Drink. Water Eng. Sci. Discuss., doi:10.5194/dwes-2017-8, 2017
Manuscript under review for journal Drink. Water Eng. Sci.
Discussion started: 22 February 2017

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All-in-one model for designing optimal water distribution pipe networks

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Abstract. This paper discusses development of an easy-to-use, all-in-one model for designing optimal water distribution networks. The model combines different optimization techniques into a single package in which a user can easily choose what optimizer to use and can compare results of different optimizers to gain confidence on the performances of the models. At present, three optimization techniques are included in the model: linear programming (LP), genetic algorithm (GA), and a heuristic one by one reduction method (OBORM) which was previously developed by the authors. The optimizers were tested on a number of benchmark problems and performed very well in terms of finding optimal or near-optimal solutions with a reasonable computation effort. The results indicate that the model effectively addresses the issues of complexity and limited performance trust associated with previous models and thus can be used for practical purposes.

1. Introduction

The conventional approach for designing water distribution pipe networks is a trial-and-error. A designer first assigns some reasonable values for the design variables and analyzes the system using a simulation model, such as Epanet, to check if system requirements are satisfied. Based on the analysis results, the designer makes some changes in the design and analyzes the system again and the process is repeated until a “satisfactory” solution is found. This method of design, however, does not guarantee a low cost system, let alone an optimal one. In addition, its application for large distribution systems tends to be exceedingly tiresome and time-consuming. An alternative to this method of design is the optimization approach, in which, the network design is formulated as an optimization problem and solved using some appropriate methods.

The optimization approach for designing pipe networks has been the focus of several studies in the past and numerous mathematical models have been developed using different optimization techniques including the classical linear programming (Calhoun, 1971, etc.) and nonlinear programming (Lansey and Mays, 1989; etc.) as well as several stochastic search techniques such as simulated annealing (Loganathan et al., 1995; Cunha and Sousa, 1999), ant colony optimization algorithm (Maier et al., 2003), shuffled frog leaping algorithm (Eusuff and Lansey, 2003) and genetic algorithms (GAs), which is by far the most widely used (Simpson et al., 1994; Savic and Walters, 1997; Wu et al., 2001; and many others).

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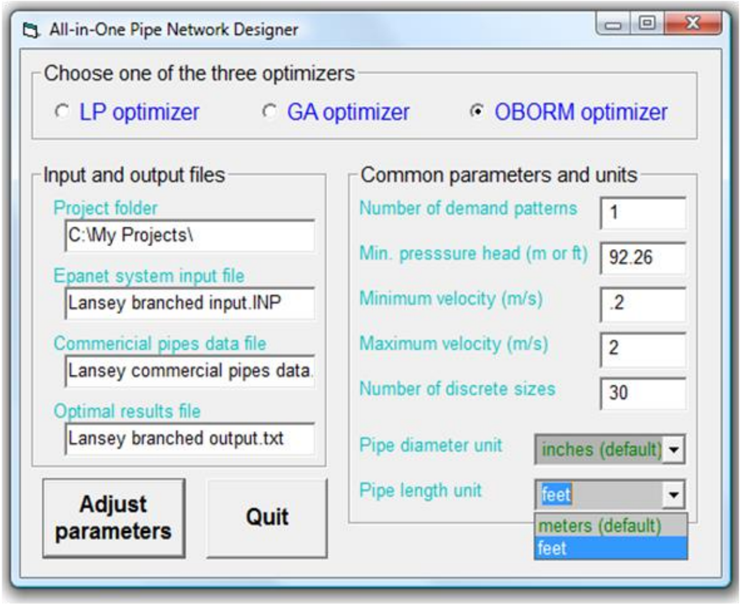
Despite significant research efforts and development of numerous models in the past several decades, application of the models for practical purposes has been limited mainly because of the complexities associated with the use of the models and inadequate trust on their performances. In this study, bearing in mind that pipe network optimization models would be useful in developing countries where there is a need to construct new systems and expand existing ones to cope with high population growth and rapid urbanization, we have attempted to address the issues of complexity and limited trust. To that end, we have developed an easy-to-use, all-in-one model by combining different optimization techniques into a single package in which a user can easily choose what optimizer to use and can compare results of different optimizers to gain confidence on their performances. At present, three optimization techniques are included in the model: linear programming (LP Optimizer), genetic algorithm (GA Optimizer), and a heuristic one by one reduction method (OBORM Optimizer). Overview of the model, how each optimizer works and performance of the optimizers on test problems are presented in the subsequent sections.


