DECISION SUPPORT SYSTEM FOR WATER PIPELINE RENEWAL PRIORITISATION

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SUMMARY: *Many Water Utilities are faced with the problem of ageing pipe networks and the associated increasing costs. In response to this challenge there has been considerable effort around the world on improving practices of pipeline asset management. There has been progress in data collection and data management practices, in risk management including failure prediction models, as well as in the area of Decision Support Systems. Decision Support Systems, such as PARMS-PLANNING support long-term planning and budget settings in relation to pipeline replacement decisions. To complement these system overviews, PARMS-PRIORITY has been developed to support pipeline renewal prioritization, which involves the analytical assessment of different activities, such as pipeline replacement and pressure reduction in terms of their associated risks. Such a prioritisation model is described in this paper and includes the development of the methodology, the calculation modules, the input data, and outputs. The modules are based on key tasks: risk calculation, failure prediction, cost assessment, data exploration and scenario evaluation. The model uses asset and failure records data within a standard risk approach. The novelty and innovation lies in the application of the particular models within a specific context and the model should therefore in the first place be judged on how useful it is to decision makers. PARMS-PRIORITY is currently being trialled by two Water Utilities with initially good feedback. The assessment of the tool is by nature on going.*

KEYWORDS: *water pipes, pipeline failures, asset management, risk, scenario analysis, data exploration.*

1. INTRODUCTION

Water pipe networks are ageing and consequently failure rates are increasing. However, there are limited funds available for Water Utilities and this necessitates the efficient use of available funds. In 1998/99 the cost of maintaining and replacing existing water infrastructure in Australia was in excess of A$250M (Water Services Association of Australia, 2000), which was equivalent to approximately $13 per Australian. In Australia, the ratio of infrastructure to population is relatively high, and much of the infrastructure including water distribution network pipes was constructed in the peak period after the end of the Second World War (Burns *et al*., 1998). Many of these pipes are now reaching an age at which the number of failures is starting to significantly increase and these failures have adverse consequences, such as customer supply interruptions, property damage by flooding, costly repairs, and lost water.

To allow Water Utilities to predict the costs associated with increasing numbers of failures, the Decision Support System PARMS-PLANNING (Burn et al, 2003, 2004) was developed to support the long term assessment of costs and implications of different management and operational asset management styles. PARMS-PRIORITY complements PARMS-PLANNING because it allows Water Utilities to spend the renewal budget in an efficient manner by supporting the renewals prioritisation process. Risks involved with different scenarios and options are assessed using a standard risk management approach, as per the Australia/New Zealand standards (Standards

Australia and Standards New Zealand, 1999). Risk is calculated by combining the output of failure prediction models with the output of cost assessment models. An enabling factor for these recent developments in Australia is the fact that many Australian Water Utilities have increased their focus on data collection, data management and data classification.

The development of PARMS-PRIORITY is described to some detail in this paper, by describing the methodology, the modules, the input data, outputs and some of the development issues. The modules are based on key tasks: risk calculation, failure prediction, cost assessment, data exploration and scenario evaluation. The novelty and innovation lies in the application of the particular models within a particular context.

1.1 Available decision support systems

In response to the challenge for improved pipeline replacement strategies, a number of decision support systems have been developed around the world. A review of Decision Support Systems applied in Norway was provided in Sægrov *et al.* (2003). Jarrett *et al.* (2000) also provided a review of asset management models available for pipeline networks. Notable examples of Decision Support Systems around the world are included in Table 1.

TABLE 1: Decision Support Systems for pipeline replacement strategies

Name	**Reference(s)**	**Comments**
KANEW	Herz (1998)	Based on statistical analysis of pipe lifetimes for homogeneous cohorts of pipes. It can be used to identify appropriate lengths of pipes of different pipe material types to be replaced in each year. As it is a cohort based model, it does not allow for detailed prioritisation of pipeline renewals.
PRAWDS	Kleiner *et al.* (1998a, 1998b)	An exponential time model which statistically models breakage rates and an equation based model estimates pressure head loss with age. This model identifies optimised rehabilitation strategies.
WRAP	Geehman (1999)	Based on a scoring methodology where factors are given subjective weights. The failure predictions are not based on a strict statistical analysis of historical pipe failures, and improvements in failure predictions could allow for more cost-efficient strategies.
UtilNets	Hadzilacos *et al.* (2000)	A system which assesses the risk of a wider range of pipeline failures, within the same methodology. It was initially only developed for grey cast iron pipes. It utilises a wide range of information.
PARMS-PLANNING	Burn *et al.* (2003)	The predecessor of PARMS-PRIORITY, which is a system for long-term planning and budget settings. Forecasts are based on a Non-Homogeneous Poisson burst count model. This model is used for predictions of failure rates, expenditure and costs for a range of strategies.
CARE-W	Sægrov (2004)	Supports Water Utilities in going from a reactive approach, to a proactive approach for pipeline replacement. It provides prioritised replacement strategies and incorporates hydrological modelling to assess pipeline reliability in the renewal prioritisation methodology.

1.2 Scarcity of data

Recording and saving data are critical in the management of pipeline assets; however, it has often been a neglected issue. According to Cox (2003): "*collection of pipeline data begins with the asset creation process and also following renewal and rehabilitation of assets. If the correct data is not recorded at this stage, then all future data management processes will suffer the consequences. Historically, little thought has been given to how and what critical pipeline data was recorded, especially for the ubiquitous distribution network pipeline networks*."

Cox continues to argue that the lack of appropriate data has led Water Utilities to rely on overly simplistic models that treat particular pipeline populations as homogeneous, neglecting the critical differences in the pipeline networks. For example, in an investigation using intelligent pigging of 28km of pipes scheduled for replacement, only 8% were found to be in a condition that would result in short term failure, and over 75% of the pipes were in good or very good condition. This leads to the conclusions that there is a considerable need for data and models that will allow Water Utilities to more efficiently target pipes that are in poor condition.

In addressing these issues, Australian Water Utilities have improved the data management procedures and a significant number of Water Utilities have been able to build up detailed databases of pipeline failures. This has in turn allowed for improved statistical analysis and improved failure models, such as the Non-homogeneous

Poisson model that is used within the PARMS-PRIORITY model. With these models it is possible to more efficiently target pipes that are likely to fail.

2. OBJECTIVES

PARMS-PRIORITY is a Decision Support System (DSS) for use within Water Utilities, to support the decision making process of which pipe assets to replace, or whether to apply pressure reduction or shut-off valve insertion. A risk-based approach is employed to support users when making these decisions. There is a strong focus on data exploration, and the DSS includes a basic Geographical Information System (GIS). PARMS-PRIORITY is complementary to the previous PARMS-PLANNING system, and has been made possible by the new standard of data, which is now available at many Australian Water Utilities.

There are four major objectives:

1. *Assessing* current and future risk levels of a particular pipe and groups of pipes.
2. *Investigating* scenarios for risk reduction and cost efficiency of pipeline failure mitigation options, thus allowing for prioritisation between pipeline replacement or pipeline management work packages.
3. *Exploration* of pipe asset and failure data.
4. *Reporting* capabilities allowing Water Utilities to quickly collect data for reports.

By reaching these objectives, it is believed that a Water Utility can achieve:

- Better value for money when applying pipeline failure mitigation options: simply the application of better and more detailed failure predictions will allow for considerable savings, and in addition, other savings are likely to occur from a more consistent strategy.
- Reductions in pipe repair costs: initial testing of scenarios indicate that savings superior to what is achieved with a purely reactive strategy may be achieved with a considerably smaller number of pipeline replacements.
- Better data management practices.
- Consistent, sound and methodical routines for making renewal decisions.
- Improved reporting capabilities.

3. METHODOLOGY

The approach taken within PARMS-PRIORITY is to make analysis simple, and to provide many tools for data exploration. The analysis is based on risk analysis in the traditional sense often used within engineering where options are assessed based on their risk calculated as the probability of failure multiplied with the cost of failure. The cost of failure includes direct costs of repair, renewal and maintenance as well as indirect costs, such as loss of water, and externalities, such as inconvenience to customers. The basis of the process is the relatively high quality asset and failure records data which are now available within at least a handful of Australian Water Utilities.

