Reliability Engineering and System Safety 142 (2015) 148–160

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

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

Minimising the total cost of renewal and risk of water infrastructure assets by grouping renewal interventions

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ARTICLE INFO

Article history:
Received 8 October 2014
Received in revised form
12 May 2015
Accepted 19 May 2015
Available online 29 May 2015

Keywords:
Infrastructure asset management
Renewal planning
Optimisation
Grouping
Economies of scale
Networked infrastructure
Water distribution systems

ABSTRACT

Planning the renewal of water infrastructure assets involves balancing the costs of renewal with the costs of risk. A considerable proportion of the renewal budget is spent on planning and mobilising resources to the intervention location. One may therefore reap benefits from the economies of scale by grouping the renewal of water mains which are spatially close. If one can express the total cost of renewal, risk and unavailability of a water main as a function of time, one may use this to find an optimal configuration of groups to be renewed together, where the benefits of grouping are balanced with the costs of shifting renewal investments in time. This paper demonstrates a methodology for optimising the grouping of renewals of connected water mains. The methodology is applied both to obtain an optimal set of groups for all mains in the network, as well as considering the contingency of renewing a group of mains in the event of a pipe burst. The methodology has been demonstrated with a case study, where the costs of leakage, and structural and hydraulic reliability are considered. The results show that there can be considerable monetary savings made by grouping the renewal of water mains.

1. Introduction

1.1. The multi-dimensionality of UWS maintenance

Urban water systems (UWS) are critical infrastructure systems [1,2] and capital-intensive by nature. The transport systems usually account for the lion's share of the investments in the water industry. The development of UWS has followed the urban development of the rest of society, and the intensity of capital investment reached its peak in the 1970–1980s in most of the water utilities in the Western world. The water infrastructure is therefore ageing today [3], and it is expected that the capital renewal intensity in UWS will increase considerably in the following decades, in order to sustain the level of service.

Planning the maintenance and renewal of networked infrastructure, such as water distribution systems (WDS), requires a systematic approach which ensures that the performance, risk and cost of the infrastructure are sustained both in a short- and long-term perspective. This type of planning is often denoted infrastructure asset management (IAM), and aims at maximising performance, while minimising cost and risk [4]. Infrastructure assets cannot be treated as a set of individual assets without considering their function as a part of a network [5–7]; this inherent network behaviour of infrastructure assets, in combination with potentially conflicting objectives over a long time horizon, makes IAM a complex issue [8].

In order to use the terms in IAM planning, we must first define them. Performance may be defined as the ability of a system to fulfil defined levels of service (functions) [9], and a failure may be defined as the inability to do so [10]. Risk may be defined as the combination of uncertainty (expressed as probability) and consequence of a failure [11,12]. Costs related to the management of WDS may be direct or indirect costs. When the required functions of a WDS have been defined, one can define the failures. A failure in a WDS may be classified as *structural*, *hydraulic* or *water quality* failure. A *structural failure* refers to a pipe burst where an active intervention (repair or replacement) is required. A *hydraulic failure* occurs when the amount and/or pressure of water in the system are not satisfied [13], and may occur when (1) the demand exceeds

Abbreviation: CI, cast iron; GIS, geographic information system; HCI, hydraulic criticality index; IAM, infrastructure asset management; LEYP, linear extension of the Yule process; LTP, long term planning; NOK, Norwegian Kroner; PE, polyethylene; UWS, urban water system; WDS, water distribution system

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http://dx.doi.org/10.1016/j.ress.2015.05.014
0951-8320/

the design capacity (consumption or leakage increase), (2) a component fails (structural failure), or (3) deterioration of the inner surface of the water main has reduced its hydraulic capacity [14]. A *water quality* failure is by far the most difficult to define and quantify. The numerous ways in which water quality failures can occur in the distribution network can be broadly classified into four categories, namely (1) negative pressures leading to contaminant intrusion, (2) bacterial regrowth, (3) leaching of chemicals or corrosion products from system components into the water, or (4) permeation of organic compounds through the system components into the water.

It has in the later decades become increasingly relevant to quantitatively assess and manage risk in WDS, for instance through the introduction of Water Safety Plans (WSP) [15]. The quantitative assessment of risk in WDS is done by defining relevant risk indicators and assess them by applying reliability models. One can define WDS reliability measures based on the aforementioned typology of failures and the required functions of a given system. The simplest and most common example is to define the structural reliability in terms of the probability of pipe burst (reliability is the probability of no failure [16]). If one also evaluates the consequences of the different failure modes (e.g. cost of unavailability by structural failure), and combines this with the reliability measures, one can express the risk related to each reliability aspect.

