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OPTIMAL REHABILITATION STRATEGY IN WATER DISTRIBUTION SYSTEMS CONSIDERING REDUCTION IN GREENHOUSE GAS EMISSIONS

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ABSTRACT

Water distribution systems (WDS) need a rehabilitation strategy due to infrastructure aging which leads to decreasing capacity, increasing leakage and consequently low performance of the WDS. Identifying an appropriate strategy including location, time of pipeline rehabilitation, rehabilitation technique and material types are the main challenge especially when the rehabilitation budget is limited. Furthermore, the environmental impacts of a rehabilitation strategy on global warming have yet to be addressed. This paper presents a multi-objective optimization model for a long-term rehabilitation strategy in WDS which minimize the two main criteria: (1) greenhouse gas (GHG) emissions from either fossil fuel & electricity or embodied energy of materials; (2) the leakage amount. The Pareto optimal front containing optimal solutions is determined using Non-dominated Sorting Genetic Algorithm NSGA-II. Decision variables are classified into a number of groups as: (1) pipeline rehabilitation including different rehabilitation techniques and material types; (2) addition of pumps; (3) addition of tanks. Rehabilitation techniques used here includes replacement, rehabilitation and lining, cleaning, pipe duplication. The long time planning horizon of the rehabilitation strategy is divided into a number of specific times for which the simulation model is applied separately. The effects of population growth, aging, hydraulic constraints and budget limitations on the WDS are considered. The developed model is demonstrated through its application to C-Town WDS. The rehabilitation strategy is analyzed for a 10 year planning horizon with 2 five-year time periods. The results show that the optimal rehabilitation strategy is able to efficiently control the total leakage amount in the WDS whilst considering environmental criteria by lowering GHG emissions.

Keywords: water distribution system, optimization, greenhouse gas emissions, leakage, rehabilitation strategy;

INTRODUCTION

Water distribution systems (WDS) are of paramount importance in urban areas due to the high potential of environmental impacts on the areas and water consumptions. Given the external drivers affecting performance of WDS (i.e. population growth and infrastructure deterioration), one of the main concerns for management of WDS is to properly plan for system rehabilitation. The pipeline rehabilitation is mainly justified to be as a necessary measure in WDS to combat the increasing leakage over a long term operation of the WDS. There are some specific causes for leakage increase in the WDS. Two main common types of the leakage in the WDS are background and burst type leakages [1]. These types especially the former are dependent on the pressure head of the WDS. The increased water demands over a long-term operation of the WDS (as a result of population/industry growth or new developments) should lead to generally lower system pressures (due to increased head losses). Theoretically, this declined pressure would cause to reduced overall system leakage. This however, never happens in real-life system as the effects of increased demands are typically outweighed substantially by the effects of system deterioration resulting in increases in both background and burst type leakage. The net result is typically an increased overall level of leakage in the system.

In contrary to the abovementioned theory, water companies would add new pumps to increase overall pressure heads (to deal with increased head losses occurring in the WDS). This, in turn, would also be the main cause for increase in both background and burst leakages. Therefore, the leakage amount can also be reduced by a proper and efficient rehabilitation through either directly decreasing pipe leaking or indirectly alleviating the need for increased pressure.

Although leakage reduction is the main purpose of a rehabilitation strategy, it needs to take into account other sustainability criteria. One of the main criteria related to the sustainability is greenhouse gas (GHG) emissions which is directly associated with climate changes and global warming. GHG emissions in water distribution systems resulted either directly from electricity & fossil fuel energy consumption or indirectly from embodied energy of pipelines given a life cycle of the pipeline [2]. Furthermore, water loss (i.e. leakage) is not only an economic issue, but also are an environmental and sustainability issue. More specifically, water loss causes more water and electricity to be consumed and thus GHG emissions increase and water supply reliability would be threatened. In addition, water losses can be a critical issue in arid regions especially during water shortage. As a result, a multi-objective rehabilitation strategy is required.

Developing rehabilitation strategy in WDS has been widely addressed by many researchers. Woodburn *et al.* [3] proposed a strategy to select the pipes for rehabilitation using a non-linear programming procedure with minimization of rehabilitation cost. Halhal *et al.* [4] developed a method for selecting the manner of rehabilitation, replacement or lining. Multi-objective messy genetic algorithm was used to minimize the costs and maximize the benefits (water quality, hydraulic, flexibility, and physical integrity). Dandy and Engelhardt [5] proposed a method to schedule the pipes replacement and diameter selection using GA. Dandy and Engelhardt [6] addressed a five-year time steps model considering cost and reliability. Nafi and Kleiner [7] proposed a method for replacement of individual pipes while considering practical issues. In the light of the abovementioned issues, this paper develops a multi-objective optimization problem for rehabilitation strategy in WDS. The paper is organized as follow: first, the methodology including problem (case study) description is presented. Within the methodology, the simulation and optimization models are described. Then, the result of the application of the methodology to the case study are presented and discussed. The paper will finally finish by drawing some conclusions.

