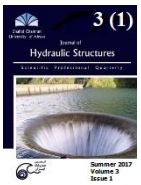
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Multiobjective design of sewer networks

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Abstract

The sewer layout in flat areas significantly influences the construction and operational costs as well as reliability of the network performance. To find an optimum design of sewer networks for flat areas, this study presents a multi-objective optimization problem with the objective functions of 1- the cost and 2- the reliability. The reliability criterion is defined as the effect of a clogging in a sewer on its upstream population. To solve the problem, the NSGA-II Algorithm is coupled to two self-adaptive design algorithms for generating the layout and sizing of sewers. A case study is solved using the proposed model to demonstrate its application and advantages.

Keywords: Sewer network, Layout, Reliability, Flat area, Multiobjective optimization.

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1. Introduction

Constructing a new sewer system, particularly in developing countries, is a very expensive and challenging task. The design of a sewage collection network needs to solve two successive subproblems: (1) generating the layout and (2) hydraulic design of the sewers and pumps. In flat areas where there is no significant change in the ground topography, the layout configuration is determined almost independently of the natural slopes. In such areas, the number of feasible layouts exponentially increases with the number of pipes in the system (Diogo and Graveto, 2006). Moreover, in flat areas, the reliability of sewer networks is threatened by phenomena such as clogging due to sediment deposition which poses significant costs to the operating companies and public inconvenience. Haghighi and E. Bakhshipour (2015b) introduced a new criterion for designing sewer layouts based on the reliability concept. They found that the reliability seriously conflicts with the system construction cost.

Considering this issue, the present work introduces a multiobjective optimization framework

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for finding trade-offs between cost and reliability in the layout design of sewer networks. For this purpose, the Non-Dominated Sorting Genetic Algorithm, version II, NSGA-II (Deb et al., 2002), is coupled to two adaptive algorithms for solving the aforementioned subproblems.

2. Methods

2.1. Layout design

The first step for designing a sewage collection system is to design its layout. Creating and evaluating all possible designs is practically impossible without using a computational graph-based algorithm joined to an optimization solver. For the sewer network optimization, a layout generator model is required in order to make the procedure systematic. The layout generator model must be able to satisfy all constraints while extracting layout alternatives from an initial base graph. In this study, the "Loop-by-loop Cutting Algorithm" is adopted for this purpose. This algorithm introduced by Haghighi (2013) is an adaptive layout generator which systematically satisfies all constraints. In short, by using this algorithm, it is possible to generate feasible layouts of a network from an initially looped and undirected base graph. For each loop in the base graph, two real normal- and binary-valued variables, which respectively determine the pipe in the loop to cut and the location of the cut (from the upstream or downstream), are randomly defined. Then, through a step-by-step procedure, all loops are cut, while all constraints associated with the sewer layout are systematically satisfied. Further details on this algorithm can be found in (Haghighi, 2013).

2.2. Sewer Design

After generating a feasible sewer layout, the second sub-problem is hydraulic design, considering sewer diameters, installation depths, and pump stations. To exploit metaheuristic methods efficiently for solving the highly constrained problem of sewer design, Haghighi and E. Bakhshipour (2012) introduced a self-adaptive hydraulic design procedure. Through this approach, all hydraulic and technical constraints of the sewer design with a given layout are systematically met, and therefore, there is no need for any constraint handling in the optimization process. More details can be found in the original paper.

After integrating the two sub-problems of sewer network design into a model, two objective functions are employed to evaluate: 1- the cost and 2- the reliability of the system

2.3. Reliability-based objective function

To evaluate the clogging consequences in sewer networks, Haghighi and E. Bakhshipour (2015b) introduce the average reliability index (ARI) that only uses the layout design properties. This criterion can indirectly evaluate how well a sewer system can react to a sewage flow blockage. On this basis, the average reliability of the entire network is measured as equation (1):

$$ARI = \bar{R}_i = 1 - \frac{1}{m}\sum_{i=1}^{m} {Q_i}/{Q_{out}} \qquad (\mathbf{1})$$

in which, Q_i is the cumulative sewage discharge through pipe i, m is the number of sewers in the network, and Q_{out} is the total sewage flow of the network toward the outlet. It is also worth noting that only sewers with a reliability index less than 90% are used to calculate the ARI, which is then denoted by $ARI_{<90}$. Considering $ARI_{<90}$ instead of ARI, makes the layout configuration and its reliability more sensitive to the main collectors which convey high sewage discharges and would be more threatened by clogging. (Haghighi and E. Bakhshipour, 2015b)

2.4. Costs

In this study, the cost function introduced by Li and Matthew (1990) is employed (equation 2).

$$C = \sum_{i=1}^{m} (CP_i + P_i \times CL_i) + \sum_{i=1}^{m+1} (CM_i) \quad (2)$$

where, CP is the construction cost of sewers, CL is the construction cost of the pumps and CM is the construction cost of manholes based on the data presented in Tab. 1. Also, P_i is the pump parameter which is 1 when there is a lift station at the upstream end of the pipe and is 0 otherwise. The construction cost is estimated as a function of sewer diameters D, sewer lengths L, installation depths H and the pump specifications.

