Development and application of a multi-period pipe replacement model utilising risk-based prioritisation for water distribution systems

by

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Thesis presented in partial fulfilment of the requirements for the degree Master of Science in Engineering at Stellenbosch University

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March 2016

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Abstract

The decision on whether to replace a pipe, with specific reference to a water distribution network, can be complicated by several aspects in the decision making process, such as available funding and required system performance. Long term budget requirements need to be assessed for the effective management of an existing water distribution network to find balance between the return on investment and customer satisfaction.

Various failure prediction models are available to calculate the probability of failure of each pipe in a water network. The probability of failure is then used to determine a replacement priority for all pipes in the network accordingly. Research has shown that the choice and implementation of failure prediction models are sensitive to the availability of data and in many cases a high degree of expertise is required to sufficiently understand the results. Semi-quantitative risk assessments provide a structured way to rank pipes by accounting for likelihood and consequence of failure while providing adaptability to the availability of data. In order to utilise the advantages of the risk-based approach a multi-period replacement model was developed to determine a suitable long term investment strategy, while taking some practical considerations into account.

A model was developed which utilised a risk-based approach to determine the pipe replacement priority. The model considers each pipe in a pipe inventory database based on several contributing pipe attributes and the available budget. A failure forecasting algorithm was also included in the model. The model could be used to determine the required budget based on certain fixed input parameters such as the total length of pipe to be replaced or the total allowed number of failures per year.

Four hypothetical investment scenarios were analysed for a case study. The results were compared to a fifth scenario, noted as the reactive strategy, which involved no pipe replacement. For the specific case study that was analysed the reactive strategy involved the lowest total cumulative expenditure. Additional investment was required to improve the performance indicators for the number of failures, service interruption duration, estimated remaining useful life and estimated remaining asset value. This research presented a methodology across the different performance indicators noted above, wherein the relative weights of the performance indicators were used to calculate a best-fit index.

Opsomming

Die besluit om 'n pyp te vervang, met spesifieke verwysing na 'n water verspreidingsnetwerk, kan ingewikkeld wees as gevolg van verskeie aspekte in die besluitnemingsproses, soos beskikbare befondsing en vereistes vir stelsel prestasie. Langtermyn vereistes vir befondsing moet geassesseer word vir die effektiewe bestuur van 'n bestaande water verspreidingsnetwerk om 'n balans te vind tussen die opbrengs op belegging en verbruiker tevredenheid.

Verskeie voorspellingsmodelle is beskikbaar om die waarskynlikheid van faling vir elke pyp in die water netwerk te bereken. Die waarskynlikheid van faling word dan gebruik om dienooreenkomstig die prioriteit van vervanging vir alle pype in die netwerk te bepaal. Navorsing toon dat die keuse en uitvoering van voorspellingsmodelle, vir faling, sensitief is ten opsigte van die beskikbare data en in baie gevalle word 'n hoë graad van kundigheid verlang om die resultate voldoende te verstaan. Semi-kwantitatiewe risiko assesserings bied 'n gestruktureerde wyse om die pyprang te bepaal deur die waarskynlikheid en gevolge van faling in ag te neem en terselfde tyd aanpasbaarheid tot die beskikbaarheid van data te bied. Ten einde die voordele van die risiko-gebaseerde benadering te gebruik, was 'n multi-tydperk vervangingsmodel ontwikkel om 'n geskikte langtermyn beleggingstrategie te bepaal, inaggenome sommige praktiese oorwegings.

Die ontwikkelde model het gebruik gemaak van die risiko-gebaseerde benadering om die vervangingsprioriteit van elke pyp te bepaal. Die model neem elke pyp teenwoordig in 'n pyp inventaris databasis in ag, gebaseer op verskeie bydraende pyp eienskappe en die beskikbare begroting. 'n Algoritme vir die vooruitskatting van falings was ook by die model ingesluit. Die model kan gebruik word om die benodigde begroting te bepaal gebaseer op sekere vaste inset parameters soos die totale lengte pyp wat vervang moet word of die totale aantal falings wat toegelaat word per jaar.

Vier hipotetiese belegging scenarios was geanaliseer vir 'n gevallestudie. Die resultate was dan vergelyk met 'n vyfde scenario, bekend as die reaktiewe strategie, waar geen pyp vervanging plaasgevind het nie. Vir die spesifieke geanaliseerde gevallestudie het die reaktiewe strategie die laagste kumulatiewe uitgawes getoon. Addisionele belegging was benodig om die prestasie-aanwysers vir die aantal falings, diens onderbrekingsduur, geskatte nuttige oorblywende lewensduur en verwagte oorblywende batewaarde. Hierdie navorsing het 'n metode aangebied waar die relatiewe gewig toegeken aan die verskeie prestasie-aanwysers, soos hierbo genoem, gebruik word om 'n beste-pas indeks te bereken.

Acknowledgements

I acknowledge my employer, GLS Consulting, for affording me the opportunity to pursue my Master's degree. A special thanks to Dr. Leon Geustyn, Dr. Alex Sinske and Adrian van Heerden for their suggestions and support.

I would like to thank my supervisor Prof. Heinz Jacobs for his guidance during the development of this thesis.

Finally, I want to thank my family and friends who stood by me and always believed in me, even in the times when I did not do so myself.

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List of abbreviations and acronyms

AARB	Available Annual Replacement Budget
AC	Asbestos Cement
ALM	Accelerated Lifetime Model
ANN	Artificial Neural Networks
AMP	Asset Management Plan
CAPEX	Capital Expenditure
CF	Consequence of Failure
CI	Cast Iron
DI	Ductile Iron
DSS	Decision Support Systems
ERAV	Estimated Remaining Asset Value
ERUL	Estimated Remaining Useful Life
ESL	Estimated service life
GIS	Geographic Information System
GWL	Ground Water Level
HDPE	High Density Polyethylene
ID	Identification
km	kilometre
KPI	Key Performance Indicator
LF	Likelihood of Failure
m	metre
mm	millimetre

MPM	Multi-period Prioritisation Model
NGSMI	National Guide to Sustainable Municipal Infrastructure
OPEX	Operational Expenditure
PE	Polyethylene
PHM	Proportional Hazard Model
PI	Performance Indicator
pH	Decimal co-logarithm of Hydrogen
PRF	Pipe Replacement Factor
PVC	Polyvinyl Chloride
REP	Replacement exclusion period
RUL	Remaining Useful Life
SID	Service interruption duration
ST	Steel
TCE	Total Cumulative Expenditure
USEPA	United States Environmental Protection Agency

List of symbols

Θ_i	LF variable weight
Θ_T	Total of all LF variable weights
μ_i	LF variable score
ϕ_T	Total of all CF variable weights
ϕ_j	CF variable weight
σ_j	CF variable score
IC_u	Unit replacement cost per unit length
RC_u	Unit repair cost per failure
N_f	Number of failures
$N(t)$	Failure rate in analysis period t
$N(t_0)$	Failure rate at start of the analysis
A	Growth rate coefficient
$N_p(t)$	Failure rate in analysis period t for pipe
$N_{d,p}(t_0)$	Failure rate at start of the analysis for diameter group of pipe
$A_{M,p}$	Growth rate coefficient for material of pipe
t	Analysis period (typically year)
t_0	Initial or starting period
a_p	Age of pipe
FF_p	Frailty factor for pipe
$F_p(t_0)$	Calculated failures for pipe at start of analysis
CF_d	Diameter group correction factor
$F_{p,d}(t_0)$	Calculated number of failures for pipe in diameter group with base data

F_d	Total initial failures for diameter group
$F_p(t)$	Expected failures for pipe in analysis period
T_p	Replacement time
T_u	Repair time
SID_p	Planned service interruption duration
$T_{p,i}$	Time for replacement of pipe selected for replacement
HH_i	Number of affected users (households)
TH	Total number of affected users (households) in the system
SID_u	Unplanned service interruption duration
$T_{u,i}$	Time for repair of pipe
CE_i	Cumulative expenditure if pipe is replaced
CE_{i-1}	Cumulative expenditure before current pipe is considered
$R_{M,i}$	Estimated remaining useful life of pipe, given pipe material and age
$E_{M,i}$	Estimated service life of pipe material

1 Introduction

1.1 Background

The world is undergoing the largest wave of urban growth in history due to the combined effect of urbanisation and population increase (UNFPA, 2014). Additional system load places an extra burden on relatively old established water distribution networks. The effective management of operational infrastructure could result in increased asset life and would subsequently reduce the required replacement of ageing components. Therefore, the effective management of water distribution network infrastructure is of great importance to ensure the sustainable delivery of water services.

Minnaar et al. (2013) stated that asset management is an important part of any organisation as it allows them to extract value from their assets and further that municipal managers are under increasing pressure to adopt an asset management plan (AMP). The ISO 55000 series of international standards provide a universally applicable set of asset management principles. An AMP involves reporting on the status of the system, on a component level according to certain criteria.

It was reported in the National Guide to Sustainable Municipal Infrastructure (NGSMI) (2003) that urban water infrastructure is deteriorating at a higher rate than the renewal rate due to various factors such as low funding, inadequate inspection, poor quality control and lack of consistency in operation practices. Pelletier et al. (2003) state that water distribution pipes are among the infrastructure that is deteriorating and that municipal water managers attribute the deterioration to the lack of investment in proactive replacement and refurbishment programmes. Effective management of operational infrastructure is required to ensure sustainable water service delivery. The majority of water distribution network's infrastructure components consist of pipes and generally represent a large proportion of the asset value and therefore their management is an important issue. Pipes have a certain expected asset life, associated with the material of the pipe necessitating replacement with a similar or improved pipe at some estimated future date.

The replacement of pipes, damaged and otherwise affected, is an integral part in the effective management of a water distribution network. Decisions on replacement or rehabilitation are made based on a perceived risk of failure, which is a combination of the probability of an asset failure occurring and the consequence of said failure. Asset condition is used to determine the risk of failure and remaining useful life, but conducting condition assessments on buried infrastructure is relatively complicated.

The probability of pipe failure is required for effective management and risk calculation. Therefore, records are required of pipe assets and subsequent failure data covering each asset's lifetime. Some challenges faced by municipalities for pipe failure data collection include limited personnel and resources, missing or incomplete historical data, conflicting data and non-computerised information in combination with the retirement of staff who hold such tacit knowledge (Pelletier, 2003; Wood et al., 2007). According to Wood and Lence (2006), data collection involves direct financial costs which present a serious constraint for municipalities with limited budgets.

Ganguly and Gupta (2004) stated that the techniques in sophisticated decision support systems (DSS) are computationally intense, but that with the continuous advancements in computing technologies and processing speeds the implementation of such systems are expected to become more commonplace. However, as stated by Zopounidis and Doumpos (2008), much insight is required to confidently apply the obtained results in the decision-making process as the decision makers themselves need to examine the obtained results to determine to the most appropriate decision. Clair and Sinha (2012) mention that many of the predictive models found in literature are relatively complicated for the average municipality to apply to their own water infrastructure.

Risk-based asset prioritisation is attaining popularity as a tool to manage assets comprehensively (Park et al., 2010) and is effective for management of pipe replacement programmes (Shaikh, 2010). Risk-based prioritisation accounts for factors that influence pipe failure, consequence of failure and management strategies. In other words, preference could be given to replace asbestos-cement (AC) pipes due to possible health risks, regardless of remaining useful life. A priority can be assigned to each pipe asset and appropriate decisions made on replacement and rehabilitation programmes.

1.2 Terminology

The terms defined below are used with their stated meaning in this research to avoid confusion as some studies use different terms to describe similar concepts.

***Consequence of failure*:** The definition for "consequence of failure" as provided by Park et al. (2010), namely "the consequence of physical failure of a component is a measure of the impact on the community and customers", was adopted for this research.

Estimated service life: The actual service life of a pipe is not known until failure occurs. Fisher (2008) stated that when deciding which material to use the life expectancy of the asset is fundamental. In this research, the "estimated service life" of a pipe is based on the material and can be obtained from a supplier catalogue or substituted with a subjective value from engineering knowledge.

Estimated remaining useful life: Sinske et al. (2009) calculated the remaining useful life by subtracting the actual age of the pipe from the life expectancy based on the pipe material. Sinske and Streicher (2013) adopted the same calculation; however the term "remaining useful life" was substituted with the more descriptive term, "catalogue remaining useful life", in order to indicate that standard expected useful life was retrieved from a supplier catalogue. Analogously to the latter, in this research, the term "estimated remaining useful life" is used, in order to indicate that the estimated service life is used to approximate the useful life of the pipe.

Failure: The term "failure" is used as described by De Oliveira et al. (2011), who stated that a failure is a set of events which are detected by the municipality and required a repair or replacement activity for which a maintenance record was issued. A failure typically results in the loss of water and might include pipe bursts and leakage, depending on how the failure records for the municipality are stored. Some authors use the term "break", in which case reference should be made to the original source to clarify the meaning.

Failure rate: The term "break rate" or "breakage rate" was widely used in analyses of pipe failures in water distribution networks (Walski and Pelleccia, 1982; Rostum, 2000; Wood and Lence, 2009). Misiunas (2005) uses the term failure frequency while others (Achim et al., 2007; Martins, 2013) use the term failure rate. In this research the term "failure rate" is used, except when in reference to studies performed by other authors. The failure rate for a given pipe or set of pipes are generally normalised on length and time (Rostum, 2000) and expressed as the number of failures per length per time. In this research the failure rate is expressed as the annual number of failures per 100km as suggested by Lambert and Taylor (2010). In this text, the unit will be expressed as ($\frac{N_f}{100km \cdot year}$).

Likelihood of failure: The likelihood of failure is an indication of the probability of a failure occurring and is often expressed as the expected value from the probability distributions in statistical or stochastic failure prediction models (Loganthan et al., 2002; Vanrenterghem-Raven, 2007; Martins, 2011). In this research, the likelihood of failure is treated analogously to that of consequence of failure whereby it represents a measure of the expected influence of a pipe attribute and its value on the possible failure of a pipe.

Pipe**:** A pipe represents the concatenation of individual pipe entities with similar characteristics. Pipe nodes act as separators to split the pipes at intersection of pipes with different characteristics (De Oliveira et al., 2011). The term pipe was similarly described by Rostum (2000) as consisting of many segments or lengths "from one node in the water network to another" (for example, a change in material) and typically with a length of between 50m and 150m. For this research a pipe will be subject to the pipe inventory database used and each record will denote a single pipe. When presenting the model (chapter 3 and 4) the total number of pipes in the database is denoted by the parameter n (always an integer).

Pipe age**:** In this research, the pipe age refers to the time, in years, that the pipe has been in operation and is calculated as the difference in years from the installation year of the pipe to the analysis year as applicable in the model.

Proactive strategy**:** The term "proactive maintenance" was described by Arsénio (2013) to be any maintenance activity that is performed to delay deterioration or failure of a component or system; Rostum (2000) stated that a strategy is deemed to be proactive in water network management if replacement or repair activities were taken prior to a failure event. In this research, any investment scenario, with an available replacement budget greater than zero, is deemed to be a proactive strategy because it will result in the replacement of a pipe before a known failure.

Reactive strategy**:** The term "reactive maintenance" was described by Arsénio (2013) to be any maintenance activity that is performed after a failure to repair damage or restore infrastructure to satisfactory operational levels; Rostum (2000) stated that a strategy is deemed to be reactive in water network management if replacement or repair action is taken after a failure event occurs. In this research, a reactive strategy is one where the available replacement budget is equal zero, because it will result in no replacement activity.

Repair**:** The terminology of Rostum (2000) was used to describe a repair as follows, "An unplanned maintenance activity carried out after the occurrence of a failure".

Repair time**:** Walski and Pelleccia (1982) indicated that the time to isolate the system and perform the repair activities depend on several factors and calculated the time in hours. In this research the repair time does not only refer to the time of repair, but is normalised by taking into account the number of consumers (households) affected by the failure and the total number of consumers in the system to compare the severity or impact of each failure in terms of the interruption in service.

Replacement**:** Rostum (2000) defined replacement as the "construction of a new pipe, on or off the line of an existing pipe" and also that "the function of the pipe will incorporate that of the old, but may also include improvements". In this research a replacement will be on the line of the existing pipe that is being replaced and also will not offer any improvements, that is, the hydraulics of the distribution network are the same as before the replacement occurred.

Replacement cost**:** Investopedia (2015) defines replacement cost as "the price that will have to be paid to replace an existing asset with a similar asset" and Johnstone (2003) mentioned that research has shown that regulators find current replacement cost to be the most appropriate valuation basis. The terminology of RAMM (2011) was used to describe the replacement cost as "a form of asset valuation where cost of replacing a pipe is determined by calculating the current cost of the most appropriate modern asset with equivalent service potential".

Replacement time**:** Similar to the repair time, the replacement time is the time for the replacement activity, the time from when the replaced pipe is taken out of service to the time the new pipe is in operation, which is then normalised by number of households to compare the replacement impact in terms of the interruption in service.

Service life**:** According to ISO Standard 15686 defined as "The period of time after installation during which a building or its parts meet or exceed the performance requirements". The same definition can be applied for water distribution networks, namely "The period of time after installation during which a water distribution network or its parts meet or exceed the performance requirements". In this research, the parts of the water distribution network that are considered are the reticulation pipes.

Service interruption duration**:** Stacha (1978) commented on the importance of service continuity to minimise customer inconvenience and provided a cost table in an attempt to quantify the cost of interruptions due to pipe failures. In this research, the inconvenience of pipe failure is measured as the expected interruption in water supply to customers due to replacement or repair operations and is expressed as the cumulative minutes of interruption for affected consumers divided by the total number of consumers in the system. The service interruption duration may also be colloquially referred to as "downtime".

1.3 Research context

Renaud et al. (2011) stated that buried water pipe networks represent "more than 80% of the total asset value for water distribution systems"; the effective management of pipe networks is essential. Wood and Lence (2006) suggested that DSS tools for prioritising the replacement or rehabilitation of water mains should be tailored according to the quality of data available to a municipality; and municipalities with minimal or incomplete data cannot use sophisticated tools such as physical or statistical pipe deterioration models and life-cycle costing. Matthews et al. (2012) noted that municipalities required DSS tools to be user-friendly and that minor training should be required to minimise the learning curve.

Wood and Lence (2006) point out that development of robust approaches are required for municipalities with minimal data records. In the South African context, the principle of a user-friendly tool that requires only minor training is of great importance. Lawless (2006) reported that 79 of South Africa's 231 local municipalities did not employ an engineer, technologist or technician.

Grigg et al. (2013) mentioned that water distribution pipe replacement planning takes place within the sphere of an asset management programme and also noted the requirement of risk assessments to identify the replacement projects that are most critical in order to wisely allocate available resources. Misiunas (2005) indicated that high costs and the slow inspection speeds were a hindrance for the extensive application of many condition assessment techniques in water distribution networks. Giustolisi et al. (2006) stated that municipal water managers need reliable plans for the replacement of critical pipes while weighing up expected benefits against investment in risk-based management scenarios. Rosness (1998) noted that the accuracy of risk analyses depend for the most part on analyst competence and their ability to integrate their own knowledge and assumptions with a critical evaluation of the information.

Crigg et al. (2013) found that the ability to predict failures in a water distribution network was poor and it is with cognisance of the poor ability to predict failures that the usefulness of risk-based prioritisation for water distribution pipe replacement comes to the fore. However, as validation, a multi-period assessment is required to determine whether the replacement based on the calculated risks are sensible, and furthermore to determine whether proposed capital investments are at an acceptable level for ensuring a sustainable water supply while providing the municipality with an indication of whether the available budget is sufficient to manage the water pipe infrastructure.

1.4 Problem statement

Lambert (2012) indicates that the purpose of a water distribution network is to deliver high quality potable water to customers and that throughout the world these networks are getting older and deteriorating. The ageing infrastructure, in combination with higher water demands from urban growth, increase the strain on the water distribution networks and can lead to a higher number of pipe failures. Financial constraints are an obstruction encountered by most municipalities and a balance between proactive assessment and reactive refurbishment is required for optimal use of assigned or available budgets.

Risk-based prioritisation is an effective and proactive way to manage pipe replacement programmes. Shaikh (2010) noted that a risk-based management approach is particularly beneficial to municipalities on a limited budget because it provides municipal managers with an insight into future budget requirements. It is therefore required to expand the useful risk-based prioritisation approach into a multi-period model to provide insight into required replacement budgets and strategies to be employed, measured against certain performance indicators (PI).

1.5 Research objectives

The aim of this research is to expand a once-off pipe risk prioritisation analysis in water distribution systems into a multi-period replacement model that can aid in decision-making processes aimed at determining the required budgets for replacement and refurbishment projects of a municipality. An algorithm was developed to estimate the number of pipe failures in a water distribution system in order to test the effectiveness of pipe replacement options and to estimate the required budget for refurbishment costs and unplanned interruption to service.

The following research objectives were set for this research:

- Provide a literature review on factors that lead to pipe failures and available water pipe failure prediction models.
- Provide a description of the risk-based prioritisation model as implemented for the case study.
- Establish a multi-period risk-based replacement analysis methodology, utilising an annual pipe replacement budget and other practical operational limitation inputs for replacement eligibility testing.
- Determine a suitable failure forecasting algorithm that incorporates the variables used for the calculation of the likelihood of failure in the risk model.
- Illustrate validation and practical application of the model by considering a case study with various input scenarios.

1.6 Description of case study

In order to verify the functionality of the developed model, the implementation of a case study was conducted to illustrate the practical application. The case study chosen was for water pipe assets for which a "once-off" risk-based prioritisation was performed by the author as part of a separate investigation. The input parameters and results of the "once-off" prioritisation were used as the base data input for the multi-period analysis.

The name of the water utility was not disclosed in this text for reasons of confidentiality. The region served comprised a total land area of approximately 885,89 km^2 and is located in central Europe. The case study dataset has n = 32 957 pipes with a combined length of 2 229,37 km. The service area includes approximately 31 832 rural and 83 168 urban consumers (households).

The reason for the choice of this case study data is the low number of annual failures recorded, amounting to a failure rate of approximately $\frac{2.85\, failures}{100km \cdot year}$; even with long-term failure records the low failure rate would make the use of alternative statistical or probabilistic models difficult to employ, due to the low confidence the predictions would yield.

The utility that is managing the water infrastructure in the case study area places emphasis on consumer satisfaction, which means that data on interruption duration is available and could therefore be calculated for use as a PI in the analysis.

1.7 Research methodology

Kothari (2004) noted that research can either be classified as applied research or fundamental research. Roll-Hansen (2009) stated that applied research is dedicated to the solution of practical economic, social and political problems and although such research depends on scientific knowledge and methods, applied research does not aim at further development of such knowledge and methods. Rajasekar et al. (2013) defines basic (fundamental) research as "an investigation on basic principles and reasons for occurrence of a particular event or process or phenomenon", and further stated that although basic research is not concerned with solving practical problems, the outcomes from such research are required for any applied research.

In this applied research project the feasiblity of utilising risk-based prioritisation in a multi-period replacement model, to aid in the determination of required budgets for pipe replacement projects, was explored. Basic research was conducted as part of the process to investigate the factors that influence the failure of pipes in a water distribution network.

A quantitative-simulation research approach was used for the development of a multi-period replacement model. Rajasekar et al. (2013) stated that the charachteristics of a quantitative approach are:

- the approach is numerical and applies statistics or mathematics and uses numbers.
- the process is iterative whereby evidence is evaluated.
- the results are often presented in tables and graphs.
- the *what*, *where* and *when* of decision making.

According to Kothari (2004), the simulation approach is a sub-class of the quantitative approach which involves the construction of an artificial environment whithin which relevant data can be generated. The term 'simulation' referes to the operation of a numerical model that represents the structure of a dynamic process. Given a set of initial variables, a simulation is run to represent the behaviour of the process over time and can be useful in constructing models for the understanding of future conditions.

The development of a numerical model to simulate the replacement process over an extended time period was required. The simulation analysis was performed on secondary data, meaning that the data as collected and available for the case study was used in this research. Figure 1-1 illustrates the approach followed in this research to accomplish the objectives as set out.

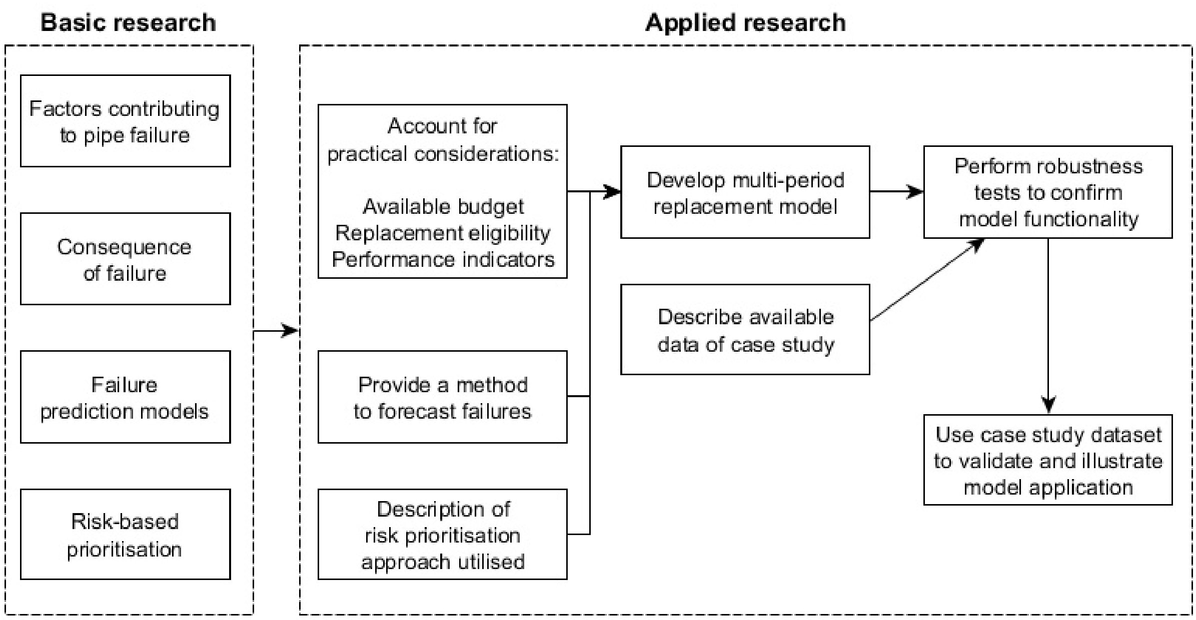


Figure 1-1: Schematic research methodology

1.8 Scope and limitations

This research focused on expanding an existing method for risk-based prioritisation. For this research it was accepted that the scores and weights of the various factors influencing the likelihood of failure, as well as those of the consequence of failure, have been established beforehand. In other words this research excluded hydraulic network modelling – the outputs of a hydraulic model for the case study concerned (for example flow rate and pressure) were used as some of the inputs in deriving the risk model presented in this research. Therefore, this research explored the expansion of the risk-based method, as employed by the case study presented, into a multi-period analysis. For this research, a time step period of one year was considered. The corresponding failure estimation algorithms are therefore based on a period of one year.

The model was limited to distinguish between the failure rates for a maximum of three pipe diameter groups. The diameter groups considered during this research were: small, medium and large pipes, based on a suitable diameter range as discussed later in the text.

The input parameters as available for the case study were used for the calculation of replacement and repair time to determine the service interruption duration (SID). Verification of the provided interruption statistics against other data was beyond the scope of this research.

Six replacement cost functions were provided for in this research. Cost functions were available for three replacement pipe material categories, namely Polyvinyl Chloride (PVC), Ductile Iron (DI) and Polyethylene (PE). Each of the three material categories is duplicated within the two location identifiers, i.e. urban or rural, and presented in tabular form for discrete pipe diameter ranges. Also important to note is that the cost functions used to determine replacement value are based on open-trench excavations; trenchless technologies were excluded. The replacement cost functions are limited to the three distinct material categories. A length-weighted average cost was calculated for substitution for other materials in the network.

The effects of replacement on a non-expanding water distribution network were considered. In other words, alterations and additions to the pipes in the water distribution network, beyond changes to material, installation date, pipe condition and failure history, were not considered as part of this research. The assumption of a static network (non-expanding) was considered reasonable for the case study as it is situated in central Europe, where many towns have not grown substantially and rather tend toward densification.

The developed tool only allows for one decision, namely whether to replace the pipe asset or not. Pipes eligible for replacement in a given period would thus be replaced. No allowance was made for further decision-tree branches such as the choice between replacement, refurbishment or condition inspection. For the analysis and verification process, it was deemed satisfactory to assume that all costs would increase at the same rate so as to compare annual incurred costs in terms of present value. Applying a discount rate to calculate the net present value as eligibility test was thus not required.

The Local Government Capital Asset Management Guideline of the Municipal Finance Management Act (2008) stated that the most common depreciation methods that can be applied are the (i) straight line, (ii) diminishing balance and (iii) sum of units depreciation methods, and further stated that National Treasury recommends the straight line method. Accordingly, the pipe asset value was calculated based on a linear depreciation function which accounted for the current replacement cost and the expected service life of the pipe material. No other depreciation models were considered for this research as Hosking and Jacoby (2013) found that the majority of the municipalities included in their research used the straight line depreciation method as recommended by National Treasury.

2 Literature Review

2.1 Water distribution network layout

Misiunas (2005) stated that the objectives of an urban water supply system are to provide safe, potable water to consumers, and adequate water at sufficient pressure for fire protection. The layout of a water distribution network is illustrated in Figure 2-1. The network can be divided into abstraction, treatment, storage and distribution components.

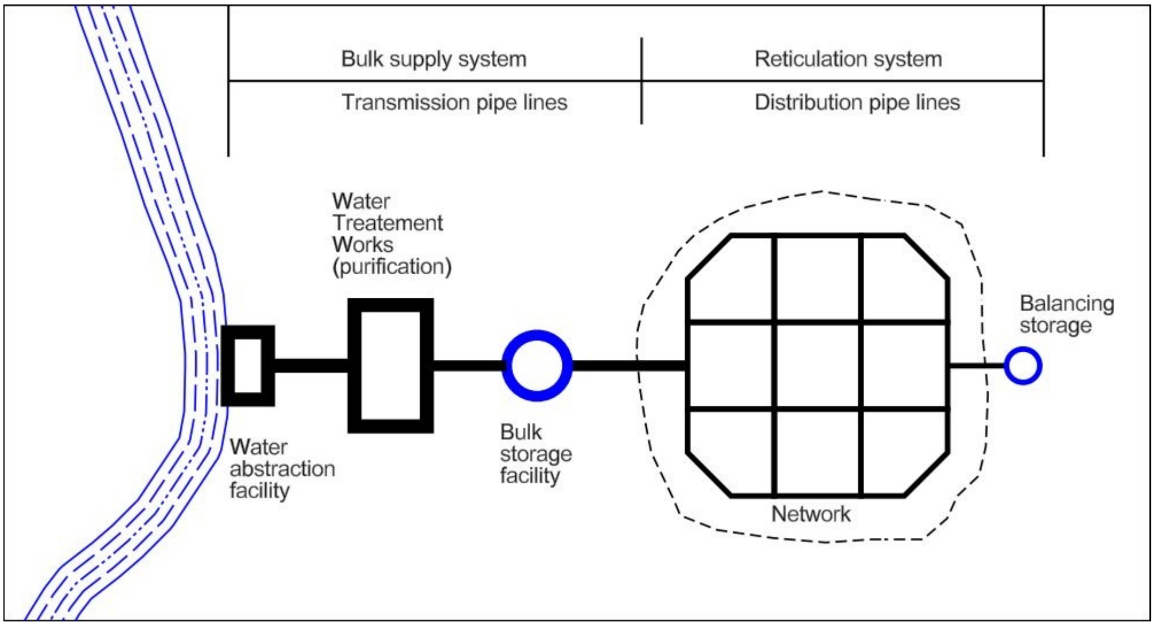


Figure 2-1: Typical water distribution network layout

Shamsi (2002) states that the bulk of a distribution network's infrastructure components consist of pipe assets. Al-Barqawi and Zayed (2006) stated that a water delivery system can be grouped into two categories: transmission and distribution systems (locally the terms bulk and reticulation are more common). Water is transferred from the main source to the storage system via transmission pipes or so-called bulk system pipes. Distribution pipes (reticulation pipes) convey water from the point of storage to the end-user. The focus of this research is on the distribution network pipelines, shown inside the dotted circle in Figure 2-1.

De Oliveira et al. (2011) stated that the usual portrayal of a distribution network is "a planar graph in which edges represent pipes and nodes represent pipe intersections". In the interest of simplification, pipes represent the concatenation of individual pipe entities with similar characteristics. Pipe nodes act as separators to split the pipes at the intersection of pipes with different characteristics.

Poulton et al. (2007) also stated that pipes records in a geographical information system (GIS) result from the splitting of long pipes into shorter sections due to various practical considerations, most notably for the purpose of hydraulic analyses, where additional pipe nodes may be required for a better spatial representation of the demand in the distribution network.

2.2 Pipe deterioration process

A multi-step process as provided by Misiunas (2005) to describe pipe failure is shown in Figure 2-2. Makar and Kleiner (2000) reported that the failure rate of pipes is a function of pipe material, operational conditions and exposure to undesirable environmental factors. Al-Barqawi and Zayed (2006) noted that deterioration varies from one distribution network to another, because these processes are based on different uncertain factors affecting the condition level.

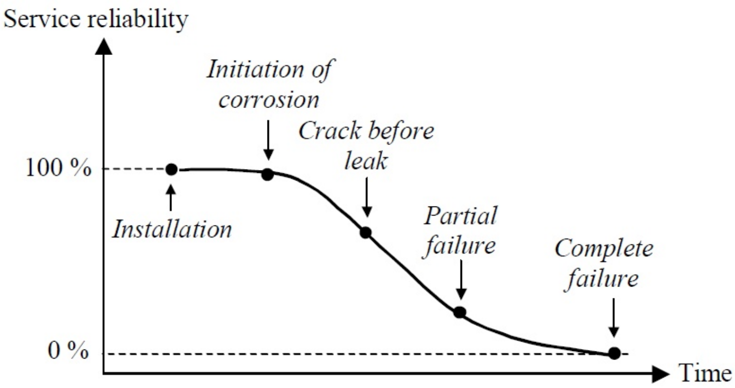


Figure 2-2: Multi-step pipe failure process (Misiunas, 2005)

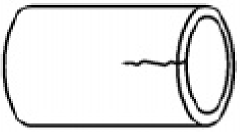
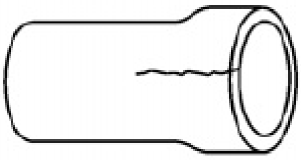
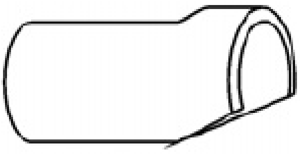
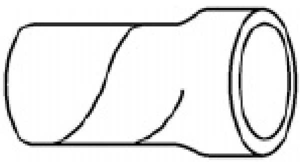
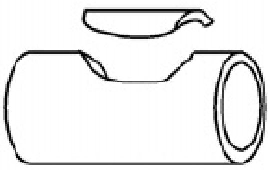
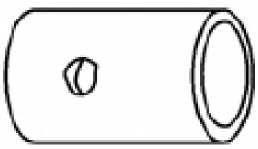
Kleiner and Rajani (2002) provided the following classification for deterioration factors:

- Static factors relating to pipe attributes remain relatively constant and include material, length and diameter.
- Dynamic factors relating to pipe environment and other factors that change over time and include age, corrosive factors and dynamic loadings such as traffic.
- Operational factors relating to replacement rates, protection methods and water pressures.

2.3 Pipe failure modes

Failure occurs in a water pipe when the extent of degradation has progressed sufficiently so that a pipe can no longer withstand the forces acting on it. Wood et al. (2007) reported that the type of pipe failure could not be correlated to a specific cause of failure, but that data on the type of failure could indicate a failure mechanism. In their assessment, Wood et al. (2007) also found that due to pipe failures being treated reactively as emergencies, and staff on site focusing on mitigation of collateral damage, the information about the cause of the failure was often not recorded; it was also stated that a degree of specialised engineering background may be required to confidently determine the cause of a failure under a response situation. In other research, Burlingame et al. (1998) also noted that the analyses of pipe failures lacked on-site inspection data. Table 2-1 shows the failure modes with possible causal forces presented by NGSMI (2003).

