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PAPERS

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Reports paint grim picture of climate change and meter condition

A new report by eminent scientists in Australia, commissioned as part of a review of funding to drought-hit farmers, has warned that the country will be hit by a ten-fold increase in heatwaves and that droughts will nearly double in frequency due to climate change, and a separate document warns that many irrigation meters are badly in need of repair.

The projections suggest rainfall will continue to decline. The country's agriculture minister Tony Burke described the climate change report as 'alarming'. He added: 'Parts of these high-level projections read more like a disaster novel than a scientific report.'

This work comes a day after another report from Professor Ross Garnaut warned that Australia had to adopt a greenhouse gas emission trading scheme or face the destruction of protected sites such as the Great Barrier Reef, the Kakadu national park and the Murray-Darling basin. Prime minister Kevin Rudd dubbed the analysis by the Bureau of Meteorology and Commonwealth Scientific and Industrial Research Organisation (CSIRO) 'very disturbing'.

The report warned that not only would droughts happen more often but that twice the current area would now be affected. The area of the country affected by unusually hot seasons could increase from 5% a year to up to 95%, it found.Extreme conditions previously thought to occur every 20 to 25 years could happen as often as every two years.

Another report, from Sinclair Knight Merz, has warned that meters used to monitor water use in rural areas of Australia are so badly in need of repair that AUD$650 million ($578.9 million) is required to upgrade them before it is possible to determine accurately the amounts being withdrawn from rivers and boreholes.

Review of rating and metering effectiveness

Anna Walker, chief executive of the Healthcare Commission, has been officially appointed to lead the independent review of household charging and metering for water and sewerage services.

The review was announced by Defra earlier this year in its 'Future water strategy' document. Ms Walker's remit includes examining the current system and assessing the effectiveness and fairness of current and alternative charging methods, considering social, economic and environmental concerns, making recommendations on any actions to be taken to ensure England and Wales have a sustainable and fair system of charging, which could include changes to current legislation and guidance.

The assessment will look at:

- the effectiveness and fairness of charging methods taking into account current metering trends and the use of the ratable value (RV) system
- the costs and benefits of metering, taking into account all costs including the full social cost of carbon
- the effectiveness of different types of innovative tariffs in helping vulnerable households and/or reducing demand
- the effectiveness of measures to manage affordability concerns for low-income households
- the impact on health and health inequalities of current and alternative charging methods
- the effectiveness of measures to incentivise people to pay for water and sewerage services and minimise the impact of bad debt on those that do pay, excluding disconnection.

GLOBAL: CRISIS MANAGEMENT GUIDELINES

ISO has published new guidelines on managing drinking water supplies during crises. The ISO International Workshop Agreement IWA6, 'Guidelines for the management of drinking water utilities under crisis conditions', is the first of its type backed by international consensus and constitute the first stage of a comprehensive suite of standards for water security.

IWA6 provides a framework for the management of water crises and proposes tools and means for ensuring drinking water security, and models for water distribution systems security. The main topics covered are water security products and methods, optimized modes (for instance for predicting and dealing with contamination) and technologies and processes for managing a water security event.

AFRICA: ACC AND USAID TEAM TO PROVIDE SAFE DRINKING WATER

The American Chemistry Council (ACC) and USAID have joined to help provide safe drinking water to Ghana, Mali and Niger.

The groups have announced a new two-year, $1.3 million partnership to implement household-based drinking water programmes in communities facing some of the most severe poverty and health challenges in the world.

The USAID-led programmes use chlorine-based disinfection and safe water storage techniques to help reduce waterborne disease and improve quality of life.
Working with local partners in each country, the programmes are aimed at reaching an estimated three million people over two years.

water
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Main break prediction, prevention and control

Breaks in water mains can disrupt services, increase costs and have a negative impact on customer perceptions. Neil Grigg and Traci Case summarise AwwaRF Report 91165, outlining the prediction, prevention and control of water main breaks.

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Water main breaks are a serious problem around the world. In the US, for example, industry surveys show that utilities suffer some 250,000 to 300,000 main breaks per year or on the order of one break per year for each kilometer of buried water main. Some countries experience higher rates of breaks than these, depending on their risk-acceptance policies.

Although estimates of the consequences of these breaks are difficult to make, the indication is that in the US they cause high levels of direct damages and indirect consequences that include loss of service, disruption, and loss of customer confidence. In addition, weak water mains cause water loss, reduced pressure and higher energy costs. To avoid or mitigate these losses, utilities should assess the condition and risk of main breaks and make capital decisions about repair, rehabilitation, and renewal of individual pipes.

As utilities prepare business cases for pipe renewal in their capital budgets, they must assess the risk of main failures so they can estimate the return on investment of renewal projects. Unfortunately, it is difficult for utilities to calculate return on investment with confidence and to decide which pipes to renew because pipes deteriorate out of view (underground) and utilities cannot accurately assess condition or predict probability of main failures. Because utilities are conservative and customers are cost-conscious, many utilities wait for problems to develop before investing in rehabilitation or replacement. Therefore, main renewal in the US proceeds at a slow rate.

To overcome this problem, utilities require more than just knowing that they have an infrastructure problem. They must be able to anticipate pipe failures, both for classes of pipe in the aggregate and for individual water mains. Assessing risk of pipe failure in the aggregate helps with general planning but not with selecting individual pipes to renew. Selecting individual pipes to renew requires risk analysis using an effective main break prediction model, but no effective model is available yet, despite a great deal research in this area. This AwwaRF report traces the efforts of researchers to develop an effective main break model and describes the current state-of-practice.

Status of main break prediction research

A body of research in the area of main break prediction has shown that analytical methods can be developed but it is difficult to verify or validate them because databases are deficient.

A recent AwwaRF report noted, 'Because of variations in the methods of reporting data and the difficulties of cross-correlation, it is recommended that an effective method of recording and organizing pipe asset and failure data be used to capture this variation. Until data can be represented in this manner, care must be taken in interpreting and comparing failure rates' (Burn, et. al., 2005).

Utilities have known for years that they should assess condition and anticipate failure of water mains. Research into factors causing main failures began around 1980 and has focused on data management and analytical methods. In recent years, many utilities have begun to keep main break records, in various forms. However, datasets lack standard methods and quality control programmes.

Data management requires

standardization of break prediction methods and protocols to collect and manage data. While emerging enterprise software systems help with data collection, standard methods are still missing. Until water main break databases become more reliable and standardized, utilities will not have confidence in main break prediction models. Therefore, improving data protocols is the most urgent need to advance main break risk analysis.

Risk factors for main breaks

The link between main break models and risk factors is in the predictor variables that show risk of breaks. Examples are pipe age, diameter, material, soil corrosivity, and pressure, among others. General knowledge within the water industry shows that main age is only a minor factor in the later stages of failure, which are the most important for replacement decisions. Research has shown that break frequency may depend on one of the variables or on products of the variables, and the relationships will vary among utilities.

If risk factors were the same across different utilities, then a generalized model could be developed. However, they are not the same, and pooled data from several utilities cannot be used to predict main breaks. However, pooled data within a given utility can replace missing data for individual main segments.

Recommendations to utilities

To achieve improved renewal rates, utilities should perform risk analysis to anticipate main breaks to prevent direct losses to their own finances and infrastructure, and to alleviate customer and public losses. To know to do this, utilities require convincing business cases for pipe renewal which requires that utilities anticipate failures of individual water mains. This supports capital programmes in which funds are applied to the most important investments and utility strategy becomes credible to customers and regulators. To be able to predict failure requires an effective main break prediction model, even if the model is not quantitative but is a judgment-based assessment by experienced utility personnel.

How to perform risk analysis for main breaks

Utility risk analysis is required for capital programmes, so utilities should strive to gain the capability to analyze main breaks. Large utilities do this now, so a major issue is to develop methods that work for smaller utilities.

If a utility chooses to study its main break frequencies, the information in this report can be used to inform its workforce about the experience of other utilities in predicting main break rates. A utility would then need to develop and test methods for application to its own system.

While the industry knows intuitively that some risk factors are common across utilities and that main age is only one of the significant factors, the influence of other risk factors requires further study at each individual utility. Recent rates of main breaks and consequences of failure drive decisions as much as analysis of these risk factors.

Having a reliable main break risk model would greatly aid utility capital planning. However, this project showed that main break modelling is complex, and requires trained modellers, even if the data is available to calibrate models.

Currently, no proven off-the-shelf models are available to predict break rate frequencies, but several models or model concepts are available for utilities to adept in planning efforts. For example, Deb et. al. (2002) offers a procedure for ranking pipes for replacement. This approach, along with others such as the one explained by Hope (2003), offer a starting point for utility applications.

Until main break prediction improves, utilities can develop replacement models based on experience-based point scores. Some leading utilities use a method that incorporates the risk factors identified by utilities. This is a straightforward approach to capital planning, and utilities can use methods outlined in the Capital Planning Strategy Model (CH2M Hill, 2002) for decision analysis. This approach has merit, but is less satisfactory than knowing probability of failure to strengthen business cases for pipe renewal.

The European Union also supported a project (CARE-W) to develop software for estimating the condition of water networks and to predict pipe failures. The software is explained in an online book published by IWA (Saegrov, 2005), but it was not evaluated during this project.

To pinpoint utility needs for main break models, utilities can identify the exact decisions that depend on knowing risk of main failure. Generally speaking, these are to allocate funds for renewal in capital improvement planning and to schedule rehabilitation and/or replacement in individual pipes. The capital allocation can be done without modelling individual mains because utilities can track the number of main breaks across the network and they can assess direct and indirect costs of main breaks to determine return on investment of renewal. The more difficult problem is to select individual mains for renewal. It pays to invest additional funds to determine specifically which main is most at risk to fail. This risk assessment inevitably involves data and modelling, but the modelling can be done to sort mains by risk factors using simple methods. The key is a consistent and coherent database.

Conclusions

The limits of model capabilities are not in mathematics or statistical analysis methods, but in lack of accurate and consistent data and in the complexity of analysis. Attempts to model main breaks use up-to-date analytical methods, and a number of mathematical models have been attempted, only to founder on the lack of consistent data.

Meanwhile, utilities can develop their own learning methods to identify risk factors, and for each new break they can add data to their databases. Utilities can train their personnel for analysis of risk of main breaks using their databases and break histories. This offers a data-centered approach to main break prediction and planning for system renewal.