Table 1. The cost function of the example in Yuan (Li and Matthew 1990).

CP (Sewer cost)	
$(4.27 + 93.59D^2 + 2.86D \times H + 2.39H^2) \times L$	$D \leq 1$m, $H \leq 3$m
$(36.47 + 88.96D^2 + 8.70D \times H + 1.78H^2) \times L$	$D \leq 1$m, $H > 3$m
$(20.50 + 149.27D^2 - 58.96D \times H + 17.75H^2) \times L$	$D > 1$m, $H \leq 4$m
$(78.44 + 29.25D^2 + 31.80D \times H - 2.32H^2) \times L$	$D > 1$m, $H > 4$m
CM (Manhole cost)	
$136.67 + 166.19D^2 + 3.50D \times H + 16.22H^2$	$D \leq 1$m, $H \leq 3$m
$132.67 + 790.94D^2 - 280.23D \times H + 34.97H^2$	$D \leq 1$m, $H > 3$m
$209.04 + 57.53D^2 + 10.93D \times H + 19.88H^2$	$D > 1$m, $H \leq 4$m
$210.66\text{-}113.04D^2 + 126.43D \times H - 0.60H^2$	$D > 1$m, $H > 4$m
CL (Pump cost)	
$270{,}021 + 316.42Q - 0.1663Q^2$	Q (l/s)

2.5. Optimization method

The metaheuristic method of NSGA-II was applied to derive the trade-off between costs and reliability. For sizing the sewers 24 commercially available diameters ranging from 0.2 to 2.40 meters were considered. The design constraints including the limits of velocities, slopes, proportional water depth and the required cover depth. Fig 1 shows a flow chart of the multiobjective optimization procedure.

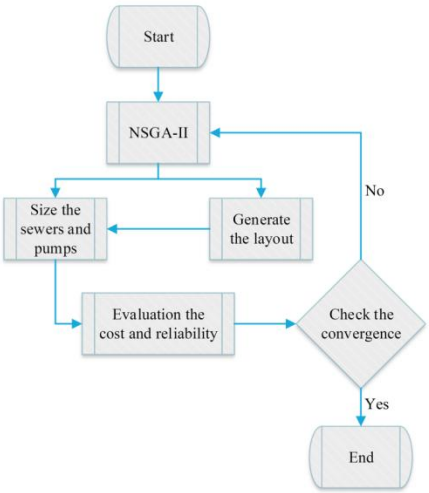


Figure 1. The multiobjective optimization framework for sewer networks design

3. Results and discussions

Fig. 2 shows the base graph used to test the procedure. It was originally developed by Li and Matthew (1990) as a benchmark example for optimization. The sewer network collects a 260-hectare residential area with a flat topography. The base graph has 79 pipes, 57 main manholes and 23 loops and its outlet is manhole 56 connected to sewer 59. Additional information on the network is also found in Li and Matthew (1990).

The loop by loop cutting algorithm and the adaptive algorithm are applied to sequentially generate a feasible layout and design it hydraulically. The model is coupled with the metaheuristic method of NSGA-II to maximize the reliability of the network based on the proposed criterion $ARI_{<90}$ and minimize the cost.

