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WDS leakage management through pressure control and pipes rehabilitation using an optimization approach

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Abstract

Leakage management through pressure control is a common practice in many water utilities to reduce water loss. The current Battle of Background Leakage Assessment for Water Networks (BBLAWN), is an attempt to combine WDS rehabilitation planning with pressure control management to achieve a better leakage ratio and lower WDS capital and operational costs. The aim of the current paper is to present the optimization results that pertain to the C-Town network as part of the BBLAWN competition. Results indicate that the selected solution is a feasible solution in regards to the battle constraint and reduces the leakage rate by 80 percent.

Keywords: Water distribution systems, leakage control, pressure management, rehabilitation planning, optimization;

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1. Introduction

Leakage management through pressure control is a common practice in many water utilities to reduce water loss which run to over 30% in some water distribution systems (WDSs). Leakage management has been an active research area in the recent years (Araujo et al., 2006; Mahdavi et al., 2011; Wu et al., 2013)[1,2,3]. Network rehabilitation planning (i.e., pipe replacement and duplication) has also a very well known impact on leakage reduction and has been the subject of many recent studies (Lindsey and Mays 1989; Kleiner et al., 1998; Roshani and Filion 2013 and 2014)[4,5,6,7]. The current Battle of Background Leakage Assessment for Water Networks

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(BBLAWN), is an attempt to combine WDS rehabilitation planning with pressure control management to achieve a better leakage ratio and lower WDS capital and operational costs.

The aim of the current paper is to present the optimization results that pertain to the C-Town network as part of the BBLAWN competition. The rest of the paper is organized as follows: first, the optimization methods used to solve the BBLAWN problem are presented. Second, the optimization results for the C-Town WDS are presented and discussed in detail.

2. Methods

The Battle problem has two main themes: network rehabilitation planning, and pressure management. Both of these topics are classical optimization problems in their own right. The optimization approach is designed to minimize the capital and operational costs of the network (1)-(2). A fast-elitist non-dominated sorting genetic algorithm (NSGA-II) by Deb et al. (2002) [8] is used to search the large decision space efficiently and minimize two objectives:

$$Obj1 = Min(CC) = \sum_{p=1}^{np}\left(RC_p + DC_p\right) + \sum_{pu=1}^{npu}\left(PuC_{pu}\right) + \sum_{v=1}^{nv}\left(VC_v\right) + \sum_{t=1}^{nt}\left(TC_t\right) \tag{1}$$

$$Obj2 = Min(OC) = \sum_{p=1}^{np}\left(LC_p\right) + \sum_{pu=1}^{npu}\left(EC_{pu}\right) \tag{2}$$

In which CC is the capital cost, OC is the operational cost, p is the pipe number, np is the maximum pipe number, RC_p is replacement cost for pth pipe, DC_p is pipe duplication cost, PuC_{pu} is pump replacement cost, pu is the pump number, npu maximum number of pumps, VC_v is pressure control valve cost, v is the valve number, nv is the maximum number of valves, TC_t is tank cost, t is the tank number, nt is the maximum number of tanks, LC_p is the leakage cost for pipe p , EC_{pu} is the energy cost. This optimization is subject to pressure constraints (i.e., minimum of 20 m in the nodes with demand and zero meter in the nodes with no demand), water level in tanks constrain (i.e., the final water level at each tank should be at least higher than the initial water level) and finally tanks are not allowed to empty. Decision variables and other design/operation considerations for each network component are discussed below.

2.1. Pipes

Based on the Battle description, pipes are only allowed to be replaced and/or duplicated from the list of available pipe diameters. For each pipe, two genes are considered. The first gene represents the replacement decision for the main pipe and the second gene represents the pipe diameter for the second (i.e., duplicated) pipe. The “zero” coding option for each gene denotes the “do nothing” option where a pipe is unimproved. Only pipes with length greater than or equal to 20 m are considered in the optimization process (i.e., 55 pipes were eliminated due to their very short length). Among the remaining pipes, only pipes with a diameter of 300 mm or greater are considered for possible duplication.

