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Component-holistic condition assessment of water distribution networks

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ABSTRACT

The work presented herein presents an expanded methodology for imprinting the condition of an urban water distribution network (WDN). Even though the majority of past research efforts related to WDNs deal with water mains (WMs), only a small part of the research studies have considered house connections (HCs) in the analysis and very few researchers have examined how the failure of pipe fittings affect the network performance. Rehabilitation actions in a WDN related to any part of it, whether it is a pipe or a fitting, have a direct effect on the condition of the whole system. Moreover, in the overall cost of repairing a leakage, the cost of the failed unit is very small compared to the cost of the work to detect, localize and restore the problem. Thus, the effect of the fittings in the network's rehabilitation cost is equally as important as that of the pipelines. Therefore, a mathematical model simulating the overall WDN condition and targeting asset management of WDNs, which includes not only data on WMs but also data on fittings and HCs, is closer to reflecting the actual condition of the network.

Key words | asset management, data analysis, risk assessment, survival analysis, water distribution networks

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INTRODUCTION

The main challenge of the water agencies worldwide is that water distribution networks (WDNs) have already exceeded their lifetime but their complete renewal is not an economically feasible choice. Hence, the ultimate mission of each water agency that manages a WDN is to maintain their pipeline system in a condition that allows them to provide a continuous supply of high quality water to their customers, with the minimum possible amount of investment. For that reason, the management of WDNs is an always contemporary and in-demand research topic for the water industry, and mathematical models for the appraisal of deterioration, vulnerability and time-to-failure are at the core of an integrated tool for the monitoring and management of WDNs. There is, actually, extended work in the research literature related to the sustainable WDN management and to water loss reduction, which is either in the format of guidance notes by the water associations (Hunaidi 2000; Farley 2001; Lahlou 2001; Morrison *et al.* 2007) or service packages by consultant companies or autonomous tools emanating from research products (Hunaidi & Giamou 1998; Lee & Tsuda 2005; Pilcher *et al.* 2007).

The modelling of the behaviour of WDNs has been widely studied, with all documented mathematical models exclusively studying the behaviour of WDN pipe elements over time and because of aging (as either individual elements, or collectively at a street level). The aim of the development of the proposed mathematical model was to eliminate some of the drawbacks of existing methods for modelling the behaviour of WDNs, with regard to the class of data included in the analysis. In particular, as the majority of WDN-related research efforts deal with water main (WM) and only a small number of the research studies

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have added house connection (HC) pipes in the analysis, whilst very few researchers have examined how the failure of specific network components (such as the fittings) affect the network performance, it was deemed necessary to expand the list of WDN components included in a vulnerability analysis and to examine how these additional component classes affect the vulnerability of a WDN.

The presented model is not limited to traditional data records (i.e. pipe-related leakage records) but it goes a step further by introducing in the analysis additional incident and rehabilitation data (repair or replacement actions) of additional network components (such as HC and fittings) within the network owned by the water agencies. The work is part of a proactive management strategy tool, comprised of mathematical models and GIS (Geographic Information System) maps, that assists network owners to evaluate the condition of their network, to assess historical incident and risk of failure data and to prioritize the work based on the inherent risks and costs of action (Agathokleous 2015). Rehabilitation of WDNs is necessary not only because of the inefficiencies of the WM pipes but it is also needed because of the failure of HC pipes and fitting elements. Further, since the cost to renew a damaged component is negligible relative to the total amount that will cost a pipeline-related rehabilitation action, it is prudent to hierarchically rank such action at a higher return-on-investment value. Therefore, a mathematical model simulating the actual condition of a pipeline system and targeting asset management of WDNs should include not only WM data but also data on fittings and HC.

STATE OF KNOWLEDGE

There is an extensive range of tools and applications for the modelling, monitoring and management of urban WDNs. However, the majority of these works deal with only WM pipelines and none of them include the fitting components into the analysis. Presented below is an indicative sample of past research studies and of available tools for the modelling of WDNs.

The works of Kanakoudis & Tsitsifli (2007, 2011), Tsitsifli & Kanakoudis (2010) and Tsitsifli *et al.* (2011) targeted the development of a model that could correctly classify water distribution pipes, and the definition of WM pipe characteristics. A model that targeted specific WM parts of WDN, presented by Jun *et al.* (2008), identifies pipes and valves of high importance within WDNs. The model consists of two failure analysis methodologies, pipe-by-pipe (PPFA) and valve-by-valve (VVFA), which were developed to prioritize the importance of pipes and valves in a water distribution system. The model is based on a matrix algorithm that can be easily implemented to any WDN and analyses that can be efficiently performed regardless of the size of the water distribution system. Results of PPFA and VVFA can be used to prioritize the order of maintenance of a water distribution system. Christodoulou *et al.* (2008) presented an integrated decision support system (DSS) for arriving at 'repair-or-replace' decisions, as part of a long-term WM system asset management program that could be used by the authorities for improving the reliability of their WDNs. Park *et al.* (2008) presented two models, one for the pipes' failure rate and one for the estimation of the optimal replacement time of pipes in a WDN. The research effort examined the performance of the log-linear rate of occurrence of failures and the power law process by the use of maximized log-likelihoods for different modelling approaches, in which the method of observing failures differs. Subsequently, Park *et al.* (2011) presented more sophisticated proportional hazard models for the time period within successive failures of water mains, which included the time-dependent effects of covariates. This methodology provides more information on the status of the pipe breaks than the one in Park *et al.* (2008). This extra information pertains to the main effects of the factors of failure, to the changes in the condition of the pipes as more breaks occur and to the survival probabilities of the pipes for each type of break.