3.1 Balance between reactive and proactive strategy

Water pipe failures span the range from “low probability and high consequence” to “high probability and low consequence” (see Fig. 1); and the risk associated with failure depends on which category a pipe belongs.

A water authority can apply either a reactive or a proactive strategy in managing a pipe asset. A reactive strategy is based on stimulus in the form of events that trigger replacement actions; for example, when a pipe has 3 or more failures within a year. In contrast, a proactive strategy is future oriented in that replacement and operational decisions are based on the anticipated evolution of failure rates in order to minimise costs and/or avoid other undesirable outcomes.

The “low probability and high consequence” pipe failures are usually managed using a proactive strategy. The “high probability and low consequence” pipe failures are usually mitigated using a reactive strategy. The primary focus of PARMS-PRIORITY is on the “high probability and low to medium consequence” pipe failures and therefore strategies are towards the reactive end of the spectrum. This essentially means no condition monitoring, no active protection methods such as cathodic protection and in most cases, only a pipe that has failed is considered for replacement.

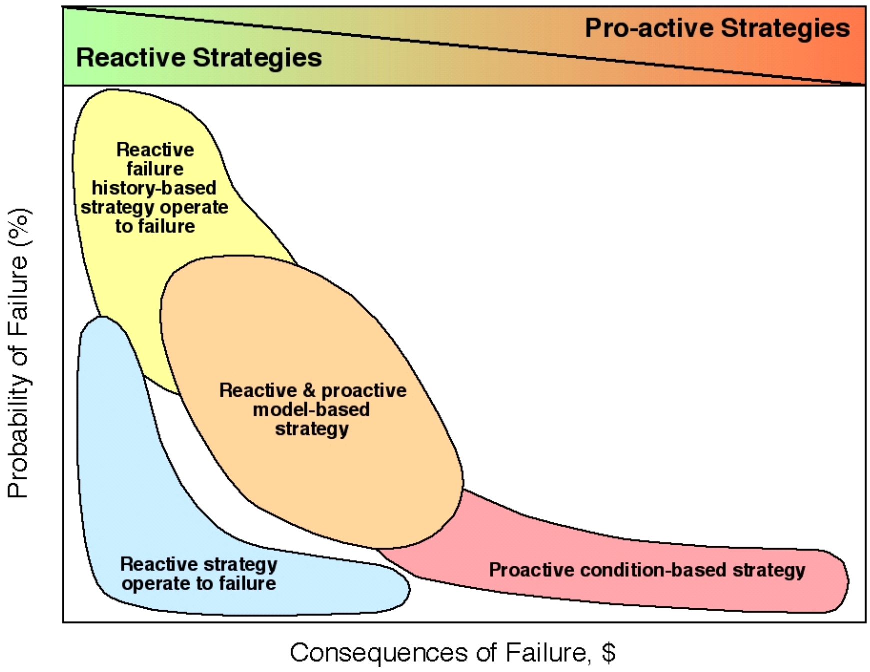


FIG. 1: Asset management strategies for assets with different failure frequencies (Burn et al. 2004).

A motivation for using a partly reactive strategy is that the process of pipe failure is complex and depends on a number of influences which are mostly unknown. It is motivated because the aggregate information of such influences is partly embedded in the failure history of a pipe (D'Agata, 2003). PARMS-PRIORITY also allows for implementing a proactive strategy in the sense that decisions can be made through a prioritisation process which is based on the predictions of future costs under different actions and scenarios.

3.2 Process and modules

Fig. 2 outlines the process in a very general sense, where the data feeds into cost assessments, failure predictions and data exploration modules. The assessed costs and probabilities of failure are then used within a scenario evaluation module, in which scenarios that have been identified in the data exploration module can be further analysed. Finally, the activities related to the analysed scenarios are prioritised and chosen for implementation.

The key modules within PARMS-PRIORITY are the following:

1. Risk calculation,
2. Failure predictions,
3. Cost assessment,
4. Scenario evaluation and
5. Data exploration.

There are also two key data sets

- Input data: asset and failure records and
- Outputs: a range of types useful for decision making

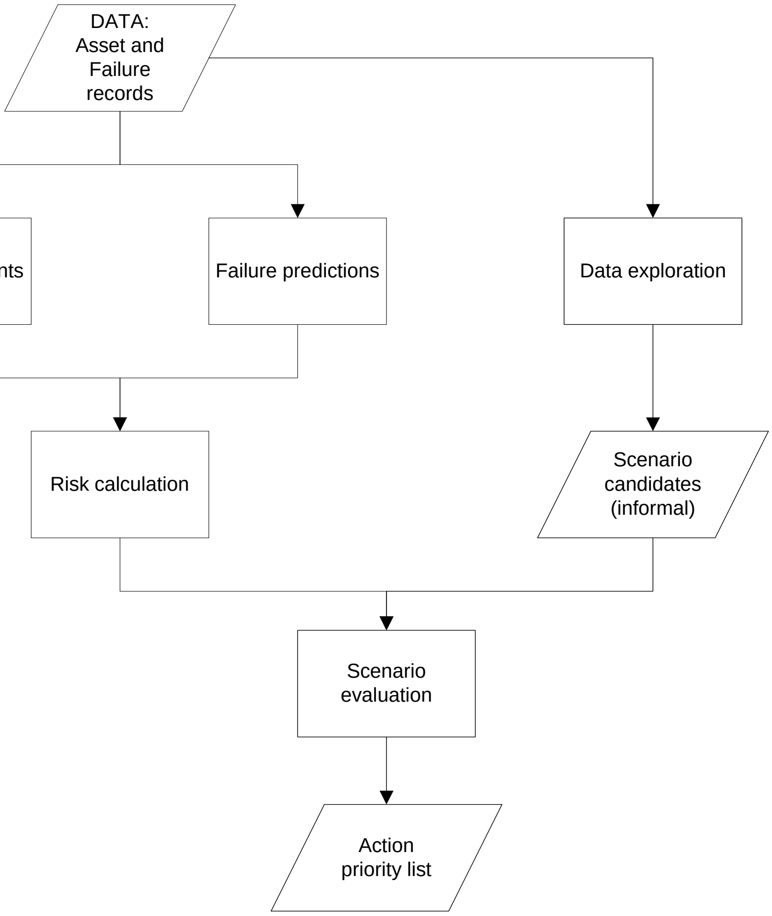


FIG. 2: Methodology applied within PARMS-PRIORITY.

4. MODULE 1: RISK CALCULATION

A risk based approach is based on the calculation of risk for different actions and scenarios. Risk here refers to an uncertain event with unwanted consequences; the uncertain events being only pipeline failures; specifically pipe failures in the range of low to medium consequence of failure. Risk is used to analyse various identified scenarios and their related actions, as seen in Fig. 2.

The appropriate risk measure is calculated as the statistical expectation of future costs caused by failure as follows:

$$R = E(C) \tag{1}$$

where R is the risk, C is a stochastic variable that refers to the uncertain future cost of failure, and E refers to the statistical expectation value of this stochastic variable. When there is only one possible failure and the cost of failure, C, is known, the risk, R is calculated as follows:

$$R = p_f \cdot C \tag{2}$$

where p_f is the probability of failure and C is the cost of failure. Examples of calculations using Eq. 1 and Eq. 2 are given in the following:

- *The costs and consequences of failure is given at* $C=\$10000$ *per failure; while the probability of failure* $P = 0.05$ *(only a maximum of one failure is possible). The risk of failure is calculated as:* $R = C \cdot P = \$10000 \cdot 0.05 = \$500$.
- *The costs and consequences of failure is given at* $C=\$10000$ *per failure. The expected number of failures is* $E(F) = 2.1$*.The risk of failure is then calculated as:* $R = C \cdot E(F) = \$10000 \cdot 2.1 = \$21000$.
- *The costs and consequences of 1 failure is given at* $C_1=\$5000$ *while the cost and consequences of 2 failures are valued at* $C_2=\$15000$*; probability of 1 failure* $P_1=0.05$*, and the probability of 2*

failures $P_2=0.01$. $P_0=0.94$. The risk of failure is then calculated as: $R = C_1 \cdot P_1 + C_2 \cdot P_2 = \$5000 \cdot 0.05 + \$150000 \cdot 0.01 = \$2500 + \$1500 = \$4000$.

