Statistical models for structural reliability analysis of water mains

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Sammendrag

Statistiske modeller for strukturell pålitelighetsanalyse av vannledninger

Dette er en litteraturstudie ment for å leses av beslutningstakerne for vannverk, og tar for seg ulike aspekter tilknyttet strukturell pålitelighet av distribusjonsnettet for drikkevann, i lys av fornyelsesplanlegging for infrastruktur (IAM). Feilprediksjon spiller en viktig rolle når man skal bestemme påliteligheten til et system. Dette er et forskningsområde i stadig utvikling, med viktige bidrag fra europeiske prosjekter som CARE-W, som tilbyr et omfattende utvalg av verktøy. En aktuell feilprediksjonsmodell som har blitt mye brukt i Europa, inklusiv i Oslo, er Yule-prosessen (LEYP). Modellen søker å løse svakhetene hos modellene i CARE-W og brukes i et nytt portugisisk prosjekt, kalt AWARE-P. Den kanskje viktigste problemstillingen knyttet til statistiske modeller for vannledninger, er knyttet til det store behovet for historiske data, som er vanskelig å imøtekomme for mange norske kommuner. Det underliggende budskapet i denne artikkelen er å få kommunene til å se fordelen ved å bruke statistiske modeller i rehabiliteringsplanlegging.

Abstract

This paper is a literature review suitable for water utility decision-makers, considering aspects of structural reliability of drinking water networks in the light of Infrastructure Asset Management (IAM). Failure prediction plays an important role in determining the reliability of a system. Immense research has been conducted within IAM, with important contributions like the European program CARE-W, providing a comprehensive selection of tools. A current failure prediction model applied many times in Europe, including in Oslo, is the linear extended Yule Process (LEYP). This model tries to solve the weaknesses of the models of CARE-W, and is now offered in the new Portuguese project, AWARE-P. One of the main issues related to statistical models of water mains is high data requirement, which for many Norwegian municipalities is difficult to accommodate. The underlying message of this paper is for municipalities to see the advantages of using statistical models in their rehabilitation planning.

Introduction

Water utilities are currently struggling with meeting the challenges ahead; the infrastructure components are ageing, and the demanded level of service is rising. In coherence with changing climatic conditions, population growth and stringent regulations, these challenges are drivers for a change in the way water utilities manage their infrastructure assets. It is ever suggested to take advantage of the extensive and increasing knowledge within the field of IAM, represented by a wide range of tools and techniques ready to be used. Motivated by a general need for upgrading the water distribution infrastructure in Europe, CARE-W (Computer Aided Rehabilitation of Water Networks) was started in 2001 (Sægrov, 2005). Another innovative project is AWARE-P, an open-source, professional-grade computer application, offering decision support tools at the three decisional levels of strategic, tactical and operational (Alegre et al. 2011). AWARE-P is an innovative IAM planning tool and has received the IWA Project Innovation Awards for 2014 and the 2014 Mulheim Water Award. Instruments like CARE-W and AWARE-P are provided to help municipalities to identify needs, evaluate solutions, and plan long-term sustainable strategies for improved infrastructure performance at the best available cost, with the least environmental impact.

The objective of a water distribution network (WDN) is to supply the consumers of the municipality including domestic, commercial and industrial customers, with water of a required quantity, quality and pressure. Hence, the reliability of the network is its ability to perform this obligated function under given environmental and operational conditions and within a given time period, without failing (ISO8402:1994). According to Farmani (2005) reliability indicators are used to evaluate the efficiency of a WDN in providing water with standard quality, sufficient quantity and within the appropriate pressure range to consumers under different operational (normal and abnormal) conditions such as component failure and hydraulic changes. Considering any component of a WDN, its reliability can be addressed in relation to structural, hydraulic or water quality reliability indicators. The structural reliability of a pipe can for instance be the number of breaks that are likely to happen to it within a period of time. On the other hand hydraulic reliability can be assigned to as the hydraulic criticality index (HCI), which indicates the loss of supply to costumers that is caused if the pipe is taken out of the system. Quality reliability can for example be measured through simulating how contaminants are likely to spread out in the distribution system. Failure processes with respect to each reliability indicator interact; breaks or bursts of pipes are likely to lead to leakages, insufficient pressure and intrusion of contaminants from the soil. Structural reliability can be viewed as the cornerstone of the reliability indicators, as it has a direct effect on both the hydraulic and quality reliability.

