters), 243 junctions, 11 existing pumps, 7 existing tanks, 1 reservoir and 1 valve were remained. An optimization model is formulated in this stage to find optimal pipes rehabilitation for skeletonized WDS, pumps scheduling and additional pumps and tanks. The two cost objectives, which are minimized include (1) total annual costs of infrastructure (*CI*) for n_r pipes which will be rehabilitated, n_p new pumps and n_t new tanks which will be added; (2) total annual costs of operations (*CO*) associated with background leakage of all n_{bl} skeletonized pipes (here n_{bl}=286) and energy consumption by all n_p pumps including existing and new ones:

$$Min\ CI = \sum_{i=1}^{n_r} Cr_i \times L_i + \sum_{i=1}^{n_p} Cp_i + \sum_{i=1}^{n_t} Ct_i \tag{1}$$

$$Min\ CO = Cl \times \sum_{i=1}^{n_{bl}} Lk_i \times L_i + 52 \times \sum_{i=1}^{168} \left(E_i \times \sum_{j=1}^{n_p} Ce_{ij} \right) \tag{2}$$

where Cr_i= cost per unit length of pipe *i*; L_i=length of pipe *i*; CP_i=cost of pump *i*; Ct_i=cost of tank *i*; *Cl*=cost of leakage; Lk_i=annual background leakage per unit length of pipe *i*; E_i= electricity cost for hour *i*; Ce_{ij}=total electricity consumed during hour *i* at pump *j*. Table 2 presents the number of components for each type of DV and total number of DVs at this stage which is equal to 636 considering the relevant values in Table 1. Note that the existing TCV at this stage is switched on and off by a constant minimum and maximum level of tank T2 and thus is excluded from being considered as a DV.

Stage #2

After obtaining ‘approximate’ optimal solutions, this stage only strives to progress towards optimal solutions with the full network configuration. Therefore, the trimmed pipes were restored to the WDS model in this stage. The optimization model at stage 2 has the same two objective functions presented in stage 1. The same DV types plus one additional type (settings of the existing TCV) are defined here. Furthermore, potential of adding 6 new pumps in stage 1 would increase to 11 pumps in this stage; thus one new pump can be placed in parallel with each of the all existing pumps. The total number of DVs at this stage is also equal to 659 (see Table

2). Therefore, the leakage objective function at stage 2 is calculated precisely rather than 'approximate' calculation due to the inclusion of all pipes in the network. Note that the number of pipes which are considered for rehabilitation at stages 1 or 2 are 65% of all pipes in the network (i.e. 286 out of 432 pipes).

Stage #3

This stage aims to optimize both pipeline rehabilitation of the trimmed pipes (i.e. 146 pipes) in stage 1 and PRV settings for reducing excessive nodal pressures. Therefore, 146 trimmed pipes at stage 1 are considered as DVs for rehabilitation at this stage. Two additional DV types in this stage are site location for both PRV installation being selected from 31 potential PRVs and closing pipes being selected from 25 potential pipelines. Other DVs for existing and new pumps, new tanks and TCV settings are the same number and types defined in stage 2. Thus, the total number of DVs in stage 3, as details shown in Table 2, is equal to 652. The optimization model is then formulated for the full network with three objectives minimizing costs including the two cost objective functions defined in Eq. (1) and (2) plus the cost (*CV*) of n_v PRV which will be installed:

$$Min\ CV = \sum_{i=1}^{n_v} Cprv_i \tag{3}$$

where $Cprv_i$=cost of PRV i installed in one of the 31 potential locations. Note that the optimized rehabilitation plan for 286 pipes obtained in the stage 2 are not involved in the optimization model of stage 3 and thus they need to be fixed in this stage. Having had multiple optimal solutions of the Pareto front (PF) in stage 2 each with different combinations of optimized rehabilitation for these pipes, several optimization models need to be implemented in this stage, each with a fixed set of optimized rehabilitation plan of the previous stage.

Results and discussion

The suggested methodology was demonstrated here through its application to the C-town WDS. The NSGA-II parameters used in all three stages include a population size of 110, simple three point crossover with the probability of 0.95 and a mutation by gene with the probability of 0.003 for the pipeline rehabilitation genes and 0.05 for other genes. The number of generations conducted in stages 1, 2 and 3 were 1000, 1500 and 1500 iterations, respectively. The optimization models were run on a personal computer with these specifications: Intel(R) Core (TM) i7 – 4770 CPU @ 3.40 GHz, installed memory (RAM): 16 GB. Each simulation run took almost 1.71 and 2.8 seconds for the skeletonized and full network, respectively. Therefore, the total run time took approximately 308 hours (~13 days) with aforementioned computer facilities.