Emphasis has been on modelling rather than data because modelling is easier and costs less. However, without adequate data, model efforts may not be useful. While main break research has been ongoing for over twenty years, progress has been slow. Rather than being a cause for discouragement, that slow progress signals a need to keep on with research in this area. The focus in the next stages of research should be on the datasets to predict main failures. ●

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Decision aiding for sewer network diagnosis

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In order to manage sewer network assets effectively, their state of deterioration have to be assessed in order to plan for replacement costs and maintain network efficiency. Caty Werey and Amir Naif explain the use of multi-criteria Electre-Tri analysis to categorise pipes according to their condition and to utilise the analysis data in a decision-aiding model.

This developed approach aims to help sewer utilities to identify critical pipes using a multi-criteria analysis and more specifically Electre-Tri, a method used to assign actions to predefined ordered categories. With the help of a trailed camera, diagnosis of sewers can be done for indicating the possible dysfunctions in the pipe. According to the observed defaults, the current application proposes a way to sort pipes into three specific categories depending on the level of deterioration and to assess dysfunction indicators according to the RERAU Methodology (rehabilitation of urban sewers network)[1] (Le Gauffre et al., 2004a). We detail the implementation of Electre-tri analysis by the definition of criteria, actions given by the pipes and the categories of pipes taken into account. In order to calibrate the decision model, we use a sample of pipes representing an assignment example built by an expert analysis, in order to define profiles and thresholds of the Electre-tri method, after calibration, it is applied on more important set of pipes. This paper presents an application of the method on a realistic sewer network in Alsace, France.

Introduction

Sewer networks represent important assets that require long-term management because of their high level of replacement costs and long lifetime. In order to use financial resources in the right way, a selection of the asset in advanced deterioration stage is done. The proposed approach defines a set of criteria to assess the deterioration state of buried infrastructures and a way to select them to be rehabilitated with the help of a multi-criteria analysis. It takes place during the asset management process, which is a long-term policy based on the inventory of the assets and the data collection of all information related to the asset throughout its service life.

For the Environmental Protection Agency (EPA, 2003) 'asset management is a planning process that ensures that you get the most value from each of your assets and have the financial resources to rehabilitate and replace them when necessary. Asset management also includes developing a plan to reduce costs while increasing the efficiency and the reliability of your assets'. The proposed approach requires the availability of specific data in order to define the criteria for decision-making. In the setting of an asset management approach, we propose a way to determine the state of sewers and select pipes to be rehabilitated according to several criteria that assess the structural, hydraulic and tightness deterioration of the mains.

This approach aims to propose a decision-aiding model calibrated according to expert analysis. In fact, we consider a subset of sewers, which are analysed by an expert. The analysed subset will be used to calibrate a decision-aiding model and allows the sorting of the pipes in a sewer network (Nafi & Werey, 2007). A current study describes the way to implement and calibrate a multi-criteria analysis, the Electre-tri method (Mousseau et Slowinski, 1998) on a realistic case study and how to use the RERAU methodology to assess dysfunction indicators. In this paper, we explore the feasibility of the implementation of Electra-tri method, and the limits of this kind of method for decision aiding by analysing the results obtained according to expert assignment.

The Problematic

Asset management has to take into account several criteria in the decision-making process. In the case of buried networks, multi-criteria analysis was already used for sorting water pipes according to their deterioration and environment impacts for short-term programmes (Le Gauffre et al., 2004b). In our case, the decision criteria correspond to dysfunction indicators assessed with the help of the RERAU methodology, and concern sewer pipes, which will be assigned to defined categories expressing their level of deterioration.

For (Roy, 1993) a realistic problem considering multi-criteria can be formulated in three basic problematics: choice, sorting and ranking. The choice problematic consists of taking from among a set of alternatives (or actions) a subset of satisfying alternatives, which are chosen as a solution. For an optimisation problem, the subset is limited to one alternative. The sorting problematic consists of defining categories according to several criteria, and assigning a considered set of alternatives into defined categories. The alternatives are not compared with each other, but compared to thresholds determined for the considered categories; the ranking problematic consists of comparing the alternatives with each other and establishing a preference based on the considered alternatives.

For the current study the problem is formulated as a sorting problem, because it seems more adapted to the problem treated than a selecting or ranking formulation. It allows for the comparison of the profile of each pipe representing an action with references corresponding to the frontiers of each category, and gives an exhaustive assessment of each pipe, according to the criteria taken into account. The aim of the application is to assess the deterioration state of the pipes and to

Table 1
Criteria considered in the current study

Identification	Dysfunctions /Criteria
INF	Infiltration
HYD	Decrease of hydraulic capacity flooding
DEV	Sand silting
ENS	Blockage
BOU	Ongoing degradation from roots intrusion
RAC	Risk of collapse
EFF	Destabilisation of ground-pipe system

Compatibility Expert & Electre-tri	Total	Percent (%)
Correctly assigned	85	93
Incompatibility	6	7
Sewers analyzed	91	

Table 2 Comparaison between expert analysis and Electre-tri method

determine categories, which the pipes belong to, according to their level of deterioration and exhaustive analysis. It is important to determine the frontiers between the categories considered, to identify the critical pipes among the considered set, in the scope of rehabilitation actions. The Electre-tri method allows us to asses the weight of each criteria in the final decision, the weights are determined according to the calibration of the model, they are an output, by opposition to a weighted method in the case of multi-criteria analysis, where the weights of criteria are considered as an input and determined first.

The multi-criteria approach for decision aiding

The decision will be taken according to the scale of the sewer pipes that compose the network. We define a pipe element as being the section between two successive manholes in the network. The use of a special camera for unvisitable pipes allows for the determination of the state of the pipes and any defects (Makar, 1999). According to the Electre-tri method, alternatives correspond to considered pipes, which are assigned to defined categories expressing the deterioration state of sewers. The defects observed are coded with the help of specific European Standard EN 13508-2 (CEN, 2003). In order to assess the level of deterioration according to observed defects, we adapt the methodology proposed by RERAU to assess dysfunctions on pipes using a matrix based on camera inspection and observed defects. In fact, a dysfunction is defined by an accumulation of specific defects. According to the available data we consider eight dysfunctions to assess a sewer's deterioration, for classifying sewers into categories according to their deterioration state. Each dysfunction is considered as a decision criterion to assign sewers into defining deterioration categories. Table 1 summarizes the dysfunctions considered in the study.

An adaptation of the RERAU methodology for the County Council of Bas-Rhin had been proposed in (Dorchies, 2005 and Werey et al., 2006) according to a specific scale expressed with the help of notes for assessing the observed defects. A note comprised between 1 for a major defect and 5 for a minor defect evaluates the defect. This note is given by the operator of camera inspection according to the deterioration level of the observed defect, using the EN13508-2 coding, which has been standard practice since September 2007.

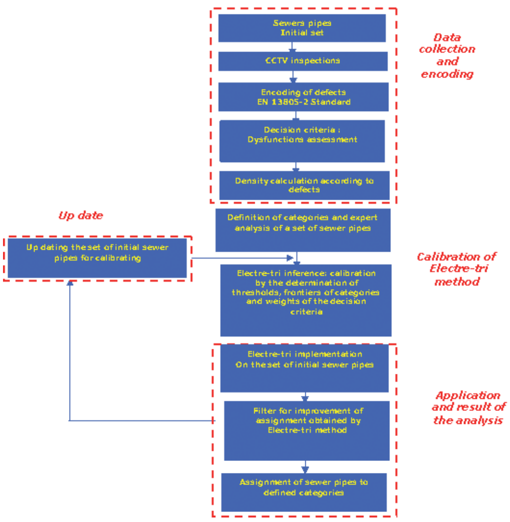

Figure 1 *Proposed methodology for decision aiding model for sewer pipes diagnosis*

The application

The approach of categorising pipes according to their deterioration was applied to a set of sewers in Bas-Rhin (France) that were inspected in 2006. We used the CCTV inspection of 337 sewer pipes to assign them to three categories expressing the level of deterioration of pipes: absence of defects (ABS), acceptable defects (ACC) and unacceptable defects (INT). The aim of the approach is to identify the frontiers between the categories to assign the sewer pipes to the categories. For this, we used an inference approach with the help of an expert. We selected randomly 91 pipes among the available sample. We asked the expert to assign each pipe to the three categories defined by their overall state and not dysfunction-by-dysfunction, as well as helping to rank the eight dysfunctions in order to assess the weight of each dysfunction in the assignment of pipe. With the help of the multi-criteria method Electre-tri, we assessed the frontiers of categories by iteration and the weights of decision criteria for each dysfunction. We analysed the result of the application on 91 pipes by comparing the results obtained by the expert's analysis and the Eletre-tri method, (see Table 2 and Table 3). After calibration of the Electre-tri method, we apply it into the sample of 337 sewer pipes.

The data

We utilised the data collected in the scope of the inventory led by the Bas-Rhin council in 2003 and stored in the Database 'Chimere'. The data available give information about sewers characteristics: diameter, length, material, and soil nature. In order to diagnose the state of the sewer, camera inspections are done on defined pipes concerning the extension of the sewer network or refection of roadway, to assess if the pipe should be rehabilitated or not before works.

For our study we use inspections done in 2006 on 335 sewers belonging to several municipalities. For each video inspection a report that summarised the observed defaults was done, and an encoding of default using the European standard En 13508-2 used. For each default, and according to dysfunctions, a density calculation *Dpd* is used. We also use specific software, PIRACA, developed by (Dorchies, 2005) to asses the density of dysfunctions for considered pipes.

The expert analysis and the assignment example

For each sewer considered in the study, we disposed of the density corresponding to each dysfunction considered in the multi-criteria analysis, giving the performance table of the considered problem. According to these data, we asked an expert to build an example to help us with inferring the parameters and thresholds of multi-criteria analysis. For the expert, the length of the considered sewers has to be more than 20m. In fact, the deterioration state of the pipes depends on the defaults and the dysfunctions assessment, the length is inversely proportional to the density, pipes with short length and minor default could have an important density value. We selected randomly 91 pipes for the assignment example that corresponds to about 30% of the total inspected pipes sample. According to the deterioration level of pipes, the expert assigned pipes to the three categories ABS, ACC and INT defined as:

- ABS: concerns the pipes without defaults or with minor defaults
- ACC: concerns pipes with acceptable defaults
- INT: concerns pipes with unacceptable default, requiring rehabilitation or diagnosis

For each pipe considered for the multi-criteria analysis, we assessed the density of the dysfunctions considered as criteria in our study, forming the performance table (Table 2). The expert assigned independently of the dysfunction criteria, to the category ABS six pipes, representing 7% of total pipes, 37 pipes to category ACC, representing 40% of total pipes and 49 to category INT, representing 53% of total pipes.

