Integrated Asset Management Systems

for Water Infrastructure

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

Signature: …………………………………………………………..

ABSTRACT

Owners of infrastructure assets have responsibility for the management of a diverse portfolio of civil engineering assets. These assets make up the foundations of modern society and are arguably pivotal in the economic growth and wellbeing of a nation. It is of no surprise therefore, that asset management business practises have risen in popularity as the UK's infrastructure asset base continues to grow and inevitably ages with time.

In the context of water and waste water infrastructure assets, which communities rely upon for health, economy and environmental sustainability, it is widely acknowledged that these assets have historically suffered from underinvestment. Whilst funding shortfalls have been evidenced historically, through the inadequacy of infrastructure to meet the needs and challenges of the past, it is of great concern that infrastructure expenditure is reducing in real terms as a result of the global financial crisis.

This is leading to a widening funding gap between the available and the required finances for infrastructure investment which is further compounded by natural phenomena and human behaviours, i.e., climate change, population growth and urbanisation. To further intensify the problem, asset planning and management in the water industry is considered a complex and challenging discipline because of high interdependencies and the vast quantity of assets themselves.

In acknowledgement of this global position, this thesis seeks to address some of the key challenges faced by utility companies in the adoption of asset management best practice across water and waste water assets, namely:

- Operational decision making - the efficient and effective specification of least-cost rehabilitation programmes from condition information that ensure behavioural alignment with an organisations strategic objectives.

- Tactical decision making - achieving risk based asset level inspection prioritisation that considers serviceability performance, for two particularly challenging asset groups: i.) High value - low volume assets and ii). Low value - high volume buried infrastructure.
- Strategic decision making - identifying optimal long-term investment plans and asset management policies for assets that have previously not benefited from such technological advancements.

To improve upon operational decision making, the author capitalises on the availability of condition inspection information for buried sewerage infrastructure by applying advanced optimisation techniques to help form an environment where the decision makers is presented with an array of optimal rehabilitation solutions. The trade-off curve that is presented uniquely evaluates solutions for the benefits they offer in-terms of: condition improvement, cost and operational performance. A financially favourable comparison (up to 45% saving) is drawn between the optimisation results which are automatically generated by the model and those that have been developed manually by experienced engineers in a 'real world' case study. However, it could be argued that the greatest benefit arises from the trade curve of feasible solutions which are presented to the decision maker across a range of investment levels.

In recognition that tactical and strategic decision making have been the focus of a substantial amount of research for commonly found infrastructure assets, i.e., public sewers and water mains, a focus has been placed on improving upon and adopting best practise across infrastructure assets which have not previously benefited from the technological developments across these decision making levels.

Firstly, a methodology for translating standardised condition inspection information into more meaningful reliability scores, to support risk based planning and decision making, is presented for service reservoirs. A service reservoir can be regarded as high value- low volume infrastructure asset and would typically have its condition evaluated between 1 (poor) to 5 (good). A case study demonstrates how this new reliability scoring mechanism has been

successfully applied during a typical structural condition survey. The output from this process is a fully document reliability assessment for each component of the service reservoir. The output can be aggregated to provide an overall reliability assessment for the structure and/or used to target specific remedial works to troublesome components.

Secondly, two methodologies are presented which address the fact that high volume – low value infrastructure assets across both the water distribution and wastewater collection networks, are typically less well understood and often sub-optimally managed in comparison to more critical or higher value assets.

1. A methodology has been developed to help UK water companies overcome the recent legislative changes associated with Section105A of the Water Act; which has transferred ownership of the private sewer network to UK water companies. The new methodology which has been developed, has allowed one of the UK's water and sewerage companies to initiate a proactive asset management programme with the aim of addressing the deteriorating condition of these assets whilst also tackling their associated serviceability performance. Initially, a number of GIS tools are used to provide an estimate of the likely extent of the transferred network before a well-established public sewer deterioration model is used to predict the condition and operational performance of these S105A assets over time.

2. A novel deterioration modelling framework is developed by coupling the latest geospatial technologies with statistical deterioration modelling techniques. The modelling framework is specifically applied to small diameter water distribution assets (25-50mm diameter), known as communication pipes, which connect individual properties to the water distribution mains. Reliability curves are developed from failure data provided by two UK based Water Companies that have captured specific communication pipe failure records since 2001. The deterioration modelling curves and supporting data are compared and contrasted to demonstrate the robustness of this modelling approach, which is shown to be capable of modelling failure rates to a high degree of accuracy. This was validated by

comparing the predicted number of failures against three years of failure data not used during the model building process. The yearly failure counts were predicted to within +/-5% accuracy and the overall cumulative modelled failure count at the end of 2014 was predicted within 1%.

To conclude, the successful deterioration modelling tools for communication pipes are explored further, via the development of a strategic whole life cost optimisation framework for these assets. The outputs from the previous geospatial mapping tool are used alongside the calibrated Weibull deterioration curves to drive a whole life cost and performance analysis. Against this improved understanding of whole life costs, an optimisation algorithm is used to evaluate the trade-off between whole life costs (totex) and the prevention of future asset failures (serviceability). The model successfully identifies optimised investment policies according to the decision maker’s priorities which is evidenced in a case study that shows outperformance against existing maintenance policies for these assets. Financial savings in the region of £8.5M, or the prevention of 1,320 asset failures, were shown to be possible over a 25 years planning horizon in the case study.

For the avoidance of confusion, the term ‘integrated’ is considered from the perspective of the three decision making levels associated with the management of an asset, namely: strategic, tactical and operational decision making. Therefore, data quality improvements and the management of information transactions between decisional levels are inherently considered within all of the methodologies developed in this thesis.

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Finally, to my wife and son, to whom this thesis is dedicated – I look forward to seeing you both again at weekends!

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

1 INTRODUCTION

In 2012, The World Bank acknowledged that all countries are facing an increasing funding gap between the available finances and those that are required to deliver the necessary rehabilitation, operation and maintenance of ageing water infrastructure. Across developed countries alone, the investment requirements are approximately £68 billion per annum, a cost which is ideally recovered by the utility company such that they remain in a financially stable position and which in-turn enables them to continually invest in infrastructure renewal and maintenance (Rodriguez et al., 2012).

At the end of 2014, the water industry regulator for England and Wales reported the total estimated capital value of fixed tangible assets in the possession of all water and sewerage companies in England and Wales to be £254.8 billion (Ofwat, 2015). According to the same source, the planned total annual capital investment across the industry between 2010 to 2015 was £22 billion, of which £12.9 billion was allocated for maintaining and replacing assets (Ofwat, 2009b).

Worryingly, it is expected that these current levels of investment in the UK water industry will be inadequate in the long-term as our aging infrastructure networks continue to fail at an ever-increasing rate (Urquhart, 2006). Furthermore, UK water companies have been put under increased political pressure to reduce customer's bills in real-terms, thereby, limiting infrastructure investment further. An example being the previous price review, 2010 to 2015, where Ofwat set the price limits water companies can charge customers to a maximum of 2009 levels (Ofwat, 2009). It is expected that the next price review period (2015-2020) will be equally as challenging. In addition, this challenge will be magnified by the increasing pressures from other regulatory bodies seeking environmental and customer serviceability performance improvements.

Attracting infrastructure investment from the private sector is also becoming more challenging due to the perceived risks and long pay back periods (Rodriguez et al., 2012). For example, water infrastructure is constructed to deliver a service life of at least 50 years, making the upfront capital costs very large and the payback periods very long. There are also inherent risks associated with the politicised nature of the industry, whereby uncertainty exists over the impact of political decisions from changing governments and external political pressures. A recent downgrading of investment ratings for all UK utilities by Brewin Dolphin plc, one of Britain's largest investment management firms, was cited on grounds of political risks in the industry (City AM, 2015).

The culmination of the above will undoubtedly place further tension between the *available* and the *required* finances in the water industry which can only be managed through the adoption of comprehensive asset management frameworks. Well-established and well-implemented asset management framework are capable of providing a positive impact across all areas of an organisation by increasing asset performance, decreasing asset outage times, reducing maintenance costs, boosting profits, delivering exceptional customer service for customers that aligns to local priorities and enhancing the reputation of the organisation (Faiz and Edirisinghe, 2009); (Federation of Canadian Municipalities and National Research Council, 2005); and (Institution of Civil Engineers, 2013). It is therefore understandable that asset management decision making is one area that water companies have been focusing on to help de-risk the industry and close the gap between the *available* and the *required* finances.

Advancements in strategic asset management, particularly for buried linear infrastructure, appear to have been concentrated towards the primary assets that make up the distribution and collection networks, Section 2.1.3. Literature within this field could not be found for less critical assets, such as those water pipes supplying individual customers and having diameters less than 50mm, or small diameter sewers laid between the main public sewer and the customers property. In fact, much literature which claims to be associated with "small diameter" water distribution pipework actually applies to assets greater than

100mm diameter, which often form a critical component of the water distribution or wastewater collection network themselves (Atkinson, et al., 2002; Marlow, et al., 2015).

Similarly, whilst the deterioration of small diameter sewers has been modelled previously, this work has primarily focused on the public sewer network which has been installed and maintained by the water utility company (Abraham and Wirahadikusumah, 1999; Baik, et al., 2006). This has therefore resulted in small diameter wastewater sewerage assets, i.e., the private sewer network, receiving significantly less attention. Although this is somewhat understandable, due to the fact that the ownership of these assets only recently transferred to the UK utilities in 2011 (Defra, 2011), water companies must react quickly to adopt best practise asset management techniques for these assets.

The same is true for small diameter clean water assets, i.e., communication pipes, which despite being under the ownership of the UK water utility providers since installation, it would still appear they are sub-optimally managed, Chapters 7 and 8. Initially, the author wrongly assumed that the shortfall in best practise asset management techniques for these assets was due to insignificant renewal and maintenance costs. This theory was however disproved upon an analysis of replacement activity across England and Wales between 2002 and 2010. The analysis showed an average renovation rate of approximately 130,000 assets/year, which in monetary terms would equate to a sizeable £100M capital investment per year (Ofwat, 2010). Thus, justifying the need for strategic asset management tools to be applied to low–value, high-volume infrastructure assets, because of the un-tapped benefits that the adoption of these techniques could bring. Even if these new tools were only fractionally as successful as similar techniques reported across other infrastructure assets groups, Deadman (2010), significant savings could be made.

In-order to realise the strategic asset management benefits, a detailed understanding of asset stock and likely future performance is firstly required (Vanier, 2000). However, for private sewers and communication pipes, this understanding is servery lacking and highly likely to be the reason for the very limited adoption of strategic asset management tools across these networks. Defra (2007) estimated the cost associated with improving this level of understanding in England and Wales, to be £188M for the private sewer network and it is believed that a similar level of investment would be required for the communication pipes. *This assessment is based on the authors eight years of experience in the water industry and a review of the extent of existing records in corporate GIS systems.*

Unfortunately, due to the aforementioned financial constraints and external pressures on water companies to reduce customer bills, it is likely that the required long-term investment in UK's infrastructure will not happen fast enough, as acknowledged by the Chairman of UK Water (WWT, 2013). This leads to the realisation that infrastructure assets will place greater strain on the long-term future of society, the environment and the economy. Unless, water companies are able to meet this challenge of achieving more value from their infrastructure assets from less available real-term finances (Ofwat, 2014a).

For assets that are well understood, i.e., public sewers and distribution mains, a 'more for less' approach is challenging enough. Whereas for small diameter buried infrastructure assets, which are poorly understood, the challenge is that much greater. Thus requiring methodologies to be developed that allow for the application of long term asset management planning techniques under limited data availability.

Reassuringly, a two-fold increase in public sewer condition inspection surveys across the UK between 2003 and 2010 is an indicator that a long-term strategic approach to asset management is being adopted for the more well understood infrastructure, (Ofwat, 2010)*. Therefore, the challenge for these assets lie in making best use of this increased condition inspection information through effective operational decision making. However, it would appear that little progress has been made to move the industry towards the adoption of more useful risk based scoring metrics and away from the original condition grade scoring systems of 1 (poor) to 5 (good).

** June Return information has ceased to be published in the public domain since 2010*

Therefore, in recognition of the potential benefits that improved asset management decision making can achieve, the overarching aim of this thesis is to develop a series of decision support tools and methodologies that can improve asset management decision making for water and wastewater assets.

Due to the immediate need for improved asset management practise in this area, a focus is placed on developing Strategic and Tactical solutions for less well understood infrastructure, i.e., private sewers and communication pipes. Whereas, Operational decision making improvements are focused on assets with high inspection rates (public sewers and service reservoirs), due to the availability of information and the direct uses for improved risk based decision making across the industry.

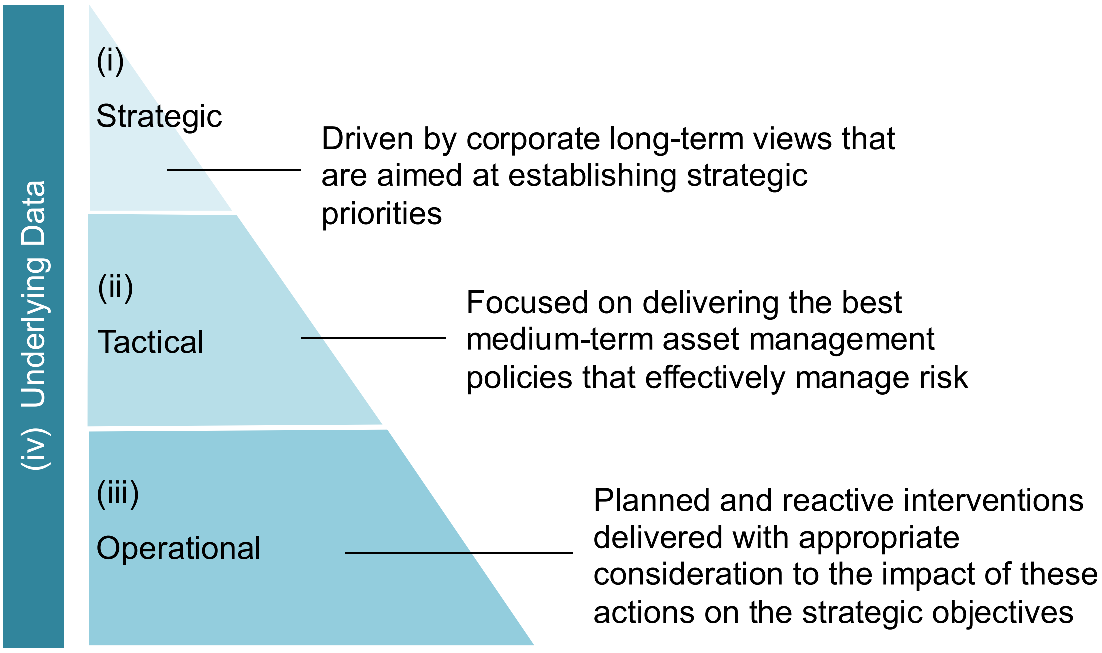

Figure 1-1. Asset management decision making levels

1.1 CHAPTER STRUCTURE

Following a literature survey, which was conducted to identify current research gaps, Chapters 3 to 8 are developed to demonstrate improvements against each of the more specific research challenges uncovered from the literature study. The structure for these chapters is as follows:

Background -	Prior to offering an improved methodology, the specific literature pertaining to the subject being reviewed is sought to be understood and documented.
Methodology -	Based on this understanding, areas for improvement are identified and new methodologies are developed to overcome this knowledge gap. This is achieved through the development of novel solutions or through the re-invention of established methodologies across different assets.
Case Study -	To demonstrate the effectiveness of the new methodology a case study is described which explains how the approach is implemented and attempts to quantify the benefits and outputs of the new approach.
Conclusion –	A conclusion is presented to summarise the research and suggest further work.
Research application* -	Finally, the methodology is reviewed for its readiness for real world deployment. In some cases, additional work has been undertaken to permit the use of the new methodology and/or the methodology is combined within an existing approach. In these instances the additional work is described in this section to explain the uses and benefits that this research has delivered.

** Research application addresses the specific requirements of an Engineering Doctorate (EngD), which is awarded for industrially relevant research.*

The research application section therefore focuses on the industrial applications of the research findings and specifically how these methodologies can offer a significant contribution to the industrial sponsors business. The industrial sponsor for this research has been AECOM, a global engineering consultancy seeking to explore the application of advanced and emerging techniques in real world asset management problems within the UK water industry.

2 LITERATURE STUDY

An overview of the more pertinent research concepts is provided in this chapter to help frame the objectives of this research. More specific and contextually relevant literature is cited within chapters 3 to 8 as the thesis goes on to address each of the asset management challenges in-turn.

2.1 INFRASTRUCTURE ASSET MANAGEMENT IN THE WATER INDUSTRY

Asset management has been defined in many different ways and by many different authors and organisations. The most closely aligned definition in the context of this thesis is from the US Federal Highway Administration who described asset management as:

> ““a systematic process of maintaining, upgrading, and operating the physical assets cost effectively. It combines engineering principles with sound business practices and economic theory to provide the tools necessary to facilitate a more effective, organized and logical approach toward *transportation* decision making” (Federal Highway Administration and American Association of State Highway and Transportation Officials, 1997)

Marlow and Burn (2008) expanded upon this definition by explaining that asset management is an all-encompassing term for the decisional levels associated with this practise, namely; strategic, tactical and operational decision making. Whereby strategic asset management refers to practises that adopt a long term view, as opposed to tactical and operational asset management which address the medium and short term challenges, respectively. Whilst this is a somewhat simplified overview of an asset management framework, it helps to contextualise the research conducted within each of the decisional levels, which are elaborated upon further in subsequent sections of this chapter.

2.1.1 Operational asset management

Since the 1950's the need for tactical and strategic planning of maintenance activities has become more widely recognised as the benefits of reliability centred maintenance were realised (Nel and Chelsom, 2007). Awwarf (2008) acknowledged that a significant proportion of work has already focused on the development of strategic and tactical modelling frameworks and that further work should be prioritised towards buried infrastructure assets which would benefit most greatly from improved operational decision making. Reassuringly, the UK water industry is already adopting a more planned and systematic approach to the maintenance of buried sewerage infrastructure assets. This is evidence through a two-fold increase in UK condition inspection rates between 2003 and 2010 (Ofwat, 2010). However, to be beneficial, this increased condition assessment data needs to be translated into effective operational decisions (McDonald and Zhao, 2010).

Furthermore, the importance of sound operational decision making based on the increased availability of condition information, has been recognised for its ability to help organisations progress more rapidly towards their long-term strategic objectives. This is in acknowledgment that all expenditure on physical assets are investments in the future and that poor decision making can negatively impact on an organisations long-term strategic objectives (Mcneil et al., 2008).

Therefore, the need for decision support tools to help ensure the selection and specification of the most efficient rehabilitation solutions from condition information is highly important. The EU funded CARE-S project was launched in Germany with the goal of helping sewerage engineers establish and maintain an effective management process for sewerage infrastructure (Baur et al., 2005; Saegrov, 2006). In a similar initiative, the Water Research Centre (WRc) in the UK launched a revised version of their Sewer Rehabilitation Manual, renamed Sewerage Risk Management, which provides detailed guidance of how to adopt an integrated and risk based approach for sewerage asset management (WRc, 2004b). Both methodologies focus on the need for the following three elements:

establishing long-term rehabilitation plans and policies (strategic), priority setting for rehabilitation (tactical) and choosing the right rehabilitation solution (operational).

A gap is observed in both methodologies surrounding the immediate and automated use of information from condition assessments, which both methodologies observe as being a critical component in the management of sewerage infrastructure. Baur et al (2003) goes someway to addressing this problem by offering a decision support tool that guides the engineer towards the most appropriate rehabilitation solution. However, the process is very rigorous and requires an engineers’ manual interpretation of the condition assessment in addition to substantial asset and rehabilitation technology information. The output from this process also lacks the ability to visualise the trade-off between localised repairs, full replacements or different types of rehabilitation technology.

Wirahadikusumah et al. (1998) provides a good overview of the more traditional condition assessment technologies that are used to capture the information needed for rehabilitation decision making. Although, the focus of this study was on the technologies themselves, the authors recognise the fundamental challenge associated with the specification of appropriate sewer rehabilitation solutions - the need for adequate information concerning the infrastructure itself. Since this research, Feeney et al. (2009) authored a white paper which comprehensively reviews condition assessment technologies and includes further information about more innovative inspection methods, i.e., Ground Penetrating Radar, Infrared Thermography, Micro-deflection and Acoustic wave technologies.

All of these developments primarily focus on delivering time and cost savings which are typically benchmarked against the cost and practicalities of CCTV inspections. Whilst there is definitely a market for these solutions, it is unlikely that the rehabilitation solutions themselves will be specified from inspections conducted from these technologies alone. Instead, it is felt that the greatest benefit in these technologies is the ability to rule-out more detailed investigations for non-defective assets. Inaccuracies associated with predicting the cost and benefit of inspection and rehabilitation interventions were also acknowledge as a critical knowledge gap in this white paper.

It can be seen that similar conclusions have been drawn from the aforementioned authors. Hereby, emphasising the need for technologies that can provide decision makers with a view of the costs and benefits associated with different levels of interventions. The ability for decision makers to understand the trade-offs that exist between the costs and benefits of multiple intervention options across a catchment, would assist in the delivery of operational decisions that align to the strategic objectives of an organisation; which is a fundamental requirement of asset management best practise (British Standards Institution, 2014).

2.1.2 Tactical asset management

Tactical asset management primarily focuses on the medium-term actions required to help an organisation move towards its longer-term strategic goals. It is applied at a finer level of detail than strategic asset management and therefore requires the prioritisation of specific assets (or cohorts of assets) for inspection, repair and maintenance (Marlow and Burn, 2008).

A review of approaches to sewer maintenance by Fenner (2000) concludes that in-order to be cost effective it is necessary for proactive inspection and maintenance programmes to be directed towards those assets which are shown to be most susceptible to early failure. Similarly, ISO 5500 acknowledges that it is necessary to thoroughly understand the potential impact of critical asset failure so that they can be managed and prioritised accordingly (British Standards Institution, 2014). Developing the framework and mechanisms to better understand and manage these critical assets typically falls within an organisations tactical asset management practise. Making it desirable for a medium-term risk based approach to be adopted for condition inspection and rehabilitation prioritisation, which is capable of evaluating both the probability and consequence of failure (Fenner et al., 2000).

Egerton (1996) recognised that the benefits of employing Quantitative Risk Analysis (QRA) techniques have been widely acknowledged in the oil, nuclear and chemical industry. However, the application of such techniques has historically been less prevalent in the management of water industry assets. Traditional approaches to estimating failure probabilities in below-ground water networks rely on historical failure data. Generally, where historical data is plentiful, statistical methods are developed by fitting water main breakage data to time-exponential functions, allowing for future failure rates to be extrapolated (Jarrett et al., 2001). While these methods continue to be widely used to support asset management decision making, they also require large failure data sets as a basis for analysis. Assuming good quality data, this does not pose a problem but for low value – high volume assets, such as communication pipes, which are often operated under a run to failure strategy, it is more difficult.

Similar difficulties are experienced for high value – low volume assets which are typically more critical assets that are owned and operated across the water industry, i.e., service reservoirs and/or treatment plants. A high degree of variability and complexity is associated with assets of this nature, making both the reliability and consequence assessments particularly challenging. This is partly due to the individuality of these assets, but it is mainly due to the low levels of recorded failure data for modelling, coupled with the need for proactive strategies to prevent high consequence failure events from occurring.

Authors have also recognised the need to more accurately understand the interaction between asset performance and the level of service being delivered to the customer and/or environment for clean and waste water infrastructure (Alegre 2006; Matos 2003) respectively. Such information is effectively used to better quantify the consequence of asset failure by assigning performance related costs to the individual assets themselves. Therefore, in-order to adopt an effective and truly risk based tactical planning framework, two critical components are required: 1. Predicted future condition or a quantifiable assessment of an assets reliability; and 2. A monetised indication of the social, environment and economic impact of asset failure.