5. MODULE 2: FAILURE PREDICTION

A key component of risk assessment and risk calculations is the ability to assess the failure rate or probability of failure. The failure prediction models are based on both a statistical Non-Homogeneous Poisson model as well as a physical/probabilistic model which provide failure rates and failure probabilities for each year into the future. For reviews of pipeline failure prediction models, see Rajani *et al.* (2001) and Kleiner *et al*. (2001). In the case of the Non-Homogeneous Poisson model the predicted number of failures in each asset in each year is the product of three factors as detailed in Eq. 3 (Jarrett *et al*., 2003b):

$$\mu = g(L) \cdot f(\theta) \cdot k(t) \tag{3}$$

where μ is the predicted number of failures, g is a function of the length L, f is a function of θ which consists of covariates, such as pressure, soil type, diameter and material type, while k is a function of t, which is the age of the pipe in years since installation.

In the case of the physical/probabilistic models, the failure prediction is based on fracture mechanics theory using the pipe material and operating characteristics (Davis *et al*., 2004).

While the Non-homogeneous Poisson model accurately models the average number of failures within a population of pipes, it needs to be modified slightly to allow for good predictions on an individual pipe level. The number of failures varies more widely in reality than in the Poisson model and therefore, the extra information given by the number of observed failures for an individual pipe can be used to improve the failure predictions for that particular pipe. This is done by what is referred to as a Best Linear Unbiased Predictor (*BLUP*), which is calculated as follows (Jarrett *et al*., 2003a):

$$BLUP = (1-\phi) \cdot \mu + \phi \cdot x \tag{4}$$

where ϕ is a weight determined from data, and x is the observed and μ the expected number of (matched) failures in the asset over the recording period. If the expected number of (matched) failures, μ, agrees with the observed number x, the *BLUP* prediction is the same as the expected number μ.

Normally, failures are classified into different failure modes and the relative proportions of failure modes vary between different pipe materials as well as between different operating conditions and soil environments. The failure prediction models at this stage do not distinguish between failures in different failure modes, although it is planned to incorporate this feature in future models.

To allow for tailoring the failure predictions models to individual Water Utilities, there is a need for extensive data on recorded failures. Having multiple years of data provides more accurate estimates and less sensitivity to the variation in the number of failures between years. However, having only two years of failure data still provides enough qualitative information, which allows for comparison between different pipe types by utilising information obtained from Water Utilities with up to two decades of data.

6. MODULE 3: COST MODELS

The cost model is similar to the cost model in PARMS-PLANNING (Burn *et al*., 2003) and is based on user input, where the specific costs are classified into categories relating to:

- Pipeline renewal: the costs of trenching or trenchless replacement of an old pipe with a new pipe. This includes the machinery and salary costs, as well as material costs and traffic management costs. The cost will vary depending on diameter, surface type (road, footpath or verge), replacement material, and type of traffic conditions.
- Valve insertions: the cost of inserting a pressure reduction valve or a shut-off valve. The cost depends on the diameter of the required valve. These costs refer to insertion, valve and maintenance.
- Pipe repairs: these costs refer to the repair of a broken pipe; and depend on the failure mode, the diameter and the pipe material type as well as on the surface type. Call-out costs, which are rolled into the pipe repair cost category, depend on the area (suburb) of the pipe. Other repair costs refer to: trenching, labour, material (backfill, clamps, and pipes), reinstatement, etc.

- Supply interruptions: this refers to penalties, rebates, loss of goodwill, and customer inconvenience and is given on a scale that increases with the number of interruptions for an individual customer. It also varies with the population density of a given area (suburb).
- Failure consequences: refers to flood damage that is caused by a broken pipe as well as lost water, installation of temporary water supply, and other costs relating to administration and customer service.

The costing of supply interruptions is a novel approach by which the cost per supply interruption increases if there are multiple interruptions to a single customer. This is based on the findings by Speers *et al* (2002), where surveyed customers were found to cope with short interruptions. The components of an interruption that were deemed important in terms of inconvenience were:

- Duration of the interruption,
- Advance notification of the interruption,
- Time of day of the interruption and
- Number of interruptions per year.

PARMS-PRIORITY allows the user to take these factors into account, except for the duration of an interruption. Of particular interest are the costs of supply interruptions that are given on a scale increasing with the number of supply interruptions. For instance the cost of three interruptions to a single customer is higher than three supply interruptions for different customers.

Speers *et al.* (2002) also found that compensation was generally not expected for planned and unplanned interruptions by domestic customers, but customers were more interested in having the problem fixed. In contrast, commercial customers, who lost business due to interruptions were very interested in compensation. Consequently according to these findings, it means that whilst Water Utilities should not feel obliged to compensate domestic customers that have been affected; the Water Utility may have a responsibility to compensate commercial customers.

The costs of supply interruptions need to include risk calculation and therefore it is necessary to have the probability distribution for the number of interruptions for a given customer. To start with, the probability of a service supply interruption can be calculated from the probability of failure and the probability of service supply interruption given a failure through the application of Bayes formula (Gut, 1995):

$$P[I] = P[I \mid F] \cdot P[F] \tag{5}$$

where *I* represents a service supply interruption, and *F* represents failure.

The probability of service supply interruption given a failure depends on the distribution of failure modes; because some failure modes require turning off the water, while others such as perforations and circumferential failures can be repaired using a clamp without turning off the water. Because the distribution of failure modes changes with the material type, and the local conditions, the probability of a supply interruption given a pipe failure is calculated for each material as:

$$\hat{p}_S = \hat{P}[I] = {}^{s}\!/_{f} \tag{6}$$

where s is the number of supply interruptions, f is the number of failures, and $\hat{p}_S$ is the estimator for the conditional probability of a supply interruption. Please note that estimators are indicated via a “hat” notation. For instance, the parameter p is estimated using an estimator $\hat{p}$.

The estimator in Eq. 6 is common in cases of Binomial distributions, and the underlying assumption is that the number of supply interruptions can be described using a Binomial distribution with the number of trials equals the number of failures; where the conditional probability of supply interruption is the same for each failure.

The probability distribution for the number of supply interruptions in a year for a single customer can generally be described as the number of supply interruptions within a shut-off block, or another group of pipe assets, where a shut-off block is the pipe network between shut-off valves. A prerequisite for calculating this risk of multiple supply interruptions is that the failure prediction models provide probabilities of failure for individual pipes; which is provided through the Non-homogeneous Poisson or physical probabilistic models. Once the individual failure probably distributions have been transformed to probabilities of interruptions as per Eq. 5, the probability distribution for the shut-off block can be calculated using probability generating functions (Gut, 1995). This involves a transformation of the probability of failure/supply interruption distributions for individual pipes to polynomials, and subsequently to multiply the individual polynomials, as in Eq. 7:

$$g_b(s) = \prod_{i=1}^{n} g_i(s) \qquad (7)$$

where $g_b(s)$ is the probability generating function describing the probability distribution for the number of supply interruptions within a shut-off block, b. $g_i(s)$ is the probability generating function describing the probability distribution for the number of supply interruptions for pipe asset i, within a shut-off block, b. Also, n is the number of pipe assets in the shut-off block b; and s is a generating function variable. A probability generating function is a transform of the probability function for a non-negative integer valued stochastic variable. It is a polynomial where the coefficients relate to the respective probabilities in the probability function.

The probability generating function (polynomial) for the shut-off block can then be transformed back to a probability distribution. All these calculations are implemented in the Python programming language using Object-Oriented Programming to create a Polynomial class which allows for automatic polynomial multiplication, and other polynomial manipulations.

7. MODULE 4: SCENARIO EVALUATION

There are four types of scenarios:

- Pipeline renewal,
- Pressure reduction scenarios,
- Shut-off block reduction scenarios and
- Cluster pipeline replacement scenarios.

All four scenarios refer to different risk mitigation options.