Table 2-1: Failure modes in water pipes (NGSMI, 2003)

Failure Mode	Illustration	Acting force/Cause
Circumferential cracking		Bending stress: frost, swelling clay Thermal contraction Longitudinal stress near valves and fittings
Longitudinal cracking		Hoop stress: internal water pressure, freezing water Ring stress: soil cover load, traffic load
Bell splitting		Expansion of joint material Bending stress from soil erosion
Bell shear		Bending stress: soil erosion, "over homing" of spigot during installation
Spiral cracking		Combination of bending and hoop stress from internal water pressure
Rupture/ Blow-out		Hoop stress from internal water pressure Corrosion of steel pre-stressing wires
Through hole		Corrosion pitting Casting flaws

2.4 Factors contributing to pipe failure

The various causes and factors that influence pipe failures have been identified by several authors (e.g. Morris, 1967; Shamir and Howard, 1979; O'Day, 1982; Makondo and Wamukwamba, 2001; Franks and Silinis, 2007). Morris (1967) listed various possible causes of pipe failures and emphasised that determining the cause of a pipe failure is not always possible because a combination of the causes is responsible for the failure. Deb et al. (2002) made recommendations to capture 45 data items for each occurrence of a pipe failure, which indicates just how complex the problem of concluding the cause of a failure can become.

Park (2004) stated the following five major factors affecting water pipe failures:

- characteristics of water supply that affect internal corrosion
- internal and external environments
- internal and external stresses
- type of pipe material
- third party interference

Table 2-2, Table 2-3 and Table 2-4 were adapted from NGSMI (2003) and USEPA (2000) to include surrogate factors, because, as suggested by Wood and Lence (2009), the data typically used and presented in models are surrogates for the actual factors leading to pipe failure.

Table 2-2: Physical factors contributing to failure in water pipes (adapted from NGSMI, 2003; USEPA, 2000; Wood and Lence, 2009)

Factor		Explanation	Surrogate factor
Physical	Pipe material	Pipe made from different materials fail in different ways.	
	Pipe wall thickness	Corrosion will penetrate thinner walled pipe more quickly.	Pipe diameter
	Pipe age	Effects of pipe degradation become more apparent over time.	
	Pipe vintage	Pipes made at a particular time and place may be more vulnerable to failure.	Pipe age
	Pipe diameter	Small diameter pipes are more susceptible to beam failure.	
	Type of joints	Some joints have experienced premature failure.	Pipe material
	Thrust restraint	Inadequate restraint can increase longitudinal stresses.	Pipe material, pipe diameter
	Pipe lining and coating	Lined and coated pipes are less susceptible to corrosion.	Pipe material
	Dissimilar metals	Dissimilar metals are susceptible to galvanic corrosion.	Pipe material, soil type
	Pipe installation	Poor installation practices can damage pipes, making them vulnerable to failure.	Pipe age
	Pipe manufacture	Defects in pipe walls produced by manufacturing errors can make pipes vulnerable to failure. This problem is most common in older pit cast pipes.	Pipe material, pipe age, pipe lining

Table 2-3: Environmental factors contributing to failure in water pipes (adapted from NGSMI, 2003; USEPA, 2000; Wood and Lence, 2009)

Factor		Explanation	Surrogate factor
Environmental	Pipe bedding	Improper bedding may result in premature pipe failure.	O&M practices
	Trench backfill	Some backfill materials are corrosive or frost susceptible.	O&M practices
	Soil type	Some soils are corrosive; some soils experience significant volume changes in response to moisture changes, resulting in changes to pipe loading. Presence of hydrocarbons and solvents in soil may result in some pipe deterioration.	
	Groundwater	Some groundwater is aggressive toward certain pipe materials.	Pipe material
	Climate	Climate influences, frost penetration and soil moisture.	Pipe age, pipe material
	Pipe location	Dynamic traffic loading under roads; road salt migration.	
	Disturbances	Underground disturbances in the immediate vicinity of an existing pipe can lead to actual damage or changes in the support and loading structure on the pipe.	
	Stray electrical currents	Stray current cause electrolytic corrosion.	Soil type
	Seismic activity	Seismic activity can increase stresses on pipe and cause pressure surges.	

Table 2-4: Operational factors contributing to failure in water pipes (adapted from NGSMI, 2003; USEPA, 2000; Wood and Lence, 2009)

Factor		Explanation	Surrogate factor
Operational	Internal water pressure, transient pressure	Changes in internal water pressure will change stresses acting on the pipe.	
	Leakage	Leakage erodes pipe bedding and increases soil moisture in the pipe vicinity.	
	Water quality	Some water is aggressive, promoting corrosion or leaching.	Pipe material
	Flow velocity	Rate of internal corrosion is greater in unlined dead-ended mains.	
	Backflow potential	Cross connections with systems that do not contain potable water can contaminate water distribution system.	
	O&M practices	Poor practices can compromise structural integrity and water quality.	Pipe age

A brief discussion of the factors which are commonly reported to have the greatest impact on pipe failure is presented.

2.4.1 Pipe age

Morris (1967) indicated that pipe age itself is not a cause of pipe failure, as pipe failures occur due to a combination of several factors. The longer a pipe has been in service, the more probable it becomes that the pipe would be affected by various possible causes of pipe failures, such as corrosion, soil movement, temperature differentials and impacts from other infrastructure construction projects. Kleiner et al. (2001) concurred that as the distribution network pipes get older, they are characterised by a decline in hydraulic capacity and an escalated frequency of failures.

Rostum (2000) stated that different installation periods demonstrate dissimilar failure characteristics and that these characteristics are more reliant upon the construction practice for each installation period than on the pipe age. As alluded to by Andreou et al. (1987b), some construction periods display a higher failure rate compared to other periods and in many instances the older pipes seem to be more resistant to failure than the younger pipes in the network. Subsequently, Makar et al. (2000) suggested that newer casting methods of cast iron (CI) pipes, which resulted in thinner wall thicknesses, may explain why newer CI pipes had higher failure rates.

Neelakantan et al. (2008) found that, with all other conditions remaining the same, the number of pipe failure events increased with age. Therefore, it is sensible that age should be used as an indicator for forecasting future failure.

The deterioration process can be illustrated by the well-known bathtub curve in Figure 2-3, showing the theoretical failure rate of a pipe in three phases over its service life.

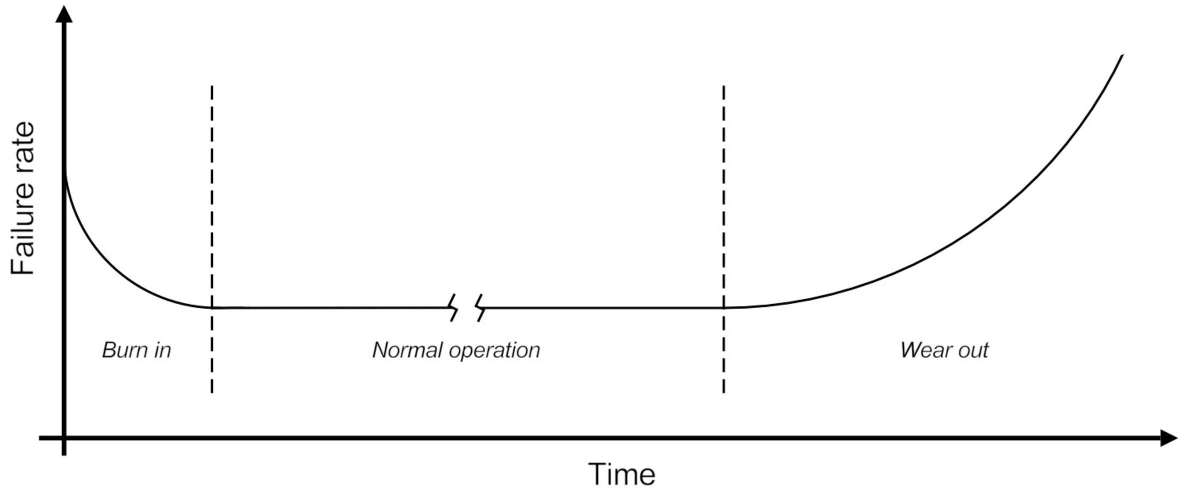


Figure 2-3: Hypothetical failure rate of water pipe over service life

2.4.2 Corrosion

Makar and Kleiner (2000) stated that metallic pipe failure is mainly caused by corrosion. Park (2004) mentioned that the characteristics of the supplied water like pH level, dissolved oxygen, free chlorine residual, temperature, velocity and microbiological activity influence the severity of internal corrosion. The external corrosion is determined by the environment around the pipe (e.g. soil characteristics and ground water) and Kaara (1984) argued that the intensity of external corrosion would vary from pipe to pipe due to the variability in soil conditions. Makar and Kleiner (2000) explained that corrosion can cause failure in non-metallic pipes. For example, pre-stressed wires could corrode and ultimately fail due to internal pipe pressure.

2.4.3 Pipe material

Rostum (2000) stated that most of the water distribution pipe infrastructure widely consisted of CI pipes and that long records of failures existed for these pipes, which lead researchers to focus on CI pipe failures. PVC and PE have been introduced for use in water distribution networks, especially for smaller diameter pipes. The characteristics of different pipe materials differ widely and should be considered and analysed separately.

Thornton et al. (2008) stated that globally, municipalities have desisted with the use of asbestos cement (AC) pipes and CI pipes for water distribution network pipes. Many municipalities favour PE or PVC pipes for new installations. A possible disadvantage with so-called plastic pipes is the difficulty reported for detecting peaks at low pressures.

Figure 2-4 was adapted from Mora-Rodriguez et al. (2014) to describe the commercialisation of pipes in water distribution networks. The installation of AC and grey cast CI pipes diminished considerably after the introduction of ductile iron and PVC pipes.

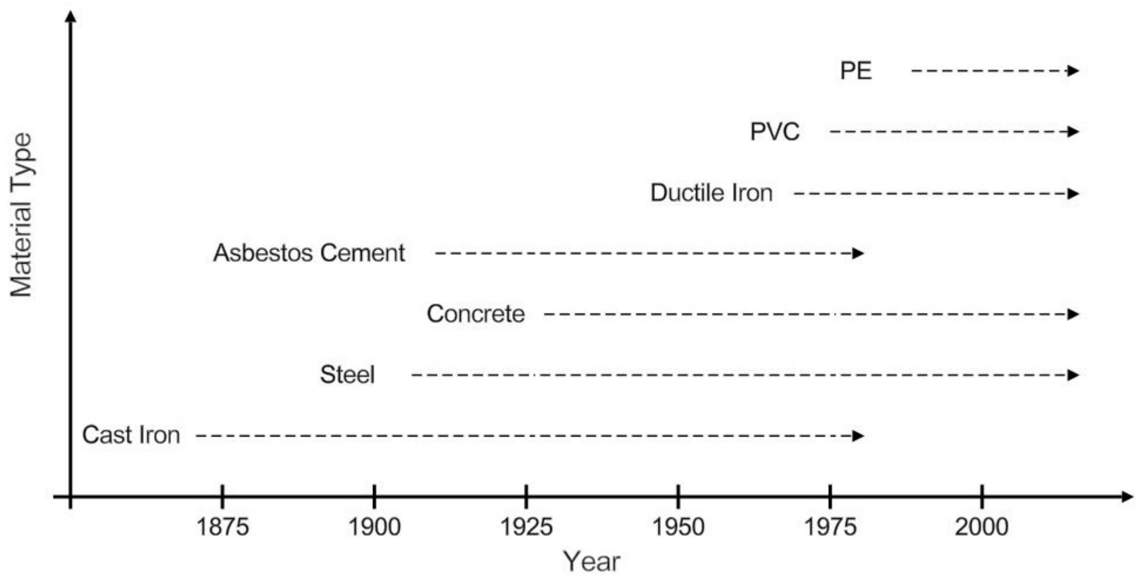


Figure 2-4: Installation periods per material (adapted from Mora-Rodriguez et al., 2014)

2.4.4 Pipe diameter

Small diameter pipes are reported to have the highest frequency of failures, as noted in various studies (e.g. Walski and Pelliccia, 1982; Andreou et al., 1987; Wengström, 1993). Rostum (2000) stated that pipes with diameters ≤ 200 mm usually have exceptionally high number of failures. The higher frequency of failure for smaller diameter pipes could be attributed to thinner pipe walls, reduced pipe strength, less reliable joints and difference in construction standards.

2.4.5 Pipe length

Pipe lengths (represented graphically by edges as discussed in paragraph 2.1) differ within a network and also between networks. For long pipes, failure related factors could be non-uniformly distributed along the pipe length (Andreou, 1987b); localised factors that may vary along the length of pipe include differences in soil conditions, traffic loading, tree root growth and inconsistent bedding. Vanrenterghem-Raven (2007) found a strong dependency for some explanatory parameters to the pipe length and argued that the dependency was due to longer pipes having more opportunity for a failure event to occur along their length. Rostum et al. (1997) recommended that pipes should be limited to lengths in the order of 100m to avoid different conditions in one length of the same pipe.

Achim et al. (2007) found that their models' predictions were significantly worse when length was excluded as an input variable. Pipe length is mainly used to express the number of failures as a rate of occurrence per distance of pipe in the network. In this research, the failure rate is expressed in the number of failures per 100 km per year ($\frac{N_f}{100km \cdot year}$).

2.4.6 Soil conditions

As stated earlier, soil conditions have an effect on the external corrosion rates and can therefore significantly influence pipe degradation. Morris (1967) discussed soil movement represented by swelling and shrinking soils, which cause weakened pipes to fail more easily. Wood and Lence (2007) also stated that some soils experience volume changes, a factor that puts an additional load on pipes. Wengström (1993) stated that a higher failure rate was reported in clays than in sandy soils. Soil resistivity, which is a measure of the extent to which the soil resists the flow of electricity, also contributes to failures, because stray currents may cause electrolytic corrosion (NGSMI, 2003). Some types of groundwater have also been noted to be aggressive toward certain pipe materials.

2.4.7 Pressure conditions

High static pressure, as well as pressure surges (water hammer), can have a severe impact on pipe failure in a water distribution system. Higher static pressures typically relate to an increased failure rate, as would be expected. Chadwick et al. (2004) noted that pressure surges occur when the flow in the pipe accelerates (or decelerates) due to a change at a controlling boundary and that the intensity of the surge pressure depends on the rate of change at the controlling boundary. Sudden changes in fluid velocity result from common operational causes such as rapid valve closure and pump starts after improper filling practices (Val-Matic, 2009).

Pressure surges could be a contributing factor for the phenomenon of failure clustering due to the closing and opening of valves during maintenance and repair activities. Thornton and Lambert (2007) stated that (i) significant reductions in the number of bursts are reported after pressure management, irrespective of pipe materials, and (ii) that pressure is a contributory factor to failure, rather than the prime factor.

2.4.8 Failure history

Walski and Pelliccia (1982) concluded that the failure history of a pipe (number of previous failures) is a significant factor for the prediction of future failures. Goulter et al. (1993) reported on water pipe failure clustering and indicated that the likelihood of future failure for a pipe was increased if another failure occurred in close proximity, and found that about 60% of all subsequent failures occurred within a three month period of a previous failure incident. They suggested that the failure clustering might be caused by damage to the pipes during maintenance operations, such as pressure surge while refilling the pipe, soil movement caused by excavation, substandard backfilling and additional external forces such as the movement of heavy vehicles. Other factors, apart from repair activities, are also responsible for the clustering of failures in a network. Pipes in the same location often have similar failure predictors, such as age, material, external and internal corrosion conditions, installation method and contractor. Misiunas (2005) stated that the failure development history is specific to each pipe and extremely difficult to predict and further noted that the situation becomes even more complicated when failures caused by third party interference are considered.

2.5 Consequence of failure

According to Park et al. (2010) the consequence of physical failure of a component is a measure of the impact on the community and customers. Ispass (2008) stated that the consequence of failure is determined based on a number of institutional factors, including public health, safety, security and level of service.

Sinske and Zietsman (2004) indicated that in addition to disrupting service, water pipe failures also result in significant loss of water, which in equates to a loss in revenue because the water could have been sold to the consumer. They further postulate that in water scarce countries, such as South Africa, water losses can negatively impact the living standard of people. Flooding as a result of pipe bursts can furthermore cause extensive damage to nearby lower-lying properties. Neelakantan et al. (2008) stated that interruption of supply to water-intensive industries, traffic disruptions, disease outbreaks and delays in firefighting ability are also possible consequences of water pipe failures.

The impact associated with a pipe failure can be divided into three main categories, namely direct costs, indirect costs and social costs. These three categories are discussed briefly below.

2.5.1 Direct costs

Direct costs refer to expenditure directly related to the current occurrence of the pipe failure. These are more easily quantified and calculated when compared to indirect costs, and even more so when compared to social costs. The direct costs are a summation of the following costs:

- Cost of repair.
- Cost of lost water.
- Cost of damage to adjacent infrastructure (flooding, road collapse, etc.).
- Cost of liabilities (injury, accidents, structural damage, etc.).

The direct costs depend on the parameters of a pipe such as diameter, material and location, as well as the severity of the failure, time to isolation of the failure and the production and conveyance cost of water. Figure 2-5 depicts an example of the increase in direct costs incurred from the time of failure (t_f) to the time of repair (t_r). The costs are not necessarily linear functions of time, but a linear function was used for illustration.

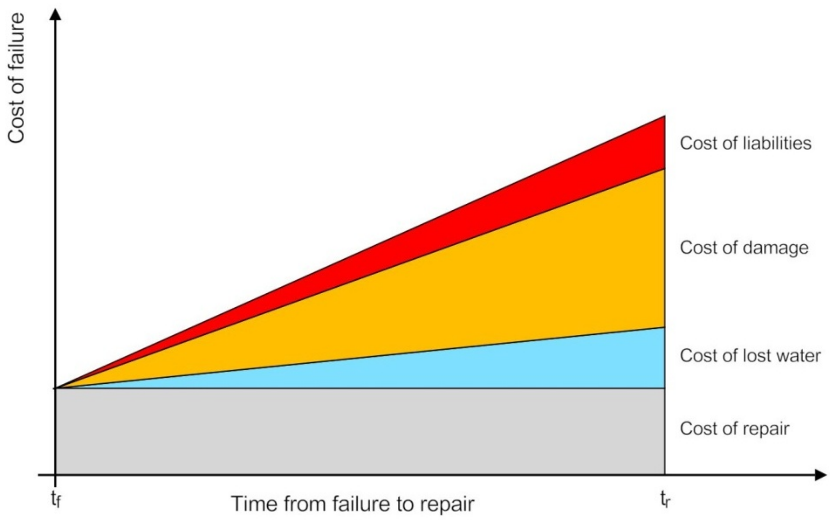


Figure 2-5: Direct costs due to a failure over time (adapted from Misiunas, 2005)

2.5.2 Indirect costs

Indirect costs refer to the inability of the system to achieve its purpose and possible expenditure that was not accounted for, which increases overall cost of failure as shown in Figure 2-6. A linear function of time is used for illustration as for the direct costs.

The indirect costs are described as follows:

- Cost of supply interruption – loss of business due to non-supply of water.
- Cost of possible increase in deterioration rate of surrounding infrastructure and subsequent devaluation.
- Cost of diminished ability for fire-fighting.

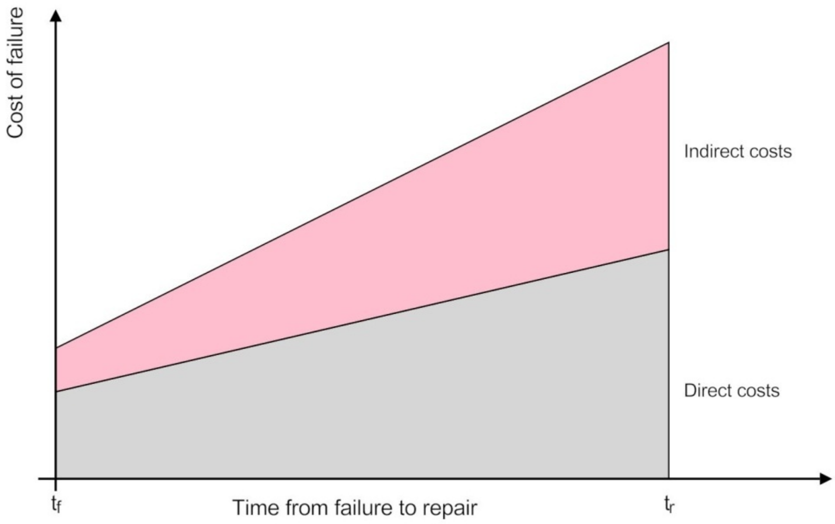


Figure 2-6: Direct and indirect cost of failure (adapted from Misiunas, 2005)

2.5.3 Social costs

Social costs are heavily influenced by the location of the failure and the time to isolation of the affected part of the network by closing the appropriate network isolation valves. The social costs are less tangible in nature and described as:

- Cost of water quality degradation – contaminant intrusion from depressuring.
- Cost of customer inconvenience – decrease in public trust.
- Cost of disruption to the traffic and businesses.
- Cost of insufficient supply to special facilities.

2.6 Failure prediction models

USEPA (2000) presented different approaches to failure prediction classified in the following three major modelling groups: (i) probabilistic or statistical models, (ii) deterministic methods and (iii) heuristic methods. Clair and Sinha (2012) presented a comprehensive review on different water pipe condition, deterioration and failure rate prediction models, and proposed that each of the models be grouped into one of the following six categories: (i) deterministic, (ii) statistical, (iii) probabilistic and advanced mathematical models which consist of (iv) artificial neural networks (ANN), (v) fuzzy logic and (vi) heuristic models. Tabesh et al. (2009) combined the ANN and fuzzy logic models into so-called data-driven modelling techniques.

Previously published failure prediction models from literature were reviewed and summarised as part of this research. Physical or mechanistic models and models that focus on single material types were excluded. The models are presented in chronological order in the following tables:

- Table 2-5: Time-relationship models,
- Table 2-6: Failure-clustering models,
- Table 2-7: Probabilistic and statistical models,
- Table 2-8: Bayesian models and
- Table 2-9: Advanced mathematical models

Table 2-5: Time-relationship models

Reference/Author	Model Description	Data Requirements
Shamir and Howard (1979)	Regression analysis to relate pipe's breakage rate to the exponent of its age. Analysis performed on homogeneous groups of pipes. Used to determine cost of pipe replacement in terms of Present value of break repair and capital investment, and optimal replacement timing is calculated. Assumption of uniform distribution of breaks along all water pipes in a group. Economic analysis neglects the cost of breakage repair after pipe replacement.	Pipe length. Installation date. Breakage history. Formation of homogeneous groups from other pipe attributes such as pipe diameter and soil type.
Walski and Pelliccia (1982)	Enhancement of exponential model includes two additional multiplicative factors based on effect of previous breaks and larger diameters. Additional proposal of two-phased prediction, with the first phase a linear equation to predict time of first failure, with the exponential equation thereafter. Assumption of uniform distribution of breaks along all water pipes in a group. Multiplicative factors inherently assumed to only affect the initial break rate and not the annual growth.	Pipe length. Installation date. Breakage history. Formation of homogeneous groups according to influencing criteria. Pipe diameter. Pipe casting method.
Clark et al. (1982)	Two different deterioration stages in water pipe life. Linear equation to time of first breakage, with covariates acting independently and additively. Exponential equation considers breakage rate as exponential function of time since first break, with other factors assumed to act multiplicatively. Low R^2 of linear equation suggests that assumption of independence may be incorrect and that factors affecting pipe deterioration act jointly.	Time of installation. Breakage rate. Pipe type. Pipe diameter. Operating pressure. Soil corrosivity. Land use overlaying location of pipe. Type of break.
Kettler and Goulter (1985)	Modelled a linear relationship between pipe breaks and age. Performed on sample of pipes in Winnipeg, Manitoba. Moderate correlation found between breakage rate and age. Strong correlation found to suggest larger pipes break less than smaller pipes.	Same as for Shamir and Howard (1979)
Mavin (1996)	Compared time-exponential model to a time-power model. The data used was filtered to only include pipes with complete known failure history (excluding failures within three years of installation and failures within six months from previous failure). Both models were found to have comparable predictive performance.	Pipe age. Failure history. Formation of homogeneous groups.
Table 2-5 continues on the next page		

Reference/Author	Model Description	Data Requirements
Loganathan et al. (2002)	Presented a methodology using threshold break rates in conjunction with failure prediction models in order to determine the optimal replacement of pipes. Analysis of the optimal threshold break rate as a function of pipe diameter in conjunction with replacement and repair costs. Optimal replacement time expressions were obtained by setting the threshold break rate equal to the projected pipe break rates from the failure prediction models.	Break rate (breaks per 1000 ft of pipe). Base year of analysis. Growth rate coefficient. Annual interest rate. Repair cost of a break. Replacement cost of entire length of pipe.
Wood and Lence (2009)	Future break rates forecasted within subgroups from break data history. Two statistical deterministic equations were developed for each group of pipes: time-linear and time-exponential equations, with regression analyses to calculate required coefficients. Concluded that predictive modelling is useful to identify replacement needs and flexibility of robust models allow for consideration of any available data and can be improved as more or better data is collected.	Pipe age. Failure history. Pipe material. Diameter. Ground surface material.

Table 2-6: Failure clustering models

Reference/Author	Model Description	Data Requirements
Goulter et al. (1993)	Model proposed to accommodate clustering phenomenon observed by Goulter and Kazemi (1988). A clustering domain was defined with a space interval, a time interval and an initial failure. Failures within the space and time intervals of first failure were considered to belong to that cluster. Probability of ensuing breaks, given an initial break, was predicted with a non-homogeneous Poisson probability distribution. Can only be applied if initial break in the cluster is known to have occurred. Failures are often discovered and recorded long after it has occurred, which is an additional source of inaccuracy in modelling the cluster phenomenon.	Pipe type. Pipe breakage data. Break location within single metre.
Jacobs and Karney (1994)	Considered the clustering phenomenon of pipe breaks. Defined independent breaks as a break that occurs more than 90 days after and/or more than 20 metres from a previous break. Linear regression performed on pipes divided into three age groups. Correlation increased when only independent breaks were considered, which confirmed their hypothesis (for the tested data) that independent breaks were uniformly distributed along the pipe length. Pipe age in the regression model improved the predictive power for old pipes significantly.	Pipe length. Age. Breakage history. More data enables formation of homogeneous groups.
Sinske and Zietsman (2004)	Developed a spatial decision support system to determine pipe-break susceptibility for municipal water distribution systems, based on pipe age, air-pocket formation and tree roots. Pipes are grouped into susceptibility categories and an evaluation factor is determined from weights that are assigned to each category.	Location. Diameter. Slope. Age. Distance from trees.
De Oliveira et al. (2011)	Utilised and adapted existing spatial scan statistic approaches commonly used for detection of disease outbreaks in two-dimensional space. Detection of potentially useful regions for prioritisation with regards to maintenance and replacement and cost-benefit analysis for capital investments was reported.	Failure rate. Age. Diameter. Location.

Table 2-7: Probabilistic and statistical models

Reference/Author	Model Description	Data Requirements
Marks (1985)	Baseline hazard function was approximated with a second degree polynomial, where the hazard initially decreases and then increases, similar to bathtub curve. Depicts the instantaneous probability of the next break after installation, or after the last break that occurred. Model appeared to have little sensitivity to left data censoring (incomplete breakage records - missing or unavailable), which was an advantage as many municipalities do not have long breakage records. Cost analysis was performed to find optimal time of replacements.	Pipe length. Operating pressure and flow rate. Land development. Pipe vintage or period of installation. Pipe age at second or higher break. Number of previous breaks in pipe. Soil conditions. Proportional hazard model (PHM) as proposed by Cox (1972).
Andreou et al. (1987) Marks et al. (1987)	Further development of work of Marks (1985) to include two-stage pipe failure process. Observed that new pipes rarely broke shortly after installation, and that the time interval between successive breaks was shortened. After the third break the breakage rate seemed to be constant regardless of the number of previous breaks. Early stage (with fewer than three breaks) was represented with PHM and late stages (more than three breaks) were represented by Poisson type model. Andreou et al. (1987b) reported a moderately low R^2 of 0.34 when the cut-off between early and late stage was three breaks, but the R^2 increased to 0.46 when the cut-off was taken as six.	
Eisenbeis et al. (1993)	Used Accelerated lifetime model (ALM). Essence of these models is that time to next failure expands or contracts relative to that at x = 0, where x is defined as a vector of explanatory variables. A random variable was assumed to follow a Gumbell distribution. Monte-Carlo simulation is required for prediction.	Number of previous failures. Diameter. Age.
Gustafson & Clancy (1999)	Breakage history of water mains modelled as semi-Markov process in which each break order (e.g. 1st, 2nd, 3rd break, etc.) is considered a state in the process and the inter-break time is considered the "holding time" between the current and previous states. Time from installation to first break was modelled as a three-parameter gamma distribution. Subsequent inter-break times were modelled as exponential distributions. Elaborate model to predict inter-break times, based on historical data, but found the model inadequate for predicting future failures. The inadequacy was reasoned to be due to change in conditions over time and predictions were then based only on the preceding 5 years.	Complete as possible breakage history. Additional data to partition the pipe inventory into homogeneous groups. Break history as a semi-Markov process.

Table 2-7 continues on the next page

Reference/Author	Model Description	Data Requirements
Le Gat and Eisenbeis (2000)	Forecasting of failures in water networks based on survival analysis with a Weibull Proportional Hazard Model (WPHM) applied to predict times to failure. The failure time of given survival probability is determined by the model. Monte Carlo simulation is used to generate random data in the model and aid in prediction of failures. Two case studies were presented.	Length. Age. Diameter. Pipe assembly technique. Soil type. Level of traffic. Supply methods (gravity or pumping). Operating pressure.
Poulton et al. (2007)	Considered the impact of pipe segment length on break predictions. A statistical model utilising linearly extended Yule process (LEYP) was presented that implements break prediction for each segment. Calculations using LEYP are performed based on an intensity function that depends on the age of the segment considered, number of previous events and a vector of additional failure influencing parameters. The intensity function includes the influence of previous events in a form derived from the LEYP, the influence of age in the form of the Weibull model and the influence of the covariates represented in the Cox PHM. A case study was presented.	Diameter. Length. Installation year. Identification of pipe segment. Date of intervention. Type of incident. Joint type. Reason for intervention. Soil type. Soil surface type. Traffic level. Water pressure.
Kleiner and Rajani (2008)	Examined the use of non-homogenous Poisson model by evaluating parameters that affect a water pipe failure. Three classes of parameters considered in analysis: (i) pipe dependent (ii) time dependent and (iii) a combination of the two. First the model is trained with process that involves use of the maximum likelihood method with a Lipschitz Global Optimizer (LGO) algorithm. Next step is forecasting the number of breaks and comparing them to observed failures. Case Study utilizing data from utility in Canada is used to verify the model.	Material. Diameter. Installation year. Length. Climate. X-Y coordinates of pipe nodes. Break date. Break type.

Table 2-8: Bayesian models

Reference/Author	Model Description	Data Requirements
Wang et al. (2010)	Model which utilises Bayesian inference to calculate pipe factor weights using pipe deterioration rates and various pipe factors. Relative influence of each factor on model performance was evaluated. Deviance Information Criterion (DIC), coefficient of determination and standard error were used as measures of fit to test and compare the model results. Analyses showed that pipe age and diameter had the most influence in determining the pipe condition. Number of road lanes, trench depth and electric recharge were eliminated.	Deterioration rates based on outer corrosion, crack, pin hole, inner corrosion and Hazen-Williams C value. Diameter. Pressure head. Age. Trench depth. Number of road lanes. Inner coating. Outer coating. Electric recharge. Bedding conditions. Soil condition. Material.
Li et al. (2013)	Use of Bayesian nonparametric learning to predict water pipe condition. Extends the hierarchical beta process as presented by Thibaux and Jordan (2007) with an inference algorithm for sparse incident data. A set of mean and concentration parameters are used to describe the failure rate of different groups of pipe. Outperformed Weibull and Cox for case study presented. Expert commentary noted the small dataset used and proposed further case studies. Data was limited to diameters above 300 mm.	Failure history. Pipe length. Pipe grouping according to pipe coating, region, and installation year.

Table 2-9: Advanced mathematical models

Reference/Author	Model Description	Data Requirements
Al-Barqawi and Zayed (2006)	Developed condition rating model to assess rehabilitation priority for water mains using an Artificial Neural Network (ANN). ANN uses back propagation algorithm analysing environmental, physical and operational factors to determine the water main condition. Data from municipalities in three Canadian provinces were used for training and testing. Breakage rate and age were shown to have the highest effect on the condition rating.	Water main condition based on: soil type, road surface, pipe cover, diameter, material, age, number of breaks. Hazen-Williams C-Factor.
Fares and Zayed (2010)	Hierarchical fuzzy expert system to determine the risk of failure of water mains. Consists of 16 risk factors within four categories (environmental, physical, operational and post-failure). Risk of failure output scale ranges from 0 to 10, with 10 the highest risk condition. Case study was applied which classified pipe segments based on their risk condition level. Particular characteristics were highlighted by illustrating statistics for the total count and length for pipes classified as fair and risky. Results concluded that small diameter and CI pipes contributed most to network risk.	Soil type. Average daily traffic. Ground water table level. Diameter. Material. Age. Protection method. Breakage age. Hydraulic factor. Water quality. Leakage rate. Cost of repair. Damage to surroundings. Loss of production. Traffic disruption. Type of service area.

Many failure prediction models utilise a probabilistic approach to model the uncertainty of pipe failures with a suitable probability distribution, for example Weibull and Poisson distributions, and Monte Carlo simulation is used to generate random data in the model and aid in prediction of failures. Pergler and Freeman (2008) explored the case against probabilistic modelling with many managers reporting that probabilistic approaches are too difficult, and although the outputs may be useful, they were reported to be inscrutable and not worth the effort. Although it was argued that, when used well, probabilistic prediction tools become essential for managing uncertainty, Pergler and Freeman (2008) warn that “those who place too much faith in sophisticated modelling get overambitious and eventually get punished by fate”. The more advanced models using neural networks, genetic algorithms and machine learning processes are reported to yield promising results for the prioritisation of expected water pipe failures.

However, these models are generally very "data hungry" and as noted by Skipworth et al. (2002), data on failure history is seldom at a reasonable level of quality and completeness. The advanced models also require an increased level of mathematical expertise and understanding (Clair and Sinha, 2013) and that could pose a problem in municipalities where there is a general lack of engineering skills (Lawless, 2006).

Risk-based approaches for prioritising water pipes for repair or replacement activities, that do not require comprehensive quantification of failure probability, have been established to account for factors influencing likelihood of failure (probability) as well as the consequence of failure (impact). This research aims to expand such a risk-based prioritisation procedure into a model that can be used to estimate the long term investment requirements by simulating pipe replacement based on the calculated risks.

2.7 Risk-based prioritisation

Loganthan et al. (2002) suggested that deterioration is a critical infrastructure problem contributing to increased replacement and repair costs which necessitates the need for prioritisation of pipe replacement. Park (2004) stated that when a failure event occurs, the structural integrity of the pipe has been lost due to environmental and operational stresses exerted on it over its service life. Research has shown that several factors influence pipe failure and that the quality, quantity and availability of failure data is critical for effective management of pipe infrastructure (Wood and Lence, 2006; Clair and Sinha, 2013).

Fletcher (2005) stated that the analysis of risk requires the examination and identification of the possible sources of an issue, including the impact and likelihood associated with the actual occurrence of an identified issue. Similarly, Simonsen and Perry (1999) provided the following three guiding questions for risk assessments:

- What can happen?
- How likely is it that it can happen?
- What are the consequences if it does happen?

Risk assessments are generally categorised as (i) qualitative, (ii) semi-quantitative and (iii) quantitative. Berg (2010) noted that all three techniques mentioned are acceptable analysis techniques, depending on the goal of the analysis, the information and type of data available and the manner in which risk is calculated or assigned. Table 2-10 provides a brief description of each of the risk assessment categories stated above.