2.2. Tanks

All of the tanks in the C-Town water distribution system are considered for possible size enlargement The tank volume options are based on the data provided in the Battle description file. In addition to the commercially-available tank sizes listed in the Battle description, two additional sizes – 1500 m^3 and 2500 m^3 – were considered in the C-Town problem. Each tank to be sized is assigned a single gene in the chromosome, such that the “zero” coding option denotes “do nothing” where the tank size is unchanged. The list of tank volume options are presented in Table 1.

Table 1. Tank size options

Volume (m^3)	Cost ($)
0	0
500	14,020
1,000	30,640
1,500	44,660
2,000	61,210
2,500	75,230
3,750	87,460
5,000	122,420
10,000	174,930

2.3. Pumps and Pump controls

All of the pumps are considered for replacement. No additional pumps are added to the system; existing pumps can be either replaced with a new pump (i.e., pump with higher efficiency) or left unchanged. Each candidate pump for replacement is assigned a single gene in the chromosome, whereby the options are to “replace” or “do nothing”.

The water level settings for each pump control is modelled as a gene with a continuous value. The high water limit is defined by the elevation difference between the tank’s top water level and the water level where the tank is half full. Similarly, the low water level limit is defined by the difference between the water level where the tank is half full, and the 0.5 m level above the tank’s bottom. This is to ensure that tanks never empty.

2.4. Valves

Pressure control valves (PRVs) are the essential tools in C-Town WDS to manage pressure and reduce leakage. In the proposed approach, these valves are designed to have variable setting pressure points as allowed in the Battle description. The authors have assumed that each valve can have up to maximum of 20 pressure settings per simulation period. Three decisions should be made in regards to each valve: a) whether a valve is needed at a certain location, b) the time schedule of valve settings, and c) the value of the pressure settings . Each candidate valve is assigned 41 genes in the chromosome. The first gene denotes whether a valve is needed at the valve location. The following 20 genes in the chromosome hold information on the time schedule of the valve setting. The last 20 genes hold information on the pressure setting values for the candidate valve. PRVs are simulated using EPANET2 [9] PRVs boundary condition therefore each PRV pressure reading point is located at the PRV’s end junction.

In the Battle problem, certain links (i.e., 19 in total) in the network are selected as candidates for PRV installation. These location are generally at the entrance to district metering areas (DMA) in the D-Town network in Figure 1. Also, link P296 is assumed to be closed to further amplify the impact of PRV on the hydraulic response of the network. This converts the downstream loop of this PRV to a branch which performs better with an installed PRV. This link could be opened in emergency cases without affecting system performance.

2.5. Leakage

Leakage in a pipe is simulated as pressure-dependent by means of the orifice discharge coefficient in EPANET2. The discharge coefficient is estimated as follows: first, the total length of the pipes connected to each junction is calculated. (Note that each pipe length is divided by 2 to divide the leakage between the two pipe ends.) Second, the total pipe length associated with a particular junction is multiplied by the β coefficient of the emitter model in EPANET2. The α coefficient in the emitter model for all of the DMAs are equal to 0.9. Third, the leakage flow for each junction is calculated by subtracting the actual demand from the demand calculated by EPANET2. Finally, the node leakage is divided between the pipes connected to the node on the basis of the ratio of pipe length to the total length of pipes connected to the node.