Bentes *et al.* (2011) put forward a decision support model targeting the condition level of WDNs, and a method for assessing the vulnerability of WDNs. Their suggestion is based on three water pipe network examples, focusing on tracing the weakest WM parts of the distribution system and giving guidance for improving the condition of the network. Xu *et al.* (2013) presented a mathematical model that uses two data-driven techniques: the Genetic Programming and the Evolutionary Polynomial Regression. The model uses data concerning the recorded pipe break incidents for the pipelines of the specific network. The results showed that the model has a great capability to obtain reliable predictions and hence it can be used to prioritize the rehabilitation of the pipes. Moving a step forward, Xu *et al.* (2013) presented the development of a DSS that is used in the deployment of cost-effective pipe maintenance plans for WDNs. The model comprises of a prediction tool which has been developed using genetic programming and an economically optimal pipe replacement tool. A research report published by Grigg *et al.* (2013) of the Water Research Foundation addressed the need for the rehabilitation of WDNs and presented a tool for assessing risk and for organizing data to aid in capital investment planning for WM pipelines. In addition, methodologies to assess whether and how to rehabilitate or replace a pipeline by integrating information about cost of failure into asset management decisions were offered.

A model studying the behaviour of WDN under abnormal conditions, presented by Christodoulou & Fragiadakis (2015), discussed how a repair rate metric put forward by the American Lifelines Alliance guidelines underestimates the seismic effects on the vulnerability of a network, and recommended how the damaged and undamaged network states should be included in the calculation of a pipe's probability of failure. Finally, Muranho *et al.* (2014) presented a model that identifies problematic zones within a WDN by the use of Technical Performance Indexes. The model, which comprises of analysis tools and a pressure-driven simulation model, can be used for the performance assessment of a WDN during WM pipe bursts or firefighting scenarios.

As mentioned above, there are research works that have incorporated data related with the HC pipes in their analysis. Christodoulou *et al.* (2009), for example, worked on data-driven modelling (DDM) techniques, such as artificial neural networks and neurofuzzy systems. These DDM techniques allow the inclusion of multiple risk factors in the analysis, make it more complicated but at the same time more accurate and realistic. Moving a step forward, Agathokleous (2015) exploited these findings for the development of a survival analysis mathematical model that simulates a WDN's behaviour. The data used are associated with failure data of WM and HC pipes. The work by Christodoulou *et al.* (2012) presented a spatio-temporal analysis model that can be used as a DSS for increasing the efficiency of maintenance strategies related to WDN. The suggested model utilizes classical statistical tools, neurofuzzy systems and GIS-based spatio-temporal clustering and visualization techniques. The analysis allows for spatio-temporal clustering and pattern recognition, it helps devise repair-or-replace strategies and it reinforces the belief that intermittent supply increases the vulnerability of WDN.

Work that utilizes data relating to the HC pipes and the fitting components of the WDN, in addition to the traditionally used data (WM pipes), has been presented by Agathokleous (2015) and Agathokleous & Christodoulou (2016a, 2016b). The main section of this work focuses on modelling a WDN's behaviour, by comparing various models that combine different levels of data. The results presented herein are part of the aforementioned work.

CASE STUDY AND DATASET

The data on which this research work is based originates from the Water Board of Nicosia (WBN) and relates to the WDN of the said city. The pipeline system managed by the WBN is divided into 60 district metered areas. According to the latest known data, it requires for its operation about 19,300,000 m^3 of water per year, while the maximum daily demand in the summer is around 63,700 m^3. The minimum consumption per day is 39,000 m^3, while the daily average water consumption is 52,700 m^3. The WBN has in operation about 112,000 water meters and the total length of WM pipes more than 1,400 km. The WBN's WDN is remotely monitored through a supervisory control and data acquisition (SCADA) system consisting of 32 electronic stations across the network, which continually collect and transmit operational information. Apart from the SCADA telemetry system database, the WBN has recently developed and put in operation a database where all information related with the network operations are stored. Finally, all leakage incident data reports since 2003 had been maintained in a specially designed database.

The data utilized for the development of the proposed methodology covers a time period of approximately eight years (01/01/2003 to 31/12/2010, with a small gap in recorded data from 01/08/2009 to 31/12/2009). The dataset includes 36,434 incidents in total.

MATHEMATICAL MODELLING

Survival analysis

Survival analysis is a branch of statistics dealing with deterioration and failure, expressing the probability of a subject's survival over time. It involves the modelling of the elapsed time between an initiating event and a terminal event (Klein & Moeschberger 1997; Hintze 2007), and it denotes the probability that a subject survives past a point in time, given that certain events affecting its condition state have occurred in the past.

In the case of WDNs, an initiating event is represented by the date of pipe installation, a near-terminal event is represented by the date of pipe repair and a terminal event is represented by the date of a pipe replacement. The mathematical model estimates the reliability of a system and its lifetime, subject to multiple risk factors. It aims to analyse the effect of these risk factors on the system's lifetime and the probability of survival, and on the expected mean time to failure (TTF) of each individual part of the system (Lee & Wang 2003; Hintze 2007). The data values used in the analysis are a mixture of complete and censored observations, where 'censored' is data with unknown initiating or terminal events.

There are two main reasons for the selection of survival analysis as the main tool for the development of analytical models for pipe degradation:

1. The first has to do with the nature of the available data. Computerization for the records on leakage incidents for WBN was started in 2003 and until that point in time there are no available data records. One of the survival analysis features is that the existence of a complete dataset is not a prerequisite for the analysis, since survival analysis has the ability to reach a reliable prediction by making assumptions about the missing data, which is then improved with the addition of new data points.
2. The second relates to the behaviour of networks during aging. The initial application of survival analysis was in biological sciences to simulate the effect of different diseases on the human organism through the passage of time. WDNs behave the same way. Over time and with the increase of failure incidents in a pipe system, the condition of the WDN worsens. For this reason, survival analysis models were applied for they are most suitable in successfully simulating the behaviour of the WDN's condition over time and of the effect of events of any type that could occur in the WDN.