Future condition is typically quantified using deterioration modelling techniques which are now well established in the water industry for more commonly found infrastructure assets. Consequence of failure has also been fairly well researched over recent years, as both network modelling and over-land flow simulations have made it possible to assess the impact of individual asset failure within a complex network and environment. Approaches to assigning monetary values for these social and environment impacts have also been developed, using customer willingness to pay surveys. A brief literature overview of different techniques for both components is provided for background.

2.1.2.1 Deterioration modelling

In support of the literature overview below, a detailed and well regarded review of deterioration modelling techniques for buried water infrastructure can be found in (Kleiner and Rajani 2001; Rajani and Kleiner 2001); covering both statistical and physical modelling techniques respectively. A summary of the more pertinent literature in these studies is provided but a focus is placed on the more recent literature published since this work.

2.1.2.1.1 Statistical based models

Statistical models were developed as an alternative solution to physically based models, so they could be applied across the entire network; including assets where data is variable in terms of quality and limited in terms of availability. To enable their application across the entire network, statistical models are focused around the grouping of assets into cohorts which behave similar to one another. This is a particularly relevant issue because of the need to establish groups of assets that are small enough to be uniform whilst retaining groups of significant population to yield meaningful results and reduce the influence of noise. For buried linear infrastructure, cohorts are typically formed from key pipe characteristics, i.e., age, size and material (Davies et al., 2001a). Where possible other external factors which have been shown to influence deterioration are also included, i.e., soil types or above ground loading conditions.

The most cited and widely recognised authors who were at the forefront of statistical based modelling developments in the water distribution industry were Shamir and Howard (1979); and Clark et al. (1982). The early developments in these models, including (O'Day et al., 1986) took a linear form and a few fundamental drawbacks were observed. The main disadvantage is that these models are heavily reliant on the availability of sufficient data for each asset class in-order for the rate of deterioration to be established without the interference of third party influences that lead to failure. These third party causes are commonly referred to as 'noise' because of their undesired influence on the identification of failure rates.

Another important and restricting factor is that these models did not include data from assets where failure had not yet occurred, even though in some instances failure was imminent. This process was subsequently developed into a more representative multiple regression model.

Transitional matrices were later used as a preferred way to describe the deterioration process of water mains due to the uncertainty surrounding the rate of deterioration which was found to be better modelled using a semi- Markovian model as opposed to projections based on linear curves (Black et al., 2005). The semi-Markovian model is a simplification of the deterioration process by modelling the current condition of an asset in one of a number of states, e.g., for the sewerage network, the WRc structural grading classification is often applied which defines asset condition on a scale of 1 (good) to 5 (poor). A probability is then applied to each asset to account for the likelihood of it moving into worsening state over a given time period. Although Wirahadikusumah et al. (1999) used these types of model to support the development of maintenance and rehabilitation policies for sewerage infrastructure, an obvious short coming lies in the granularity of how the structural scoring is applied to the entire asset, which is then subsequently modelled through the transitional matrices. By way of example, a 20m sewer with a single grade 5 defect occupying only 0.5m of the sewers length, would be classified as a grade 5 sewer. Despite the fact that 97.5% of the assets overall length is in perfectly good condition, i.e., condition grade 1.

Artificial neural networks (ANN) have also been applied to watermain networks with the aim of learning the pipe breakage frequency rate through the use of incident data. Sacluti (1999) demonstrated their effectiveness by the application of an ANN to the watermains network in Edmonton, Canada. The model was applied to the entire network, ignoring individual pipe characteristics, and it was trained using weather data and incidents reports. The authors reported that the model was a successful short-term prediction tool capable of working using 7-day weather forecasts. More recently, Jafar et al. (2010) used ANN and Multiple-Linear Regression (MLR) to analyse pipe failure in a distribution network in Wattrelos, France. Results from their study showed that the ANN model was a powerful tool for predicting the number of failures in the network and the authors recognised its use for establishing a rehabilitation strategy.

However, the successful deployment of Artificial Neural Network's is highly dependent on extensive data acquisition and substantial upfront work to define the architecture of the model which is critical to its performance. Unlike other modelling techniques, a comprehensive understanding of the full network attribution and operating conditions is required, i.e., pipe material, diameter, length, age, location, operating pressures and pressure fluctuations. Patterns and relationships are then established between these input parameters and the modelling outputs (future failures). Therefore, a comprehensive failure history across the network is also required in-order to calibrate the model.

In the absence of historical data, Physical-Probabilistic Models (PPM) are a method that has been used previously to support the asset management of large diameter cast iron mains (Davis and Marlow, 2008) and newer mains with limited failure history (Davis et al., 2007). This approach relies on physical models that are based on a fundamental understanding of the actual deterioration and failure processes that occur in practice. While the physical model simulates true deterioration processes, uncertainty is also introduced via the representation of key model variables as stochastic parameters, rather than single-valued quantities.

In practice, PPM variables are represented by appropriate probability distributions, with mean values and variances, as opposed to single numbers. Monte Carlo simulation methods are then used to repeatedly “sample” the predicted lifetime of a hypothetical set of pipelines each with a randomly assigned input variables from the underlying distribution (Mogila et al., 2008). This technique is beneficial as it bridges the gap between physical and statistical modelling for assets with limited failure histories. However, these models rely on sufficient input data based on an understanding of the deterioration and failure mechanisms of the pipework. This is usually determined from some form of intrusive field sampling which can be an expensive process.

One of the latest advances in the industry, is the use of a hybrid data mining technique called Evolutionary Polynomial Regression (EPR). EPR has been used as a data mining tool in urban water networks to discover patterns across sewerage and clean water infrastructure (Savić et al., 2006) and (Berardi et al. 2008), respectively. The EPR models of this nature have produced simple relationship equations between a number of variables and confirmed the importance of pipe age, diameter and length; when considering pipe burst frequencies and occurrences. The benefit of EPR over more conventional data mining techniques, is the simplicity of the relationship equations that it generates and thus its ability to include engineering knowledge in the validation of these equations. It appears that engineering knowledge is required to prevent the algorithm from over-fitting equations and model structures to the data it is trained against. This is evidenced in the vastly different equations developed by the algorithm when modelling the same phenomena, and by the fact that all of these modelling structures achieve equally good statistical correlations.

A variety of deterioration modelling techniques have been evaluated and although the ability for these technologies to accurately predict future failures in the water and wastewater networks cannot be disputed, there is a clear gap in the literature which supports the use of these technologies for assets with limited or uncertain datasets, i.e., small diameter and less critical assets such as communication pipes, supply pipes and private sewers. Although these assets may be less critical in nature, the fact remains that a large proportion of the buried infrastructure network is sufficiently less well understood and is therefore likely to be sub-optimally managed in comparison to their more critical counterparts.

2.1.2.1.2 Physically based models

Generally speaking, physically based models seek to derive a mathematical expression that links input factors to the condition of an asset. Therefore, a true physical based model would include all of the inter-relationships between the factors affecting deterioration and failure (Rajani and Kleiner, 2001). For buried linear assets it has been particularly challenging to model pipe failure mechanisms using physically based models due to the uncertainty associated with these phenomena. Hence the water industries general bias towards probabilistic based models across buried infrastructure (Ahammed and Melchers, 1994).

However, more critical above-ground infrastructure assets, such as service reservoirs, tend to have more relevant literature for physical modelling approaches, often borrowing from techniques developed in structural and bridge engineering. Therefore specific failure mechanisms can be modelled by better understanding: the relationship between reinforcement corrosion and concrete deterioration (Cabrera, 1996); the impact of corrosion on cracking (Liu and Weyers, 1998); *and* the effects of chemical attack on deterioration (Glasser, et al., 2008).

Finite Element Analysis (FEA) is also a popular physically based modelling technique, built around the understanding of the underlying physical parameters that govern the structural failure of an asset (Fagan, 1992). The behaviour of these physical parameters are modelled to determine the response of the structure to a variety of conditions. FEA achieves this by solving a series of underlying structural analysis equations for an inter-connected mesh of smaller elements used to represent the overall structure. For accurate behavioural predictions to be obtained, these models require a detailed level of input information. This includes knowledge of the geometry and material properties of the structure itself, along with the loading configurations it is subjected to. Whilst the approach is well-established and well-researched in the engineering industry, its use for modelling the behaviour of water infrastructure assets is not often feasible.

This is partly due to the linear nature of the assets which gives rise to variations in loading conditions, soil characteristics and asset geometry, along the structures length. It is also not widely applied to non-linear assets due to the cost and data requirements associated with the model build and analysis process.

In recognition of the specific water industry challenges associated with high value – low volume infrastructure, UKWIR commissioned a study to help improve the investment planning and deterioration modelling process for these assets. The published guidance focused on supporting water utilities in the development of a series of scientifically based condition modelling tools such that asset deterioration and failure is modelled and quantified scientifically as opposed to using expert judgement (UKWIR, 2011). Modelling tools were developed which predict the residual remaining life of an asset from observational data for three types of concrete failure; Carbonate, Chloride and Sulphate deterioration. Chan (1996) developed another similar expert system to assist in the diagnostics of concrete deterioration without the reliance on professionally qualified structural engineers. Although these tools are developed for generic use, the large amount of parameter tuning and input data that is required is often off putting and confusing for the industry.

Therefore, in comparison to other markets, the water industry appears to be reluctant in the adoption of more meaningful metrics to express asset condition for high value – low volume infrastructure, such as reliability, which can be used within risk based asset management practises. . Instead the industry continues to adopt traditional condition inspection and grading systems despite published literature demonstrating the benefits of more comprehensive modelling techniques. Perhaps an approach which is founded on condition inspection information, but capable of translating observations into more meaningful metrics, would assist the water industry in this transition towards best practise.

2.1.2.2 Service performance levels

The social impacts of failing infrastructure are evident in the direct and in-direct disruptions associated with infrastructure asset failure, namely; flooding, property damage, supply interruptions, road closures, pollution incidents and potential public health issues. Therefore, it is of upmost importance that future investment and maintenance decision making is undertaken from an informed position that appropriately considers the social, environmental and financial impact of different decisions.

Cromwell et al. (2002) acknowledged that at the time of his study the water industry was absent of a common and comprehensive methodology for estimating tangible and intangible costs associated with infrastructure failure. Since the publication by Cromwell et al., the UK water industry has made significant improvements, although more notably from a strategic asset management perspective. Where-by, customer preferences and willingness to pay surveys have been integrated within long-term business planning decision making, such that investment can be targeted towards schemes and maintenance programmes that deliver the improvements and security of service that customers value most. Originally, MacDonald et al. (2003) and Hensher et al. (2005) assessed customers willingness to pay for water supply services in Australia based on the avoidance of service failures which were defined in-terms of frequency, timing and duration.

A similar methodology was deployed in the UK but with subtle changes that focused respondents to consider questions around the value they place on service improvements across the region, i.e., the number of customers that benefit, rather than the value placed on personal benefits (Willis et al., 2005). This approach was deemed to provide more realistic results because participants were not asked to respond to situations outside of their own experiences. It also allowed for the authors to determine the most valued infrastructure improvements by the customer.

This research by Willis et al., (2005), enabled Yorkshire Water to identify customer priorities and to estimate the value their customers place on the changes in service levels provided. By comparing the cost of maintaining and improving service, Yorkshire Water were able to identify the economic level of service and the associated investment which was justified to the economic regulator in 2009 on these grounds.

In 2015 Ofwat launched a new Outcome Delivery Incentive mechanism across the UK Water industry, which is believed to be one mechanism capable of driving these types of customer valued service improvements across more tactical and short-term decision making levels (Oxera, 2012). In response to these incentive mechanisms, Water companies are now looking beyond customer opinion surveys and towards new and innovative ways that can help them understand the short, medium and long term impact that investment decisions have on their customers' experience and interaction with their infrastructure.

2.1.3 Strategic asset management

The International Standard for Asset Management, PAS-55 which was later superseded by ISO-5500, offers the following definition for asset management:

> *"systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organizational strategic plan"* (British Standards Institution, 2008).

Of which, an important component is an organisations strategic asset management/maintenance plan. This plan provides the detail behind how a portfolio of assets will be managed over a long-term horizon, typically 25- 50 years, and how this maintenance strategy aligns to the delivery of the organisations strategic goals (Hooper et al., 2009).

As the descriptions above suggests, strategic asset management decision making forms part of the overall approach to asset management and focuses on the maintenance activities associated with the ownership of assets, i.e., planned expenditure, maintenance policies, planned asset renewal programmes, risk and target levels of service. Strategic maintenance planning is effectively an extension of the tactical modelling phase, where-by the deterioration and performance modelling outputs are typically integrated within a life-cycle cost analysis, such that a long-term appreciation of asset expenditure can be understood and budgets set aside accordingly.

Under the terms of the UK privatisation, the 1989 Water Act, the water industry regulator, Ofwat, is given the responsibility for the operation of the industry price cap system. The price cap system currently involves a five yearly Periodic Review (PR) process to determine the price increase that all of the UK's water and sewerage providers can apply to their customers. The process is based on the Retail Price Index (RPI) + 'K' formula, where K is a value that reflects the companies' need to finance investment to meet customer service requirements (Helm and Rajan, 1994).

Therefore at each five yearly periodic review, utility providers must demonstrate a comprehensive understanding of their asset stock and their future investment requirements, i.e., a strategic investment and maintenance plan, in order to justify price rises above the retail price index. The capital investment requirement for underground assets is submitted to Ofwat in the form of five yearly asset management plans (AMP). Following the privatisation of the UK water and sewerage provisions in 1989, AMP1 covered the period of 1989 to 1994. In 1994 the first price limit cap was introduced in the form of a Periodic Review in 1994 (PR94). This process has continued to date such that the Periodic Review of 2014 (PR14) has determined price limit rises for the capital investment period of 2015 – 2020 (AMP6).

Over this time, water companies have matured in their approach to strategic investment planning through the adoption of risk based planning frameworks that justify investments on the grounds of current and future failure probabilities (UKWIR, 2002). Consideration to the impact of failure on the environment, communities and customers is also an inherent part of the planning process which has received support from Ofwat, the Environment Agency and Defra (Lumbers and Kirby, 2003). Since this research, water companies have also adopted best practise from the International Standards for Asset Management (ISO 5500), other UKWIR research projects and developments from over-seas and in other sectors.

Some of the developments and challenges associated with the more relevant components of strategic maintenance planning and life-cycle cost analysis are discussed here-in.

2.1.3.1 Strategic maintenance planning

From a linear infrastructure perspective, which is the focus of this thesis, network renewal and maintenance planning is seen as a process that seeks to establish the most appropriate and cost effective intervention and timing for each asset in the network (Halfawy and Baker, 2009). Identifying the optimal timing for interventions to occur has long been recognised as an important factor in asset management decision making (Shamir and Howard, 1979). In 2001, Kleiner undertook a study to demonstrate that the most effective timing occurred immediately prior to failure. At this point, the maximum benefit from the asset is achieved because it is the point at which the lowest intervention costs arise before failure occurs. Conversely, the costs for repairs and restoration are escalated as soon as failure is allowed to occur because of the expense and disruption caused by repairs of a reactive nature (Kleiner, 2001).

Ugarelli and Di Federico (2010) expanded upon these principles by producing a model to compare the associated costs of maintaining sewerage infrastructure assets against the cost of rehabilitating or replacing them. Ugarelli and Di Federico compare intervention options using a risk of failure cost model to define the optimal replacement time. Since this study, the uptake of trenchless rehabilitation technologies has increased rapidly across the industry. Therefore, this research would benefit from being revisited to understand if the optimal timing has changed as a result of these new trenchless solutions. It is suspected that due to the nature of these techniques, which often replace the asset in situ, i.e., slip-lining, would lead to the intervention timing being much earlier than more traditional interventions. This is to ensure that the trenchless solution can be successfully installed before the asset deteriorates too far and hereby prevents the trenchless solution from being installed or becoming less effective.

Strategic network management has also been expressed as a cost versus reliability trade-off concept where-by the objectives for optimal rehabilitation planning are conflicting (Halhal, et al., 1997). This implies that the rehabilitation solutions that vastly improve the structural condition of an asset have typically high associated costs. Therefore, to permit effective planning and investment to occur, it is important that decision makers understand the cost vs benefit trade-off that different policies can provide (Dandy and Engelhardt, 2006). The complexity of such a problem, across a large water distribution or sewerage collection network, has led to the formulation of the problem by the aforementioned authors in a way that allows advanced heuristic optimisation algorithms to be used to solve it.

These optimisation algorithms have been shown to outperform more traditional techniques for prolonging asset life and/or improving network performance. Outperformance is achieved through the ability of heuristic optimisation techniques to consider the longer-term benefits that intervention programmes can achieve rather than simply prioritising based on asset risk in a single year. Under such 'optimised' intervention programmes, investment is often reallocated away from some immediately high priority infrastructure such that funding can be directed towards assets with steeper deterioration profiles, albeit with lower immediate priority.

In-order to successfully implement these methodologies, a framework that embraces life-cycle costs analysis is required such that the true cost of these assets can be simulated over a long-term planning horizon. Such modelling frameworks have been developed for more commonly found or critical infrastructure, where-as less critical infrastructure has often been overlooked (Fuchs-Hanusch, et al., 2012; Shahata and Zayed, 2013; Tee, et al., 2014). It would also appear that the integration of established practises to accurately reflect the social, environmental and economic costs of asset failure, within a whole life cost framework, have also been overlooked for buried networks.

2.1.3.2 Life-cycle cost analysis

Life-cycle cost (LCC) analysis, also known as whole-life cost (WLC) analysis, is a fundamental practise used across a portfolio of infrastructure assets to determine long range management and maintenance programmes. It is essentially an accounting platform that draws on engineering and operational best practise to predict the total life cycle cost associated with the ownership of an asset by considering all incurred expenditure, i.e, maintenance, operational, social and environmental costs. The use of life-cycle cost analysis across the UK water industry has risen rapidly. This is thought to be because of its ability to help decision makers develop asset management strategies that balance financial constraints with tight environmental and drinking water standards. There-by addressing one of Ofwats major concerns, that customers are provided with water and sewerage services at an affordable price (Ofwat, 2011a).

The fundamental life-cycle costing process is based on modelling the time value of money, which is widely acknowledged as best practise for asset management decision making and has been around in principle for more than 100 years (NCHRP, 2003). However, its application to civil infrastructure in a commonly accepted and comprehensive methodology has only been widely adopted in the past 10 -15 years; with the transport industry being early adopters.

More recently, life cycle cost analysis has been used to determine the most economic rehabilitation techniques and intervention type (repair or replacement) by seeking to minimise the future risk of failure and whole-life maintenance costs for large diameter sanitary and storm water pipework (Tee et al., 2014). Life-cycle cost analysis of this nature has also been developed to evaluate the costs and benefits associated with trenchless and open cut solutions (Shahata and Zayed, 2013). It is no surprise that trenchless techniques are more cost effective, however a limited understanding of the future performance and deterioration of these techniques needs to be considered in the uncertainty analysis applied within such methods.

Whilst these principles have been widely accepted and acknowledged as theoretically sound by the water industry (UKWIR, 2002a), the practical application of these techniques have been much slower for water infrastructure. This is believed to be due to the predominately buried nature of water infrastructure assets, making it difficult to accurately quantify some of the input parameters needed for this type of analysis, namely: 1. the benefits and cost of different maintenance regimes, i.e., operational and capital programmes; and 2. future performance, i.e., asset deterioration rates and the cost of failure. However, as the global water industry has evolved its asset management practise, the understanding of asset performance including the social, environmental and customer benefits delivered by different maintenance regimes has vastly improved (Jones et al., 2014).Thus making whole-life cost analysis increasingly more applicable to water infrastructure.

Tee et al. (2014) recognised how the coupling of life-cycle cost models with advanced optimisation algorithms were becoming increasingly popular across all civil engineering industries, albeit with buried pipelines lagging someway behind other infrastructure.

Life-cycle cost analysis can also provide an effective mechanism for water companies to evaluate and optimise the total expenditure associated with the management of these assets. The concept of planning for total expenditure (totex) is a substantial change to the UK water industries approach to asset management and therefore requires a considerable behavioural shift by the industry. To support in this behavioural transformation, the decision making tools that are used by the industry for operational, tactical and strategic asset management, need to evolve.

2.2 CONCLUSIONS AND THESIS OBJECTIVES

The overarching aim of this research is to develop a series of decision support tools and methodologies that can improve asset management decision making for water and waste water assets across all decision making levels, namely; Operational, Tactical and Strategic decision making.

In recognition that the literature survey has uncovered varying levels of asset management maturity for different groups of assets within the water industry, this thesis is directed towards those assets which have previously not benefited from the latest technological advancements.

Specifically:

- Operational decision making improvements are focused on the buried sewer network and service reservoirs, due to the availability of condition inspection information for both asset types, which continues to form the basis of maintenance decision making.
- Tactical decision making improvements are focused towards low value – high volume buried infrastructure assets. These assets have had surprisingly little research into deterioration modelling applied in the past, despite the reported benefits from the aforementioned literature for water mains and sewers, Section 2.1.2. Therefore, research is conducted into the application of deterioration modelling techniques for more commonly found buried infrastructure assets across their low value-high volume counterparts, i.e., communication pipes and private sewers.
- Strategic decision making improvements seek to capitalise on the improvement in deterioration modelling, by exploring the potential for utilising the improved predictive information for low value – high volume assets, within a whole-life cost optimisation environment.

Of critical importance, is the need to ensure that all tools and methodologies deliver underlying data quality improvements that can be used to benefit other decision making levels and subsequently provide alignment and consistency between operational, tactical and strategic decision making.

Considering that some areas of asset management have suffered from over complexity it is recognised that any solution to the above must be delivered within a comprehensive modelling framework that is fully auditable, logical and based on sound engineering knowledge. For industrial application, the framework must also be deliverable within an environment that requires little parameter tuning and specialist expertise, to ensure that the end user (the decision maker) is equipped with the knowledge and confidence to act upon the modelling outputs.

3 A MULTI-OBJECTIVE OPTIMISATION MODEL FOR SEWER REHABILITATION CONSIDERING CRITICAL RISK OF FAILURE

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Declaration

This chapter presents the methodology developed and presented in the author's MSc Dissertation at the University of Exeter in 2010. Whilst the methodology is fundamentally unchanged, this chapter expands upon that original work to include a detailed interrogation of individual asset level solutions, the process itself and benefits are provided from a more focused and relevant literature study.

3.1 BACKGROUND

Due to the age and neglect of the UK water infrastructure system there is an increasing reliance on human intervention to ensure adequate service is delivered to the customer (Scott, 2003). A concerning fact is that under the current rate of replacement, reported by Ofwat to be an average of 334.9km per year against a portfolio of 324,500km, sewerage companies are relying on their assets serving a useful life, without intervention, of nearly 1,000 years (Ofwat, 2010). Considering the Concrete Pipeline Systems Association (CPSA, 2012) estimated that well manufactured and installed sewerage assets are capable of achieving a service life of 100 - 120 years, a ten-fold shortfall between life expectancy and intervention rates is identified.

When this shortfall in historic investment is considered against Ofwat's financial estimate for the replacement / renovation cost of the UK's sewerage infrastructure systems to be in excess of £200 billion, the need for efficient and effective sewer rehabilitation strategies has never been more prominent, Ofwat (2002).

In recognition of this driver, chapter 3 is motivated to develop a new methodology capable of optimising the specification of sewer rehabilitation solutions such that investment is better targeted towards the most high risk assets. It attempts to achieve this by exploring the feasibility and benefit(s) of applying modern optimisation techniques versus conventional processes for sewer rehabilitation specification. Thus, hoping to overcome some of the limitations associated with the conventional process for determining the nature and extent of the rehabilitation solution, namely:

1. The reliance upon the expertise of professional engineers to manually evaluate CCTV inspection information;
2. The subjectiveness of the manual process; and
3. The in-ability to identify optimal solutions, or possible combinations of optimal solutions in the delivery of catchment wide rehabilitation programmes.

Such limitations have all led to a series of unanswered questions which are sought to be addressed by this research:

i. Does the solution offer the greatest structural benefit to the network?
ii. Is the solution the most cost effective solution available?
iii. Does the solution most greatly reduce the risk of critical asset failure?

