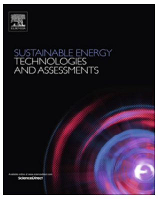
Sustainable Energy Technologies and Assessments xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

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



Original article

Use of network theory and reliability indexes for the validation of synthetic water distribution systems case studies

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ARTICLE INFO

Article history:
Received 25 August 2016
Revised 29 November 2016
Accepted 5 December 2016
Available online xxxx

Keywords:
Water distribution systems
Graph theory
Resilience
Synthetic case studies

ABSTRACT

The examination of the relationship between energy use, reliability and network characteristics in water distribution systems (WDS) requires a set of sufficient case studies to give statistical significance to the conclusions. Considering the difficulty of finding real-world systems that can be used in this kind of research, synthetic (virtual) distribution systems are the next available alternative to use as case studies. This paper describes the use of a new method for the generation of synthetic distribution systems and its subsequent comparison against real-world systems to validate the suitability of the synthetic set to drive the conclusions of future research.

The algorithm for the generation of synthetic WDSs is based on the work, methods and software presented by Mair et al. (2014). For the validation procedure, five metrics or indexes that account for the network's connectivity (link density, average node degree, meshedness coefficient) and the system's reliability (Resilience Index, Network Resilience) are evaluated; the ranges in each of the metrics are then compared. The generation of synthetic WDS required an enhancement of the connectivity of the networks and a pipe sizing that accounted for practical system design. An acceptable degree of similarity between the synthetic and the real-life sets of WDSs was achieved, although some modifications to the networks may be required in the future.

Introduction

Currently, there is a lack of realistic data to drive research on water distribution systems (WDS), based especially on safety reasons [2], and on time and costs associated with data collection [3]. These restrictions have meant that realistic case studies typically are detailed but representative of small neighbours and rural settlements (e.g. [4,5]) or larger but highly skeletonized (e.g. [6–8]). To overcome that difficulty, virtual or synthetic systems can be used given the smaller effort required to generate them and the small or null risk that its publication can imply.

Brumbelow et al. [2] made one of the first attempts to propose virtual WDSs with realistic data, with two virtual cities named "Micropolis" and "Mesopolis" based on some real data available to the authors. A more automated approach was proposed by Sitzenfrei et al. [3] who developed the software DynaVIBe-Web [1] for the generation of synthetic WDSs based on street networks patterns and some GIS data described in Section "Topography and layout" of this paper. Murano et al. [9] also proposed and developed a tool for the generation of synthetic networks based on some user-defined parameters and constraints. Finally, Trifunovic et al. [10] presented another algorithm which makes use of graph theory algorithms that allow the randomized and non-randomized generation of networks.

Given the novelty of the algorithms for the generation of synthetic WDSs, and the small use they have had so far, a validation of its results is required before they can be used for further research, especially to ensure that the models are representative. This paper presents the use of the methodology and software developed by [1] to generate 45 synthetic WDSs and the posterior comparison against 15 real-world systems gathered by [4]. The comparison was made to validate the synthetic set using networks' connectivity metrics [11] and systems' reliability indexes based on their energy allocation [12]; which are considered two main aspects for further research on WDSs.

Indexes description

A WDS can be represented as a graph $G = (V, E)$ where V is the set of vertices and E is the set of edges within G. All junctions, demand nodes and sources of a WDS are considered elements of V, while all pipes and link-represented elements (e.g., pumps and

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http://dx.doi.org/10.1016/j.seta.2016.12.002

Please cite this article in press as: Paez D, Filion Y. Use of network theory and reliability indexes for the validation of synthetic water distribution systems case studies. Sustainable Energy Technologies and Assessments (2016), http://dx.doi.org/10.1016/j.seta.2016.12.002

valves in EPANET) are elements of E. Defining n as the number of elements in V and m as the number of elements in E, the following connectivity indexes can be defined [11]:

$$q = \frac{2m}{n(n-1)} \tag{1}$$

$$< k >= \frac{2m}{n} \tag{2}$$

$$R_m = \frac{m-n+1}{2n-5} \tag{3}$$

where q is the "link density" that represents the fraction between the current number of links and the maximum number of links in a non-multigraph graph; $< k >$ is the "average node degree" defined as the average number of links connected to a node; and R_m is the "meshedness coefficient" that represents the fraction between the current number of loops and the maximum number of loops in a planar graph.