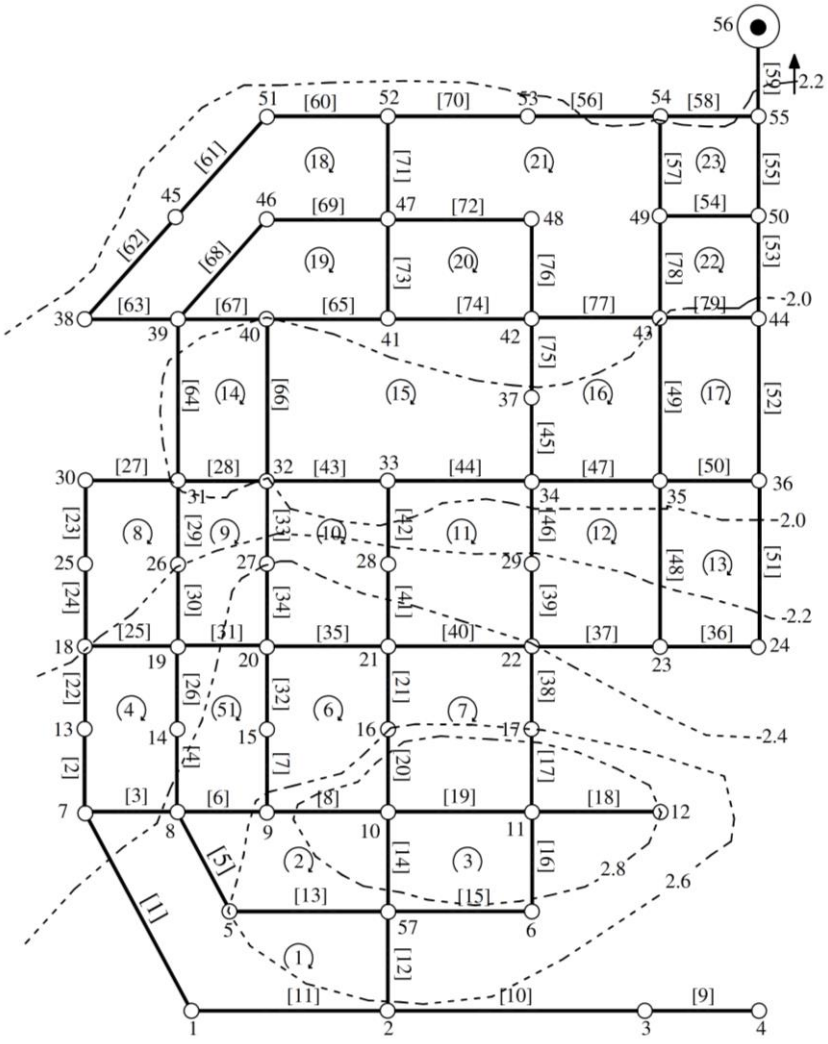


Figure 2. Base graph of the case study (data from Li and Matthew 1990)

Fig. 3 shows the Pareto front of NSGA-II for this case. The front can be divided into two sections of optimal solutions where cost and reliability are almost linearly correlated. The slope

breaks at around 70 %. Increasing the reliability from 60 % to 70 % increases the cost by 25 % (from 2.0 Mio. Yuan to 2.5 Mio. Yuan). Above 70 % any gain in reliability is much more expensive. For example, the solution that costs 4.5 Mio. Yuan provides a reliability of only 72 %. It worth to mention that the NSGA-II algorithm used in this study was unable to find all non-dominant solutions like the design found by Haghighi and E. Bakhshipour (2015b) with $ARI_{<90} = 77\%$ and $Cost = 2.41e6$. To deal with this issue application of more efficient multiobjective optimization algorithms for the future studies is suggested.

One point from the Pareto front, with $ARI_{<90} = 68\%$ and $Cost = 2.18e6$ Yuan is selected to be compared with results of previous studies that optimized the network with respect to only the cost or the reliability index. Fig. 4 illustrates the layout and hydraulic specification of this design.

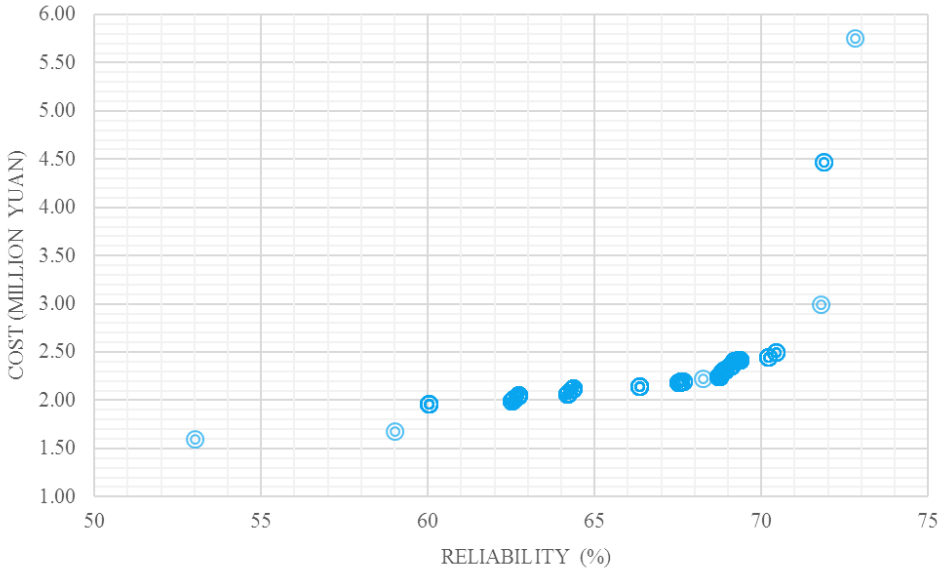


Figure 3. The optimal Pareto front for the case study

Table 2 summarizes the results of different approaches applied in the previous studies.