7.1 Pipeline renewal

Pipeline renewal is essentially replacing an old pipe with a new pipe. This reduces failures in the long run but it is also known that some pipe materials have a “bathtub-like” lifetime probability distribution, meaning that there will be a relatively high frequency of failures in the time period immediately following installation. As a consequence of the degradation process, after the initial period, failure rates will increase with time according to some function, albeit for some pipe materials rather slowly. To make pipeline renewal a cost efficient option, it is critical to replace pipes with expected high failure rates with pipes with expected low failure rates. While most new pipe materials such as PVC (polyvinyl chloride), PE (polyethylene) and Ductile Iron (DI) have low failure rates, the task to find pipes with high failure rates to replace is more difficult. This requires analysis of existing failure data, or modelling of the pipe and its environment.

7.2 Pressure reduction

A buried pipe has an inherent strength by which it can resist the internal and external forces: soil loading and internal pressure. As the pipe deteriorates with age, the strength of the pipe is reduced; making it increasingly vulnerable to loads that will eventually exceed the pipe’s remaining strength value. Therefore, an option used to reduce the number of failures is to reduce the operating pressure in the network, by using pressure reduction valves in specific high-pressure zones. It should be noted, however, that when decreasing the limit value of the load at which a pipe fails, pressure reduction only increases a pipe’s lifetime for a finite period, and this will delay pipe failure but not eliminate its occurrence. The Non-homogeneous Poisson statistical model for forecasting pipeline failures uses pressure as one of the covariates. This means that the calculated failure prediction for a particular pipe will change with a change of pressure. This in turn allows for investigating the probable effects of reducing the operating pressure in a certain pipe or a region in the pipe network, such as a Pressure zone.

To run a pressure reduction scenario, the user needs to specify:

- The pressure zone under investigation,
- The intended pressure decrease given in metres head and
- The diameter of the pressure reduction valve, which will implicitly give the expected valve lifetime, its maintenance costs, and its installation costs.

The results of such an investigation give:

- Expected number of failures for each year up until the prediction horizon, with pressure reduction and without pressure reduction implying fewer expected pipe failures.
- Expected savings as a consequence of fewer pipe failures.
- Financial indicators: Return on investment, Payback period, Net-present value of savings, Lifecycle cost of the valve, etc.

This feature allows water authority to prioritize pressure reduction efforts so that the maximum benefit is achieved, and to investigate where it is appropriate to install pressure reduction valves.

7.3 Shut-off block reduction

Shut-off block reduction refers to reducing the number of customer connections being affected by customer supply interruptions in a particular area. It is an option that does not actually reduce the number of pipeline failures but reduces the consequences of failures, or more specifically the number of supply interruptions to customers. Pipeline failures lead to customer supply interruptions in the service to private, commercial or industrial customers. First, such customer supply interruptions can lead to costs to customers, which customers can sometimes refer back to the Water Utility through insurance claims or legal processes. Second, customer supply interruptions also lead to inconvenience and disturbance to a customer, with loss of goodwill to the company and customer dissatisfaction. Third and most importantly, customer supply interruptions are regulated in some Australian states, and customer supply interruptions are important in a Water Utility's key performance indicators, on which they have to report. Therefore, Water Utilities are often eager to reduce the number of customer supply interruptions. An option for reducing the number of customer supply interruptions is a reduction of the size of a city block (or network) that is shut-off. The size of block being shut-off is governed by the locations of the shut-off valves, and this dictates which customers will be without water in the event of a significant pipe failure. Inserting additional shut-off valves in the network will reduce the size of a shut-off block and the number of customers affected.

7.4 Cluster replacement scenarios

Because of relatively high setup costs, pipeline renewal is often more efficient if it is done in clusters rather than on an individual pipe-by-pipe basis. Clusters of pipes can be chosen for instance on the basis of shut-off blocks with many previous failures, and with many supply interruptions; or on the basis of an area with high predicted failure rates; in both cases leading to high risk. When a high risk area has been identified through this fairly simple process, the area is analysed in more detail so that a decision can be made to establish exactly which pipes to replace. The decision to replace a cluster of pipes is done in a sequential process as described below:

1. **Shut-off block triggered:** A pre-specified event, such as 3 failures in the last 12 months, triggers a shut-off block to be considered for analysis; or alternatively a pipe is identified as a suitable candidate for replacement on a specific characteristic such as water quality or high predicted failure rates.
2. **Shut-off block query**: In a query on the database, the shut-off block is identified as a candidate for cluster analysis; or a pipe has been identified by the combined use of database queries and tables of key indicators such as relating to cost predictions and/or failure predictions.
3. **Cluster analysis**: Pipes within the cluster can be chosen for replacement, and the expected reduction in failures and costs can be calculated to provide payback periods, and other financial indicators.
4. **Add pipes to cluster:** If the user chooses, additional pipe assets in nearby shut-off blocks can be added to the renewal cluster for analysis. This is done by simply clicking on a pipe asset within the GIS.
5. **Construction of renewal project**: Once the user has decided on whether pipe renewal or shut-off valve insertion is appropriate and which pipe assets to include in the renewal project, a renewal project object is saved for later consideration.
6. **Prioritisation of renewal projects**: The renewal projects can be ranked based on various indicators, such as the reduction in number of failures, payback period, return on investment, etc.

The process for investigating whether shut-off block insertion is appropriate is embedded into the cluster replacement scenarios analysis.

8. MODULE 5: DATA EXPLORATION

Because of the improved data quality at many Australian Water Utilities, it has been possible to incorporate a range of more sophisticated features into the new tools for pipe asset and failure data exploration, such as:

- **Database query tools:** The user can query the database, allowing users with less database experience to quickly identify groups of pipes that are of particular interest. This is also helpful for providing the wide range of reports that a Water Utility requires, as well as in exploring spatial differences between regions, differences between certain pipe materials and diameters, etc. For instance, to identify renewal candidate pipes, the Water Utility can find all pipes that have had more than a given number of failures within a given time period. A database query results in a selection of pipes which can be further analysed.
- **Data summary tools:** Summaries and histograms of relevant properties for selected network components are displayed. These summaries and reports are useful in exploring and reporting.
- **Geographical Information System:** The Geographical Information System is implemented using MapObjects LT to provide the user with basic features such as displaying a selection of pipes, highlighted in the spatial network. It also allows users to add additional pipes into a pipeline renewal cluster.
- **Aggregate tables:** Aggregating material types, shut-off blocks, suburbs, pressure zones, soil type and location types; allows the user to quickly identify troublesome areas or pipe types.

8.1 Database queries

A user interface enables querying the pipes table in the database, which allows the user to narrow down the search for pipe renewal candidates. Fields that can be queried are:

- **Pipe characteristics:** Material type, Pipe diameter, Operating pressure, Length of the pipe asset
- **Spatial location:** Asset ID, Shut-off block ID, Pressure zone, Location, Suburb, Soil, Hot spot area
- **Failures / Interruptions:** Number of failures or interruptions within a time period
- **Special treatment categories:** whether there is any reason to treat some pipes separately

In addition, graphical outputs such as histograms provide a visual image of the attributes of pipe failures and their occurrences in different pipe groups. The histograms refer to either failure properties or pipe properties. For instance, the Failure Modes histogram identifies the severity of the failures in the selection, and provides information about how pipes have failed. It is not difficult to imagine that a different action would be recommended depending on whether pipe failures were mainly joint leaks or perforations rather than pipe failures due to blown sections and circumferential fractures. Some types of failure modes indicate a corrosive soil is present while other failure modes indicate that a large proportion of failures are due to soil movements; and hence are dependent on seasonal variations. Another example is the information given from the Operating Pressure histogram which indicates whether pressure is high or low, and whether pressure reduction could be a useful option.

8.2 GIS features

Pipe selections can be viewed in the GIS feature, which has been implemented using Map Objects LT. Information about Map Objects LT can be found at http://www.esri.com/software/mapobjectslt/. In PARMS-PRIORITY this feature is used for two reasons:

- **Display selections of pipes:** A spatial network can be displayed with pipes in a specified category highlighted in a different colour. The user can also click on individual pipes in order to bring up properties. This display is linked to the database query, so that the resulting selection from a query can be displayed.
- **Viewing work packages and adding new pipes into a pipe cluster:** When analysing and specifying a work package, it is important to investigate whether there are pipes in the vicinity that ought to be replaced at the same time. This is particularly appropriate when there is a reason to visit the site for replacements; for example, when triggered by a pipe failure; or when cost savings can be achieved via simultaneous replacement.