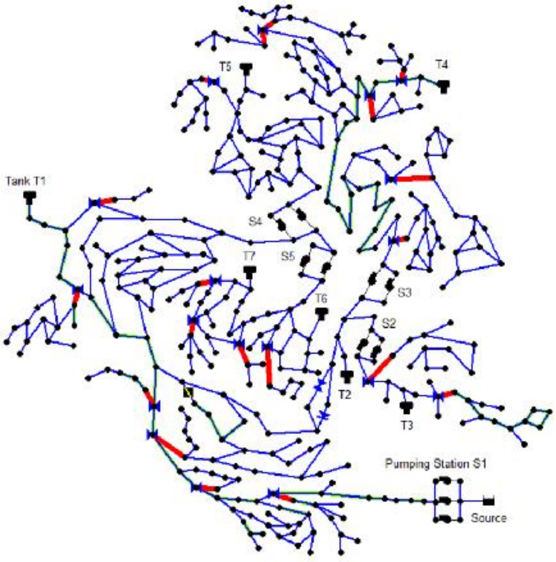


Fig. 1. The C-Town Water Distribution System. The red links are the location of possible PRVs and the greed links are considered for duplication.

2.6. Model Development and Simulations

The EPANET2 toolkit (Rossman 2000) is used to simulate each solution. The EPANET2 network solver is used to evaluate the hydraulic constraints (i.e., nodal pressures, tank levels, etc.) and the optimization algorithm is used to calculate the objectives and constraint-violation penalty errors as in (3).

$$Err = \sum_{j=1}^{nj}\left(Pe_j\right) + \sum_{t=1}^{nt}\left(WLe_t\right) + nEpa \tag{3}$$

In which Err is the solution error valve, Pe_j is the difference between required minimum pressure and the estimated pressure in the node j^{th}, if it is less then requirement, nj is the maximum number of nodes, WLe_t is the difference between initial water level and final water level in each tank. Finally, $nEpa$ is the total number of errors and warnings generated by EPANET2 toolkit in the course of a simulation. Solutions are feasible if the error value is zero.

The C# programming language was used to couple the EPANET2 network solver with the NSGA-II engine. Multi-threading (parallel processing) was used to reduce the computational time of the algorithm. The flow chart in Fig. 2 **Fig. 2** indicates the conceptual working of the optimization algorithm.

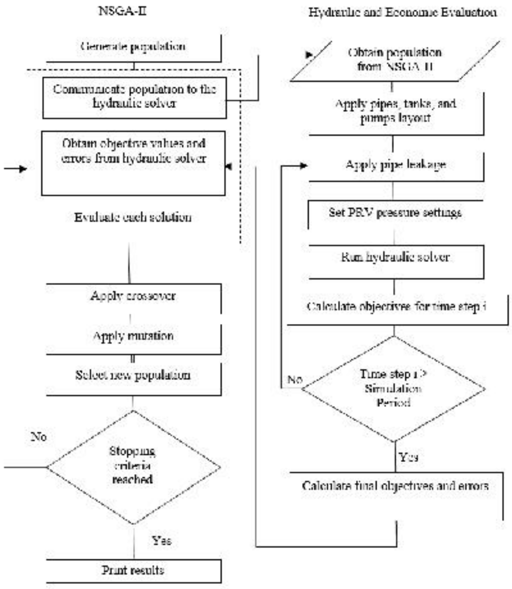
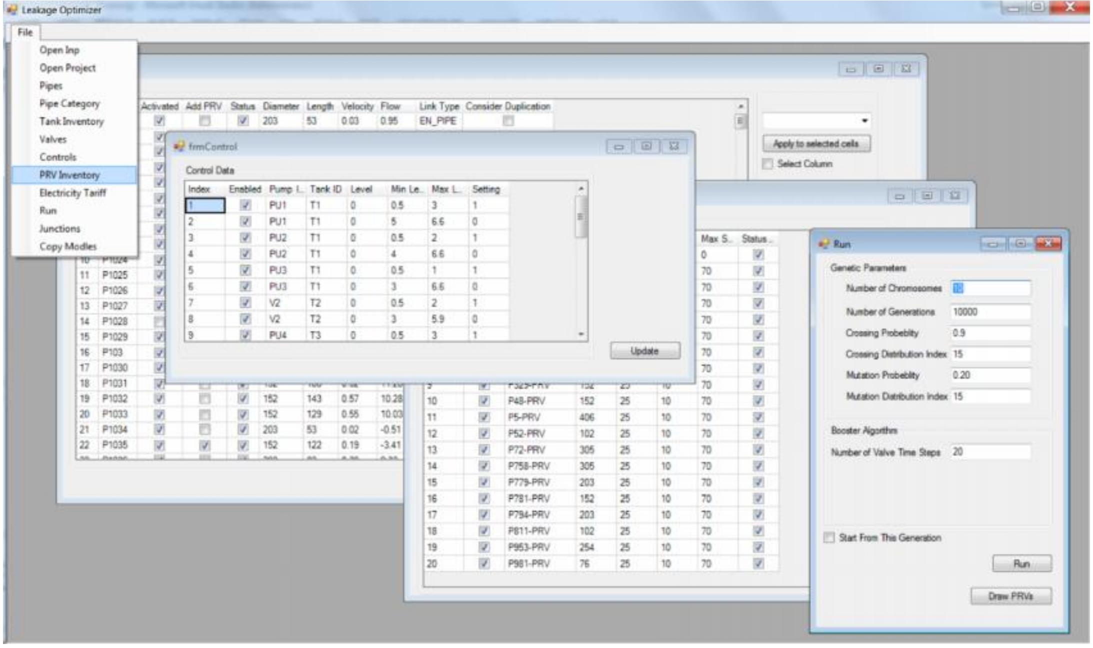