Background

Redundancy is an important term highly related to reliability, constituting an aspect of the overall system performance that is often neglected (Javanberg, 2007). Redundancy for a WDN is represented by its reserve capacity. If a link goes out of service, there must be alternative supply paths connected to the nodes depending on this link, to ensure that they are still provided with water. A redundant network is a network built up in a way similar to a parallel system, in which all components must fail simultaneously in order for the system to fail, as opposed to a series, where only one component needs to fail for the whole system to fail (Ugarelli & Bruaset, 2010). Ugarelli and Bruaset (2010) also propose that in order to have a system of high reliability consisting of low reliability components, it must be constructed in a way that, as far as possible, each failure is independent.

Referring to the conceptual flow of tools in IAM, see Figure 1, the management of individual structures requires a systematic approach (Ugarelli & Bruaset, 2010). The aim is to maintain the structure's reliability and condition within the budget and resource constraints. Maintenance models attempt to determine the best operational plan in the decision model, on the basis of the predicted future performance of the structure calculated in the deterioration model. Thus, structural reliability models contribute in the risk assessment by representing the probability of pipes to fail, which are then combined with the failure consequence to form the

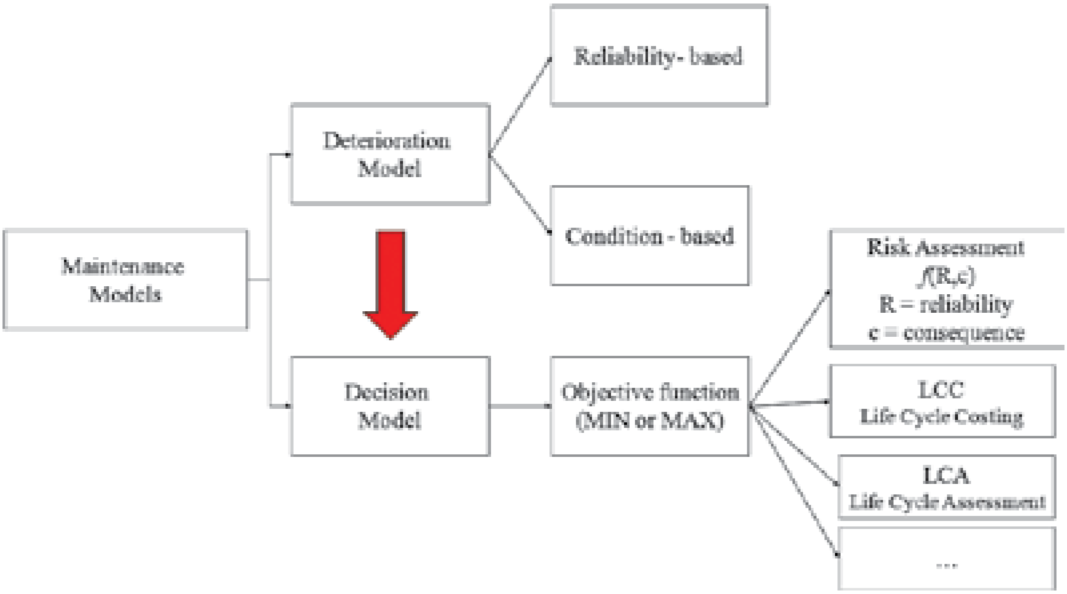

Figure 1. Conceptual flow of tools in IAM (Ugarelli & Bruaset, 2010)

failure risk. On the basis of maximizing performance and minimizing risk and costs, the multi-objective decision model determines the optimal time of intervention, being repair or replacement (Ugarelli & Bruaset, 2010).