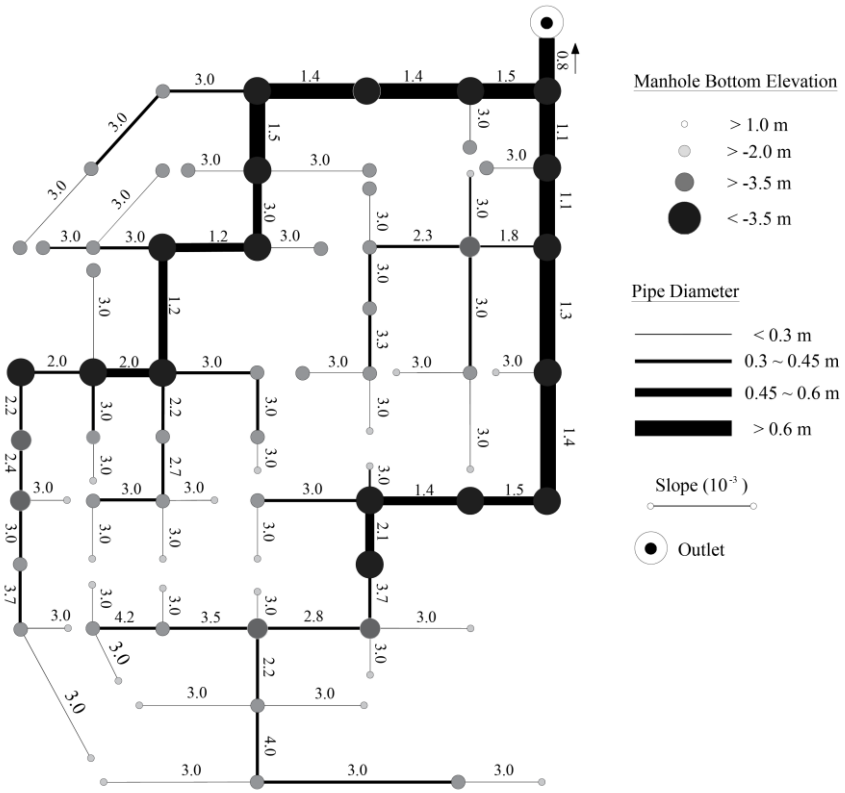


Figure 4. The optimal design, selected from the Pareto front ($ARI_{<90} = 68\%$ and $Cost = 2.18e6$)

Table 2. The reliability and cost values of the design alternatives.

The Authors:	**Costs (Mio. Yuan)**	$ARI_{<90}$ (%)
Li and Matthew (1990)	2.18	61
Li and Matthew (1990)	1.67	58
Pan and Kao (2009)	1.74	58
Haghighi and E. Bakhshipour (2012)	1.69	58
Haghighi (2013)	1.59	53
Haghighi and E. Bakhshipour (2015a)	**1.43**	41
Haghighi and E. Bakhshipour (2015b)	2.41	**77**
The present work	2.18	68

To illustrate how layout configuration influences the reliability of a sewer network, three different designs from previous works and the design introduced in the current work are depicted in fig. 5. The consequence of a random pipe clogging (here the 5th pipe in the main collector from the outlet) for each layout is investigated.

The pipe clogging in the design (b) and (c) causes massive trouble in the network and most parts of the network will be out of service. These two designs are the cheapest alternatives. In the design (a) the given pipe clogging has less effect on the whole system. However, this design is 17% more expensive than the cheapest design.