Specifically this chapter seeks to develop a methodology capable of improving Operational decision making for buried sewerage infrastructure assets.

3.2 INTRODUCTION

Most sewerage networks are compiled of ageing assets that are becoming increasingly more susceptible to failure. Abraham and Gillani (1999) categorise sewer system failure into three distinct modes; hydraulic, environmental and structural. Structural failure can have varying degrees of severity, ranging from minor sewer fabric defects, such as cracking, to complete loss of structural integrity where a full or partial collapse may be observed. The failure rate, or collapse rate, within a network is one of the major indicators that a sewerage system is deteriorating. In the two most recent Asset Management Plan (AMP) submissions, all 10 of the UK's water and sewerage utility companies have demonstrated a commitment to improve their wastewater infrastructure serviceability (Ofwat, 2009a;Ofwat, 2014a). This is normally achieved through increased investment towards sewerage asset maintenance. To ensure that this increased level of investment returns the highest possible benefit, it will be crucial for comprehensive sewerage rehabilitation strategies to be developed and implemented over the next few years.

In the last decade, authors began to report on the application of Hydroinformatic tools to the problem of optimal sewerage asset management (Adey et al., 2003; Elachachi and Breysse, 2007). In comparison, methodologies addressing the optimal management of water distribution systems have been widely reported since the 1980's (Shamir and Howard, 1979, Woodburn et al., 1987; Kim and Mays, 1994; Halhal et al., 1997; Malandain et al., 1998). If we purely consider the amount of published literature in the two fields, it would appear that the management of sewerage assets is less suited to the application of such Hydroinformatic tools.

However, it will be shown here that the sewerage industry is in fact well suited to take advantage of such Hydroinformatic tools. Notably, how the specification of optimal rehabilitation strategies can be improved through the increased use of structural condition grading information to inform decision making processes. In this respect, sewers have a distinct advantage over their clean water asset counterparts; in that their condition can be ascertained relatively efficiently

(Feeney et al., 2009; Kathula et al., 1999), which in-turn can be utilised for the implementation of prioritised maintenance and rehabilitation strategies (Newton and Vanier, 2006).

3.3 METHODS

The multi-objective optimisation model presented in this paper utilises the standard sewer condition classification grading information obtained from CCTV inspections which are undertaken in-line with the current WRc, 2004 Method of Sewer Condition Classification (MSCC4), to identify optimal rehabilitation solutions in terms of three conflicting objectives:

1. Maximise structural condition improvement;
2. Reduce construction cost; and
3. Minimise critical asset risk of failure.

A data management process and optimisation environment has been specifically developed to solve for these three conflicting objectives that are associated with the optimal specification of sewer rehabilitation solutions, shown in Figure 3-1. The optimisation environment is based upon a genetic algorithm (GA) approach, which is now a mature technology often used in water and wastewater planning and management (Nicklow et al., 2010). Genetic algorithms stem from the field of evolutionary computation and they are widely used within multi disciplinary industries to generate solutions to search and optimisation problems by mimicking behaviours found in biological evolution, namely, survival of the fittest, cross-over and mutation.

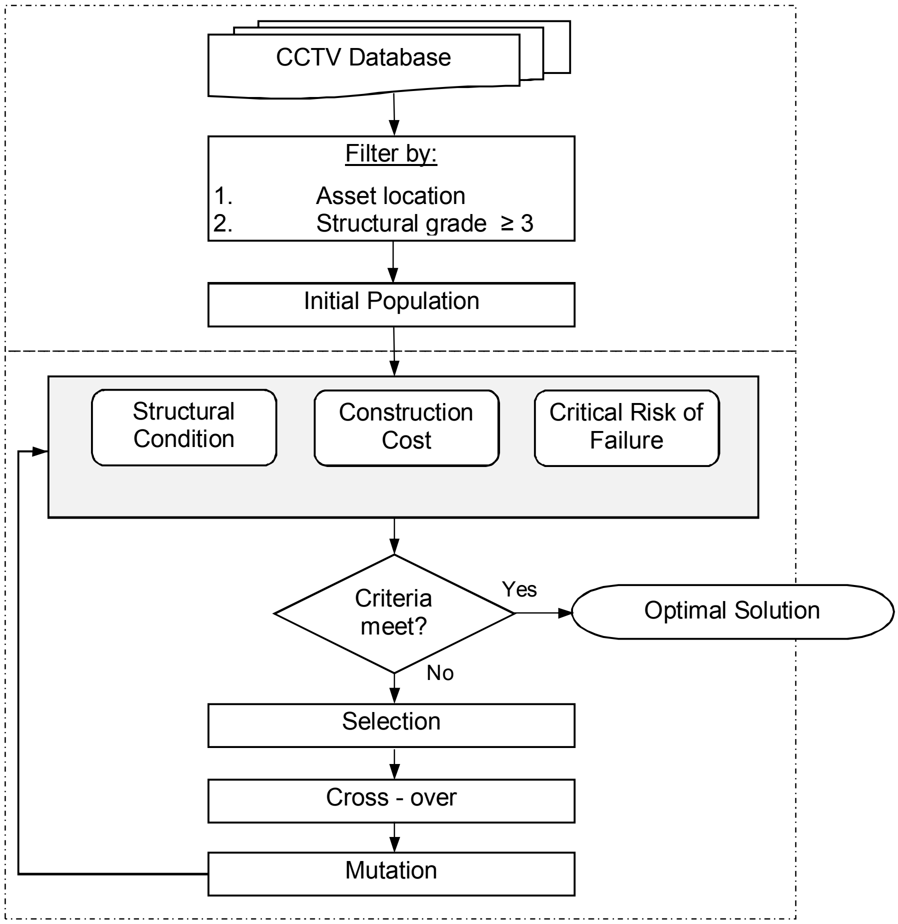

Figure 3-1. Data processing and optimisation environment

3.3.1.1 Data Pre-processing

The CCTV data is managed and coded using a commercial software package, InfoNet, developed by Innovyze (2010). InfoNet is used as a data pre-processing tool because of its geospatial data storage functionality and its ability to calculate structural and service condition grade information from raw CCTV data. A two staged filter process is used within InfoNet to select assets for optimisation that are within close geographic proximity to one another and to remove sewers in good physical condition that should not be considered for rehabilitation. This process is visualised in Figure 3-1. The optimisation model is then driven by the extracted survey data meeting the previously described criteria, which is directly processed within the optimisation environment, to permit the application of a multi-objective optimisation algorithm.

3.3.1.2 Optimisation environment

The optimisation environment uses a macro driven programme to collate and present the raw CCTV into a format which allows the assignment of rehabilitation solutions to each segment of asset. The macro undertakes this process by creating a “chainage” (distance) value at increments along the assets. In this example, the term “chainage” is used to describe an imaginary line that is used to measure distance along a sewer. In sewer survey measurements, the chainage starts at 0m in the starting manhole and observations are reported at 0.1m increments until the end manhole is reached, or, the survey is terminated, e.g., a collapse or blockage is observed. Within the optimisation environment, the repair chainage is defined to 1.0m accuracies which have been termed as segments.

Whilst it is recognised that rehabilitation solutions can be delivered to accuracies of 0.1m, which are equal to the resolution obtained from the condition inspection equipment, it was deemed more practical to define the accuracy of the model in accordance with the minimum isolated repair length, i.e., 1m. Therefore, within each 1m segment the accumulative structural score is calculated and displayed. The objective function formula, embedded in the optimisation spreadsheet template, then updates itself to encompass the cell ranges for each individual sewer length. Thus permitting the evaluation of the objective function(s) at asset level, i.e., the score improvement, construction costs and risk of failure can be considered per individual sewer length. In accordance with this level of accuracy, the condition of each 1m segment of sewer is represented as the sum value of the defect scores within that meter. Similarly, for practical purposes, a minimum repair length of 1m is adopted.

3.3.1.3 Optimisation tool

This model uses a well established GA optimisation tool developed by the University of Exeter, GANetXL, (Bicik et al., 2006; Savić et al., 2011). The optimisation model evaluates numerous rehabilitation solutions within the optimisation environment using a multi-objective GA. Upon establishing the optimisation environment, the GA assigns an initial random population of solutions, as a string of 1's and 0's, against each segment of the sewer. These 1's and 0's become the decision variables in the problem which represent the rehabilitation action; either rehabilitate (1) or do nothing (0). After an initial random population of decision variables are assigned, the GA evaluates the fitness of each solution based on the objective function(s) scores which are calculated dependent upon the decision variable values.

If the fitness of the solution meets the stopping criteria for the algorithm then the optimal solution is said to be found. A maximum number of generations were used as the stopping criterion for the optimiser. A maximum value of 10,000 generations was decided upon based on experimental results. However, if the solution falls short of the criteria then the following GA operators are performed; selection, cross-over, mutation (Murphy et al., 1993) and the new solutions are re-evaluated. An important aspect in the optimisation process is how the algorithm uses the objective function(s) to prescribe the optimality of a particular solution, such that solutions can be ranked against one-another. The main advantage of this approach is the ability of a GA to find a set of Pareto-optimal (trade off) solutions in a single run of the algorithm.

3.3.2 Model development

Between 1980 and early 2000, UK water and sewerage companies largely employed asset management policies that involved the implementation of selective rehabilitation. Selective rehabilitation meant that non-critical sewers (Category C) would only receive maintenance on a reactive basis (Fenner et al., 2000). As we observe a behavioural shift in the industry towards more proactive maintenance, utility companies are becoming increasingly more and more concerned with the identification of critical assets, due to the high associated costs to the business when failure of said assets occur. Modern deterioration models that task themselves with the identification of defective assets are not typically founded on the use of asset criticality as a primary means for investigation (Berardi et al., 2008; Black et al., 2005).

Instead, other factors that might contribute to the observation of different deterioration rates amongst sewerage assets are often used, i.e., material, age and ground conditions (Davies et al., 2001b). Indeed, the use of criticality is often considered as an additional decision support element, used for evaluating the consequence element of the risk of failure. Whilst the identification of defective assets should not be prioritised towards critical sewers, it would be fundamentally flawed if a rehabilitation strategy were developed which considered the consequence of failure of critical and non-critical assets as equal. Thus, a balance must be struck to ensure that assets of equal likelihood of failure are rehabilitated in order of priority, i.e., where a bias towards the rehabilitation of critical sewers is given. This can be achieved using criticality as a surrogate measure to define the consequence of failure, Table 3-1. It is important, however, that non-critical assets displaying characteristics of high failure probability are not neglected; hence the use of a bias function such as a criticality weighting is used instead of a blanket ruling for the repair of critical assets first.

3.3.3 Objective functions

3.3.3.1 Structural condition improvement objective function

The MSCC4 coding system developed by the WRc (2004), assigns a structural condition score to all structural defects that are observed along the asset's length during a condition inspection. The score value given to each observation is directly proportional to the severity of the defect observed. The optimisation tool utilizes this scoring system to evaluate the structural condition of the asset prior to and post different intervention scenario's, Equations 3-1, 3-2, 3-3 and Table 3-2.

$$\Delta S = S^0 - S^1 \qquad \text{Equation 3-1}$$

Where;

ΔS = structural score improvement

S^0 = initial structural score

S^1 = post rehabilitation structural score

The initial structural condition (S^0) of an asset can be calculated as the sum of all structural defect observation scores (S_d^0) observed along its length. Similarly, the post rehabilitation structural score (S^1) can be calculated from the sum of the observed defect scores (S_d^1) along its length, post rehabilitation. The notation (x) is used to define the decision variables in this problem. The decision variables can take the form of either 1 or 0 which respectively reflects the decision to either; rehabilitate or do nothing.

$$S^0 = \sum_{x=1}^{L} S_d^0(x) \qquad \text{Equation 3-2}$$

Where;

x = 1, 2, ..., L (1m length segments of sewer)

S_d^0 = structural defect observation score prior to rehabilitation

L = sewer length (m)

The structural score post rehabilitation (S^1) is simply the sum of the structural defect scores (S_d) that remain after the rehabilitation solution is modelled.

$$S^1 = \sum_{x=1}^{L} S_d^1(x) \qquad \text{Equation 3-3}$$

Where;

x = 1, 2, ..., L (1m length segments of sewer)

S_d^1 = structural defect observation score post rehabilitation

3.3.3.2 Rehabilitation cost objective function

The cost objective is one of the most important elements in this model. It successfully allows the comparison of numerous different rehabilitation solutions against one another, in order to determine which solutions are more financially favourable than others. For example, the model can be tailored to distinguish between different contractor costs; where one contractor's rates may favour contiguous lining as opposed to another contractor whose rate favours patch repairs. If these costs are accurately captured in the model the outputs will promote solutions according to each of the contractor's individual preferences. Similarly, the client may over-rule the objective function to promote their preference. To facilitate the accurate modelling of rehabilitation costs the total cost (C) of any rehabilitation strategy is a function of the raw unit rate cost (Cr), the rehabilitation factor (α) and the mobilisation cost (C_m) which are associated with the repairs, Equation 3-4.

$$C = \sum_{x=1}^{L} \beta \cdot \left(C_r \times \alpha\right) \cdot + C_m \qquad \text{Equation 3-4}$$

Where;

x = 1, 2, ..., L (1m length segments of sewer)

C = total cost (£)

C_r = raw unit rate (£/m)

β = On-cost factor

α = rehabilitation factor

C_m = mobilisation cost (£)

L = sewer length (m)

The rehabilitation unit rate cost formula is founded on South West Water's sewage infrastructure (process 32) sewer pipe rehabilitation methodology, which formed part of the companies PR09 business plan submission to Ofwat (South West Water, 2008). The formula has been modified, via Equation 3-5, to distinguish between patch repairs and continuous lining repairs. If consecutive rehabilitation is specified, i.e., a string of unbroken 1's, this is referred to as a continuous lining repair and different unit rates are returned dependant on the length of the continuous repair being specified,

$$C_r = \begin{cases} 0, & \text{if } \sum x_{\text{Consecutive}} = 0 \\ 0.22409D + 106.61, & \text{if } \sum x_{\text{Consecutive}} > 5 \\ \dfrac{5(0.22409D + 106.61)}{\sum x_{\text{Consecutive}}}, & \text{if } \sum x_{\text{Consecutive}} \leq 5 \end{cases} \qquad \text{Equation 3-5}$$

Where;

D = diameter (mm)

Cr = raw unit rate (£/m)

x = decision variable

A rehabilitation factor is also used to promote full sewer length repairs by discounting the raw unit cost rate for solutions that span from manhole to manhole, Equation 3-6.

$$\alpha = \begin{cases} 0.75, & \text{if } \sum_{x=1}^{L} x = L \\ 1.0, & \text{if } \sum_{x=1}^{L} x < L \end{cases} \qquad \text{Equation 3-6}$$

Where;

x = 1, 2, ..., L (1m length segments of sewer)

α = rehabilitation factor

Finally an on-cost multiplier is included to suit the needs of each individual client by ensuring that the clients incurred costs are accounted for, i.e., company overheads, risk, and estates costs. The following on-cost multiplier was used in this thesis to account for these costs $\beta = 1.507$. Typically, mobilisation costs would be accounted for within the on-cost multiplier. However, it was deemed important that the cost model recognised the fact that it is cheaper to install multiple repairs on a single pipe length than it is to install multiple repairs on un-related lengths. Therefore, mobilisation costs are calculated in accordance with Equation 3-7.

$$C_m = \begin{cases} 0, & if \quad \sum_{x=1}^{L} x = 0 \\ 500, & if \quad \sum_{x=1}^{L} x > 0 \end{cases}$$ Equation 3-7

Where;

x = 1, 2, ..., L (1m length segments of sewer)

C_m = mobilisation cost (£)

3.3.3.3 Critical risk of failure objective function

Risk is an important element to consider in any sewer rehabilitation strategy. Kaplan and Garrick (1981) acknowledge that risk considers the likelihood of something occurring and the consequence of such an occurrence. This paper adopts a “critical risk” philosophy which attempts to model risk by understanding and evaluating the likelihood of a sewer failing and the consequence of that failure. The optimisation model uses the peak structural score observed for each asset, under the MSCC4 coding system, as a surrogate measure for the likelihood of failure. The methodology used to evaluate a sewers’ criticality uses five consequence grades which are defined by a system that broadly follows the criticality grading guidance set-out in the Sewer Risk Manual (SRM), (WRc, 2004). Following this guidance, a sewerage asset is termed “critical” if the collapse or repair of the asset is either disruptive, expensive and/or if the asset is deemed to be of strategic importance.

The UK Water Industry uses three criticality categories to distinguish between the different impacts of asset failure: Category “A” refers to sewers where the cost of rehabilitation post asset failure would typically be in excess of double the planned renewal costs; Category “B” identifies assets where the cost of failure is less than “A”, but where the associated disruptions caused by collapse would make failure of these assets less desire able; And Category “C” applies to assets that are deemed non-critical from the above criteria. It is typical for Category “A” assets to possess any of the following characteristics; large diameter, greater than 3m deep, beneath traffic sensitive streets, in bad ground, present troublesome access conditions and/or lie in close proximity to other infrastructure assets.

The consequence based criticality approach used in this paper applies a further level of granularity to the existing approach by allowing for the original sewer criticality codes, “A” and “B”, to be escalated by the appendment of an “x”. The appendment is applied where the consequence of failure is deemed to be of significant importance, for example where asset failure would almost undoubtedly cause disruption to surrounding critical infrastructure, i.e., railways or major roads. The consequence criteria, which is applied via the use of Geographical Information System (GIS) analysis tools, is listed in Table 3-1 and its associated formula is presented in Equation 3-8.

$$R_c = \underset{x=1}{\overset{L}{Max}}\left[S_d^1(x)\right]\cdot C_w \qquad \text{Equation 3-8}$$

Where;

x = 1, 2, ..., L (1m length segments of sewer)

R_c =critical risk of failure

S_d = structural defect observation score

Cw = critical weighting

Table 3-1. Example consequence criticality definitions

Code	Description of Sewer Category
Ax	Under Railway Under Motorway/Protected Street Under Traffic Sensitive Street Would Disrupt Hospital Traffic Would Disrupt Fire Station Access
A	WRc (2004) SRM sewer criticality classification
Bx	Would Pollute Class 1 or 2 Main River In Hospital Complex Under Traffic Sensitive Street
B	WRc (2004) SRM sewer criticality classification
C	Non Critical

3.4 RESULTS

A unique methodology for the optimal specification of sewer rehabilitation investment is presented in this paper. By accounting for the critical risk of asset failure during the specification of rehabilitation solutions, this methodology builds on the recent work of (Ugarelli and Federico, 2010 and Ward and Savić, 2011) which has reported notable benefits in the use of optimisation tools to assist engineers in the specification of optimal rehabilitation strategies. To ascertain the effectiveness of this approach a catchment case study is considered.

The CCTV data used in the study originates from a recent sewer rehabilitation project implemented by South West Water, UK. The objective of the project was to use a deterioration model to efficiently target CCTV survey investigations within catchments leading to the identification and rehabilitation of defective sewers. The case study catchment has a total sewerage network of 37.4km, of which circa. 8% (2.9km) was surveyed using South West Water's targeted deterioration model. The effectiveness of the deterioration model being able to successfully identify sewers in a defective condition is evident in the structural condition grade summary, Figure 3-2, which shows a high percentage of structural condition grade 4 and 5 sewers from these targeted investigations.

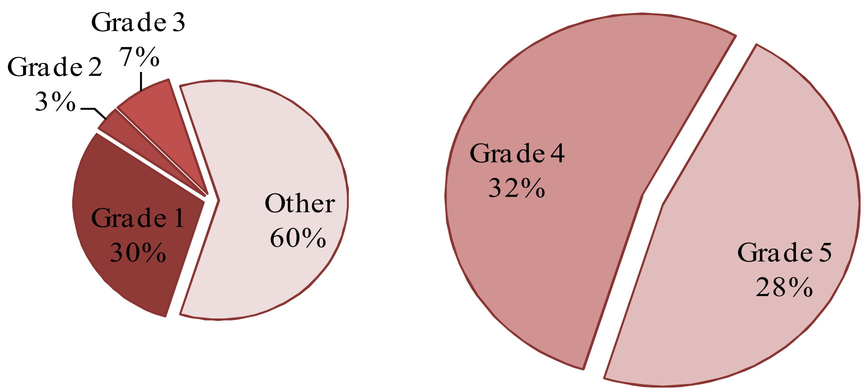

Figure 3-2. Structural condition profile summary

An initial filtering process was conducted outside of the optimisation environment to remove all structural sound assets from consideration by model. Approximately 60% (1.727km) of the raw CCTV data was passed forward into the optimisation modelling environment. The key characteristics of the 1,727m of data which includes; sewer age, diameter, material and criticality classification, is presented in Figure 3-3.

Read and Vickridge (1997) estimate that 78% of all sewers in England and Wales are constructed from Vitrified Clay. Therefore, given the relatively small nature of the catchment, it is not surprising that the majority of the surveyed assets in this study are less than 225mm diameter Vitrified Clay sewers. The high volume of sewers populating the oldest age band, i.e., pre 1896, is also typical of a data set obtained from a targeted deterioration model. The model aims to identify asset that are most likely to be in a poor condition; therefore, it is of no surprise that pre 1896 assets are prevalent in this data set. Most importantly, the data has sewers spanning all of the enhanced criticality classification codes from Ax - C.

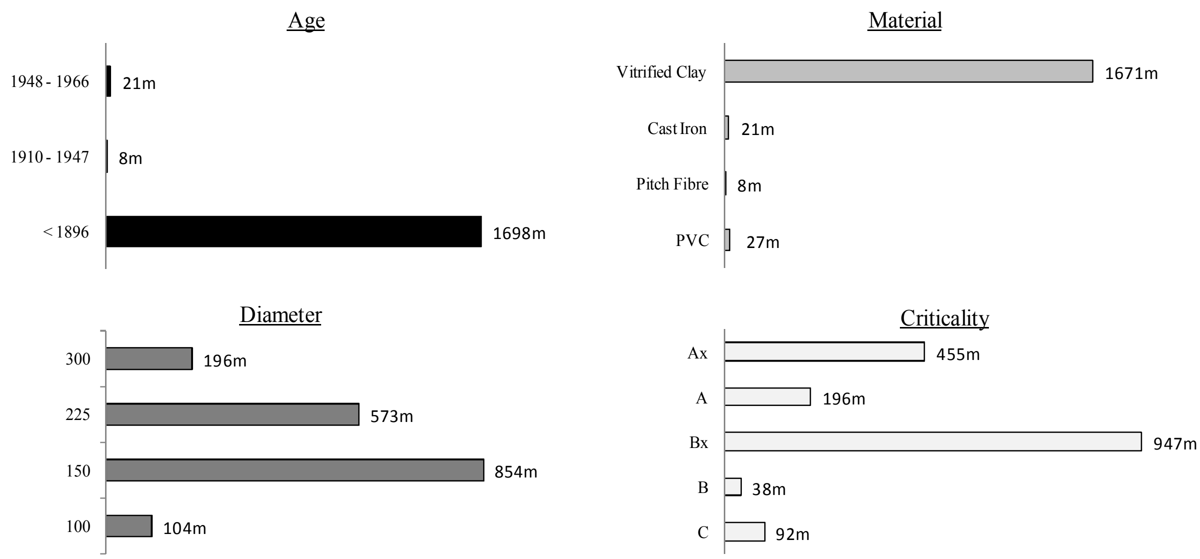

Figure 3-3. Sewer characteristics

Upon establishing the raw data within the optimisation environment, a Macro driven process is performed to incorporate the three objective functions within the model environment. This process permits the live evaluation of different rehabilitation solutions as the GA iteratively searches the solution spaces for optimal rehabilitation strategies. For any given rehabilitation solution, the following aspects, which constitute the main objective functions, are evaluated; pre and post intervention structural condition scores (S0 and S1), raw rehabilitation cost and mobilisation cost (C_{raw} and C_{mob}), post rehabilitation peak structural condition score (S_{peak}) and the asset criticality weighting (C_{weight}). A tabulated example of an evaluated output from a rehabilitation strategy for 10 assets is produced in Table 3-2.