Optimizing the intervention time of a specific pipe may be seen as a compromise between preventive and corrective maintenance of the pipe. Preventive maintenance can in some cases entail replacement of a pipe that is still performing well, while in other situations the consequence of a failure (in terms of costs) is considered higher than the costs saved by waiting for the failure to happen. In other words, the extent of a pipe failure consequence can often be the foundation itself for modeling failure predictions of that specific pipe. The results from a deterioration model in terms of a probability for a failure to happen, will serve as important aids in finding the right time to address the pipes of the system.

Deterioration models of water mains are mainly reliability based, as there are currently only a few inspection technologies developed for condition monitoring, due to the limited access to drinking water pipes. Liu and Kleiner (2013) presents the available methods. Some involve high costs, and some are restricted to diameters above a certain size. Therefore they are more relevant for important transmission mains, for which a failure will cause a significant impact on the network. As opposed to the case of water mains, condition based models are consequently applied for wastewater pipes, as they are much more accessible. Most certainly this tendency will change in the future, as there are possibilities of transferring between the fields. In a project on wastewater pipes in Oslo Water Utility, Ugarelli et al. (2013) shows that condition-based deterioration models can be transformed into representing reliability. The probability for a pipe to change from one condition state to the next within a time step can be calculated by using the Markov model (Ugarelli, et al., 2013).

In order to secure the reliability of a water distribution network it is important for the municipalities to manage their network, aiming at avoiding or reducing the impact of pipe bursts. In this context, structural reliability models will provide a better basis for the choices to be made.

Structural reliability models

Statistical modeling of a water main's structural reliability is considered a very important tool in IAM, and has been extensively investigated and carried out over the last decades. A paper that has been widely used as reference is written by Kleiner and Rajani (2001), covering most of the literature material until the year of its release. Essentially all the models attempt to describe the structural deterioration of a water main. This is considered a very complicated process, affected by a wide range of factors, or covariates, relative to the underlying failure mechanism (Boxall et al. 2007). There are structural factors, including age, material, length and diameter, and also environmental, where climate, soil conditions, traffic loads, external loads and depth play important roles. Pressure may also influence the pipe break as well as catodic protection, pointing out the relevance of hydraulic and quality reliability in this context. Le Gat (2013) stated that the diversity of approaches stems from a complex range of issues that rises in the analysis of pipe failure data. Along with more sophisticated mathematical approaches, usually comes a larger data demand. There is currently no model developed that explicitly and quantitatively allow for all the components (Kleiner & Rajani, 2001).

The life cycle of a typical buried pipe has been frequently described in the literature by a so-called bathtub curve, which represents the failure rates of a pipe in the three different stages of its life (Kleiner & Rajani, 2001). The first phase describes its young period right after installation, where the faults are mainly related to poor installation or faulty pipes. In phase two the failures are reduced, and the rate is assumed as constant. Phase three represents the latest stage of the pipe life, or the "wear-out"-phase, in which the rate increases due to ageing and pipe decay. At what level the rate is likely to increase is the question that many models developed have tried to answer. Babykina and Couallier (2010) discussed the shape of the curve at this stage, and concluded that most likely it is determined by the form of maintenance applied to the pipe, because different states are obtained by different maintenance actions. The model categories and some example models are presented next, to give the municipalities an overview of some existing approaches.

Failure rate models

Deterministic models or regression models basically use the past failures of a pipe to predict the future failure rate. In order to differentiate the factors affecting the break rate of the pipes, the population of pipes needs to be partitioned into uniform, homogeneous groups. In turn, two or three parameters will attempt to capture the break patterns of the pipes. Such parameters could typically be pipe age, material and length. Since most of the analysis work is done in the data splitting process, the mathematical equations are relatively simple (Kleiner & Rajani, 2001). Deterministic models were developed by Shamir & Howard (1979) and Clark et al. (1982), where the relationship between the break rate and pipe age was assumed to be exponential or linear. However, these models lose some information in the grouping of the pipes since the effect of the variables are not considered properly. Probabilistic models are developed to account for the random nature of the pipe failures, by using the covariates explicitly. There are two types of probabilistic models, either single-variate or multi-variate.

