Journal of Environmental Management 226 (2018) 308–319

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Many-objective optimization model for the flexible design of water distribution networks

João Marques[a,*], Maria Cunha[a], Dragan Savić[b]

[a] INESC Coimbra – Institute for Systems Engineering and Computers at Coimbra, Department of Civil Engineering, University of Coimbra, Coimbra, Portugal
[b] Centre for Water Systems, School of Engineering, Computing and Mathematics, University of Exeter, United Kingdom

ARTICLE INFO

Keywords:
Water distribution networks
Many-objective optimization
Uncertainty
Multi-stage design
Flexibility
Simulated annealing

ABSTRACT

This paper proposes a many-objective optimization model for the flexible design of water distribution networks (WDNs), including four objectives. Two objectives are related to the WDNs' hydraulic capacity, the minimization of the pressure deficit and the undelivered demand. The third objective is the traditional cost minimization while the fourth minimizes carbon emissions. These objectives concern network reliability, and financial and environmental concerns. They can give rise to solutions embedding new trade-off in design perspectives. There is a gap in the literature when it comes to dealing with many-objective problems for designing and constructing a WDN over a long-term planning horizon and using a staged design scheme that includes the consideration of uncertainty. A solution obtained through this process can be implemented in the first stage and the WDN is prepared for the possible occurrence of various future scenarios. These scenarios can consider expansions of WDNs to different development areas, in different time stages. Furthermore, defining a multi-staged design allows implementing the design of the first stage and reassessing the whole process in the end of each stage when more plausible future scenarios can be investigated. The solution of complex problems such as these needs improved algorithms to produce the Pareto front and so enable the trade-off between the objectives to be examined. An enhanced algorithm, based on the simulated annealing concept and capable of handling the critical scalability issues encountered in previous algorithms with respect to drawing the Pareto front for many-objective problems where a high-dimensional space is involves, is presented. The results obtained allow a thorough analysis of trade-offs between objectives and confirm the importance of considering the minimization of all those four objectives and the advantages of using a flexible approach to design WDNs to better inform decision makers.

1. Introduction

Water distribution network (WDN) design is one of the most complex problems in the management of urban water systems (Mala-Jetmarova et al., 2018). The complexity of the design problem stems mainly from its discrete and nonlinear nature, multiple criteria for evaluation, as well as uncertainties inherent in long-term planning. This work presents a many-objective model for the flexible design of WDNs, based on a multi-stage scheme. The aim is to account for multiple benefits of the design by minimizing four objectives, namely, pressure deficits, undelivered demand, construction costs, and carbon emissions. Many studies of the optimal design of WDNs have been published over the last three decades. Mala-Jetmarova et al. (2018), present a detailed literature review where all the concepts, main contributions, developments, trends and limitations on this subject are analysed and highlighted.

Different approaches have been followed, ranging from the initial attempts in which single objective models were solved by the linear programming gradient method (Alperovits and Shamir, 1977), through nonlinear programming methods (Lansey and Mays, 1989), to the more recent heuristics methods used to solve more complex problems such as real WDNs. Examples of heuristics that dealt with the single objective (cost minimization) problem optimization of WDNs include genetic algorithms (Savic and Walters, 1997), simulated annealing (Cunha and Sousa, 1999), ant colony optimization (Maier et al., 2003) and harmony search (Geem, 2006). The simplest approach to minimizing the cost via a single-objective optimization model was most likely developed because of the high complexity of these systems, and because financial resources to construct infrastructure are always limited. However, approaches involving more objectives have subsequently been devised because WDN design often exhibits multiple, conflicting objectives (Savic, 2002).

---

[*] Corresponding author.
E-mail addresses: jmarques@dec.uc.pt (J. Marques), mccunha@dec.uc.pt (M. Cunha), D.Savic@ex.ac.uk (D. Savić).

https://doi.org/10.1016/j.jenvman.2018.08.054
Received 20 July 2017; Received in revised form 10 August 2018; Accepted 12 August 2018

In addition to cost minimization, a considerable body of literature has considered other objectives, mostly using two-objective models. For example, the pressure deficit reduction at nodes as a measure of network reliability was included by Keedwell and Khu (2004), Kapelan et al. (2005) and Fu and Kapelan (2011) for the optimal rehabilitation of an existing WDN (New York Tunnels case study). Similarly, Atiquzzaman et al. (2006) applied the same objective for the Hanoi and Alperovits and Shamir (1977) networks. The minimization of the undelivered demand was used by Tanyimboh and Seyoum (2016) for a real UK case study. The maximization of a network resilience index was included by Wang et al. (2015), while the minimization of greenhouse gas emissions was studied by Wu et al. (2008), Herstein et al. (2009), Wu et al. (2010) and Stokes et al. (2015) for the optimal design and operation of new WDNs. Shokoohi et al. (2017) added the maximization of water quality as another objective. Although the two-objective WDN design problem is sufficiently complex to warrant the use of sophisticated heuristic methods, going beyond two objectives brings additional challenges for optimization methods (Deb, 1999).