Fig. 2. The proposed model flowchart.

The developed model is called Leakage Optimizer and a graphical user interface was developed for data input and for visualization and interpretation of model outputs. A typical screenshot of the Leakage Optimizer software is indicated in Fig. 3.



Activated	Add PRV	Status	Diameter	Length	Velocity	Flow	Link Type	Consider Duplication
☑	☐	☑	203	53	0.03	0.95	EN_PIPE	☐

Control Data

Index	Enabled	Pump I..	Tank ID	Level	Min Le..	Max L..	Setting
1	☑	PU1	T1	0	0.5	3	1
2	☑	PU1	T1	0	5	6.6	0
3	☑	PU2	T1	0	0.5	2	1
4	☑	PU2	T1	0	4	6.6	0
5	☑	PU3	T1	0	0.5	1	1
6	☑	PU3	T1	0	3	6.6	0
7	☑	V2	T2	0	0.5	2	1
8	☑	V2	T2	0	3	5.9	0
9	☑	PU4	T3	0	0.5	3	1

						Max S..	Status..
10	☑	P48-PRV	152	25	10	70	☑
11	☑	P5-PRV	406	25	10	70	☑
12	☑	P52-PRV	102	25	10	70	☑
13	☑	P72-PRV	305	25	10	70	☑
14	☑	P758-PRV	305	25	10	70	☑
15	☑	P779-PRV	203	25	10	70	☑
16	☑	P781-PRV	152	25	10	70	☑
17	☑	P794-PRV	203	25	10	70	☑
18	☑	P811-PRV	102	25	10	70	☑
19	☑	P953-PRV	254	25	10	70	☑
20	☑	P981-PRV	76	25	10	70	☑

Genetic Parameters

Number of Chromosomes	12
Number of Generations	10000
Crossing Probebilty	0.9
Crossing Distribution Index	15
Mutation Probebilty	0.20
Mutation Distribution Index	15

Booster Algorithm

Number of Valve Time Steps: 20

☐ Start From This Generation

Fig. 3. Snapshots of the graphical user interface for Leakage Optimizer

Simulations were run on a high-performance computer with 24 cores with Windows HPC Server 2008R2. Each run comprised of 500 solutions evolved over 10,000 generations. Each candidate solution has a chromosome with a length of 1,256 genes. Each run took approximately 4 days to complete on the high-performance computer. The crossover probability was set to 0.9 and the mutation probability was set to 0.05 for all runs.