8.3 Visualisation of predictions

The user can display both the failure and cost predictions for a pipe selection or for individual pipes. A selection can be loaded into a failure predictions module. Results can be displayed in a table or in a graph, as well as for an individual pipe or for an entire selection. For individual pipe assets, the probabilities of failure can also be viewed. In the table, pipes can be ranked based on the various categories: failure rate, flood damage cost, repair costs or total costs. The net present values are calculated by aggregating the costs for the individual years until the time horizon year; which is set by the user.

The ranking based on failure rates and other indicators allows the user to prioritise the need for pipeline renewal between different pipe assets that are already candidates for pipeline renewal. Like all other pipeline failure prediction models, the failure predictions do not distinguish between different failure modes. While it is theoretically possible to achieve such failure predictions, they would generally require larger data sets than are currently available.

9. INPUTS: ASSET AND FAILURE RECORDS

The asset and failure records data are stored in a Microsoft Access database, with tables for asset and failure records. These datasets are further described below.

9.1 Asset records

The asset records table contains information as shown in Table 2. The fields in Table 2 are arranged in decreasing order of need. Fields 1-6 are critical; fields 7-11 are very useful; and fields 12-15 are useful but not critical for running PARMS-PRIORITY.

TABLE 2: Fields in Pipes Database Table

Field Name	Description	Example
1. Asset ID	Unique identifier of a pipe.	1332112
2. Material type code	Material type according to given classifications, such as CICL (Cast Iron Cement Lined), DI (Ductile Iron) or MS (Mild Steel).	CICL
3. Length of pipe	Length of the pipe in metres.	123.2
4. Diameter	Nominal diameter of a pipe in millimetres, typically between 20mm and 450mm.	100
5. Operating pressure	Pressure of the water inside the pipe in metres.	72.3
6. Construction date	Date of installation in the form YYYYMMDD.	19750802
7. Shut-off block ID	Unique identifier of a shut-off block. A shut-off block consists of the number of pipes that will be without water in the case the shut-off valves are turned off. It is defined through its enclosure of shut-off valves.	1233861
8. Pressure zone	Unique identifier of the pipe's pressure zones. Pressure zones are pipe groupings that are often used by Water Utilities to indicate areas with relatively homogeneous pressure levels.	Frankston
9. Number of customer connections	Number of customer connections along the pipe asset	31
10. Coordinates of end nodes	x-y coordinates of the end nodes, as well as one z-coordinate.	1233165.1,12335.3,1233196.1, 12335.3, 32.1
11. Suburb	Area (suburb) where the pipe is located, in the form of a suburb name.	Langwarrin
12. Soil type code	Type of soil, typically clay, sand, etc.	Sandy Clay
13. Location	Classification of the type of area, typically Outer Suburban, Inner Suburban or Central Business District (CBD).	Inner Suburban
14. Lining	Type of lining of the pipe.	Unlined
15. Number of failures	Number of recorded pipe failures that have occurred in pipe asset since installation (this field is in fact queried from the Failures Database Table in Table 2).	1

9.2 Failure records

The required ‘Failures’ data table can contain information as shown in Table 3. The fields 1-3 are critical; field 4 is useful but not critical; information in fields 5-14 improves cost models; fields 15-16 provide information about a failure which may prove useful in decision making, but is not critical for running PARMS-PRIORITY.

TABLE 3: Fields in Failures Database Table

Field Name	Description	Example
1. Failure ID	Unique identifier of a pipe failure.	7421
2. Asset ID	Unique identifier of a pipe and link to Pipes Database Table.	1332112
3. Failure date	Date of the failure in the format YYYYMMDD.	20011215
4. Failure type	Failure mode as per definitions in Davis *et al*. (2001).	Circumferential failure
5. Time of failure	Time of day at which the failure was reported. Format: HHMM.	1500
6. Coordinates	Coordinates of the failure, if such coordinates are collected.	1233165.1,12335.3
7. Number of supply interruptions	Number of times which the water had to be turned off due to the failure.	2
8. Pipe length replaced	Length of pipe that was replaced in metres.	7.1
9. Cost of repair	Cost of repairing the pipe in dollars ($).	2900
10. Flood damage	Whether there was flood damage due to the water emanating from the broken pipe: yes/no.	Yes
11. Cost of damage	Total cost of the damage in dollars ($).	2300
12. Type of repair	Type of repair required to fix the broken pipe; e.g. clamping, pipe replacement, replace joints, etc.	Pipe replacement
13. Temporary water supply installed	Whether temporary water supply was installed.	Yes
14. Comment	Any comment relevant to the future maintenance, renewal decision or other management of the broken pipe. Examples: “below groundwater”, “optic cable next to pipe”, “traffic management is difficult”, “angry customer”, “difficulties in finding valve”, “caused traffic delays”, “poor street lighting”, etc.	Angry customers
15. Road name	Street name at which the pipe failure occurred.	Blanche Pde
16. Map reference	Reference to some chosen map.	43J3

Failure here refers to a pipe failure in accordance with the terminology specified by Davis *et al*. (2001):

- **Blown section:** Removal of a piece of pipe wall. This form of failure is brittle in nature. Size can vary depending on pipe material but generally greater than 100 cm^2.
- **Perforation:** Small holes usually less than 10 mm^2.
- **Circumferential failure:** A single crack extending part or full way around the pipe circumference.
- **Longitudinal split:** A crack along the pipe axis. The length can vary from a few mm to the full length of the pipe.
- **Joint leaking:** Water leakage through the joint, and not a fitting failure.
- **Fitting failure:** Damage to fitting.
- **Other:** Failures that do not fit to another class.

When collecting failure records data, it is not only the time period over which failure data has been collected that is important, but the accuracy of reporting is also critical as it considerably reduces the need for data cleansing. Typical issues and sources of error relating to the recording of failure data are:

- Not all failures are linked to a pipe asset; and therefore matching rates are calculated as the proportions of failures that were matched to pipe assets in each of the failure recording years.
- Due to climatic variations or possible oscillations in temperature or rainfall there are variations in the number of failures in different years. Therefore, failure predictions based on only a limited number of years (e.g. 1 or 2 years) of failure data may overestimate or underestimate the number of failures.

9.3 Other inputs

In addition to failure and asset records, the user can enter additional information about a particular pipe, such as:

- Whether a pipe belongs to a special treatment category, Examples include: 'Water quality issues', 'Hydrological issues', 'Angry customers', 'Vicinity of tram line', 'Planned construction work'.
- Whether a pipe lies within a user-specified 'Hot spot'.
- Whether the pipe will be part of a pressure reduction program.
- Other customer complaints information.

10. OUTPUTS: EXAMPLES

To illustrate the use of PARMS-PRIORITY in practice, three examples are given below:

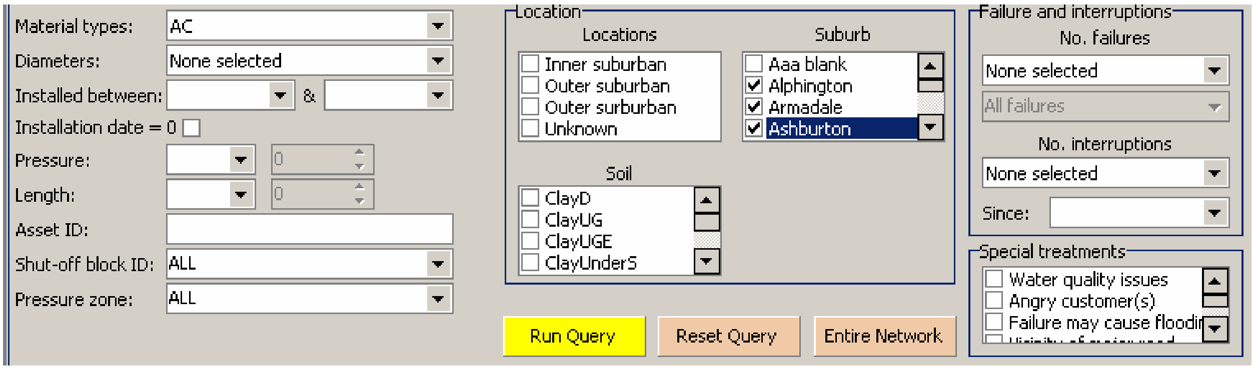
1. Data exploration,
2. Comparison of historical and predicted failure rates and
3. Scenario analysis.