Wu et al. (2013) proposed a three-objective model, including minimizing costs, improving reliability and reducing greenhouse gas emissions. Khu and Keedwell (2005) analyse the additional design choices given by an optimization model with six objectives compared with design solutions obtained with a two-objective NSGA-II model. Giustolisi and Berardi (2009) considered four objectives (investment costs, cost of pipe breaks, preferential selection of only one pipe material and reliability) for the rehabilitation of water distribution networks (case study, real UK water distribution network), using the multiobjective genetic algorithm, OPTIMOGA. Fu et al. (2013) solved the rehabilitation and operation of water distribution networks (case study: Anytown) with the following objectives: investment costs, operating costs, hydraulic failure, leakage, water age, and fire-fighting capacity, using the ε-NSGA-II algorithm. However, none of these studies deals with the much more complex problem of the design and construction of a WDN over a long-term planning horizon through a staged design scheme including consideration of uncertainty.

Staged design is important for considering uncertainty issues (e.g., uncertain nodal demands or network deterioration), as it allows intervention at different stages of the planning horizon by defining flexible solutions in the process of WDN development and permitting planners to act (and change decisions) as new information becomes available (Spiller et al., 2015). This has an advantage over the traditional single-stage design where an intervention is fixed for the entire planning horizon, which can result in an under- or over-designed WDN. Huang et al. (2010) address the problem of the optimal design of WDNs in stages that takes uncertainties of future water demand into account. They developed flexible solutions but used a single-objective model for cost minimization. Creaco et al. (2015) investigate three distinct approaches to phasing (or staging) the design of WDNs while also considering a minimum cost objective. Creaco et al. (2014) also propose an approach for phasing the construction of WDNs considering two objectives, the minimization of costs and the pressure surplus. Their solution uses a multiobjective genetic algorithm and draws some comparisons with the fixed design solutions, which shows that the staged design is better. Basupi and Kapelan (2015a) and Basupi and Kapelan (2015b) propose a different approach to develop flexible solutions, taking demand uncertainty into account by applying staged interventions in the network and considering a two-objective model. The model that minimizes cost and maximizes resilience was solved by an NSGA-II algorithm. Marques et al. (2015a) include the flexible WDN design problem with a two-objective optimization formulation involving the minimization of costs and pressure deficits. Marques et al. (2017) solved a three-objective optimization problem by minimizing costs, carbon emissions and pressure deficits. Both studies used a simulated annealing algorithm to solve the optimization problem.

The analysis of literature on WDN and on several other fields, when there are many objectives at stake, shows the ineffectiveness of the Pareto dominance relation in high-dimensional space. In fact, the performance of the Pareto dominance-based algorithms developed for solving problems involving two or three objectives decreases considerably as the number of objectives increases. Various Multiobjective Evolutionary Algorithms - MOEAs (NSGA-II, PAES, MOEA/D-PBI, etc., as presented in Jiang and Yang, 2017), and Multiobjective Simulated Annealing Algorithms - MOSAs (SMOSA, PDMOSA, WDMOSA, etc., as presented in Suman and Kumar, 2006, Bandyopadhyay et al., 2008 and Sengupta and Saha, 2018), developed in the past face severe scalability issues (Jiang and Yang, 2017; Sengupta and Saha, 2018). Many-objective optimization poses new challenges, such as the increasing proportion of non-dominated solutions and the inadequacy of Pareto dominance to create enough selection pressure in problems with a higher number of objectives.

To emphasize the difference between the needs for solving problems involving more than three objectives, a new term "many-objective optimization problems" (MaOPs) has appeared in the literature (Farina and Amato, 2002; Purshouse and Fleming, 2003, 2007). Since Chand and Wagner (2015) established that at least three objectives are needed for a problem to be considered an MaOP the concept has gained widespread popularity (Li et al., 2015; Jiang and Yang, 2017; Sengupta and Saha, 2018).

This paper proposes a many-objective optimization model for the design of WDNs that can be expanded over the planning horizon. The literature shows that the four objectives considered in this work can significantly influence WDN design. However, no research has yet examined the trade-offs between these four objectives (minimizing pressure deficits, undelivered demand, costs and carbon emissions) while also considering a multi-stage design for WDNs to tackle uncertainty issues and, as such, define flexible solutions. Therefore, it is important to address this research gap by understanding the compromises that can be achieved between these objectives to better inform utility decision makers. A scenario-based approach is proposed to deal with uncertain future circumstances by considering a planning horizon that consists of a number of construction stages during which new urban areas can be established over time. Only the design for the first stage of the planning horizon has to be implemented at the time of decision making. However, the scenarios for the future staged development are essential to provide flexibility (de Neufville and Scholtes, 2011) so that the first stage solution can cope with a range of possible future conditions. As an adaptive scheme is implemented, the whole process can be repeated at the end of each stage when more plausible future scenarios can be investigated.

Solving a four-objective and multi-stage design problem is a major challenge for optimization algorithms as it involves exploring a large solution space and comparing many solutions during the optimization process. This complexity increases significantly when a staged design (one that is carried out in stages using short time steps at each stage) is considered under uncertain futures (Mala-Jetmarova et al., 2018). Another challenge is extracting information from a large number of non-dominated solutions found on the approximation to the Pareto front.

The model developed in this paper is solved by an enhanced simulated annealing algorithm, based on the concepts presented in Kirkpatrick et al. (1983), and exploring the amount of domination concept (Bandyopadhyay et al., 2008) capable of overcoming the major drawbacks of scalability previously mentioned.

The remainder of the paper is organized as follows. In section 2, the optimization model is formulated, and section 3 details the optimization tool used to solve the many-objective model. The case study, the results and discussion are presented in section 4 and, finally, the last section sets out the conclusions.

2. Multi-stage and many-objective model

The proposed many-objective model can solve problems in urban