For each dysfunction, the RERAU methodology defines a matrix that uses the defaults observed by camera inspections to define dysfunctions. The default is coded with the EN13508-2 according to the camera inspections. Depending on the note for defaults, for a default *i*, the level of dysfunctions is defined as $n_i = 0,1,2,3$. We use the function $N_i = \alpha^{n_i}$ to characterise the default *i*, and α is a coefficient expressing the gravity of default, in general equal to 3 or 4. Each dysfunction is defined according to RERAU methodology with a list of defaults. For a given pipe and specific dysfunction, the density of dysfunction is given by:

$$D_{pd} = \sum_{i=1}^{n_{def}} \frac{100 \, x \, N_i}{L_p}$$

(Boinel, 1995) with L_p the length of pipe and n_{def} the number of defaults corresponding to the dysfunction (*d*) on the pipe (*p*). Using the defined function, we assess a density for each pipe, according to a given dysfunction. According to the Electre-tri method, alternatives correspond to sewers, the profiles represent the limits between the categories ACC and INT. The assessment of each alternative is given by the density D_{pd}.

Multi-criteria decision model

With the help of the assignment example built by the expert, we use the IRIS (Dias and Mousseau, 2003) software to implement the Electre-tri method. IRIS allows the use of the expert analysis to calibrate the Electre-tri method, and calculate the weights of decision criteria (dysfunctions) and determine the thresholds for each criterion, representing the frontiers between the three categories considered. After calibration of the Electre-tri method, we run IRIS on the sample of 91 sewer pipes analysed by the expert in order to compare the results calculated to the expert analysis. As shown in Table 2, the calibrated model assigns correctly 85 pipes to the same categories as the expert, which represents 93% of the considered pipes. But six are not assigned in the same category by the decision aiding model and the expert. It seems that the Electre-tri method does assign pipes to the correct category, but an assignment error is possible. There are three reason why this may occur:

- The Electre-tri does not take into account the sewers pipes with only one significant dysfunction
- An error of assignment of the pipes by the expert
- For the expert, the aggregation of minor dysfunctions put the pipe in an advanced deterioration state; the phenomenon of aggregation is not well enough taken into account well by the Electre-tri method for it to be significant.

Criteria	BOU	EFF	ENS	HYD	INF	RAC	ATC	DSC
Weights	0.05	0.25	0.05	0.25	0.24	0.05	0.05	0.24

Table 3
Weight assessing of decision criteria

The use of the calibrated model allows us to assess the value of the weight of each criterion in the final decision, as shown by Table 3. After the calibration of the model, we apply the Electre-tri method with the help of IRIS on the set of 337 pipes in order to assign the pipes to categories ABS, ACC and INT. This application sorts the pipes into categories in order to identify the priority of rehabilitation actions or an accurate inspection. It is clear that for validation, an expert must check the results obtained, as assignment errors are possible, and the model is for decision aiding, the final decision remains to be the expert or sewer utility manager's. Another important result is the proposition of a methodology to use CCTV inspection for decision aiding with the help of multi-criteria analysis. Figure 1 summarizes the main steps needed in order to build a decision aiding model in the setting of an asset management policy.

Conclusion

The aim of the current study is to implement and calibrate an Electere-tri method on a realistic case study concerning decision aiding for sewer networks. The implementation of the method allows us to measure the limit of the multi-criteria approach to handle all criteria in a decision-making procedure and reproduce efficiently the expert analysis. The calibration of Electre-tri is based on inference procedure according to expert assignment on a sample of sewers pipes and for defined categories. The approach proposed allows a good assignment for the major share of pipes considered in the analysis, but for some others, the assignment obtained was inaccurate. The possible explanation is that the Electre-tri method does not take into account the phenomenon of accumulation of information on several criteria; the method does not consider sufficiently extreme values on a minimum number of criteria. The use of ad-hoc approach was required to help the Electre-tri method to reproduce the assignment expert and handle the decision criteria in the correct way. The proposed approach should be coupled with an ad-hoc procedure in order to limit the assignment error of the method and improve the result obtained by the Electre-tri method. ●

[1] French National Project

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Analyses of an example GIS database of an anonymous water company

Geographic Information Systems can be used to analyse the existing assets of a pipe network and through using the analysis data, help develop investment and replacement policies. Jack A Seuren outlines the analysis process and the opportunities available to water companies, through using example data from a pipe network.

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Nijmegen, the Netherlands, July 2008 – most water companies have installed and are maintaining a Geographic Information System (GIS) for their water network, but do not use all of the possibilities the systematically collected data in the GIS has to offer! Through using the registered data regarding assets and asset-related events (failures, maintenance) in GIS, you are able to optimize your investment and replacement policies. You can also carry out realistic asset benchmarks and valuations based on the actual age of the assets. It is possible to produce reliable analyses about these subjects, even without registered (failure and maintenance) data over a long period of time or a direct link from the failure to the related asset, to create reliable fixed asset analyses.

Introduction to the investigation

This example GIS (Geographic Information System) has a database, containing water mains. The data used are anonymous, but represent a real life situation. We will show some analyses that can be performed with limited data.

Replacement values

The replacement value is based on the principle of the nearest technical asset: the values of the assets of today are used. For example, this company will not replace cast iron pipes with cast iron but with PEH (polyethylene hard) and for the non-common diameters it will use the nearest, most commonly used diameters.

Life span

To start with, the life span is determined, based on what is normal for utilities and the actual life span spread.

Figure 1
Total investments

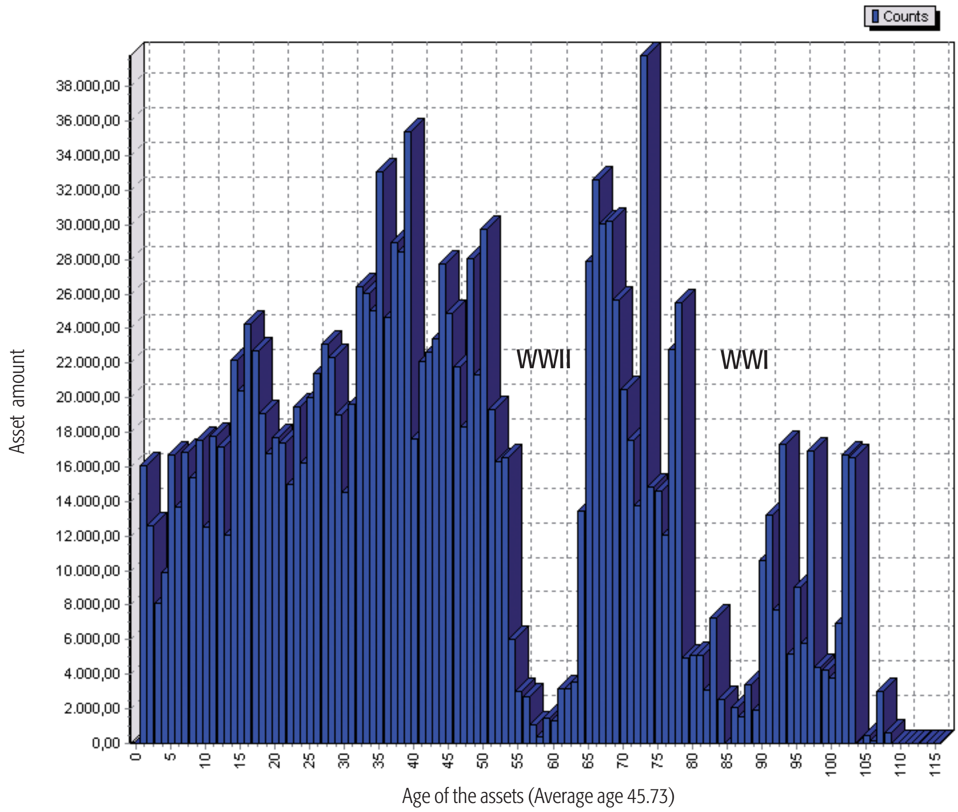


Table 1
Technical data

Length of pipes in use (m)	%	Length of pipes not in use (m)	%	Length of pipes 'other' (m)	%	Total length of pipes (m)	Total number of objects	Average length (m)
1,333,131.80	83	271,795	17	17,868	1	1,604,927	24,383	66

(Dec 31 2002)

Material	In use	Not in use	% in use	% not in use
Cast iron grey	651,294	234,150	74%	26%
Cast iron nodular	588,280	20,634	97%	3%
Unknown	74	63	54%	46%
Steel	15,678	11,716	57%	43%
Polyvinylchloride (PVC)	3237	831	80%	20%
Polyethylene hard (PEH)	35,935	2417	94%	6%
Polyethylene (PEw)	10,169	1448	88%	12%
Cross-linked polyethylene (VPE)	28,642	536	98%	2%
Total	**1,333,131**	**27,1795**	**83%**	**17%**

Table 2
Proportions of pipes in use and not in use

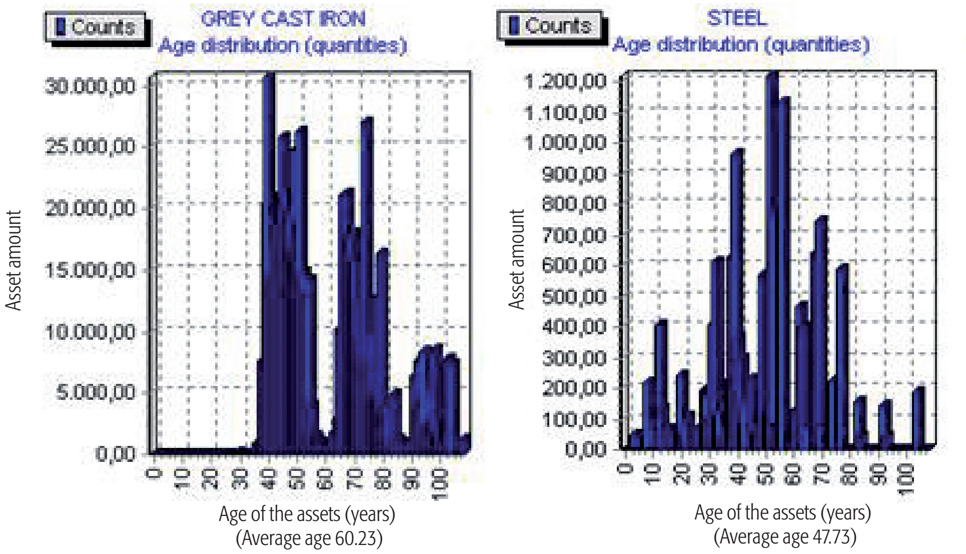


Figure 2
Age of distribution for cast iron and steel

Financial depreciation

The default depreciation period is 25 years. However, in the calculations the alternative of 40 years and the calculation period over the life span are used. These calculation periods are useful to show future costs and the effects in terms of regulations.