METHODOLOGY

The rehabilitation strategy proposed in this paper includes a method for optimal pumps scheduling, pipelines rehabilitation and addition of tanks in a WDS over a long term planning horizon. Hence, the strategy is defined as: (1) how the pipelines should be scheduled for rehabilitation; (2) the pumps should be scheduled for operation; and (3) the tanks should be added over some specific planning horizon given the following assumptions:

- given a WDS with pipes, junctions, pumps, tanks and reservoirs;
- given a long time planning horizon of *T;*
- given a specified annual rehabilitation budget;
- given hydraulic constraints such as minimum nodal pressure and tank water level,
- given the possible methods of rehabilitation such as replacement, lining, cleaning;

Ideally, any rehabilitation strategy should extend over the whole planning horizon to include pipeline deterioration and water demand growth. A typical time for this hydraulic simulation would be 30 years with an hourly time step. This long-term simulation cannot be feasible with respect to run time in the hydraulic model (e.g. EPANET [8]). Specifically, this issue would be even more critical in optimization problem where a large number of simulations need to be run. Instead, here it is assumed a number of subsequent short term (i.e. daily) simulation models, each represent the behavior of hydraulic model for a specific interval.

Each simulation model reflects the two major changes over time: (1) population growth and (2) pipelines deterioration. The increase in nodal demands reflects the population growth and increase in pipe roughness coefficients (i.e. Darcy-Weisbach method) represents the pipeline aging. Given a planning horizon of *T* years divided into *N* time intervals, the nodal water demands and pipe roughness coefficients are changed in each of *N* intervals according to population growth and pipeline aging rate.

Furthermore, the rehabilitation strategy in this study also aims to conduct the following four individual intervention options for each time intervals over the planning horizon: (1) select the appropriate pipes and the relevant technique for rehabilitation. It is assumed that there are four available rehabilitation techniques (i.e. replacement, lining, duplication, and cleaning); (2) pump upgrading which add any new pump to the existing pumping stations; (3) pump scheduling which specifies how often each pump works during a day plus the minimum and maximum levels of the associated tanks in which the pump will be on and off, respectively; and (4) addition of tanks in each time interval over the planning horizon.

To avoid a large search space for selecting the appropriate pipes for rehabilitation, the rehabilitation strategy used here follows an improved version of the 'oldest first' approach [9]. The main shortcoming of 'oldest first' method is related to considering only one criterion (i.e. age) for rehabilitation regardless of other factors such as the pipe location and their pressure head. However, selection of pipes for rehabilitation is straight forward and somehow logical. To use the benefits of this approach, the rehabilitation strategy in this study will first shortlist the rehabilitation pipes as selecting 23 percent of the oldest pipes for each time interval (100 pipes from 432 pipes). Then, the final selection from this shortlist group will be based on the four influencing factors: costs, hydraulic constraints, amount of leakage reduction and GHG emissions. Note that here only background leakage based on the equation proposed by Germanopoulos is used for leakage calculations [10]. Therefore, the total leakage is the sum of the leakages from each pipe which is calculated based on the mean pressure of the ending nodes and its length according to Giustolisi *et al.* [1].

The rehabilitation strategy outlined above creates an enormous search space of feasible solutions which needs an optimization problem coupled with a simulation WDS model. The following section will address the simulation and optimization models in this study.

Simulation model

To assess the performance of each candidate solution for rehabilitation strategy, simulation of the hydraulic WDS model is required. EPANET software is used here for WDS model simulation [8]. EPANET model simulates a hydraulic WDS model during an extended period assuming a demand driven approach. A modified version of EPANET is applied here to include head driven simulation for leakage calculation. In addition, hydraulic constraints handling such as pressure limits in WDS nodes and water levels in tanks which are required in this study are satisfied by the hydraulic simulation model.

Optimization model

This paper uses a multi-objective evolutionary algorithm based on non-dominated sorting genetic algorithm (NSGA-II) to identify the appropriate rehabilitation strategy in the WDS[11]. The objective functions (fitness values) used in the optimization problem are to minimize (1) the total amount of leakage and (2) total GHG emissions over the planning horizon. The GHG emissions are calculated as kg-CO_2 equivalent resulted from both electricity energy used and energy embodied in the materials.