The existing network cannot satisfy the pressure constraints due to high water demands and subsequently high pressure head loss. Therefore, the optimization model of stage 1 was run to find (1) a feasible solution and (2) 'approximate' optimal solution using the skeletonized network. Hence, the optimal solutions of the PF in stage 1 were obtained as shown in Fig. 1. All optimal solutions in stage 1 add at least one new pump to increase pressure head and therefore achieve feasible solutions whilst no tank upgrade occurs at this stage. The total costs of the optimal solutions obtained from this stage changes between around € 3 and € 3.8 Million.

The PF obtained from stage 1 was then used as initial population of the optimization model in stage 2. The PF obtained in stage 2, shown in Fig. 1, can be compared to stage 1. This PF can better represent a trade-off between capital investment for infrastructure and operational costs. In other words, the more capital investment, the more reduction in operational cost would occur. Thus, when optimal capital investment changes between € 0.1 and € 0.9 Million, the range of associated annual operational costs is between € 3.4 and € 1.8 Million, respectively. The total costs of the solutions in this stage change between around € 2.5 and € 3.4 Million. Unlike the solutions in stage 1, the solutions in this stage usually have neither pump nor tank upgrades but they employ significant pipeline rehabilitation and smarter scheduling for existing pump to control leakage and thus operational cost. Total number of rehabilitated pipes in stages 1 and 2 was up to 227 (~20.3 km) in which the total length of rehabilitation using parallel pipes was up to 120 meters. This is because parallel pipes not only keep the same rate of background leakage due to the existing pipes being in place but new parallel pipe would also increase leakage.

To preserve the diversity of the optimal rehabilitation plan for the 286 skeletonized pipes which are no longer used as DVs in stage 3, this stage deployed three individual optimization models each using fixed optimal rehabilitation plan for those pipes in stage 2. Hence, these three solutions (shown as solutions A, B and C in Fig. 1) were selected from different parts of the PF indicating different contribution of optimal rehabilitation plan obtained from stage 2. Table 3 presents the costs associated with different rehabilitation components for these solutions. The total costs of solutions A, B and C vary between around € 2.5 and € 2.7 Million.

Each of the three aforementioned solutions was used in stage 3 to develop an individual three-objective optimization model. These optimization models were run in parallel to constitute part of the final optimal front. For instance, Fig. 2 shows the trade-offs between the three objectives of the PF achieved from solution B. As it can be seen, there only exist a strong correlation between infrastructure and operational costs. Despite the existence of this high correlation, a weak correlation exists between PRV installation and operational cost. More specifically, adding more PRVs would generally result in a descending trend of operational costs and thus can be considered a surrogate for infrastructure upgrade in the network as the second priority.

Finally, the trade-offs between infrastructure and operational costs in the PF of the three optimization models were obtained in stage 3 as shown in Fig. 3. Each PF constitutes part of the overall PF for rehabilitation of the WDS. Comparison of the solutions in this PF with solutions A, B and C extracted from stage 2 shows that the reduction of leakage cost relative to a feasible solution in stage 1 would change from 28% to 58%, 41% to 70% and 46% to 75%, respectively.

The results also show that pipe rehabilitation especially pipe replacement can decrease the water losses because of efficiently decreasing parameter β in the background leakage relation (Giustolisi et al. 2014). It also shows that tank upgrading is unnecessary in more than 80% of the optimal solutions (Fig. 4) but some solutions use a large volume of tank sizes i.e. adding 4250 m^3 to T4 and T5 (over 800% increase) and 2000 m^3 to T2 (100% increase). It can be inferred that increase in the tank volume are mainly on T3 and T1 for optimal solutions originating from initial solution A, T1 and T5 for optimal solutions with originating from initial solution B and T4, T2 and T5 for optimal solutions with originating from initial solution C, respectively. Addition of new pumps is inevitable in almost all of the solutions with large tank sizes due to increased capability for filling tanks.

Comparison of the optimal solutions in the overall PF suggests two groups of rehabilitation solutions. The first group replies on mainly rehabilitating pipelines without any tank upgrade to reduce the background leakage down to around € 0.63 Million (80% of the solution in Figs 3 and 4). This minimum leakage can be obtained when the capital investment for infrastructure rehabilitation activities is almost € 0.83 Million. However, the second group, accounted for the 20% of the right-hand optimal solutions in Fig. 3, includes those with increased tank capacity (see Fig. 4). In fact, once additional tank volume is added in the solutions, the optimal system operation changes to fully utilize this additional capacity by pumping more water at less expensive hours to fill additional storage and save water for releasing water from tanks by gravity during more expensive hours. This has resulted in almost 15% reduction in energy cost although the energy cost is accounted for a small percentage of operational cost (~20%) and total costs (~10%). Eventually, this group can result in a lower operational cost but the infrastructure costs would increase due to the cost of additional tanks.