On the other hand, to quantify the reliability associated with a WDS it has been proposed to use indexes that do not require a stochastic analysis of hydraulic or mechanical perturbations that a WDS could have (e.g., [13], [14] and [15]), but that represent in different ways the impact and response of the network to those uncertain perturbations. For this research, two energy related indexes were used: the Resilience Index (RI) proposed by [13]; the Network Resilience (NR) proposed by [14]:

$$RI = \frac{E_U - E_U^{(min)}}{E_0 - E_U^{(min)}} = \frac{\sum_{i=1}^{n_n} D_i \left(H_i - H_i^{(req)}\right)}{\sum_{k=1}^{n_r} D_{out_k} H_k + \sum_{j=1}^{m_p} P_j/\gamma - \sum_{i=1}^{n_n} D_i H_i^{(req)}} \tag{4}$$

$$NR = \frac{UN \cdot \left(E_U - E_U^{(min)}\right)}{E_0 - E_U^{(min)}} = \frac{\sum_{i=1}^{n_n} UN_i \cdot D_i \left(H_i - H_i^{(req)}\right)}{\sum_{k=1}^{n_r} D_{out_k} H_k + \sum_{j=1}^{m_p} P_j/\gamma - \sum_{i=1}^{n_n} D_i H_i^{(req)}} \tag{5}$$

where E_0 is the total energy per unit weight and per unit time supplied to the system by the water sources and the pumps (input energy) in m^4/s; E_U in the energy per unit weight and per unit time delivered to the end-users (output energy) in m^4/s; $E_U^{(min)}$ is the minimum E_U required to fulfill the end-users' requirements of demand and pressure, computed as the product of the required demand and minimum required head for each demand node; D_i is the demand in node i in m^3/s; H_i is the computed (delivered) head in node i in m; $H_i^{(req)}$ is the required head in node i in m, usually calculated as the node's elevation plus the minimum allowable pressure; D_{out_k} is the outflow from reservoir k in m^3/s; H_k is the head in reservoir k in m; P_j is the power of pump j in W, γ is the specific weight of water in N/m^3; UN_i is the diameter uniformity coefficient of node i calculated as the ratio of the diameters connected to the node and the maximum of those diameters; UN is the diameter uniformity coefficient for the whole network computed as the weighted average of UN_i; n_n is the number of demand nodes, n_r is the number of reservoir or water sources (may include some tanks); and m_p is the number of pumps.

Real-world study cases

Even though the use of synthetic systems is one of the alternatives to solve the scarcity of realistic data, some researchers (e.g. [4,16]) have assembled databases of real-world models for their own research. In the case of [4] they presented and made public 12 systems (although the current database has 15 systems), based on the attributes of real WDSs from the state of Kentucky, which have been slightly modified to prevent the identification of their location. Table 1 presents the ranges of some properties of the database systems (column "Real set").

Generation of synthetic study cases

Topography and layout

DynaVIBe-Web is a software that generates synthetic case studies at a city scale using the algorithm proposed by [3]. The software generates WDSs based on street patterns of real cities by following 3 steps: 1. Location of demand nodes, 2. Generation of the layout based on an initial tree layout and a posterior generation of loops with a defined probability, and 3. Pipe sizing that accounts for non-optimal design and even some installation errors using the concept of economic flow velocity (maximum velocity for economic purposes).

Using DynaVIBe-Web, 5 real cities were selected as baselines for the generation of 45 WDSs (9 WDSs per city). Two of the cities are located in Europe, two in North America and one in Asia, and they cover a range of area between 41 and 974 km^2, and a population densities between 684 and 8453 PD./km^2 (People Density per square kilometer), as seen on Table 1 (column "Synthetic Sets"). The main attributes of the systems were assigned based on data publically available online such as the population, the consumption per capita and the location some elements as treatment plants and tanks.

The execution of the software DynaVIBe-Web was made varying the parameters for demand distribution, spanning tree for the layout, the cycle indicator, and the main pipe offset. The demand distribution can be either uniform or normal depending on how the demand per area varies in the system. The spanning tree for the layout can be generated using either a random tree on a minimum spanning tree that minimizes the length of the pipes. The cycle indicator defines which loops are closed by selecting only the ones with a total length higher than the product of the cycle indicator and the length of the added pipe. Finally, the main pipe offset is the offset distance used to locate the trunk pipes of the network. After varying each of these parameters, an enhancement of the models was required to cover a wider range for the connectivity indexes. This need was evidenced after computing q, $< k >$, and R_m for the real WDSs set and for the five sets of synthetic WDSs (e.g., Table 2 column "Before increasing connectivity"), and noting the differences in the maximum, average and standard deviation values with the real set.

In order to increase the connectivity, another option recently implemented in DynaVIBe-Web called "maximum possible graph" was used. With this option, all possible pipes that lay under a street are drawn and included in the resulting network. Using this maximum-connectivity network, randomly-selected pipes were added to the existing models making sure to connect junctions already present in the network and without including parallel pipes. The results of the procedure can be seen in Table 2 by comparing the columns "Before increasing connectivity" and "After increasing connectivity".

Pipe sizing

Expert criteria is more likely to have driven (and probably continue to drive) the design of WDSs, than optimization methods [17]. Therefore, to make the synthetic systems more realistic, different expert criteria was used. Table 3 presents values and constraints recommended for different expert sources. It includes values for the minimum diameter (d_{min}), the maximum flow

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