Interest rate

The interest rate used is 6%. In the analyses, we have calculated the interest over the total funding (so we do not take into account equity capital).

The content of the data

The data consist of mains that are the assets/investments, and registered failures. Sometimes a specific pipe has more than one failure.

The installation of the first pipes took place in 1895. In the data, the actual replaced objects are not or may not be available. The pipes 'not in use' are objects still in place, but decommissioned because of various reasons.

Investments in the past

The following figures will show you the past asset investments. In Figure 1, we show the ages of all pipes (in meters) from 1895 up to 1 January 2002.

Figure 1 shows us that there is still a substantial amount of assets from before 1900 up to 1940. There is also a clear reduction in investment during the two World War periods. Most investments were made between 1950 and 1973.

In the last 35 years, the annual investments have decreased slightly, while in general the growth rate is lower in the later years. This could indicate a 'people based' investment strategy instead of an 'asset based' investment strategy. Figure 2 is an example age distribution of two types of pipe material – cast iron and steel, whilst Table 2 shows the proportions of these in use and not in use. This company has replaced 26% of cast iron grey and 46% of steel. However, the population of steel is limited.

Corrosion protection

The steel pipes are protected against corrosion. Figure 3 shows the different materials used as the corrosion protection.

If we compare the material compilation of the pipes in use and not in use, there turns out to be a clear shift from bitumen to polyethylene coating (see Figure 4). The most used form of protection against corrosion however is still the bitumen coating.

Almost all steel is protected against corrosion. Bitumen protection has been the old way of coating, but since 1970, the bitumen protection has been

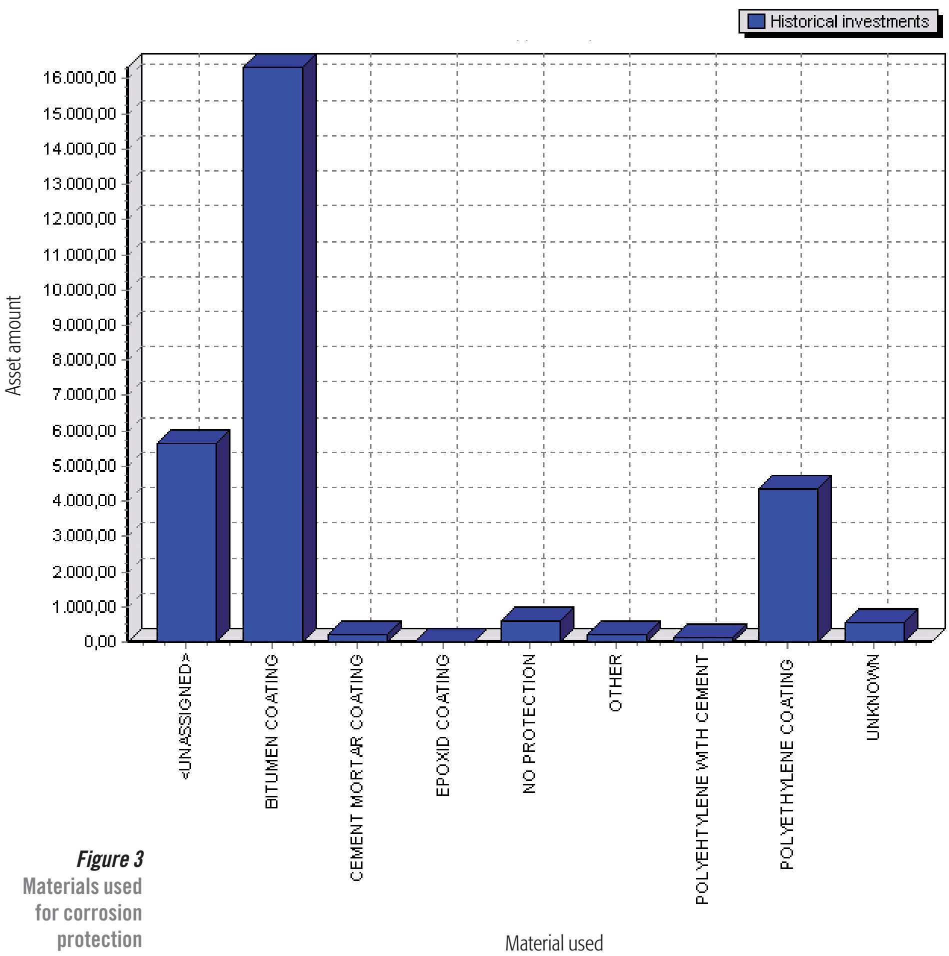


Figure 3
Materials used for corrosion protection

replaced by polyethylene coating. Lately, polyethylene coating with cement has also been used. There are almost no pipes with internal protection against corrosion.

The method of installation

The method of installation could have an influence on the life span and future failure rate. In Figure 5 we show the spread of installation methods. In Figure 6 we do not show the unassigned as we assume unassigned is the normal method of installation. Relining will lengthen the lifespan of original, older pipes and has been used by this organisation since 1988.

Type of connection between pipes

Most connections are formed by a 'pairing' connection, 'screwed' connection, or 'thyton' connection.

In the full report we show graphs of the investment years or age distributions of all types of connection, and have divided them according to whether the pipes are 'in use' or 'not in use'. In this way we have come to the following conclusions:

- Most pipes with 'pairing' connections are not in use, these connections were used until about 1955.
- The screwed connections were used from 1950 until 1970.
- Thyton connections have been used since 1965.
- Nowadays we use 'thyton' connections and 'clamp' connections. The oldest type of connection is 'pairing', followed by 'screwed' connections.

In this way we can also make elaborate analyses of the method of rehabilitation, the number of valves to a pipe, the location of the assets (districts) etc. All aspects can be compared and analysed over the life span.