Single-variate models still rely on dividing pipes into groups at some level, based on pipe characteristics. Such models are presented in Herz (1996) and in Gustafson & Clancy (1999). Implemented in this work is the single-variate Poisson process (SVPP), a counting process considering a constant failure rate for each uniform group. The model assumes that the expected number of events is proportional to the length of the pipe and the observation time. Single-variate models are shown to be able to deal with different data amounts. However, their need for dividing the data into homogeneous groups remains a drawback, occasionally leading to lack of information in some groups. In turn the overall predictions may not be significant (Martins, 2011).

Probabilistic multi-variate models are made to predict future failure rate on the basis of pipe history, while utilising the covariates in the mathematical equations. Thereby the need for dividing the data into groups in advance is reduced. It should be highlighted that such models are very data demanding, and may not be able to give results for data sets beneath a certain level of quality and quantity. Even though the method gives a better understanding of how the parameters affect the failure occurrences, the framework becomes more complex and may require experts in statistics to run them. The proportional hazards model, PHM by Cox (1972) is one of the most common models used, where the instantaneous failure rate is linearly affected by the covariates. Another important model is the Accelerated lifetime by Eisenbeis (1994), which differs from the PHM in that the covariates act on the time to next failure and not the failure rate. Later an extended version was made, called the Weibull Accelerated Lifetime Model (WALM), where the times between failures are considered Weibull distributed (Le Gat & Eisenbeis, 2000).

The European research program, CARE-W used both the single-variate Poisson process and the Weibull accelerated lifetime model in their failure prediction model, respectively named as CARE-W Poisson and CARE-W PHM (Sægrov, 2004). The models were applied in a case study in Trondheim, Stuttgart and Lausanne. Failure data was recorded in a period of 22-25 years, and the analyses yielded that the two models mostly gave the same satisfactory results. When decreasing the data history length however, it became clear that the number of previous failures was the most sensitive parameter for failure forecasting for both of the models (Sægrov, 2005). It had earlier been demonstrated that the two models were capable of providing extra information through simulation, in cases of short data history or missing data in the records. Shortages were found in this ability, and the CARE-W therefore chose to set a minimum value for break history of 3-5 years (Sægrov, 2004). According to Renaud et al. (2007) this implies that the integrated system is adapted for fairly large utility services with reliable and comprehensive databases, including a rather long history of failures. Often, there are too few pipelines and recorded failures in the small or medium network, which means that such probabilistic models cannot be used (Renaud et al. 2007).

Linear Extended Yule Process, LEYP

Within the category of probabilistic models for water main failure prediction the Linear Extended Yule Process, LEYP, is by far, the most prominent and advanced model available. It is considered the second generation of multivariate models, after the PHM (Ugarelli & Bruaset, 2010). It was developed by the team of Cemagref in the continuation of the work of CARE-W, which actually was coordinated by SINTEF-water and environment, and of which NTNU was also partner (Sægrov, 2005). One can say that the development of LEYP was motivated by the shortages found in the failure forecasting tool of CARE-W, as presented earlier.

Le Gat (2013) gives a detailed description of the features of LEYP. The parametric nature of the model enables to predict future failures, accounting for the effect of previous failures, pipe ageing, and explanatory factors. Building upon the PHM, the model also assumes proportional hazards. The model is a linear extension of the Yule process, a classical probabilistic tool initially proposed by Greenwood and Yule (1920). Since material, diameter, length and age are considered the most important characteristics, the segments are defined as connected pipe units that are homogeneous with respect to these parameters. Hence, the data preparation is an important part of using this model.