Table 2-10: Summary of risk assessment categories

Risk assessment category	Description
Qualitative	Comprises of the categorisation of risk with textual descriptions (high, medium, low). The use of a risk matrix for decision making is most common. Allows for use of operational staff with risk identification.
Semi-quantitative	Textual descriptions are replaced with numerical value assignments to describe relative risk scale. Risk matrices are also used, but individual elements can be compared based on ranked indices. The objective is to develop a hierarchy of risks which reveals the order that should be reviewed and no real relationship between them.
Quantitative	Quantification of risk with numerical modelling and probabilities and requires mathematical and statistical expertise. Suitable assessment technique with sufficient data and appropriate mathematical models to quantify specific risks.

Iacob (2014) stated that qualitative assessments are descriptive and do not imply an exact quantification and often provide support for further investigation and use of more quantitative approaches. Radu (2009) indicated that a qualitative risk assessment is most appropriate when numerical data are inadequate and limited expertise is available. Pollard and MacGillivray (2008) noted the importance of stakeholder engagement and the benefit of more qualitative approaches to include non-specialists part of the operational staff to provide useful insights.

Aven (2008) stated that risk analysis simply provides decision support and not the decision itself and qualitative or semi-quantitative analysis could present a more comprehensive risk picture, taking underlying factors that influence risk into account, when compared to a quantitative analysis, for which the calculations are tedious and could include a strong element of randomness. Swartz et al. (2010) concluded that risk estimation with risk matrices is a useful and efficient tool as it is easy to understand and present data.

FAO (2009) stated that a semi-quantitative risk assessment is most useful in providing a structured way to rank risks and is achieved through a predefined scoring system. Holmgren and Thedéen (2009) noted that the advantage of quantitative risk analysis is that it yields precise risk measures, but concede that such approaches should be avoided when the data quality is poor and the data sources are questionable. FAO (2009) mentioned that at least part of the assessment team should have rigorous mathematical training when quantitative risk assessments are considered.

Research shows that a semi-quantitative risk approach is preferable when there is limited or questionable data and provides adaptability in including additional risk factors as it provides an intermediary level between the textual descriptions qualitative assessments and numerically modelled risk measures from quantitative assessments (FAO, 2009). In general, semi-quantitative risk analysis offers a more consistent approach for comparing risks than qualitative risk analysis and does not require the same level of mathematical skill or data requirements of quantitative risk analysis.

The risk-based prioritisation model used as part of this research has been developed as a practical method to account for factors that influence pipe failure, consequence of failure and management strategies (e.g. preference to replace asbestos-cement pipes due to possible health risks, regardless of remaining useful life). A final risk value is calculated from the likelihood and consequence of failure, which is based on scores and weights assigned to individual factors. The pipes are then ranked and prioritised according to the resultant risk value, with highest risk value receiving the highest priority. The risk model employed is therefore considered to fall within the semi-quantitative assessment category.

3 Description of the once-off risk prioritisation approach

In this research, the risk-based prioritisation approach as explained in Sinske et al. (2009; 2011) and Sinske and Streicher (2013) and discussed by Scruton (2012) is used, as it has been widely implemented in South Africa in addition to the case study. Risk is calculated by multiplying factors that describe likelihood of failure (LF) and consequence of failure (CF). The factors are determined using several variables and their respective assigned scores and weights. A higher assigned score (and weight) will have a greater impact on the final risk calculation.

3.1 Risk model framework

Figure 3-1 illustrates the approach of the risk model used in this research.

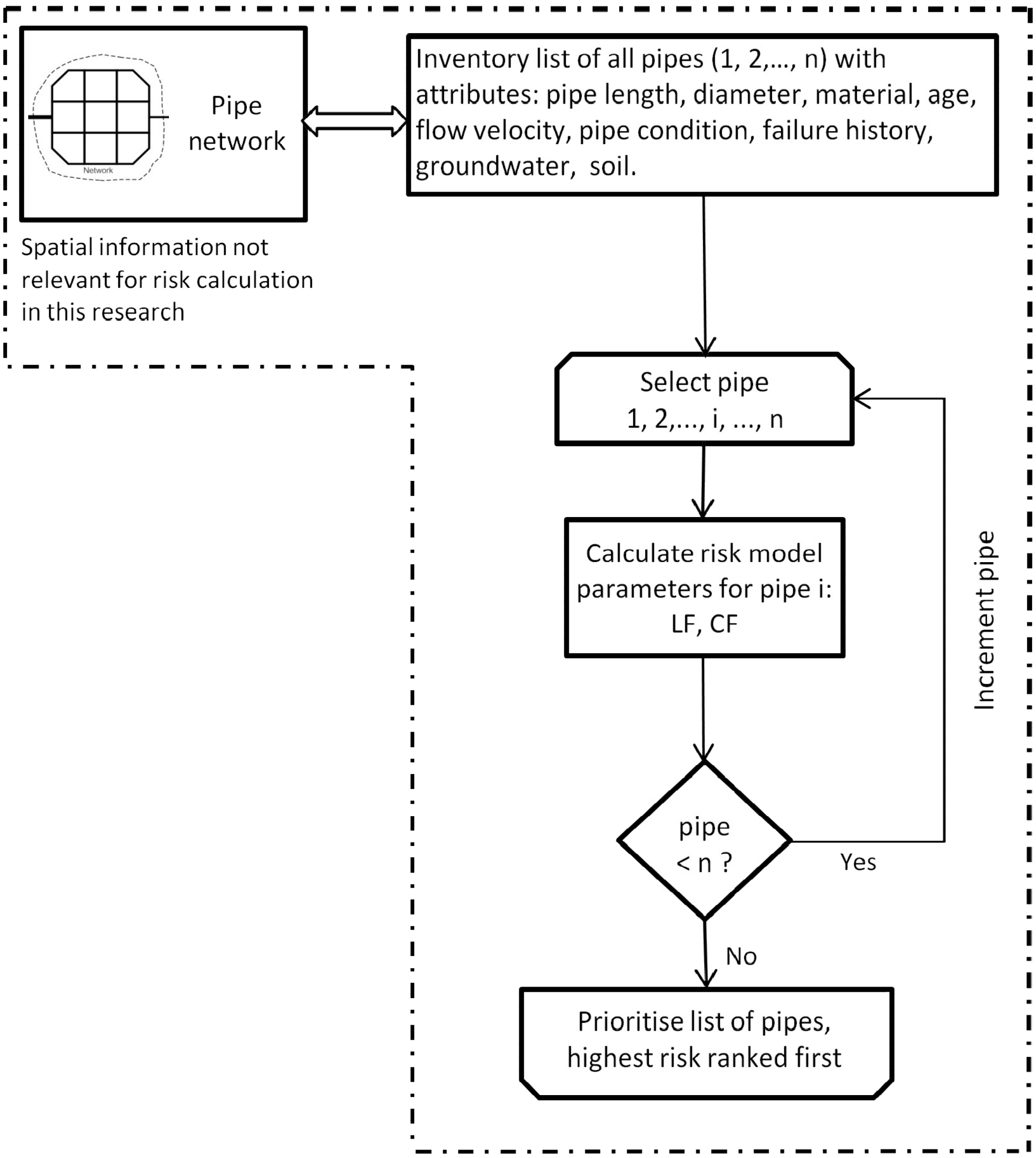


Figure 3-1: Once-off risk prioritisation framework

3.2 Risk calculation

For each pipe a score is assigned to each contributing variable. The scores are determined based on the expected influence of the specific value of the variable in comparison with the other values present for that variable (e.g. small diameter pipes receive a higher score than large diameter pipes due to higher failure rate amongst small diameter pipes). Therefore, all pipes can be compared to one another based on the scores assigned per variable. These scores are typically assigned as integer values ranging between 1 and 5 to denote very good to very poor confidence. In addition to the assignment of scores, each variable is assigned a weight to indicate its relative importance in determining the factor it contributes toward (i.e. likelihood or consequence).

In the risk of failure calculation, the LF and CF factors are calculated and then multiplied to determine a risk of failure score or value, which is noted as the pipe replacement factor (PRF) for the risk-based method employed as part of this research. The LF and CF factors values are calculated through assigning weights and scores to certain quantifiable criteria for each contributing variable. These weights and scores are decided upon through engineering judgement and workshops with the operational staff and are therefore determined heuristically. A rank can then be assigned to a pipe to determine its replacement priority.

The LF factor is calculated as shown in Equation 1. The likelihood variables, as used in the once-off risk prioritisation of the case study, are shown in Table 3-1.

$$LF = \sum_{i=1}^{y} \frac{\theta_i}{\theta_T} \times \mu_i$$

Equation 1: Likelihood of failure (adapted from Sinske et al., 2011)

Where

LF	=	LF factor value
i	=	LF variable
y	=	Number of LF variables
θ_T	=	Total of all LF variable weights
θ_i	=	LF variable weight
μ_i	=	LF variable score.

Table 3-1: Likelihood variables for case study

Likelihood variable name	Description
L_NomDiam	Variable to account for different pipe diameters
L_Hammer	Variable to account for water hammer
L_ERUL	Variable to account for age
L_Settling	Variable to account for settling
L_LeakVol	Variable to account for Leakage Volume (no data)
L_FlucWL	Variable to account for fluctuating GWL
L_CorrPot	Variable to account for corrosion potential
L_Material	Variable to account for pipe material
L_FailFreq	Variable to account for failure history
L_Conditn	Variable to account for pipe condition (no data)

The CF factor is calculated as shown in Equation 2. The consequence variables, as used in the once-off risk prioritisation of the case study, are shown in Table 3-2.

$$CF = \sum_{j=1}^{z} \frac{\emptyset_j}{\emptyset_T} \times \sigma_j$$

Equation 2: Consequence of failure (adapted from Sinske et al., 2011)

Where

CF = CF factor value

j = CF variable

z = Number of CF variables

$\emptyset_T$ = Total of all CF variable weights

$\emptyset_j$ = CF variable weight

σ_j = CF variable score

Table 3-2: Consequence variables for case study

Consequence variable name	Description
C_RepCost	Variable to account for replacement cost
C_VulnCust	Variable to account for vulnerable customers
C_NWRedund	Variable to account for number of affected consumers

The factors resulting from Equation 1 and Equation 2, LF and CF respectively, are then multiplied to calculate the PRF in Equation 3.

$$PRF = LF \times CF$$

Equation 3: Pipe replacement factor (adapted from Sinske et al., 2011)

Where

PRF	=	Pipe replacement factor.
LF	=	LF factor value
CF	=	CF factor value.

The PRF value is then used to rank the pipes in terms of replacement priority with the largest PRF value indicating the pipe with the highest replacement priority in the water distribution network.

4 Development of the multi-period prioritisation model (MPM)

4.1 MPM framework

Figure 4-1 illustrates the incorporation of the once-off risk prioritisation approach in a multi-period replacement model. Key model concepts with regards to the practical considerations taken into account for the replacement model are discussed in paragraph 4.2 and the mathematical description is given in paragraph 4.3. The tool developed, as part of this research to simulate the replacement process, is described in paragraph 4.4.

The available data for the case study, as presented in chapter 5, is used in paragraph 4.2 to improve the understanding of the concept of unit replacement and repair cost tables. The case study data is also extensively used in paragraph 4.4 for illustrative purposes for the type of data required in the input tables of the developed tool.

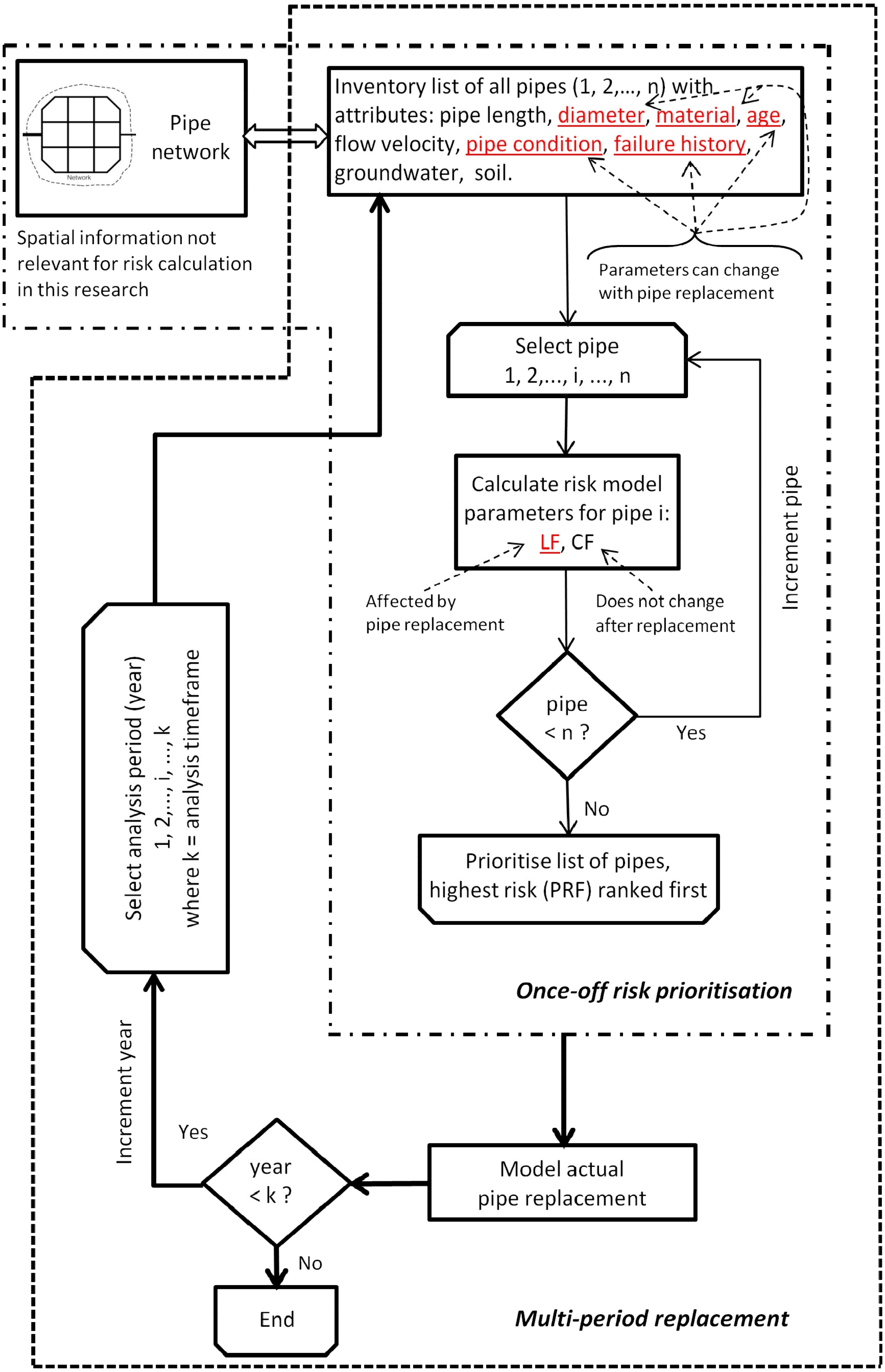


Figure 4-1: Multi-period replacement model framework

4.2 Key model concepts

4.2.1 Pipe replacement

Loganthan et al. (2002) stated that the actual replacement of ranked pipes depends on the available budget and other practical considerations deemed relevant by the municipality. The development of a multi-period pipe replacement analysis from a "once-off" risk-based prioritisation analysis, in its simplest form, would therefore be to replace the pipes according to their rank from highest to lowest risk, as calculated by the prioritisation analysis, until the cumulative capital expenditure reaches the available annual replacement budget (AARB) for each analysis period. The pipes that have been chosen for replacement are then deemed ineligible for replacement for the remainder of the analysis. The same replacement procedure is then applied to the remaining eligible pipes in the next analysis period, and so forth, for the desired analysis time-frame.

4.2.2 Replacement cost

The replacement cost of each of the pipes is calculated with a cost function that includes the material, diameter, length and location of the pipe. Table 4-1 gives an example of a typical replacement cost function that gives a cost per unit length (metres in the case of this research) of pipe for a certain diameter, material and location.

The cost function entries were adjusted from real world costs so that the minimum unit cost was equal to 10 and all other costs were adjusted accordingly. Therefore, expenditure values reported on do not imply any specific currency and are referred to as credits (C_r) in the remainder of this text.

The selection of a particular value for this purpose is not important because costs are compared on a relative basis. A value of 10 was chosen instead of 1 because 10 allowed for sensible rounding of unit costs to full integers, as presented in Table 4-1.

Table 4-1: Replacement cost function

Diameter (mm)	Replacement cost per unit length (C_r/m)					
	Rural			Urban		
	PVC	DI	PE	PVC	DI	PE
≤ 50	10	10	10	15	15	15
≤ 63	11	11	11	16	16	16
≤ 75	12	12	12	17	17	17
≤ 110	13	13	13	19	19	19
≤ 160	16	16	16	24	24	24
≤ 200	20	20	20	30	30	30
≤ 250	21	21	21	31	31	31
≤ 315	24	24	24	36	36	36
≤ 400	36	36	36	54	54	54
≤ 500	47	47	47	70	70	70
≤ 630	70	70	70	105	105	105
≤ 700	78	78	78	117	117	117
≤ 800	89	89	89	134	134	134
> 800	112	112	112	167	167	167

4.2.3 Scheduled replacements

Another unavoidable aspect of many pipe refurbishment or replacement projects is that they occur as part of urban renewal plans due to socio-political motivations, or to hydraulic upgrading projects. It is possible for pipes to be included in replacement projects regardless of their priority rank as determined by the annual risk prioritisation analysis. The model should therefore be able to address these predetermined scheduled pipe replacement projects, since the cost of such replacements will reduce the AARB for utilisation for risk-based pipe replacements in the analysis.

Nafi and Kleiner (2010) stated that when pipe replacement is coordinated with scheduled roadworks it could lead to significant overall cost reduction. Sinske et al. (2009) mention that combining a pipe replacement programme with other required infrastructure programmes ensures that upgrades and replacements are planned and implemented in an efficient and cost effective manner.

It is therefore required that, when replacement decisions are made, allowance is made for pipe replacement projects that have been established by other means and that have already been planned and approved.

4.2.4 Budget utilisation

4.2.4.1 Pipe skip count

The aim is to spend as much of the available budget on pipe replacement to minimise the number of failures and ultimately the unforeseen expenditure resulting from repairs. Therefore, if the replacement of a pipe (sorted based on replacement rank) will cause the cumulative expenditure to exceed the available budget, replacement will not be allowed, and the next-ranked pipe is tested, and so on until the available budget is achieved (barring none of the other eligibility factors have halted the process). However, this process can cause many low-cost pipes, most notably due to short pipe length, to be replaced to meet the available budget spending requirement. An input parameter is provided to stop the replacement procedure after a certain number of consecutive pipes have been skipped for replacement.

4.2.4.2 Minimum budget expenditure

Relying on the pipe skip count parameter, as discussed above, alone to improve the replacement spending procedure may possibly lead to another problem. Keeping in mind that replacement occurs on a ranked list of pipes based on the risk, it is possible to have many consecutive large-cost pipes, greater than the selected maximum pipe skip count, which could then lead to the replacement procedure being halted without spending an adequate percentage of the available budget. Therefore an additional input parameter is provided to indicate the minimum budget expenditure percentage that should be achieved before the maximum pipe skip count test is to be employed.

4.2.4.3 Contingency buffer

Similarly, it might be allowable to overspend on the available budget if a high-ranked pipe will be skipped due to its replacement cost, causing the cumulative expenditure to slightly exceed the available budget. Therefore, an input parameter is introduced to temporarily allow the budget to be exceeded by a certain percentage when the cumulative expenditure will exceed the original available budget. Once such a replacement is allowed, the replacement for the current period is halted as the cumulative expenditure will exceed the initial available budget.

4.2.5 Replacement exclusion period

Excluding the new replacement pipes for replacement consideration for the entire analysis could potentially pose a problem when long analysis timeframes are considered. The purpose of risk-based replacement is the proactive mitigation of pipe failures. When a pipe is replaced the risk of failure is reduced by lowering the likelihood of failure. However, the consequence of failure is unaltered and, with time, the likelihood of failure of the new replacement pipe will also increase, which could result in a high enough risk value to be eligible for replacement. Therefore a replacement exclusion period (REP) is introduced after which a pipe will once again become eligible for replacement. The REP serves as a risk acceptance parameter in the analysis by indicating a period of time for which the risk will be accepted, regardless of rank. For example, a REP of 0 years indicates that no risk is tolerated and high consequence pipes may be replaced every year. Conversely, a REP ≥ year k (analysis timeframe) indicates that all future risk for replaced pipes will be accepted and no recurring replacement will be allowed.

4.2.6 Replacement eligibility

The priority rank is used for each period to present a "snap-shot" of pipes at risk during that period, based on predetermined acceptance criteria. The predetermined acceptance criteria will determine if a pipe with a high rank, based on the risk value, will be deemed eligible for replacement during the specific analysis period iteration. If a pipe is eligible for replacement, certain pipe attributes for the pipe is adjusted, which may or may not alter the scores and ultimately the LF for future period iterations. The eligibility test is required when budget constraints are considered and to prevent the short-term cyclic replacement of high consequence pipes.

Apart from the AARB and the REP, other optional eligibility tests are the total number of failures allowed per year, the total replacement length allowed per year and the service interruption limit as discussed later in this chapter.

4.2.7 Performance indicators

4.2.7.1 Failure forecasting

Forecasting of historical pipe failures is required as these unplanned occurrences lead to operational expenditure (OPEX) and possible interruptions in service to the end-user, each of which can be used as a performance indicator (PI) when comparing different scenarios.

Extended failure records are required for statistical methods to be used with any significant confidence level. The type of failure prediction model used depends on the type of information available for the distribution system. Kleiner and Rajani (2001) stated that probabilistic multi-variate models are well suited for application to individual pipes, but require significant technical expertise and data that are sufficient to handle multiple failure parameters. Also, with methods other than those of deterministic models a degree of randomness is presented to mimic real life situations. Results of such models utilising random events are therefore not reproducible which may hinder the use of the pipe prioritisation results for long-term pipe replacement investment strategies. Furthermore, as stated by Pergler and Freeman (2008), some managers indicate distrust in the "black box" techniques accompanying probabilistic models.

In order to test the applicability of the multi-year replacement model developed as part of this research, a test on the health of the water distribution network is required. The health of the water distribution network is assessed by considering several performance indicators. In this research, the performance indicators that are considered include remaining useful life, asset value, number of expected pipe failures, OPEX and SID. The choice of the failure forecasting model to use should allow for the following characteristics:

- The variables that influence the LF should be incorporated in the failure prediction model.
- The failure algorithm should be of such a nature that the calculated number of failures should be easily reproducible, at individual pipe level, especially when comparisons between investment periods and strategies are considered.

Therefore, due to the requirement of reproducibility to compare failures for various input scenarios, a deterministic time-relationship failure model is used to calculate the expected number of failures from given inputs.

4.2.7.2 Operational expenditure

With satisfactory failure forecasting, it is possible that OPEX, in the form of refurbishment costs, can be estimated in a similar way to that of replacement costs and calculated using a cost function. Table 4-2 gives an example of a typical pipe refurbishment cost function table that gives a cost per failure indication for a certain diameter and material. The real world repair costs were adjusted congruent to that of the replacement costs, as discussed in paragraph 4.2.2, to ensure comparability and to report on all expenditure values in credits.

Table 4-2: Repair cost function

Diameter (mm)	Repair cost per failure (C_r)			
	AC	DI	PVC	Other
≤ 50	154	154	154	154
≤ 63	204	199	159	171
≤ 75	185	185	185	185
≤ 110	370	277	241	322
≤ 160	551	427	245	406
≤ 200	582	304	346	394
≤ 250	621	176	342	414
≤ 315	435	350	443	425
≤ 400	937	435	954	937
≤ 500	1170	1873	1112	1258
> 500	2341	2341	2341	2341

4.2.7.3 Service interruption duration

Expected interruption in water supply to customers, or SID, can be quantified with a time per failure or time per replacement value, at the same time taking the number of affected consumers into account.

There are generally fewer service interruptions due to planned replacements, than those due to pipe failure. Depending on the severity of the failure, the duration of said interruptions is also less in the case of planned replacements as there are no response times to account for. Replacement time in the context of this research is the interruption in service due to pipe replacement, expressed as minutes per metre of pipe, whereas the repair time refers to the interruption in service due to pipe failure and is expressed in total minutes per failure.

4.2.7.4 Estimated remaining useful life

In this research, the expected service life of a pipe material, from a supplier product catalogue or as supplemented subjectively from engineering staff, is expressed as the estimated service life (ESL). The estimated remaining useful life (ERUL) is the difference between the actual age of a pipe and the ESL as mentioned above.

4.2.7.5 Estimated remaining asset value

The pipe asset value is introduced as an additional PI and calculated as the depreciated current replacement cost of the pipe, utilising the straight line depreciation method. It is assumed for this research that there is zero residual value for the pipe asset at the end of its ESL. The pipe asset value is termed the estimated remaining asset value (ERAV) in this research, as it based on the ESL, as discussed in paragraph 4.2.7.4.

4.2.8 Annual risk calculation

As stated earlier, the simple annual replacement approach is adequate when short investment periods are considered due to the reasonable assumption that the effect of a time-dependant variable such as age will not change significantly and therefore the likelihood scores assigned to individual pipes are less likely to increase. However, when long investment periods are considered, a risk prioritisation, in which all likelihood variables will be recalculated, will be required for each analysis period as depicted in Figure 4-1.

After each year, the likelihood parameter scores assigned to pipes may change due to the replacement of pipes and the ageing of non-replaced pipes. The likelihood parameter score assignments of the pipes will affect the likelihood factor calculation and subsequently change the risk value and rank of the individual pipes. In other words, it is possible for pipe i to be ranked lower than pipe j in year k and then, due to increase in age and subsequent likelihood score assignment, for pipe i to be ranked higher than pipe j in year $k+1$. The concept of the REP (paragraph 4.2.5), was introduced to account for the possible cyclical replacement of high consequence pipes.

Another reason to perform a risk prioritisation exercise for each analysis period is that the likelihood factors should be incorporated in the failure prediction. Therefore it is required to recalculate scores for all likelihood variables for each analysis period.

4.3 Mathematical description

4.3.1 Cost functions

The cost of replacement or repair of a pipe is dependent on several factors. The unit cost per length is determined by considering the diameter, material and location attributes of the pipe. The unit replacement or installation cost is shown in Equation 4 and the unit repair cost shown in Equation 5.

$$IC_u = f(D, M, S)$$

Equation 4: Unit replacement cost

Where

IC_u	=	Unit replacement cost
D	=	Diameter
M	=	Material
S	=	Locality.

$$RC_u = f(D, M)$$

Equation 5: Unit repair cost

Where

RC_u	=	Unit repair cost
D	=	Diameter
M	=	Material

In this research, the unit replacement and unit repair costs are determined for discrete diameter ranges as presented in Table 4-1 (paragraph 4.2.2) and Table 4-2 (paragraph 4.2.7.2), respectively.

4.3.2 Failure prediction

The time-exponential equation as presented by Shamir and Howard (1979), as given in Equation 6, was chosen to represent expected increase in failure rate and calculate the expected number of failures for the system in a given year.

$$N(t) = N(t_0) \cdot e^{A(t-t_0)}$$

Equation 6: Time-exponential failure rate increase (Shamir and Howard, 1979)

Where

$N(t)$	=	Failure rate in analysis period t
$N(t_0)$	=	Failure rate at start of the analysis
A	=	Growth rate coefficient (year^{-1})
t	=	Analysis period (typically year)
t_0	=	Base year for the analysis (pipe installation year, or the first year for which data are available).

Walski and Pellecia (1982) suggested that t_0 should not refer to some arbitrarily chosen base year for the analysis, but to the pipe installation date, k. In so doing, when $t_0 = k$, the (t-k) becomes the actual age of the pipe considered.

The choice of the prediction equation is deemed satisfactory due to its deterministic nature, and therefore its reproducibility; it is also the most widely referenced failure prediction equation and was used recently by Neelakantan et al. (2008) as base for their optimization procedure. The exponential form is generally accepted to represent the wear-out phase of the bathtub curve, therefore the implicit assumption was made that the distribution network was represented by pipes that are in the wear-out phase.

The alterations made as part of this research to the general form of the equation, as presented by Shamir and Howard (1979) and partial alteration as suggested by Walski and Pelliccia (1982) and used by Loganthan et al. (2002) and Neelakantan et al. (2008), are discussed below. As stated in paragraph 1.5, it is one of the objectives of this research to determine a failure-forecasting algorithm that incorporates all the variables used for the calculation of the likelihood of failure in the risk prioritisation model used.

Martins (2011) stated that the lack of pipe characteristic data collected is an issue that needs to be taken into account for the prediction of failures and that the majority of failure models use pipe diameter, material, installation year and length as variables in the prediction of pipe failures. In accordance with the majority of failure models, the pipe diameter, pipe material and pipe age were chosen to formulate the basis of the time-exponential equation, for this research, as they are the most readily available factors in the pipe inventory database and used as surrogate factors for several other factors that contribute to pipe failure, as presented in Table 2-2, Table 2-3 and Table 2-4.

The pipe diameter is accounted for by splitting the pipe assets into three distinct groups, noted in as small, medium and large pipes in this research. The initial failure rate of each pipe will therefore be equal to the failure rate of the diameter group within which it falls. The material is accounted for by assigning a value to represent the growth rate coefficient (A from Equation 6) to each material.

The age of the pipe is accounted for as in Equation 6, with the suggested alteration to set $t_0 = k$. Allowing for these alterations results in the following equation:

$$N_p(t) = N_{d,p}(t_0) \cdot e^{A_{M,p}(a_p)}$$

Equation 7: Alteration to the time-exponential failure rate increase equation

Where

$N_p(t)$	=	Failure rate in analysis period t for pipe
$N_{d,p}(t_0)$	=	Failure rate at start of the analysis for diameter group of pipe
$A_{M,p}$	=	Growth rate coefficient for material of pipe
t	=	Analysis period
a_p	=	Pipe age.

The A_M factor can be determined by regression analysis if sufficient failure data, with pipe attribute information, are available. However, for the purposes of this research, the A_M factors will be used comparatively, to simulate a case where there are insufficient data to perform satisfactory regression analysis, by assigning a growth rate coefficient to each material in order to indicate the relative expectation of failure progression per material. For example if the exponential factor is considered, with $A_M = 0.01$, the failure rate of the pipe will be double that of the initial failure rate of the pipe diameter group at an age of 70 years. Conversely, if an $A_M = 0.02$ is considered, the failure rate will be double the initial rate at an age of 35 years.

The remaining variables used in the calculation of the LF were incorporated into the failure algorithm by considering the concept of frailty, which as stated by Clark et al. (2010) is a positive variable that is used to model individual multiplicative random effects on the hazard function. Clark et al. (2010) found that the frailty term was highly significant and more explanatory for pipe runs which reflect local conditions and history, than easily observable variables such as pipe diameter and pipe material. However, to ensure reproducibility, the frailty term in this research is not represented by a probability function as presented by Clark et al. (2010), but explicitly calculated from the contribution of the remaining likelihood variables (excluding pipe diameter, pipe age and pipe material) and the variables' respective weights.

Equation 8 shows the calculation of the frailty factor for each pipe.

$$FF_p = \sum_{i=4}^{y} \frac{\theta_i}{\theta_T} \times \mu_i$$

Equation 8: Frailty factor

Where

FF_p	=	Frailty factor for pipe
i	=	LF variable
y	=	Number of LF variables
θ_T	=	Total of all LF variable weights
θ_i	=	LF variable weight
μ_i	=	LF variable score.

It can be seen that the calculation of the frailty factor is an alteration on the LF calculation (Equation 1), where the number of factors considered are altered by excluding the contribution of diameter, material and age, which have already been allowed for in Equation 7.

In order to explain, presume that there are six LF factors in total, including material, diameter and age, and that all factors for the LF are weighted equally (16.66%). Therefore, three factors are available to use for the calculation of the FF_p. If each of these factors had score values of one (LS_i = 1), then Equation 8 would yield:

$$FF_p = \sum_{i=4}^{6} \frac{1/6}{1} \times 1 = 0.5$$

Now consider if all factors had a score value of five (LS_i = 5), then Equation 8 would yield:

$$FF_p = \sum_{i=4}^{6} \frac{1/6}{1} \times 5 = 2.5$$

This implies that for the example above, the FF_p will range from 0.5 to 2.5 depending on the scores assigned to the remaining likelihood factors. Similarly, if the remaining factors each had a lower weight of 10%, the resulting range for FF_p would be 0.3 to 1.5.

Normalising the FF_p to a value where neutral scores (i.e. 3) for all remaining LF variables would result in a FF_p = 1, would subsequently result in a range from 0.333 to 1.666 in all cases. An argument against normalising the FF_p is that the explanatory power of these factors will become somewhat diluted, especially in cases where the likelihood factors employed in the FF_p calculation enjoy a higher weight assignment than the factors employed for the time-exponential portion of the failure equation, namely pipe diameter, material and age. Therefore, in this research, the FF_p is not normalised.

The frailty factor acts multiplicatively and for this reason, in addition to the assignment of growth rates to pipe materials without regression analysis, an additional correction or scaling factor is required to scale the calculated number of failures using the base data to that of the known initial failures provided per diameter group. As the failure data is grouped into different diameter groups, a correction factor is required for each of the diameter groups.

Equation 7 and Equation 8 are combined and the length of pipe is introduced to calculate the expected number of failures of each individual pipe from the base data.

$$F_p(t_0) = FF_p \cdot N_p(t_0).L$$

Equation 9: Initial failure calculation

Where

$F_p(t_0)$	=	Calculated failures for pipe at start of analysis
FF_p	=	Frailty factor of pipe (Equation 8)
$N_p(t_0)$	=	Calculated failure rate of pipe at start of analysis (Equation 7)
t_0	=	Start of analysis (base year)
L	=	Pipe length.

The individual failures are summated for each diameter group to compare with the known initial number of failures for each diameter group (F_d in Equation 10) in order to calculate the correction factor.

$$CF_d = \frac{\sum_{i=1}^{n} F_{p,d}(t_0)}{F_d}$$

Equation 10: Correction factor per diameter group

Where

CF_d	=	Diameter group correction factor
$F_{p,d}(t_0)$	=	Calculated number of initial failures for pipe in diameter group
F_d	=	Total initial failures for diameter group.

With the correction factor for each diameter group calculated, the number of failures for each pipe can be calculated in each analysis period with Equation 11.

$$F_p(t) = CF_d \cdot FF_p \cdot N_p(t) \cdot L$$

Equation 11: Expected number of failures for pipe in analysis period

Where

$F_p(t)$	=	Expected failures for pipe in analysis period
CF_d	=	Diameter group correction factor
FF_p	=	Frailty factor of pipe
$N_p(t)$	=	Failure rate in analysis period t for pipe
L	=	Pipe length.

4.3.3 Interruption functions

Similar to cost functions, the interruption duration is dependent on several factors. The available data on interruption due to replacements indicate that it is a function of diameter, material, locality and length of the pipe being replaced. Conversely, the interruptions due to repair operations are indicated as functions of material and region. Equation 12 and Equation 13 show the calculation of the interruption time.

$$T_p = f(D, M, S) \cdot \mathrm{L}$$

Equation 12: Replacement time

Where

T_p	=	Replacement time
D	=	Diameter
M	=	Material
S	=	Locality
L	=	Length.

$$T_u = f(M, S)$$

Equation 13: Repair time

Where

T_u	=	Repair time
M	=	Material
S	=	Locality.

4.3.4 Eligibility values

The metric used to measure SID is the expected time of interruption in minutes multiplied by the number of affected users and then scaled by the total number of users in the system. The SID can further be divided into two categories, namely planned and unplanned SID. Planned SID is the expected interruption duration for pipe replacements, whereas the unplanned SID is the expected interruption due to repair operations, and therefore based on the expected number of failures.