All-in-One Pipe Network Designer

Choose one of the three optimizers
○ LP optimizer ○ GA optimizer ● OBORM optimizer

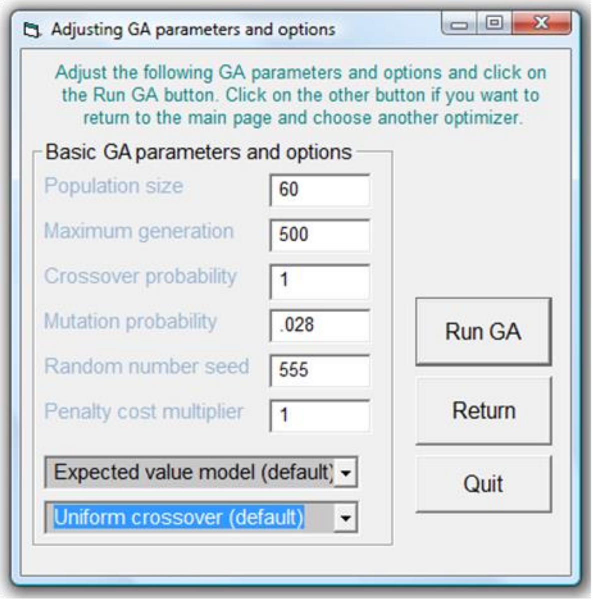
Input and output files
Project folder: C:\My Projects\
Epanet system input file: Lansey branched input.INP
Commercial pipes data file: Lansey commercial pipes data
Optimal results file: Lansey branched output.txt

Common parameters and units
Number of demand patterns: 1
Min. presssure head (m or ft): 92.26
Minimum velocity (m/s): .2
Maximum velocity (m/s): 2
Number of discrete sizes: 30
Pipe diameter unit: inches (default)
Pipe length unit: feet

Figure 1: User interface of the all-in-one model

2. Overview of the model

The model is organized with special attention to simplicity and ease of use. Fig. 1 shows user interface of the model, which is developed in Microsoft Visual Basic 6.0. The first step a user needs to do to use the model is to create Epanet input file of the system to be designed and save it in the project folder. Here, Epanet's input file format is adopted because Epanet is believed to be the most widely used water distribution system modelling software. The next step is to create a text file containing commercial pipes data, which is a list of the available discrete sizes and their unit costs, and save it in the same project folder. If the system has to be designed under multiple loading conditions, a demand pattern data file should also be created and saved in the


Adjusting GA parameters and options

Adjust the following GA parameters and options and click on the Run GA button. Click on the other button if you want to return to the main page and choose another optimizer.

Basic GA parameters and options
Population size: 60
Maximum generation: 500
Crossover probability: 1
Mutation probability: .028
Random number seed: 555
Penalty cost multiplier: 1
Expected value model (default)
Uniform crossover (default)

Figure 2: Dialog box for GA parameters adjustment

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same folder. After specifying the name of the output file and setting the common parameters and units shown on the right side the user interface, the user simply needs to choose and run one of the three optimizers by checking the radio button in front of them. If the first radio button is checked, the LP optimizer will be ready to be run without any parameter adjustment. Both the GA and OBORM optimizers have a few parameters to be adjusted. Fig. 2 shows the dialog box for GA parameters adjustment.

3. The three optimizers

The three optimizers were previously developed by the authors in FORTRAN and recently compiled as separate dll functions and added into the VB project as modules. Therefore, as a precondition to use the model on Windows platform, copies of the dll functions of the optimizers should be put in the Windows System folder.

3.1 LP Optimizer – for branched networks

Since pipes are available only in discrete sizes and pipe costs and friction losses are both linearly related with pipe length, the branched network design can be easily formulated as an LP problem by partitioning a pipe section into several segments of different diameters and then finding the optimal lengths of each segment with the aim of minimizing total pipe cost of the network while satisfying constraints.