Here it is assumed that the total cost including capital and operational costs is considered as a constraint. More specifically, capital costs are accounted for any upgrades in number of pumps, addition of tanks, pipeline rehabilitation (replacement, duplication, lining, cleaning). Operational costs are calculated based on the cost of electricity energy used in pump stations over the whole planning horizon. In this optimization problem, total annual costs must be less than the annual cost specified for the particular WDS. Hence, the solutions with total cost less than the annual cost will be accepted otherwise a penalty value is added to the fitness value. Note that the constraints of the hydraulic model are handled by multiplying a penalty value to the fitness values such that the solutions which do not comply with the constraints are discarded through the progress of evolutionary algorithm.

The decision variables (genes) of each solution (chromosome) are defined according to the interventions of the rehabilitation strategy described in the methodology. Consequently, a chromosome consists of *N* rehabilitation time interval to cover a long term planning horizon *T*. Decision variables (genes) for each rehabilitation time interval are defined in three parts as shown in Figure 1. They are (1) pipeline rehabilitation for *n* pipes each contains three genes as pipe number, rehabilitation type, pipe diameter if replaced or duplicated, and material of the pipeline (2) addition of pump_for *k* existing pumps each contains four genes as addition of pump in the particular station at each time step, additional pump type, minimum and maximum levels of the tank associated with the pump station; (3) additional tank for the *m* existing tanks. Note that the total genes of each chromosome are *N* times the number of genes for each rehabilitation interval.

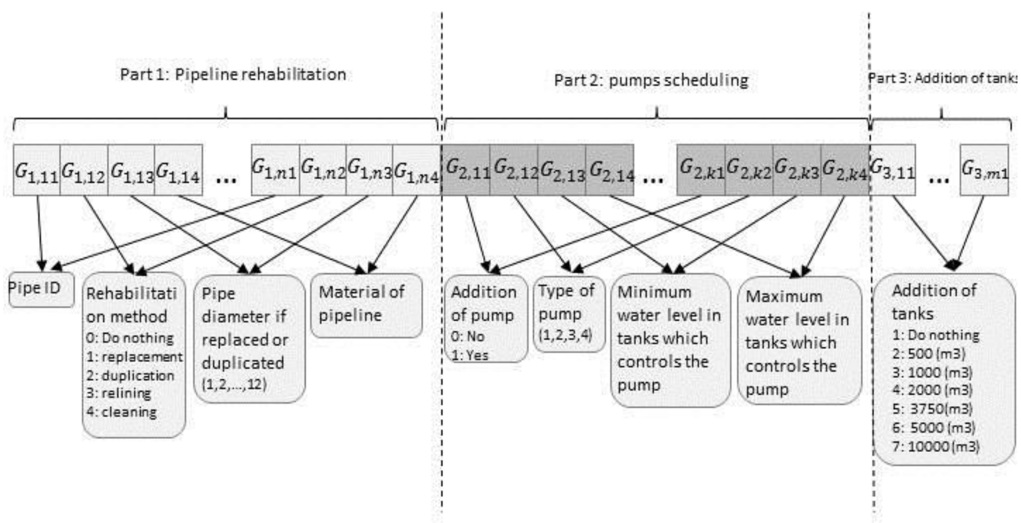

Figure 1. Schematic representation of genes for one rehabilitation time interval

A multi-point crossover is used for this problem due to a large number of genes in a chromosome outlined below. This study considers a new mutation operator with multiple mutation probability rates. As a result, the probability of mutation is different for different genes of a chromosome.

CASE STUDY

The C-Town network consists of 388 junctions, 7 storage tanks, 1 valve, 432 pipes, 11 (existing) pumps, 5 pumping stations and one reservoir which have been widely used by researchers [12]. C-Town consists of 5 district metered areas (DMAs) which have different patterns of consumptions at the various regions of the WDS in 24 hours. Figure 2 shows the C-Town WDS, pumps, tanks and reservoir locations, incidence of pipelines.