Planned and unplanned SID is calculated as shown in Equation 14 and Equation 15, respectively.

$$SID_p(t) = \frac{\sum T_{p,i} \cdot HH_i}{TH}$$

Equation 14: Planned SID

Where

$SID_p(t)$	=	Planned SID for the analysis period
$T_{p,i}$	=	Time for replacement of pipe selected for replacement
HH_i	=	Number of affected users (households)
TH	=	Total number of affected users (households) in the system.

$$SID_u(t) = \frac{\sum F_{p,i}(t) \cdot T_{u,i} \cdot HH_i}{TH}$$

Equation 15: Unplanned SID

Where

$SID_u(t)$	=	Unplanned SID for the analysis period
$F_{p,i}(t)$	=	Calculated failures for pipe that is not selected for replacement
$T_{u,i}$	=	Time for repair of pipe
HH_i	=	Number of affected users (households)
TH	=	Total number of affected users (households) in the system.

As seen in Equation 15, only the failures for pipes that are not selected for replacement in a given analysis period are used in the calculation of the unplanned SID. It is therefore assumed that adequate replacement plans will be compiled by the municipality for each of the analysis periods to account for pipes that are to be replaced, as determined by the analysis. Therefore, if a pipe that is scheduled for replacement fails, no maintenance activities will be performed on said pipe.

Cumulative expenditure is simply calculated on the prioritised list of pipes, with Equation 16, as:

$$CE_i = CE_{i-1} + IC_u \cdot L_i, \qquad with\ CE_0 = 0$$

Equation 16: Cumulative expenditure

Where

CE_i	=	Cumulative expenditure if pipe is replaced
CE_{i-1}	=	Cumulative expenditure before current pipe is considered
IC_u	=	Unit replacement cost function
L_i	=	Length of pipe

The OPEX in an analysis period is calculated as the sum of the estimated refurbishment cost for all non-replaced pipes as shown in Equation 17.

$$OPEX = \sum_{i=1}^{n} F_{p,i}(t) \cdot RC_{u,i}$$

Equation 17: Operational expenditure

Where

$OPEX$	=	Operational expenditure
$F_{p,i}(t)$	=	Number of calculated failures for pipe that is not selected for replacement
$RC_{u,i}$	=	Unit repair cost function for pipe
i	=	Individual pipe
n	=	Number of pipes.

4.3.5 Estimated remaining asset value

The estimated remaining asset value (ERAV) is calculated for all pipes and summed to give the total expected pipe infrastructure value for each period as shown in Equation 18.

$$ERAV = \sum_{i=1}^{n} \frac{R_{M,i}}{E_{M,i}} \cdot IC_{u,i} \cdot L_i \ , \qquad R_{M,i} \geq 0$$

Equation 18: Estimated remaining asset value

Where

ERAV	=	Estimated remaining asset value
$R_{M,i}$	=	ERUL of pipe, given pipe material and age
$E_{M,i}$	=	ESL of pipe material
$IC_{u,i}$	=	Unit replacement cost function for pipe
L_i	=	Length of pipe
i	=	Individual pipe
n	=	Number of pipes.

4.4 Description of MPM tool

4.4.1 Software implementation

Excel with the embedded Visual Basic for Applications (VBA), was used for the development of the procedure that uses risk-based prioritisation to model multi-period replacement. An excel tool provides the ability to easily modify and verify input data and results. Another benefit is that it is readily available to most users.

Pipe data is presented in tabular format. The input data tables in sheets and the VBA procedures combine to form the Multi-period Prioritisation Model (MPM) tool. Table 4-3 illustrates the sheets utilised for the MPM tool. In this text, "sheet" refers to a worksheet tab that is available in the Excel model developed as part of this research.

Table 4-3: Sheet layout for MPM tool

SHEET	DESCRIPTION
Capex Budget Table	Annual available replacement budget
Diameter Replacement List	Diameter replacement rules and report grouping
Replacement Cost	Replacement cost per unit length
Repair Cost	Repair cost per failure
Pipe Material Life	Material replacement rules and report grouping
LF Legend	Likelihood of failure property score assignment
LF Weights	Likelihood of failure property weight assignment
Base Data	Required pipe inventory data to perform multi-period analysis
Replacement Schedule	List of scheduled replacements per period
Scheduled items - Not Found	Scheduled items not found in the pipe inventory
INPUT	Input parameters for analysis
ITER START	Enforcement of scoring changes for previous period replacements
OUTPUT	Results for CAPEX, OPEX, SID and number of failures per period
STATS	Results for network age, ERUL and replaced length
Year (1, 2,…,k)	Prioritised list for each period

Figure 4-2 illustrates a summary of the steps in the multi-period prioritisation model (MPM) tool for risk-based prioritisation and the implementation of the replacement decision making process. Refer to Appendix A for a more detailed breakdown of the steps performed during the analysis.

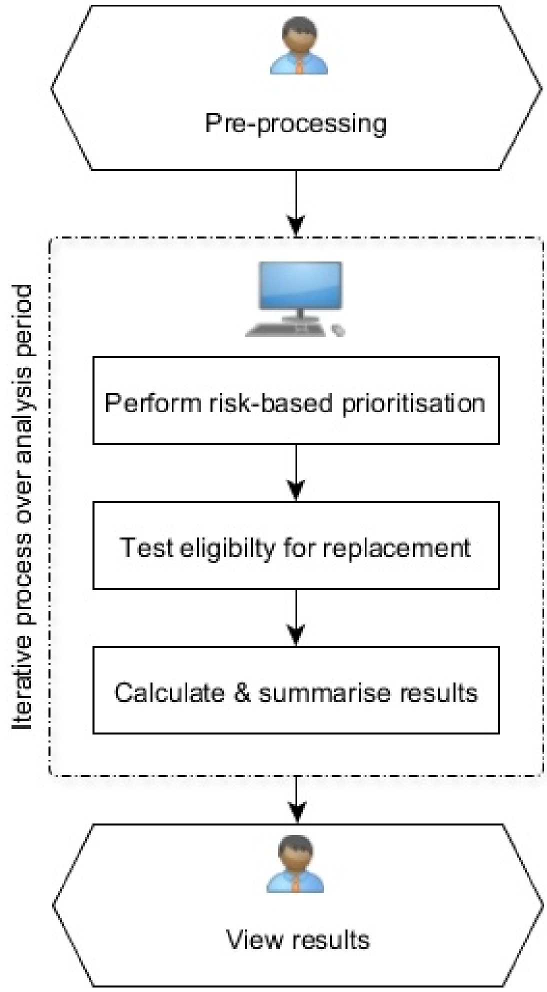


Figure 4-2: MPM process

4.4.2 Pre-processing

Various pre-processing procedures are conducted prior to running the MPM tool, which mainly consist of filling the tables with relevant values for decision making purposes. Figure 4-3 shows the general workflow followed in completing the required data filling procedure. Refer to the paragraphs indicated for explanation on the tasks required. A more detailed pre-processing workflow with intermediary steps is available in Appendix A.

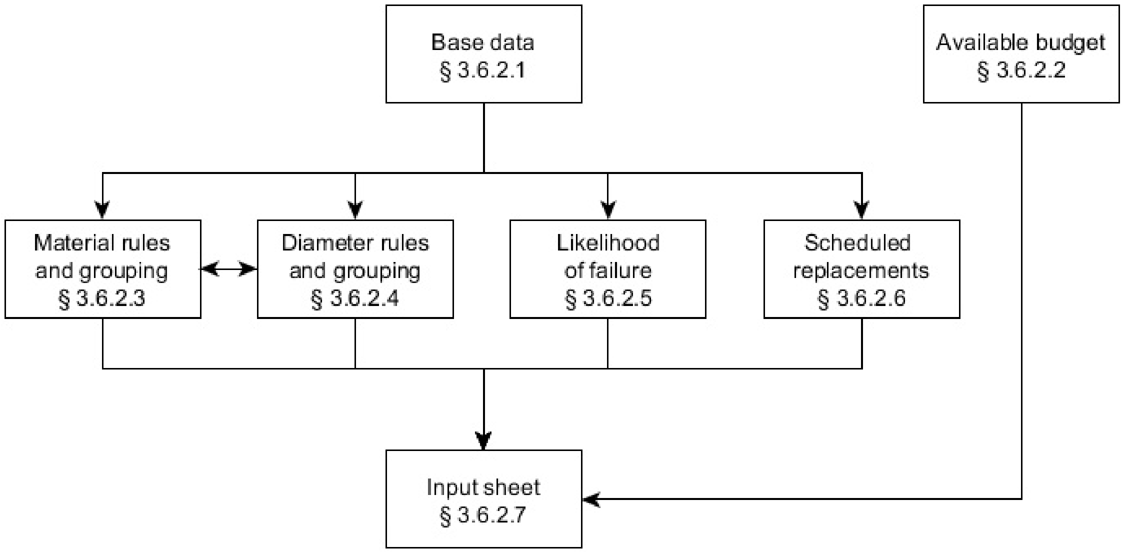


Figure 4-3: Pre-processing procedure workflow

4.4.2.1 Base data

The required pipe inventory table is a collection of all pipes, each identified by a unique identification code and characterised by several attributes, such as pipe diameter, pipe material, pipe length and installation date. The pipe inventory table is copied into the "Base Data" sheet with relevant values in columns as given.

It is important to note that an initial prioritisation is completed outside of this tool and the results are then pasted in the "Base Data" sheet. The initial prioritisation produces the CF factors for each pipe. For this research, the assumption is made that the consequence of failure for a specific pipe will not change during the analysis period, and therefore is a constant input and will not require recalculation on a period to period basis.

The minimum required fields that are required and extracted from the base data as discussed above are presented in Table 4-4. In this text, a field refers to a column in a table that contains data and can be text entries or numerical values depending on the field data type.

Table 4-4: Minimum required data

FIELD	DESCRIPTION
Pipe ID	Unique identifier of each pipe asset
Length	Length of pipe asset
Locality	Locality of pipe for cost function
Material	Material of pipe asset
Diameter	Diameter of pipe asset
Year	Installation year of pipe asset
Users	Number of users supplied by pipe asset
L_NomDiam	Individual likelihood scores as assigned by initial prioritisation (Fields applicable to case study used for descriptive purposes)
L_ResPR	
L_ERUL	
L_Settling	
L_LeakVol	
L_FlucWL	
L_CorrPot	
L_Material	
L_FailFreq	
L_Conditn	
CF	Consequence of failure as calculated by initial prioritisation

4.4.2.2 Available budget

The available budget for each year is entered in tabular format in the "Capex Budget Table" sheet. The table requires inputs for each period covered by an available budget. If the analysis timeframe exceeds the number of periods established in the "Capex Budget Table", the last input value will be used for the remainder of the analysis.

4.4.2.3 Material rules and grouping

The "Pipe Material Life" sheet allows for the tabular input of the ESL, REP, failure growth rate coefficient (A_M), replacement rule and material group for each material, as seen in Table 4-5. The REP represents the period, in years, for which a pipe will not be eligible for replacement if it has been selected for replacement during the analysis. The replacement rule is either selected as "Material" or "Diameter". Materials with a "Material" replacement rule entry are deemed to be an acceptable replacement material choice, and the replacement will thus be of the same material type. Materials with a "Diameter" replacement rule entry are deemed to be an unacceptable replacement material choice and the replacement material is determined by the replacement diameter (see paragraph 4.4.2.4).

Finally, the materials are grouped into material group categories. The data on number of failures, replaced length and remaining length is summed and presented per material group as discussed in paragraph 4.4.3.

Table 4-5: Pipe Material Life input table

Material	ESL	REP	A_M	Replacement Rule: Diameter/Material	Material group
(undefined)	60	35	0.010	Diameter	Other
AC	60	35	0.020	Diameter	AC
CI	80	35	0.010	Diameter	CI
DI	80	35	0.010	Material	DI
PE	100	35	0.005	Material	PE
PVC	100	35	0.005	Material	PVC
Steel (ST)	90	35	0.010	Diameter	ST

4.4.2.4 Diameter rules and grouping

The “Replacement Cost” sheet allows for the tabular input of the unit replacement cost values as described in 4.2.2 for diameter, material and locality combinations. The “Diameter Replacement List” sheet allows for the tabular input of the replacement diameter and replacement material combinations used when replacing a pipe, as seen in Table 4-6.

The diameter ranges are also grouped into diameter group categories. The data on number of failures, replaced length and remaining length is summed and presented per diameter group as discussed in paragraph 4.4.3, similar to that of material groups.

Table 4-6: Diameter grouping and replacement

Original Diameter (mm)	Replacement Diameter	Diameter Group	Replacement Material
< 51	50	small	PVC
< 64	63	small	PVC
< 77	75	small	PVC
< 92	90	small	PVC
< 112	110	small	PVC
< 129	125	small	PVC
< 164	160	small	PVC
< 212	200	medium	PVC
< 324	315	medium	PVC
< 410	400	large	DI
< 513	500	large	DI
<643	630	large	DI
<710	700	large	DI
<810	800	large	DI
<910	900	large	DI
<1010	1000	large	DI
>=1010	1100	large	DI

4.4.2.5 Likelihood of failure properties

The “LF_Legend” sheet allows for the tabular input of score rating assignment for each of the likelihood properties based on the chosen criteria, typically a range, as shown in Table 4-7. Similarly, the “LF_Weights” sheet allows for the tabular input of the relative weights attributed to each of the likelihood properties as shown in Table 4-8. The score ratings and weights of each likelihood parameter are substituted into Equation 1 (paragraph 3.2) to calculate the LF for each pipe. The criteria and score values from Table 4-7 and the weight values from Table 4-8 represent the likelihood of failure properties as available for the case study.

Table 4-7: Example of Likelihood score rating legend

Likelihood variable name	Criteria	Score
L_NomDiam	(unknown)	3
L_NomDiam	50	5
L_NomDiam	75	5
L_NomDiam	160	4
L_NomDiam	315	3
L_NomDiam	10000	1
L_ResPR	5	1
L_ResPR	10	2
L_ResPR	15	3
L_ResPR	20	4
L_ResPR	10000	5
L_ERUL	5	5
L_ERUL	10	4
L_ERUL	20	3
L_ERUL	50	2
L_ERUL	10000	1
L_Settling	K-0.1	2
L_Settling	K-0.2	3
L_Settling	O-0.2	1
L_Settling	V-0.1	1
etc.		

Table 4-8: Example of Likelihood factor weight assignment

Likelihood variable name	Weight
L_NomDiam	5
L_ResPR	10
L_ERUL	50
L_Settling	0
L_LeakVol	0
L_FlucWL	10
L_CorrPot	5
L_Material	15
L_FailFreq	5
L_Conditn	0

4.4.2.6 Scheduled replacements

The "Replacement Schedule" sheet allows for the tabular input of a list of the pipe assets that have been scheduled for replacement in a specific period, either known before the start of an initial analysis or selected from a previous analysis. The pipe asset ID is listed in the field corresponding to the period for which the pipe asset has been scheduled for replacement.

All pipe assets which are listed in the "Replacement schedule" sheet, but do not exist in the pipe inventory as provided in the "Base Data" sheet, will be listed in the "Schedule items – Not Found" sheet, in a field corresponding to the applicable analysis period as for the "Replacement Schedule" sheet.

4.4.2.7 Input sheet

The "INPUT" sheet allows for the tabular input of several analysis parameters as shown in Table 4-9. The analysis scenario will have a starting period (base year) and analysis timeframe. Additional eligibility factors, apart from available budget and design life, are included in the "INPUT" sheet.

The additional eligibility factors included in this research are the length of replaced pipe, the planned SID and the maximum number of failures allowed per period. Each of the aforementioned factors has the possibility of a "no restriction" input if the factor is to be ignored. The number of failures per year for each diameter group is entered (three diameter groups are provided) and finally, the values for the maximum pipe skip count, minimum budget expenditure and contingency buffer are supplied as discussed in paragraphs 4.2.4.1, 4.2.4.2 and 4.2.4.3, respectively. Table 4-9 presents the tabular form for the input parameters as discussed above.

Table 4-9: Input sheet options

Input parameter	**Input value**	**Comment**
Base year	2013	Select year of Base Data
Analysis timeframe (years)	50	
Length of replaced pipes allowed per year	0	[0 or smaller] for no restriction
Planned SID allowed per year	0	[0 or smaller] for no restriction
Number of failures allowed per year	0	[0 or smaller] for no restriction
Base failures for Diameter group 1	200	Failures/year for small pipes
Base failures for Diameter group 2	100	Failures/year for medium pipes
Base failures for Diameter group 3	50	Failures/year for large pipes
Number of connections or households (HH)	115 000	
Minimum Budget Expenditure	99	% of budget that must be spent before replacement search can stop
Pipe count for minimum expenditure	10	Number of consecutive pipes that are not replaced before test
Contingency Buffer	0	% of budget that can be exceeded

4.4.3 Analysis results

4.4.3.1 Analysis period

A sheet is created for each iteration of the replacement model (1, 2, …, k), where k is the analysis timeframe. The risk-based prioritisation is performed and then scheduled replacements are enforced by overriding the calculated priority rank. Thereafter, all other eligible pipes are selected for replacement and relevant capital expenditure and planned service interruption duration calculated. The installation year, material type, diameter and failure history are altered for all pipes selected for replacement from one period to the next. These changes affect the LF calculated for subsequent periods, as well as the expected number of failures.

4.4.3.2 Result summary

The "OUTPUT" sheet provides results for capital expenditure achieved (Equation 16, given $i = n$), the OPEX, the SID (planned and unplanned) and the ERAV. The planned and unplanned SID, as calculated from Equation 14 and Equation 15, are summed to give the total expected SID for each year. The number of failures forecast is shown for the different diameter and material groups. Figure 4-4 provides an example of the "OUTPUT" sheet with analysis results.

A	B	C	D	E	F	G
Analysis year		**2014**	**2015**	**2016**	**2017**	**2018**
Available budget (AARB)		466 576	466 576	466 576	466 576	466 576
MODEL OUTPUT: 1:100 budget scenario						
Average network ERAV	Calculated remaining asset value	17 515 950	17 399 128	17 296 469	17 178 951	17 084 891
CAPEX for scheduled items	Calculated based on override lists	0	0	0	0	0
CAPEX for PRF	Calculated based on Replacement costs per meter	466 574	466 495	466 514	466 575	466 483
Total CAPEX for pipe infrastructure		466 574	466 495	466 514	466 575	466 483
Total OPEX for pipe infrastructure		30 341	30 270	30 274	30 246	30 143
Planned SID	Non-service minutes due to Replacements/Total HH	20.89	13.29	13.27	11.50	10.44
Unplanned SID	Non-service minutes due to Repair/Total HH	1.69	1.67	1.64	1.61	1.59
Total SID	Planned SID + Unplanned SID	22.58	14.97	14.91	13.11	12.02
#Failures	Total calculated number of failures	64.40	64.63	65.16	65.23	65.38
#Failures for small pipes	Calculated number of failures for small pipes	57.34	57.51	57.98	58.07	58.17
#Failures for medium pipes	Calculated number of failures for medium pipes	6.05	6.11	6.16	6.13	6.16
#Failures for large pipes	Calculated number of failures for large pipes	1.01	1.01	1.02	1.04	1.05
#Failures for Other pipes	Calculated number of failures for Other pipes	0.02	0.03	0.03	0.03	0.03
#Failures for AC pipes	Calculated number of failures for AC pipes	42.00	41.74	42.02	41.59	41.06
#Failures for CI pipes	Calculated number of failures for CI pipes	6.77	6.52	6.10	6.09	6.11
#Failures for DI pipes	Calculated number of failures for DI pipes	0.32	0.32	0.33	0.34	0.35
#Failures for PE pipes	Calculated number of failures for PE pipes	1.68	1.71	1.74	1.77	1.84
#Failures for PVC pipes	Calculated number of failures for PVC pipes	13.57	14.27	14.89	15.36	15.95
#Failures for ST pipes	Calculated number of failures for ST pipes	0.04	0.04	0.04	0.04	0.04

BASE DATA / Pipe_Material_Life / LF_Legend / LF_Weights / INPUT SHEET / ITER START / OUTPUT / STATS / Replacement schedule / Schedule items - NOT FOUND

Figure 4-4: Example of "OUTPUT" sheet with results

An additional sheet, "STATS", gives information regarding the age and ERUL of the network for each of the analysis periods. The length and replaced length for each of the diameter and material groups are also provided. Figure 4-5 provides an example of the "STATS" sheet with analysis results.

A	B	C	D	E	F	G	H	I	J	K	L	M
MODEL STATS: 1:100 budget scenario		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
VARIABLE	COMMENT											
Network age	normalised on length	41.69987	41.75732	41.86721	42.08027	42.33111	42.54005	42.9854	43.17299	43.40937	43.72199	43.97121
Network CRUL	normalised on length	34.03299	34.57221	34.92997	35.02798	35.26617	35.58416	35.46294	35.79823	36.04146	36.13082	36.25398
Replaced pipe age	normalised on length	60.36227	64.50458	70.19528	58.30274	58.52305	61.29069	59.99639	60.62703	64.13764	64.9389	65.10282
Replaced pipe CRUL	normalised on length	1.255659	0.653145	0.80718	3.614847	2.494749	1.345915	0.449485	1.234339	-2.54802	2.473261	4.154304
Length of small pipes	(m)	1 784 577	1 784 577	1 784 577	1 784 577	1 784 577	1 784 577	1 784 577	1 784 577	1 784 577	1 784 577	1 784 577
Length of medium pipes	(m)	313 788	313 788	313 788	313 788	313 788	313 788	313 788	313 788	313 788	313 788	313 788
Length of large pipes	(m)	131 005	131 005	131 005	131 005	131 005	131 005	131 005	131 005	131 005	131 005	131 005
Total network length	(m)	2 229 370	2 229 370	2 229 370	2 229 370	2 229 370	2 229 370	2 229 370	2 229 370	2 229 370	2 229 370	2 229 370
Replaced length of small pipes	(m)	31 216	26 254	20 097	22 183	25 053	16 395	26 736	23 983	21 379	16 227	17 367
Replaced length of medium pipe	(m)	1 227	1 284	1 928	4 733	3 272	1 491	318	2 498	1 936	7 642	2 911
Replaced length of large pipes	(m)	278	1 378	1 468	22	0	1 315	1 333	0	180	448	1 884
Replaced length of Other pipes	(m)	0	0	0	0	0	0	0	0	33	0	17
Replaced length of AC pipes	(m)	30 074	21 459	10 569	24 359	26 884	16 768	27 753	24 041	21 839	15 351	11 895
Replaced length of CI pipes	(m)	2 647	7 457	12 923	2 579	1 441	2 432	633	2 440	1 623	8 965	10 250
Replaced length of DI pipes	(m)	0	0	0	0	0	0	0	0	0	0	0
Replaced length of PE pipes	(m)	0	0	0	0	0	0	0	0	0	0	0
Replaced length of PVC pipes	(m)	0	0	0	0	0	0	0	0	0	0	0
Replaced length of ST pipes	(m)	0	0	0	0	0	0	0	0	0	0	0
Length of Other pipes	(m)	725	725	725	725	725	725	725	725	692	692	674
Length of AC pipes	(m)	1 151 067	1 129 608	1 119 039	1 094 680	1 067 796	1 051 028	1 023 275	999 234	977 395	962 044	950 149
Length of CI pipes	(m)	229 675	222 217	209 294	206 715	205 274	202 842	202 209	199 768	198 145	189 179	178 930
Length of DI pipes	(m)	25 438	26 816	28 284	28 306	28 306	29 621	30 953	30 953	31 133	31 581	33 465

BASE DATA / Pipe_Material_Life / LF_Legend / LF_Weights / INPUT SHEET / ITER START / OUTPUT / STATS / Replacement schedule / Schedule items - NOT FOUND

Figure 4-5: Example of "STATS" sheet with results

These results are used to compare different scenarios to one another in the decision making process for selection of a suitable investment strategy.

5 Illustration of model application to a water distribution system

5.1 Case study available data

5.1.1 Failure data

The failure history comprises of failures recorded for a six year period, prior to and including the base year. Failure data which are not applicable to the distribution network, represented by the pipe inventory list with 32 957 individual records, were not included in the analysis. In other words, only the failures on pipes that are present in the inventory list, as extracted for the base year, were considered. The failure data within the recorded period was used to determine the failure rate for the different diameter ranges and material groups.

The time of failure for the failure data prior to the six year recorded period was not known and could only be accounted for as the number of previous failures that have occurred on a pipe present in the inventory list. The older failure data for the case study presented and used in this research is therefore considered to be left-censored, because it is only known that a failure occurred before the start of the recorded period, but not when the failure occurred.

All the failure data was used to account for the failure history of a pipe (number of failures) in the risk-based prioritisation.

5.1.2 Pipe diameter

Table 5-1 shows the length of pipe assets for discrete diameter ranges and applicable failures and the percentage of total length per diameter range is represented graphically in Figure 5-1. The length is extracted from the pipe inventory list for the base year.

Table 5-1: Length and failures per diameter range

Diameter (mm)	Length (km)	Failures (6 years)	Failures	
			$\frac{N_f}{year}$	$\frac{N_f}{100km \cdot year}$
≤ 50	533	93	15.50	2.91
≤ 63	15	7	1.17	7.76
≤ 75	128	31	5.17	4.02
≤ 110	667	128	21.33	3.20
≤ 160	440	86	14.33	3.26
≤ 200	183	20	3.33	1.82
≤ 250	46	5	0.83	1.80
≤ 315	84	8	1.33	1.58
≤ 400	37	2	0.33	0.90
≤ 500	64	0	0.00	0.00
≤ 630	13	1	0.17	1.33
≤ 700	13	0	0.00	0.00
≤ 800	5	0	0.00	0.00
TOTAL	**2 229**	**381**	**63.50**	**2.85**

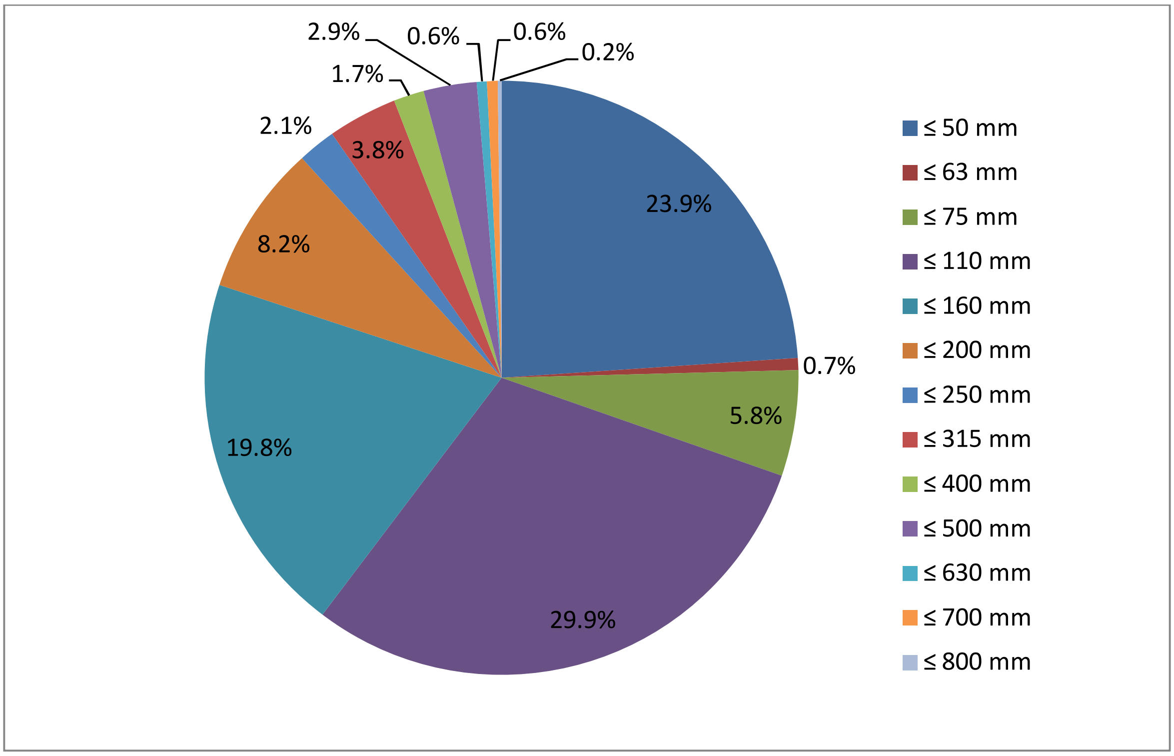


Figure 5-1: Percentage of total length per diameter range

The pipe failure distribution conforms to the generally accepted notion in literature that small diameter pipes have a higher failure frequency than that of larger diameter pipes, although it is worth noting that the total failure rate of $\frac{2.85\ failures}{100km \cdot year}$ is very low when compared to the minimum suggested value of $\frac{13\ failures}{100km \cdot year}$, as suggested by Lambert and Taylor (2010) for well managed pipe network infrastructure.

5.1.3 Pipe age

Figure 5-2 shows the length of pipe installed for discrete installation periods that are still in operation.

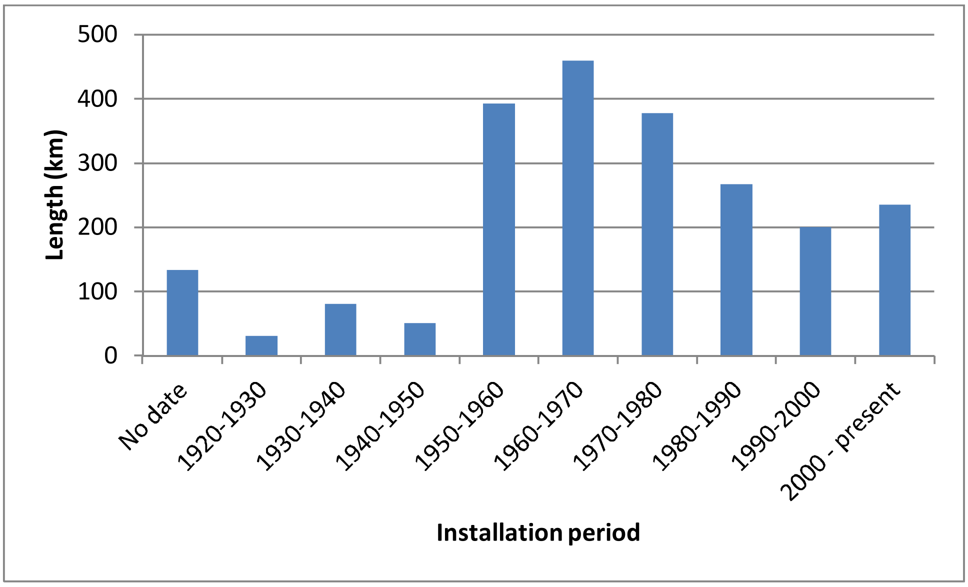


Figure 5-2: Length of pipe per installation period

Figure 5-3 shows the number of recorded failures in relation to the installation period of the pipe assets. The higher rate of failure for newly installed pipes could be explained by the "burn in" phase of the bathtub curve as presented in Figure 2-3 and possible poor installation practices for which pipe age is a surrogate factor as shown in Table 2-4.

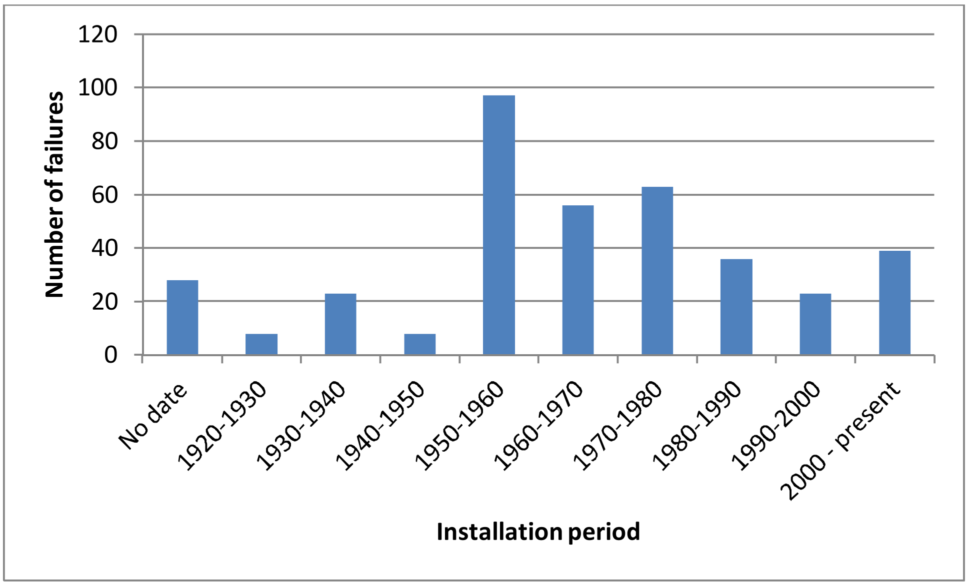


Figure 5-3: Number of recorded failures per installation period

Figure 5-4 shows the failures per 100km for each installation period. The failure occurrence per length of pipe generally seems to decrease as age decreases, which supports the inclusion of pipe age for failure forecasting.

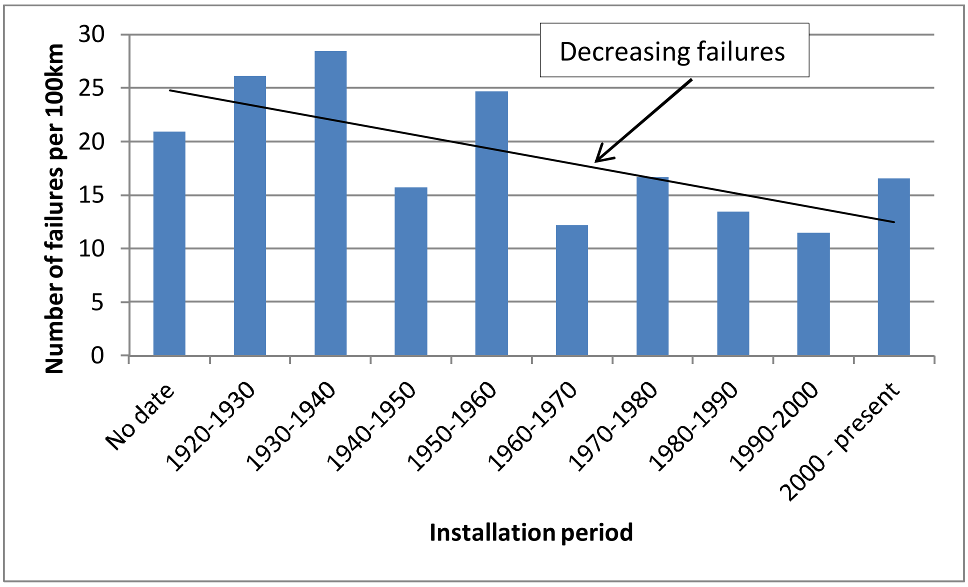


Figure 5-4: Failures per 100km per installation period

5.1.4 Pipe material

Table 5-2 shows the length of pipe assets per material type and applicable failures. The percentage of total length per material is represented graphically in Figure 5-5. The failure history comprises failures recorded for a six year period.