The LP optimizer solves the non standard LP problem formulated this way using the *two phase* method, which applies the well known ***simplex*** method in two phases. As depicted in Fig. 3, after getting the necessary information through the user interface, the LP optimizer first reads input data, which includes network pipes and nodes as well as commercial pipes data. Then it identifies the end nodes in the network and generates the flow paths to each end node. In order to make the flow path generation easy, the system data should be arranged in way that ID of the downstream node of a pipe is similar to the ID of the pipe (see Fig. 6). Velocity of flow in each pipe and each discrete size is then calculated so as to exclude sizes that violate velocity constraints. Generation of first tableau matrix elements is a crucial step that requires a careful look into the formulation of the branched network LP problem. Once this matrix is generated properly, the problem can be easily solved using the two phase method.

Application of LP for pipe network design is not new, but the improvement in this study is that the routine tasks such as generating the flow paths and matrix elements of the first tableau as well as interpreting the optimal results are all automated in order to make the model easy to use and hence save effort and time of the user.

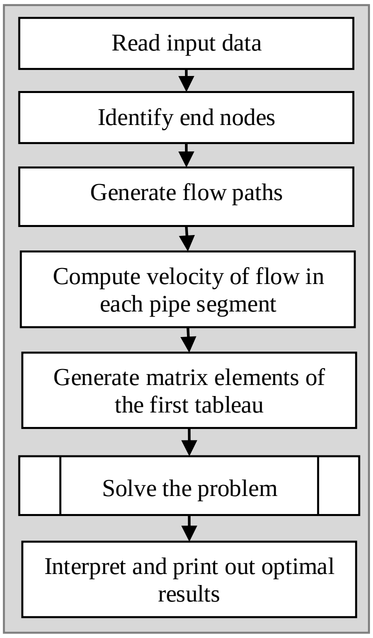

Figure 3: Simplified flowchart of the LP optimizer

3.2 GA Optimizer

The *GA optimizer* basically applies the standard GA procedure shown in Fig. 4. First an initial population is generated randomly. The individuals in the population are strings that are usually made of binary bits (0s and 1s) and decimal value of each string represents a trial solution of the problem. The initial population is transformed into a new population by using the three basic GA operators: **selection**, **crossover** and **mutation**. The new population then undergoes similar transformation and the process is repeated until a preset maximum generation number is reached. Of the three GA operators, selection is the most important. To select individuals from the current population for further reproduction, survival probability (SP) of each string should be calculated and this requires analyzing the network represented by each trial solution, adding penalty costs onto the objective functions when pressure head and other constraints are violated, calculating fitness and performing scaling to avoid premature convergence.

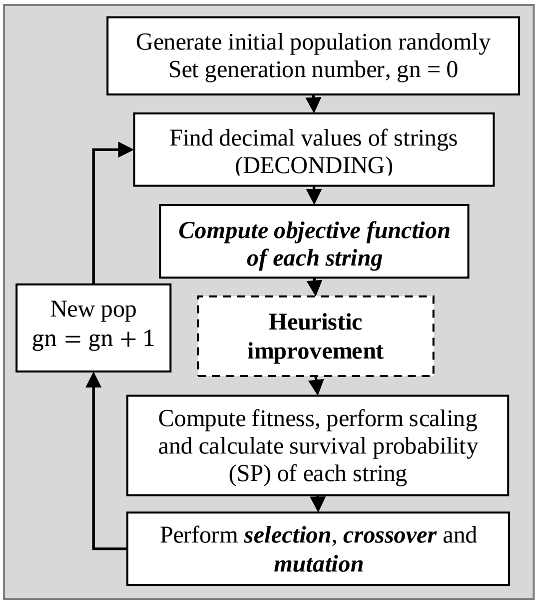

Figure 4: Basic steps in standard GA

In addition to these basic steps, in the GA optimizers, a heuristic improvement is introduced to address the slow convergence issue that is associated with standard GA. The improvement is based on the hypothesis that, probability of getting better individuals (strings) increases with the increase in average performance of the population. Average population performance is supposed to, and generally does, increase from generation to generation. However, in some "bad" occasions, it deteriorates, and does the performance of the best string in a given generation, which contributes to the slow convergence. In the heuristic improvement, strings are ranked based on their objective values and a deteriorating string is replaced with a string in the same rank of the previous population. This avoids the occasional deterioration of the population while maintaining its variability or randomness.