Table 3-2. Sewer rehabilitation strategy analysis

Asset Data			Structural Condition			Construction Cost			Critical Risk		
#	Dia	Criticality Code	S^0	S^1	ΔS	C_{raw}	C_{mob}	C	S_{peak}	C_{weight}	R
1	100	A	80	80	0	£0	£0	£0	80	4	320
2	225	C	770	0	770	£6,863	£500	£7,363	0	1	0
3	225	Bx	3845	0	3845	£35,497	£500	£35,997	0	3	0
4	225	A	165	165	0	£0	£0	£0	165	4	660
5	150	B	314	0	314	£3,600	£500	£4,100	0	2	0
6	300	Ax	290	0	290	£3,930	£500	£4,430	0	5	0
7	225	Ax	220	40	180	£1,183	£500	£1,683	30	5	150
8	300	A	80	80	0	£0	£0	£0	80	4	320
9	150	C	241	0	241	£3,668	£500	£4,168	0	1	0
10	150	A	1137	0	1137	£16,694	£500	£17,194	0	4	0
Objective function outputs					**6,777**			**£74,934**			**1,450**

In this example the rehabilitation strategy scores the following for each of the objective functions:

1. Structural condition improvement (ΔS) = 6,777
2. Rehabilitation construction cost (C) = £74,934
3. Critical risk of failure (R) = 1,450

The values of the objective function items 1 and 3, condition improvement and critical risk of failure, are meaningless numbers except where a Pareto optimal trade-off curve is presented to the user. Halhal et al. (1997) explained that each point on the Pareto optimal curve is not dominated by any other point, i.e. in going from one point to another it is not possible to improve on one criterion without making at least one of the other criteria worse. The GANetXL optimisation model used in this analysis (Savić et al., 2011) evaluates each of the objective functions separately. In contrast, a single-objective optimisation problem is solved by finding a single optimal solution. Therefore, when a multi-objective problem is solved successfully, wide arrays of solutions are presented as Pareto optimal trade-off curves.

In this instance, these solutions show the trade-off between the three objective functions being considered. Thereby, a range of Pareto optimal solutions is presented to the user to aid in their selection of the most suitable rehabilitation strategy. It is most common for decision makers to evaluate solutions in terms of cost. Therefore, the two non monetary based objective functions that are evaluated in this case study, are presented graphically along the y-axis against a common financial base-line along the x-axis of Figure 3-4. Figure 3-4 provides a direct comparison between conventional engineering solutions that have been produced for the catchment and those solutions identified by the optimisation tool.

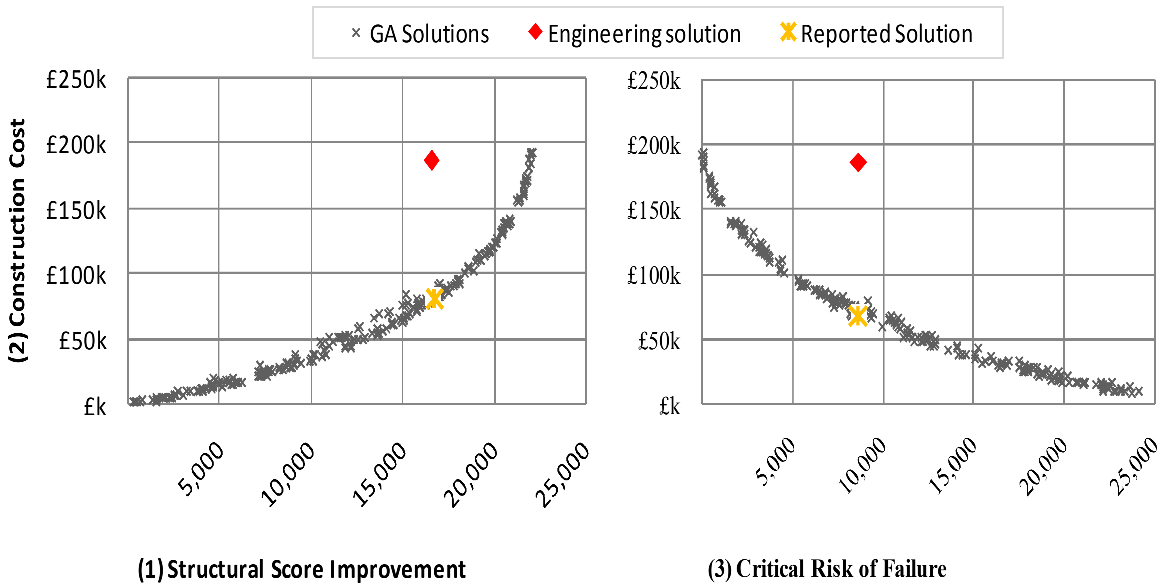

Figure 3-4. Engineering and optimisation solution comparison

It can be seen that a conventional approach to sewer rehabilitation produced a solution to the problem at an estimated construction value of £186,541. In terms of Objective Function (1) Structural condition improvement, this solution was evaluated at 16,650. However, an equivalent solution in-terms of structural condition improvement, is identified by the optimisation model at a cost of only £80,393. Hereby, acknowledging a potential saving in excess of £100,000 between the conventional engineering solution and that of the optimisation model. Appendix B documents the full details of this solution and the difference between the optimised and the engineering solution for each of the 67 sewers reported in this case study.

Similarly, an even greater saving of £116,000 can be achieved for the delivery of an equally beneficial solution in-terms of Objective Function (3) Critical risk of failure, when it is compared using a financial base-line of Objective Function (2) Construction cost. Figure 3-4 illustrates that the GA optimisation tool is capable of producing a wide array of non-dominated solutions for the user to select; ranging from an investment value of £200,000 to £0, which represent the options for fixing all or none of the observed structural defects respectively. Alternatively, the user can use these trade-off solution curves to fix an acceptable level of critical risk within each catchment by delivering the combination of rehabilitation solutions that reduce the critical risk of failure to below this pre-defined level.

This advance level of solution expenditure vision and improved understand of rehabilitation solution benefit, provides both planners and engineers alike with a unique platform for engineering creativity and advanced financial planning capabilities.

3.5 CONCLUSION

Sewerage systems are an essential element of the urban water infrastructure system. The rehabilitation and maintenance work associated with these assets form a large part of a utility company's annual expenditure. Therefore, as these infrastructure systems age, the pressure to effectively manage and rehabilitate these systems is also increasing. The result is a demand in the need for engineers to develop rehabilitation strategies that meet multiple conflicting objectives; maximisation of the overall structural condition improvement of the network (Objective Function 1), minimisation of construction costs (Objective Function 2), and minimisation of the risk of critical asset failure (Objective Function 3).

Conventionally, it has only been possible to develop sewer rehabilitation strategies on an asset-by-asset basis which calls on engineering best practise guidance to determine when a sewers' condition is deemed worthy of rehabilitative action. In addition, the lack in human ability to evaluate problems of a conflicting and complex nature makes the optimal specification of rehabilitation strategies within a catchment an almost impossible manual task to achieve. However, via the introduction of a multi-objective optimisation tool to the problem, a unique methodology capable of quantifiably appraising optimal rehabilitation strategies is developed.

An appraisal of the models effectiveness and suitability has been conducted on a catchment case study provided by South West Water, UK. The catchment rehabilitation strategy, produced manually using engineering best practice, was evaluated by the rehabilitation cost model developed in this study at £186,500. In comparison, the optimisation model identified equally beneficial solutions, as defined by the aforementioned Objective Functions 1 and 3, at a cost of only £82,300 and £69,000 respectively. Whilst the global optimality of the solutions identified cannot be guaranteed, the model clearly demonstrates the ability to converge towards optimal solutions which would otherwise be over-looked through manual interpretation of the data alone.

Therefore, given the identified improvement over the manual specification of sewer rehabilitation strategies, coupled with the ability of the optimisation tool to use widely available condition data, this study further reinforces the need to effectively integrate such Hydroinformatic tools into business as usual processes within the UK sewerage industry.

3.6 RESEARCH APPLICATION

This chapter has acknowledged that the specification of sewer rehabilitation interventions had previously been based on engineering judgement and rules (WRc, 2004b). This is in contrast to other industries and even other problems in the water industry which have successfully applied multi criteria decision making algorithms to help identify least cost and maximum benefit solutions, e.g., construction management (Zheng et al., 2004); liquefied natural gas terminal design (Boulougouris and Papanikolaou, 2008); water management (Xevi and Khan, 2005); and water distribution network design (Farmani et al., 2005).

The new modelling approach, since named the ‘asset investment Decision Environment’ (aiDE), demonstrates that considerable financial savings can be realised by evaluating the costs and benefits of a wide array of intervention options across the sewerage network, during the design and planning phases – often referred to as outline design.

In order to realise these benefits, further work has been conducted to integrate aiDE with commercially available data management software, InfoNet ©. InfoNet is a commonly used data management system that acts as a centralised data repository and geospatial information system (GIS) for corporate asset data, inspection information and rehabilitation works. Linkages between aiDE and InfoNet have been developed such that optimised rehabilitation programmes are capable of being output into InfoNet, which can be subsequently used as the delivery vehicle for the rehabilitation programme itself. There-by creating an immediate digital record of the proposed work, which is scheduled, automatically costed and monitored during delivery. The commercial benefits are two-fold: Firstly, significantly lower cost solutions can be identified when compared to manually developed solutions, as evidenced in the case study. Secondly, the decision support system offers an improved review process for the engineer. By screening out low benefit solutions, the engineering process is more efficient.

4 AN OPTIMISED TOTAL EXPENDITURE APPROACH TO SEWERAGE MANAGEMENT

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4.1 BACKGROUND

Chapter 3 focused on delivering improvements to the tedious and subjective process of specifying rehabilitation solutions from condition inspection information. This was achieved through the development of a multi-objective decision support methodology, capable of evaluating different combinations of optimal solutions in the delivery of catchment wide rehabilitation programmes. The research demonstrated how optimal schemes could be identified across a catchment from raw CCTV data, by presenting the problem as a multi-objective trade-off between maximising asset life vs. minimising costs.

Significant benefits were demonstrated in comparison to traditionally developed engineering solutions, although the model was found to lack the ability to consider the operational performance benefits associated with different schemes. Resulting in the model overlooking slightly more expensive solutions despite the ability of these solutions to provide significant operational benefits. Upon reflection, the initial model aligned itself to the behaviour of the industry at the time where-by capital investment was being prioritised over operation expenditure.

Prior to 2013, Water Companies had been remunerated for their costs using an Infrastructure Renewals Charge, which includes an allowance for depreciation and an allowance made against the Regulated Capital Value [RCV] to calculate the return on capital allowed. The OFWAT method assesses the value of the regulated business that can earn a return on investment. It represents the initial market value (200-day average), including debt, plus subsequent net new capital expenditure as assumed at the time of initial price setting. Given that the RCV includes an allowance for new capital expenditure, it encourages Capex solutions rather than Opex, therefore encouraging inefficient investment and making it difficult to incentivise innovations that do not rely on Capex.

However, in January 2013 Ofwat released its first published guidance surrounding the framework for setting price limits for the next regulatory period, commencing 2015. This guidance generally reflected Ofwat beliefs that the current investment planning system where-by capital and operational expenditure are accounted for separately, is complex and burdensome. Therefore, in this guidance, Ofwat advises that the preferred approach to cost assessment is one which considers Capital and Operational Expenditure as one, i.e., Total Expenditure (Totex), (Ofwat, 2013).

In response to these regulatory changes, Chapter 4 is produced to help sewerage engineers adopt a total expenditure approach to operational decisional making, through the development of a methodology and a platform capable of evaluating the trade-offs that exist between the capital and operational benefits associated with different sewer rehabilitation schemes.

The research is focused on the development of a series of GIS based processes and tools that can be integrated within the existing modelling environment to help prioritise high benefit sewer rehabilitation schemes, by evaluating the potential serviceability improvements that can be realised in addition to the purely structural condition improvements, i.e., reduced pollution, blockage and/or flooding events.

This also ensures alignment with recognised best practise, that requires truly optimal rehabilitation strategies to consider the cost to service interruptions from the perspective of operational costs, environmental damage and customer impact (Adey et al., 2003).

Specifically this chapter seeks to introduce operational maintenance decision within the previously improved capital decision making methodology, Chapter 3..

4.2 INTRODUCTION

Sewer rehabilitation planning is currently a slow and repetitive process which often requires the decision maker to review condition inspection information when deciding upon the best course of intervention techniques (Yang and Su, 2006). During this process, it is highly unlikely that the decision maker will attempt to evaluate the strategic business benefits surrounding their investment decisions from a catchment or network wide perspective. This is due to the complexities associated with being able to quantify the change in risk of failure, or serviceability improvements, which can be achieved through different combinations of rehabilitation strategies.

Halfawy and Baker (2009) define sewer network renewal planning as a process that establishes the most appropriate and cost effective intervention action for each pipe segment in the network. The approach draws similarities to the cost and reliability trade-off concept observed by (Dandy and Engelhardt, 2006) for potable water mains replacement; where-by the objectives for optimal sewer rehabilitation planning are also conflicting. This implies that the rehabilitation solutions that vastly improve the structural condition of an asset would typically have high associated costs. Therefore, to permit effective planning and investment to occur, it is important that decision makers understand and appreciated the cost vs. benefit trade-off between different rehabilitation solutions and the possible combinations of these solutions that can be delivered across a catchment.

Over the past two decades, researchers and practitioners have begun to utilise the availability of standardised CCTV sewer inspection information (National Association of Sewer Service Companies NASSCO, 2001; WRc, 2004; and Water Environment Federation, American Society of Civil Engineers, & Water, 2009) to formulate reliable and repeatable approaches to predict the future condition of sewerage assets (Kathula et al., 1999; Wirahadikusumah et al., 1999; Baik et al., 2006).

It was recognised by Wirahadikusumah et al. (1998) that the defect coding outputs produced by these condition inspection methods are the single most important element of information used by planners, contractors and consulting engineers to help ascertain the current condition of sewerage assets. In support of this statement, more recent Hydroinformatic tools are also founded on these standardised inspection formats as they seek to support the rehabilitation decision making process (Baur et al., 2005; Saegrov, 2006). Similarly, the availability of ever increasing computational power, when coupled with the inspection information, has allowed for the application of optimisation algorithms to identify cost effective intervention options and inspection timings for complex networks (Ugarelli and Federico, 2010; Yang and Su, 2006; Halfawy et al., 2008; Berardi et al., 2008).

Despite the success of the above literature, which has all contributed in some way towards improving sewer rehabilitation planning, criticisms have focused on the lack of transparency and user interaction with the tools which are often referred to as black box systems (Marsalek et al., 1998). It is also evident that none of the above methodologies allow for the decision maker to adopt a truly strategic vision of the trade-off’s that exist between different rehabilitation schemes at an asset or catchment level. This understanding of the trade-offs that exist between different solutions is particularly valuable in the current economic climate where-by rehabilitation budgets are constrained which is in-turn forcing decision makers to prioritise assets for investment.

4.3 A PROPOSED TOTAL EXPENDITURE APPROACH USING OPTIMISATION

It is generally accepted by Ofwat that the current system, where-by capital and operational expenditure (Capex and Opex) are accounted for separately, is complex and burdensome. It is also reported that the water industry currently exhibits a bias towards capital rather than operational expenditure (Engelhardt and Turner, 2011; Ofwat, 2011; Utility Week, 2012). The problem with this type of bias is that utility providers are being financially incentivised to invest in capital schemes instead of more operationally related solutions - almost irrespective of which option is better suited to addressing the problem (Ofwat, 2011c). In light of the above, it is widely foreseen that the UK water industry will begin to evaluate investment on a total expenditure (TotEx) basis.

To assist in this transition, a previously successful sewer rehabilitation optimisation model (Ward and Savić, 2012) has been modified to adopt a TotEx approach to the problem of strategic sewer rehabilitation. This approach allows for the user to consider the trade-offs that exist between the capital and operational benefits of different intervention strategies. It was deemed more appropriate to present the problem as a trade-off between CapEX and OpEx benefits, instead of evaluating schemes for their combined operational and capital benefits i.e., TotEX. Representing the problem as a multi-objective trade-off is well suited to the application of optimisation based algorithms because it ultimately provides greater flexibility to the decision maker.

Optimisation is a technique that represents a problem so that a mathematical procedure can be applied to solve it. Generally speaking, optimisation tools look to either maximise or minimise an objective function(s) by changing the decision variables of the problem. These decision variables are changeable to form a solution within the limits of the problems constraints, which are used to impart reality and/or to ensure that only desirable solutions are found. Nicklow et al. (2010) recognised how genetic algorithms have become a mature technology in the water and waste water industry because of their ability to solve complex network management and planning problems by mimicking natural evolution. In order for a multi-objective genetic algorithm to be applied to the problem of optimal sewer rehabilitation specification, a decision environment is used to formulate the problem in-terms of the aforementioned objective functions, decision variables and constraints.

This environment structures the raw data into an organised and interpretable sewer rehabilitation matrix. This is subsequently used by the model to converge upon optimal solutions using a well-established multi-objective genetic algorithm (Savić et al., 2011). Table 4-1 displays the organised data structure alongside the corresponding possible range of values for each field and Table 4-2 provides an example for a short CCTV survey that has been translated ready for analysis by the genetic algorithm. Essentially, the structure is formed by assigning individual rows to every defect observation in the condition survey. This is done through interrogation of an industry standard CCTV survey format, the Manual of Sewer Condition Classification 4th Edition (MSCC4), which was developed by the WRc (2004).

Table 4-1. Optimisation data structure

Field	Description	Range of values
1	Position along the pipe (m)	[0 – length]
2	Decision variable	[0 – 3]
3	Defect code	[code]
4	Observed Defect Score (S^0)	[score]
5	Post Rehabilitation Defect Score (S^1)	[score]
6	Maximum repair length (m)	[position – position+1.5]
7	Patch or lining (Y/N)	[0 – 2]
8	Contiguous lining (Y/N)	[0 – 1]

Table 4-2. Sample problem representation for a single sewer length

Position along the pipe (m)	*Decision variable*	*Defect code*	*Observed Defect Score (S^0)*	*Post Rehabilitation Defect Score (S^1)*	*Maximum repair length (m)*	*Patch or lining (Y/N)*	*Contiguous lining (Y/N)*
0	0	OJ	80	0	1.5	0	1
2	1	CC	10	0	3.5	1	1
10	3	FM	80	0	11.5	0	1

The following information is extracted directly from the conventional MSCC4 CCTV inspection report: the position of the defect along the sewer; the defect code; and its corresponding score, as shown in fields 1, 3 and 4 of Table 4-1 respectively. The decision variable field is added by the model for use by the genetic algorithm to select between different solutions. It may take the form of one of four potential values. Where: (0) represents no rehabilitation; (1) represents a patch repair; (2) represents lining from the upstream manhole towards the downstream manhole; and (3) indicates lining from the downstream manhole upwards. The post rehabilitation defect score (S1) is calculated as the sum total of the remaining defect scores after rehabilitation, i.e., the un-remediated defects.

Unlike previous work by Ward and Savić (2012), the model described in this paper presents the problem in a much more computationally efficient manner. Rather than assigning decision variables to each one meter section of the sewer, to indicate whether the section is being repaired (1) or not (0), the decision variables are now only applied to the defective sections of sewer. Figure 4-1 is provided to help visualise the improved search space in the new model via the removal of sections of pipework where structural defects have not been observed. It is important to note that despite condensing the problem from a modelling perspective, the logical repairs which span healthy sections of pipework, i.e., contiguous re-lining lengths between defects, can still be selected by the optimisation algorithm.

This also demonstrates how the solutions can span other decision variables which are essentially “turned-off” from consideration by the model when contiguous lining would encompasses them. This is achieved via the use of a set of logical rules set up in fields 7 and 8 of Table 4-1 and Table 4-2.

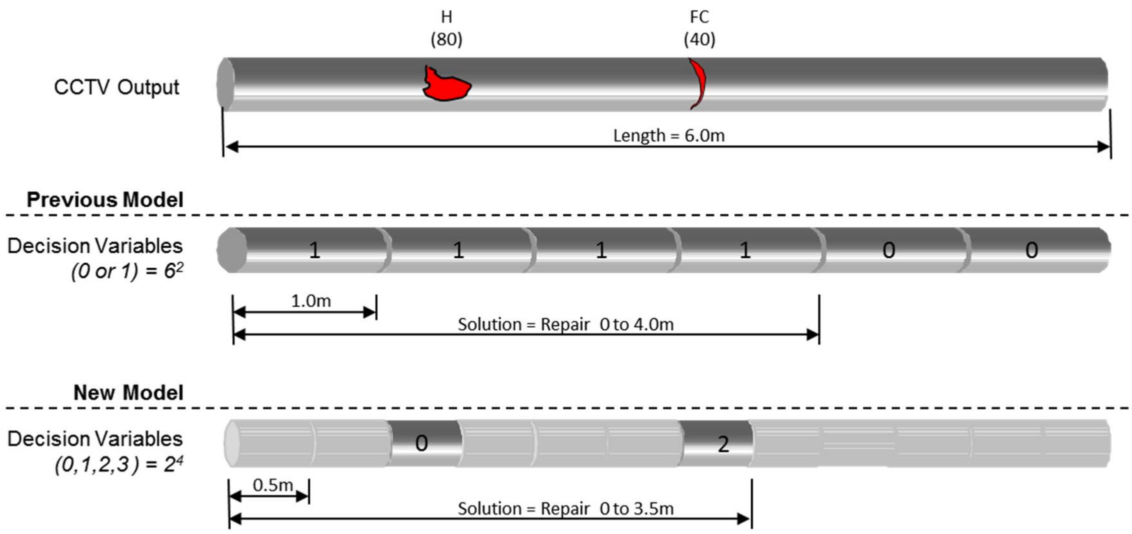

Figure 4-1. Comparison of modelled solution search space

The new representation of the problem has delivered a significant processing performance improvement which has enabled the tool to produce an array of optimal rehabilitation solutions for individual assets within seconds. These solutions each present a trade-off between asset life preservation (capital benefit) vs. rehabilitation cost, thus allowing for the tool to be used as a “real time” decision support system that quickly identifies the performance and cost of all feasible rehabilitation solutions. At this point the engineer is presented with an array of optimised solutions for each asset which he/she can override, e.g., the repair methodology can be changed from a trenchless to excavated solution, or, additional repairs can be added to the set of solutions identified by the genetic algorithm alone. The final stage of the model uses these outputs to develop an asset management strategy by optimising for a set of network-wide rehabilitation schemes from the pre-selected rehabilitation solutions identified for each individual asset.

The approach uses the same multi-objective genetic algorithm as before, but with a new operational performance objective function in place of the original third objective which considered critical risk of failure. The new objective function is developed using a series of GIS tools to interrogate historical operational and maintenance activities when determining the potential benefits associated with the restoration of one asset over another. Therefore, the output from the second phase of optimisation is a trade-off between investment cost vs. asset life preservation (CapEX) vs. serviceability improvements (OpEX).

Once the user has selected a scheme, which is defined as a group of assets for rehabilitation within a catchment, this selection of assets and the necessary remedial activity for each asset, i.e., rehabilitation length and technique, is fed back via a semi-automated process to a commercially available geospatial asset management tool, InfoNet © (Innovyze, 2012). InfoNet is used to host the utility providers' corporate sewerage asset database which is eventually overlaid with the asset specific rehabilitation information as identified by the optimisation algorithm. There-by showing what assets to rehabilitate and the extent and nature of each rehabilitation solution.

Defining optimal rehabilitation solutions

The global objective of any infrastructure network rehabilitation programme is typically to improve performance or increase the networks reliability (Sitzenfrei, Mair, et al., 2011). However, the problem of how best to represent network performance is a topic that has generated much variance between different models and published literature (Fenner, 2000). This is mostly caused by the complexity of the problem in conjunction with the fact that network performance is often interpreted differently by different stake holders. The authors present three objective functions which are used to evaluate and trade-off between the benefits of different rehabilitation solutions at catchment, or network, level: (1) maximise asset life; vs. (2) minimise investment cost; vs. (3) proactively address serviceability problems. The processes undertaken to calculate objective functions 1 and 2 are well documented in (Ward and Savić, 2011) and remain largely unchanged.