Table 5-2: Length and failure per material

Material	Length (km)	Failures (6 years)	Failures	
			$\frac{N_f}{year}$	$\frac{N_f}{100km \cdot year}$
(undefined)	1	0	0.00	0.00
AC	1 181	221	36.83	3.12
CI	232	44	7.33	3.16
DI	25	0	0.00	0.00
PE	96	8	1.33	1.39
PVC	692	108	18.00	2.60
ST	2	0	0.00	0.00
TOTAL	**2 229**	**381**	**63.50**	**2.85**

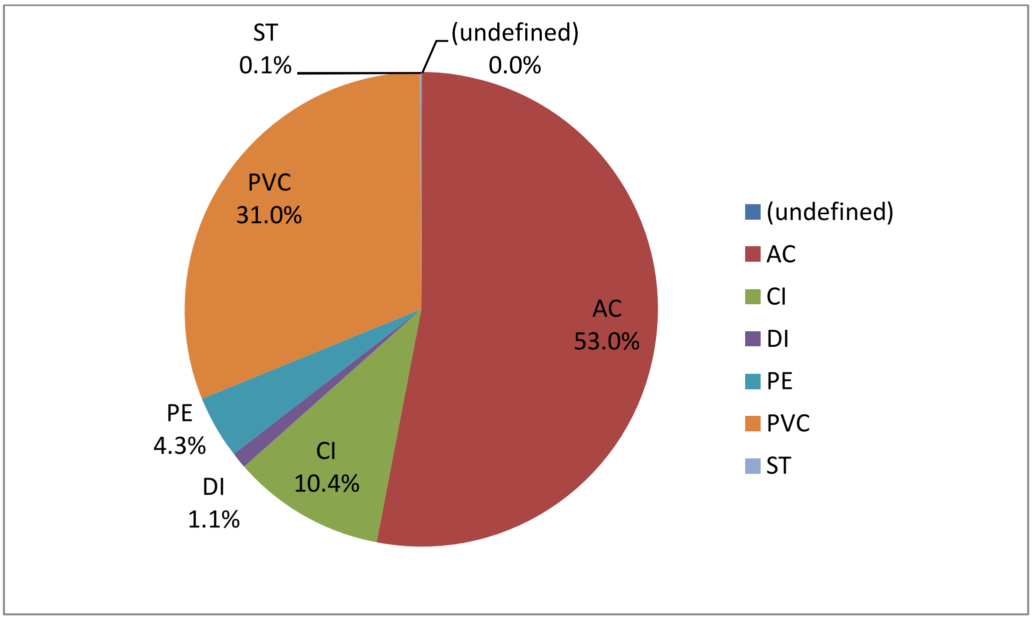


Figure 5-5: Percentage of total length per material

The higher failure rates for AC and CI pipes are also generally accepted in literature, mainly due to their older age and susceptibility to fluctuating soil conditions. The failure rate for PVC could be attributed to a combination of reduced pipe strength and poor installation practices in addition to the “burn in” phase phenomena.

The failure rate for the same material can vary greatly over time for different installation periods, as stated by Rostum (2000). The results of the investigation of material types and installation periods for the case study were plotted as shown in Figure 5-6; the case study data adheres to the notion of failure rate variance for materials with respect to different installation periods. Possible causes include difference in manufacturing standards and poor maintenance procedures for different installation periods.

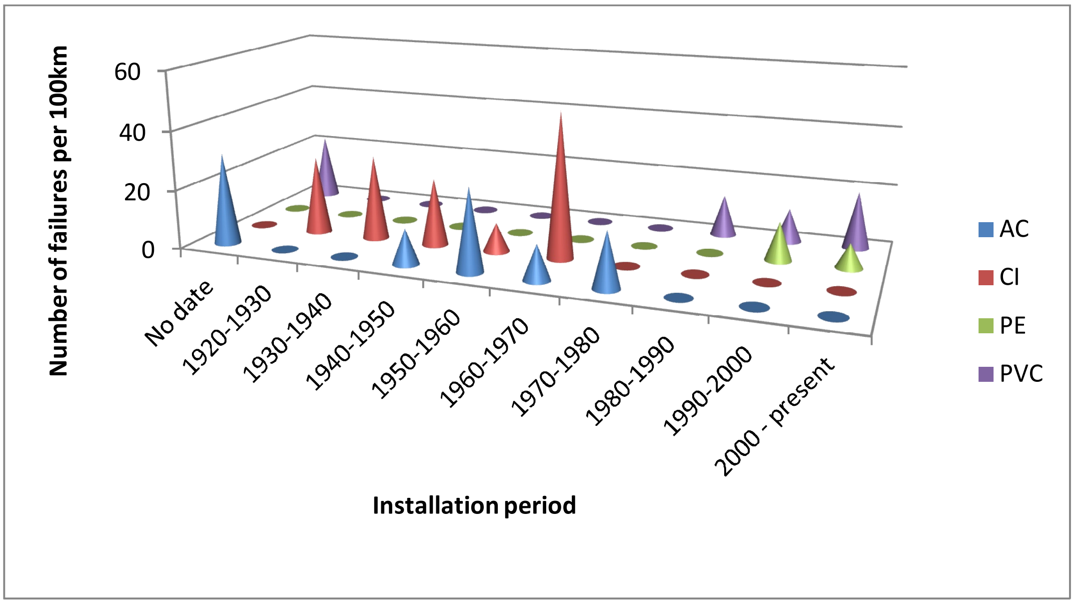


Figure 5-6: Number of failures per 100km per material

The ESL for each material as determined for the case study is given in Table 5-3. The distribution of the calculated ERUL (the difference between the actual age of a pipe and the ESL) for each pipe is shown in Figure 5-7. The AC and CI material pipes make up the majority of the pipe assets with a lower ERUL as expected, due to their lower ESL and earlier installation dates.

These pipes are however still in operation and functioning adequately which further implies that pipe age alone is not a sufficient indicator of deterioration, but it is the combination of factors that lead to pipe failure. This observation necessitates the inclusion of a variable, the frailty factor (FF_p) in the case of this research, to account for other explanatory factors when forecasting failures.

Table 5-3: Estimated service life

Material	ESL
(undefined)	60
AC	60
CI	80
DI	80
PE	100
PVC	100
ST	90

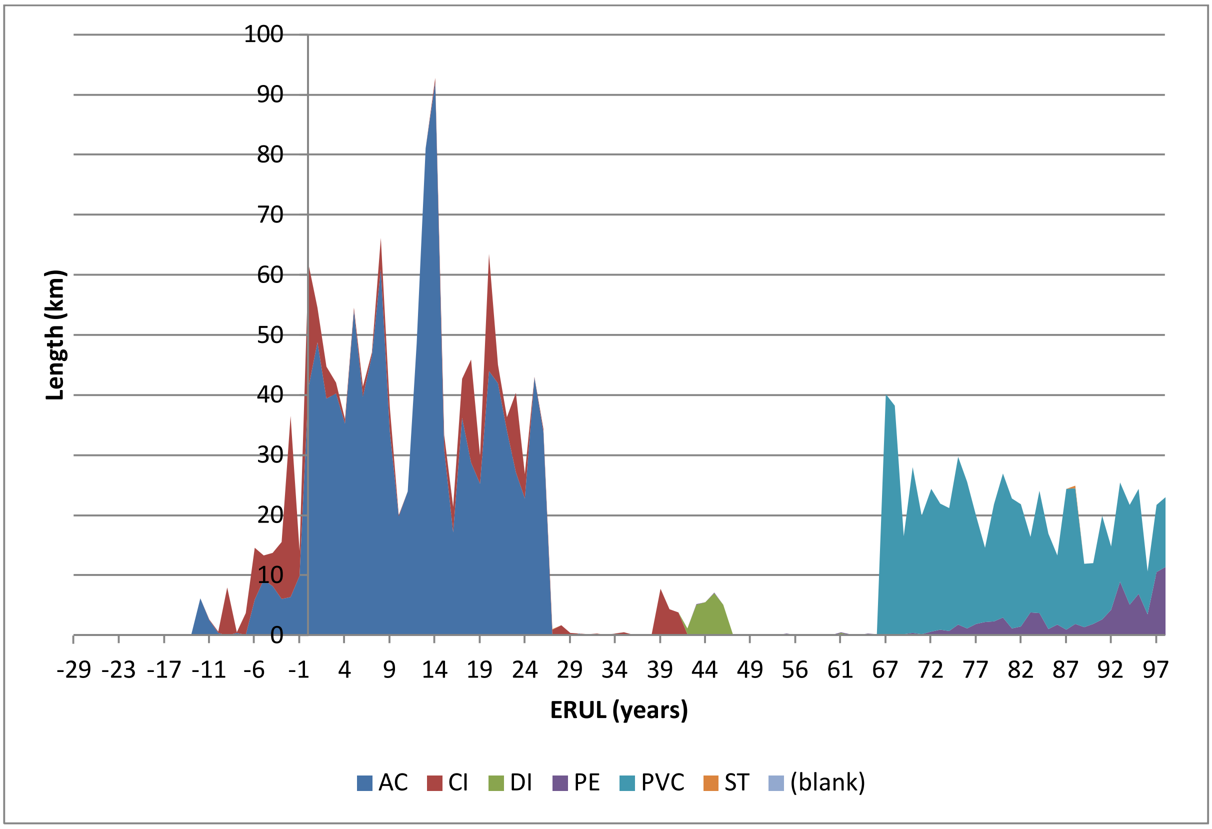


Figure 5-7: Distribution of ERUL per material

5.1.5 Replacement cost

The replacement cost of the pipe asset depends on the pipe asset's length, diameter, material and location as per paragraph 4.2.2. The available unit costs per unit length (C_r/m) for each of the available replacement materials, as shown in Table 4-1, were used for replacement cost calculations. The total replacement cost for the network (sum of all pipes' replacement cost) is calculated as 46 657 559 C_r.

5.1.6 Repair cost

The repair cost of the pipe asset depends on the pipe asset's diameter and material as per paragraph 4.2.7.2 and the unit costs as shown in Table 4-2, with the cost adjustment ratio as for the replacement cost also applied, were used for repair cost calculations. For materials other than those with known repair costs per failure, a length weighted mean value was applied, as per "Other" in Table 4-2.

5.1.7 Service interruption duration

As mentioned, the utility that manages the water distribution system chosen as case study collects data on interruption duration. Table 5-4 shows the average expected time of interruption in minutes per failure. Table 5-5 shows the expected time of interruption in minutes per metre length for specific diameter ranges.

As discussed in paragraph 1.8, the indicated estimates for interruption due to replacement projects and repair operations were used as available and no verification was conducted.

Table 5-4: Interruption due to repairs (min/failure)

AC	DI	PVC & PE	Other
158	174	147	183

Table 5-5: Interruption due to replacements

Diameter (mm)	Interruption duration per unit length (minutes/m)					
	Rural			Urban		
	PVC	DI	(H)PE	PVC	DI	(H)PE
< 200	0.90	0.90	0.90	0.90	0.90	0.90
≥ 200	1.20	1.20	1.20	1.20	1.20	1.20

5.1.8 Likelihood of failure inputs

The LF is calculated as per Equation 1 (paragraph 3.2) which is dependent on two tables. Table 5-7 provides the criteria and score assignment combinations for each of the LF variables, while Table 5-6 provides the weight assignment of each individual LF variable. The scores, criteria and weights were established through workshops with the operational and managerial staff for the once-off risk prioritisation of the case study as part of a previous investigation.

Table 5-6: Likelihood of failure score assignment

Likelihood variable	Criteria (≤)	Score	Comment
L_NomDiam	(unknown)	3	Variable to account for different pipe diameters
	50	5	
	75	5	
	160	4	
	315	3	
	10000	1	
L_Hammer	5	1	Variable to account for water hammer based on hydraulic flow results
	10	2	
	15	3	
	20	4	
	10000	5	
L_ERUL	5	5	Variable to account for age
	10	4	
	20	3	
	50	2	
	10000	1	
L_Settling	K-0.1	2	Variable to account for settling
	K-0.2	3	
	O-0.2	1	
	O-0.3	2	
	V-0.1	1	
L_LeakVol	0	3	Variable to account for Leakage Volume (No Data)
L_FlucWL		3	Variable to account for fluctuating ground water level (GWL)
	I	5	
	II	4	
	III	3	
	IV	2	
L_CorrPot		3	Variable to account for corrosion potential
	A-AC	1	
	C-AC	5	
L_Material		3	Variable to account for pipe material
	AC	5	
	CI	3	
	DI	3	
	PE	1	
	PVC	1	
	ST	3	
L_FailFreq	0	3	Variable to account for failure history
	1	4	
	999	5	
L_Conditn		3	Variable to account for pipe condition (no data)

Table 5-7: Likelihood of failure weight assignment

Likelihood variable	Weight	Comment
L_NomDiam	5	Variable to account for different pipe diameters
L_Hammer	10	Variable to account for water hammer
L_ERUL	50	Variable to account for age
L_Settling	0	Variable to account for settling
L_LeakVol	0	Variable to account for Leakage Volume (no data)
L_FlucWL	10	Variable to account for fluctuating GWL
L_CorrPot	5	Variable to account for corrosion potential
L_Material	15	Variable to account for pipe material
L_FailFreq	5	Variable to account for failure history
L_Conditn	0	Variable to account for pipe condition (no data)

5.1.9 Replacement rules

After a pipe asset has been selected and deemed eligible for replacement, certain replacement criteria or rules can be established to govern which material and diameter will be chosen when replacement occurs as discussed in paragraphs 4.4.2.3 and 4.4.2.4. Table 5-8 represents the tabular input as required in the "Pipe material life" sheet, as discussed in paragraph 4.4.2.3.

Table 5-8: Pipe material replacement and grouping

Material	ESL	REP	A_M	Replacement: Diameter/Material	Material group
	60	35	0.0167	Diameter	Other
AC	60	35	0.0167	Diameter	AC
CI	80	35	0.0125	Diameter	CI
DI	80	35	0.0125	Material	DI
PE	100	35	0.0100	Material	PE
PVC	100	35	0.0100	Material	PVC
ST	90	35	0.0111	Diameter	ST

The growth rate coefficient, A_M, of each material can be related to the service life – pipe materials with longer ESL are expected to last longer and therefore to display a lower failure rate increase over the pipe's service life. The exponent in Equation 7 is a function of the growth rate coefficient and age and therefore, to model the expectation of different failure rate increase over the service life of pipes with different materials, the A_M was considered to be equal to the inverse of the ESL for the case study as used in this research.

The A_M values calculated in this way (refer to Table 5-8) are comparable to values as suggested by different authors for the implementation in a time-exponential equation, as shown in Table 5-9. A graphical comparison of the increase in the exponential factor, as calculated with the substituted values for A_M, is presented in Figure 5-8.

Table 5-9: Failure growth rate coefficients (Neelakantan et al., 2008)

Author(s)	Growth rate coefficient, A (per year)
Shamir and Howard (1979)	0.0100 to 0.1500
Walski and Pelliccia (1982)	0.0137, 0.0207
Kleiner and Rajani (1999)	0.0010 to 0.1880
Mailhot et al. (2003)	0.0100 to 0.1900

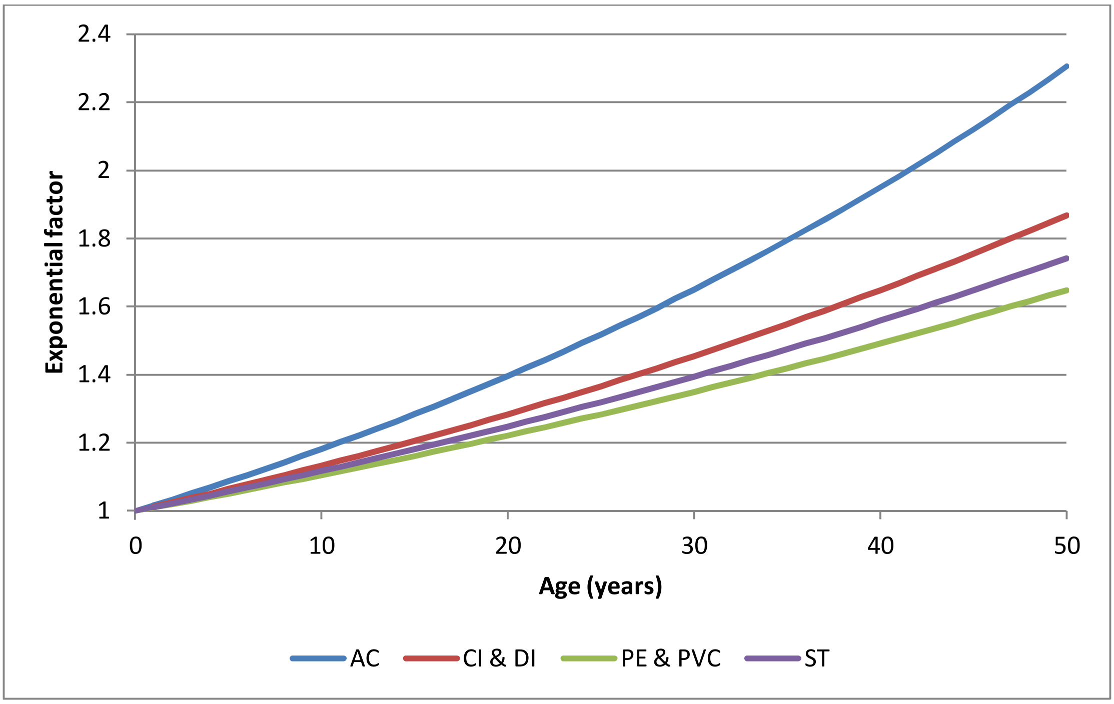


Figure 5-8: Increase in exponential factor per material

The diameters were also grouped for failure forecasting purposes into three diameter groups, namely small, medium and large, as shown in Table 5-10. The pipe groupings were chosen based on the failure rates as presented in Table 5-1, which shows failure rates above $\frac{3\ failures}{100km \cdot year}$ for diameters up to 160 mm and failure rates below $\frac{1\ failures}{100km \cdot year}$ for diameter above 315 mm.

Table 5-10: Diameter replacement and grouping

Diameter (mm)	Replacement Diameter	Diameter Group	Replacement Material
≤ 50	50	small	PVC
≤ 63	63	small	PVC
≤ 75	75	small	PVC
≤ 110	110	small	PVC
≤ 160	160	small	PVC
≤ 200	200	medium	PE
≤ 250	250	medium	PE
≤ 315	315	medium	PE
≤ 400	400	large	DI
≤ 500	500	large	DI
≤ 630	630	large	DI
≤ 700	700	large	DI
≤ 800	800	large	DI

5.2 Model robustness tests

Validation of the model functionality is required before its application on the case study. The robustness tests that were performed are briefly discussed below and all results are given in Appendix B.

5.2.1 Input data for robustness tests

The available data for the case study, as given in Table 5-2 to Table 5-10, was chosen as input data for the error and robustness tests, with alterations as required discussed for each test case. From literature it is evident that there is a large variability in the reported failure rates across the different case studies considered and Neelakantan et al. (2008) stated that many failure rate values available from literature are average failure rates or assumed values.

The selections of particular failure rate inputs for the robustness tests are not important because the diameter group results are independent of one another. From practical experience a value of $\frac{30\,failures}{100km \cdot year}$ was chosen to represent the failure rate for the “small” diameter group for implementation in the tests. Due to the general acceptance that the failure rate decreases with increase in pipe size, failure rates for “medium” and “large” diameter groups were chosen as $\frac{20\,failures}{100km \cdot year}$ and $\frac{10\,failures}{100km \cdot year}$, respectively. The diameter group assignment is given in Table 5-10.

The chosen failure rates, as stated above, resulted in a total of 603 failures when the lengths of each of the diameter groups were considered. The number of failures for each of the diameter groups' entries in the "Input sheet" as per paragraph 4.4.2.7 was:

- 535 for small pipes
- 46 for medium pipes
- 22 for large pipes.

An analysis period of 20 years was used for the robustness tests, unless otherwise stated. The period of 20 years resulted in a reasonable resolution to illustrate the results and comparisons graphically for various robustness tests as presented hereafter.

Table 5-11 provides a brief description of the robustness tests conducted. The applicable paragraph in the text is indicated, along with the location of the full result set in Appendix B.

Table 5-11: Summary of robustness tests for MPM model

Test number	Description	Applicable to paragraph	Refer to Appendix B: page
1	Test if Equation 11 yields required results ≡ "Robustness test 1"	§ 4.1.2; § 4.1.3; § 4.1.10	VII
2	Test the utilisation of available budget ≡ "Robustness test 2"	§ 4.1.3; § 4.1.5	VIII
3	Test the "length allowed" input parameter ≡ "Robustness test 3"	§ 4.1.4	IX
4	Test the "planned SID allowed" input parameter ≡ "Robustness test 4"	§ 4.1.5	X
5	Test the "failures accepted" input parameter ≡ "Robustness test 5"	§ 4.1.6	XI
6	Test the "minimum budget expenditure" parameter ≡ "Robustness test 6"	§ 4.1.7; § 4.1.8	XII
7	Test the "pipe skip count" parameter ≡ "Robustness test 7"	§ 4.1.8	XIII; XIV; XV; XVI
8	Test the "contingency buffer" parameter ≡ "Robustness test 8"	§ 4.1.9	XVII; XVIII
9	Illustrate the effect of the growth rate coefficient on Equation 11 ≡ "Robustness test 9"	§ 4.1.10	XIX
10	Illustrate the effect of the replacement exclusion period ≡ "Robustness test 10"	§ 4.1.1	XX; XXI
11	Illustrate the effect of scheduled replacements ≡ "Robustness test 11"	§ 4.1.1	XXII; XXIII

5.2.2 Robustness test 1: Failure forecasting

In order to test the failure algorithm as presented in paragraph 4.3.2, the AARB is set to zero for the entire analysis timeframe so that no pipe replacement occurs. With zero pipe replacement the age of all pipes will be incremented from one year to the next. The results from Equation 7, the time-exponential equation without allowance for frailty and correction factors, can easily be calculated because the failures for each pipe (and year) only increase by a factor of $e^{A_{M,p}}$ from the previous year. To simplify the illustration of the results a single growth rate coefficient is selected for all materials. The A_M is selected as 0.0137 from Walski and Pelliccia (1982) as shown in Table 5-9. The chosen A_M value is deemed suitable as it falls within the range of values as presented for the case study.

With the introduction of the frailty factor (Equation 8) the initial failures that are calculated with Equation 9, for the base data, will not necessarily be equal to the known failure input parameters, and therefore a correction factor (Equation 10) is required. The frailty factor (Equation 8) of each pipe remains constant in the analysis when no pipe replacement occurs, as only the pipe age is altered, and would therefore not adversely influence the failure calculation for subsequent years. It was therefore expected that the number of failures from the analysis would be the same for each year as when simply multiplying with the e^{A_M} factor from one year to the next.

The calculated failures from the analysis, subject to a correction factor for each diameter group as shown in Table 5-12, are compared to the expected failures when simply multiplying the initial base failures with the e^{A_M} factor. The results are compared in Table 5-13 and show that the same results are achieved for all practical purposes, with an absolute difference less than 1.00E-10.

Table 5-12: Correction factor per diameter group for robustness tests

Pipe diameter group	Initial failure calculation (Equation 9)	Correction factor (Equation 10)
small	745.3263	0.7178
medium	77.3886	0.5944
large	40.4576	0.5438

Table 5-13: Comparison of failures for Robustness test 1

Period	Exponential equation		Analysis failures	Difference
	$e^{A_M} \cdot \text{years}$	Total failures		
5 years	1.071	645.753	645.753	5.57E-12
10 years	1.147	691.537	691.537	4.43E-12
15 years	1.228	740.568	740.568	3.87E-12
20 years	1.315	793.075	793.075	1.59E-12

5.2.3 Robustness test 2: Utilisation of available budget

The average replacement cost for the pipes in the inventory list was 1 416 C_r, with a minimum replacement cost of 50 C_r and a maximum replacement cost of 260 146 C_r. In order to illustrate the utilisation of the available budget during the replacement procedure, the AARB was chosen as 100 000 C_r as this value is small enough to ensure that 11 pipes with high replacement costs would be ineligible for replacement and also negates the requirement for additional calculation to determine the percentage expenditure of AARB. With the minimum budget expenditure set as 100%, full utilisation of the AARB was expected.

Figure 5-9 reveals that full utilisation of the budget was indeed achieved when it is considered that the minimum replacement cost across all pipes in the inventory was equal to 50 C_r and the minimum CAPEX for Robustness test 2 was 99 957 C_r.

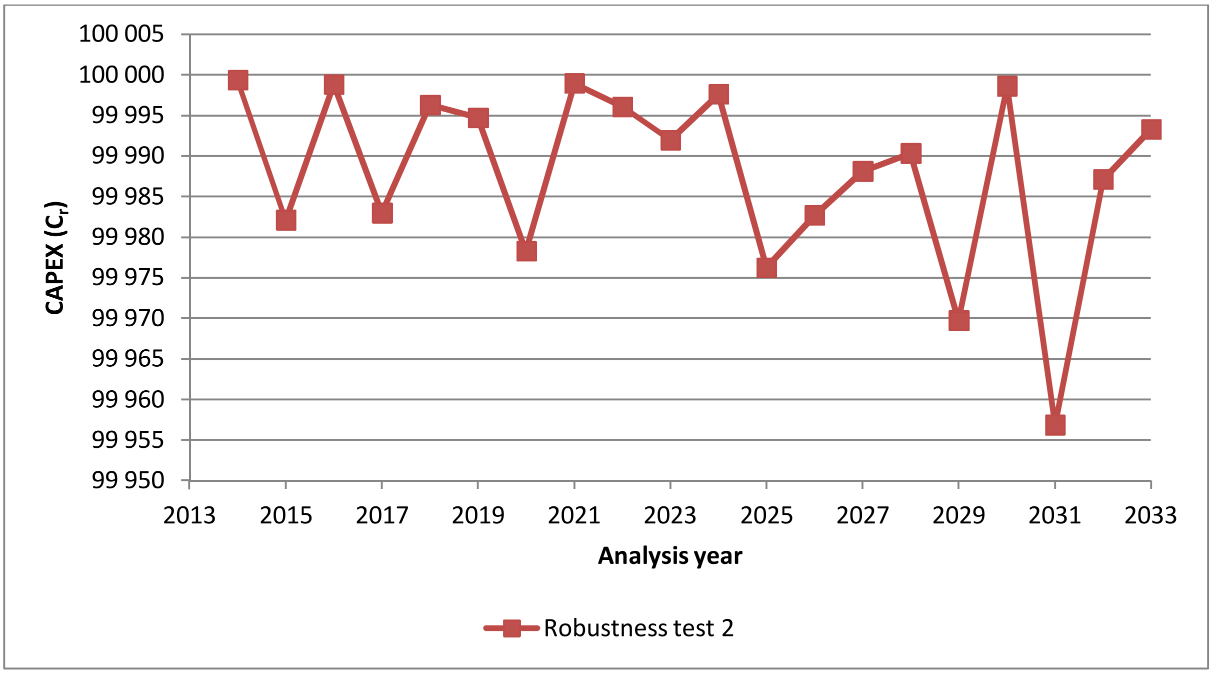


Figure 5-9: CAPEX for Robustness test 2

It was also expected that, due to replacement, the number of failures will decrease as compared to the failures from Robustness test 1 and also that the ERAV for each year will be higher than for the values calculated in Robustness test 1. Figure 5-10 and Figure 5-11 also confirm the expectations for failures and ERAV as mentioned above, with Figure 5-10 showing a higher number of failures for Robustness test 1 and Figure 5-11 showing an improved ERAV for Robustness test 2.

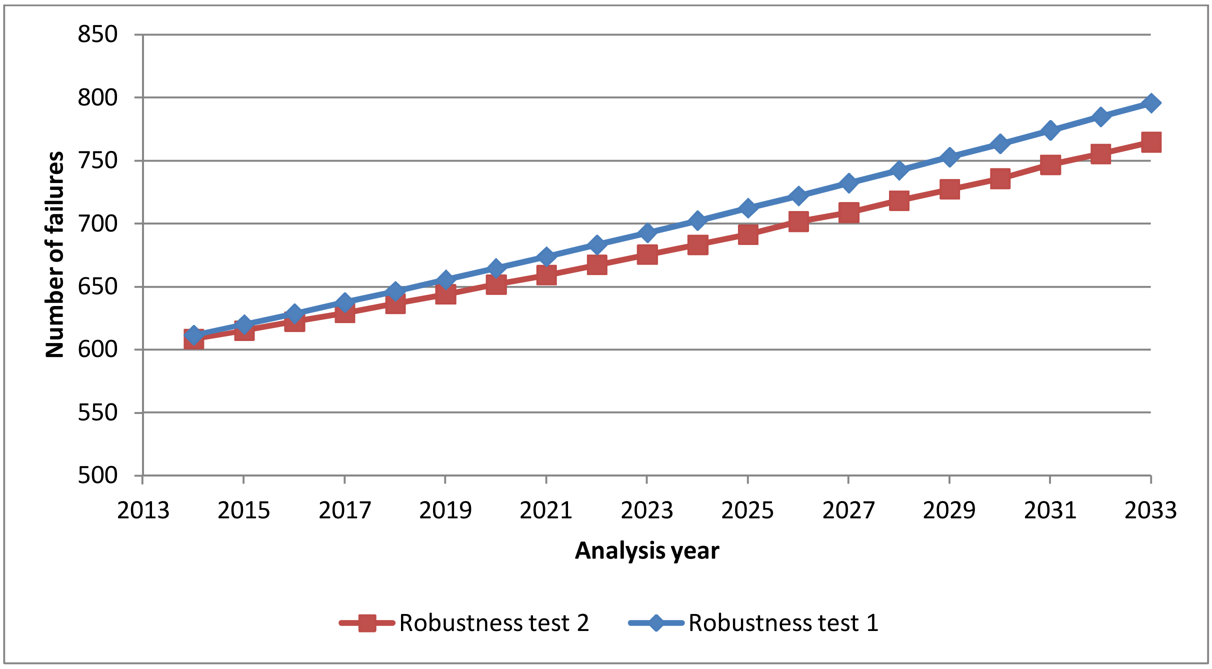


Figure 5-10: Comparison of number of failures between Robustness tests 1 and 2

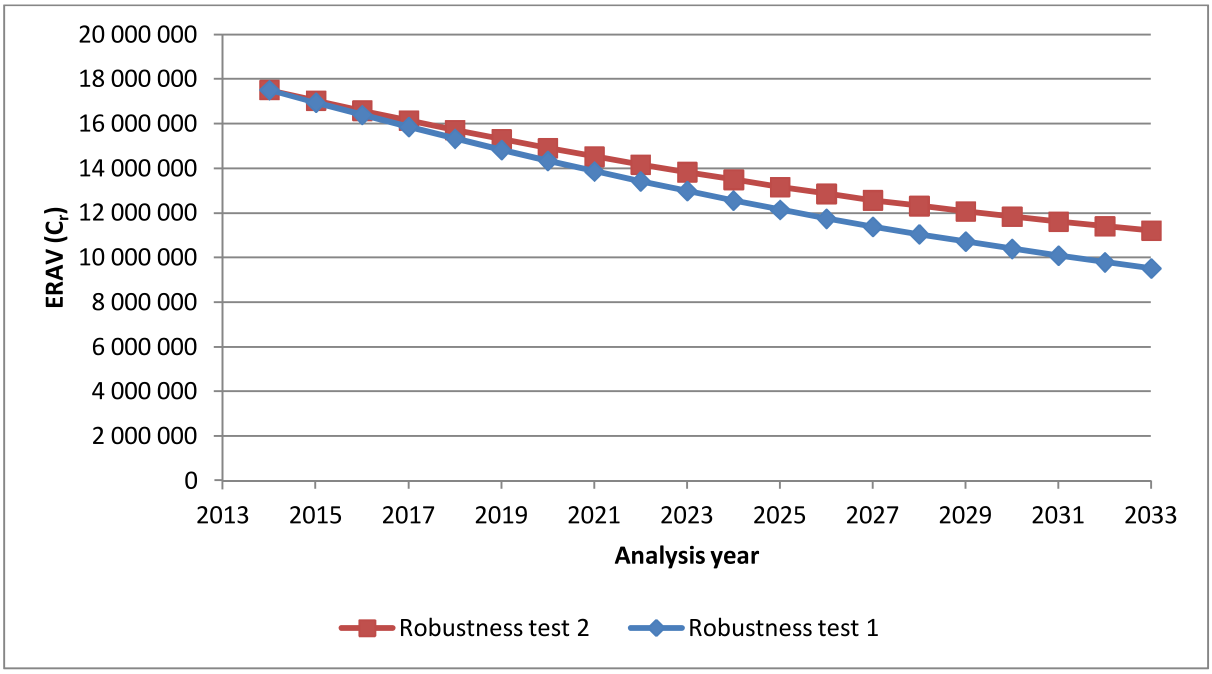


Figure 5-11: Comparison of ERAV between Robustness tests 1 and 2

5.2.4 Robustness test 3: Replacement length allowed

In order to test if the replacement procedure is halted once the "replacement length allowed" input parameter value is reached, the same input as for Robustness test 2 is used for Robustness test 3, with the "length allowed" parameter set to 1000 m. The "length allowed" parameter of 1000 m is less than the average replaced length of 6 121 m for Robustness test 2, and the results could therefore illustrate that the replaced length does not exceed the restriction as set.

Figure 5-12 shows that the length restriction is not exceeded, with none of the years indicating a length of replacement more than 1000 m. The last year (2033) resulted in a replacement length of 891 m, which is noticeably less than the restriction of 1000 m, when compared to the results of the preceding years in the test.

The results for Robustness test 3 show that for year 2033 the CAPEX = 99 962 $C_{r,}$ and as mentioned in paragraph 5.2.3, the minimum replacement cost is equal to 50 C_r, and therefore the budget limitation of 100 000 C_r is reached before the length restriction of 1000 m. The results also show that the majority of replacement length for the last period was for pipes in the large diameter group; large pipes have a higher cost per unit length, which explains the high expenditure relative to the achieved length of replacement.

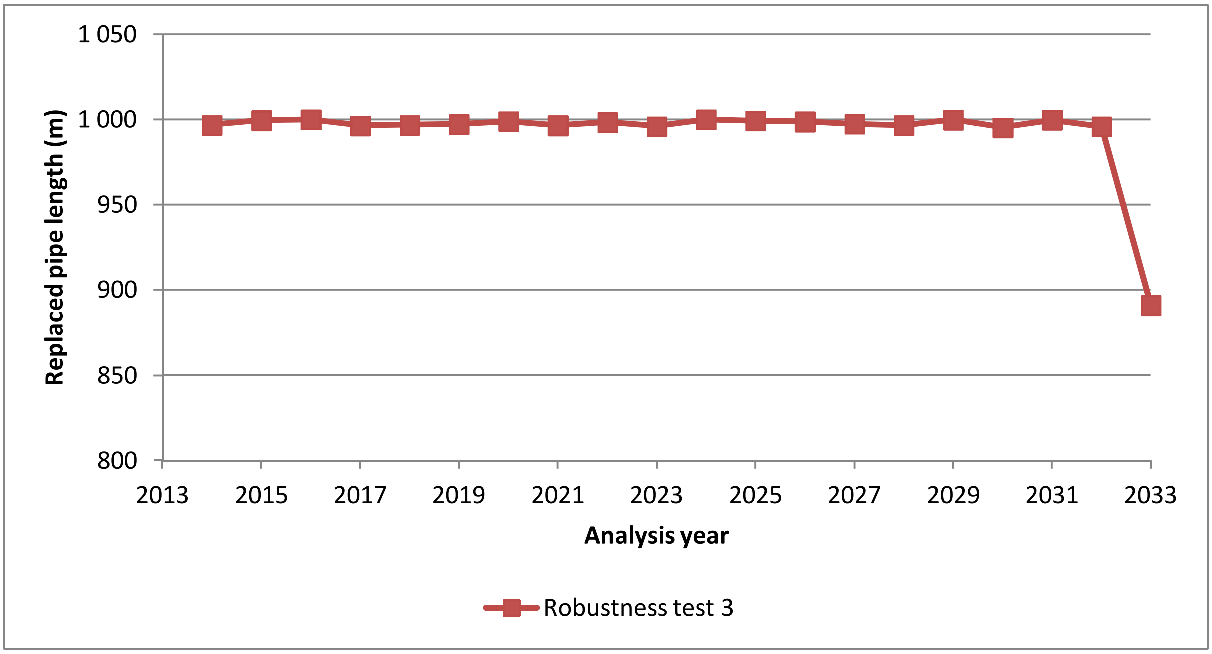


Figure 5-12: Replaced length for Robustness test 3

5.2.5 Robustness test 4: Planned SID allowed

In order to test if the replacement procedure is halted once the "planned SID allowed" input parameter value is reached, the same input as for Robustness test 2 is used with the planned SID parameter set to value of 2.00. The planned SID parameter value of 2.00 is less than the average planned SID of 3.08 for Robustness test 2, and the results could therefore be compared to illustrate that the planned SID does not exceed the set restriction.