The applied mathematical model estimates the survival function by use of the non-parametric Kaplan & Meier (1958) estimator (Equation (1)):

$$\hat{s}(t) = \begin{cases} 1 & \textit{if} \quad T_{\min} > T \\ \prod\limits_{T_{\min} \le T_i \le T} \left[1 - \dfrac{d_i}{r_i} \right] & \textit{if} \quad T_{\min} \le T \end{cases} \qquad (1)$$

where T is the elapsed time until the occurrence of a specified event; i is an index; D_t is the set of all failures (deaths) that occur at time T_t and d_t is the number of deaths in this set; R_t is the set of all individuals that are at risk immediately before time T_t and r_t is the number of individuals in this risk set. $T_{\min}$ refers to a minimum time below which failures are not considered (often used when data are left truncated).

The hazard rate (or conditional failure rate) is a metric which is used for identifying the appropriate probability distribution of a particular mechanism (Hintze 2007). During survival analysis it is very useful to compare the hazard rates of groups of similar attributes within the examined dataset, by employing the hazard ratio (HR), which is a metric that estimates the relative risk of an event.

The proposed mathematical model estimates the HR by use of the Cox semi-parametric proportional hazards model (Equation (2)) by Cox (1972):

$$HR\,(t, x, \beta) = e^{\beta(x_1 - x_0)} \qquad (2)$$

where x_i is the predictor variable; e^{β} is the instantaneous relative risk of an event, at any time, for an individual with an increase of 1 in the value of the covariate compare with another individual, given both individuals are the same on all other covariates.

A more detailed discussion on the applicability of the survival analysis method to WDNs and to deterioration/failure modelling, coupled with related case-studies, can be found in Christodoulou (2010) and Agathokleous & Christodoulou (2016a, 2016b).

Classes of pipes and categories of analysis

The different component part types of a WDN, which were used in the analysis, are the pipe and fitting elements. The data stratification was based on three pipe classes: WM ('water main'); HC ('house connection'), and C ('couple'). The 'couple' class is the coupling of the first two classes. In essence, the number of records in the C class is the sum of the WM incidents plus the HC incidents.

Further, the mathematical analysis presented herein consists of two model categories: (a) Pipeline model and (b) Pipeline Network model. Each one of the categories consists of models of the three pipeline classes mentioned above. The 'Pipeline' models include only the data associated with the pipe part type. The 'Pipeline Network' models go one step further by introducing data associated with the fittings, which are used to connect together the pipes of the network. This analysis category is considerably more accurate in analysing the condition of the WDNs compared to the 'Pipeline' analysis.

The data currently used for modelling the condition of WDNs are those used by the 'WM – Pipeline' model.

ANALYSIS, RESULTS AND DISCUSSION

Statistical analysis

The dataset that has been used for the analysis presented herein is presented in Table 1.

It is clear that the incidents related to the HC class constitute the majority of the dataset, which confirms the general perception that HC are the parts of the WDNs suffering from failure incidents. Furthermore, the number of incidents associated with the fitting components and the HC pipes is much higher than those associated with WM pipes. This fact supports the suggestion of this work, that data related with fittings and HC pipes should be included in the mathematical models simulating the overall WDN condition.

Table 1 | Distribution of the dataset's incidents into the 'part type', 'class' and 'action' fields

Class	Part type	Repair (number of incidents)	Replacement (number of incidents)	Total	
HC	HC (pipes)	28,760	2,853	31,613	32,120
	HC (fittings)	5	502	507	
WM	WM (pipes)	510	3,214	3,724	4,314
	WM (fittings)	14	576	590	
Total		29.289	7,145		36.434

Also, more than 90% of the 'HC pipes' incidents associated with the 'Repair action', while the percentage of the 'WM pipes' incidents for the same action does not exceed 14%. The corresponding number of incidents for the fitting elements is very low because their replacement is cost effective compared to their repair.

Survival analysis

The first part of the results presented below relates to the WM class models, while the second presents the analysis outcome for the models associated with the HC class. The final part presents the results of the analyses which have been made for comparison purposes between the WM and HC classes. The results are presented by means of graphs, whose horizontal axis denotes the TTF, in days while their vertical axis denotes survival probability or hazard rate in the form of a ratio (0.0–1.0).

WM class

Figure 1 illustrates the survival plots of the models associated with the WM class. Figure 1(a) corresponds to the survival plot for the 'Pipeline' model. The survival probability is reduced by 53% during the first five years of the pipes' life. The rate of decrease in the survival probability is low up to the 38th year of the model's lifespan while after that point it suddenly increases. A pipe's lifetime has a probability of 18% to exceed this age.

Figure 1(b) corresponds to the survival plot for the 'Pipeline Network' model. The line of the survival probability is similar to that of Figure 3(a). It is slightly shifted downwards, indicating that the inclusion of the fitting components data has worsened the model's condition. The survival probability of the model is reduced by 50% during the first five years of their life, with an element's lifetime having a probability of 15% to exceed this age.