Type of material for all pipes in the WDS is ductile iron at the start of rehabilitation. It is assumed that the replaced or duplicated pipes are Polyethylene (PE), the allowed rehabilitation types are replacement, duplication, lining and cleaning. To save the computational time, an extended period of 24 hours with 1 hour time pattern of water demand relative to average day flows was used considering the different water consumptions. The hydraulic constraints are: minimum pressure of 20 meter in nodes with positive demand; each tank has to have at least the same volume of water at the end of extended period of simulation in comparison with the beginning of the simulation; positive pressure in nodes without demands. In this study, the simulation and optimization is performed for a planning horizon of 10 years including 2 five-year time duration for interventions of rehabilitation (N=2). Simulation of the first rehabilitation period starts with the existing conditions but the second rehabilitation time (year 5) starts with the decision variables of the first period plus the required changes indicating the 5 year time elapsed. More specifically, nodal demands were increased as a result of population growth by multiplying the nodal demands of the first rehabilitation step by 1.15 and for the second rehabilitation step by 1.1. The same procedure considers for pipelines roughness coefficients as a result of infrastructure aging.

For each specific time, a shortlist of 100 pipes containing the pipes with the least roughness coefficients (Hazen-Williams) are selected as candidates for pipeline rehabilitation in optimization process. After each rehabilitation time interval, this shortlist is updated based on the changes in the pipes in the last interval.

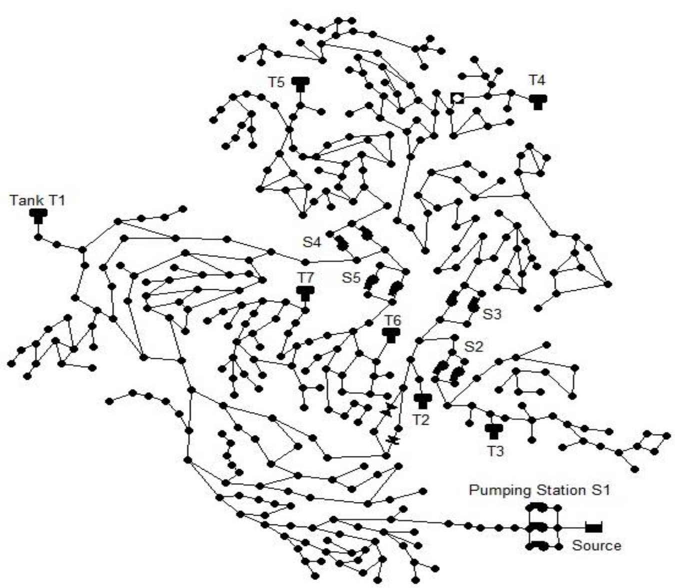

Figure 2. C-Town WDS

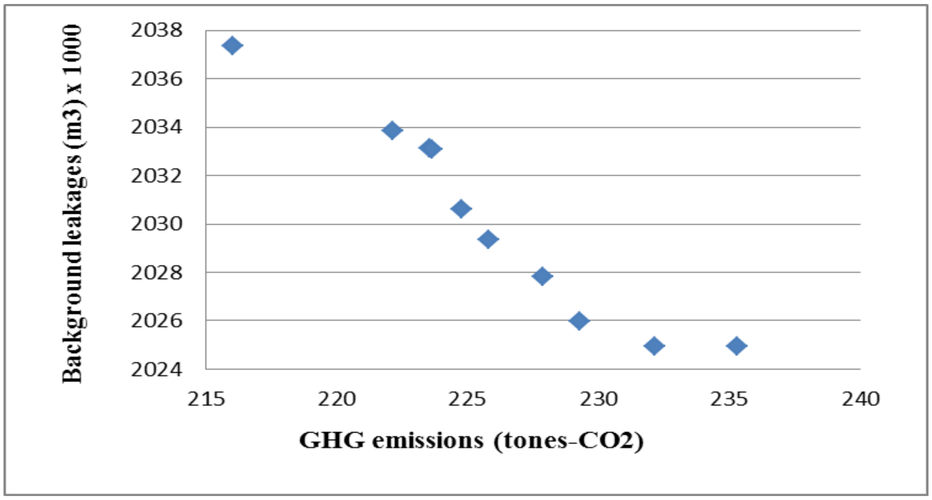

Figure 3.Pareto-optimal solution for rehabilitation strategy in the C-Town WDS

The NSGA-II parameters were set as follows: a population size of 100; 242 genes for each chromosome containing 121 genes for each rehabilitation interval. The genetic structure of these 121 genes are: 90 genes for pipelines rehabilitations for a maximum of 30 pipes, 24 genes for pump stations and 7 genes for seven tanks.

We used a three-point crossover with random choice of locations of crossover with the probability of 0.9; and a mutation with the rates of probability as: 0.05 for the pipeline rehabilitation parts and 0.10 for pump scheduling and tanks addition parts. All NSGA-II parameters were rigorously analyzed such that the best performance of the optimization model is obtained.