Figure 5-13 shows the comparison of planned SID for Robustness test 4 and Robustness test 2. The low value for planned SID of 0.01, for analysis year 2033 (Robustness test 4), was a result of the replacement of large diameter high cost pipes with no affected users ($HH_i = 0$), attributed to network redundancy, that would result in zero planned SID (see paragraph 4.3.4 and Equation 14). The same occurrence of low planned SID is seen in the results for Robustness test 2, with low values of 0.09 and 0.03 in analysis years 2026 and 2031, respectively.

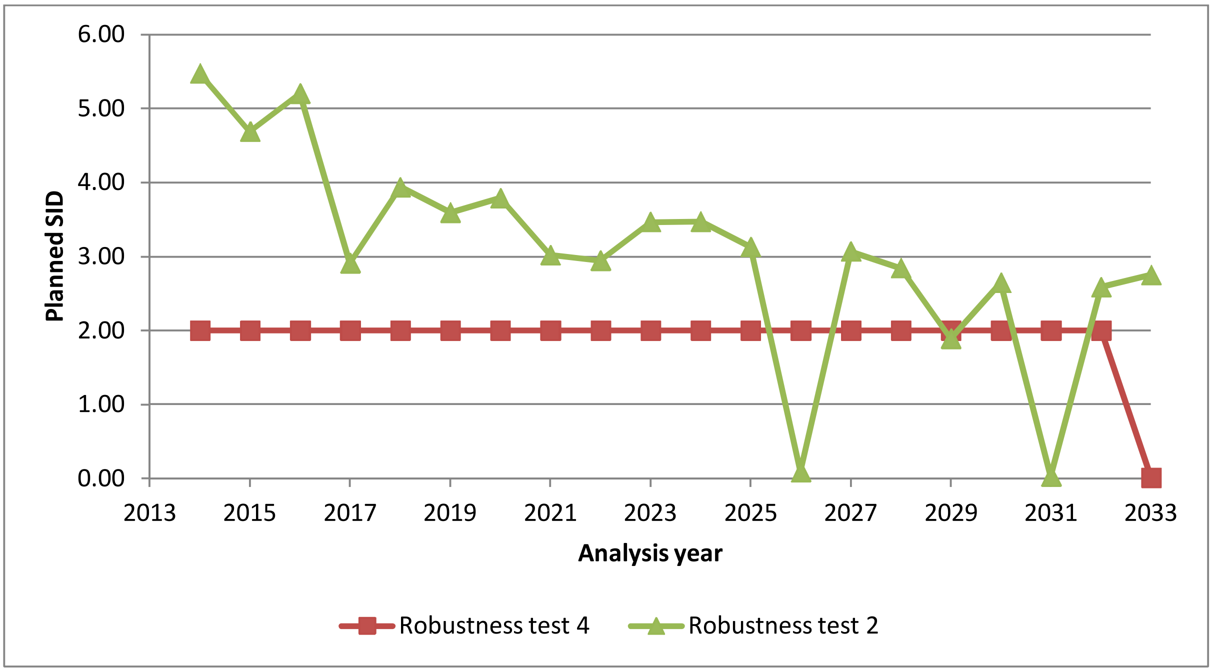


Figure 5-13: Comparison of planned SID between Robustness tests 2 and 4

5.2.6 Robustness test 5: Number of failures accepted

In order to test if the replacement procedure is halted once the "number of failures accepted" input parameter value is reached, the same input as for Robustness test 2 were used with the AARB set to 50 000 000 C_r. The chosen AARB was higher than the total replacement value of the entire pipe inventory (46 657 559 C_r) and could therefore result in total system replacement if the replacement procedure was not halted by an eligibility factor and consequently result in very low expected failures as all pipes will only be 1 year old in the next analysis period.

The "failures accepted" parameter was set to 600 (a round number just below the base failures of 603) in order to illustrate how a budget to keep the failures constant throughout the analysis timeframe could be determined. Figure 5-14 shows that the annual failures does not exceed the restriction of 600 failures; the required CAPEX to restrict the number of failures per period is indicated in Figure 5-15. The required CAPEX is far less than the AARB of 50 000 000 C_r, which indicates that full budget utilisation has not been achieved and therefore illustrates how the number of "failures accepted" parameter could be used to restricted unnecessary spending when a certain number of failures could be acceptable in an investment strategy.

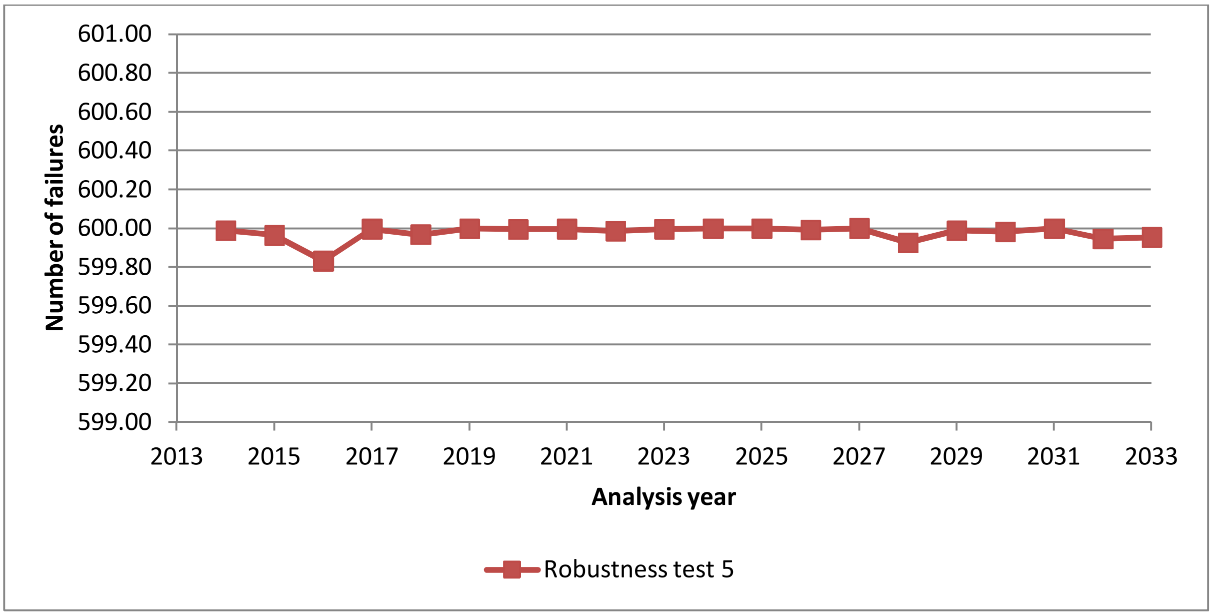


Figure 5-14: Total number of failures for Robustness test 5

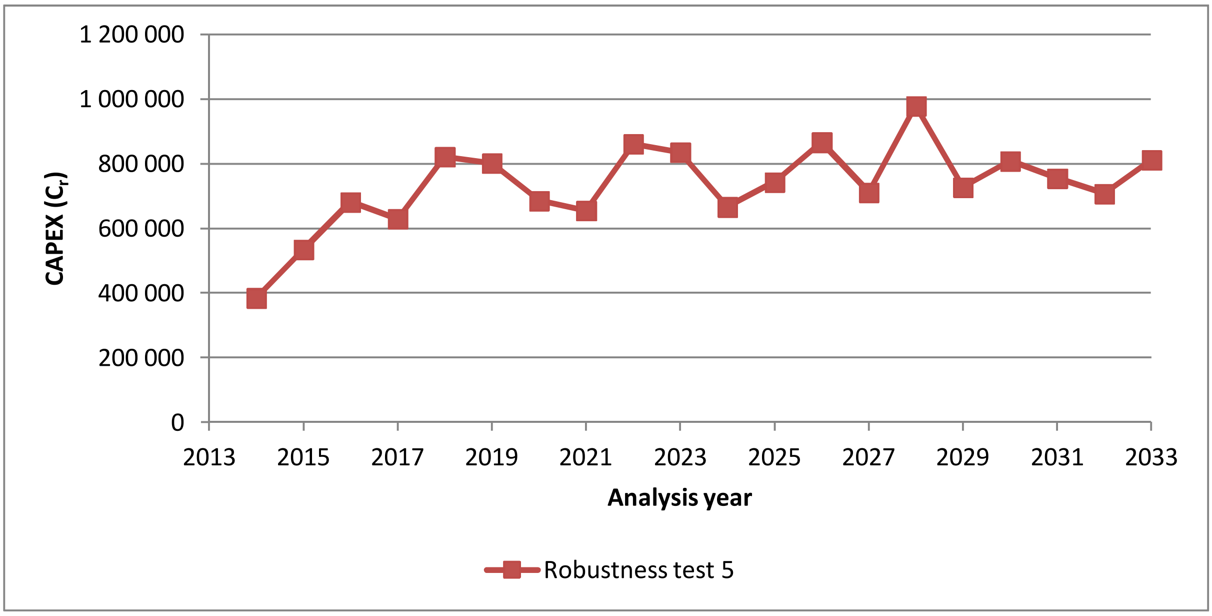


Figure 5-15: CAPEX for Robustness test 5 (required AARB to restrict failures)

5.2.7 Robustness test 6: Minimum budget expenditure

In order to test if the replacement procedure is halted after the CAPEX, resulting from the "minimum budget expenditure" input parameter value, is exceeded, the same input as for Robustness test 2 is used for Robustness test 6, with the "minimum budget expenditure" set to 90%, which is equal to 90 000 C_r.

Figure 5-16 shows the CAPEX > 90 000 C_r in all analysis years for Robustness test 6, with a minimum value of 90 010 C_r and a maximum value of 99 505 C_r. All the CAPEX values for Robustness test 6 are therefore lower than the minimum CAPEX for Robustness test 2 (99 957 C_r), which indicates that even though the AARB of 100 000 C_r was high enough to replace more pipes, the procedure was halted immediately after the "minimum budget expenditure" of 90 000 C_r was exceeded.

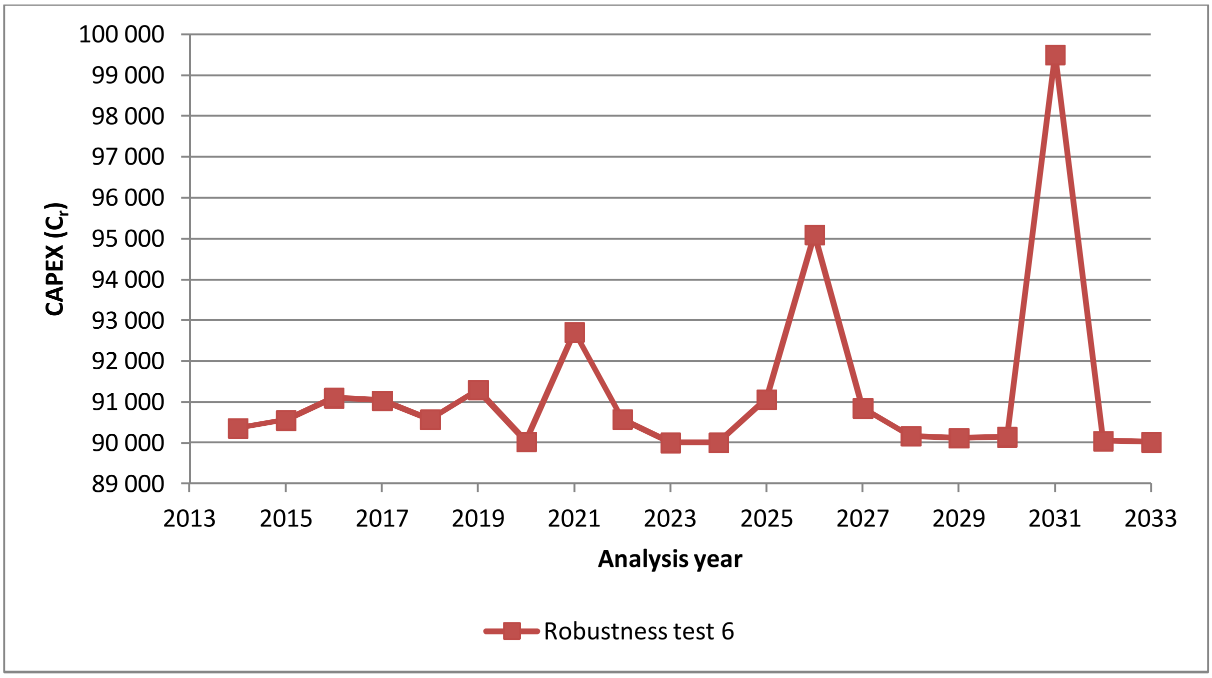


Figure 5-16: CAPEX for Robustness test 6

5.2.8 Robustness test 7: Pipe skip count

The "pipe skip count" parameter regulates the number of consecutive pipes that are required to be passed over (skipped) for replacement before the minimum budget expenditure test is conducted. In order to test the "pipe skip count parameter" and show its relevance to be included in the analysis, the same input as for Robustness test 6 is used, with the pipe count parameter set to 1, 5, 10 and 100 for four separate scenarios. Robustness test 6 had a pipe skip count of 0, which means that the minimum budget expenditure test was conducted after each replacement.

The CAPEX of the four scenarios for Robustness test 7 and that of Robustness test 6 were compared. Table 5-14 shows the resultant CAPEX with the introduction of the pipe count parameter to maximise the utilisation of the AARB, while still providing the ability to ignore very low risk pipes as replacement options. Figure 5-17 provides a graphical illustration of the data provided in Table 5-14.

Table 5-14: CAPEX with pipe skip count parameters for Robustness test 7

Analysis period	**CAPEX (C_r) for a pipe skip count of:**				
	0	**1**	**5**	**10**	**100**
2014	90 365	99 565	99 949	99 949	99 949
2015	90 560	99 669	99 982	99 982	99 982
2016	91 109	99 858	99 940	99 940	99 940
2017	91 041	99 319	99 983	99 983	99 983
2018	90 576	98 963	99 932	99 932	99 991
2019	91 303	99 019	99 936	99 936	99 965
2020	90 034	99 578	99 896	99 994	99 945
2021	92 716	99 209	99 959	99 860	99 976
2022	90 583	98 194	99 913	99 913	99 967
2023	90 010	99 911	99 973	99 973	99 944
2024	90 012	99 353	99 991	99 991	99 992
2025	91 072	99 541	99 969	99 969	99 941
2026	95 100	94 599	99 855	99 855	99 983
2027	90 856	99 893	99 848	99 848	99 991
2028	90 174	99 612	99 967	99 967	99 985
2029	90 124	99 919	99 812	99 995	99 988
2030	90 152	99 854	99 966	99 941	99 957
2031	99 505	99 505	99 957	99 957	99 957
2032	90 052	99 902	99 900	99 967	99 994
2033	90 025	99 184	99 982	99 974	99 954

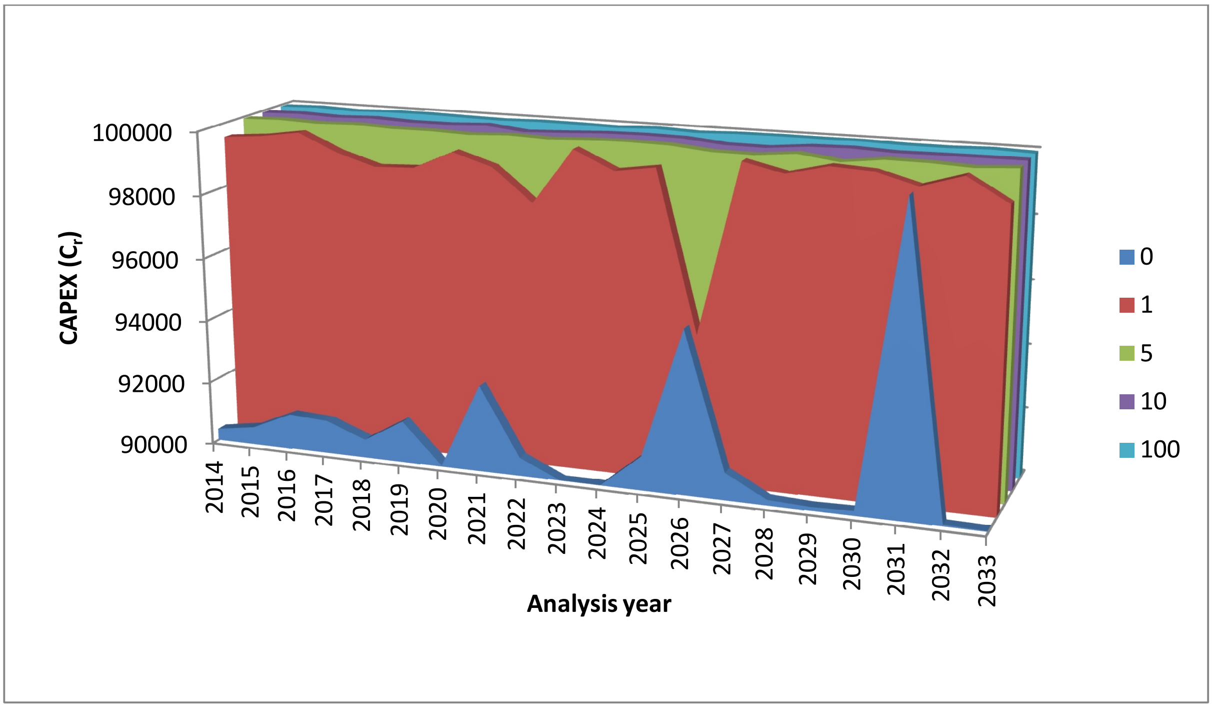


Figure 5-17: CAPEX based on pipe skip count parameter for Robustness test 7

5.2.9 Robustness test 8: Contingency buffer

In order to illustrate the effect of an increased temporary replacement budget, resulting from the "contingency buffer" input parameter value, and to test if the replacement procedure is halted after the initial AARB was exceeded, the same input as for Robustness test 2 is used, with the contingency buffer parameter set to 1% and 5%, for two separate scenarios. The allowable capital expenditures are therefore temporarily set to 101 000 C_r and 105 000 C_r, respectively for the cumulative expenditure test. Table 5-15 shows the CAPEX values for each analysis year for the different "contingency buffer" parameters inputs.

From Table 5-15, it can be seen that for the first four years, the same pipes have been selected and replaced, however in the fifth year (2018), the higher buffer percentage allowed a higher cost pipe to be replaced due to an increased temporary budget of 105 000 C_r and resulted in CAPEX > 101 000 C_r. However, in analysis year 2019, the CAPEX for the 1% contingency buffer scenario is higher than that of the 5% contingency buffer scenario, which confirmed that the replacement was halted after the initial AARB of 100 000 C_r was exceeded, which conforms to the contingency buffer replacement eligibility criteria as discussed in paragraph 4.2.4.3.

Table 5-15: CAPEX with contingency buffer for Robustness test 8

Analysis period	CAPEX (C_r) for a contingency buffer (%) of:	
	1	5
2014	100 484	100 484
2015	100 709	100 709
2016	100 247	100 247
2017	100 642	100 642
2018	100 393	101 634
2019	100 956	100 264
2020	100 132	100 705
2021	100 474	100 128
2022	100 670	100 103
2023	100 806	100 598
2024	100 220	100 220
2025	100 391	100 391
2026	100 796	100 796
2027	100 143	100 143
2028	100 731	103 239
2029	100 645	100 447
2030	100 665	100 435
2031	100 615	100 615
2032	100 098	100 439
2033	100 426	100 411

5.2.10 Robustness test 9: Growth rate coefficient

In order to illustrate the effect of the "growth rate coefficient" the same input as used for Robustness test 1 was used for Robustness test 9, with the A_M coefficients altered and set as the inverse of the ESL as seen in Table 5-16 (refer to paragraph 5.1.9 for discussion regarding selection of selected A_M values). The calculated failures for Robustness test 9 were compared to those of Robustness test 1 and the results are shown in Figure 5-18. The AC and PVC material groups were chosen to illustrate the difference in the calculated failures for each of the material groups, over and above that of the network. The results for the AC and PVC comparisons are shown in Figure 5-19 and Figure 5-20, respectively.

Table 5-16: Comparison of A_M for Robustness test 9 and. Robustness test 1

MATERIAL	ESL	A_M : Robustness test 9	A_M : Robustness test 1
	60	0.0167	0.0137
AC	60	0.0167	0.0137
CI	80	0.0125	0.0137
DI	80	0.0125	0.0137
PE	100	0.0100	0.0137
PVC	100	0.0100	0.0137
ST	90	0.0111	0.0137

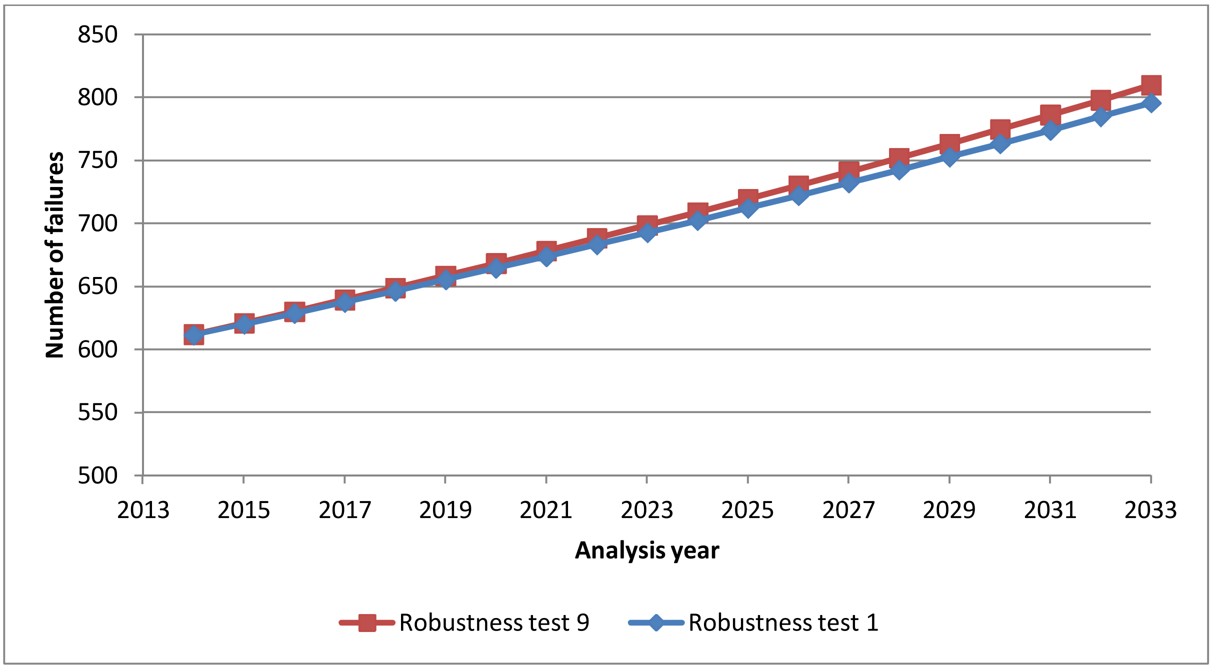


Figure 5-18: Comparison of number of failures for Robustness tests 1 and 9

The higher A_M for AC pipes in Robustness test 9 results in a higher number of failures and similarly for PVC pipes, a lower A_M results in fewer failures, when compared to the number of failures in Robustness test 1, as seen in Figure 5-19 and Figure 5-20.

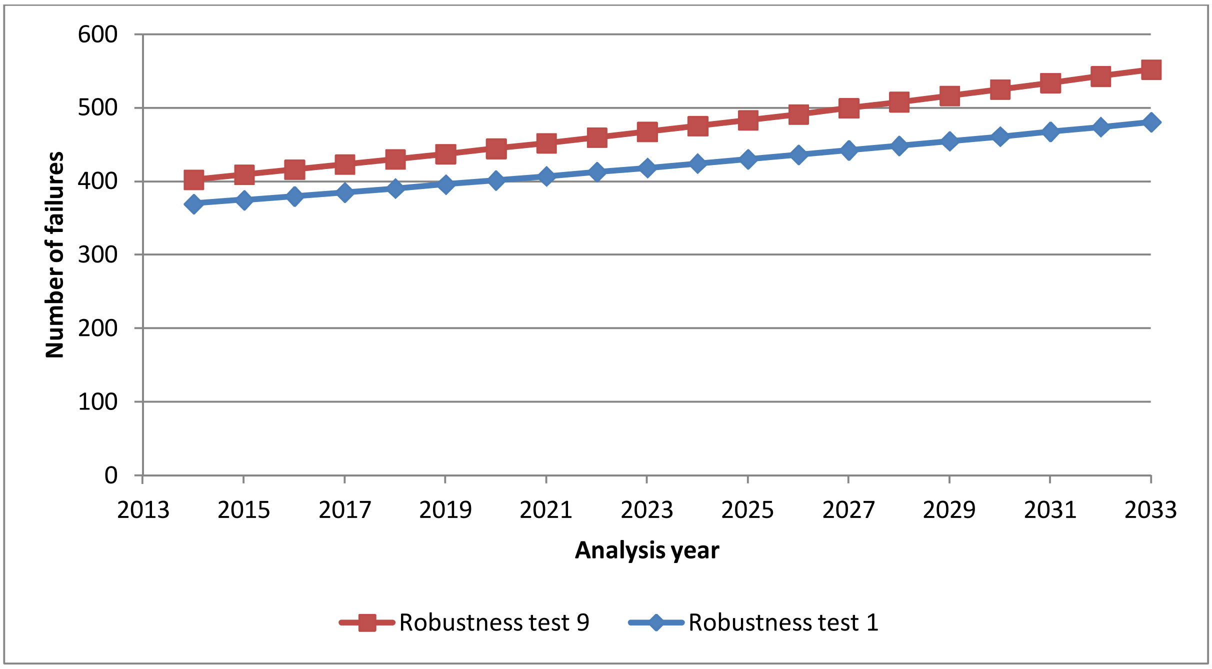


Figure 5-19: Comparison of total number of failures on AC pipes

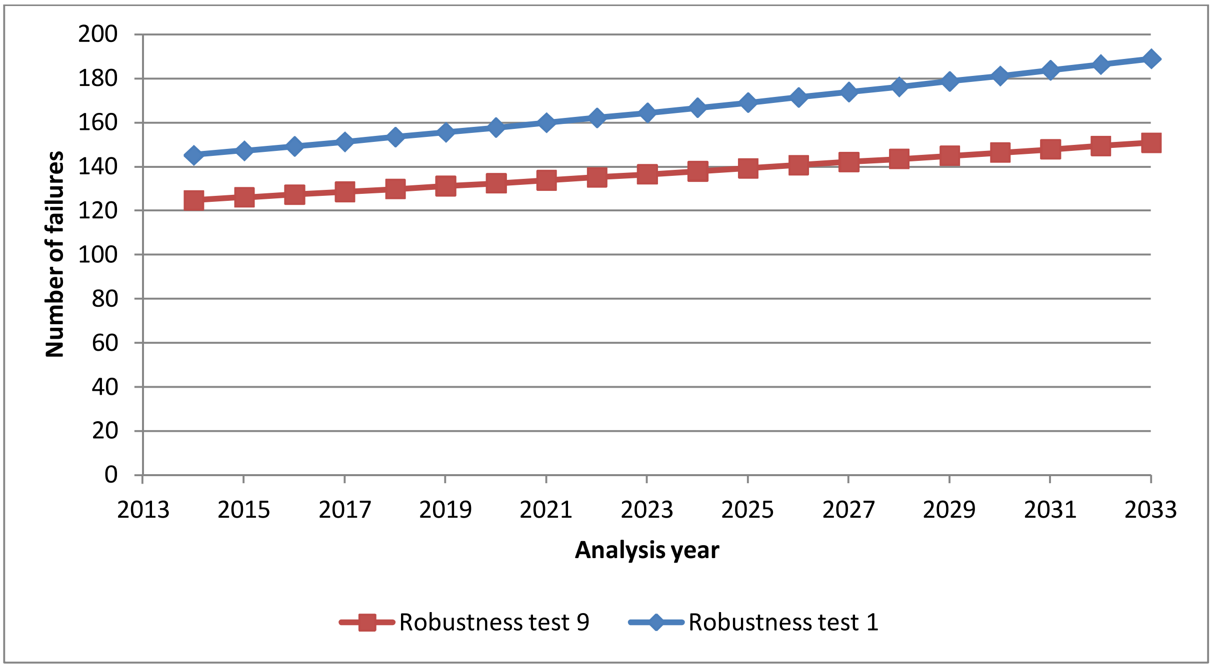


Figure 5-20: Comparison of total number of failures on PVC pipes

5.2.11 Robustness test 10: Replacement exclusion period

As stated in paragraph 4.2.5, the CF of each pipe is constant throughout the analysis and the REP serves as a risk acceptance parameter by indicating a period of time for which the risk will be accepted, most notably for new pipes with a high CF and therefore a high risk value (PRF). Therefore, a low REP value will infer a lower acceptance of risk and a high REP value will infer reasonable acceptance of risk.

In order to test the the REP parameter, i.e. the period for which a pipe is not considered eligible for replacement after it has been replaced during the analysis, the same input as for Robustness test 9 is used for Robustness test 10. The AARB set to 5% of the replacement value of the entire system (2 332 900 C_r) which should allow for all pipes to be replaced in a 20 year analysis timeframe, unless recurring replacement occurs.

The REP for all materials was set as 0 years and 5 years for two separate scenarios. With REP = 0, no risk is accepted, regardless of pipe age and a pipe is eligible for replacement in each year of the analysis, whereas with REP = 5, a pipe that has been replaced during any year in the analysis will not be eligible for replacement for a 5 year period, regardless its rank.

Table 5-17 and Figure 5-21 show the percentage of replaced pipe length per period which has already been replaced during the analysis. The 0% recurring replacement for the first five years (2014-2018) for the REP = 5 scenario indicates that the exclusion period is achieved. This test also demonstrated the effect of the REP parameter on cyclical replacement due to high CF and how it can be used to reduce the number of recurring replacements of new pipes, without disregarding the requirement for possible replacement of a high CF in the future, especially when long analysis timeframes are considered.

Table 5-17: Recurring replacement as percentage of replaced length for Robustness test 10

Analysis period	Percentage of total replaced length (%)	
	REP = 0	REP = 5
2014	0	0
2015	0	0
2016	0.11	0
2017	0.41	0
2018	2.66	0
2019	2.93	0.12
2020	2.89	1.33
2021	2.9	1.03
2022	2.55	0
2023	2.96	0.29

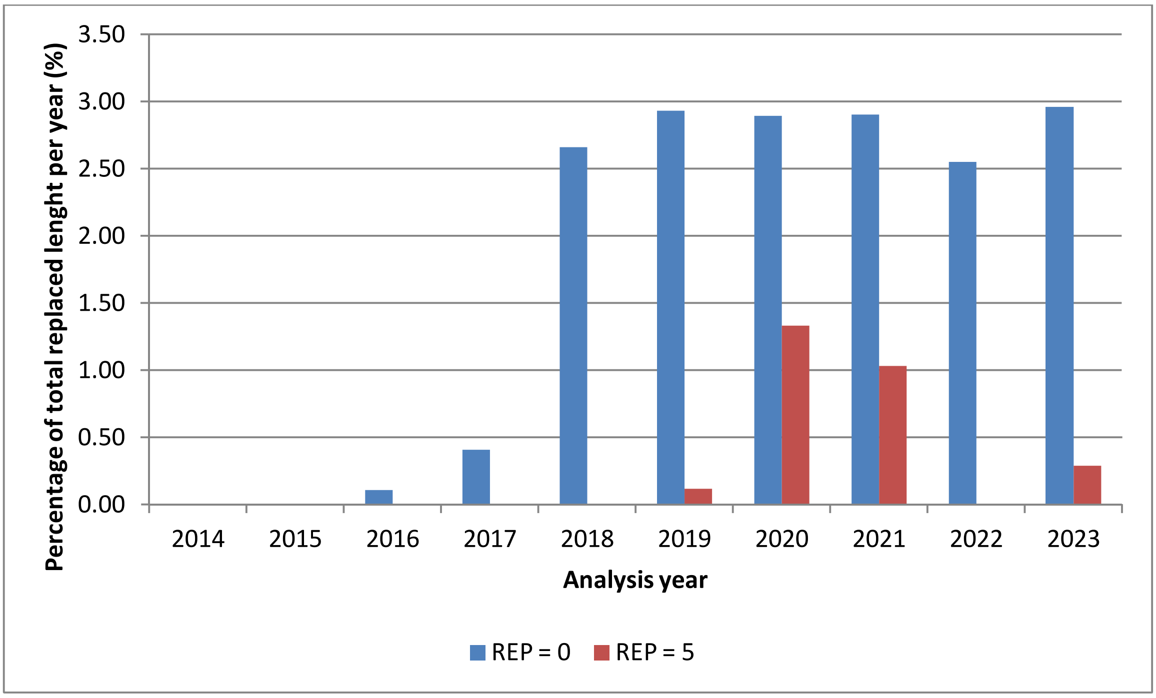


Figure 5-21: Illustration of recurring replacement with different REPs

5.2.12 Robustness test 11: Scheduled replacements

To illustrate the concept of the allowance of scheduled replacements and compare CAPEX results the same AARB input as for Robustness test 2 was used for Robustness test 11. Also, to ensure that the costs for the pipes selected as scheduled replacements, as discussed below, were not simply extracted from the results of Robustness test 2, the "minimum budget expenditure" was set as 99%, the "pipe skip count" was set as 100, the REP was set to 5 for all materials and an analysis timeframe of 7 years was selected.

The first 30 pipes from the pipe inventory in the "Base data" sheet were selected and used to create a fictitious replacement schedule by listing the pipe ID. The first 10 pipes were selected for the first period (2014), the next 15 pipes for the third period (2016) and the last 5 pipes for the fourth period (2017). The first 10 pipes that were selected for the first period (2014) were re-selected for the fifth and sixth periods (2018 and 2019).

Pipe data that is not available in the dataset was included in the second, third and fourth period (2015, 2016 and 2017) schedule lists in order to test the detection and reporting of such items in the applicable sheet. An additional 150 pipes from the base data was selected for the seventh period (2020) to show what would happen if the total cost of the replacement schedule items were to be more than the AARB. The 150 pipes would also show that replacement eligibility tests are conducted for the replacement schedule items.

The analysis results of Robustness test 7, along with the entries in the "Replacement Schedule" and "Schedule items – Not Found" sheets (as discussed in paragraph 4.4.2.6), are available in Appendix B.17.

In the analysis, the scheduled items for each of the years were assigned a PRF of 999 to ensure they are deemed as highest priority. Allocating the highest priority was necessary to ensure that all scheduled items would be considered for replacement before any other pipes, regardless of what a scheduled item's calculated PRF might be. The pipes that are not present in the "Base data" sheet are reflected in the "Schedule items – Not Found" sheet for the correct periods. The results from the fifth period (2018) show that the pipes from the scheduled replacement list, a duplication of the first period, have not been enforced due to their ineligibility for replacement as governed by the REP parameter, whereas in the case of the sixth period (also a duplication of the first period), replacement is allowed because the REP = 5 no longer restricts their replacement.

For the seventh period (2020), four of the 150 pipes listed were ineligible as per the REP variable. Table 5-18 shows the expenditure for replacements based on the scheduled list and additional risk-based replacements. Near full utilisation was achieved for the first six periods (CAPEX ≈ 100 000 C_r). The seventh period indicated CAPEX ≫100 000 C_r. and it can also be seen that the cost of pipes that were deemed ineligible for the last period are indicated as negative expenditure in order for the actual CAPEX to be reflected. Therefore, scheduled replacements are not halted by inefficient AARB, only by the other eligibility parameters.