10.1 Example 1: Data exploration

Exploring the data is the first step towards understanding the data. There are many aspects which ought to be taken into account in the decision making processes, such as what are the typical causes of failures for a certain group of pipes. This may potentially inform the user about how such failures can be prevented. This data exploration also provides focus to the decision making process in the sense that it allows the user to identify scenarios and action plans which can be analysed using risk analysis.

The following series of exploration is typical for what you can do in PARMS-PRIORITY:

1. Querying the Asbestos-Cement asset records for pipes within certain suburbs. Fig. 3 shows how a database query is specified and some of the filtering options that are available.
2. Displaying those assets within the network, using GIS as shown in Fig. 4.
3. Viewing of the failure records for these assets, aggregated on an asset-by-asset basis. In this particular example, several pipe assets may have a limited number of failures and interruptions, but one pipe asset may have multiple failures and interruptions, indicating that this pipe needs to be assessed in terms of replacement. This feature narrows down the search for potential renewal actions.
4. Viewing of the summary for this selection of assets. Examples of summary information are:
   - There are 36 assets in the selection.
   - There is a total length of 2.36km of pipes.
   - There were 42 recorded failures over the 7 year failure recording period.
   - The average pipe age is 58 years.
   - The selection has had a failure rate of 253 failures per 100 km per year; which is significantly higher than the network average of 53 failures per 100 km per year. This indicates that this group of pipes has had high recorded failure rates and should hence attract more attention than other groups of pipes.
5. Viewing the histogram of failure modes for this selection of assets, which gives a break down of which failure modes that the recorded failures have been linked to. In our example, there are 19 failures described as 'Longitudinal Splits' and 13 failures described as 'Piece blown out'. In fact, these two failure modes represent over ¾ of all failures within the pipe selection. 'Longitudinal splits' indicate failure because of high internal pressure, while the failure mode 'Piece blown out' indicates more dynamic failures, such as can be expected from pressure surges (Davis, 2005). In light of this information it is possible that pressure management is an alternative for this particular group of pipes.


Material types: AC
Diameters: None selected
Installed between: &
Installation date = 0 ☐
Pressure: 0
Length: 0
Asset ID:
Shut-off block ID: ALL
Pressure zone: ALL

Location
Locations
☐ Inner suburban
☐ Outer suburban
☐ Outer surburban
☐ Unknown

Suburb
☐ Aaa blank
☑ Alphington
☑ Armadale
☑ Ashburton

Soil
☐ ClayD
☐ ClayUG
☐ ClayUGE
☐ ClayUnderS

Failure and interruptions
No. failures: None selected
All failures
No. interruptions: None selected
Since:

Special treatments
☐ Water quality issues
☐ Angry customer(s)
☐ Failure may cause floodi

FIG. 3: Specifying database query to retrieve selection of pipeline assets.

FIG. 4: GIS display of selected assets.

10.2 Example 2: Comparison of historical and predicted failure rates

The calculation module provides a capability for calculating failure predictions for any selection of pipe assets. Also historical failure rates are calculated by simply taking the number of failures for the selection in each year and dividing by the total pipe length of the selection. After having calculated both historical and predicted failure rates, it is possible to compare and evaluate how these failure rate curves relate to each other.

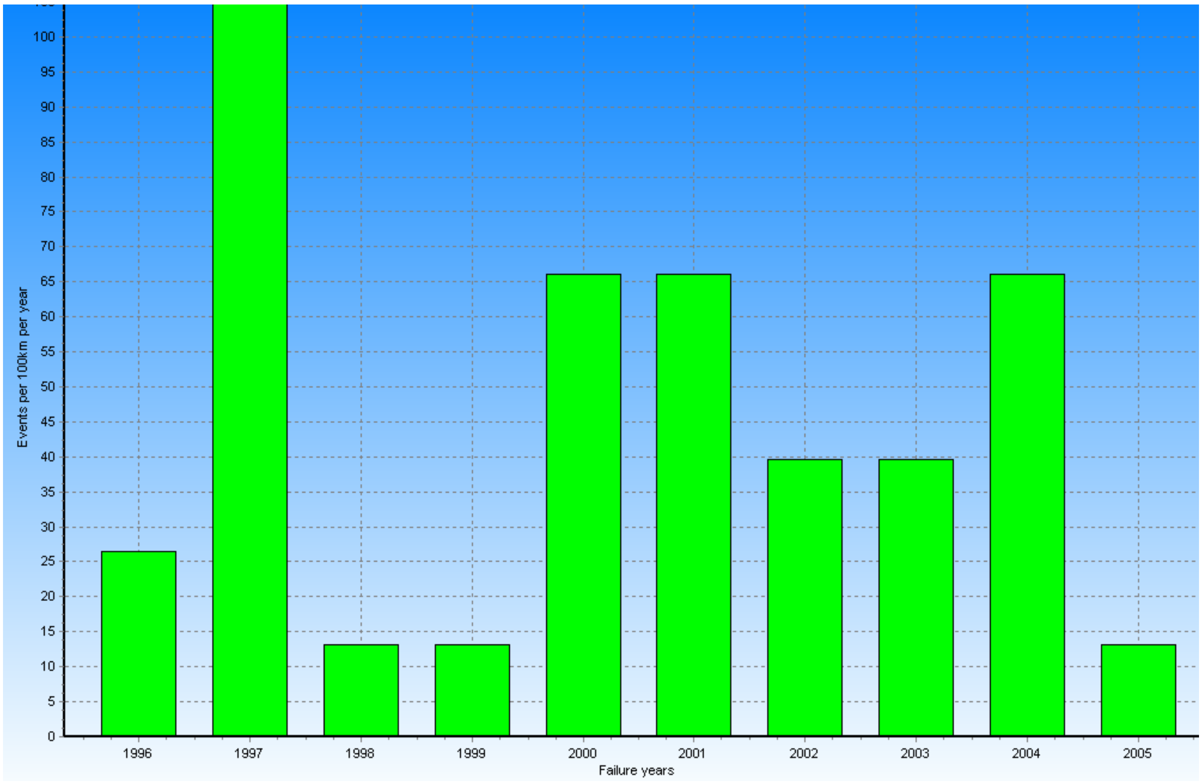


FIG. 5: Selection failure rates for each year in the failure history (1996-2005).

Fig. 5 shows the observed failure rates for a subset of Cast Iron pipes in the network, in the years during which failures have been recorded 1996-2005. It is observed that failure rates vary between around 12 failures per 100km per year in some years and up to approximately 105 failures per 100km per year in 1997. The average failure rate for all years is approximately 43 failures per 100km per year.

