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Simultaneous topology and sizing optimization of a water distribution network using a hybrid multiobjective evolutionary algorithm

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ABSTRACT

This paper proposes a new direction for design optimization of a water distribution network (WDN). The new approach introduces an optimization process to the conceptual design stage of a WDN. The use of multiobjective evolutionary algorithms (MOEAs) for simultaneous topology and sizing design of piping networks is presented. The design problem includes both topological and sizing design variables while the objective functions are network cost and total head loss in pipes. The numerical technique, called a network repairing technique (NRT), is proposed to overcome difficulties in operating MOEAs for network topological design. The problem is then solved by using a number of established and newly developed MOEAs. Also, two new MOEAs namely multiobjective real code population-based incremental learning (RPBIL) and a hybrid algorithm of RPBIL with differential evolution (termed RPBIL–DE) are proposed to tackle the design problems. The optimum results obtained are illustrated and compared. It is shown that the proposed network repairing technique is an efficient and effective tool for topological design of WDNs. Based on the hypervolume indicator, the proposed RPBIL–DE is among the best MOEA performers.

1. Introduction

A piping or water distribution network is one of the most important engineering systems found in daily life. The network normally consists of pumps, tanks, reservoirs, valves, and other devices interconnected by pipes for providing water to the public. It can be viewed as a graph having pipes as links while nodes represent sources, consumers, pipe connections, and hydraulic control elements. Piping network design can be classified into three phases as conceptual, preliminary and detailed design. These are not completely separated design phases since we can sometimes perform several design phases simultaneously. The conceptual design is usually accomplished in such a way that a network topology (layout) is defined based on the premise that a network with loops will become more reliable and more expensive whereas one with branches will be less reliable but cheaper [1,2]. The network topology is also dependent on many restrictions such as households, roads, and other obstructions.

Having obtained a predefined network layout, network parameters e.g. pipe diameters, tank and pump sizes, are determined to meet the optimum design objectives while fulfilling network constraints. Optimal pipe sizing of WDN has been investigated for many years. The optimization problems for pipe networks can have either single [1,3–9] or multiple [1,10–13] design objectives. A typical single-objective design problem is assigned to find a minimum network cost while nodal heads are constrained ensuring that the network is sufficiently reliable. Since Walski in 2001 [14] and other researchers illustrated that minimizing the network cost will reduce network benefits (reliability) or vice versa, it means there are multiple design objectives to be optimized for one WDN. This study leads to a new direction for the preliminary design of WDN. Network reliability can be defined as the ability of a network system to provide adequate performance under both normal and abnormal conditions [15]. Some work has been made towards network reliability models due to mechanical and hydraulic failures [4,16–20]. The network simulation by means of head-driven analysis has been proposed so as to make up for the shortcomings of the demand-driven model [15,20,21]. The criteria used to measure network reliability for use in an optimization process have been defined. The minimum surplus head index was probably the first reliability index proposed for an optimization process by Walski and Gessler in 90s [22]. Later, there have been other indices proposed for measuring the WDN reliability e.g. the total surplus head index [22], the resilience index [10], and the network resilience [2]. As for the optimizers, gradient-based linear and nonlinear optimization methods were implemented in the early years [4]. The use of evolutionary algorithms has later become more popular and attractive due to their robustness, simplicity and universality [1–3,10–13].

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Some work related to the more practical detailed design and analysis of WDNs has been made. The network connectivity/topology analysis [23] as well as the algorithm for an automatic detection of topological changes in WDN due to abnormal operating conditions [15] has been developed. As the real network system uses valves to isolate some segments from the network, the impacts of valve location and distribution on the network in both normal and abnormal conditions have been studied [24–27].

From the above-mentioned literature, considerable progress has been made towards the preliminary and detailed design stages of WDN but there has been limited work contributing to the use of optimization techniques to find optimum WDN layouts at the conceptual design stage. However, in other engineering fields, it has been found that the application of topological optimization at the conceptual design stage usually leads to better design results e.g. communication networks [28], internet topology [29], and artificial neural networks [30]. In practice, a network topology is normally formed by an experienced design engineer. If implementation of topology optimization on water distribution networks is possible, it means even inexperienced designers can perform a design task whereas practical and high performance network topology can be expected.