Table 5-18: CAPEX breakdown for Robustness test 11

Analysis period	CAPEX (C_r)		
	Scheduled item replacements	Risk-based replacements	Total
2014	41 022	58 946	99 968
2015	0	99 987	99 987
2016	27 437	72 540	99 977
2017	17 650	82 304	99 954
2018	41 022	58 929	99 951
2019	41 022	58 924	99 947
2020	327 401	-3 650	323 751

5.3 Validation of risk-based replacement

As stated, it is required to determine if the replacement of pipe assets based on the risk-based prioritisation model are sensible when compared to other replacement strategies. To validate the efficacy of the risk-based prioritisation model, as available for the case study, three supplementary procedures, namely random replacement, age-based replacement and ERUL-based replacement are provided, each of which ignores the calculated PRF when replacement prioritisation is established. The same input scenario as used for Robustness test 2 (utilisation of available budget) is implemented, with an analysis period of 50 years, the minimum budget expenditure set to 99% and the pipe skip count set to 100 for all prioritisation procedures. The results of each is compared to that of the risk-based replacement model based on PI's of (i) number of failures, (ii) total SID and (iii) average network ERUL. The REP is also chosen as 50 for all materials to ensure that no recurring pipe replacement is possible in the analyses.

Table 5-19 provides a brief description of the validation scenarios. The applicable paragraph in the text is indicated were the validation tests are briefly discussed, along with the location of the full result set in Appendix C.

Table 5-19: Summary of validation scenarios

Validation scenario	Description	Applicable to paragraph	Refer to Appendix C: page
Risk-based	Multi-period replacement with a risk-based prioritisation procedure.	§ 5.3.1; § 5.3.2; § 5.3.3	XXV; XXVI
Random 1	Multi-period replacement with a random prioritisation procedure.	§ 5.3.1	XXVII;XXVIII
Random 2			XXIX, XXX
Random 3			XXXI; XXXII
Age-based	Multi-period replacement with an age-based prioritisation procedure.	§ 5.3.2	XXXIII; XXXIV
ERUL-based	Multi-period replacement with an ERUL-based prioritisation procedure.	§ 5.3.3	XXXV; XXXVI

5.3.1 Random replacement

In order to simulate random replacement, a random value between 1 and 25 is assigned to each pipe to produce an unbiased priority for each pipe and sorted in descending order to produce the prioritised list for every analysis period. All other eligibility tests are applicable. Three random replacement analyses were performed for comparison to reduce the chance of coincidental favourable results.

The number of failures predicted, total SID and average network ERUL are compared in Figure 5-22, Figure 5-23 and Figure 5-24, respectively and the results indicate that the risk-based replacement is more efficient than random replacement. Figure 5-22 shows that the number of failures reported for the risk-based replacement is lower than each of the random replacement analyses.

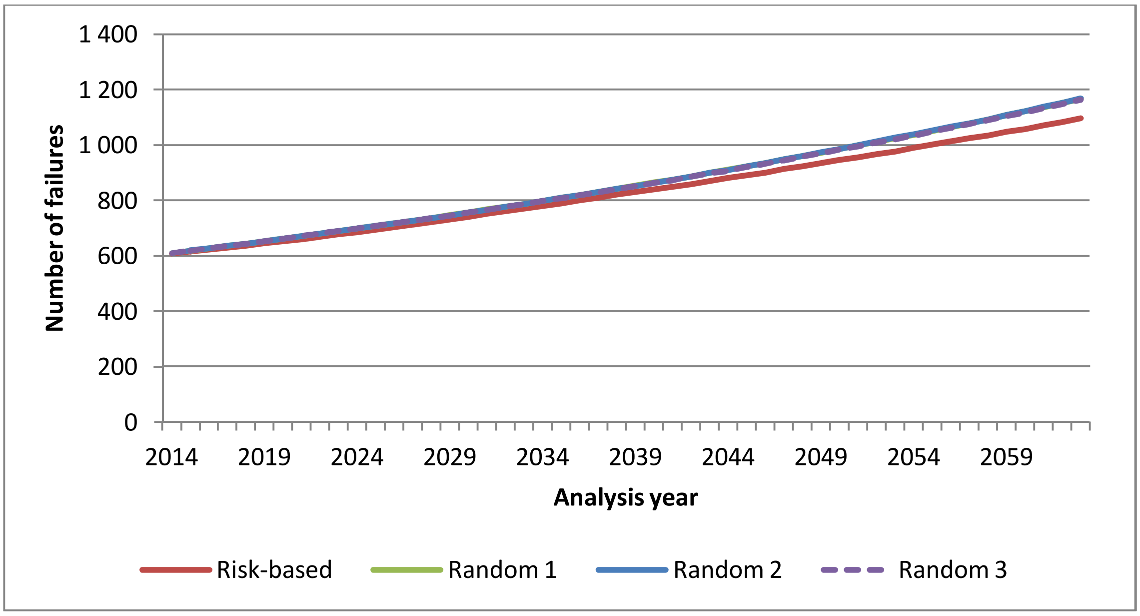


Figure 5-22: Random replacement - Failures predicted

Figure 5-23 shows that the total SID steadily increases over the total analysis timeframe for each of the random replacement simulations, whereas the risk-based replacement resulted in a more stable total SID value, ranging between 20 and 25 minutes, for the majority of the analysis.

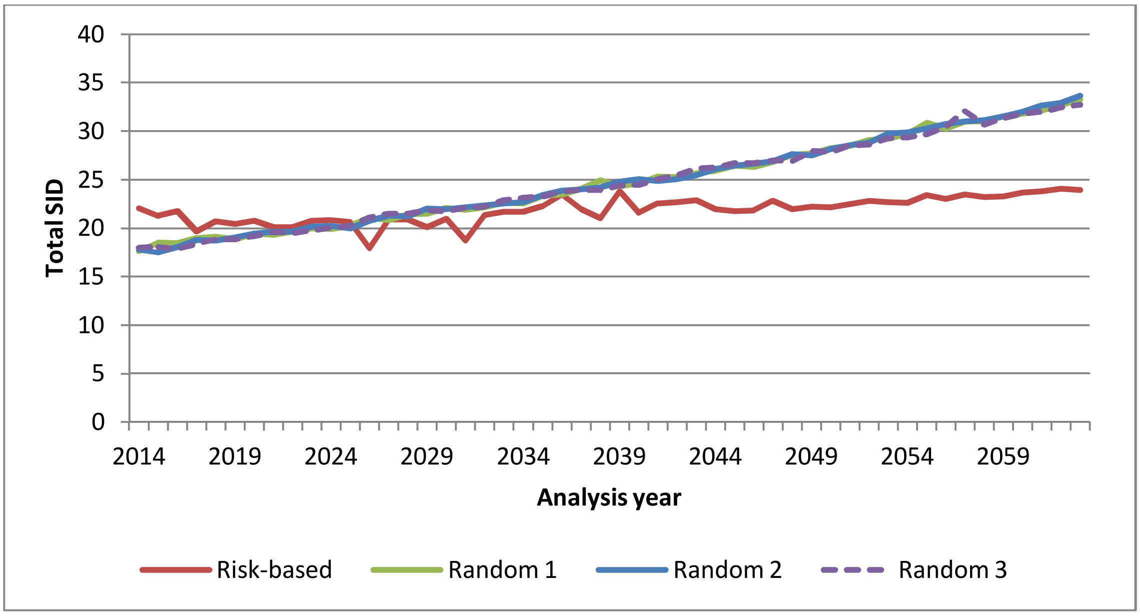


Figure 5-23: Random replacement - Total SID

Figure 5-24 shows that the average network ERUL is higher at the end of the analysis timeframe for risk-based replacement than for each of the random replacement analyses.

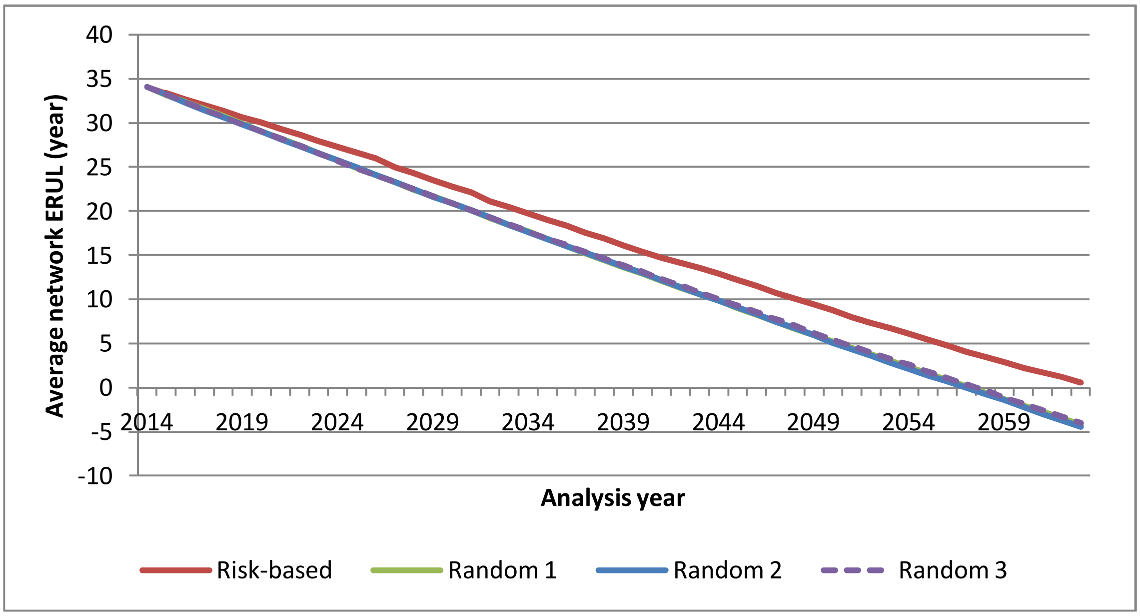


Figure 5-24: Random replacement - Average network ERUL

5.3.2 Age-based replacement

In order to simulate age-based replacement, the age of each pipe, calculated as the difference between the analysis year and the installation year, is sorted in descending order to produce the prioritised list for every analysis period. All other eligibility tests are applicable. The number of failures predicted, total SID and average network ERUL are compared in Figure 5-25, Figure 5-26 and Figure 5-27, respectively and the results indicate that the risk-based replacement is more efficient than age-based replacement. Figure 5-25 shows that the number of failures reported for the risk-based replacement is lower than the failures for the age-based replacement, although age-based replacement does show slight improvement in restricting the number of failures when compared to each of the random replacement analyses.

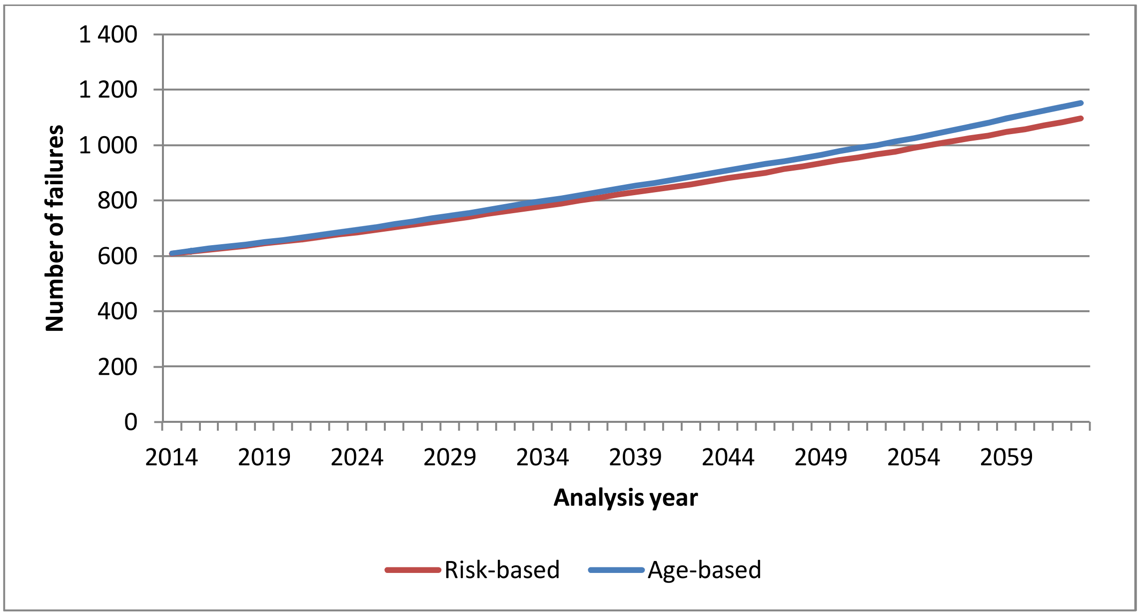


Figure 5-25: Age-based replacement - Failures predicted

Figure 5-26 shows that the total SID steadily increases over the total analysis timeframe for the age-based replacement, whereas the risk-based replacement resulted in a more stable total SID value, ranging between 20 and 25 minutes, for the majority of the analysis.

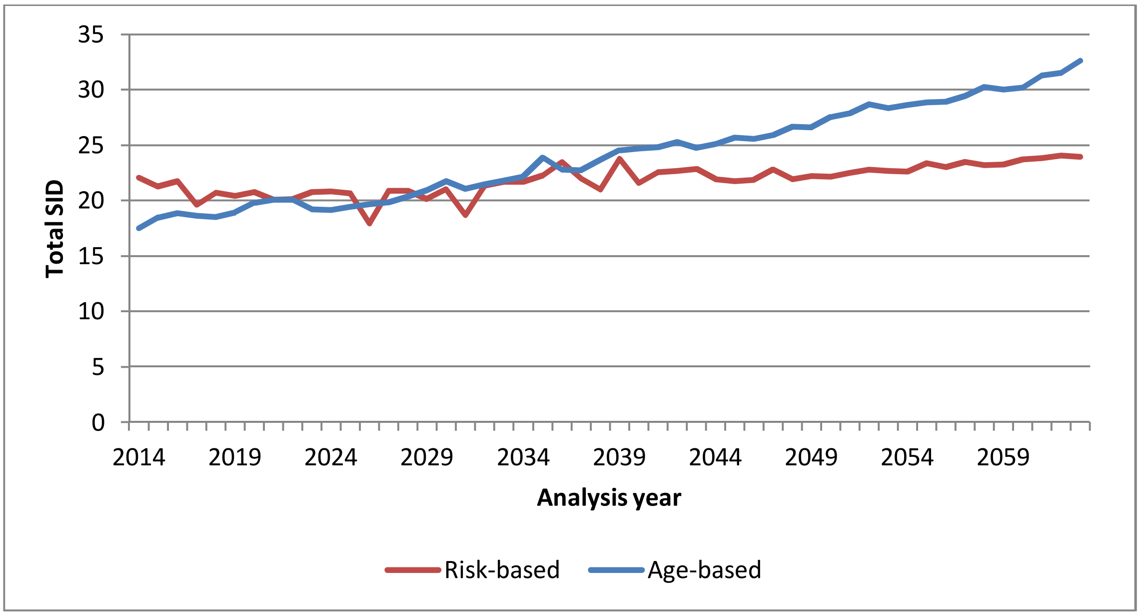


Figure 5-26: Age-based replacement - Total SID

Figure 5-27 shows that the average network ERUL is higher at the end of the analysis timeframe for risk-based replacement than for age-based replacement.

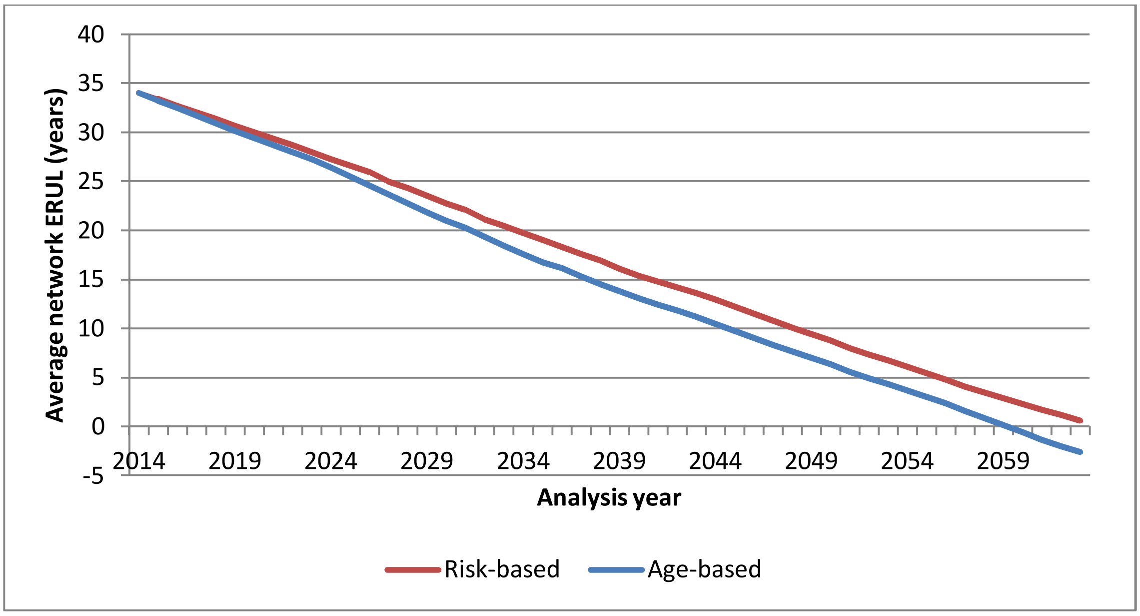


Figure 5-27: Age-based replacement - Average network ERUL

5.3.3 ERUL-based replacement

In order to simulate ERUL-based replacement, the ERUL of each pipe, is sorted in ascending order to produce the prioritised list for every analysis period. All other eligibility tests are applicable. The number of failures predicted, total SID and average network ERUL are compared in Figure 5-28, Figure 5-29 and Figure 5-30, respectively and the results indicate that the risk-based replacement is more efficient than ERUL-based replacement.

Figure 5-28 shows that the number of failures reported for the risk-based replacement is lower than the failures for the ERUL-based replacement, with ERUL -based replacement resulting in lowest number of failures for all of the supplementary replacement procedures used in this research.

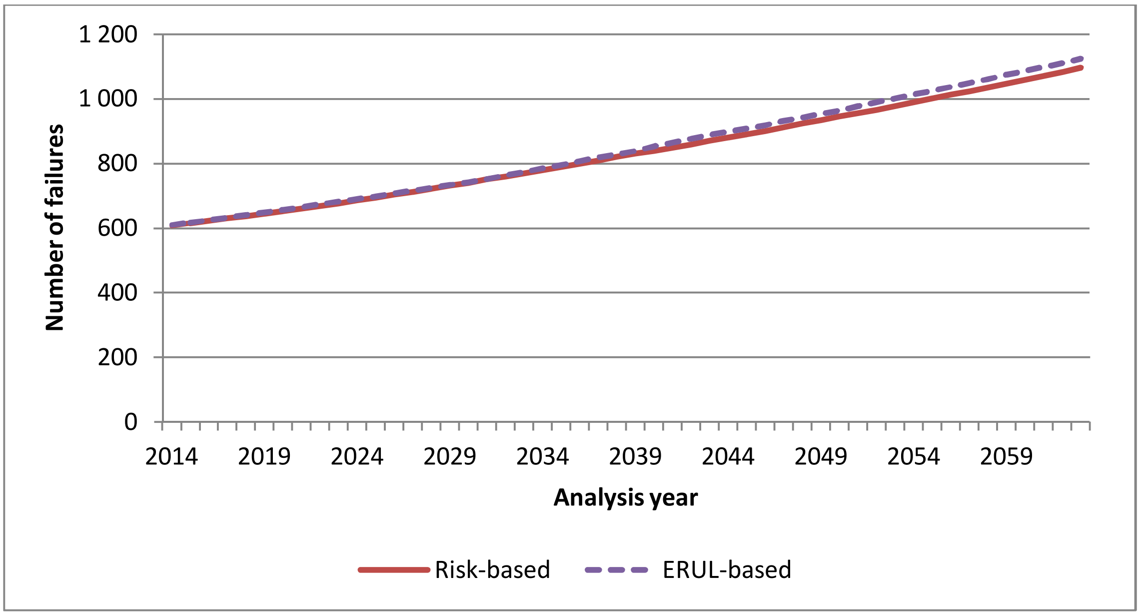


Figure 5-28: ERUL-based replacement - Failures predicted

Figure 5-29 shows that the total SID steadily increases over the total analysis timeframe for the ERUL-based replacement, whereas the risk-based replacement resulted in a more stable total SID value, ranging between 20 and 25 minutes, for the majority of the analysis.

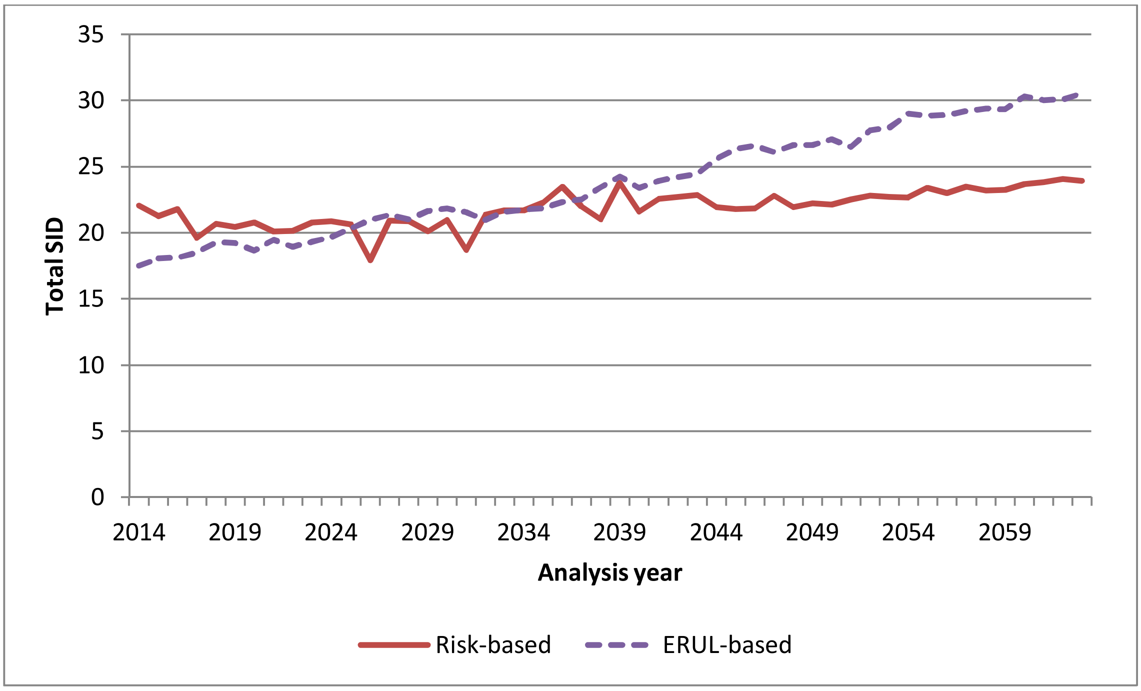


Figure 5-29: ERUL-based replacement - Total SID

Figure 5-30 shows that the average network ERUL is higher at the end of the analysis timeframe for risk-based replacement than for ERUL-based replacement.

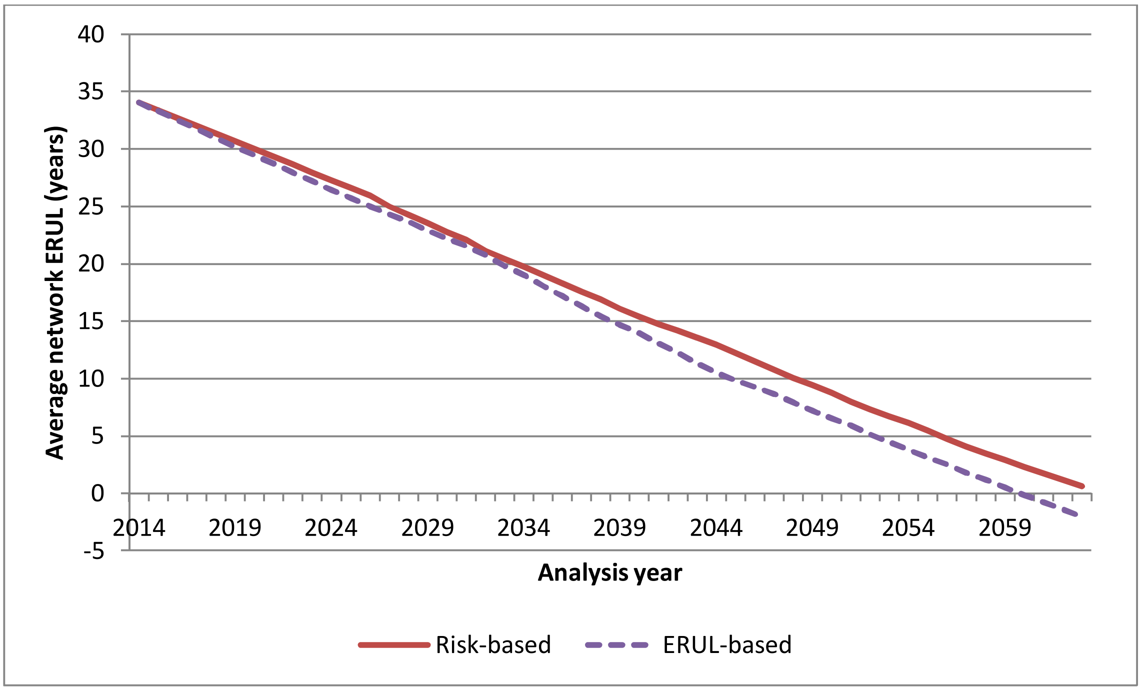


Figure 5-30: ERUL-based replacement - Average network ERUL

5.4 Investment strategy comparison for case study

An analysis period of 50 years was chosen to evaluate the long term effects of investment strategies and compare the results to a reactive strategy where no replacement budget is available. The REP is also chosen as 50 for all materials to ensure that no recurring pipe replacement occurs in the analysis. The current investment strategy employed for the case study is to replace 1% of the network per year. The available data for the case study as discussed in 5.1 was used as the input data for each of the scenarios. The failures for each of the diameter groups, for all scenarios, are given in Table 5-20.

Table 5-20: Base failure input per diameter group

Diameter group	**Description**	**Failure rate (#/100km/year)**	**Length (km)**	**Input: Failures per year**
Diameter group 1	small	3.25	1785	**58**
Diameter group 2	medium	1.8	314	**6**
Diameter group 3	large	0.9	131	**1**

The investment scenarios that were performed are briefly discussed below and all results are given in Appendix D.

5.4.1 Investment scenarios

Table 5-21 provides a brief description of the investment scenarios that were modelled and results compared.

Table 5-21: Summary of investment scenarios

Investment scenario	Description	AARB (C_r)
Reactive strategy	The AARB is set to zero. Therefore this is the baseline scenario where no replacement occurs and only operational costs are incurred.	0
1:100 budget	The AARB is calculated as 1% of the total replacement value of the network (46 657 559 C_r) in order to test the status quo strategy for the utility. The available budget could result in total replacement of the system in 100 years.	466 576
1:50 budget	In order to test a larger spend strategy, the AARB is calculated as 2% of the total replacement value of the network. The available budget could result in total replacement of the system in 50 years.	933 152
Failures allowed	In order to determine the required annual budget to keep the number of failures constant at 65 failures per year, the AARB is set to a value larger than the total replacement value of the network and the failures allowed parameter is set to 65.	50 000 000
Combination	In order to test the 1:100 budget scenario in combination with additional restriction parameters, the length allowed parameter is set to 22,3 km (1% of the total network length), the failures allowed parameter is set to 65 and the planned SID allowed parameter is set to 5.00.	466 576

5.4.2 Result comparisons

The analysis results of the investment scenarios in Table 5-21 are given in Appendix D. This paragraph provides a brief discussion on the comparison of the analysis results for the '1:100 budget', '1:50 budget', 'Failures allowed' and 'Combination' investment scenarios in terms of costs and other PI's.

A comparison of the annual CAPEX is given in Figure 5-31. Near full budget utilisation is achieved for the '1:100 budget' and '1:50 budget' scenarios. Large fluctuation in the CAPEX is visible for the 'Failures allowed' and 'Combination' scenarios due to influence of the eligibility parameters. Throughout the analysis timeframe the CAPEX of the 'Failures allowed' scenario is less than that of the '1:50 budget' scenario, which means that with the latter scenario there is adequate replacement to reduce the number of failures as can be seen in Figure 5-32.

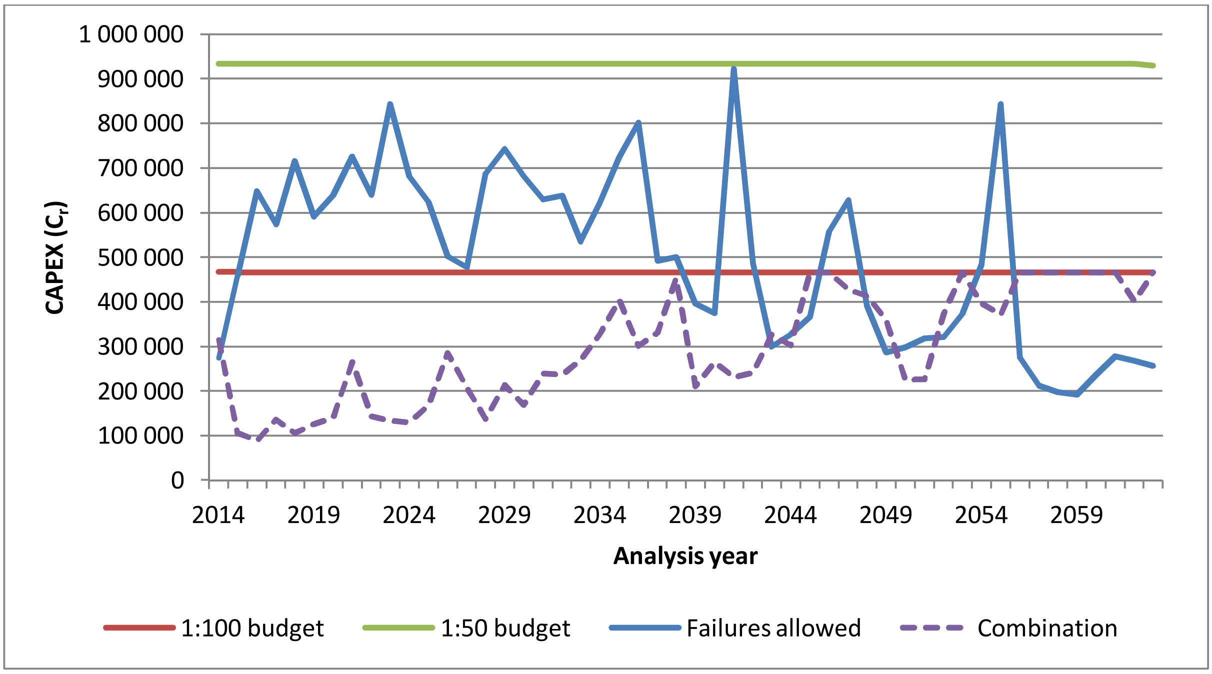


Figure 5-31: Comparison of annual CAPEX for investment scenarios

A comparison of the total annual number of failures is given in Figure 5-32. The results indicate that the '1:100 budget' shows promising results for "controlling" the number of failures when compared to that of the 'Failures allowed' scenario over a 50 year period, because after a gradual increase in the number of failures, a downward trend is experienced from year 2051 to 2060. The 'Combination' scenario offers the least "control" for the number of failures, which can be expected when it is considered that it represents the investment scenario with the lowest CAPEX, as seen in Figure 5-31.

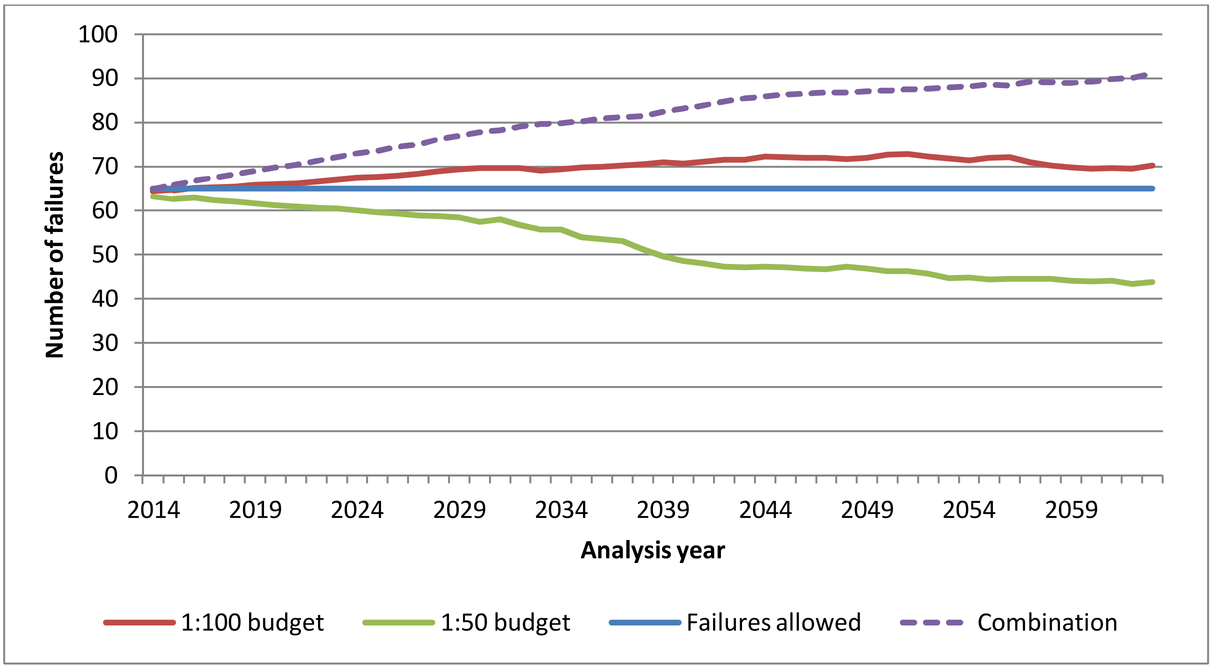


Figure 5-32: Comparison of annual number of failures for investment scenarios

A comparison of the annual OPEX is given in Figure 5-33. The OPEX generally follows the same trend as for the number of failures as seen in Figure 5-32, however it is worth noting that both the '1:100 budget' and 'Failures allowed' scenarios indicate a downward trend for OPEX. This can be explained if one considers the repair cost as presented in Table 4-2.

The repair cost for the AC material is higher and as many of these pipes have low ERUL values (refer to Figure 5-7), they will have high LF values which will increase their PRF and will therefore be prone to replacement candidacy. These pipes are then replaced with a more desirable material (refer to paragraph 5.1.9 and consider Table 5-8 and Table 5-10) which have lower repair costs. Therefore, even with constant failures ('Failures allowed') or a slight increase in number of failures ('1:100 budget') the OPEX is able to decrease as seen in Figure 5-33.