The first objective function in this model, Equation 4-1, considers a very simplified approach to the problem of quantifying network improvement. It builds on previous work undertaken in clean water distribution planning by Halhal et al. (1997) where-by the authors assumed that any length of pipe replaced in the network would provide for an improvement in overall water quality. Thus allowing the total length of water mains replaced to be representative of the networks water quality improvement. Similarly, the sum of the observed defect scores (S0) from the coded CCTV condition inspection report for each sewer (i) are used here to represent the current condition of a catchment or network with (N) number of sewers.

It also assumes that an improvement in a sewers structural condition can only be obtained by interventions to remediate the observed defects. Therefore, the structural score post rehabilitation for each sewer (S1) is simply the sum of the structural defect scores that remain unaltered by the rehabilitation solution. As a result, any change to this total can be used to quantify the total benefit provided by the rehabilitation strategy being implemented.

$$Structural\ Improvement = \sum_{i=1}^{N} [S_i^0 - S_i^1]$$

Equation 4-1

$$where\ i = 1, 2, \ldots, N$$

The second objective function focuses on minimisation of construction costs. Therefore, it is of fundamental importance that the cost of each rehabilitation strategy is calculated accurately to ensure that the comparison of different strategies is representative of the actual delivery costs that will be incurred. To account for local cost differences between different utility providers and/or different rehabilitation contractors, the model presented in this paper has been developed with the flexibility to include bespoke cost models into its analysis.

The case study that is cited in this paper uses an audited cost model that has been provided by South West Water which distinguishes between; the type of repair, repair length, sewer diameter and the above ground conditions for excavated solutions, i.e., highway, verge or grassland. Minor modifications have been made to the cost model that account for contractor mobilisation costs and economies of scale for consecutive repairs which were previously omitted.

The third objective function is a new feature that has been introduced to the model to help decision makers adopt a more sustainable asset management practise, by considering the serviceability improvements that different rehabilitation schemes can offer in the network (Ugarelli et al., 2010). This third objective function has been integrated via a series of bespoke Geographic Information System (GIS) tools which are run within ESRI's ArcGIS® software. These tools are used to help account for the geo-spatial nature of serviceability incidents when determining and quantifying the operational benefits of different rehabilitation solutions, i.e., the prevention of a future flooding and/or pollution event resulting from a collapse.

The assessment is firstly made by evaluating the spatial proximity of historic serviceability incidents to the sewer being considered for rehabilitation. As a general rule, the further away an incident is from the pipe being considered equals a lower likelihood of the incident being related to that pipe. Therefore, a GIS buffering exercise is used to reduce the risk of collecting events which fall outside the sphere of a sewers influence. An adjustable buffer size, dependent upon the address point density, is used such that areas of high address point densities are assigned smaller buffer sizes to reduce the risk of selecting events that are occurring on adjacent streets. Where-as in areas of low address point density (e.g. rural areas) the buffer size is increased to recognise that the public sewers will often be further away from the properties they immediately serve.

The GIS model then applies a logical set of criteria depending on the type of incident that the rehabilitation solution is thought to resolve, to establish the perceived avoided private cost (PR) associated with the rehabilitation scheme. A confidence factor of 0.5 is applied to the avoided private costs associated with each of the incidents recorded as “blockage paper/rag” (BPR) and “potential collapse” (CPO), there-by demonstrating less certainty that the rehabilitation solution will in-fact address these incidents. Where-as the incidents recorded as “blockage roots”, “partial collapse” and/or “collapse” are assigned a confidence factor of 1.0 to signify a higher level of certainty that these incidents will be directly addressed and prevented from occurring in future.

Table 4-3. Operational benefit costs by incident type

Incident Ref (x)	Incident Code	Probability of incident resolution (f)	Incident Description	Private Cost per incident (PR)
1	B_{PR}	0.5	Blockage paper/rag	£1,000
2	B_{RO}	1.0	Blockage roots	£1,500
3	C_O	1.0	Collapse	£15,000
4	C_{PA}	1.0	Partial Collapse	£10,000
5	C_{PO}	0.5	Potential Collapse	£500

The annualised frequency of an incident occurring each year is calculated from the historic recorded event data and it is assumed that the historic frequency of occurrence would proceed at the same rate if a rehabilitation solution were not specified. This is accounted for in Equation 4-2 which calculates the total period of time that each incident has been experienced for and then allows for the cost benefit of the rehabilitation scheme to be represented as an annualised benefit value.

$$Annual\ operational\ benefit\ \left(\frac{£}{yr}\right) = \sum_{x=1}^{5} f_x \left[\frac{\sum PR_x}{T2_x - T1_x}\right]$$

Equation 4-2

$$where\ x = 1, 2, \ldots, 5$$

In addition to the resolution of these annualised incidents, additional one-off benefits are realised through the prevention of sewer failure. The one-off costs arising as a direct result of sewer failure are quantified in monetary terms under two categories; Private (PR) and Social/Environmental (S/E) costs. Private costs are those that are incurred by the business in response to a sewer failure and include all costs incurred to remedy the collapse. These are typically well understood and can be derived from an assessment of historic costs. Social and environmental costs are those that are incurred by society and/or the environment as a result of a collapse, i.e., disruption to traffic or pollution of a water course. These costs are typically more difficult to define and water utility providers often refer to guidance set out by the Environment Agency (2003) to help quantify the environmental impact, or, they rely on customer willingness to pay information linked to Operational Performance Measures (OPM's), (Willis et al., 2005; Heather and Bridgeman, 2007).

To apply these costs to each rehabilitation scheme the following formula is used in conjunction with Table 4, which gives consideration to the unique characteristics and spatial proximity of each sewer to other infrastructure and environmental features. A list of probabilities (P) and the costs that are assigned to the prevention of an operational performance measure, associated with a sewer collapse, are listed in Table 4 for OPMs A to J.

$$Collapse\ Cost\ (£) = \sum_{Ref\ =\ A}^{J} \left[\mathrm{P_{Ref}} * (\mathrm{PR}_{Ref} + \frac{\mathrm{S}}{\mathrm{E_{Ref}}}) \right]$$

Equation 4-3

$$where\ Ref = A, B, \dots, J$$

Table 4-4. Operation performance measures, probability of occurrence and costs

Ref	Operational Performance Measure (OPM)	Measure	Probability per collapse (P)	Criteria	Cost per event (£ 000)	
A	Traffic Disruption	All	1	All sewers	PR	20
					S/E	-
B		A Road		All sewers beneath A roads	S/E	100
C		B Road		All sewers beneath B roads	S/E	50
D		Minor Road		All sewers beneath minor roads	S/E	10
E	Flooding	Internal event	0.01	All sewers in densely populated areas	PR	5
					S/E	100
F		External event	0.05	All sewers in densely populated areas	PR	1
					S/E	8
G		A Road flooding	0.1	All sewers beneath A roads	PR	1
					S/E	15
H		B Road flooding	0.1	All sewers beneath B roads	PR	0.5
					S/E	5
I	Pollution	Category 2 event	0.004	All foul/combined sewers <625mm diameter	PR	10
					S/E	1,000
J		Category 3 event	0.004	All foul/combined sewers >625mm diameter	PR	3
					S/E	50
K		EA prosecution	0.5	Conditional probability per pollution event for foul/combined sewers that results in EA prosecution	PR	20
					S/E	-
L		Bathing Water pollution	0.2	Conditional probability per EA prosecution for foul/combined sewers within 200m of special site	PR	10
					S/E	300
M		Shellfishery pollution	0.2		PR	10
					S/E	50
N		Biodiversity & heritage pollution	0.2		PR	5
					S/E	200
O	Customer Contact	Call	50	Average no. of customers experienced per collapse	PR	0.02
					S/E	0.01
P		Letter	0.05	Conditional probability per customer call that results in a letter	PR	0.05
					S/E	-

* *The costs shown are for indicative purposes only*

** *All applicable costs are additive if any of the proceeding criteria are valid*

Therefore, when the annualised savings associated with the resolution of historic serviceability incidents is combined with the one-off costs avoided via the prevention of a sewer collapse, a monetary value that reflects the annual operational expenditure and the avoided serviceability costs is assigned to each rehabilitation solution. Assuming that the resolution of historic serviceability incidents will last for 25 years then the third objective function, operational benefit, is expressed mathematical in Equation 4-4.

$$\begin{aligned} Operational\ Benefit\ (£) &= Avoided\ Collapse\ Cost \\ &+ (Annual\ Operational\ Benefit * 25) \end{aligned} \quad \text{Equation 4-4}$$

4.4 CASE STUDY

A new methodology for optimising sewer rehabilitation has been developed which uses conventional CCTV data to identify which sewers to rehabilitate and the extent and nature of the rehabilitation required, whilst also considering the serviceability benefits that different rehabilitation schemes bring to the customer. The study was commissioned by South West Water (UK) with the aim of embedding sewer network performance, as a decision making criteria, into a previously successful sewer rehabilitation model developed by Ward and Savić (2012). The 2012 study documents the benefits associated with using a multi-objective optimisation model to evaluate the trade-offs between structural condition improvement (objective function 1) and cost (objective function 2).

An appraisal of the models effectiveness, Section 3.4 and Appendix B, demonstrated the models capability of identifying equally beneficial solutions for approximately 50% of the construction value when compared to manually produced solutions. A number of limitations and challenges were identified by the authors when considering its use as a day-to-day decision support tool, namely; the solution feasibility (from an engineering delivery perspective), run time and the lack of consideration to the improvements in sewer network performance that different rehabilitation schemes can offer, i.e., via the resolution of historic incidents or by mitigating sewer collapse risk.

A new model is presented in this paper which improves upon all of these limitations, whilst retaining the underline principles of their work. The challenge of embedding sewer network performance into the decision making framework is achieved via the use of advanced geospatial information technology to quantify the network performance improvements associated with different rehabilitation schemes across a catchment, as described in Section 4.3. This resulted in the development of a new objective function (operational benefit) which has been used in replacement of the previous third objective function (critical risk).

Solution feasibility was addressed by screening the optimised solution presented by the model to exclude those that are not practicable from an engineering perspective, i.e., by removing solutions specifying multiple patch repairs which in reality would be delivered as a full lining. The outputs from this process have been tabulated in Appendix C, as a series of feasible engineering solutions for each individual asset. These solutions were then presented for network wide optimisation. The results from which are presented in Figure 4-2.

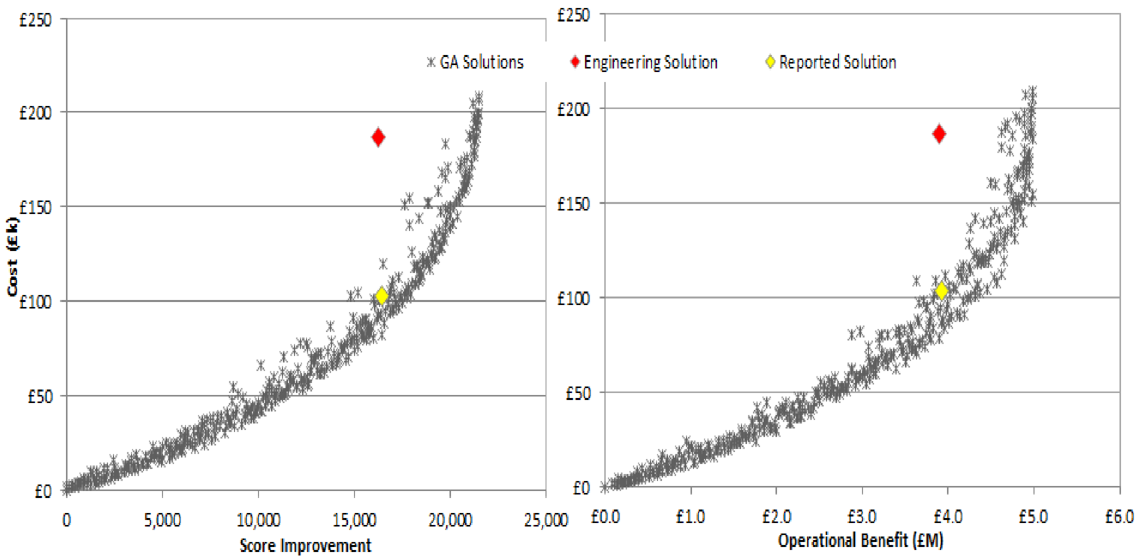

Figure 4-2. Optimisation results vs. engineering solution

The results are presented in an identical format as those produced in Section 3.4 for ease of comparison. It can be seen that an optimised solution which delivers a structural condition grade improvement and operational benefits equal to the engineering solution, can be achieved at a cost of only £103,099. Although this solution is marginally less cost effective as the solution reported in Section 3.4 (£80,393), the practical delivery of this solution is feasible and still represents a saving of £83,648 from the original engineering solution. A detailed review of the difference between the engineering solution and the selected optimised solution is presented in Appendix D.

By introducing this third objective function, the model now considers sewer rehabilitation from a total expenditure perspective by actively promoting solutions that offer direct serviceability benefits for customers and therefore reduced operational costs for the utility providers. These optimal serviceability solutions were also found to outperform the original engineering solution from a capital expenditure perspective in their own right.

The integration of this new objective function, alongside the vastly improved computational processing time, has established the model as a feasible and truly strategic decision support tool that can be used for optimal sewer rehabilitation planning. For some time the water industry has recognised the need for more sustainable and comprehensive sewerage assets management methodologies because of the increasing customer and political pressures in conjunction with tightening regulations (Fenner et al., 2000). Heightened financial costs due to the reactive nature of the work, damaged business reputations and the increased likelihood of social and environmental impacts are all reasons that justify the use of this type of approach which is receiving increasing support (Ofwat, 2006; UKWIR, 2002a).

4.5 CONCLUSION

Decision making and planning for sewerage asset renewal/rehabilitation is a process that seeks to evaluate the condition of an asset, its risk of failure, the cost of remediation and to understand the serviceability improvements that could be recognised by different interventions. Typically the objectives of a rehabilitation programme are conflicting, which implies that the interventions that vastly improve the structural condition or serviceability of an asset have typically high associated costs. Therefore, to permit effective planning and investment, it is important that decision makers understand the cost vs benefit trade-offs that exist between different schemes.

Historically, the specification of sewer rehabilitation solutions has been a tedious and manual process which is highly subjective due to its dependency on engineering interpretation. It is also a process which is often undertaken in isolation, i.e., on a pipe-by-pipe basis, with little consideration given to the global asset management strategy. The short-comings of the historic approach can largely be attributed to the complexity of the global asset management problem where-by the interaction between multiple assets across a network is too complex to tackle without the aid of decision support tools which are often seen as a luxury rather than a necessity.

As the water industry in the UK continues to mature, the attitudes and customer expectations are changing, which is in turn driving change in asset management best practice across water and wastewater infrastructure. One example is that greater emphasis is being placed on the need to deliver proactive rehabilitation programmes which improve serviceability performance for customers at low costs. In order for the industry to respond to this change, truly optimal rehabilitation investment programmes need to be delivered which are capable of considering the upfront trade-offs that exist between different schemes.

The optimisation environment presented here, uniquely considers sewerage asset rehabilitation from a global perspective. It quantifiably evaluates and optimises numerous rehabilitation solutions, such that the decision maker is presented with an understanding of the trade-off solution space between high benefit - low cost solutions and the optimal solutions that lie within that search space. The model has successfully demonstrated its capability to identify these optimal solutions which are presented back to the decision maker as a list of sewers to rehabilitate, plus the extent and nature of the rehabilitation that is required, depending on the elected solution.

However, by integrating operational benefits into the decision making process, the model now considers sewer rehabilitation from a total expenditure perspective. The advantage of this approach is that the decision maker is directed towards rehabilitation solutions that deliver on going serviceability benefits to customers whilst also outperform any originally developed engineering solution from a capital expenditure perspective in their own right.

This is one example of how the water industry is beginning to capitalise on the advancements in information technology and asset management best practice, but more work needs to be done to better integrate optimisation techniques and geospatial analysis into the day-to-day decision making philosophy across the industry. It is no longer acceptable to invest in infrastructure that will not yield direct benefits to the customer and the authors have successfully demonstrated one approach to ensure optimised rehabilitation programmes are delivered.

4.6 RESEARCH APPLICATION

In 2013, Ofwat, introduced a Totex perspective to cost recovery in addition to the traditional RCV-based approach to over-come inefficiencies associated with separate accounting and to remove previous incentives for bad behaviours, i.e., encouraging more expensive capital lead solutions rather than maintaining existing infrastructure through operational led solutions, (Ofwat 2013). By allowing for a Totex based cost recovery system, OFWAT will permit the assessment to be based on the total of the Capex and Opex expenditure over the period. Therefore, allowing efficiency and incentive targets to be set against Totex which will reduce the administrative burden and make the system simpler to use.

Most typically these regulatory changes are being addressed by the water company from a strategic perspective, by balancing the level of capital and operational expenditure across the organisation. However, it was felt that operational decision making, i.e., day-to-day decisions made at individual asset level, should also give consideration to potential longer-term Totex beneficial interventions. To realise the full potential of this improved operational decision making approach, it was necessary to accurately capture the consequence of failure costs that are associated with the failure of each sewer. Thus, requiring the development of a comprehensive methodology to capture the monetary value associated with the direct and indirect costs of failure. Where-by the term ‘direct costs’ refer to the cost incurred to restore the functionality of the asset as opposed to ‘indirect costs’ which account for the additional costs that may arise from its failure, e.g., infrastructure damage, customer disruptions or regulatory fines.

The ability for the optimisation algorithm to present a trade-off between Operational and Capital benefits associated with different solutions offers a benefit to the decision maker, by ensuring that capital solutions are only specified where they outweigh the operational alternative.

Therefore, deployment of this approach can help a water utility achieve the most cost effective balance between capital and operational expenditure. The model can also be used by the water company provider to justify their selected balance of Capex and Opex schemes to Ofwat.

To realise the full commercial potential from this research, the modelling framework has been developed to sit alongside other commercial software (InfoNet) which is being used for the management of large inspection and rehabilitation programmes by a number of utility operators across the World. Therefore the model has been configured as a stand-alone piece of software with an intuitive user interface that guides the decision maker through the following process:

i. Processing of survey outputs directly from InfoNet (Figure 4-3)
ii. Undertake the rehabilitation optimisation process (Figure 4-4)
iii. Visualise and manually modify the optimised solutions at individual asset level (Figure 4-5)
iv. Feedback these optimal solutions into InfoNet (Figure 4-6)