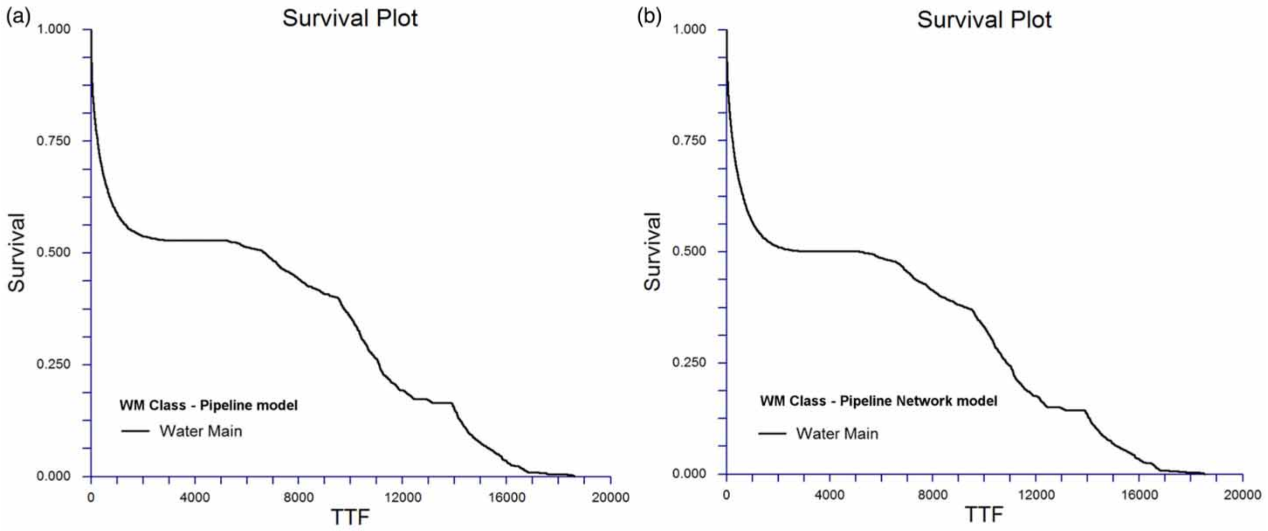

Figure 1 | Survival plots of the models associated with the WM class.

Figure 2 corresponds to the hazard rate plot for the 'Pipeline Network model'. The first observation is that the hazard rate plot does not start from point zero. The subsequent failure of a pipe that is located in the same street will add to the data a complete incident whose age is equal to the difference in time between the two successive complete incidents. Thus, as the number of element failure incidents in a street that have short time intervals between them increases, the phenomenon in which the hazard rate does not start from zero becomes more likely.

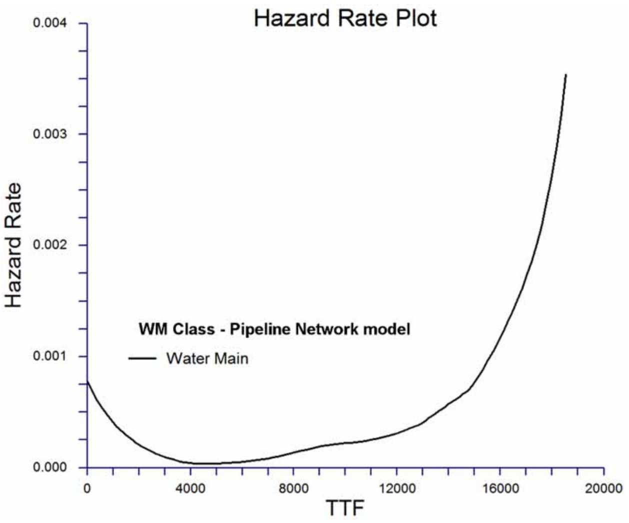

Figure 2 | Hazard rate plot of the 'Pipeline Network model' (WM class).

The hazard rate plot illustrates that during the first 18 years of a pipe's life, the probability of mortality for the model is very low and it will probably exceed the 35 years of lifetime. The hazard rate is dramatically increased 37 years after a pipe's installation.

Figure 3 corresponds to the survival and hazard rate plots for the Part Type variable of the 'Pipeline Network model' (WM Class). The survival probability of the 'Pipe' and 'Fitting' is almost the same. The probability for a component's lifetime to overcome 30 years is only 23%. Hazard rate curves illustrate that pipe elements have lower hazard rate levels that fitting elements between the 16th and 35th year of life, while after the 37th year the hazard rate is dramatically increased for both part types.

HC class

Figure 4 illustrates the survival plots of the models associated with the HC class. Figure 4(a) corresponds to the survival plot for the 'Pipeline' model. The survival probability is reduced only by 5% during the first five years of the life of the elements. The drop in the survival probability is low up to the 48th year of the model's lifespan, and it suddenly increases after that point. The component's lifetime has a probability of 66% to exceed this age.

Figure 4(b) corresponds to the survival plot for the 'Pipeline Network' model. The survival probability of the model

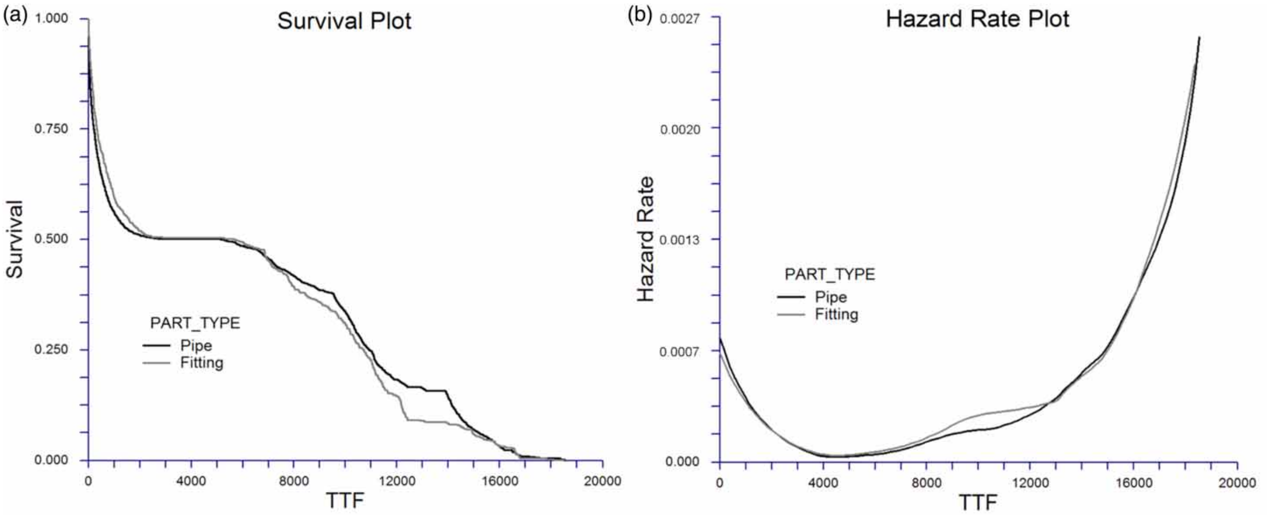

Figure 3 | Survival and hazard rate plots for the part type variables of the 'Pipeline Network model' (WM class).

is slightly lower compared to that of Figure 5(a). It is reduced only by 6% during the first five years of the element's life. The drop of the survival probability is low up to the 48th year of the model's lifespan while after that point it suddenly increases. The elements' lifetime has a probability of 60% to exceed this age. Hence, fitting components data have negatively affected the model's condition.