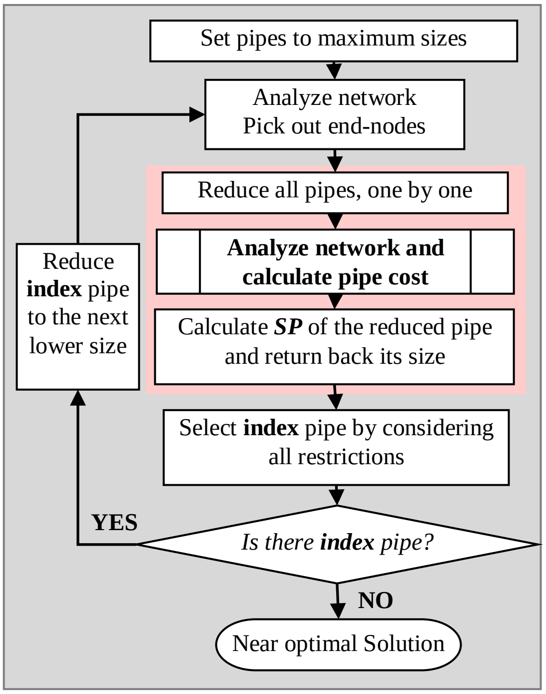

Figure 5: Simplified flowchart of the OBORM

3.3 OBORM Optimizer

The OBORM, simplified flowchart of which is shown in Fig. 5, is a simple yet efficient heuristic method previously developed by the authors mainly for designing looped networks but can also be applied for solving other nonlinear combinatorial optimization problems in which the decision variables have finite discrete solution spaces. When applied for pipe network design, the OBORM initially sets the sizes of all the pipes to some maximum values. At this stage, both pipe cost and pressure head at end nodes have maximum values. Then pipe sizes are reduced one by one until any further reduction will result in violation of any of the constraints. At every step, the pipe that, when reduced to the next lower discrete size, results in the smallest pressure head drop at the most depressed node of the network (Δhx) per reduction in pipe cost (ΔCP) is selected as index pipe. Hence, the selection parameter (SP) of each pipe *i* is calculated as:

$$SP_i = \frac{\Delta hx_i^{\alpha}}{\Delta CP_i^{\beta}} \qquad (1)$$

where α and β are model parameters with typical value of 1 (one) for all pipes but may sometimes take different values for different pipes. Another important factor in index pipe selection is pressure drop at other end nodes than the most depressed node. In this optimizer, if Δhx is less than some small value (sv), the pressure drop in other end nodes is considered. sv is a model parameter with typical value of 0 (zero) for looped networks.

4. Performance test

Performances of the optimizers have been tested on a number of benchmark problems. Here, only two of the problems are presented for the purpose of performance illustration. The first one is a new branched network design while the second one is simple, yet typical, looped network expansion problem.