Further analysis can be conducted by comparing the contribution of different cost components of the non-dominated optimal solutions to the total cost (Fig 4). The cost of leakage in operation and cost of pipeline rehabilitation in infrastructure are accounted for the major factor in the total cost. On the other hand, energy cost arising from pump operation is almost constant over all the optimal solutions ranging. This suggests pipeline rehabilitation has the most significant influence on reducing leakage and thus operational cost of the WDS. Furthermore, maximum reduction of operational costs can be achieved when infrastructure cost can partially replace pipeline rehabilitation with tank upgrading. However, this replacement does not necessarily result in a lower total costs as it can be seen in Fig. 4. Therefore, the minimum total cost (i.e. the most cost-effective optimal solution) is almost around the intersection of the aforementioned two groups in which pipeline rehabilitation would result in the maximum reduction in total leakage. This solution is with a total cost of € 1,657,324 can be introduced as the selected solution with the detailed costs presented in Table 3. This solution should be selected from a part of the PF where the high cost of infrastructure would result in a considerable reduction in operational cost especially background leakage. This is because capital investment of infrastructure is a one-off cost in the WDS while it leads to huge annual reduction in operational costs iterated each year.

Conclusions

Optimal rehabilitation plan for the water distribution system was analyzed here using pipelines rehabilitation, upgrading of tanks and pumps, scheduling of pumps and PRVs, site location for PRVs installation and closing pipes. The objectives were to minimize the costs associated with background leakage, pumping energy, infrastructure investments and PRV installation. Three sequential multi-objective optimization models used to gradually find the near optimal solutions using the skeletonized network (stage 1) and then improved within stages 2 and 3 using the full network. The reasonable computational efforts and time to achieve the final optimal solutions proved the efficiency of the proposed methodology for solving rehabilitation for a large WDS problem with many DVs. Results suggest two groups of rehabilitation plan including the solutions mainly based on pipeline rehabilitation without tank upgrade and the solutions with tank upgrade. The second group, although would lead to lower operational costs in the network. The selected solution with the minimum total costs equal to € 1,657,324 is suggested around the intersection of the aforementioned two groups in which pipeline rehabilitation would result in the maximum reduction in the total leakage. Note that a comprehensive rehabilitation strategy should be analyzed for a real-world WDS over a long term planning horizon and consider schedule of implementing individual rehabilitation options in this time period. Also, some other influencing factors needs to be considered such as deterioration of pipelines and water demand increase in the real-world WDS within this time period.

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List of Tables:

Table 1. Rehabilitation techniques and associated decision variables

No	Rehabilitation technique	Decision variables (DVs)	DV type	number of DVs for each component
1	Pipe rehabilitation	Rehabilitation method (3 states: replacement, duplication and 'do nothing')	Integer	2
		New pipe diameter (12 states[1])	Integer	
2	Existing pump settings	Pump status (2 states: open and closed)	Integer	3
		minimum water level of the associated tank controlling pump	Real	
		maximum water level of the associated tank controlling pump	Real	
3	New/additional pumps	Type of pump (4 states[1])	Integer	4
		Status of pump (2 states: open and closed)	Integer	
		minimum water level of the associated tank controlling pump	Real	
		maximum water level of the associated tank controlling pump	Real	
4	New/additional tank	Tank volume (32 states[2])	Integer	1
5	TCV settings	TCV status (3 states: active, open, closed and)	Integer	3
		minimum water level of the tank T2 controlling TCV	Real	
		maximum water level of the tank T2 controlling TCV	Real	
6	PRV settings	PRV status (3 states: open, closed, active)	Integer	8
		PRV diameter (12 states[1])	Integer	
		6 PRV pressure setting values (60 states: indicating 0 meter to 60 meters)	Integer	
7	Pipe closing	pipe status (2 states: open and closed)	Integer	1

[1] List of pipe diameters, pump sizes and tank volumes are available in the problem description
[2] Six standard tank sizes which are available in the problem description can make up 33 different composite volumes

Table 2. Number of components for DV type and total number of DVs at different stages

	Pipes rehabilitated	Existing pump	New pumps	New tanks	TCVs	PRVs	pipe closing	Total number of DVs[1]
Stage#1	286	11	6	7	0	0	0	636
Stage#2	286	11	11	7	1	0	0	659
Stage#3	146	11	11	7	1	31	25	652

[1] Total number of DVs is calculated by summing the multiplication of the number of WDS components in this Table by the associated number of DVs in Table1.

Table 3. Costs (€) of different rehabilitation components obtained from the candidate solutions (A, B and C) in stage 2 and selected solution in stage 3

	pipelines rehabilitation	pumps upgrading	tanks upgrading	background leakage	pump energy	PRVs installation	Total cost
solution A	253,636	0	0	2,280,607	215,641	0	2,749,884
solution B	399,093	0	0	1,898,230	215,530	0	2,512,853
solution C	549,394	0	0	1,725,320	210,545	0	2,485,259
Selected solution	779,636	14,252	0	660,671	189,208	13,557	1,657,324