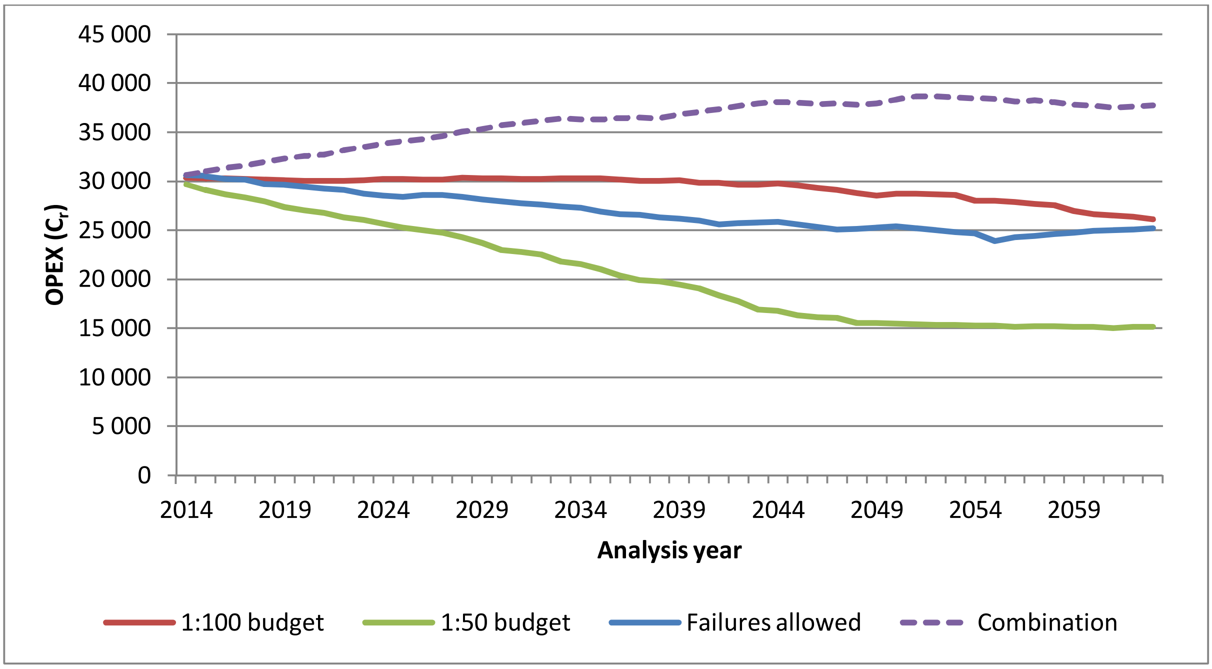


Figure 5-33: Comparison of annual OPEX for investment scenarios

A comparison of the annual total SID is given in Figure 5-34. The high total SID values in the first 10 analysis years for the investment scenarios, excluding the 'Combination' scenario which has a SID restriction, is due to the high consequence pipes which will have high priority ranks and therefore be replaced.

The high consequence is in many cases attributed to the high number of consumers (households) that will be affected in case of failure and the SID is highly dependent on the number of affected consumers (refer to Equation 14 and Equation 15). The spikes in the SID for the '1:150 budget' scenario, seen from years 2047 to 2051, is attributed to the replacement of lower risk pipes with a high number of affected consumers, which are not replaced by any of the other scenarios due to the inferior available budgets.

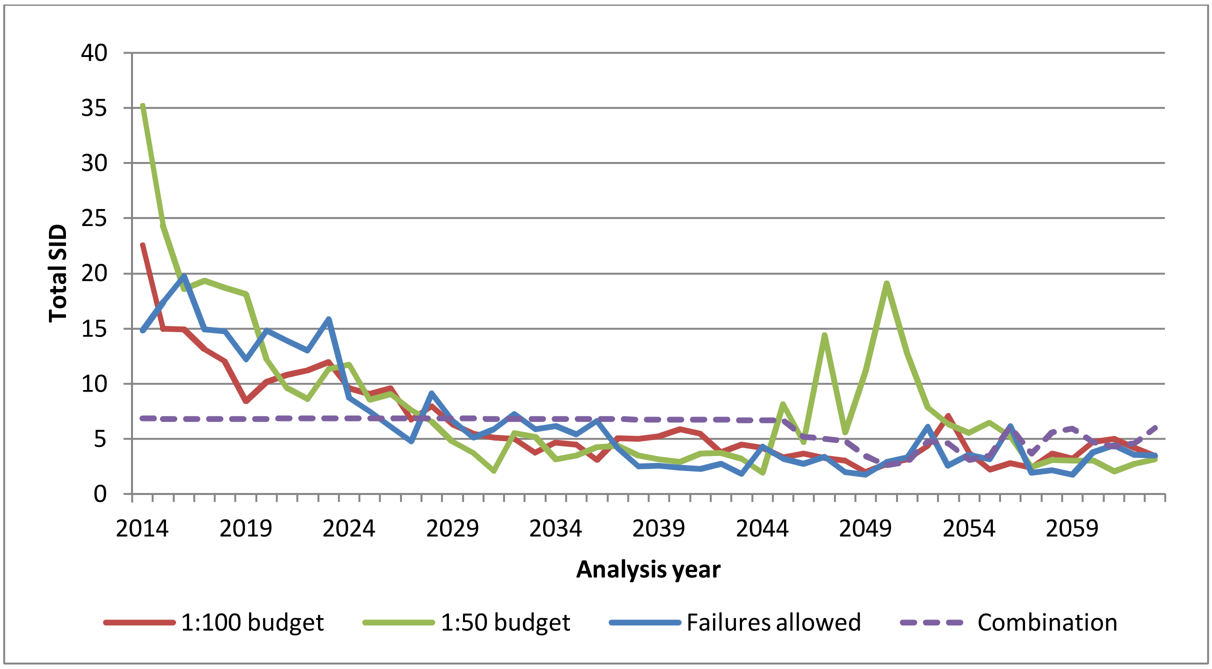


Figure 5-34: Comparison of annual total SID for investment scenarios

A comparison of the annual ERAV is given in Figure 5-35. All the investment scenarios, excluding the 'Combination" scenario, show improvement in the ERAV after the 50 year analysis period. It is worth noting that although the 'Combination' scenario has a decreased ERAV after the 50 year analysis, an upward trend is visible from year 2034.

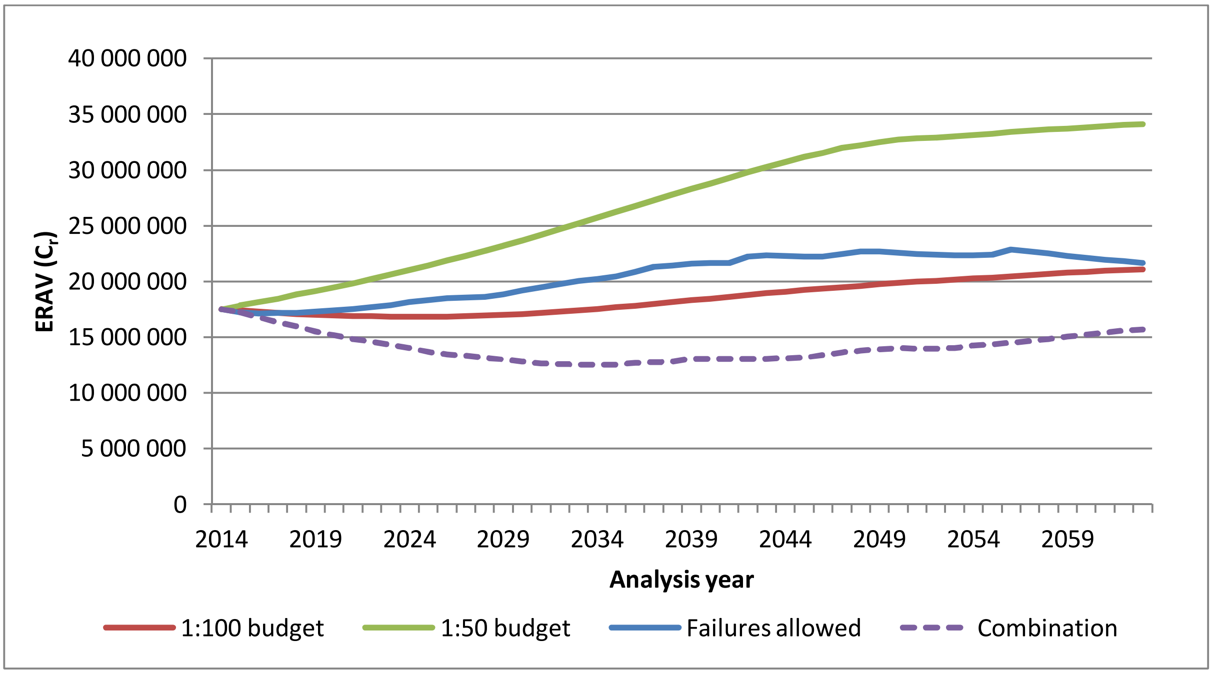


Figure 5-35: Comparison of annual ERAV for investment scenarios

A comparison of the total cumulative expenditure (TCE), the sum of CAPEX and OPEX, is given in Figure 5-36 which reveals the lowest TCE scenario as the 'Combination' scenario and the highest TCE scenario as the '1:50 budget' scenario.

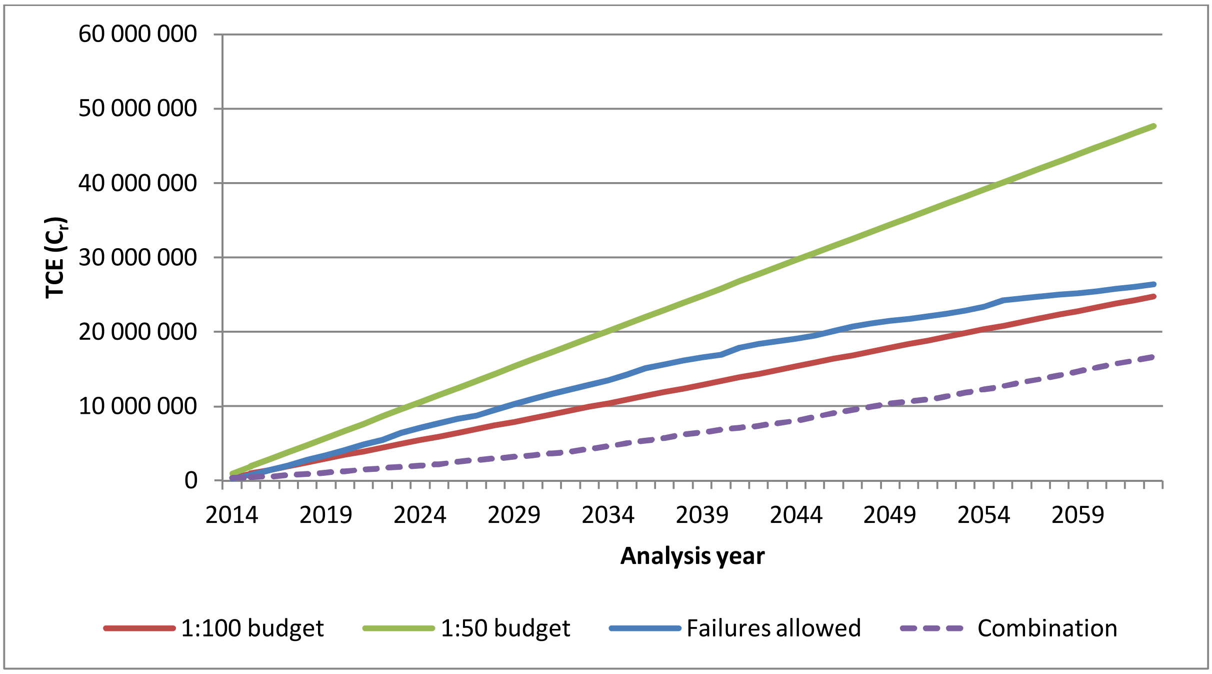


Figure 5-36: Comparison of TCE for investment scenarios

A comparison of the difference in ERAV and TCE is given in Figure 5-37 and reveals that the 'Combination' scenario seems to yield the most desirable result when network value and total expenditure are compared even though the ERAV at the end of the analysis period is the lowest for the 'Combination' scenario, as seen in Figure 5-35. The results also indicate that the expenditure from the '1:50 budget' scenario is much greater than the resultant benefit, represented by the increase in ERAV for the network.

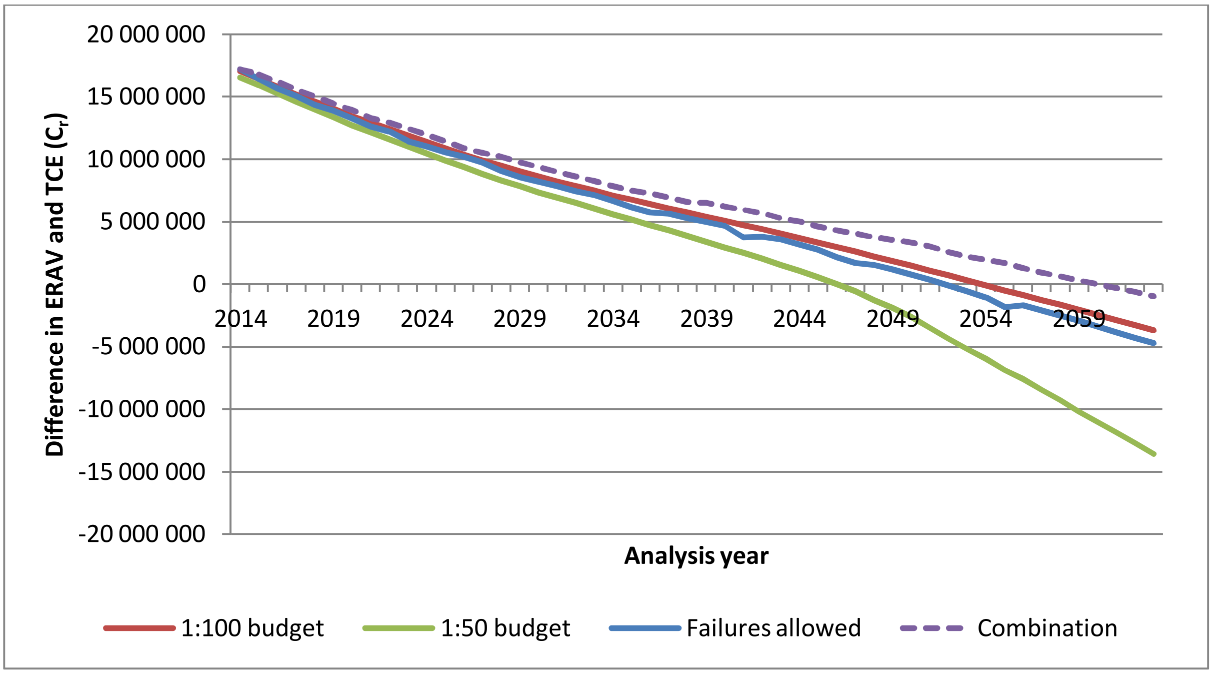


Figure 5-37: Comparison of the difference in ERAV and TCE for investment scenarios

A comparison of the annual average network ERUL is given in Figure 5-38. The 'Combination' scenario has the least desirable results, as it results in the lowest ERUL of all investment scenarios, but does however start to show an upward trend from year 2044. This upward trend indicates that even the least desirable investment scenario, with regards to ERUL, offers some "control" for network age.

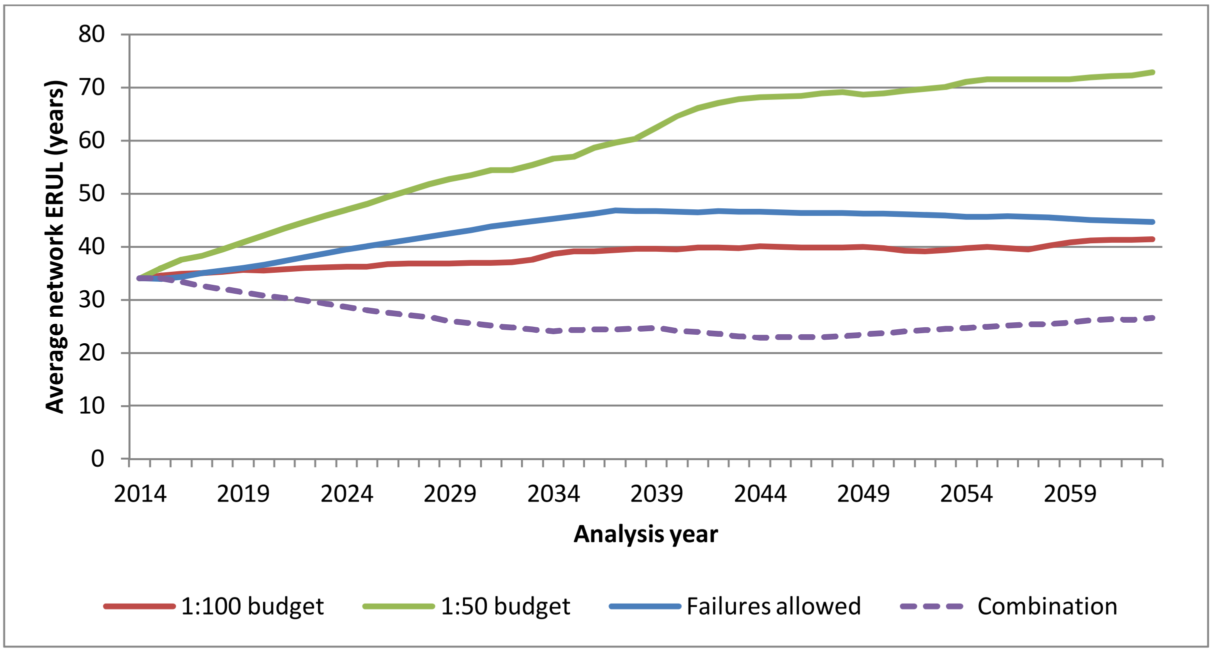


Figure 5-38: Comparison of annual average network ERUL for investment scenarios

Finally, a comparison of the cumulative replacement length is given in Figure 5-39. For the '1:50 budget' scenario, all pipes (2 229,37 km) have been replaced after the 50 year analysis period and all pipes in the network are either of DI, PE or PVC material. The results show that for the '1:100 budget' scenario, 50.51% of the total network length has been replaced after 50 years, which amounts to an additional 11,41 km of pipe over and above the expected length of 1 114,69 km (half of the network length), which is coincidentally reached after 49 years.

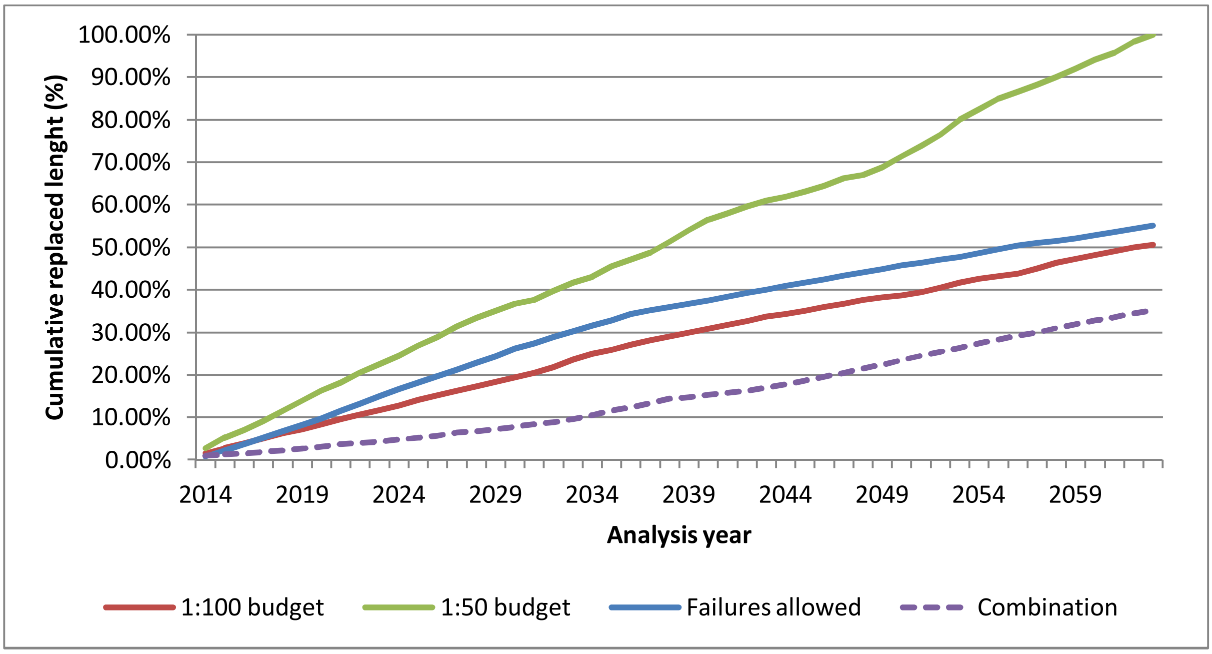


Figure 5-39: Comparison of cumulative replacement length as percentage of total length

5.4.3 Best-fit solution

From the result comparisons and discussions in paragraph 5.4.2, it can be seen that the choice of investment scenario depends on the goal of the decision maker, as there are multiple PI's to consider in addition to available funds. To find the best-fit solution when comparing investment scenarios across multiple PI's, the following comparison methodology was established.

For each of the scenarios a comparison with the reactive strategy (AARB = 0) is conducted and the difference in TCE, number of failures and total SID for the analysis, as well as the difference in the ERAV and ERUL at the end of the analysis, are calculated. For each of the PI's the values are transformed into indices between zero and one (0-1), with one assigned to the most favourable result and zero assigned to the least favourable. The remaining indices (two in this case study) are then calculated relatively by considering the absolute difference between the most and least favourable options.

A weight is assigned to each of the PI's, which can be described as the minimisation of TCE, number of failures and total SID and the maximisation of the ERAV and ERUL. Each weight is then multiplied with the relevant index and all are summed to produce the decision index, called the Best-fit index in this research. The highest resulting value will be the best-fit solution for the assigned weights.

In order to demonstrate the index calculation methodology, the calculation of the TCE index is presented. The 'Reactive strategy' has a TCE = 2 304 426 C_r and the difference between each scenario's TCE and that of the reactive strategy (dE) is shown in Table 5-22. The most favourable result in this case would be the result for the 'Combination' scenario as it has the lowest dE value, with the '1:50 budget' scenario the least favourable result. The 'Combination' scenario dE value would thus be assigned a TCE index = 1 and the '1:50 budget' scenario a TCE index = 0. Figure 5-40 illustrates how the remaining two scenarios' TCE indices are determined.

Table 5-22: Comparison of TCE with reactive strategy

Scenario	TCE (C_r)	dE (C_r)
1:100 budget	24 792 255	22 487 830
1:50 budget	47 672 454	45 368 028
Failures allowed	26 372 219	24 067 793
Combination	16 674 052	14 369 627

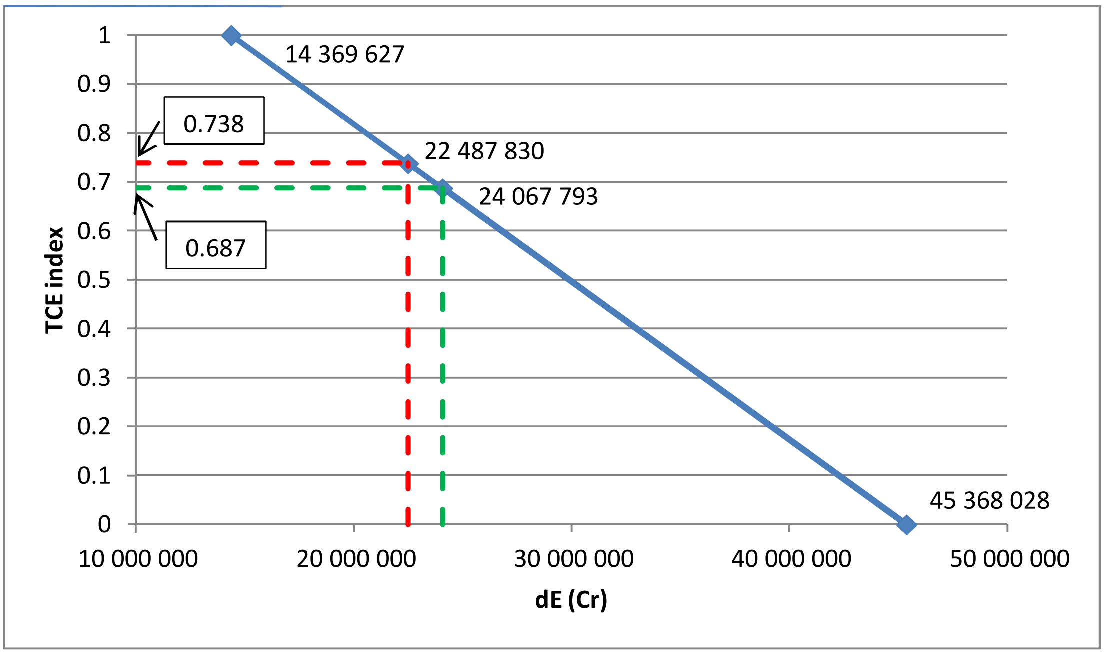


Figure 5-40: Calculation of TCE index

Likewise, Figure 5-41 illustrates the calculation of the Failures index. The reactive strategy yields the highest number of total failures amongst all scenarios as expected, because there are no pipe replacements to curb the growth of failure due to ageing infrastructure. In this case the greater the difference in number of failures the better. Appendix E provides the results used to determine the comparative values used for the calculation of the indices for each scenario.

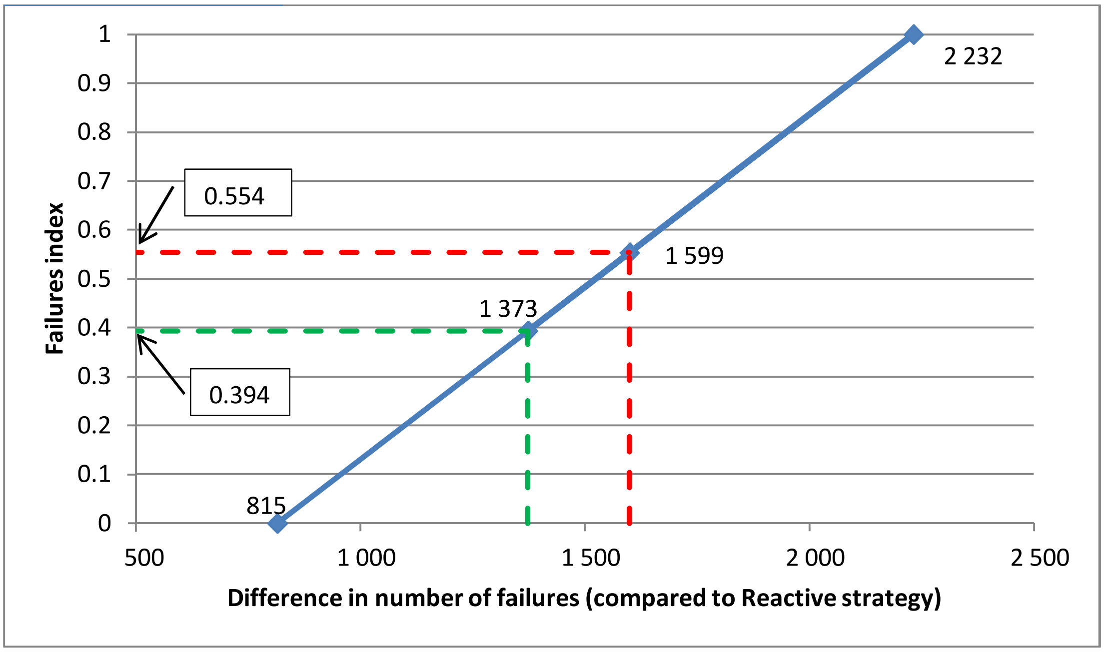


Figure 5-41: Calculation of Failures index

Table 5-23 shows three examples of weighting schemes. The three weighting schemes shown were chosen as each resulted in a different scenario selected as the best-fit solution with the proposed methodology. Table 5-24, Table 5-25 and Table 5-26 show the results for the best-fit solution, for which the individual indices are the same, with the three weighting schemes as presented in Table 5-23, with all comparisons of values given in Appendix E

Table 5-23: Weighting scheme examples for comparison of best-fit solution

Performance indicator	Weighting scheme		
	Scheme 1	Scheme 2	Scheme 3
TCE	20.00%	33.33%	50.00%
Number of failures	20.00%	16.67%	12.50%
Total SID	20.00%	16.67%	12.50%
ERAV	20.00%	16.67%	12.50%
ERUL	20.00%	16.67%	12.50%
TOTAL	100.00%	100.00%	100.00%

Table 5-24 shows that for weighting scheme 1, the best-fit solution is the ‘1:50 budget’ scenario, with a Best-fit index of 0.600

Table 5-24: Best-fit solution - weighting scheme 1

Scenario	TCE index	Failures index	SID index	ERAV index	ERUL index	Best-fit index
1:100 budget	0.738	0.394	0.815	0.294	0.320	0.512
1:50 budget	0.000	1.000	0.000	1.000	1.000	**0.600**
Failures allowed	0.687	0.554	0.787	0.324	0.391	0.549
Combination	1.000	0.000	1.000	0.000	0.000	0.400

Table 5-25 shows that for weighting scheme 2, the best-fit solution is the ‘Failures allowed’ scenario, with a Best-fit index of 0.572.

Table 5-25: Best-fit solution - weighting scheme 2

Scenario	TECE index	Failures index	SID index	ERAV index	ERUL index	Best-fit index
1:100 budget	0.738	0.394	0.815	0.294	0.320	0.550
1:50 budget	0.000	1.000	0.000	1.000	1.000	0.500
Failures allowed	0.687	0.554	0.787	0.324	0.391	**0.572**
Combination	1.000	0.000	1.000	0.000	0.000	0.500

Table 5-26 shows that for weighting scheme 3, the best-fit solution is the ‘Combination’ scenario, with a Best-fit index of 0.625.

Table 5-26: Best-fit solution - weighting scheme 3

Scenario	TCE index	Failures index	SID index	ERAV index	ERUL index	Best-fit index
1:100 budget	0.738	0.394	0.815	0.294	0.320	0.597
1:50 budget	0.000	1.000	0.000	1.000	1.000	0.375
Failures allowed	0.687	0.554	0.787	0.324	0.391	0.601
Combination	1.000	0.000	1.000	0.000	0.000	**0.625**

The three weighting schemes illustrate how, as the weight for minimisation of TCE increases, the best-fit solution tends toward the selection of a scenario with a lower total investment cost in the analysis period. However, although the ‘1:100 budget’ scenario has a higher TCE index than the ‘Failures allowed’ scenario, which means that the ‘1:100 budget’ results in a lower TCE, the more favourable outcomes for the other PI’s result in the ‘Failures allowed’ scenario to be a more favourable investment strategy overall for the three weighting scheme examples presented.

6 Conclusion

6.1 Findings from literature

Studies have shown that pipe age, material and diameter, although not causes themselves, are good estimators of pipe deterioration (Pelletier, et al., 2003; Misiunas, 2005; Wood and Lence, 2009). These surrogate factors are therefore used as explanatory factors that lead to pipe failure. All the factors that influence corrosion, for instance, vary with time and are not always recorded – the same applies for dynamic loading, such as traffic and soil movements, for which pipe age acts as a surrogate factor. Material types react in different ways to environmental influences and have different strength characteristics, whereas pipes with smaller diameters generally have reduced wall thickness and pipe strength.

Capital replacement budgets need to be properly planned years in advance in order to obtain finance and pipes should be prioritised for replacement to make valid business cases for funding through capital improvement programmes. Risk-based prioritisation can give the manager an idea of the risk associated with a pipe and therefore give insight into short term mitigation requirements; however it does not sufficiently inform on the long-term investment requirements to improve overall system health, such as remaining useful life and other performance indicators such as expected operational expenditure and service interruption.

6.2 MPM tool

An existing method for the “once-off” pipe risk prioritisation in water distribution networks was expanded with this research into a multi-period prioritisation replacement model (MPM). The use of the MPM is feasible as it could aid in decision-making processes aimed at determining the required budgets for replacement and refurbishment projects of a municipality’s water distribution pipe network infrastructure. An algorithm to forecast the number of expected pipe failures in a water distribution system was developed and used to estimate the operational expenditure, in terms of relative credit values, and service interruption of a case study pipe network.

Replacement rules regarding the choice of replacement material and diameter were introduced to reflect operational procedures. In order to limit the cyclical replacement of pipes with a high CF value, the REP parameter was added which ensured that a pipe could only be eligible for a second replacement in the analysis after a certain number of periods. Additional eligibility factors were introduced and could be used to restrict replacement or determine required budgets.

Additional replacement prioritisation procedures, namely random pipe replacement, age-based replacement and ERUL-based replacement, were used to validate the efficiency of the risk-based prioritisation method over an extended analysis timeframe. The results of the MPM, as applied to a case study, were compared with one another to determine if the risk model provided satisfactory prioritisation results for use in a replacement model in relation to other prioritisation approaches. For the case study, the validation tests revealed that the risk-based replacement yielded more favourable results over the extended analysis timeframe compared to the other prioritisation approaches provided. Particularly noticeable was that the average network ERUL was lower for the risk-based replacement approach compared to that of the ERUL-based prioritisation. This observation is explained when the results are considered (See Appendix C), which show that a greater length of pipe was replaced with risk-based prioritisation than with ERUL-based prioritisation; the difference in the replaced length of the small diameter group pipes is especially noticeable. The greater replaced length affects the average network ERUL calculation because it is calculated as a length-weighted mean value. The combination of the small diameter pipes' higher PRF values due to the higher likelihood of failure and also the lower replacement cost is attributed to the greater length of replacement for the small diameter pipes.

Four hypothetical investment scenarios (or strategies) were analysed for the case study and compared to one another by evaluating the results in relation to a reactive strategy where no pipe replacement occurs. A template was established wherein the relative weight of the PI's, which act as decision variables, are entered and the best-fit solution is calculated. The decision variables included in this research consist of cost, number of failures and SID, all of which are to be minimised, as well as ERUL and ERAV, which are to be maximised. The results from the investment strategies yield useful results, but it is imperative to understand the ultimate goal, not only in order to assign the relevant weights to each decision variable, but to confidently assess whether an investment strategy should be considered for comparison. For example, it should be understood whether the goal is to control ERAV and ERUL or to improve upon it. The comparison of results (paragraph 5.4.2) indicated that all the scenarios offered some degree of "control" of the ERAV and ERUL decision variables, as there is no scenario which yields a continuous decline throughout the analysis period, with upward trends observed near the end of the analysis for even the least desirable scenario ('Combination'). However, the high cost investment strategy ('1:50 budget') offers vast improvement for the ERAV and ERUL over the analysis period, compared to the other investment strategies, and would therefore heavily skew the results in the calculation of the best-fit solution in its favour if high weights are given to these two decision variables.

It is however worth mentioning that the results are based on a single case study and that the MPM tool requires further verification with additional case studies.

6.3 Future investigation and improvements

In addition to verification through additional case studies there are several improvements that can be introduced to improve the MPM tool. This section provides ideas for possible future research based on the research conducted as part of this thesis.

A requirement that could be of help on datasets with extended failure records is the allowance of unlimited diameter groups and extension to allow for diameter groups per material or material group and also to specify the failure rate associated with a group instead of the number of base failures.

An improvement that could be of benefit for scheduled replacements, especially short-term projects, is the allowance of replacement cost substitution for the scheduled pipes as these projects have typically gone through detailed costing exercises and have been approved as such which could significantly alter the remaining replacement budget.

Investigation is required for the calculation of remaining useful life (RUL) of a pipe which is a better reflection of pipe condition than the age-based ERUL value. Subsequently, the RUL value would also replace the ERUL value in the depreciated asset value calculation.

The replacement model could be improved by restricting all pipes based on the REP variable and not only the pipes that have been selected for replacement during the analysis. Another consideration could be the introduction of an additional eligibility factor to restrict replacement based on ERUL for those pipes that have not been replaced during the analysis, for example only pipes with ERUL ≤ 20 years is deemed eligible for replacement.

Further decision-tree branches could be included in the decision rules in order to determine whether replacement or inspection should occur based on risk group quadrant or high priority pipes with low ERUL values. Further inputs will be required such as inspection rule tables as well as inspection cost tables.

Investigation into the determination of the start and end points of the different phases presented in the "bath-tub" curve for a water distribution network as a whole, or based on individual characteristics such as material and diameter. This will allow for improvements in the failure algorithm to take different phases of the "bath-tub" curve into account based on the age, material and diameter of the pipes.

The pipe inventory database could be connected to a geographic information system (GIS) for a spatial representation of the pipe data which will aid the grouping of pipes to form replacement schedules. A GIS connected database could further assist in the grouping of pipes into reporting groups and therefore further investigation and improvement is required to expand the MPM tool to report on, and replace pipes, based on group risk calculated from individual pipes.

The application of the MPM tool for different asset types could also be investigated, each of which would have specific replacement rules associated with the asset type.

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Appendix A: MPM process steps

Appendix B: Robustness test results

Appendix C: Validation test results

Appendix D: Investment scenario results

Appendix E: Best-fit solution comparisons