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Multi-objective optimization of water distribution systems based on a real options approach

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ABSTRACT

This paper describes a multi-objective optimization model including Real Options concepts for the design and operation of water distribution networks. This approach is explained through a case study with some possible expansion areas defined to fit different future scenarios. A multi-objective decision model with conflicting objectives is detailed. Also, environmental impacts are considered that take into account not only the life cycle carbon emissions of the different materials used during the construction of the networks but also the emissions related to energy consumption during operation. These impacts are translated by giving a cost to each tonne of carbon dioxide emitted. This work presents a new multi-objective simulated annealing algorithm linked to a hydraulic simulator to verify the hydraulic constraints, and the results are represented as points on the Pareto front. The results show that the approach can deal explicitly with conflicting objectives, with environmental impacts and with future uncertainty.

1. Introduction

Water distribution networks today are complex systems that require high investment for their construction and maintenance. The storage and transport of water has been extensively investigated in recent decades by applying optimization techniques to water distribution systems design (Sacks et al., 1989). In developed countries almost everyone has access to water systems, but several problems remain to be solved such as intermittent supply and the high level of water losses. Furthermore, as urban centers continue to grow so does the amount of water used. The networks have to continually adapt to new circumstances to provide an adequate service.

The design of water distribution networks is often viewed as a single-objective, least-cost optimization problem with pipe diameters being the primary decision variables. But when we need to address several objectives, multi-objective optimization can be used to design of water distribution network instead. A number of researchers and practitioners have noted that the optimal design of water distribution systems is a multi-objective issue since it involves compromises between conflicting objectives, such as total cost, reliability and level of service. Savic (2002) demonstrates some shortcomings of single-objective optimization approaches and uses a multi-objective based genetic algorithm (Fonseca and Fleming, 1993) to avoid these difficulties. Farmani et al. (2004), Prasad et al. (2003), Creaco and Franchini (2012) and Todini (2000) explored the application of multi-objective optimization where the minimization of cost and maximization of reliability are the main objectives. Di Pierro et al. (2009) compared two multi-objective algorithms for the design of real size networks. This paper describes the solution of a multi-objective optimization model with two conflicting objectives.

This work aims to include the cost of carbon emissions in the design and operation of water networks. We must therefore quantify the emissions from the very beginning of extraction of the different materials used in the water systems until their final disposal. Dennison et al. (1999) use life cycle analysis to compare the environmental impact of different pipe materials. Dandy et al. (2006) developed a multi-objective model that uses sustainability objectives in life cycle cost analysis, energy consumption, greenhouse gas emissions and resources consumption. The tool compared the minimum cost design with the sustainable environmental design. Herstein et al. (2011) presents an index-based method to assess the environmental impact of water supply systems. The index aggregates the consumption of resources, environmental discharges and environmental impacts in a single index.

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Different materials for tanks, manholes and moorings construction must be used to build up the water supply infrastructure. The most common are: the steel used in pipes, accessories and pumps; reinforced concrete; plastic for pipes and accessories; aggregates for pipeline backfill and asphalt for repaving. The methodology presented Marques et al. (2014a) is used to evaluate the carbon emissions involved, considering the whole life cycle including the extraction of the raw materials, transport, manufacture, assembly, installation, disassembly, demolition and/or decomposition. The methodology also computes carbon emissions from the energy used during the network's operation. Adding together the partial contributions of pipe installation and energy consumption it is possible to compute the total carbon emissions. It is also necessary to fix a value for the carbon emissions cost for each tonne emitted. These costs are included in the optimization model presented in the next section.

According to Haimes (1998) the great challenge for the scientific community in the third millennium will be to develop tools and technologies to support and maintain infrastructure. Several methods for the effective planning of water systems have appeared in the literature. If flexible planning can be adopted, the infrastructure will be able to cope with future uncertainty. Real options (ROs), originally from financial theory, could make an important contribution in this area. Myers (1977) was the first to introduce the term real options. Since then a large number of studies have been published where the concepts of ROs have been used in several fields.