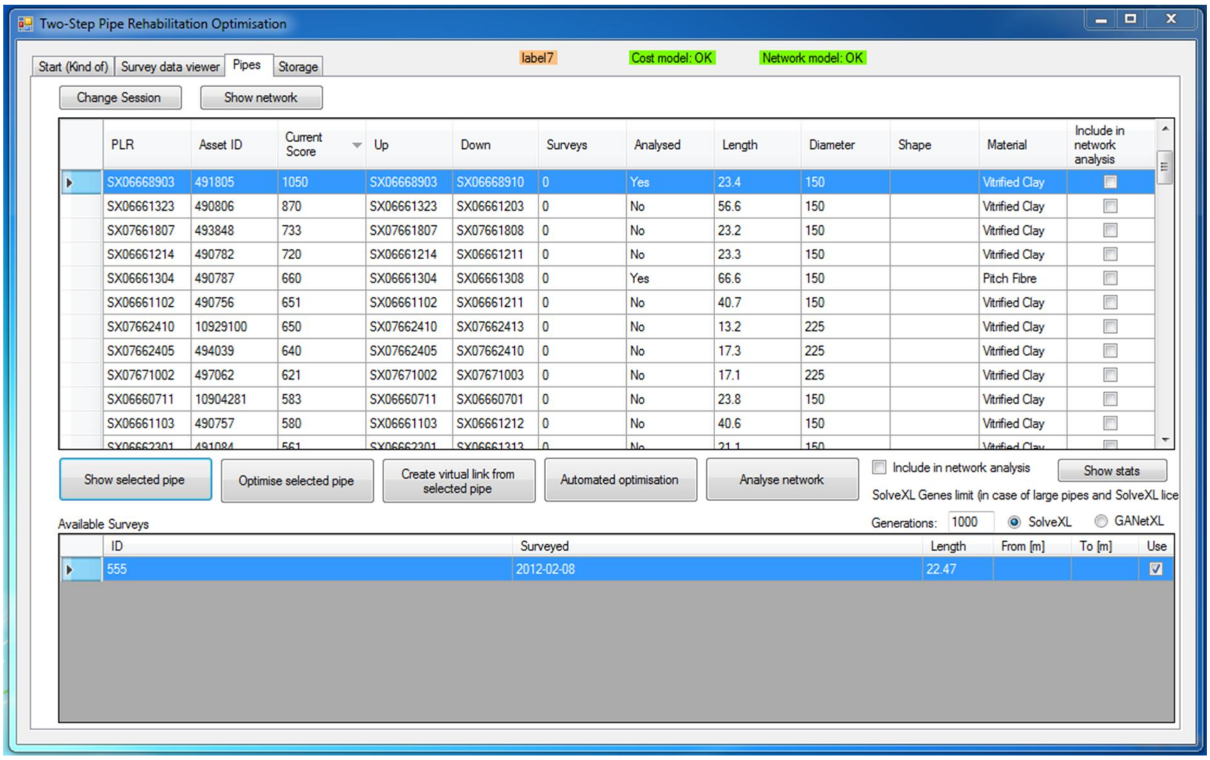

Figure 4-3. aiDE, user interface

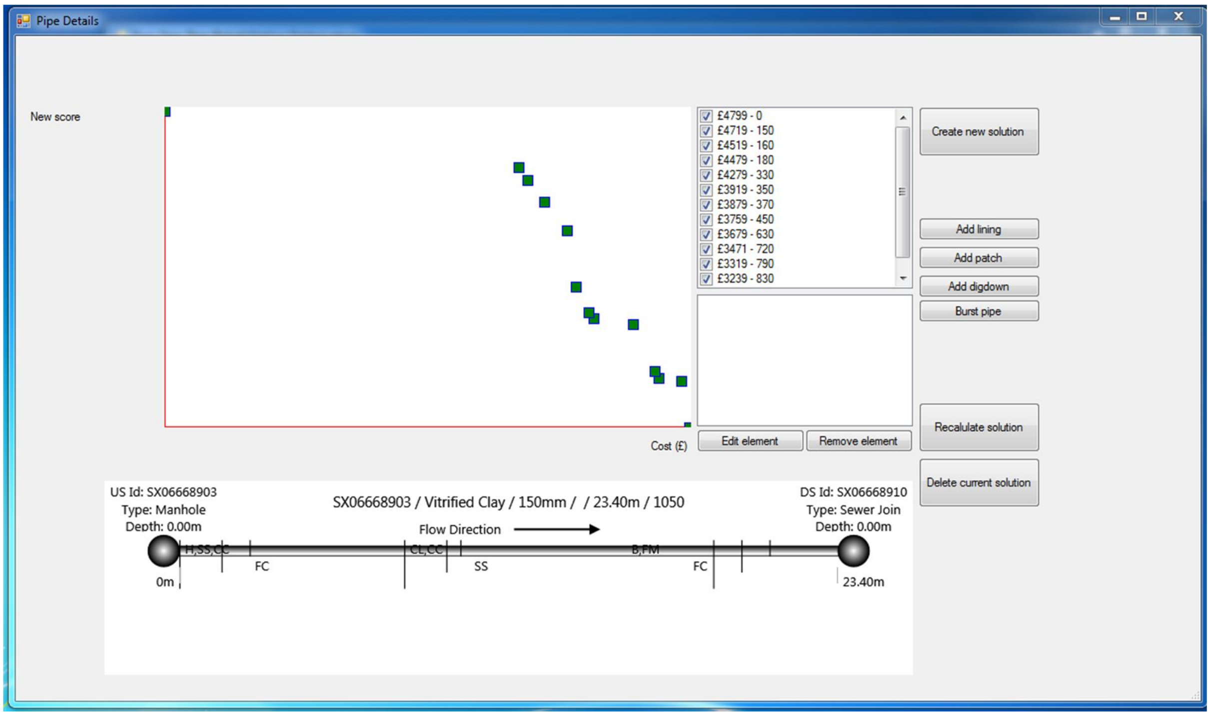

Figure 4-4. aiDE, asset level optimisation trade-off

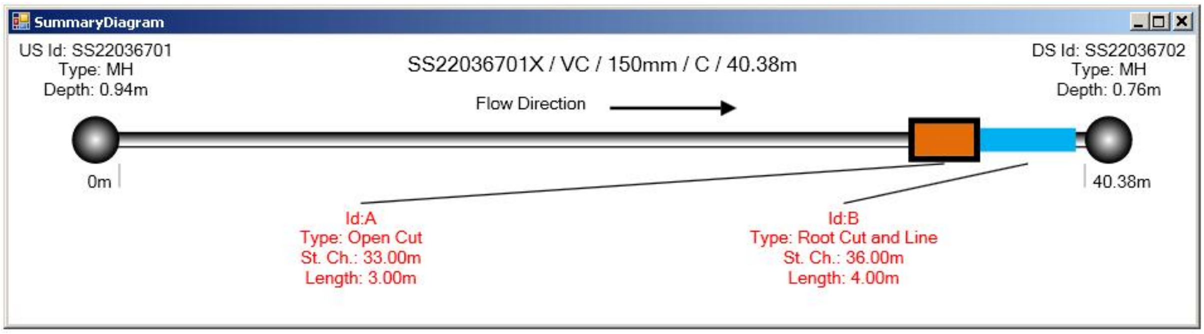

Figure 4-5. aiDE, asset level solution summary

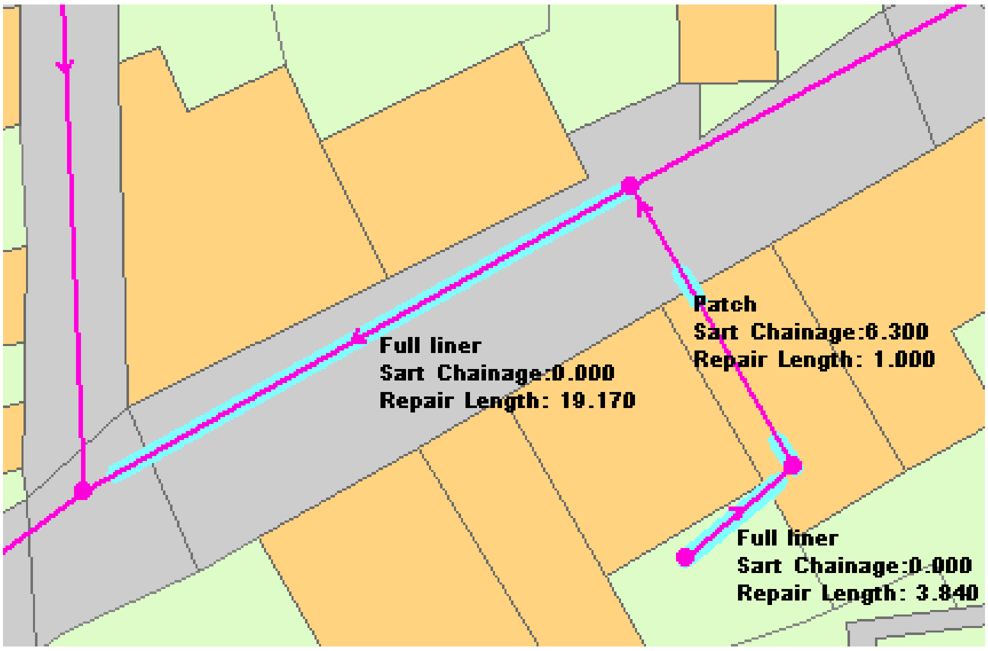

Figure 4-6. Catchment wide solutions exported and managed in InfoNet®

The model and associated software is readily deployable for any water company conducting CCTV inspections in accordance to the WRc Method of Sewer Condition Classification (MSCC4). This is a commonly used inspection coding system across the UK and some European cities. Minor modifications to the software would be required for other coding systems, i.e., Nassco's PACP, commonly used in North America.

5 QUANTITATIVE RISK ANALYSIS FOR LONG-LIVED WATER INFRASTRUCTURE ASSETS

This chapter was published in the proceedings of OzWater

Ward B and Savić D. A (2013). Quantitative Risk Analysis for Long-lived Water Infrastructure Assets. Proceedings of OzWater. Perth, Australia.

5.1 BACKGROUND

Long-lived water infrastructure assets represent a challenging and typically highly critical asset stock for water companies to effectively manage. The low failure rates associated with such assets, prevent the use of stochastic based deterioration models which are more commonly used to inform and prioritise investment decisions across other water infrastructure assets. Other industries have responded to this challenge by adopting a well advanced risk management technique known as Quantitative Risk Analysis (QRA) which provides decision makers with an established platform to prioritise expenditure based on the minimisation of risk across their portfolio of assets. This is achieved by assigning quantitative values to the component parts of risk: 1. Likelihood of asset failure; and 2. Consequence of asset failure.

The QRA methodology is well suited to assets where risk can be well defined and has long been used in other industries such as, aeronautics (Weinstock et al., 2001); and the oil and gas industry (Jo and Ahn, 2005). Despite this fact, the application of these techniques has been somewhat lacking for the management of long-lived water industry assets, i.e., tunnels, conduits, masonry aqueducts and service reservoirs. Instead, inspection techniques which provide very basic scoring systems, typically ranging from 1 (good) to 5 (poor), are relied upon to make multi-million pound investment decisions.

In acknowledgement of the limited application of QRA within the water industry, coupled with its success in others, Chapter 5 is motivated to develop an effective QRA framework for the management of long-lived water infrastructure assets within a user friendly application, with the aim of helping to promote the up-take across the water industry.

Specifically this chapter seeks to develop risk management techniques that can be applied to service reservoirs, which are known as a high value – low volume asset group.

5.2 INTRODUCTION

It is a requirement of the UK Water industry's economic regulator OFWAT to justify capital investment using risk based approaches. The Capital Maintenance Planning Framework (CMPF), published by UKWIR (2002), sets the industry benchmark for risk based decision making, considering the probability and consequence of failure. However, it has been recognised that despite the successful application of the CMPF principals for assets with a robust history of failure, the principles present a number of challenges for assets with limited failure data; termed "long-life, low probability" assets (UKWIR, 2011).

The fundamental approach to risk analysis is the ability to define an assets reliability and the associated consequence of the assets failure (Pollard et al., 2004). The water industry owns and operates a large number of long-lived and potentially highly critical infrastructure assets which tend to be variable and complex in nature. Within water infrastructure systems a high degree of variability and complexity exists in the analysis of both reliability and consequence. This is partly due to the individuality of water infrastructure assets, but it is mainly due to the dependencies and interactions that exist between individual components, sub-assets and assets.

To overcome these challenges, the authors present a number of bespoke risk based modelling tools that establish an effective QRA approach for water assets. The approach has been applied within the UK water industry to a variety of linear assets (tunnels, conduits and siphons) and non-linear assets (masonry aqueducts, pipe bridges, well houses and service reservoirs). The outputs from the QRA framework have formed the foundation of asset management plans by allowing for optimised maintenance regimes and pro-active interventions to be planned systematically. Whilst the approach is suited to a variety of different assets, a service reservoir example is documented in this paper to help convey the principles surrounding the methodology to the reader.

5.2.1 Quantitative Risk Analysis in the Water Industry

Egerton (1996) recognised that the benefits of employing Quantitative Risk Analysis (QRA) techniques have been widely acknowledged in the oil, nuclear and chemical industry. However, the application of such techniques has historically been less prevalent in the management of water industry assets. Traditional approaches to estimating failure probabilities in below-ground water networks rely on historical failure data. Generally, where historical data is plentiful, statistical methods are used in which failure data is fitted to time-exponential functions such that future failure rates can be extrapolated (Jarrett et al., 2001).

While these methods continue to be widely used to support asset management decisions, they also require large failure databases as a foundation for the analysis. Assuming good quality failure data, this does not pose a problem, i.e., for small diameter low consequence water mains or sewers, which are often operated under a “run to failure” strategy. However for more critical assets, such as service reservoir and aqueducts, failure data of this nature does not exist because the assets are prevented from deteriorating into conditions where failure would be likely. This is achieved either by decommissioning these structures or through the use of costly proactive preventative maintenance.

Pre-emptive techniques for critical assets often take the form of visual condition inspections to ascertain their current operational and structural condition, as well as allowing for estimations to be made regarding remaining service life and asset value to help prioritise maintenance and longer term investments (Feeney et al., 2009). However, routine inspections are not a statutory requirement under the 1975 Reservoirs Act in the UK, for reservoirs that do not have ‘a capacity greater than 25,000 cubic meters of water above the natural level of the land adjoining the reservoir’. Therefore, the frequency of these inspections for the majority of the service reservoirs in the UK will vary depending on the inspection strategies of the individual utility provider who owns and operates the asset (Johnson, 1995).

Despite not being legislatively obliged to conduct routine structural inspections, water companies are increasingly realising the benefits associated with the information captured during such inspections, to inform maintenance and capital investment programmes. Water companies often use risk ranking procedures to target inspections towards poorly performing assets or towards assets whose failure would cause a higher consequence, as a way of maximising risk reduction for their given resources (Pollard et al., 2004).

Whilst traditional condition inspection techniques are useful for understanding the necessary remedial works required to restore an assets structural condition, it remains difficult to benchmark the current performance of one asset against another, or, to evaluate how far along the deterioration process the asset might be. This is a common problem when the condition or performance of an asset is simply measured using a 1 to 5 scale (good/new to poor/failed), (Lumbers and Kirby, 2003; UKWIR, 2002). In recognition of these limitations the authors attempt to maximise the usefulness of the condition information obtained from routine inspections by translating condition inspections into reliability values using a severity and extent approach.

The other benefit associated with presenting the information as a reliability value is that other performance measures, i.e., water quality performance and health and safety, can be measured. A weighting factor is introduced to translate the observed severity and extent information into a reliability value for each failure mode, depending on each individual components influence on the performance of the failure mode that is being considered.

The subsequent sections of this report describe: (1) the severity and extent methodology used to capture information about the performance of each sub-component of an asset during condition inspections; (2) how different failure modes (structural performance, water quality and health and safety) can all be modelled using the severity and extent information; and (3) predicting reliability for any of the defined failure mechanisms using simple mathematical operators.

Finally (4), an innovative iPAD and ‘cloud’ application is described to show how this approach has been embedded within widely available tablet computing devices to make the process of data collection, storage, retrieval, transmission and the management of information more efficient.

5.3 CONDITION TO RELIABILITY MODELLING

An assessment methodology has been developed to better understand and quantify the reliability of “long-life, low probability of failure assets”, by utilising either existing, or purposefully obtained, condition inspection information. The approach has been used to derive a reliability score for a number of water assets, i.e., service reservoirs, masonry aqueducts, valve houses and for a variety of different performance indicators, i.e., structural condition, water quality and health and safety performance. One of the major benefits of the approach is its consistency and integration with the other deterministic models via the scoring of assets and sub-components as reliability values between 0 (highly unreliable) and 1 (highly reliable) for each of their respective performance indicators. Thus, allowing a consistent platform to compare the reliability of assets, modelled using one or more assessment methodology, across a water utility provider’s portfolio of assets.

The condition to reliability methodology is developed based on a severity and extent approach, where-by the severity of the damage/defect and the spatial extent of the damage/defect are assessed to give a condition score for a particular element, similar to the approach widely used for bridge condition (CSS Bridges Group, 2002; CSS Bridges Group, 2004). Both severity and extent are parameters that are used to inform decisions about maintenance planning and management.

Table 5-1. Severity descriptions

Severity Code	Description
1	As new condition or defect has no significant effect on the element
2	Early signs of deterioration, minor defect/damage, no reduction in functionality of element
3	Moderate defect/damage, some loss of functionality could be expected
4	Severe defect/damage, significant loss of functionality and/or element is close to failure/collapse
5	The element is non-functional / failed

Table 5-2. Extent descriptions

Extent Code	Description
A	No significant defect
B	Slight, not more than 5% of surface area/length/number
C	Moderate, 5% - 20% of surface area/length/number
D	Wide: 20% - 50% of surface area/length/number
E	Extensive, more than 50% of surface area/length/number

5.3.1 Modelling other failure modes

Leverett (2003) described a semi-quantitative risk ranking methodology employed by Severn Trent Water (UK), used to assess the risk of failure for treatment processes with regard to water quality, health and safety, environment and water quantity. The severity and extent scoring system, described previously, is a mechanism to provide a consistent and quantitative indication of the visible condition of each sub-component of the overall structure. Whilst it is not an indication of how the asset is performing with respect to previously acknowledged failure mechanisms. Therefore, further grading tables have been created within the pro-forma to identify those elements that are critical to the assets functionality for each performance measure. Where-by the term “functionality” is used to describe the assets performance in respect to critical failure modes/ performance measures.

Using a service reservoir as an example, the failure modes considered here are:

- Structural stability
- Water quality
- Health and Safety

The condition score for a particular sub-component is linked to the appropriate failure modes using weighting factors. Therefore, a weighting factor is applied as a multiplication factor to all sub-components, via the use of engineering and operational knowledge to determine the importance of each sub-component on the overall functionality of the structure with respect to the failure modes being modelled. This in-turn produces a weighted condition score to assist with prioritising defects based on the asset manager's priorities. Each of the descriptions behind the weighting factors used to describe the influence of each sub-component on the functionality of the asset in-terms of the failure mode(s) being considered are listed in Table 5-3.

It is important to realise that any sub-component of the asset can have a unique weighting factor for each of the failure modes being considered. For example, the condition of the pipework in a service reservoir has a significant effect on the water quality performance (water quality weighting factor = 0.75). However, pipework condition has little to no influence on the overall structural stability of the reservoir (structural stability weighting factor = 0.0).

Table 5-3. Weighting factor descriptions

Weighting Factor	*Description*
0.0	The component has no influence on the functionality
0.25	Severe deterioration of the component would affect functionality
0.5	The component is important to functionality
0.75	The component is critical to functionality
1.0	The component is critical to the overall assets functionality

Table 5-4. Condition grade mapping

		Permissible Condition Grade (Severity: 1 – 5; Extent: A – E)													
					2D			3D			4D				
		1A	2B	2C	3B	2E	3C	4B	3E	4C	5B	4E	5C	5D	5E
		Condition Grade Score (Severity x Extent)▼													
Weighting Factor▼		**0.2**	**0.8**	**1.2**	**1.6**	**2**	**2.4**	**3.2**	**4**	**4.8**	**6.4**	**8**	**9.6**	**12.8**	**16**
No effect to stability	**0.00**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Important to long term durability	**0.25**	0.05	0.2	0.3	0.4	0.5	0.6	0.8	1	1.2	1.6	2	2.4	3.2	4
Important to long term stability	**0.50**	0.1	0.4	0.6	0.8	1	1.2	1.6	2	2.4	3.2	4	4.8	6.4	8
Critical to the partial stability	**0.75**	0.15	0.6	0.9	1.2	1.5	1.8	2.4	3	3.6	4.8	6	7.2	9.6	12
Critical to the overall stability	**1.00**	0.2	0.8	1.2	1.6	2	2.4	3.2	4	4.8	6.4	8	9.6	12.8	16

Good	Fair	Adequate	Poor	Inadequate

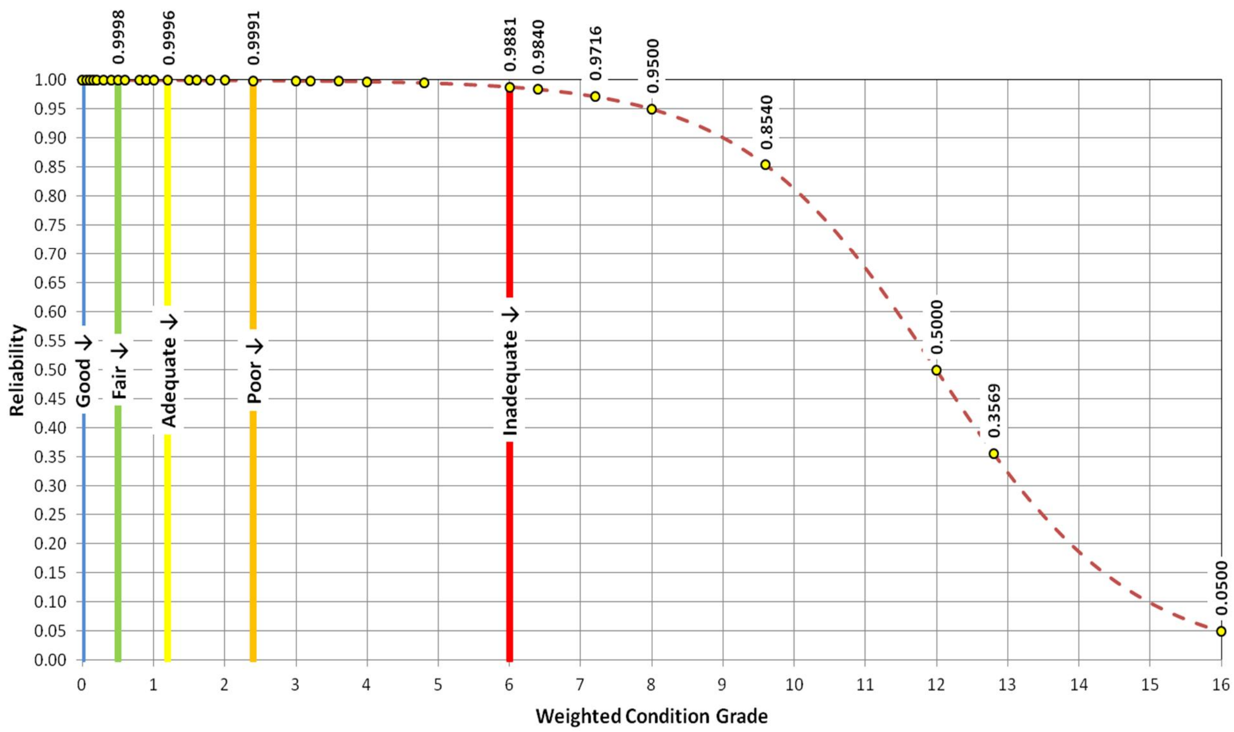

Figure 5-1. Condition to reliability mapping graph

The combination of a weighting factor approach alongside a quantifiable measure of sub-component condition, using severity and extent, allows for this methodology to be well suited to modelling multiple failure mechanisms for all types of water infrastructure assets. As a result, the failure mechanisms observed by Leverett (2003) for treatment process assets can be modelled successfully using different weighting factors to account for each of the sub-components influence on the: environmental; water quantity; water quality; and health and safety performance.

The benefit using a severity, extent and weighting factor approach is that the outcome of the condition inspection is translated into a reliability score for all of the failure mode(s). The use of separate codes for each parameter eliminates any obscurity in the distinction between, for example, a single but severe defect and extensive but superficial deterioration. Table 5-1 and Table 5-2 list the CSS severity and extent descriptions that have been used. For example, a code of 5C would define an element as non-functional to a moderate extent. The mathematical translation from the severity, extent and weighting factor observations to a reliability value uses a logistic function, described in following section via Equations 5-1 to 5-3. The approach may also be applied retrospectively to model failure modes which were either previously considered irrelevant or were overlooked. This is because the severity and extent information is the only source of data captured on-site. This information is later used to determine the condition of each sub-component using the aforementioned weighting factors which are scored between 0 and 1 depending on the level of influence the sub-component has on the failure mode(s) considered.

5.4 QUANTIFYING RELIABILITY

Given that limited failure data are available for these assets, and by definition this type of modelling is binary, i.e., there are only two states; either survival or failure, it has been assumed that the Logistic function is appropriate for modelling reliability. In order to calibrate the logistic function, it is necessary to define it by at least two points. However, given that there are no tangible benchmarks available in terms of actual failures, these points are assessed on a reasoned basis, using a weighted condition grading. The Weighted Condition Grades consist of 70 values, of which 31 are distinct and these range between 0 and 16. Table 4 shows the mapping from the Permissible Condition Grades to give the weighted values, for each combination. From this table a logistic function is proposed to define reliability using two parameters to fully specify it in the form of Equation 5-1.

$$P(w) = \left[\frac{1}{1 + \exp(-(A + B.w))}\right] \qquad \text{Equation 5-1}$$

Where;

A = the location parameter
B = the shape parameter
w = the weighted condition score.

This function is similar in shape to the cumulative Normal Distribution (ie "S-shaped") and when it is expressed as a probability distribution function, it is symmetrical about its mean.

Upon examination of Table 5-1, Table 5-2, Table 5-3 and Table 5-4, the following assumptions are made that allow the condition scores to be mapped to a reliability function: (1) It is possible to calibrate the logistic function in a manner that reflects the likely reliability behaviour for each element of the asset with respect to its weighted condition score; (2) Whilst the weighted condition scores are discrete, they lie on the smooth logistic function curve and where they are equal they will produce the same reliability value; and (3) It is assumed that there is a significant range of reliabilities within the weighted condition scores in the Red (“Inadequate”) region, effectively providing a failure likelihood that ranges from relatively minor to major. Interpreting these assumptions within the mathematical relationship for a Logistic Function, gives the reliability of the two defined points as follows:

i. R1=P(w1) = P(16) = 0.05 = 95% survival rate
ii. R2=P(w2) = P(8) = 0.95 = 5%. survival rate

Where;

wx = the weighted condition grade
P(wx) = reliability of an asset in this state

The resultant mid-score of 12 will map to a Reliability of 0.50, due to the symmetry of the Logistic function. On the basis of this mapping, the severity, extent and weighting factors are related to the reliability parameters A and B through a rearrangement of the Logistic Function in the form of Equations 5-2 and 5-3.

$$B = \left[\frac{\ln\left[\frac{P(w_2).(1-P(w_1))}{P(w_1).(1-P(w_2))}\right]}{(w_2-w_1)}\right] = \left[\frac{\ln\left[\frac{R_2.(1-R_1)}{R_1.(1-R_2)}\right]}{(w_2-w_1)}\right]$$ Equation 5-2

$$A = \left[\ln\left[\frac{R_1}{1-R_1}\right] - B.w_1\right]$$ Equation 5-3

Substituting in for (R1, w1) and (R2, w2), it can be shown that A ≈ 8.83331 and B ≈ -0.73610. The Logistic Equation is then used to produce the reliability mapping over the range of weighted condition scores shown in Table 5-4 and Figure 5-1.

Whilst the mapping is founded on a qualitative interpretation of the weighted condition score for each component, it is considered that this approach provides an appropriate means for high-level assessment of the asset's viability in a fair and balanced manner. The product of the reliability scores for individual components is then used to provide an overall reliability score for the entire asset against different failure modes, represented mathematical in Equation 5-4.

$$R_{Asset} = \prod_{x=1}^{y} [R_x] \qquad where\ x = 1, 2, \dots, y$$ Equation 5-4

Where;

R = reliability
x = first sub-component of the asset
y = last sub-component of the asset

5.5 CASE STUDY AND CONCLUSIONS

The methodology presented in this paper demonstrates an enhanced approach for understanding and benchmarking the performance of water industry assets. The approach is founded on a severity and extent scoring system which is used to translate sub-component condition observations into reliability scores against a variety of failure modes, namely; structural integrity, water quality and health and safety performance. The integrated approach has been applied by the author through a series of specialist structural condition surveys for service reservoirs in the UK. A fully document example is provided in Appendix (E), which can be interpreted as follows, Table 5-5

Table 5-5. Interpretation of a service reservoir condition survey, Appendix E

Column Reference	Explanation
A	List of all service reservoir elements
B	List of all associated defects for each element
C	Defect Severity score observed during condition inspection, ref to Table 5-1
D	Defect Extent score observed during condition inspection, ref to Table 5-2
E	Initial condition grade score based on Severity and Extent, ref to Table 5-4,
F, G, H	Individual defect weighting scores for each failure mode, ref to Table 5-3
I, J, K	Weighted condition grade score for each failure mode, obtained from the product of the initial condition grade * associated weighting score above.
L	A description of the defect observation captured for reference
M, N.O	Calculated reliability values for each failure mode and for each individual element using the logistic function transformation, ref to Figure 5-1.