Figure 5 corresponds to the hazard rate plot for the 'Pipeline Network model' of the 'HC class'. The hazard rate plot illustrates that during the first 30 years of its life, the probability of mortality for the model is very low and it will probably exceed the 38 years of lifetime. The hazard rate dramatically increases 41 years after a pipe's installation.

The analyses presented in Figure 4 show that the introduction of data associated with the fitting components is negatively affecting the survival probability of WDNs. This observation is confirmed by Figure 6(a), which corresponds to the survival plot for the Part Type variable of the 'Pipeline Network model' (HC class). The rate of decrease in the

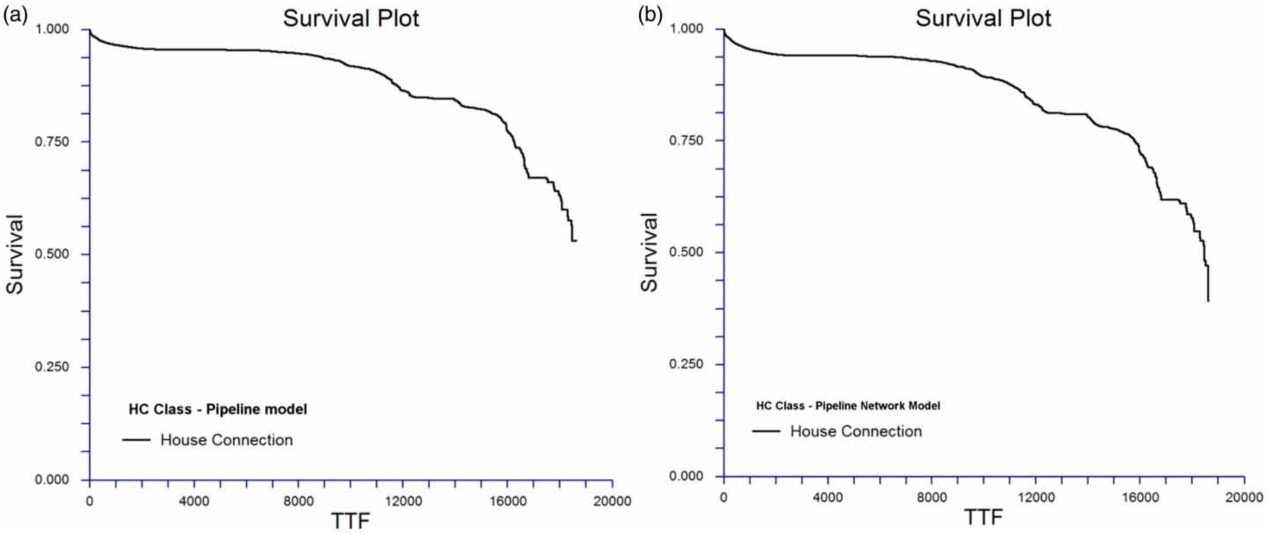

Figure 4 | Survival plots of the models associated with the C class.

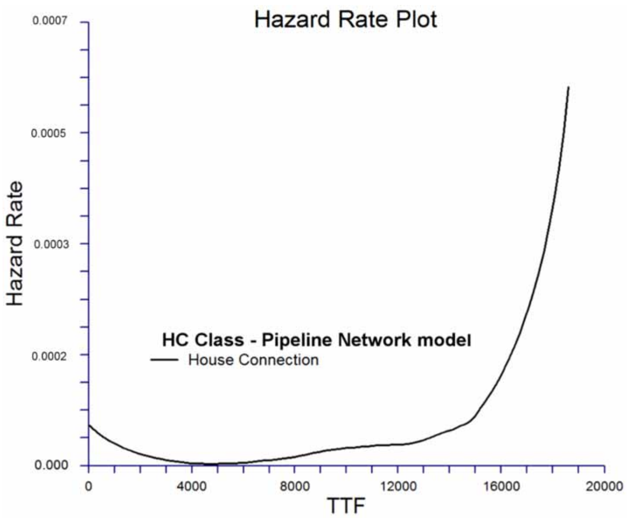

Figure 5 | Hazard rate plot of the 'Pipeline Network model' (HC class).

survival probability for a 'Fitting' at the early stages of its lifespan is much higher compared to that of a 'Pipe'. The drop in the survival probability for the pipe is low up to the 48th year of its lifespan when the probability to survive is 67%. For the same lifespan, the survival probability of the 'Fitting' is less than 5%.

Figure 6(b) corresponds to the hazard rate plots for the Part Type variable of the 'Pipeline Network model' (HC class). Hazard rate curves illustrate that pipe elements have lower hazard rate levels than fitting elements. The hazard rate of pipes is low up to the 41st year of its lifespan while the hazard rate of fittings is low up to the 25th year.

'C' class

Figure 7 illustrates the survival plots of the models associated with the 'C class'. Figure 7(a) corresponds to the survival plot for the 'Pipeline' model while Figure 7(b) corresponds to the survival plot for the 'Pipeline Network' model.

As shown in Figure 7(a), the survival probability of the model is reduced by 13% during the first five years of its life. The declining rate of the survival probability is low up to the 38th year of the model's lifespan while after that point it suddenly increases. The lifetime of the components has a survival probability of 71%.

Figure 7(b) corresponds to the survival plot for the 'Pipeline Network' model. The shape of the model's survival line is similar to that of the 'Pipeline' model. The survival probability of this model is reduced only by 17% during the first five years of their life. The decline rate of the survival probability is low up to the 38th year of the model's lifespan while after that point it suddenly increases. The components' lifetime has a probability of 65% to exceed this age.