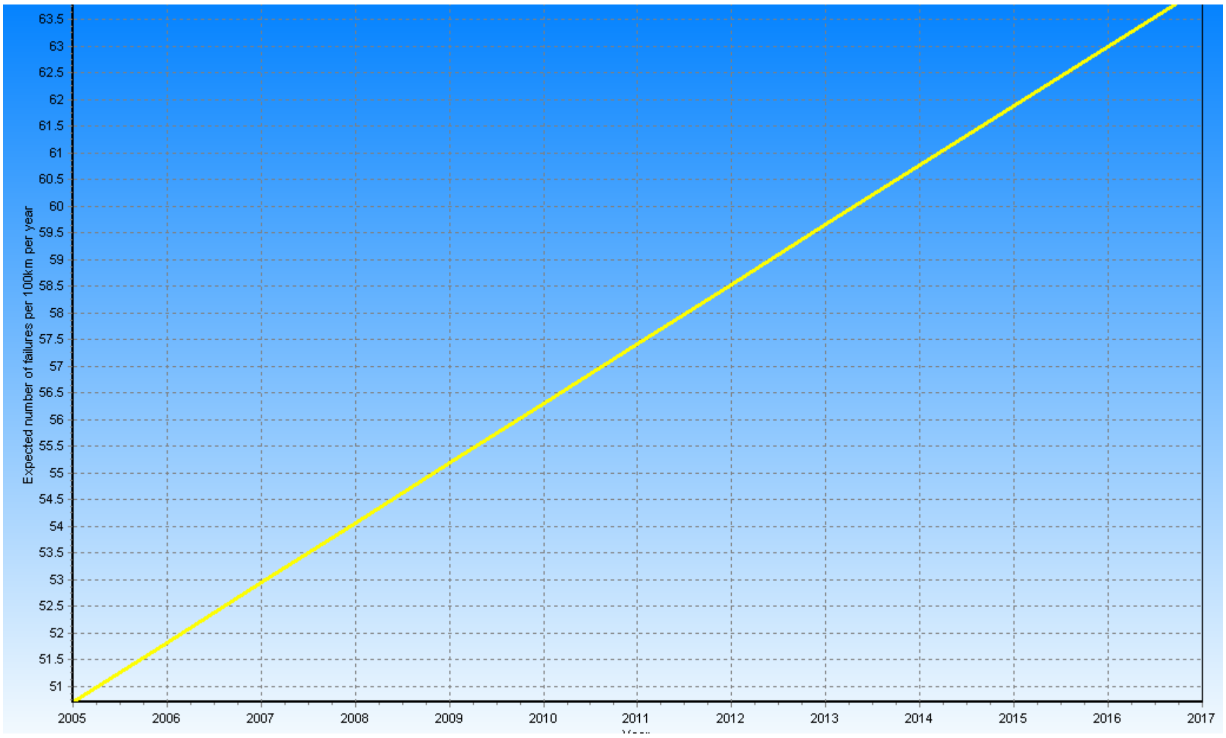


FIG. 6: Predicted failure rates for 13 years into the future (2006-2017).

Predictions of failure rates for any number of years into the future can be calculated and viewed. As can be seen in Fig. 6, the failure rates for the selection used in Fig. 5 start at about 50 failures per 100km per year and increases linearly to about 64 failures per 100km per year. This seems like a reasonable extrapolation of the historical failure rates seen in Fig. 5 but it is also noted that there are 2 discrepancies:

1. The failure predictions appear to be slightly higher than what would be expected from a straight extrapolation of the historical failure rates.
2. There is considerable random variation from year to year in the historical failure rates, while there is no such random variation in the failure prediction models.

Both these discrepancies are to some extent expected, because:

1. In terms of discrepancy number 1, a good failure prediction model takes information collected in the entire network to find the expected behaviour based on factors that have a statistically significant influence. Assuming some level of random variation, within populations that have the same values on covariates, some sub-populations will have higher failure rates, and others will have lower failure rates. In a good statistical model however where all systematic variation is accounted for, information from such random variations should not be used for making judgements on future failure rates.
2. In terms of discrepancy number 2, the output of the failure prediction model represents an average year. In reality failure rates will vary from year to year for a range of reasons. With the current state of knowledge, it is not possible to predict whether one year will have higher failure rates than another.

10.3 Example 3: Scenario analysis

Analysing alternative scenarios using risk analysis is useful for evaluating which option to choose. An example of a scenario comparison is given in Fig. 7 where it can be seen that pressure reduction reduces the number of failures by approximately 3 failures per year. Whether pressure reduction is economically justified is then assessed within a cost prediction model, where the cost of pressure valve installation and maintenance is compared to the predicted cost reduction. If the cost of valve installation and maintenance is lower than the predicted cost reduction, valve insertion is recommended. Results of the analysis are also used to calculate numbers such as the payback period, and the return on investment.

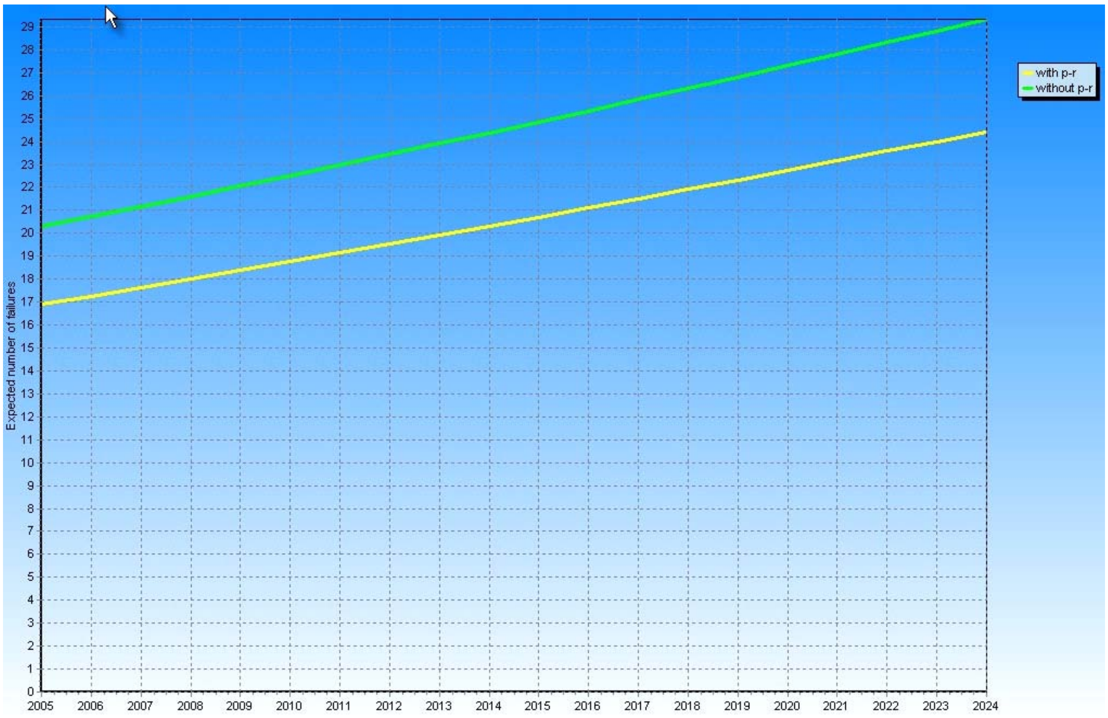
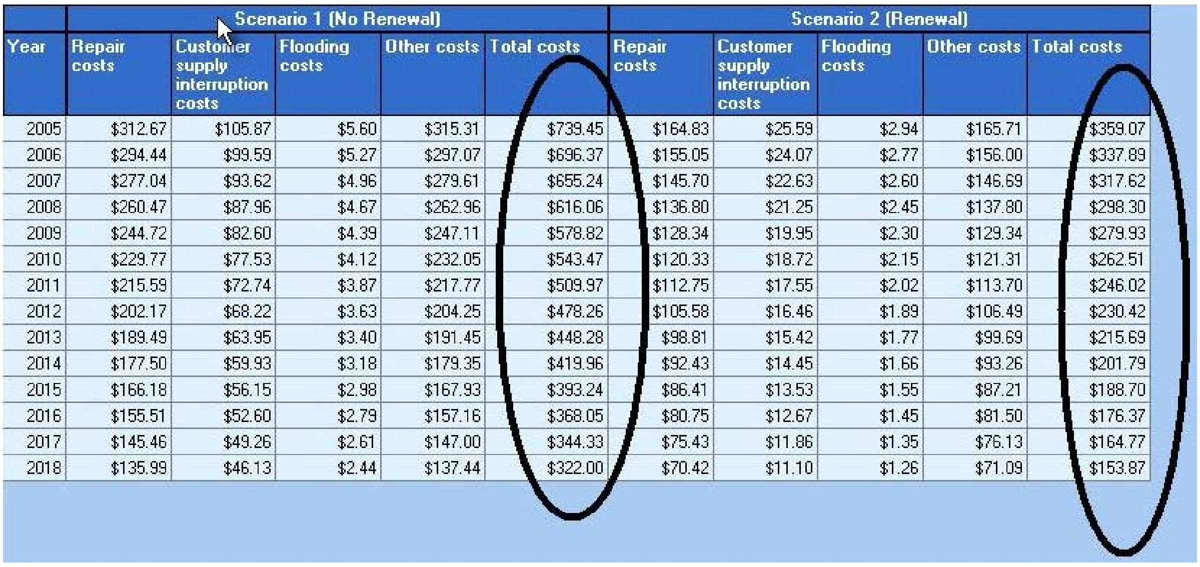


FIG. 7: *Predicted failure rates for 13 years into the future (2006-2017) for 2 scenarios.*

Fig. 8 shows cost predictions for the two alternative scenarios of renewal and no renewal. In Fig. 8, it can also be seen that costs are classified into several different types: repair costs, customer supply interruptions costs, flooding costs, and other costs. Fig. 8 shows that renewal reduces the discounted predicted costs from $150 to $500 per year. The sum of these cost reductions should be compared to the cost of renewal, and if the total cost reductions exceed the costs of installation, renewal is recommended. It can also be noted that costs decrease with each year into the future, which is owing to the use of a discount rate. There is significant variation between different Water Utilities in the choice of discount rate, and PARMS-PRIORITY does not prescribe a particular value.