GHG emissions include (1) the embodied energy for the whole life cycle of the pipe materials which have been replaced, duplicated, lining or cleaning; and (2) energy of electricity and fossil fuel used in pumps operating and rehabilitations types. The GHG emission resulted from electricity consumption is 0.21 (kg Co_2-eq/KWh) and embodied energy for PE is 2.34 (kg Co_2-eq/kg rehabilitated material).

Results

The optimization model was run for 5,000 generations several times. Figure 3 shows the Pareto optimal front resulted from a NSGA-II run after 5000 iterations. Each point in this front can be represented as a solution containing two sets of rehabilitation activities and pump scheduling and tank addition for the two period of rehabilitation in this WDS. The figure show that the solutions characterized by very low background leakages can lead to a high amount of GHG emissions in the network.

For further analysis, three solutions are selected from different part of the Pareto optimal front (i.e. the best solutions in terms of either background leakages or GHG emissions and the third in the middle) to reflect different features of the Pareto-optimal solutions. These solutions which are shown in Table 1 includes the total length of pipeline rehabilitations for each method, additional pump for each station, additional tanks and their size for each rehabilitation period. Other details of the solutions (e.g. type of additional pumps and etc.) are not shown in this Table. The solution which has the highest rate of GHG emissions (i.e. third solution) has the greatest amount of pipelines replacement and duplication plus additional pump. Therefore, the most GHG emissions resulted from energy embodied and energy usage is expected however the least background leakage has been obtained from this solution. As a result, it can be inferred that the more annual budget for replacement and duplications rather than lining and cleaning, the more the background leakage is expected to decrease whilst GHG emissions relevant to embodied energies of materials would increase. Addition of new pumps would cause nodal pressures and electricity consumptions to increase and consequently increase both GHG emissions and background leakages; hence the pump addition may be ineffective action with respect to these objective values. However, pumps addition to the WDS is unavoidable due to population growth and pipeline aging. Therefore, the GHG emissions resulted from electricity consumed by pumps are inevitable which may cause pipeline leakage increase. The results of all three solutions indicate that the need for additional tank is more demanded within the first period of rehabilitation.

Table1. Results Obtained from the simulation optimization model for C-Town

Solutions	Objective functions		Planning horizon	pipeline rehabilitation				Addition of a pump to the stations					Addition of tanks						
	GHG emissions (tones-CO_2)	Background Leakages (m^3) x1000		Replacement (m)	Duplication (m)	Lining (m)	Cleaning (m)	S1	S2	S3	S4	S5	T1 (m^3)	T2 (m^3)	T3 (m^3)	T4 (m^3)	T5 (m^3)	T6 (m^3)	T7 (m^3)
First solution	216	2,037	First 5 years	376	589	1119	692	√	-	-	-	-	500	-	-	500	1000	1000	1000
			Second 5 years	630	283	662	168	-	√	-	-	√	5000	-	500	-	500	-	500
Second solution	225	2,029	First 5 years	520	246	706	463	√	-	-	-	-	2000	-	1000	-	2000	1000	2000
			Second 5 years	643	312	504	367	-	-	-	√	√	3750	-	-	1000	-	-	-
Third solution	235	2,024	First 5 years	754	785	643	319	√	-	-	-	√	5000	-	500	-	-	2000	3750
			Second 5 years	820	196	690	276	-	-	-	√	√	-	-	-	1000	1000	-	-

CONCLUSIONS

This paper presented a multi-objective rehabilitation strategy in a WDS in which both leakage and GHG emissions are concurrently decreased by pipeline rehabilitation, pump and tank additions. The multi-objective optimization problem used NSGA-II to find Pareto optimal front of the best solutions. The pipeline rehabilitation included the type of rehabilitation and replaced material type. The rehabilitation strategy applied for two 5 year periods over a 10 year planning horizon. To avoid a large search space of decision variables, a technique based on first shortlisting the oldest pipes and then selecting was effective which could efficiently speed up the convergence of the evolutionary algorithm.

It is concluded that rehabilitation techniques by replacement and duplication have the more impact on background leakage reduction but increase GHG emissions due to embodied energies of new materials. On the other hand, addition of new pumps would be inevitable due to population growth and pipeline aging but would increase both GHG emissions and background leakages due to increase in water pressure and electricity consumptions. Nevertheless, more research is recommended to investigate the genuine impact of pump and tank addition on the variation of leakage amount over a long term planning horizon considering infrastructure aging and population growth.

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