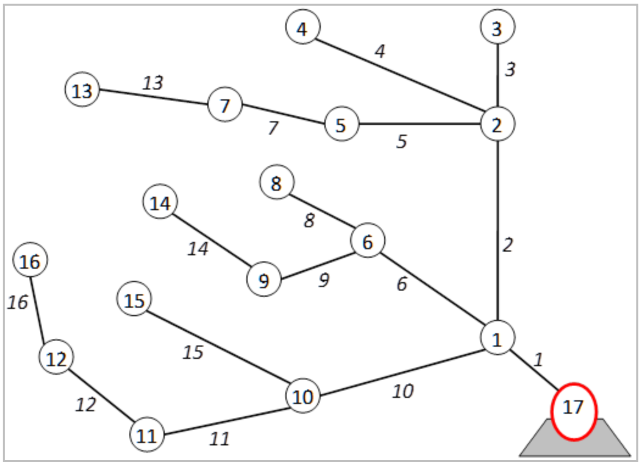

Figure 6: Layout of a hypothetical branched network

Table 1: Nodes and pipes data for problem 1

Nodes data			Pipes data	
Node No.	Elevation (ft^{*1})	Demand (gpm^{*2})	Pipe No.	Length (ft)
1	20	500	1	100
2	50	200	2	12000
3	50	200	3	6000
4	50	200	4	9000
5	50	500	5	6000
6	50	500	6	12000
7	50	500	7	6000
8	50	1000	8	6000
9	50	500	9	6000
10	50	500	10	12000
11	120	200	11	6000
12	120	200	12	6000
13	80	200	13	6000
14	120	200	14	6000
15	120	800	15	6000
16	120	200	16	6000
17	220.2	-6400		

^{*1} 1ft = 0.304794 m ^{*2} 1gpm = 0.2271m^3/hr

4.1. Problem 1: Branched network design

Fig. 6 shows layout of a hypothetical branched network, which was modified from Lansey and Mays (1989) and has 16 pipes, 16 junction nodes, 7 end nodes and a single source. The source pump at Node 17 is assumed to operate at steady

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condition with a flow of 6400gpm and total head 220.2ft. Network nodes and pipes data are given in Table 1. Thirty discrete pipe sizes, 1in to 30in, are considered and unit cost of pipes ($/ft) is assumed to be 3.45D if $D \leq 10.93$in and $2.41D^{1.15}$ otherwise. All pipes are assumed to have Hazen Williams's roughness coefficient of 120. A minimum pressure of 40psi is required at all junction nodes and velocity of flow through pipes is required to be between 0.2 m/sec and 2.0 m/sec.

The LP model for this problem has 23 equations and 487 $(16 \times 30 + 7)$ unknowns including the slack variables. This is a fairly huge problem but the LP optimizer run on 2.80GHz desktop computer took only a fraction of a second to arrive at the optimal solution. The problem was also solved using the GA and OBORM optimizers and best results were found with the GA model parameters set to the values shown in Fig. 2 and OBORM parameters set to α =1, β =1.5 and *sv*=0.3 . Table 2 compares results of the three optimizers. The results show that the LP is the most efficient both in terms of cost and computation time and is therefore the best choice for branched network design. However, both the GA and OBORM were also able to find near-optimal solutions. This indicates that both can be used for branched network design if split-pipe lengths of the LP are considered undesirable. In this and other test problems, the GA performed slightly better than the OBORM in terms of cost but required much more computation effort and also more time and effort for parameter adjustment.

Table 2 Comparison of results of the branched network design problem

Pipe No.	LP Results		GA Results	OBORM Results
	Diameter (in)	Length (ft)	Diameter (in)	Diameter (in)
1	30	100	30	30
2	17, 16	9416, 2584	16	16
3	6, 5	998, 5002	6	6
4	6, 5	6119, 2881	6	6
5	14	6000	14	15
6	25, 24	5046, 6954	24	24
7	12	6000	13	12
8	9, 8	5840, 160	9	9
9	17	6000	17	17
10	25, 24	970, 11030	25	23
11	17, 16	2882, 3118	16	17
12	15	6000	14	15
13	8	6000	9	9
14	11	6000	12	12
15	15	6000	15	16
16	11	6000	11	13
Pipe cost ($)	***6,049,228***		***6,096,012***	***6,112,920***
Execution time (sec)	***0.03***		***2.45***	***0.34***

4.2 Problem 2: Looped network expansion

The 14 pipe network shown in Fig. 7, which was first studied by Simpson et al. (1994), is used to illustrate the performance the GA and OBORM in designing looped networks. As shown in the figure, five of the 14 pipes are new and have to be sized (with one of the eight available discrete sizes); three of the existing pipes may be duplicated with a new pipe in parallel, but not necessarily so; and the remaining six existing pipes are to be left as they are. The network has to be designed to satisfy three demand patterns: a peak hour demand and two fire demands. With a solution space of 8^8 (each of the eight pipes to be sized can take one of the eight discrete sizes), this problem is relatively simple. But it is a typical problem that represents the case in many cities and towns of developing countries where existing distribution networks should be expanded both in parallel and laterally to cope with rapid population growth and urbanization.