3. Results

Due to the time limitation, only two optimization runs were performed and compared. The dominant Pareto front was selected. The objective function values in the last generation are shown in Fig. 4. Among these solutions, the solution with the minimum total cost (i.e., operational cost plus capital cost) was selected as the final solution submitted to the competition. This solution is shown in a triangle in **Fig. X**. The cost and energy summary for this solution is indicated in Table 2. The results in this table suggest that the water loss cost is the most significant cost in the selected solution as it accounts for 53% of the total cost. This high cost forces the optimization engine to seek a solution which has a very small total leakage rate. (i.e., 15 lps which is equal to less than 8 percent of total consumed water in C-Town). To reduce this cost, a significant portion of pipes in the C-Town WDS are replaced (i.e., 30,408 m which is equal to 54 percent of total pipes). Moreover, 8,777 m of pipes (i.e., 15 percent of total) are duplicated.

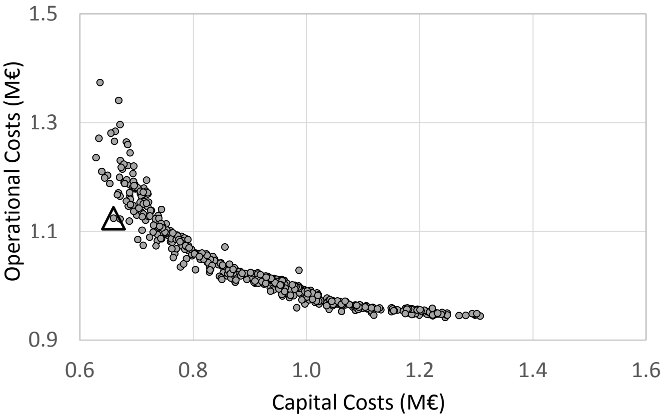


Fig. 4. The objective values for the last generation. The selected solution is shown in a triangle.

Table 2. Cost and energy summary. All costs are in Euros

Description	Value	Percent of Total Cost (%)
Duplication Cost	144,852	8.1
Replacement Cost	392,981	22.0
Valve Cost	13,630	0.8
Tank Cost	75,300	4.2
Pump Cost	30,652	1.7
Leakage Cost	948,358	53.0
Energy Cost	181,947	10.2
Energy Consumption (kW)	1,525,420	N/A
Total Capital Cost	657,415	36.8
Total Operational Costs	1,130,305	63.2
Total Costs	1,787,721	100.0

The water level settings for the control rules are designed in a way that none of the tanks empty. This is illustrated in

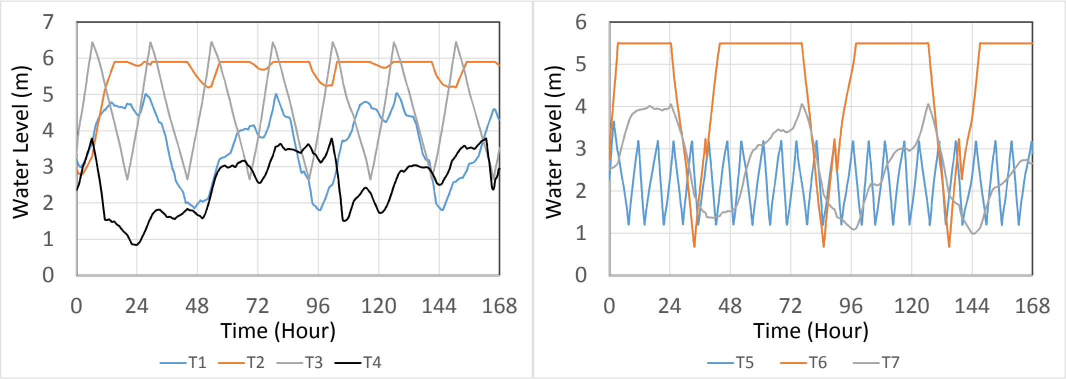


Fig. 5. The selected tank volumes and corresponding cost is shown in Table 2.