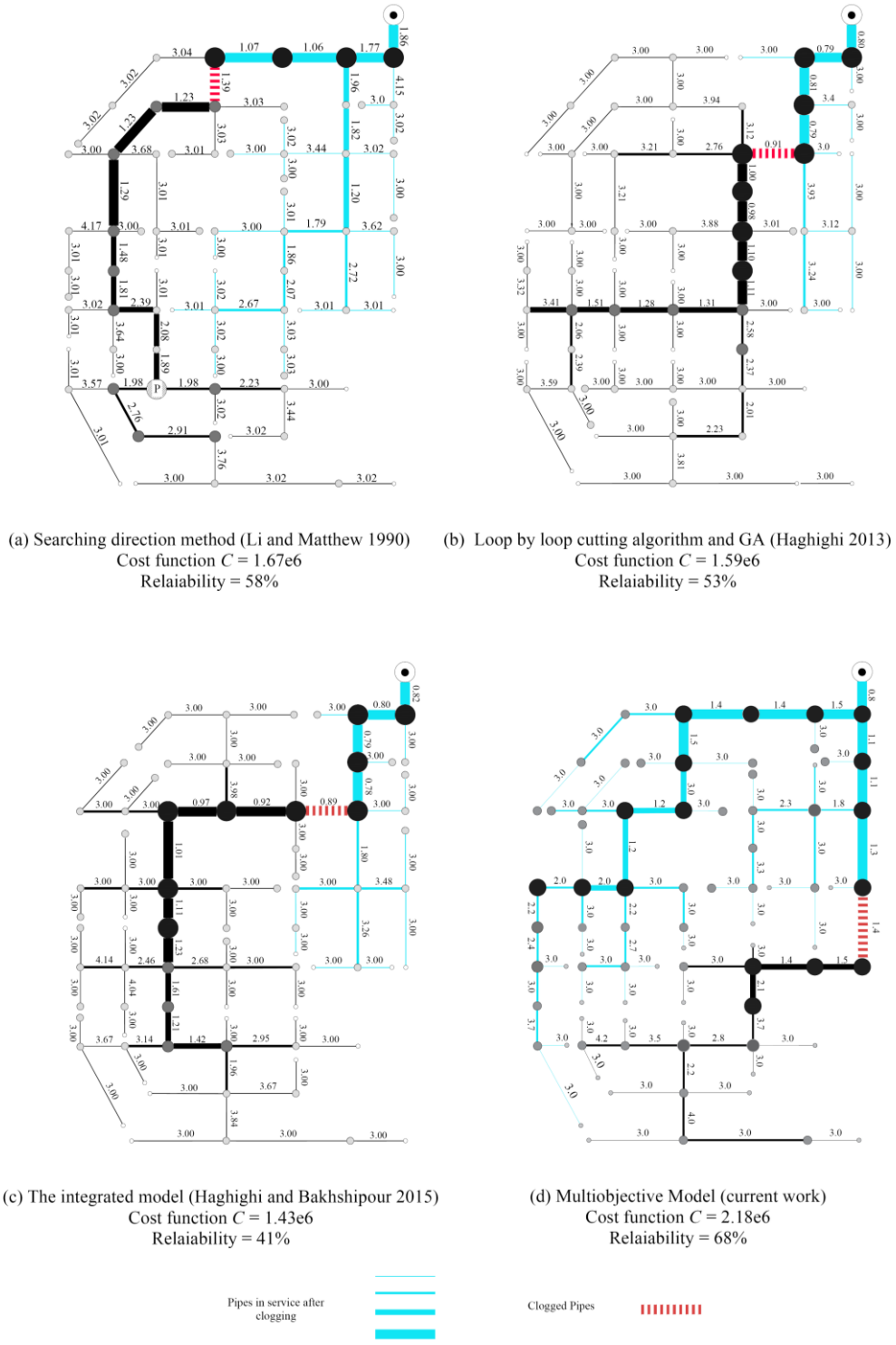


Figure 5. Layout alternatives and the effect of a random pipe clogging.

Lastly, in the layout introduced in the present work, design (d), it is apparent that the most part of the network will be in service after the occurrence of the random pipe clogging. However, decision makers should invest 50% more in comparison with design (c), for this desirable alternative.

The significant difference between design (d) and the three other designs, those optimized with respect to only the cost function is that two main collectors instead of one are responsible for the drainage of the network in this alternative, which leads to more construction cost and more reliability.

4. Conclusions

A multiobjective optimization framework was applied to optimize the two contrasting objective functions of 1- the cost and 2- the reliability for the design of sewer networks. However, the decision on the adequate level of reliability of a sewer system and on the appropriate investment cannot be made by engineers alone. In most cases, local politics decide how much money is allocated to each field of infrastructure.

The example shows that the Pareto front is a good approach to communicate trade-off problems to political decision makers with limited or no technical background. Yet, the definition of the reliability is not intuitively understood and requires further explanation, e.g. by practical examples.

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