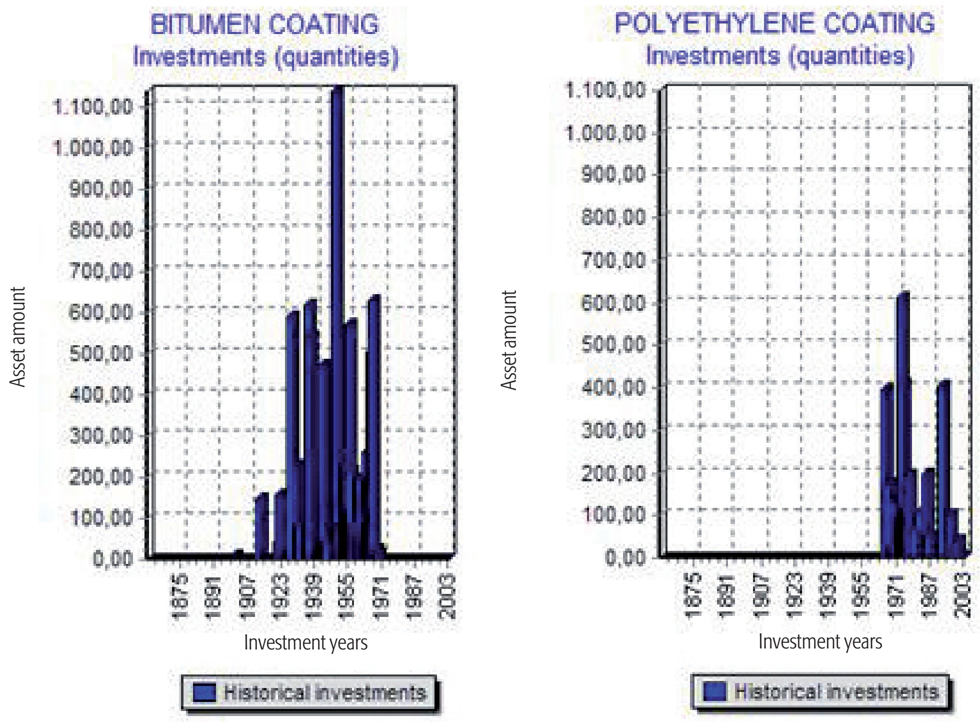


Figure 4
Use of bitumen and polyethylene coatings

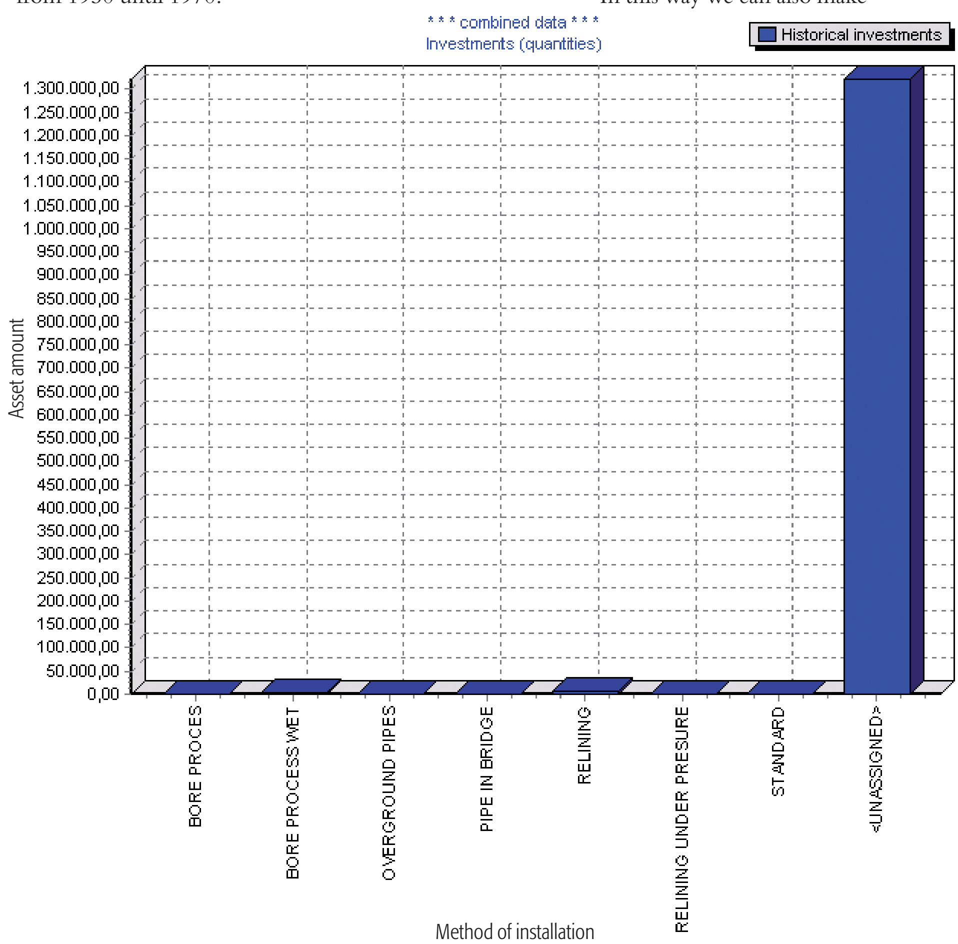


Figure 5
Installation method

Analyses summary

The policy of this company is obviously the following:

- The oldest material is grey cast iron, followed by cast iron nodular, and lastly by PEH and VPE. Steel pipes are not used much. The coating of the steel pipes was changed in 1970 from bitumen to polyethylene.
- In time, the diameters have been more standardized.
- The connections have been changed, from 'pairing' connections to 'screwed', then to 'thyton' and 'clamp' connections. Changes in connections have been made as some type of connections tend leak more than others. Leaking connections are a major cause of pipe failure.
- Lately, in a limited way there is some rehabilitation, mostly folio relining on steel and cast iron.

Looking back at Figure 1, we see that the investments are 'people orientated', based on the average investment growth rate, which has been low over the past decade. That means that the number of people serviced determine the investment level. Many pipes have been replaced at a young age and there is an investment peak in the period between the two World Wars. There seems to be no policy to replace pipes based on their age.

Event-analyses: failures and maintenance

After analysing the history of the investment, questions arise, such as:

- Has the introduction of new materials been successful in terms of reducing failures?
- What is the actual life span of the assets and how long can we postpone replacement investments?
- Why did this organisation replace objects with a short life span?
- Other questions: are relining and other rehabilitation programmes to improve lifespan justified if we consider the extra costs?

When you have analysed the compilation of the assets, you are ready to take the next step and take a look at the events – failures and maintenance.

The total amount of registered failures regarding the assets in use and not in use has increased until around 1991 and decreased thereafter (Figure 8), a pattern also displayed in Figure 9, which shows only the failures of assets in use. Through analysing the number of failures for each type of material, it was determined that all materials show a decrease in failures over the last ten years, with almost no increase in failures for any type of object.

Failure description

Here we show the development of the failures per most frequent failure description. In Figure 10 you can see the compilation of all failures, divided into descriptions. In Figure 11, we show the development in time for two failure descriptions.

The most frequent failures turn out to be transversal crack, complete corrosion, crack in length, leaking connection and crack in armour.

General overview of failures of pipes

Using data from 1999-2002, Figure 12 shows the failures over the life span for all pipes, and the average number of failures over the life span. The left vertical axis shows the average failures per year per meter of pipe, the right axis and the blue line together show us the number of measured assets (measured for failure status) per year, but on a logarithmic scale.

- There are low failure rates in the period 0-20 years. This could be because nowadays we use different materials. Then there is an increasing failure rate and the failure rate stays more or less constant, but a peak appears around 35 years. The average failure rate is 0.105 failures per km.
- It is amazing that the older assets have a declining failure rate.
- In the full report you can also see the graphs of the different materials. The best material seems to be VPE, the worst PEH. Cast iron nodular seems to be a good material. However, these are averages and they do not take into account age differences and patterns. It does not look good that cast iron nodular has a much higher failure rate for the ‘not in use part’ while the average age is much younger then the cast iron grey.
- PEH, which is a good material for gas systems, is less suitable for water.
- The objects with failures can be repaired ‘as new’. They may, however turn out not ‘as new’, in which case new failures will happen sooner.

Future costs with differing life spans

With this method – supported by the LCC-AM/QM software – we can project into the future time-related costs, such as capital costs and

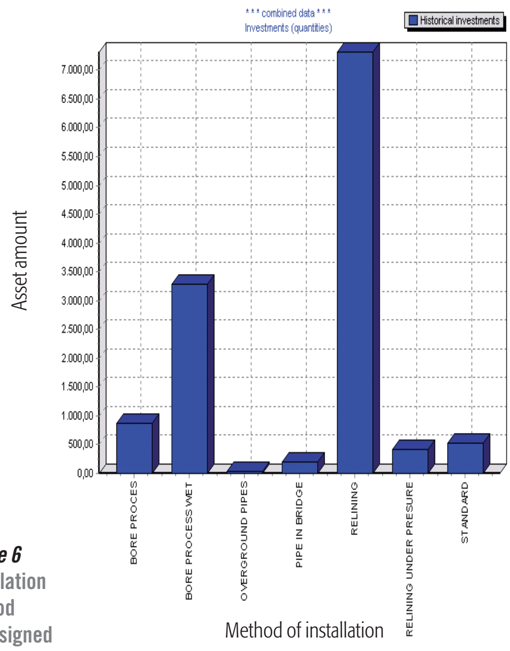


Figure 6 Installation method (unassigned assets excluded)

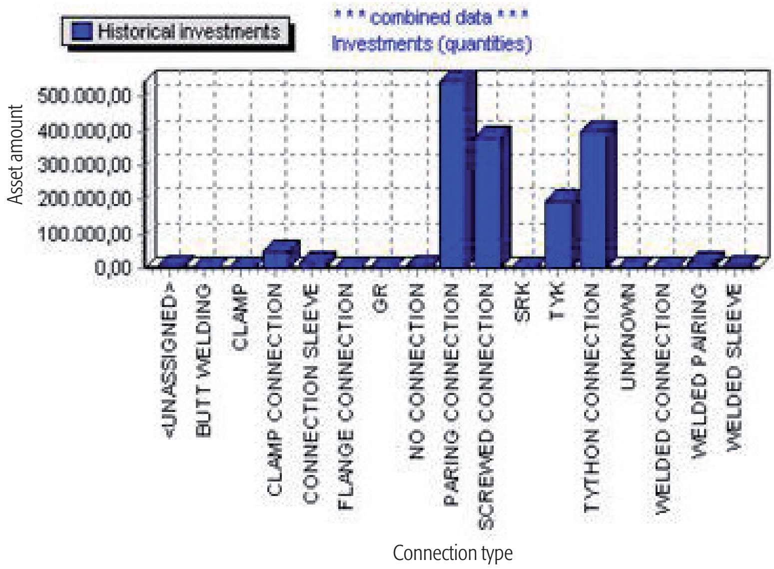


Figure 7 Connections

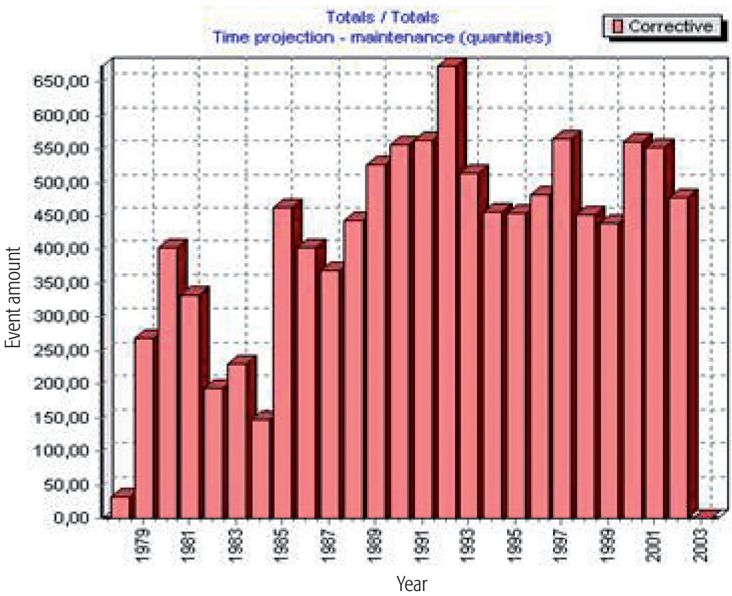


Figure 8 Failures between 1978 and 2002 (all failures)

Table 3
Water utility value

Detail ID	Amount	Replacement value	Current value	Life age	Life span	Life rest
Cast iron	607,566.70	81,847,167.21	64,624,527.24	19.05	97.90	78.85
Cast iron grey	900,355.10	34,267,323.70	14,545,917.07	52.72	95.07	42.35
PEh Polyethylene hard	31,753.70	3,677,208.51	3,197,170.34	10.11	96.91	86.79
PEw Polyethylene	11,723.20	838,937.68	599,248.96	20.02	90.95	70.92
PVC Polyvinylchlorid	4068.00	233,680.23	78,732.62	35.32	55.41	20.09
Steel	28,043.20	2,743,112.38	1,227,182.79	36.70	72.23	35.53
Unknown	137.00	1889.02	6.40	101.59	101.92	0.34
VPE Polyethylene	23,091.00	2,945,892.79	2,780,816.46	3.86	97.79	93.93
Water	**1,606,737.90**	**126,555,211.53**	**87,053,601.87**	**27.97**	**96.42**	**68.45**

operational costs, such as maintenance.