The authors have integrated this new methodology within an innovative iPad and Cloud storage data management system to provide an efficient and common framework complaint approach which is able to quantifiably prioritise maintenance and investment programmes of work. For these programmes of work, significant benefits are being observed when compared to conventional condition assessment techniques.

For instance, Table 5-6 is produce to demonstrate how the reliability values can be used to identify the most problematic reservoir component for each of the failure modes being considered, i.e., Structural reliability = External Walls; Water Quality = Roof slab and membrane; Security /Safety = Gates).

Table 5-6. Reliability values summarised at component level for a service reservoir condition inspection, Appendix E

Reservoir Component	Reliability Scores		
	Structural Stability	Water Quality	Security/Safety
Roof Slab	99.60%	99.50%	
External Walls	99.54%	99.37%	
Columns	99.64%	99.88%	
Column Bases	99.64%	99.84%	
Floor Slab	99.56%	99.81%	
Roof slab & membrane	99.98%	94.99%	
Embankments	99.96%	99.95%	
Reservoir roof cover (access)	99.98%	99.90%	
Safety Grid	99.98%	99.90%	
Ventilation inlets (mesh screens)	99.98%	99.97%	
Ladder Access Steelwork		97.93%	
Roof drainage - Edge gullies and pipes		99.72%	
Drainage Channels		99.72%	
Guttering and downpipes		99.72%	
Inlet Pipe		99.83%	99.94%
Outlet Pipe		99.83%	99.94%
Overflow pipe	99.97%	99.83%	99.91%
Washout Valve		99.95%	99.97%
Other Control valves		99.95%	99.97%
Perimeter Fence			99.86%
Gates			99.85%
Paths			99.95%
Access road			99.95%
Hardstanding			99.95%

Furthermore, additional benefits would be realised if the methodology were applied across a portfolio of service reservoirs, which would allow maintenance regimes to be appropriately targeted towards the most unreliable assets for each failure mode.

5.6 RESEARCH APPLICATION

It is widely recognised that on-site data capture and the management of condition inspection information is costly and time consuming (Bekiaris and Nakanishi, 2004; Akinci et al., 2006). In light of today's emphasis on cost control and data quality, the need to deploy cost effective solutions for the purposes of accurate data capture is even more prevalent. In the transport industry smarter data collection systems are more widely cited and similar solutions have been developed for building and property management (Barry et al., 2001). Kykloud is one such company offering secure cloud based platforms helping asset managers and operational teams to collect data efficiently and use this information to manage the life-time cost of major infrastructure and property portfolios (Wilkinson, 2012).

The research presented within this chapter has been coded into KyKlouds specifically developed data capture and life-cycle management software program. The software operates on a universal tablet device, Figure 5-2, and web based cloud storage system which acts as the data depository and intelligent management system. The integrated approach has been applied to a series of service reservoir inspections in the UK to offer an end-to-end asset management solution.

Figure 5-2. iPad survey application

The approach not only allows for efficient data collection and management, but it provides a mechanism to quantifiably prioritise maintenance and investment programmes, using some of the in-built functionality with the KyKloud software coupled with this research. The KyKloud model is based on a workflow in line with the latest asset management industry standards such as ISO 55000 (British Standards Institution, 2014) that sets out a Capture-Manage-Report process, as shown in Figure 5-3.

Figure 5-3. Capture – Manage – Report workflow

The iPAD inspection application is an innovative approach to field based data capture because it offers a number of unique features that fit seamlessly within the online data management process to equip utility managers with an easy to use interface that provides instant access to their data. The benefits observed from the condition inspection programmes being conducted in the KyKloud application for service reservoirs are summarised in Table 5-7.

Table 5-7. Benefits delivered from the condition inspection programme in KyKloud

Benefits	*Description*
Efficient programming of inspections	Since inspections are created with the KyKloud web portal they allow allocation to named engineers which send the templates to their iPads with a notification email. Inspections are then visible in a Gantt chart that allows programing of inspections and monitoring of progress.
Multiple data collectors	Surveyors are able to work in parallel, based on commonly agreed standards leading to significantly improved data quality and programme efficiencies.
Mapping of assets	Users are presented with a global overview of their asset stock which is mapped geo-spatially. The system allows for the user to interrogate assets individually to access the information held against each asset e.g., dimensions, last inspection records, condition, risk, etc.
Reliability assessment for each component of the structure	The defect description, condition and a photographic record is tagged to each component of the structure. Such detailed information provides an easily auditable record and ensures consistency between multiple surveyors.
Remedial works specification	Remedial interventions can be preloaded into the app to allow the engineer to focus on the assessment itself.
Embedded bill of quantities	Each asset type can have a standard replacement or repair cost associated to it, in the inspection template which will be visible to the inspector while on site.

6 ASSESSING IMPACTS OF THE PRIVATE SEWER TRANSFER ON UK UTILITIES

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6.1 BACKGROUND

In 2013 significant asset management challenges were imposed on the water companies operating in England and Wales by the legislative change in ownership and maintenance responsibilities for private sewers. Statements and publications released by consumer councils, research bodies, industry magazines and government departments in anticipation of this change identified significant challenges as a result of this transfer (CC Water 2012; UKWIR 2013; Stimpson 2011; and Defra 2007). Despite the understanding and anticipation of the forthcoming problems, literature offering potential solutions or methodologies to improve asset management practise in this area were not forthcoming.

It was also obvious that the upper decision making levels in asset management, where the most significant savings can be identified, were less commonly applied to non-critical infrastructure and almost non-existent for assets with limited or poor data quality, i.e., private sewers. In itself this represents both a challenge and opportunity. The challenge here-in, lies in establishing a suitable framework to improve the underlying asset data quality associated with these assets, such that both tactical and strategic asset management concepts can be applied. The opportunity therefore is to realise the widely publicised benefits associated with these asset management disciplines across infrastructure assets which are notoriously poorly managed.

The subsequent chapters of this thesis were developed in response to the immediate challenges and opportunities faced by the water companies operating in England and Wales, and the less immediate but fundamentally equal challenges and opportunities faced by other water companies in ownership of low value – high volume infrastructure.

Specifically this chapter seeks to develop equally successful deterioration modelling techniques for the private sewer network, a high volume – low value asset group, as those used to predict the condition of the public sewer network. Additionally, the chapter explores the downstream benefits which could be achieved through improved deterioration modelling analysis, i.e., long-term investment planning

6.2 LEGISLATIVE BACKGROUND

Section 105A of The Water Act 2003 (Great Britain, 2003) introduced new legislation to the Water Industry Act of 1991 (Great Britain, 1991) which gave the UK Government the power to require sewerage undertakers to adopt privately owned sewers and lateral drains in England and Wales. Since 2003 the ten statutory water and sewerage companies operating in England and Wales had all recognised that the transfer of these assets would significantly impact upon their companies' existing resources, and further concerns had been raised surrounding the likely condition and operational performance of these assets (Stimpson, 2011). Prior to transfer, the UK government's Department for Environment, Food and Rural Affairs (Defra) had estimated that approximately 154,000km of privately owned sewers would be transferred in terms of responsibility to the water companies; an increase of approximately 50% in sewerage assets per utility provider (Defra, 2007).

In February 2007, the Government announced its decision to proceed in principle with the transfer (Pearson, 2007), which was later affirmed in a statutory instrument known as "The Water Industry (Schemes for Adoption of Private Sewers) Regulations 2011" . This legislation enforced the transfer of responsibility for privately owned sewers and lateral drains that connect to the public sewer network from the 1st October 2011. Figure 6-1 is produced to show the typical drainage arrangements for the transferred sewer assets which are henceforth referred to as Section 105A (S105A) sewers. Prior to the transfer, these S105A sewers were the responsibility of the homeowner(s) unless they were constructed prior to 1 October 1937. For the avoidance of doubt, the only sewers or lateral drains in England and Wales which were classified as being in private ownership where those constructed after 1 October 1937. This reflects the previous adoption of privately owned sewers constructed before this date under Section 24 of the Public Health Act 1936 (Great Britain, 1936).

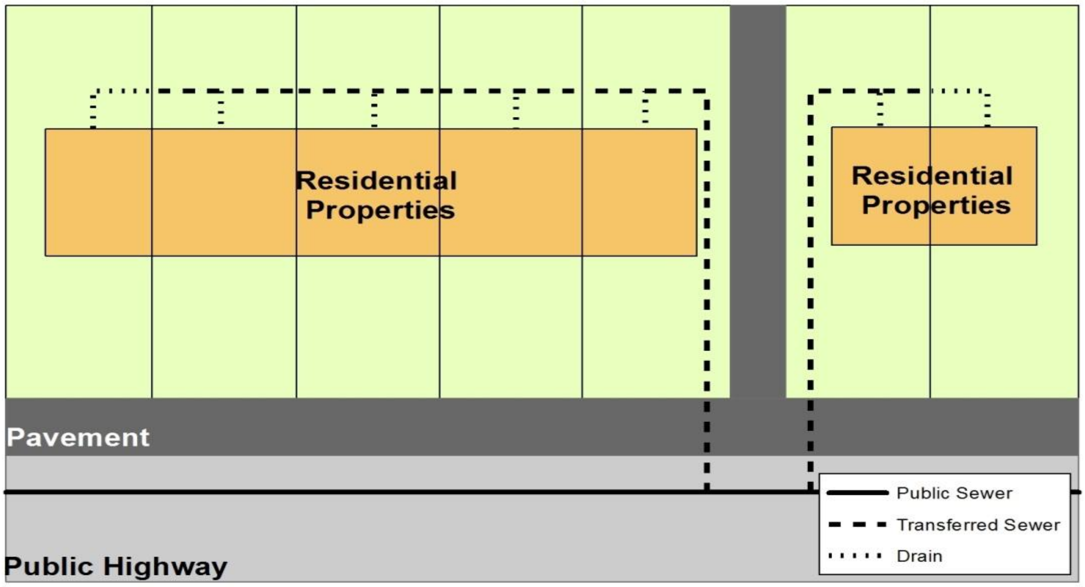


Figure 6-1. Typical S105A drainage arrangements

6.2.1 Challenges

The lack of data surrounding the condition of buried water and wastewater infrastructure is often the main obstacle in the deployment of an effective asset management strategy (Vangdal and Reksten, 2011). This is even more prevalent in the case of the private sewer network in England and Wales due to the very recent change in ownership from the customer to the utility provider. Water UK (2013), acknowledge that basic information for these newly transferred assets, such as; asset location, condition, basic attribution and maintenance history, is largely unknown and the survey costs associated with the necessary data collection have been estimated to be as high as £118m (Defra, 2007).

In light of these findings, some water companies have already begun an extensive mapping and record keeping programme for these assets, involving the digitisation of historic plans from local authorities and the use of in field data capture to locate unmapped assets – leading to CCTV condition surveys to better understand asset performance.

Information of this nature is extremely valuable, although it is no surprise that it is costly to obtain and unlikely to cover the entire network for quite some time. Therefore, the need for cost effective decision support frameworks capable of integrating all available data into a single framework to help asset managers make complex investment decisions has been acknowledge as a high priority area for future research (AwwaRF, 2008). Ideally, such tools would be founded on the use of geospatial approximation techniques, to quantify the extent of the transferred network, coupled with a deterioration or collapse model to simulate asset performance.

A number of UK Water and Sewerage Companies were involved in an unpublished study undertaken by the WRc for UK Water Industry Research (UKWIR, 2002b). This study helped to produce a high level model that could be adapted by each water company to provide their own local estimates for private sewer lengths, work volumes and costs. UKWIR (2002) captured the approach in an unpublished document "The Real Cost of taking over Private Sewers and Drains". The foundations of the UKWIR model are centred on the following: the number of households within each utility provider's service area; the property type of these households, i.e., detached, semi-detached and terrace; and the property age range. Using this information the model assigns typical average lengths for drains and sewers to form an overall estimate for network length, which is subsequently used in a secondary model to estimate the nature and extent of the work required to manage these drains and sewers appropriately.

Whilst the UKWIR model has served its original purpose by providing a mechanism to estimate the likely extent and potential financial impact of the newly transferred sewers, the top-down approach is considered too crude for rigorous business planning with margins of error cited to be in the region of +/– 40% (Sanderson, 2012). Furthermore, it does not provide a mechanism to model the performance of these assets based on known or predicted asset condition and it is even more difficult to prioritise investment programmes towards poorly performing assets due to the top-down nature of the modelling process.

As a result, utility providers are now looking to apply more comprehensive deterioration and collapse models which have been established using a variety of different techniques over-time, e.g: logistic regression (Ariaratnam et al., 2001); exponential models (Wirahadikusumah et al., 2001); time based and state based Markov models (Kleiner and Rajani, 2001; Baik et al., 2006); fuzzy based techniques (Kleiner et al., 2006); and more recently through machine learning such Artificial / Neural Network models (Najafi and Kulandaivel, 2005); and evolutionary computing techniques (Savić et al., 2006). One common theme through all of the above literature is the importance of data aggregation into homogenous pipes groups; although this is often highly governed by the availability and quality of data across the network (Savić et al., 2009).

Data availability and quality are also two of the governing factors currently presenting a real barrier to the successful deployment of effective asset management techniques for the newly transferred private sewer network, or in-fact any asset base whereby information surrounding the extent, attribution and condition of the asset stock is limited. To overcome this knowledge gap, an end-to-end asset management methodology has been developed for South West Water, who provide wastewater services across an operational area of 11,137km2 which encompasses 1.6 million residents served by around 14,800km of public sewers (South West Water, 2013). At the time of this study 2,452 km of newly transferred private sewers had already been mapped and reasonably well attributed by the business. Therefore, the subsequent sections of this paper describe the methodology that was applied to estimate the extent, condition and business investment needs to manage the unmapped and unattributed S105A network. It was later estimated from this study that South West Water's existing mapping (2,452km) formed 39% of their overall transferred network length.

6.3 MODELLING THE EXTENT OF THE S105A TRANSFERRED NETWORK

To help develop an improved understanding of the newly transferred private sewer network, the authors have developed a universal approach which can be integrated with any corporate GIS system to provide the foundations of a successful asset management strategy. The methodology, presented here, differs from the UKWIR approach (2002) by making estimates for S105A sewer length at individual property level. This is achieved using widely available geospatial data sets, in the form of OS MasterMap Topography ® and AddressBase ® layers. These datasets are interrogated by the model and used to geospatially position a “notional” sewer connection between each property group and the nearest applicable public sewer, Figure 1.

Due to the nature of the digitisation process used for the mapped S105A sewers, a single private sewer that connects from the property group to the public sewer is likely to consist of multiple sewer spans connected between manholes. Therefore to ensure that the notional sewer is compared to a single length that represents the entire extent of the private sewer length, all inter-connected sewer spans are joined together where a common manhole is shared. Furthermore, to accommodate the nature of private sewers whereby more than one property connected by a shared boundary is served by a single S105A sewer, a number of property groups are established in GIS. This is achieved by merging common property boundaries to create a single property group polygon from OS MasterMap ® data,Figure 6-2.

Each property group, created using the above process, is then attributed with the number of merged properties in order to determine the property group type, i.e., terrace property groups encompass greater than two properties. Once all of property groups have been formed, the centroid of the group is used to create the notional asset connection by taking the most appropriate straight-line path to the nearest public sewer. A connection is created for both the surface water drainage and foul-combined sewerage.

Whilst it is not strictly true that all properties will have separate surface water drainage arrangements, further downstream processes which involve cross-checking the utility providers customer billing information and estimating the likelihood of a soakaway being present to remove the surface water sewers from those properties with soakaways or combined drainage arrangements. Figure 6-2 is produced to provide a visualisation of the network pre and post processing. The benefit of this approach is that the geospatial proximity of a property group to the public sewer network is considered during the estimate of the S105A sewer length.

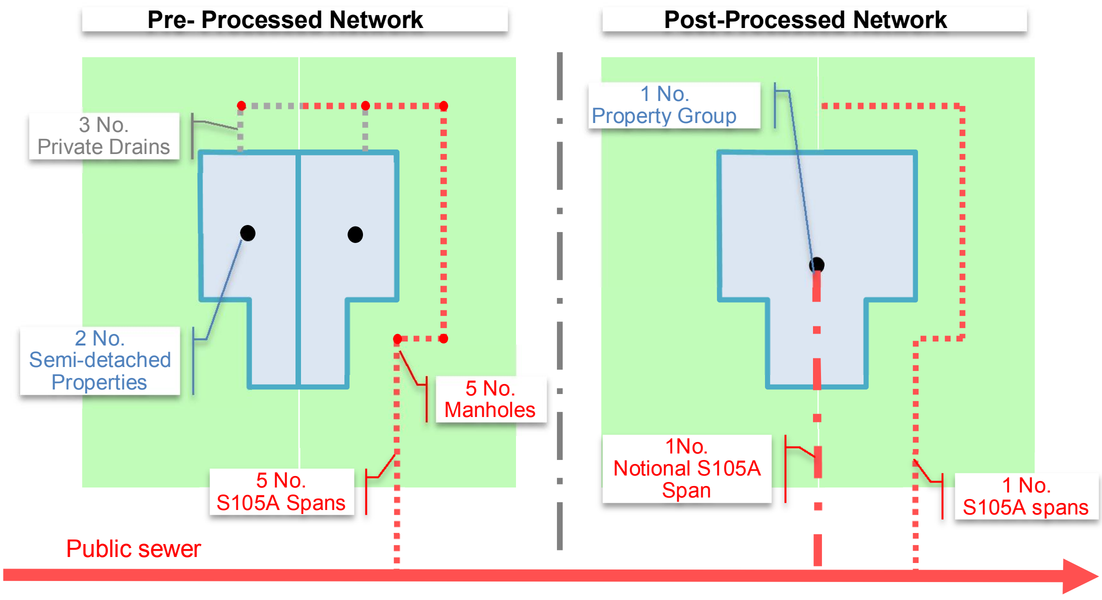


Figure 6-2. Pre and post network processing models

The process of calibrating the model is two-phased. Firstly, a complete set of notional assets are created for each property group across the entire network. Secondly, the notional asset lengths are compared in controlled areas where existing and accurate mapping already exists for these assets. Notional assets in these areas are only used for the purposes of calibrating a series of coefficients and are later removed from the overall network analysis. The coefficients are used to estimate the length of the unmapped areas by being applied as multiplication factors against the notional straight-line distances.

Nine coefficients were calibrated for each sewer function (foul-combined and surface water) to account for the differing drainage arrangements due to property type (detached, semi-detached, terrace) and property age (1937-69, 1970-99, >1999). These age bands where selected to provide an even coverage for S105A sewers, i.e., those sewers laid post 1937 and up until the present day. The dates were also governed by the availability of historic mapping data and property age classifications provided by the UK government valuation office agency. This coefficient based approach is deemed to be more representative of the actual drainage arrangement because it is able to account for the geospatial features associated with each individual sewer, ie, property distance to public sewer. The model is calibrated by adjusting each modelling coefficient to minimise the overall error across the region between the observed and notional sewer lengths. The statistical results of the model calibration process for each coefficient are captured in Table 6-1.

Table 6-1. S105A length and calibration factor properties

			Sewer Length (observed)		**Coefficient**	
Property Type	Age Band	Function	Mean (m)	Upper 95 percentile (m)	Mean	Standard Deviation
Detached	1937-69	Surface Water	24.0	67.2	0.39	0.020
		Foul/Combined	18.4	57.3	0.63	0.271
	1970-99	Surface Water	15.3	43.1	0.71	0.179
		Foul/Combined	11.5	33.0	0.80	0.022
	>1999	Surface Water	11.5	29.3	0.75	0.213
		Foul/Combined	9.4	26.4	0.93	0.165
Semi-Detached	1937-69	Surface Water	20.8	59.6	0.68	0.172
		Foul/Combined	13.7	40.5	0.70	0.324
	1970-99	Surface Water	14.1	39.4	1.03	0.027
		Foul/Combined	10.5	29.9	0.86	0.937
	>1999	Surface Water	10.5	25.6	1.12	0.156
		Foul/Combined	8.3	23.5	1.36	0.226
Terrace	1937-69	Surface Water	20.0	54.5	1.39	0.627
		Foul/Combined	13.2	40.7	1.52	0.999
	1970-99	Surface Water	15.1	39.8	1.71	0.204
		Foul/Combined	8.8	26.0	2.19	0.715
	>1999	Surface Water	10.9	27.0	1.83	0.364
		Foul/Combined	7.6	22.7	2.48	0.298

Given the uncertainty surrounding the calibration factors, a Monte Carlo simulation was run using each coefficients mean and standard deviation values, Table 6-1, to understand the statistical properties of the output when a probability distribution is assigned to the input factors. Whereby, the output forms the estimate of private sewer length and the inputs are the individual coefficients.

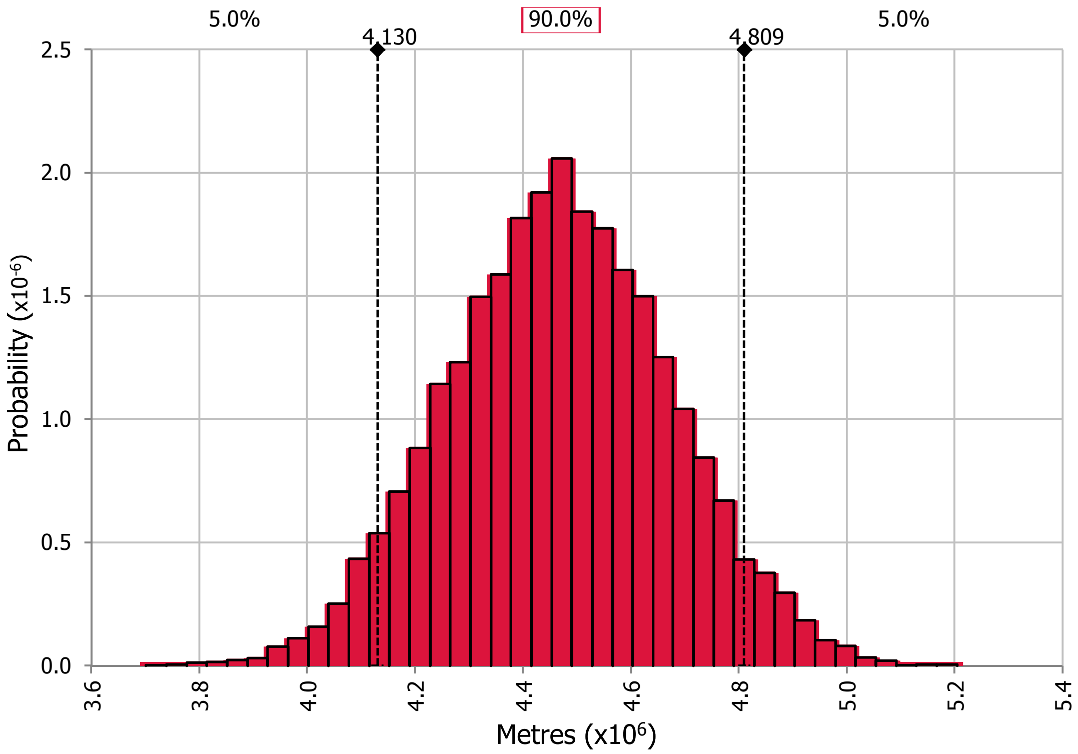


Figure 6-3. Total S105A foul-combined length distribution

Figure 6-3 displays the output from the Monte-Carlo simulation as a probability density for the overall Foul-Combined S105A sewer network length in SWW's region, thus predicting the network to be between 4,130km and 4,809km at a 90% confidence interval. The same output is produced for the S105A surface water sewer network to form an overall estimate of transferred sewer length. The output is therefore a more comprehensive understanding of S105A network length which can be visualised graphically to help understand uncertainty.