Figure 8 corresponds to the hazard rate plot for 'Pipeline Network model' of the 'C class'. The hazard rate plot illustrates that during the first 30 years of its life, probability of

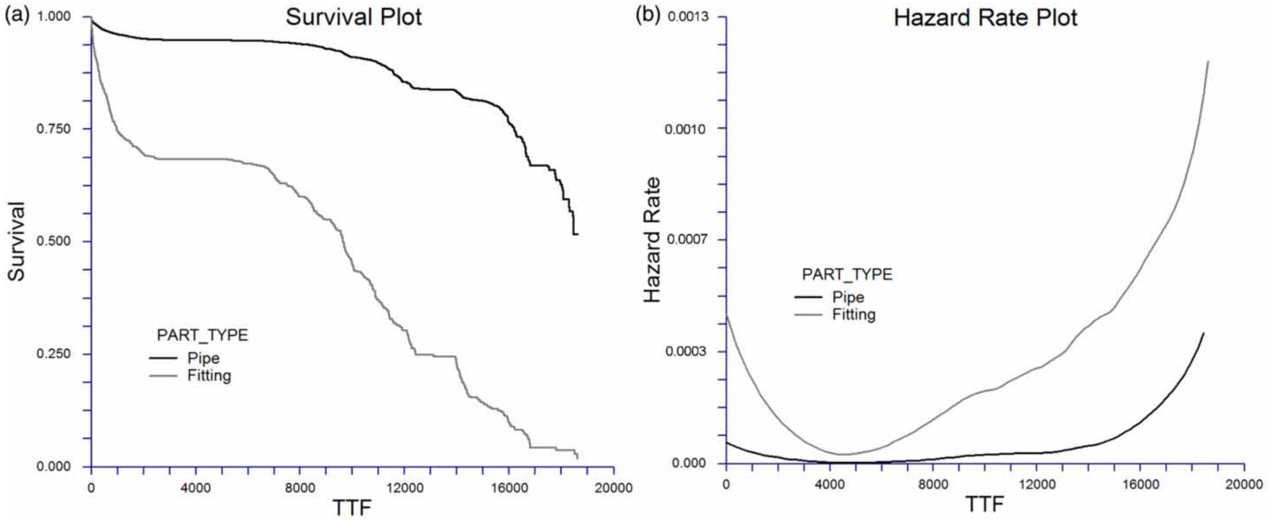

Figure 6 | Survival and hazard rate plots for the part type variables of the 'Pipeline Network model' (HC class).

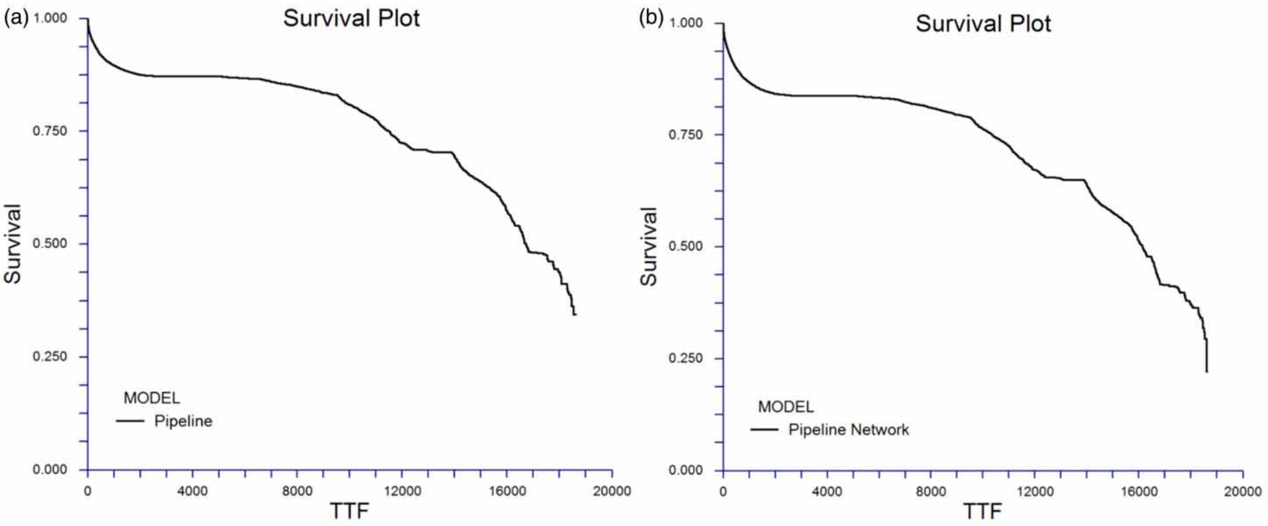

Figure 7 | Survival plots of the models associated with the C class.

mortality for the model is very low and the hazard rate dramatically increases 40 years after its installation.

Figure 9 corresponds to the survival and hazard rate plots for the Part Type variable of the 'Pipeline Network model' (C class). Figure 9(a) illustrates that survival probability of the pipe is the highest. The rate of decrease in the survival probability for a fitting at the early stages of its lifespan is much higher compared to that of a pipe. A pipe has a high probability to exceed the 45 years of lifetime while a fitting does not. Figure 9(b) illustrates the hazard rate curves of the pipe elements have lower hazard rate levels that fitting elements.