The projection can be only based on the life span (technical, minimum, maximum, economic) or also on a prediction of future investments. Also the predicted future number of failures can be taken into account. In this situation we will define levelled groups (material, coating, time period, environment) as we think is appropriate. These groups have been created based on the analyses over the past period.

In Figure 13, we show the future capital costs based on different life spans: a relatively short and a relatively long life span of the assets. The results show that there are significant differences in cost price and investment level.

Long-term capital and maintenance costs based on a relatively short life span

Figure 13 shows the future development of capital costs and maintenance. If we do not change our policy the average costs will stay on about 4.5 million ($7.1 million) a year.

Figure 13 consists of a period in the past (1980-2003) and the predicted future (2003-2053). The dark blue shows us the depreciations from the past. The yellow shows the maintenance costs. The red represents interest costs. The light blue represents the depreciations of replacement investments. As you can see, the maintenance costs are very low in relation to the capital costs.

Long-term capital and maintenance costs based on a relatively longer life span

Figure 14 shows the long-term costs using a longer asset life span. In this option the average costs can decline to 2.4 million ($3.8 million) a year.

The projected failure rate does not differ much in both options. As you see, a longer life span pays off. There is an increase of failures, but the total costs decrease to 2.4 million ($3.8 million) a year. This is about 46% less expensive than the current policy!

Valuation

Because maintenance costs and innovation only influence the economic replacement costs in a limited way, the value can be determined based on the present replacement value and the remaining life span. Table 3 shows the value of this water utility.

Regulation

Regulation in Europe and the USA is based on the following principles:

- The Regulatory Asset Base (RAB), that is the investment value and the book value according to depreciation rules of the Regulator, is the basis:
  - for the Weighed Average Costs of Capital (WACC). In simple terms, this means the profit, including interest costs;
  - the depreciation, which should be enough to make replacement possible.
- The operational costs.

These cost categories of the different utilities are compared and an efficiency factor is determined. The utility with the highest efficiency will be the role model for the others: these other utilities should also become that efficient. To stimulate this development, the regulator often reduces the tariffs of the other utilities by using the calculated 'efficiency factor'.

Nevertheless, this method will lead to situations in which utilities invest too much. While on the other hand they save too much money for operational costs, because the WACC is only based on book value and not on operational costs. In this way regulation is counterproductive. To invest too much is wasteful. Using this method it likely will be possible to convince regulative institutions that they should change their method of regulation.

To convince a regulator, however, is difficult and takes time. Therefore, in any case, one should optimize based on today's rules.

In this example we show the effect of variables the regulator could use, such as using historic value, corrected historic value, a longer or shorter depreciation period. In some countries, the RAB is based on historical costs. As we will consider, today's fixed asset files are not complete. We can calculate a corrected historical investment value, using LCC-AM/QM software.

The corrected initial value we have calculated, using a price index on the replacement value of all assets. Today's initial values, as appearing in the annual reports (and fixed asset files), seldom are complete, because of the following reasons:

- Deleting all records with book value zero
- Not including (enough) indirect costs
- Take-overs for symbolic prices
- Change of financial systems
- Not activating investments under a certain amount of money, by booking them as maintenance costs

The investment value in the annual report is 69.55 million ($110.3 million) (based on historical costs). The book value is17,387,500 ($27,563,551). We use in this example a WACC of 6.5%. In Table 4, we focus on capital costs and show the WACC and depreciations. As you can see, it will make quite a difference for the WACC which data and variables you use. Some organizations use the historical value and use a price index to calculate a replacement value. Because of the fact that most of the fixed asset files are incomplete, this leads to incorrect results.

Table 4
Historic and replacement values

Method	Investments	Book value	WACC	Depreciations	Total WACC and depreciations
Historic value					
Depreciation 25 years	69,550	17,387	1130	1206	**2336**
Corrected historic value					
Depreciation 25 years	126,555	30,134	1959	9345	**11,304**
Depreciation 50 years	126,555	61,046	3968	10,219	**14,187**
Depreciation over life span	126,555	87,053	5658	7638	**13,296**
Replacement value					
Depreciation 25 years	325,714	34,620	2250	9997	**12247**
Depreciation 50 years	325,714	91,257	5932	13,686	**19618**
Depreciation over life span	325,714	165,580	10,763	9775	**20538**

Summary of this investigation

The major part of the costs of the infrastructure of a utility are capital costs. In relation to capital costs, cost of failures are low. Maintenance in this respect should be the tool to prevent unnecessary or premature replacement investments.

In this water company, the investments decisions seem to be 'people based'. That means, given an amount of personnel, a certain amount of investments will be achieved. If the investment policy would have been 'asset based' – with replacement investments based on the failure rate of the assets – the investments would have been much lower in the early years. There has been a high investment peak in the 1970s. The growth rate today is much lower or should be much lower.

The utility has a wrong understanding of failure rate. This rate should not be an average over total life span, but an average over the life cycle. To compare types of material, the life span aspects should be considered. For example in this respect cast iron grey is better material than cast iron nodular or PEH. Therefore, the right policy for this water company should be considering only replacing cast iron grey based on a high failure rate and to investigate what should be done about the corrosion problem of cast iron nodular and the cracks in length of the PEH pipes.

The failure developments of the present pipes can be described as follows:

- Failures will increase in the next 25 years; dependent on the policy now they will increase or decrease from that point.
- For cast iron nodular, however, the failure rate goes up progressively and

Figure 9
Failures of pipes in use

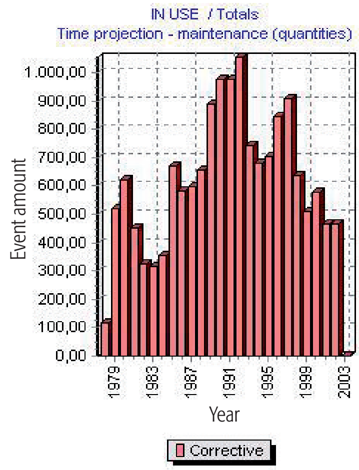


Figure 10
Types of failures

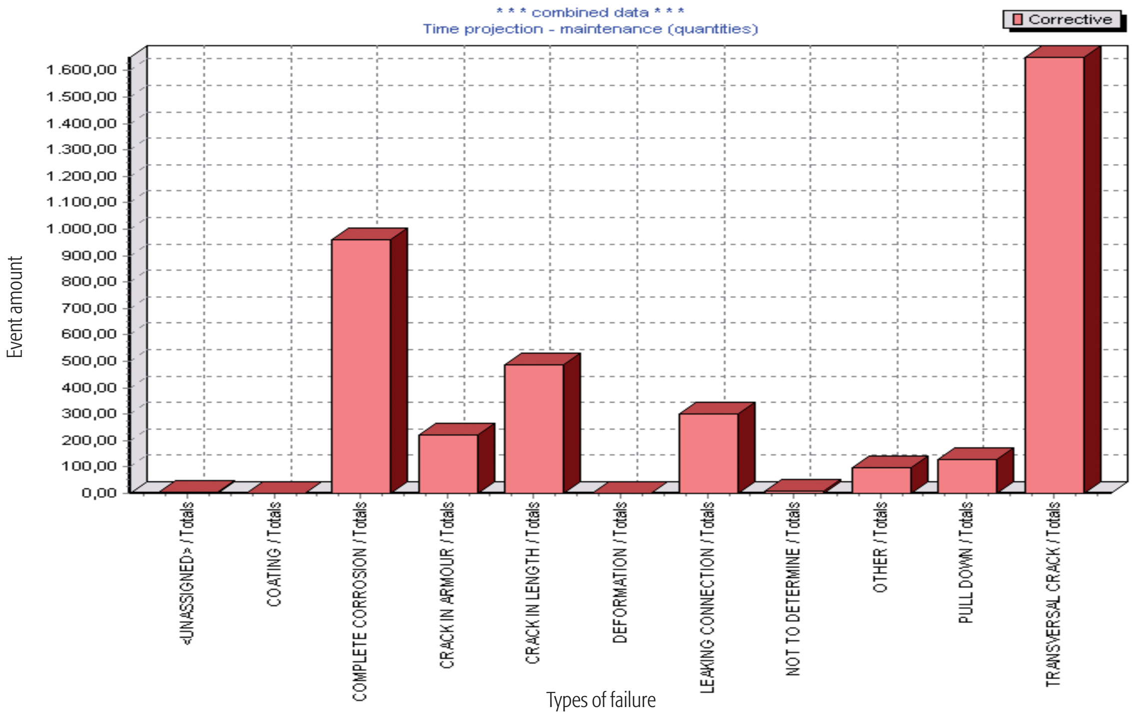
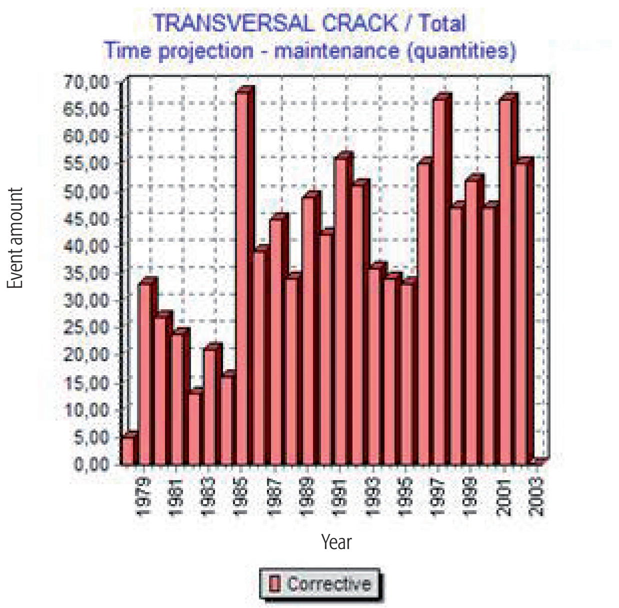
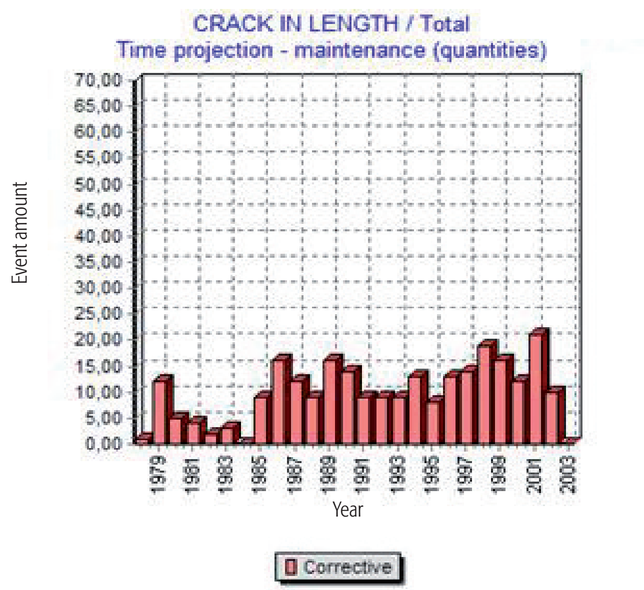