	Scenario 1 (No Renewal)					Scenario 2 (Renewal)				
Year	Repair costs	Customer supply interruption costs	Flooding costs	Other costs	Total costs	Repair costs	Customer supply interruption costs	Flooding costs	Other costs	Total costs
2005	$312.67	$105.87	$5.60	$315.31	$739.45	$164.83	$25.59	$2.94	$165.71	$359.07
2006	$294.44	$99.59	$5.27	$297.07	$696.37	$155.05	$24.07	$2.77	$156.00	$337.89
2007	$277.04	$93.62	$4.96	$279.61	$655.24	$145.70	$22.63	$2.60	$146.69	$317.62
2008	$260.47	$87.96	$4.67	$262.96	$616.06	$136.80	$21.25	$2.45	$137.80	$298.30
2009	$244.72	$82.60	$4.39	$247.11	$578.82	$128.34	$19.95	$2.30	$129.34	$279.93
2010	$229.77	$77.53	$4.12	$232.05	$543.47	$120.33	$18.72	$2.15	$121.31	$262.51
2011	$215.59	$72.74	$3.87	$217.77	$509.97	$112.75	$17.55	$2.02	$113.70	$246.02
2012	$202.17	$68.22	$3.63	$204.25	$478.26	$105.58	$16.46	$1.89	$106.49	$230.42
2013	$189.49	$63.95	$3.40	$191.45	$448.28	$98.81	$15.42	$1.77	$99.69	$215.69
2014	$177.50	$59.93	$3.18	$179.35	$419.96	$92.43	$14.45	$1.66	$93.26	$201.79
2015	$166.18	$56.15	$2.98	$167.93	$393.24	$86.41	$13.53	$1.55	$87.21	$188.70
2016	$155.51	$52.60	$2.79	$157.16	$368.05	$80.75	$12.67	$1.45	$81.50	$176.37
2017	$145.46	$49.26	$2.61	$147.00	$344.33	$75.43	$11.86	$1.35	$76.13	$164.77
2018	$135.99	$46.13	$2.44	$137.44	$322.00	$70.42	$11.10	$1.26	$71.09	$153.87

FIG. 8: Predicted costs for 15 years into the future (2005-2018).

11. DISCUSSION

This paper describes the PARMS-PRIORITY decision support system. At the time of writing, the decision support system is being tested by two Water Utilities, and the following feedback has been received:

- Water Utilities keep databases with asset and failure records. The issues with transferring this data to PARMS-PRIORITY are two-fold: firstly there are data quality issues, and secondly there are issues of data transfer. Therefore linking the software directly to a Water Utility's database can be challenging, especially when data should be transferred relatively frequently. In order to keep data up to date, but depending on the preference of the Water Utility, data needs to be updated on a frequency varying between twice a week and once a fortnight. There is a need for further work on the issue of data transfer from a Water Utility database.
- The reporting capabilities are very useful, especially because they allow users to quickly report on some key performance indicators, such as relating to customer supply interruptions or multiple failures, for almost any sub-set of the network. However, the development team has found that the reporting requirements of different Water Utilities are sometimes rather different, and there is therefore on-going work on supporting more and more types of reports.
- Data handling tools are very useful for developing an understanding of the data. For instance, the ability to investigate spatial variation in failure rates, or failure modes can provide understanding of where high risk areas are, as well as an understanding of the options for risk mitigation for such areas. Similarly, variations in failure rates and failure modes between different vintages of pipes can be explored and better understood.
- There are some discrepancies between the failure prediction models previously used by the Water Utilities and the failure prediction model supplied with PARMS-PRIORITY; and these discrepancies will be investigated. It should be noted however that if there are no significant differences between the results of a Water Utility's in-house failure models and the results of failure models in PARMS-PRIORITY, then that Water Utility should perhaps use their in-house model.

- Many staff members working with asset renewal within Water Utilities have limited experience, and a staff member will sometimes only stay in the position for a short period of time. Therefore, there is a need for a framework which supports a more stringent process for choosing asset renewal, and which allows for backtracking through the decision process, to investigate how decisions have been made. This provides increased transparency as well as decreased dependency on qualified staff. PARMS-PRIORITY supports this because it requires less content knowledge from the user, and the decision trail is easier to follow.

The decision making process is based on a standard approach to risk management approach, as per the AS/NZS 4360:1999 Australian Standard for Risk Management (Standards Australia and Standards New Zealand 1999). While this approach has already been adopted by most Water Utilities in Australia for their risk management, the PARMS-PRIORITY approach is novel in that it to some extent automates the risk management process and that it integrates the use of new data and models within the framework. Novel models here refer to the use of the failure prediction model, the method for costing customer supply interruptions and other externalities, and the ability to run scenarios. The PARMS-PRIORITY approach also utilises the fact that most Water Utilities of any size in Australia now have relatively complete failure and asset records data sets which are of acceptable quality.

Evaluation of how efficiently renewal prioritisation can be performed with PARMS-PRIORITY is not strictly possible without trial by users. This is because it is not prescriptive in terms of a definite priority list for asset renewal.

The following areas have been identified as the focus for further work:

- Supporting the adoption and use of the system by Water Utilities.
- Evaluation of the system by users.
- Improvement of the ability for transferring data from a Water Utility database.
- Providing a wider range of report types.
- Extending the GIS capabilities to include visual displays of failure predictions and scheduled actions.
- Further evaluation of the failure prediction models.
- Exploration of the impact that the discount rate has on decisions.

12. CONCLUSIONS

A Decision Support System for prioritised pipeline renewal has been developed for pipes with low to medium costs of failure. A standard risk approach was adopted to analyse scenarios, which allows for the minimisation of the aggregated predicted costs involved with pipeline failures and the related maintenance and renewal. This is a standard risk management approach which has already been applied by many Water Utilities in their risk management. What is novel however is the integration of new models within this risk management framework. Examples of such models are the modified Non-homogeneous Poisson burst count model for failure prediction, the model for costing customer supply interruptions and other externalities, and the model for running scenarios.

The methodology applied is partly reactive because it is triggered by events such as pipeline failure, but at the same time it is proactive because it relies on analysis of strategy options using predictive models. Strategy options available for investigation include pipeline renewal, pressure reduction and shut-off valve insertion. Risk assessment of strategy options is achieved by using a number of modules for cost assessment, failure prediction, risk calculation, data exploration and scenario evaluation. The key model is the failure predictions model, which has previously already been applied and evaluated within the existing Decision Support System called PARMS-PLANNING. By leveraging the fact that the failure prediction model provides good estimates of probabilities of failure on an individual asset basis, a method for costing externalities relating to customer supply interruptions has been embedded into the cost assessment module.

The application of PARMS-PRIORITY was made possible by the new standard of data quality that is now more commonly available at some Australian Water Utilities. Two of these Water Utilities are currently testing the software system, with some initial positive feedback. This point towards the usefulness of PARMS-PRIORITY, but the assessment is not yet conclusive.

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