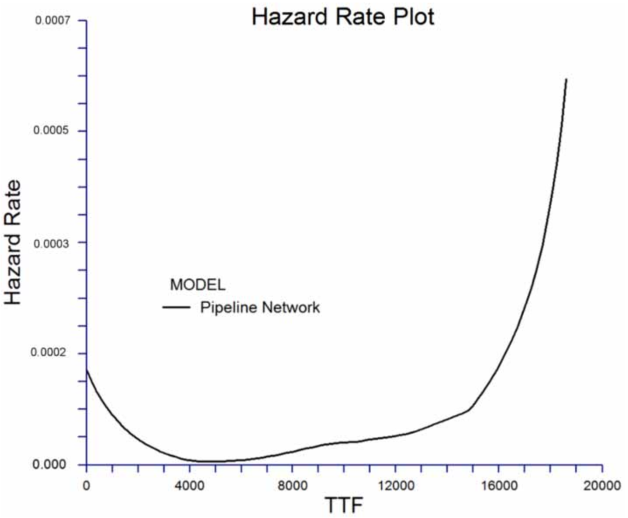

Figure 8 | Hazard rate plot of the 'Pipeline Network model' (HC class).

The conclusion drawn from the previous figures is that the development of a model that simulates the WDN, using data associated only with pipe components, results in optimistic appraisals and that the imprint of the WDN is not accurate because of the absence of other WDN components from the analysis. This is confirmed by the results of all the different models (WM, HC and C class models) presented herein. Two further conclusions that can be extracted from the results presented above are: (a) the 'C class' survival analysis results are very close to that of the 'HC Class' (this is due to the fact that the volume of data associated with the HC class is much larger compared to that of the WM class); and (b) 'WM class' components seem to be more vulnerable over time compared to 'HC class' components, and fitting components seem to be more vulnerable compared to pipes.

This last conclusion, though, is not accurate. The reason that 'WM Class' components are more vulnerable over time compared to 'HC Class' components is associated with the fact that the majority of the 'HC Class' incidents are associated with the 'Repair action' (Censor event), while the majority of the 'WM Class' incidents are associated with the 'Replacement action' (Terminal event). As a result, the survival curve of the 'HC Class' is maintained at high survival probability levels over time. Despite this, the survival

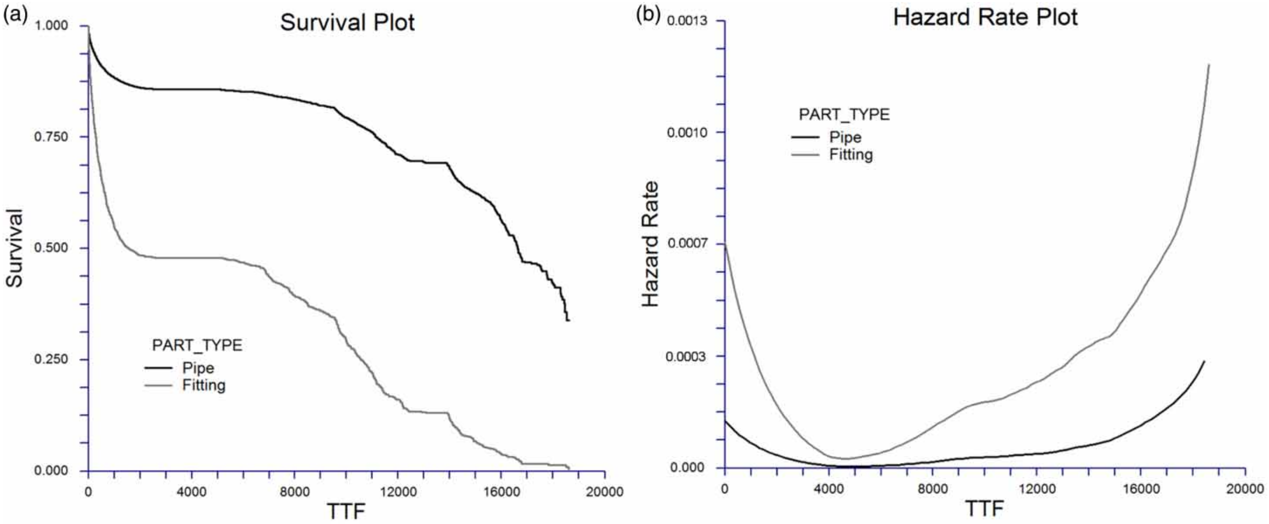

Figure 9 | Survival and hazard rate plots for the part type variables of the 'Pipeline Network model' (C class).

curves illustrate that the variation of condition for the different components through time has a different profile. This suggests that mathematical models targeting asset management of WDNs should include not only WM data but also data on fittings and HC.

CONCLUSIONS

The rehabilitation actions in an urban WDN, whether they are related to pipes or fittings, have a direct effect on the condition of the whole water distribution system. Moreover, the effect of the fittings in the network's rehabilitation cost is equally as important as that of the pipelines. For that reason, the work presented in this paper suggests that the simulation of a WDN's condition should, apart from the WM components, include the HC class and fitting components.

The results showed that the number of incidents associated with the 'Fittings' and 'HC pipes' components is significantly high compared with that associated with 'WM pipes'. Also, the deterioration through time of the different components follows a different pattern. These observations support the suggestion that mathematical models simulating the WDN behaviour through time and focusing on the management of WDNs, apart from the WM data, should also include data associated with fittings and HC. Therefore, enrichment of the mathematical model with data pertaining to fitting components and HC pipes enhances the simulation of the overall WDN condition, bringing such condition appraisals closer to reflecting the actual condition of the network.

The work presented herein is part of a proactive management strategy that assists the network owners in evaluating the condition of their network, assesses historical incident and risk of failure data and prioritizes the work based on the inherent risk. The ultimate goal is to devise mathematical models to extract useful information and conclusions on the study's WDN. The results showed that the WBN is facing more leakage incidents on the HC than on the WM. The developed mathematical tool will help compose priority lists for the maintenance of pipelines (repairs and replacements) and eventually for the arrival at a more economical and efficient management of the water supply networks.

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REFERENCES

Agathokleous, A. 2015 Sensor-based sustainable management of urban water distribution networks utilizing survival analysis modelling. PhD Thesis, University of Cyprus, Nicosia, Cyprus.

Agathokleous, A. & Christodoulou, S. 2016a An expanded methodology for imprinting the condition of an urban water distribution network. In: *Proceedings of the 2nd EWaS International Conference 2016*, June 1–4, Platanias, Crete, Greece.