Figure 11
Development in time of repairable failures





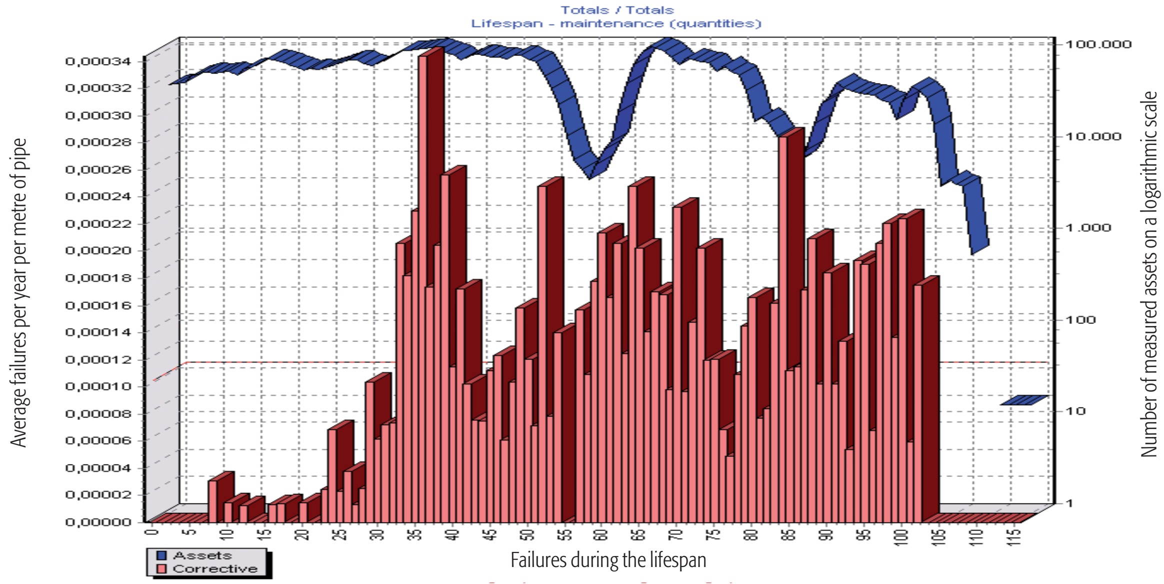


Figure 12
Failures over pipe life span

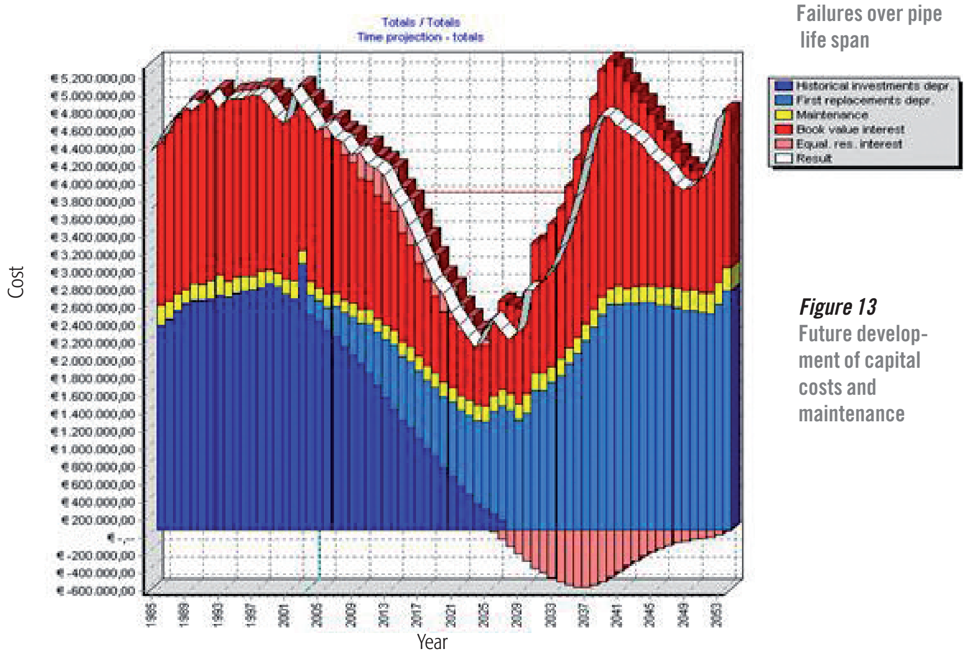


Figure 13
Future development of capital costs and maintenance

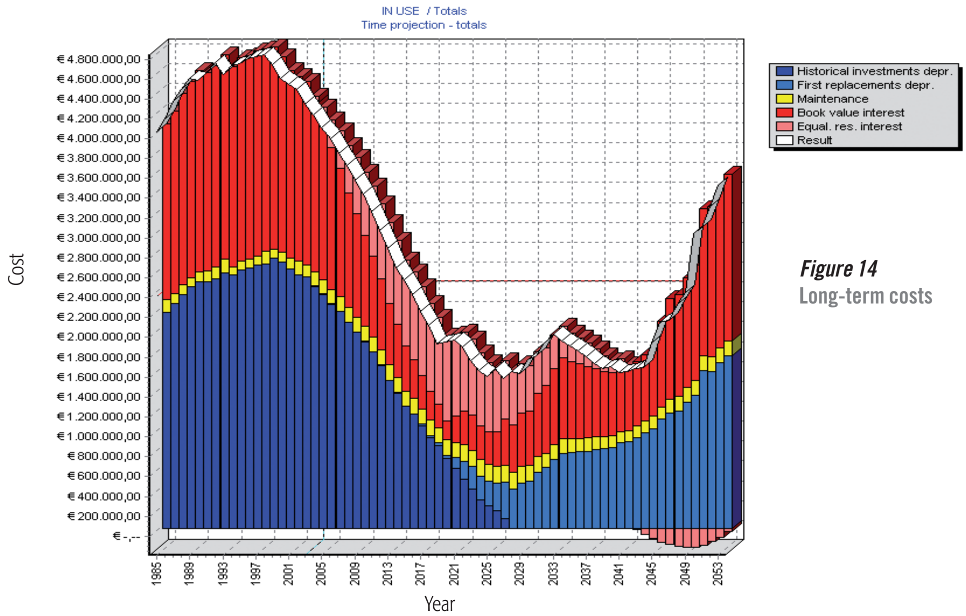


Figure 14
Long-term costs

the same goes for PEH. If this increase continues, cast iron nodular will prove to be worse material than cast iron grey. The same is true for PEH.

Here we can conclude *age should not be an issue* when considering replacement.

Managing the organization based on the assets and not primary on the available manpower can lead to substantial savings. The achieved savings are about 40% a year.

S&G and partners

If you wish to obtain a full version of the report of this investigation, please contact the office of the author, Mr. Jack A. Seuren (Tel. +31 24 6450006).

Mr. Seuren is the managing director of S&G and Partners: consultants, specialized on asset management, based on life cycle costing techniques.

The basic principle of S&G and partners is that advisory must be combined with the disposition of tools and training for the benefit and independence of the customer.

The following specialized software packages have been developed by S&G and partners:

- LCC-AM/QM: Life Cycle Costing: Asset Management/Quantitative Maintenance
- LCC-Ant: advanced conversion tool for e.g. GIS-data into LCC-AM/QM
- LCC-Lite: Life Cycle Costing: cost/benefit analyses on project level

Customers are utilities (water companies, electricity and natural gas suppliers, communication cable companies), chemical companies, engineering offices, airports, railroad companies, universities, public services and banks. ●

Using historical repair data to create customized predictive failure curves for sewer pipe risk modelling

Several years ago, Seattle Public Utilities (SPU) instigated an asset management programme in order to assess the structural state of Seattle's existing sewer pipe network, with the data compiled used to produce a risk-based replacement/ rehabilitation strategy.

The Sewer Pipe Risk Model developed by SPU uses specific information about each pipe to estimate the consequence of failure. Failure curves were generated using this model, but in order to more accurately predict pipe failure, customized failure curves were developed using histrical repair data.

Terry Martin, Darin Johnson and Scott Anschell report on the use of risk modelling to predict the risk cost of pipe failure.

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Seattle Public Utilities (SPU) is a municipal utility owned by the City of Seattle that provides retail water, wastewater, drainage, and solid waste services to approximately 700,000 Seattle residents as well as over 1.3 million wholesale water customers. SPU began the implementation of an asset management programme a little over six years ago in response to a combination of events including heightened public scrutiny resulting from a series of annual rate increases, an aging infrastructure of mostly unknown condition, tightening environmental regulations, and an increasing desire to concentrate on core utility services. An important initial step within the sewer line of business at the time was to inventory the existing pipe infrastructure and develop a modelling methodology which would provide the foundation for a successful risk-based

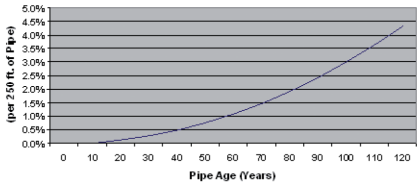


Figure 1
Annual likelihood of failure for vitrified clay sewer pipe

replacement/rehabilitation strategy. The immediate goal was to minimize the risk that infrastructure failures were likely bringing to the utility.