A number of studies have developed ROs approaches to solve a variety of problems: Nembhard and Aktan (2010), who systemized applications of ROs to design and resolve engineering problems; De Neufville et al. (2006) report the use of ROs in car parking problems, and Gersonius et al. (2010) apply ROs analysis to the option planning process in urban drainage systems to incorporate flexibility to accommodate climate change while reducing future flood risk. In the water industry, a ROs technique appears in the work of Woodward et al. (2011) to define maritime coastal defenses to reduce the risk of flooding. In the area of water systems expansion, Suttinon and Nasu (2010) present a ROs based approach where the demand increases. Zhang and Babovic (2012) use a ROs approach to evaluate different water technologies in water supply systems under uncertainty. The work of Creaco et al. (2014) proposes a multi-objective methodology aiming at considering the phasing of construction within the design of the water distribution systems, which grow in terms of layout size. The work of Huang et al. (2010) describes the application of ROs to the design of water distribution networks and Basupi and Kapelan (2013) presents a methodology to the flexible and optimal decision making dealing with future demand uncertainty. Finally the authors have already used ROs in two prior works: Marques et al. (2014b) to the optimal design of water distribution systems using a single objective model formulation demonstrated in a simple case study and Marques et al. (2014a) taking into account carbon emissions and by using a different single objective model formulation demonstrated in "Anytown network". Here a new multi-objective optimization tool based on simulated annealing is proposed to solve the multi-objective optimization model based on ROs that incorporates two conflicting objectives explicitly. There is a vast body of literature on multi-objective approaches that have been used in several fields, and it includes: Hakanen et al. (2013), in wastewater treatment plant design and operation; Ahmadi et al. (2014), to calibrate of watershed models for pollutant source identification and watershed management; Giuliani et al. (2014), for the operation of complex environmental systems, and Zheng and Zecchin (2014), for designing water distribution systems with multiple supply sources are just some recent examples.

It is very important in water systems planning to predict future operating conditions. However, cities are continually changing and the water supply networks have to be adapted to these changes. Sometimes a new urban or industrial area is built and the network has to be improved to accommodate the new conditions. The opposite can occur in areas where population declines and demand falls. This work presents a multi-objective approach where uncertainty is related to new expansion scenarios for the network.

Some benefits of flexible design are associated with the ease of accommodating different future scenarios. However, flexibility usually incurs an extra cost at the initial stage of a water network design. A flexible design is one that enables the designer, developer, or operator to actively manage or further develop the configuration of the system downstream and adapt it to changes in the supply, demand, or economic environment. The ROs approach presented in this work uses a decision tree to reflect different scenarios that may occur during the planning horizon. The process uses a multi-objective optimization model to find solutions for the first period and for different possible future realities according to the decision tree. The model uses two objectives: a minimum cost objective function that takes into account the carbon emission costs and a level of service measure that minimizes the pressure failures that can occur over the entire planning horizon. Various scenarios are analyzed to predict alternative future conditions.

The new ROs approach presented in this work handles future uncertainties and two conflicting objectives, over the whole planning horizon. Decision planning based on trying to delay some decisions for the future, enables current investment to be reduced. This delay also incurs some costs because the initial solution has to be flexible enough to accommodate all the future conditions, and such flexibility comes at a price.

The remainder of this paper is organized as follows: in the next section the ROs framework and the case study are set out. This is followed by a multi-objective decision model based on a ROs approach, and then the results are presented. The last section contains the conclusions.

2. Real options framework and case study

A real options approach makes it possible to consider different adaptations over the lifetime horizon, according to urban growth. Areas can become depopulated or urbanized. These modifications have impacts on the hydraulic behavior of the networks and should be taken into account. In this section, a case study demonstrating how the multi-objective model considering ROs can be employed is presented. Fig. 1 represents a water distribution network inspired by the work of Walski et al. (1990). In the original case study the layout of the network is confined to the part enclosed by the dashed line. However, we consider the possibility of expanding the network into four different areas A1, A2, A3 and A4, and we have included an area, A5, where there may be a depopulated area.

The network is supplied by three fixed-level reservoirs and there is a pumping station placed at link 1 to transmit energy to the flow from reservoir R1. The characteristics of the nodes at demand conditions (1) and (2) are presented in Table 1. This work considers two kinds of minimum pressure: the desired pressure and the admissible pressure of reference. The lower pressure limit (admissible pressure) is assumed to be high enough to totally satisfy demand. Pressure deficits for which the demand cannot be totally satisfied (Wagner et al., 1988) are not considered here. The two different pressure levels are included to analyze the tradeoff between cost and service levels measured in terms of the minimum nodal pressures that are desired and the pressures that are effectively provided.