This paper presents a new approach for optimizing WDNs at the conceptual design stage. Multiobjective evolutionary algorithms are employed to find initial WDN layouts by means of simultaneous topological and sizing optimization. This design approach is said to combine and carry out the conceptual and preliminary design stages of WDNs within one simulation run. Design of piping networks using multiobjective evolutionary algorithms is demonstrated. The design problem includes both topological and sizing design variables while the objective functions are network cost and total head loss in pipes. The numerical technique, called a network repairing technique, is proposed to overcome difficulties in operating MOEAs for network topology optimization. The design problem is then solved by using a number of MOEAs, i.e. version two of strength Pareto evolutionary algorithm (SPEA2) using real codes [31], version two of non-dominated sorting genetic algorithm (NSGAII) using real codes [32], multiobjective particle swarm optimization (MPSO) [33], unrestricted population size-evolutionary multiobjective optimization algorithm (UPS-EMOA) [34], and multiobjective harmony search (MOHS) [35]. Apart from those state-of-the-art MOEAs, two new multiobjective meta-heuristics RPBIL and RPBIL–DE are introduced. The former is based on real code population-based incremental leaning [36] while the latter is a hybrid algorithm that integrates the operator of RPBIL and DE. The Pareto optimal solutions obtained from the various MOEAs are illustrated and compared. The comparative performance of MOEAs is investigated. Based on the hypervolume indicator, the proposed hybrid optimizer RPBIL–DE is among the top performers. The proposed network repairing technique is an efficient tool for topological design of water distribution networks.

The rest of the paper is organized as follows. Section 2 briefly details a simultaneous topology and sizing optimization of pipe networks. The network repairing technique used to deal with illegitimate design solution is explained in Section 3. Section 4 presents a new hybrid multiobjective evolutionary algorithm which is the combination of RPBIL and DE. Design demonstration and performance assessment of various MOEAs are setup in Section 5 whereas the comparative results are given in Section 6. Finally, the conclusions are drawn in Section 7.

2. Design problem

In practice, a pipe network is designed by taking into account economics, safety, maintenance and public health. The common design criteria include network cost and reliability, redundancy [21], total head loss in pipes, water quality, network infrastructure etc. The optimization process is not only applied to the design of a new network but also used in the rehabilitation of an existing network. Network cost is an unavoidable design objective for many engineering systems. For pipe network design, minimizing cost always affects network reliability; therefore, practical network design needs to simultaneously minimize cost and maximize reliability. Several indicators are proposed for measuring pipe network reliability such as network resilience [2], and total head loss in pipes.

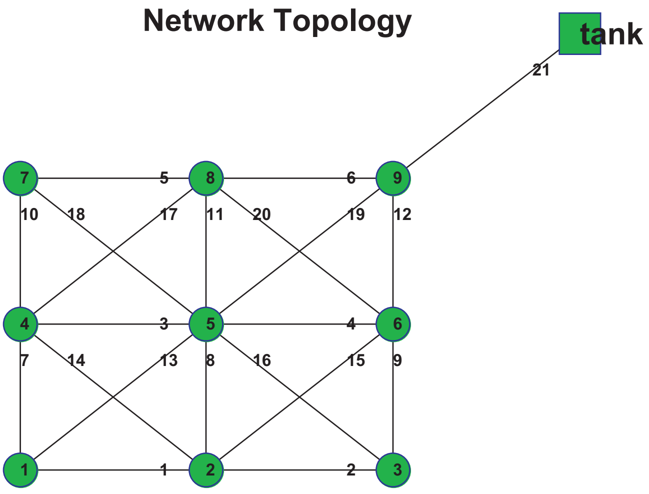

Fig. 1. Ground network.

A multiobjective optimization problem used in this work can be written as:

$$\min_{x} : \{f_1, f_2\} \tag{1}$$

subject to

$$F_i(\mathbf{H},\mathbf{D}) = 0; \quad i = 1, \ldots nn$$

$$H_i \geq H_i^{\min}; \quad i = 1, \ldots nn$$

where $\boldsymbol{x}$ is a design vector determining a network topology and pipe sizes, f_1 is the total network cost, f_2 is the total head loss in the network, H_i is the head at node i, and $H_i^{\min}$ is a minimum allowable nodal head of node i. The hydraulic constraints $F_i(\mathbf{H},\mathbf{D})$ are nodal mass balance, and loop or path energy balance equations, which can be handled by using the EPANET 2 software. The objective functions can be computed as:

$$\begin{aligned} f_1 &= \sum_{i=1}^{np} \text{Cost}_i(D_i, L_i) \\ f_2 &= \sum_{i=1}^{np} L_i h_i(D_i) \end{aligned} \tag{2}$$

where Cost_i is the cost of pipe i, L_i are pipe lengths, h_i are head loss per unit length, and D_i are the discrete pipe sizes.

In order to achieve a simultaneous topological and sizing optimization, the predefined nodes, links, and other network conditions are assigned. Fig. 1 shows a particular 9-node network having 3 × 3 junctions and one tank. Then, the ground network containing all possible pipe elements connecting between nodes in the network is generated as shown in the figure. This ground network has 21 pipes where pipe 21 linking node 9 and the tank is not assigned to be a design variable. The design variables determine the 20 pipe diameters while the list of available pipe diameters, their