SPU's existing sewer pipe network includes approximately 35,000 pipe runs, contains over 2000 miles (~3300 kilometres) of pipe, averages 75 years in age, and has an estimated replacement value of approximately $2.5 billion in 2008 US dollars. The Sewer Pipe Risk Model was developed by SPU as a means to calculate not only the annual risk cost to the utility of this sewer pipe network but also to determine the individual risk cost of failure for each pipe segment. Fundamentally, the Sewer Pipe Risk Model calculates the risk cost of failure for each individual pipe by multiplying the estimated consequence of failure by the estimated likelihood of failure.

To calculate a particular failure consequence the model interfaces directly with the city's GIS system and extracts information pertaining to each pipe (i.e. elevation, installation date, material type, proximity to geologic and structural features, etc.). It uses this information to calculate individual monetary (and via indirect means non-monetary social and environmental) consequences of failure based on these attributes. As an example, code was written into the model such that each pipe located underneath a building is automatically affixed a multiplier of consequence based on the added cost of repairing a pipe located under a building.

Conversely, the model's primary means for calculating the likelihood of failure is by applying time-based predictive failure curves using a normalized Weibull-type distribution. It applies a unique failure curve to each pipe in the system based on age and material type. This method assumes that sewer pipes will display an approximately normal and exponential distribution of failure over time due to material deterioration.

Figure 1 shows a graphical example of this Weibull-based failure distribution currently used by Seattle Public Utilities for vitrified clay pipe.

Once the Sewer Pipe Risk Model has calculated a unique consequence of failure value for each pipe within the system this cost is multiplied by the unique likelihood of failure calculated for each pipe. The product is the total risk cost. The risk cost for each pipe is then annualized by incorporating the accumulated failure rate predicted by the Weibull curve for the current year plus five successive years. The time period of five years is used since this is the default CCTV return time for 'high risk' pipe condition assessment at Seattle Public Utilities. In this way the model evaluates the monetary risk borne by the utility for each pipe during the interim period between CCTV cycles.

Discussion and results of historical sewer pipe failure analysis

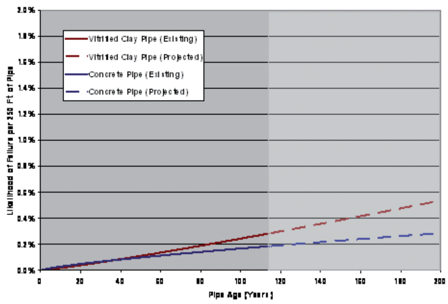
Applying Seattle's historical repair data to create new likelihood of failure curves

Suspicions have arisen at SPU over the last several years regarding the validity of the predictive failure curves used in the Sewer Pipe Risk Model. Some staff felt that the curves used in the model were over-predicting failure of most pipes as well as not adequately characterizing the failure mode differences occurring in differing materials. Anecdotal field reporting, CCTV inspection evidence, and the relatively low number of ongoing scheduled and emergency repairs seemed to support this claim.

In an attempt to improve the accuracy of its predictive failure curves SPU developed customized failure curves based on recent experiential sewer pipe failure data. These new curves would be created using actual historical pipe repair information as well as existing CCTV inspection data. To this end, repairs and video inspections for both concrete and vitrified clay pipes, together comprising more than 90% of SPU's sewer pipe population, were analyzed for the years from 1989 to 2005. Since pipe repair data from 1988 and earlier was either nonexistent or of poor quality 1989 was chosen as the cutoff date for the inception of the study. Pipe materials other than concrete and vitrified clay were omitted from the analysis due primarily to statistical complications relating to their small sample size.

The number of pipe repairs related to material failure which occurred during the study period was analyzed, and those pipes that had yet to fail taken into account in the analysis. Weibull failure probability curves were generated for concrete and vitrified clay pipes using a statistical parameter estimation method known as Maximum Likelihood Estimation (MLE). The MLE method accounts for pipes that have not yet failed as well as those that have.

Figure 2
Base failure probability curves



The most likely Weibull failure curves for the concrete and vitrified clay pipes are shown in Figure 2. The failure curves are extrapolated to 200 years, past the current maximum age of 114 years for both concrete and clay pipes.

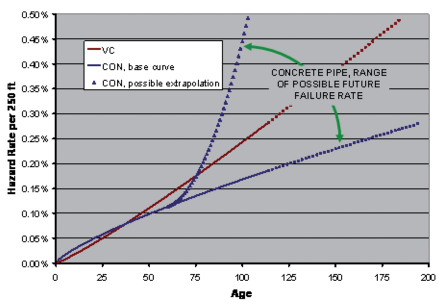
Explaining the flatness of the concrete pipe failure curve

As shown in Figure 2, the concrete failure curve has a flatter slope than the vitrified clay pipe curve. This is a somewhat surprising result, since the common assumption is that concrete pipes wear out more quickly than clay, so they should have a higher failure rate, particularly at an advanced age. There are four possible explanations for this outcome:

The effect of inspection history

One potential cause of the flatness of the concrete curve is the difference in inspection history between the two

Figure 3
Unknown future failure rate of concrete pipe



Pipe Material	Location Factor	Estimated increase in number of expected pipe failures
Vitrified Clay	Steep slope	72%
Vitrified Clay	Clay soil	74%
Vitrified Clay	Type ‘m’ soil	57%
Concrete	Steep slope	62%
Concrete	Clay soil	50%
Concrete	Type ‘m’ soil	50%

Table 1
Results when comparing location factors to estimated increase in pipe failures

pipe types. The records indicate that 37 percent of the vitrified clay pipes were inspected more than once while only 20 percent of concrete pipes have been inspected more than once. Therefore, since more of the clay pipes have been inspected more often, a higher percentage of failures have been noticed.

The age of SPU’s concrete sewer pipe population

Another possible explanation for the relatively flat concrete curve is that the population of concrete pipe is too young to fully demonstrate its performance as it ages. About 80 percent of the concrete pipe is less than 60 years old. For the clay pipe, the 80th percentile age is 97 years, so the concrete pipe does appear to be much younger in general than the clay.

Failure mode not yet occurring

A third possible explanation for the lower concrete failure curve is that there is a failure mode that has not begun to show up in the failure history yet. In this scenario, the past failure history of the pipe is not a reliable predictor of future failures. There is some reason to believe that this might be the case. Anecdotal information from SPU inspection personnel suggests that the condition of the concrete pipes in general, while not necessarily requiring repair is degrading noticeably and that a significant increase in failure rates is expected sometime in the future. To date, limited work has been done by SPU to determine the degradation rate of the concrete pipe or to correlate condition with failure rate, although a significant amount of such work is planned for the near future.

Figure 3 demonstrates the unknown future failure rate of the concrete pipe. In the scenario described here, the range of uncertainty may be very wide.

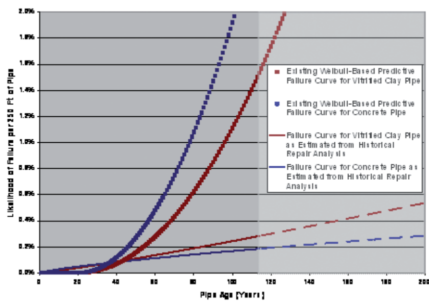
The base concrete curve is correct

A final possibility, of course, is that the base failure probability curve developed here is essentially accurate, and that concrete pipe has at least a somewhat flatter failure probability curve than clay pipe. This would be contrary to the expectations of most engineering and field personnel at SPU and elsewhere, but it does fit with the actual data used in this study.

Existing SPU time-based Weibull distribution failure curves

Figure 4 compares the original Weibull distribution failure curves currently used by SPU (originally provided by Hunter Water, Australia), with the

Figure 4
Comparing pre- and post-study failure curves



failure curves produced in this analysis. The difference is immediately obvious, as the original curves have a much steeper slope, diverging dramatically near age 50 with the curves produced in this analysis. This implies that the economic life of these pipes is much longer than what has been previously assumed.

Additional study analysis and results – location specific failure curve modifications

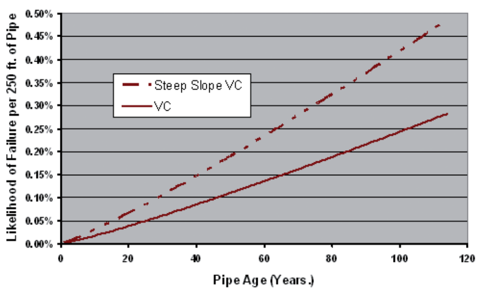
In addition to the material-based degradation issues discussed above three location factors were analyzed for possible correlations to increased failure probabilities:

- Pipes on steep slopes
- Pipes in clay soil
- Pipes in type ‘m’ soil (areas of unknown fill as well as potential liquefaction areas located primarily in tidal zones)

An effort was undertaken as to whether, and by how much, the above location factors affect the base failure curves. To assess the correlation of these factors with the observed failures, a statistical hypothesis-testing method was used based on the paired samples of pipe inspections and failures. Table 1 summarizes the results of this analysis, all of which were statistically significant.

Figure 5 shows the base vitrified clay pipe failure curve along with the corresponding steep slope failure curve. The increased failure percentage shown in the first row of Table 1 has been applied to the steep slope failure curve.

Figure 5
Base VC failure curve and steep slope VC curve



Conclusions

This historical sewer pipe repair analysis shows that:

- SPU’s sewer pipe failure pattern is different than originally assumed. The failure rate is low, linear, and shows no signs of exponential increase at this time.
- Pipes fail at different rates depending (at a minimum) on material, age, slope, and indigenous soil type. Particularly apparent is the fact that sewer pipes located on steep slopes, in clay soil, and in fill soil fail much more often in Seattle than those that are not in these locations.
- Seattle’s relatively young population of concrete sewer pipe has apparently not yet reached a rapid increase in failure, but it is felt that these pipes should continue to be monitored closely.

Limitations of the analysis include:

- It does not show the end of economic life for Seattle’s sewer pipe. The analysis demonstrates the rate at which spot failures appear to be occurring. End of economic life is a function of the cost of continued repair vs. the cost of rehab and replacement as it relates to the rate at which pipes incur discrete failures.
- It does not predict the future number of repairs, only the future expected number of material-related failures. Data showed that there may be typically twice as many repairs as there are pipe failures due to external factors such as third party construction-related damage, dropped side sewers, etc.
- It cannot be used to estimate the failure rates for the roughly 10% of SPU’s sewer pipes which are not concrete or vitrified clay since the study only analyzed these two materials. ●