LEYP is supposed to be a tool that combines the advantages of the non-homogeneous Poisson process, NHPP (Kleiner and Rajani 2010; Røstum 2000) and the Weibull accelerated lifetime model (WALM) of Eisenbeis (1994; 2000), but aims at avoiding their drawbacks or limitations (Le Gat, 2013). Basically, the model adds memory of the past events to the NHPP and suggests solutions to some of the main data issues associated with NHPP and WALM. Such issues include the duality of their representation due to the use of continuous time intervals versus discrete time intervals, respectively. LEYP also suggests solutions to the effect of zero-inflation, a phenomenon caused by the common over-dispersion of failure counts in a network. Clusters, i.e. failures accumulating on a limited number of pipes, will in fact leave the failure analysis characterized by a large number of zero-valued failure rates. Left-censored data and its consequence of selective survival bias are also important issues. When observing an old pipe, it is likely that due to lack of recording, we do not know the pipe history. This is referred to as left-censored data. As a direct consequence of this is, the really old pipes observed may not be representatives from their pipe group, being rather the most robust survivors. The intuitive idea of the survival selection bias is to determine the likelihood if a pipe similar to the observed has been replaced in the past, and correct the likelihood function accordingly. As stated by Scheidegger et al. (2013), LEYP is the only model so far developed that is able to deal with the survival selective bias.

Recalling the bathtub curve as discussed earlier, the ageing process of a pipe is likely to be highly affected by whether the pipe is considered "as good as new", "as bad as old", or "worse than old" after a maintenance operation. In Babykina & Couallier (2010) these assumptions were discussed thoroughly. They concluded that LEYP is one of the few models able to model imperfect repair actions, resulting in a "worse than old" condition. In many cases this is considered to be the most correct assumption. Kleiner & Rajani (2010) points out yet another essential question pertaining time-dependent covariates, i.e. factors that vary over time such as climate changes, traffic loads, repairs in nearby parts of the networks and so on (Kleiner & Rajani, 2010). Their model, I-WARP, is modified to consider three climate-related covariates related to freezing and precipitation. Babykina (2010) shows how to extend the LEYP setup to account for the practical issue of covariates that vary over time (Babykina, 2010 - PhD)

Applications and case studies

LEYP is a complex model and the usage has long been a specialist matter. Cemagref decided to develop the freeware, Casses, to enable the utilities to use the LEYP model themselves (Cemagref, 2008). The software output is the number of breaks for each pipe within a period of time in the future. Additionally, this output can be used as input in another product by Cemagref; the multi-criteria decision tool of SIROCO, which in turn will rank the pipes as rehabilitation candidates. More can be read about SIROCO in Renaud et al. (2007). Thus, in the light of IAM, these two software models form a maintenance model, where Casses represents the deterioration model and SIROCO the decision model. Casses has recently been employed by Oslo municipality, and is the failure prediction program to be used as basis for their rehabilitation plan for 2010-2020. Several tests carried out by Cemagref allow for the evolution of pipe breaks to be compared for different rehabilitation policies, yielding different conditions of the pipes after the rehabilitation. One of the tests can be found in Babykina & Couallier (2010). Additionally, the tests demonstrate that the LEYP model provides a good estimation of the number of breaks predicted (Renaud, 2012).

LEYP is also part of the acknowledged IAM research initiative AWARE-P, in the failure analysis tool, FAIL, though as a simplified version. The model can be very complex if one allows it to configure all its capabilities. Therefore only the data more commonly available, and experimentally proved to be relevant, is taken on board (Alegre et al. 2011). The complete data is reduced to pipe ID, material, length, diameter and installation date, and the date of failure. In addition to the LEYP model, the SVPP is also offered for calculating failure predictions. With a low data demand, asking for no more than past failures and pipe length, this model is simple to understand and apply. In the M.D. of Reichborn (2013), the SVPP was proven to be more suitable than LEYP for the case of Oppegård municipality, providing a data history of only 87 recorded failures (Reichborn, 2013). AWARE-P has been applied widely in Portugal, though the results from these studies are not considered in this paper.

Le Gat (2013) presents a case study on a major French water supply system of a total 627.2 km of steel core concrete pipes, comparing LEYP to the NHPP. Failure data within a one day time step is recorded between 1995 and 2008, and the number of failures is 401. These failures have occurred on 3 % of the total population, which characterizes a sample of clustering events. The training data sample (the period of data to be put into the model) is taken from 1995 to 2005, whereas the test data sample (the period for which the failures are predicted and compared) includes both the training data sample and the remaining three years between 2006 and 2008. The results show that the area under the predictive performance curve is 0.842 for LEYP and 0.815 for NHPP. Figure 2 shows the predictive performance curve for LEYP, and justifies the potential benefits that may follow from systematically using LEYP in pipe replacement decision making.