Agathokleous, A. & Christodoulou, S. 2016b Vulnerability of urban water distribution networks under intermittent water supply operations. *Water Resour. Manage.* **30** (13), 4731–4750.

Bentes, I., Afonso, L., Varum, H., Pinto, J., Varajão, J., Duarte, A. & Agarwal, J. 2011 A new tool to assess water pipe networks vulnerability and robustness. *Eng. Fail. Anal.* **18** (7), 1637–1644.

Christodoulou, S. 2010 Water network assessment and reliability analysis by use of survival analysis. *Water Resour. Manage.* **25** (4), 1229–1238.

Christodoulou, S. & Fragiadakis, M. 2015 Vulnerability assessment of water distribution networks considering performance data. *J. Infrastruct. Syst.* **21** (2), 04014040.

Christodoulou, S., Charalambous, B. & Adamou, A. 2008 Rehabilitation and maintenance of water distribution network assets. *Water Sci. Technol. Water Supply* **8** (2), 231–237.

Christodoulou, S., Deligianni, A., Aslani, P. & Agathokleous, A. 2009 Risk-based asset management of water piping networks using neurofuzzy systems. *Comput. Environ. Urban Syst.* **33** (2), 138–149.

Christodoulou, S. E., Gagatsis, A., Agathokleous, A., Xanthos, S. & Kranioti, S. 2012 Urban water distribution network asset management using spatio-temporal analysis of pipe-failure data. In: *Proceedings of 14th International Conference on Computing in Civil and Building Engineering*, June 27–29, Moscow, Russia.

Cox, D. R. 1972 Regression models and life-tables. *J. R. Stat. Soc. B Stat. Methodol.* **34** (2), 187–220.

Farley, M. 2001 *Leakage Management and Control: A Best Practice Training Manual.* World Health Organization, Geneva, Switzerland.

Grigg, N. S., Fontane, D. G. & Van Zyl, J. 2013 *Water Distribution System Risk Tool for Investment Planning.* Water Research Foundation, EPA, USA.

Hintze, J. 2007 *NCSS 2007.* NCSS, LLC. Kaysville, Utah, USA.

Hunaidi, O. 2000 Detecting leaks in water-distribution pipes. *Constr. Technol. Update* **40**, 1–6.

Hunaidi, O. & Giamou, P. 1998 Ground penetrating radar for detection of leaks in buried plastic water distribution pipes. In: *Proceedings of Seventh International Conference on Ground-Penetrating Radar.* May 27–30, University of Kansas, Lawrence, Kansas, USA, 2, pp. 783–786.

Jun, H., Loganathan, G. V., Kim, J. H. & Park, S. 2008 Identifying pipes and valves of high importance for efficient operation and maintenance of water distribution systems. *Water Resour. Manage.* **22** (6), 719–736.

Kanakoudis, V. & Tsitsifli, S. 2007 Reliability assessment and data classification using discriminant functions and factor analysis. In: *Proceedings of the Water Loss 2007*, September 23–26, Bucharest, Romania, vol. III, pp. 836–845.

Kanakoudis, V. & Tsitsifli, S. 2011 Water pipe network reliability assessment using the DAC method. *Desal. Water Treat.* **33** (1–3), 97–106.

Kaplan, E. L. & Meier, P. 1958 Nonparametric estimation from incomplete observations. *J. Am. Stat. Assoc.* **53** (282), 457–481.

Klein, J. P. & Moeschberger, M. L. 1997 *Survival Analysis: Techniques for Censored and Truncated Data.* Springer, New York.

Lahlou, Z. M. 2001 *Leak Detection and Water Loss Control.* National Drinking Water Clearinghouse, West Virginia University, USA.

Lee, E. T. & Wang, J. W. 2003 *Statistical Methods for Survival Data Analysis,* 3rd edn. John Wiley & Sons Ltd, New York.

Lee, J. R. & Tsuda, H. 2005 Fiber optic liquid leak detection technique with an ultrasonic actuator and a fiber Bragg grating. *Opt. Lett.* **30** (24), 3293–3295.

Morrison, J., Tooms, S. & Rogers, D. 2007 *Guidance Notes on District Metered Areas.* International Water Association, London, UK.

Muranho, J., Ferreira, A., Sousa, J., Gomes, A. & Sá Marques, A. 2014 Technical performance evaluation of water distribution networks based on EPANET. *Proc. Eng.* **70**, 1201–1210.

Park, S., Jun, H., Kim, B. J. & Meier, P. 2008 Modelling of water main failure rates using the log-linear ROCOF and the power law process. *Water Resour. Manage.* **22** (9), 1311–1324.

Park, S., Jun, H., Agbenowosi, N., Kim, B. J. & Lim, K. 2011 The proportional hazards modelling of water main failure data incorporating the time-dependent effects of covariates. *Water Resour. Manage.* **25** (1), 1–19.

Pilcher, R., Hamilton, S., Chapman, H., Field, D., Ristovski, B. & Stapely, S. 2007 *Guidance Notes on Leak Detection and Repair.* International Water Association, London, UK.

Tsitsifli, S. & Kanakoudis, V. 2010 Predicting the behaviour of a pipe network using the 'critical Z-score' as its performance indicator. *Desalination* **250** (1), 258–265.

Tsitsifli, S., Kanakoudis, V. & Bakouros, I. 2011 Pipe networks risk assessment based on survival analysis. *Water Resour. Manage.* **25** (14), 3729–3746.

Xu, Q., Chen, Q., Li, W. & Ma, J. 2011 Pipe break prediction based on evolutionary data-driven methods with brief recorded data. *Reliability Engineering & System Safety* **96** (8), 942–948.

Xu, Q., Chen, Q., Ma, J. & Blanckaert, K. 2013 Optimal pipe replacement strategy based on break rate prediction through genetic programming for water distribution network. *J. Hydro-Environ. Res.* **7** (2), 134–140.

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