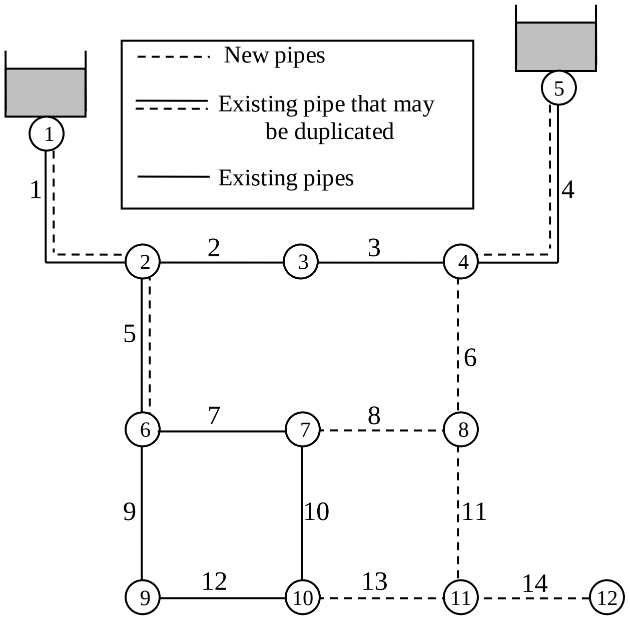

Figure 7: Network layout for problem 2 (after Simpson et al., 1994)

The problem was solved using the GA and OBORM optimizers and both arrived at the global optimal solution that was obtained by previous studies. To see how fast the GA optimizer could converge to the optimal solution, population size and maximum generation number were set to 50 and 100, respectively, and the optimizer was run ten times with different seed numbers. Optimal solution was found in all the ten runs. The generation number at which optimal solution was attained varied from 19 to 59 and had an average value of 38. This makes the average number of evaluations needed to arrive at the optimal solution 5,700 (= 38 × 50 × 3). Table 3 compares optimal costs obtained and number of evaluations needed by different researchers (models). From this table, we can see that the GA optimizer is computationally more effecient compared to the previous methods and this improvement is attributed to the new heuristic method introduced to address the convergence issue of the standard GA. The OBORM optimizer, which was run with all the parameters set to their typical values (*i.e.,* $sv = 0$, and $\alpha = \beta = 1$ for all pipes), required by far the least number of evaluations. This clearly indicates that the OBORM outperforms the randomized search techniques in terms of computational efficiency.

Table 3 Comparison of results for problem 2

Solution Method	Cost (M$)	Evaluations
Simpson et al., 1994 (GA- proportionate selection)	1.750	20,790
Simpson and Goldberg, 1994 (GA - tournament selection)	1.750	8,700
Maier et al., 2003 (ACOA - iteration best ant)	1.750	8,509
GA Optimizer	1.750	**5,700**
OBORM Optimizer	1.750	**1,101**

5. Conclusion and remarks

Determining the most appropriate sizes of pipes is one of the most difficult tasks for water supply system designers. The traditional trial-and-error approach is neither effective nor efficient while the optimization approach and most of the models developed so far have problems of mathematical complexity and limited performance trust. In this study, with the aim of addressing the problems associated with optimization models, we developed an easy-to-use, all-in-one model by combining three optimization techniques into a single package in which a user can easily choose what optimizer to use and can compare results of different optimizers to gain confidence on their performances. The model has to be tested on real-world problems yet, but based on its simplicity and outstanding performance of the optimizers on test problems, it is hoped that the model can be used for practical purposes particularly in developing countries where a lot has to be done to reach the roughly 700 million people who do not still have access to safe drinking water and to provide uninterrupted supply of drinking water in the rapidly growing urban areas.

Research is currently underway to include other heuristic optimization techniques such “ant colony optimization” and “shuffled frog leaping algorithms” into the all-in-one model. Also, use of a pressure driven hydraulic model and reliability based design of pipe networks as wells inclusion of pumps and storage tanks are under consideration.

6. References

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