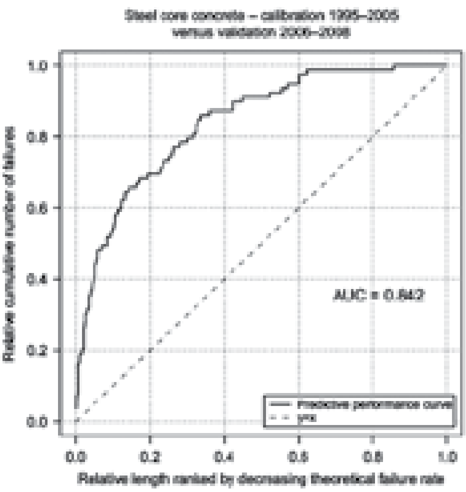

Figure 2. Predictive performance of LEYP – calibration (1995-2005) versus validation (2006-2008).

LEYP is included in a comparative analysis by Martins (2011), along with WALM and SVPP. The training data sample is taken from 2001 to 2007 and the test data sample from 2007 to 2011. From the results, WALM appears to be the best model, as it combines accurate predictions with a good ability of detecting pipes more exposed to failing. However WALM has the drawback that it is based on a Monte Carlo simulation, which can be a time-consuming process. Bringing back into mind the intended property enhancement of LEYP against WALM, it is quite unexpected that LEYP tends to overestimate the number of failures for the pipes with a failure history. Yet, it performed well when detecting pipes more prone to fail. SVPP comes out as the worst performer. It needs to be noted that the SVPP was included in the case study to represent a simpler model, which is easier to understand and to implement. Unlike its competitors it is defined by pipe categories and not covariates, causing all the pipes of one group to share the same failure rate. Martins (2011) concludes that LEYP and particularly WALM may be recommended for use in a municipality, though it is crucial to have a complete and updated pipe database properly linked to the pipe inventory (Martins, 2011).

Discussion and conclusion

In this paper, topics concerning structural reliability of a WDN have been surveyed, mainly focusing on statistical models for water main deterioration. It seems that a recurring problem with using such models is their sensitivity to data scarcity. Since many municipalities only recently have started recording, the data may provide limiting use when applied in a model. Yet, if a model is able to give some results from analyzing poor data, it may also be able to give some clue of criticality, for example with respect to clusters in the network. For such data the SVPP is suitable. Generally, analyses of good quality data can be utilized in risk assessment, while those of moderate data can give some sort of a vulnerability overview. LEYP, WALM and the NHPP are all fitted to be used for risk assessment, given a sufficient data history. In the process of applying statistical models, the municipality will become more informed about the need for data, in matters of quality and quantity, and then be able to develop appropriate routines in data collection based on this experience.

AWARE-P is one complete decision-support system of tools, in which these topics are integrated, including the LEYP and SVPP. It can be advantageous to look into this system, as it provides excellent guidelines both for running the models, as for interpreting the results. In the case studies section, the argued benefits of LEYP compared to WALM and NHPP are endorsed by Le Gat (2013), while being challenged by Martins (2011). Why LEYP is not the indisputable winner is plausibly connected to the past failures variable of a pipe, forcing the model to predict a questionable high number of future failures. LEYP and WALM are ever favored by the experts, notably for the greater municipality with a complicated pipe network. For the smaller municipalities a rather simple model is preferable, for which SVPP could be an appropriate choice as indicated earlier.

What is suggested in recent IAM strategies is that costs and efforts laid down in data recording can be seen as an investment in expenditure savings for the future. When later applying the data in a suitable framework, one receives important indicators of what actions to prioritize. It is likely to exist a junction between the costs spent on data collection and preparation, and the conceivable costs saved by using IAM maintenance tools of various levels of complexity. Utilities are recommended to choose a statistical model of a desired complexity, and consequently prepare the adequate data to run the model. As a result, the utility will receive greater ability to optimize rehabilitation in long- and short-term perspectives.

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