In order to apply reliability models on water mains, one must define at what scale the models should be applied, i.e. what constitutes as a *network segment*. A water main is typically built up by a line of individual *pipe segments* of fixed length (e.g. 6 m cast iron elements) which are welded or glued together. The line of pipe segments stretch from one valve to another, and together they form an *hydraulic link* in the WDS, which may be considered as a *functional unit*. This functional unit is typically what is considered as a network segment in GIS inventories, hydraulic models and failure models, and it makes sense to interpret reliability parameters on this scale. The models consequently produce output for the each hydraulic link.

Research efforts in the past decades have led to the development of numerous models and software packages which can aid the water managers and operators in determining the renewal strategy for a WDS, based on rational criteria such as risk of structural failure. The software packages usually include standard cost models, models which evaluate reliability performance measures (e.g. *probability of structural failure* or *probability of intrusion*), and risk models (e.g. *expected total cost of structural failure*). UtilNets [17], WiLCO [18], PARMS [19], CARE-W [20], I-WARP [21] and AWARE-P [22] are all examples of decision support systems specifically designed for planning the management of water infrastructure in an integrated manner. The decision support systems apply models which allow the decision-maker to administer limited budgets in a cost-effective manner, while still providing the desired level of service. However, these tools have not been applied as extensively as one would expect. One of the major criticisms of the current planning tools is that they do not explicitly consider that WDS are often most economical and practical to renew in blocks or groups. I.e. the models produce output for each *hydraulic link*, and considers that as the network segment, but the hydraulic link is generally not what is commonly considered as a *renewal project*. The setup costs for renewing water infrastructure are often very high, as one will usually have to make new design plans, acquire contractors, mobilise resources, and plan road and water service distribution in order to realise a renewal project. Practitioners therefore often consider group renewal of water infrastructure as an economically convenient and effective strategy for managing the risk of the WDS assets. The potential savings of renewal grouping are not explicitly considered in the current decision support packages, and the practical considerations of the water managers are therefore often used in the decision making-process, rather than utilising the advantages which exist in the current decision support systems to its full extent, i.e. to use theoretical models to support the decision-making.

Another issue which the existing tools have been criticised for is the fact that they do not consider that unforeseen or random occurrences often necessitate the modification of the initial plans and reset the priorities. For example, if a major pipe burst occurs, there will often be a “in the spur of the moment” decision to advance renewal of water mains in the area in which the failure has occurred, even if the plans indicate otherwise. The initial plans are thus not able to account for the grey area between reactive and proactive renewal strategies, and this leaves a gap between theoretical models and practical decision-making.

Using maintenance grouping strategies may help to improve the applicability of the models which have been developed for supporting maintenance decisions in water infrastructure.

1.2. Grouping renewals of water mains

Water infrastructure which is spatially close often share the same cost, risk and performance properties, since the infrastructure usually is built according to the economic and demographic development of an area. It is therefore reasonable to assume that there is a considerable potential for saving resources by grouping the renewal of networked infrastructure. Water mains which are close to each other may benefit from being re-designed and tendered jointly, as well as benefiting from reduced mobilisation costs. A water main is usually not replaced “like for like”, and the attributes of a replaced main are dependent on the standards and expected performance needs at the time of replacement, rather than the attributes of the current main. Since production quality standards and the expected needs of a WDS evolve over time, and the expected service life of a main is very long, one can generally not predict the service lives of mains which are going to be constructed in the future. As a consequence, it is most reasonable to plan the grouping of renewals dynamically one renewal cycle at the time, i.e. considering the time horizon until all mains which are currently in stock are replaced.

There exist many examples of exploiting economies of scale when planning the maintenance and inspection of a multi-component system, including vehicles [23], industrial pump bearings [24], offshore wind turbines [25,26], compressor equipment [27], software [28], and railway systems [29], to mention some. The topic of grouping the renewal of water infrastructure has, in spite of the potential for monetary savings, not received much attention in the literature, although there are some examples which are presented in the following paragraphs.

Poulton et al. [30] pointed out that pipe segments often are arbitrarily defined in GIS databases, and discussed the merits of grouping pipe segments both for the purpose of improving analysis results, as well as making eligible renewal candidate groups. A set of rules for grouping pipe segments was presented by Poulton et al.

Nafi and Kleiner [31] and Fengfeng et al. [32] both demonstrated how water mains can benefit from economies of scale (mobilisation costs, quantity discount, co-investment with road works) by grouping renewal projects. Both papers used spatial proximity as a criterion for being able to group components. Nafi and Kleiner formulated the decision problem as a multi-objective problem, and solved it for a five year horizon with a multi-objective genetic algorithm (MOGA), while Fengfeng et al. considered a cost-optimisation problem (single-objective), and solved it with a genetic algorithm in 20-year investment horizon. Both