Table 3. Tanks volume and costs for the selected solution

Tank ID	Initial Volume (CM)	Final Volume (CM)	Cost (€)
T1	0	0	0
T2	2000	2000	0
T3	1000	1500	14020
T4	500	1500	30640
T5	0	0	0
T6	300	300	0
T7	200	1200	30640
Total Cost			75300

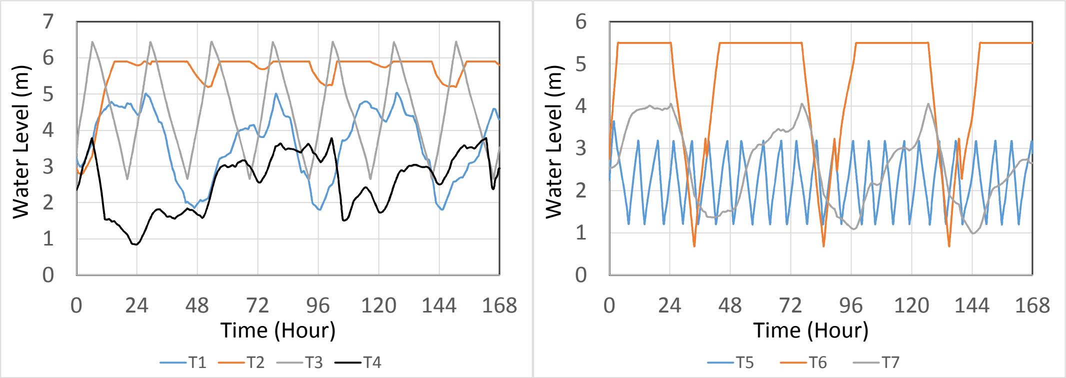


Fig. 5. Water level variation in C-Town tanks

Among 19 possible PRV locations, only 14 where selected by the optimization engine. These locations are listed in Table 3. The variable pressure settings for each PRV could be found in the supplementary files. These data are not shown here due to a space limitation.

Table 3. Pressure reducing valves location and costs

PRV Location	Diameter	Cost (€)
P10-PRV	76	323
P1024-PRV	203	779
P1035-PRV	152	529
P1039-PRV	356	2282

P115-PRV	0	0
P125-PRV	0	0
P305-PRV	203	779
P329-PRV	152	529
P48-PRV	0	0
P5-PRV	152	529
P52-PRV	102	323
P72-PRV	0	0
P758-PRV	305	1892
P779-PRV	203	779
P781-PRV	305	1892
P794-PRV	305	1892
P811-PRV	102	323
P953-PRV	0	0
P981-PRV	203	779
Total Cost		13630

The proposed methodology reduces the total leakage rate to less than 20% of original leakage rate (i.e., status quo). To calculate the total original leakage, the model was run without adding any new components (i.e., tanks, pumps, valves), and/or replacing, duplicating any pipes in the system. The low leakage could be attributed to the lower leakage rate of new pipes. It seems that the leakage variation by time for the original network is much higher than the selected solution which might be due to the performances of PRVs.

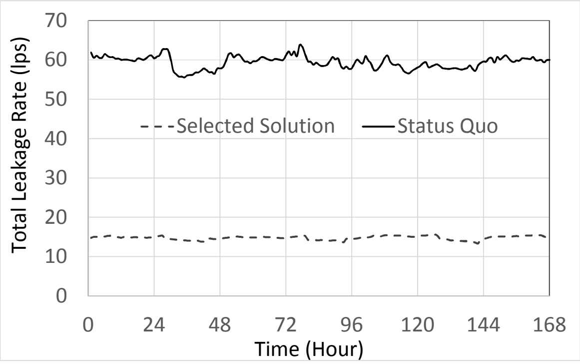


Fig. 6. Hourly total leakage rate for the selected solution vs. the original leakage rate

4. Conclusions

The aim of the current paper is to present the optimization results that pertain to the C-Town network as part of the BBLAWN competition. The proposed methodology is based on multi-objective optimization, and is able to quickly generate feasible solutions after 10 generations. Results indicate that the selected solution is a feasible solution in regards to the battle constraint and reduces the leakage rate by 80 percent.

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