6.4 MODELLING DETERIORATION AND COLLAPSE RISK FOR S105A ASSETS

Due to the challenges associated with the largely unmapped and unattributed nature of the transferred private sewer network, the segregation of assets into cohorts is even more challenging and uncertain. A three staged process was followed: (1) a literature study is conducted to identify the factors influencing pipe deterioration; (2) a review of the possible sewer attribution available is compared against the influencing sewer characteristics identified; and (3), the availability of historic condition information across the public and S105A network is collated, analysed and understood. This process ensures the selection of cohorts which form sufficient groups that are small enough to be uniform and meaningful in the way that they behave, whilst retaining a significant population to yield meaningful results and reduce the influence of noise (Kleiner and Rajani, 1999).

In-terms of influencing sewer characteristics, Davies et al. (2001a) provides a comprehensive review of rigid sewer characteristics that commonly influence the deterioration of these assets. The deterioration model presented in this paper uses, age, diameter, material and soil type, to portion the sewer network into unique cohorts for the following reasons. Age was selected as a portioning attribute because it is commonly regarded as an influential factor in pipe deterioration. This can be as a result of more defects being observed on older pipes (O'Reilly et al., 1989) or because of particular age bands causing more problems that others, e.g., 1940's to 50's (Lester and Farrar, 1979). However, determining and attributing sewer installation dates retrospectively cannot be precise. Therefore, a logical data hierarchical procedure was developed to take advantage of the most appropriate data sources. The process used a mixture of corporate sewer asset age data, property age estimates from the HM Revenue and Customs (HMRC) Valuation Office Agency and historic mapping, depending on data availability.

Diameter is a widely attributed characteristic which also accounts for the differences between Public and S105A sewers; where-by the former are more often of larger diameter. Ariaratnam et al. (2001) identified the statistically significant relationship between sewer diameter and failure rates in a logistic regression model which was applied in a study conducted in Edmonton, Canada. The material of the sewer was also considered in this model and deemed a significant factor influencing the rate of deterioration. In the Public sewer network, material is often well attributed. However, in order to estimate the likely material of S105A assets a rule set was solicited from a compilation of operational staff knowledge across South West Water.

It can be seen that in some installation years more than one pipe material was in common usage. This table therefore expresses the percentage likelihood of an asset being of a certain material based on its installation year, Table 2. These percentages are applied to the individual assets so that a single sewer installed in 1967 would have its length proportioned across Clay and Pitch Fibre at the appropriate ratios shown in Table 6-2.

Table 6-2. S105A Age bands, surface water arrangements and material probabilities.

Age Band	Likelihood of separate surface water sewer	Material and (Code)		
		Clay (4)	Pitch Fibre (5)	Plastic (6)
1937 – 69	25%	74.84%	25.16%	0.0%
1970- 99	60%	67.0%	0.0%	33.0%
>1999	90%	10.0%	0.0%	90.0%

Soil type is the fourth and final portioning factor. A statistical evaluation of public sewer collapse events against soil type was completed using the National Soil Map of England and Wales (NATMAP) vector and Soil Risk mapping purchased from National Soil Resources Institute (NSRI, 2013). This identified statistically significant differences between different groupings of soils which were ranked into four collapse risk bands ranging from None to High risk.

From a geotechnical engineering perspective the outputs were logical, whereby sewers in soils with low cohesivity (i.e. sandy, silty soils) and that allow free movement of water were found to be more likely to collapse than those in soils with high cohesivity (e.g. clay). Other attributes, including; depth, workmanship, overland use, ground disturbance and ground water level, have been disregarded for some, or all, of the following reasons: (i) the attribute is sparsely populated and difficult to infer for newly transferred private sewers with any reasonable level of accuracy; (ii) the attribute is less influential to the sewers performance; and/or (iii) inclusion of the particular attribute would not retain a statistically significant set of cohorts, (Davies et al., 2001a).

In order to define, evaluate and forecast the probability of sewer collapse, a unique sewer deterioration model was established to predict the future condition of the network. The model uses the analysis of historic CCTV survey information to identify unique deterioration trends for different cohorts of sewer. Extrapolation of these deterioration trends allow for the entire sewer network to be expressed in terms of its length within each of the appropriate condition grade scores (1 to 5) at any point in time, whereby the WRc (2004a) Method of Sewer Condition Classification (MSCC4) is used to define condition grade, Figure 6-4. Against this understanding of past, current and future condition, a collapse rate is predicted based on a statistical analysis of historic events against the observed sewer condition profiles for each cohort. The result is a novel relationship which is drawn between sewer collapse rate and sewer condition profile; using a linear function that allows for the future prediction of collapse rate over-time.

Sewer condition is uniquely expressed in this model as the length of each sewer within each of the five condition grades which are derived by modelling the sewers gradual transition from grade 1 (as new) to 5 (defective or collapsed) using a Semi-Markov chain. Semi-Markov chains are a long established technique for the mathematical modelling of infrastructure deterioration (Li and Haimes, 1992; Wirahadikusumah et al., 1999; Kleiner 2001; Micevski et al., 2002). It is commonly referred to as a simplification of the deterioration process because the modelling is often performed at asset level, with a single sewer occupying only one of a number of states e.g. 1 to 5. A probability is then applied to each asset to account for the likelihood of the entire asset moving into another state over a given time period, e.g., one year.

However, by adopting a condition profile based approach, the authors have established a more representative modelling technique for sewerage assets that reflects the fact that a single sewer maybe in multiple states at a single point in time (Micevski et al., 2002). This is achieved through the analysis of historic condition surveys to determine how the actual proportions of a sewer gradually flows into the five condition grades using a Semi-Markov matrix. In essence, the condition “profile” of a sewer is simply the proportion of its length within each condition grade (1 to 5), shown in Figure 3. For this analysis, a condition “profile” is computed for all available historic survey information, using a bespoke algorithm. The algorithm progresses a 4m wide observation window along the length of the condition survey in 0.1m intervals. Within each 0.1m step, the condition grade derived from the aggregate defect scores is held against that length and the associated lengths within each of the condition grades are then summed and divided by the total length of the survey to produce the profile.

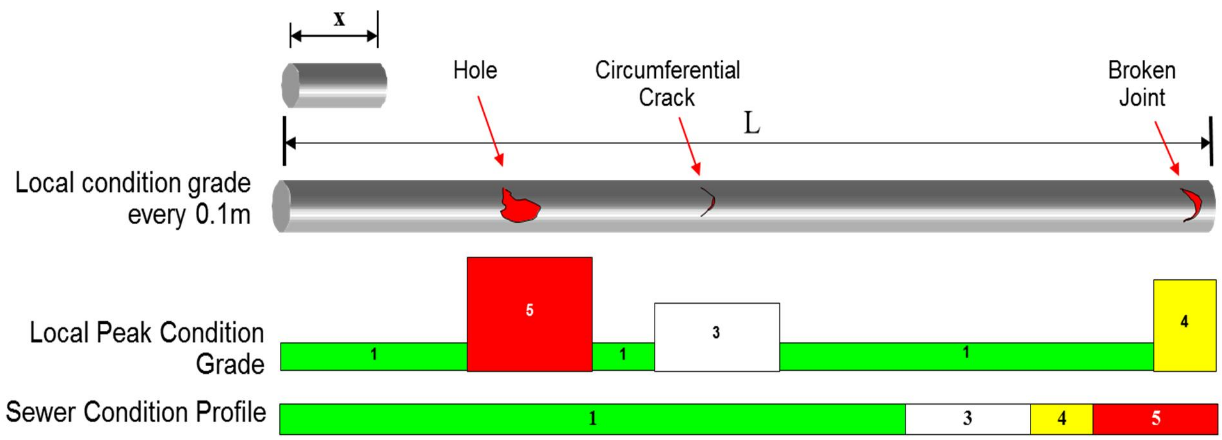


Figure 6-4. Sample sewer condition profile

This deterioration modelling process aligns itself with a similar methodology used for the statistical modelling of water distribution pipe failure and sewer failure respectively, (Berardi et al., 2008; Savić et al., 2009). Both of the approaches group the entire network into fictitious pipes based on their attribution for which the relevant variables of the deterioration model are calculated using a length weighted mean. In this instance, the condition surveys represent the pipes and the proportion of the sewer occupying condition grades (1 to 5) represent the variables. When the proportions of the sewer in each of the conditions grades are grouped together, this is referred to as the sewer's condition profile. The condition profile can be calculated for an individual sewer or it can be used to express the overall condition of a group of pipes (cohort) using the length weighted mean approach. In this instance, the condition profile is calculated for all sewer cohorts but only within a single survey year. The survey year is held as a segregating factor because it represents the age of the pipe at the time of the survey and is thus the time variable in the assets deterioration profile, Figure 6-5.

Once the survey and sewer attribution data are analysed, a semi-Markov deterioration matrix is calibrated against the observed sewer condition profiles on an annualised basis for each cohort of sewer. The resultant calibrated deterioration matrix, depicted in Table 6-3, can be interpreted as follows: The values in the leading diagonal of the matrix are the probable proportions retained in the same grade, e.g., after one year it is probable that 98.69% of the length will remain in condition grade 2. The values directly below the leading diagonal refer to the probable proportions that will deteriorate to the next condition grade, e.g. after one year it is probable that 1.31% of the length in sewer condition grade 2 will deteriorate to grade 3.

Table 6-3. Example of a Calibrated Semi-Markov Deterioration Matrix

		From Grade				
		1	2	3	4	5
To Grade	1	**99.8%**	0.0%	0.0%	0.0%	0.0%
	2	*0.2%*	**98.7%**	0.0%	0.0%	0.0%
	3	0.0%	*1.3%*	**97.3%**	0.0%	0.0%
	4	0.0%	0.0%	*2.7%*	**99.6%**	0.0%
	5	0.0%	0.0%	0.0%	*0.4%*	**100.0%**
		100.0%	100.0%	100.0%	100.0%	100.0%

Using this annualised deterioration matrix to predict future condition, Figure 6-5 is drawn to illustrate the comparison of the observed condition profiles (vertical bars) and the modelled estimate (linear trend). It can be seen that in some years the observed deterioration profiles are not particularly well aligned with the deterioration profile, i.e., 2000. This reflects the fact that the model applies a weighting mechanism based on the length of survey information available in each year to either lessen or heighten the condition profiles influence on the overall model calibration. This is witness by the two earlier observations in Figure 6-5, which represent only a small percentage of the overall survey length used in the models calibration and hence their seemingly insignificant influence. This approach provides for a more balanced and stabilised deterioration profile by smoothing the effects of small and potentially disruptive samples.

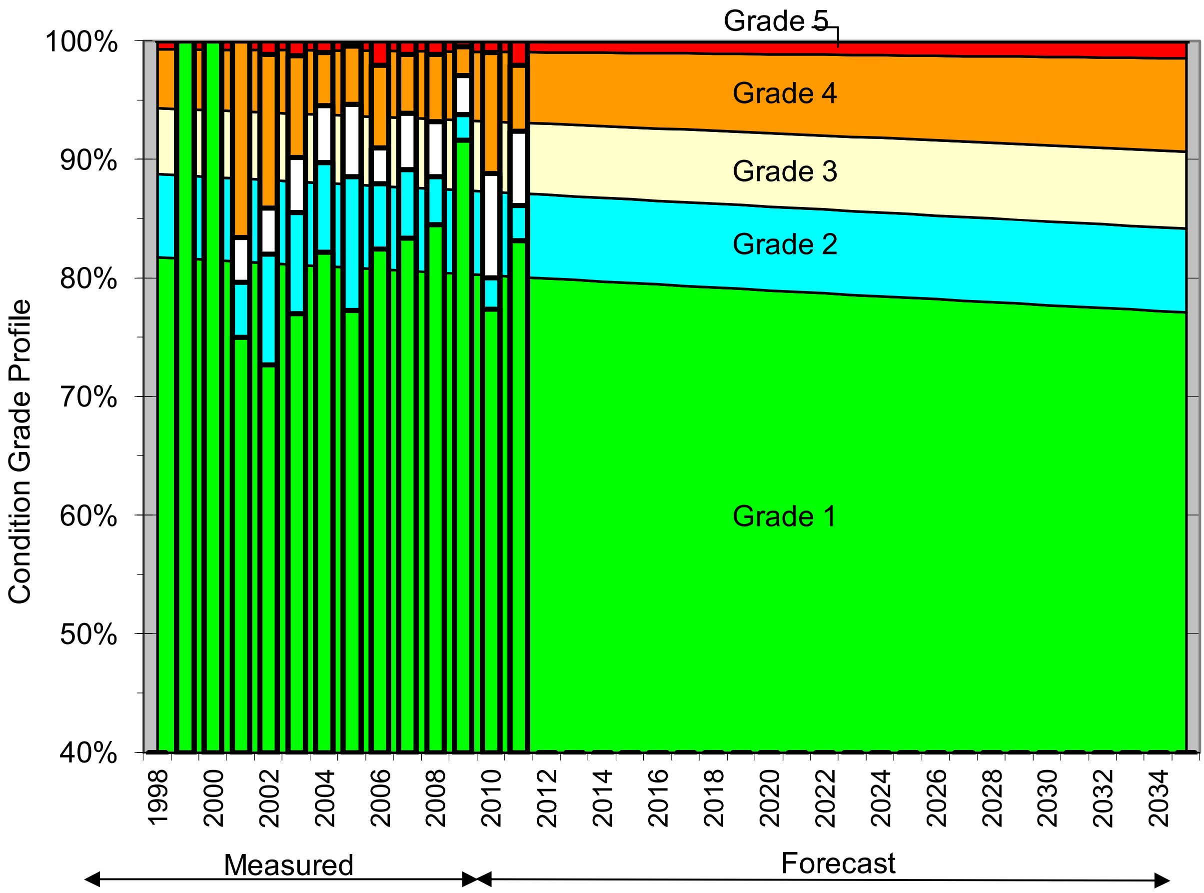


Figure 6-5. Example showing measured and forecast sewer condition profiles

In the process of finding the optimal calibration factors for the model, the following constraints have been applied to the optimising routine: It is assumed that in general, the collapse probabilities of lengths in grade 5 is greater than or equal to those in grade 4. Similarly it is assumed that collapse probabilities of lengths in grade 4 are greater than or equal to those in grade 3. Finally, all of these values are constrained to be non-negative. Hence, the constraint: $P5 \geq P4 \geq P3 \geq 0$ has been applied.

6.4.1 Collapse rate calibration from historic failures

Semi-Markov deterioration modelling is a proven technique to simulate the gradually deteriorating profile of the sewerage network (Black et al., 2005; Ruwanpura et al., 2004; and Scheidegger and Maurer, 2012). Whilst it is important to predict and understand the length of sewerage assets across the network in each of the condition grades (1 to 5), the condition grade alone provides little information about the actual performance of the network in a reportable metric, such as collapse frequency. For example, a sewer of a particular material may remain in condition grade 5 without resulting in a reportable sewer collapse or experiencing any serviceability problems for a number of years. Whereas a sewer constructed in a more fragile material may experience more rapid deterioration and therefore its collapse would be imminent.

In an attempt to over-come this challenge, the authors uniquely model sewer collapse rate as a function of the sewers predicted condition profile. This is achieved using a linear equation that seeks to determine an overall sewer collapse rate (λ), for each cohort, by calculating a series of coefficients (Ci) that are applied to the proportion of sewer length predicted to be in condition grades 3 to 5 (Pi). Therefore as the pipe deteriorates over-time and the proportion of sewer classified as condition grade 3 to 5 increases, then the predicted sewer collapse rate will also increase proportionally; following the relationship presented mathematically below, Equation 6-1:

$$\lambda = \left[L \times \sum_{i=3}^{5} (C_i \cdot P_i) \right] + C_C \qquad \text{Equation 6-1}$$

Where;

λ = Sewer Collapse Rate (Number/Year)
L = Total Sewer Length by cohort (km)
Ci = Coefficient by condition grade (nr/km/yr)
Pi = Proportion of sewer length in respective condition grade (%)
Cc = Constant coefficient to account for third party incidents (nr/km/yr)

The coefficients in this expression are determined by minimising the error between the observed sewer collapse rate and the predicted collapse rate (λ) for each cohort; there-by accounting for the differing rates of collapse for each material. The process uses the historic sewer collapse rate, for each cohort, as a known entity that can be expressed as a cumulative count per calendar year over-time, Figure 6-6.

Similarly, the proportion of sewer (Pi), in condition grades 3 to 5, is derived using the previously described sewer deterioration modelling techniques and it can also be expressed over-time. From this position, an optimisation routine is applied to minimise the error between the predicted and observed collapse rates by adjusting the coefficients in the expression (C3, C4, C5 and Cc) which are the only unknowns in the equation. It is then assumed that these calibrated coefficients remain constant over time so that when they are applied to a deteriorating sewer condition profile, the collapse rate will increase proportionately.

The output from the model is a predicted sewer collapse rate (λ) for each cohort, expressed as a count per 1,000km per year, at any given year into the future. Therefore, the cumulative length of sewer across the network in each cohort can be multiplied by the collapse rate to obtain the number of predicted collapses in that year.

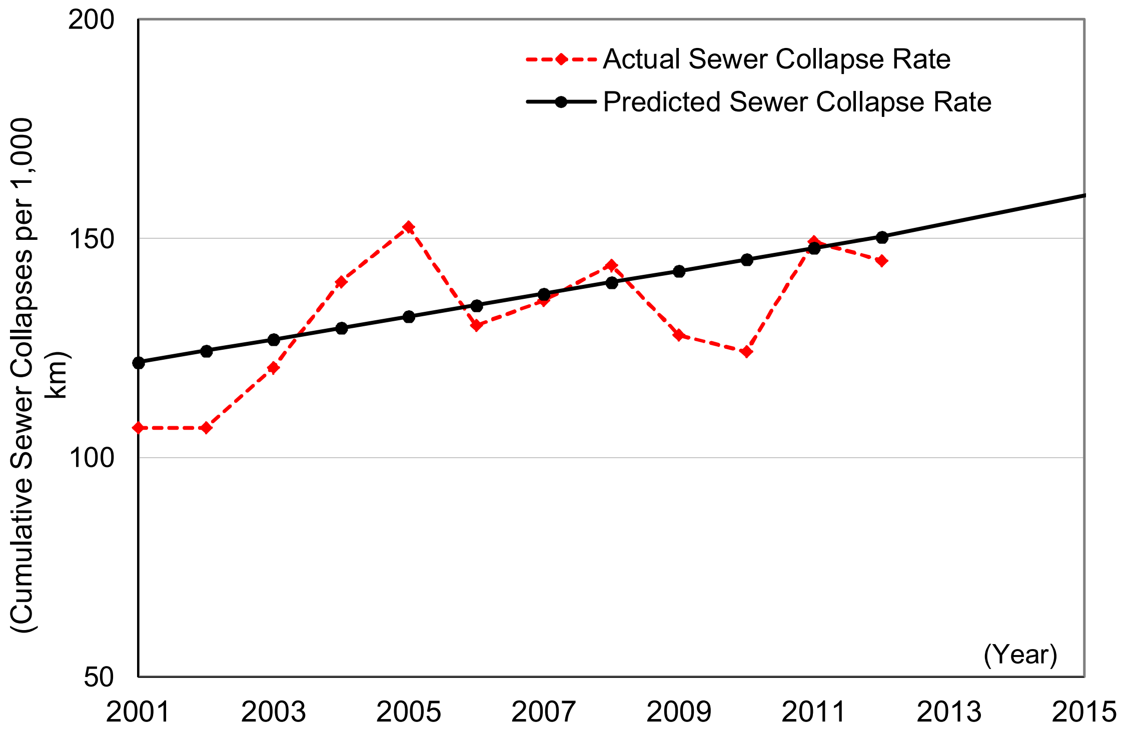


Figure 6-6. Cumulative reported and forecast collapses for Pitch Fibre (1980-89)

In light of the fact that S105A sewer collapses are largely unregistered, due to the transfer in ownership happening very recently, the collapse events witnessed on the public sewer network have been used as proxy in the model calibration process for cohorts of S105A sewers with the same attribution as their public sewer counterparts. The outputs from this deterioration and collapse modelling process can also be expressed as a collapse frequency for each cohort of sewer over-time, there-by indicating the most vulnerable sewer cohorts and the rate at which their collapse frequency increases, Figure 6-7.

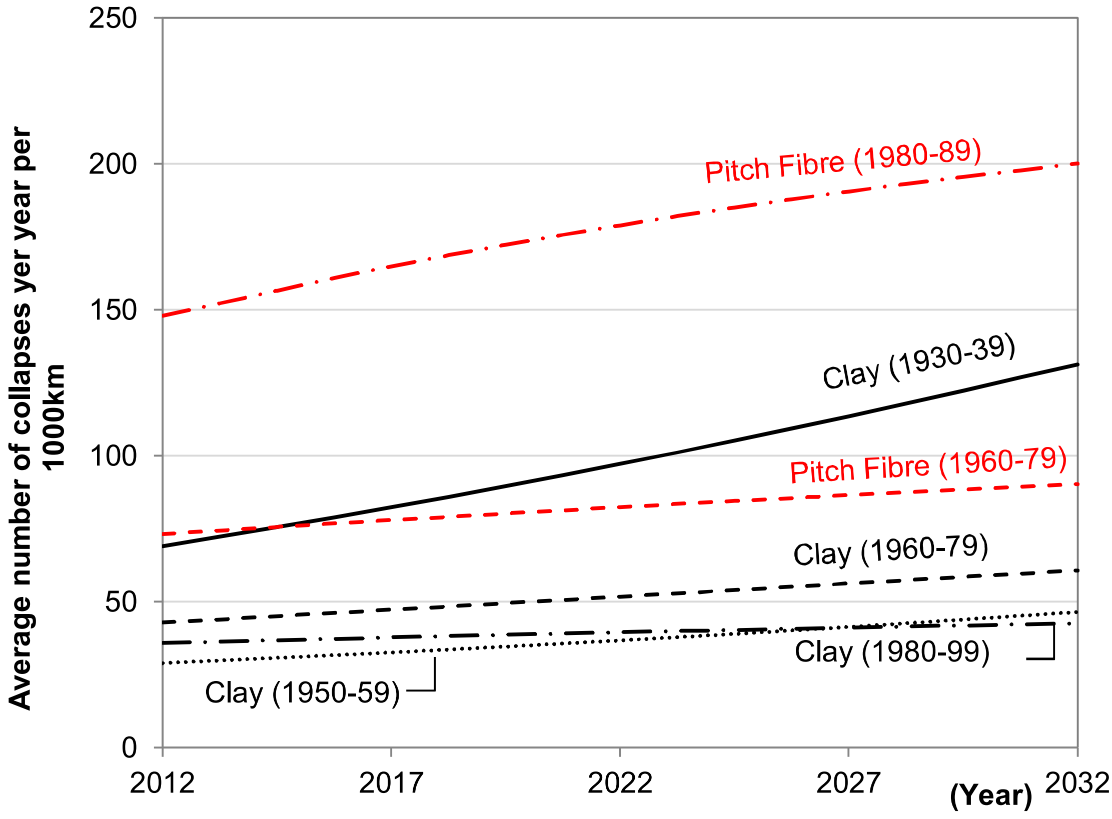


Figure 6-7. Sample sewer collapse frequencies

The relevance of using the window of Public sewer condition and collapse information to inform a deterioration model for the newly transfer S105A network, has been proven statistically by testing the following assumption: “sewers with the same fundamental characteristics (age, material, diameter, soil) will behave the same regardless of their acquisition status, i.e., Public or S105A”.

The validation process was conducted by comparing a random sample of the mapped S105A network, which were obtained solely for this purpose, against the historic survey information used in the deterioration modelling phase for the public network. The random samples across the S105A network were translated into condition profiles following the same modelling principles as the public sewer network, described previously. A statistical test using Analysis of Variance (ANOVA) was then carried out on the estimated collapse rates for each cohort where sufficient sample sizes existed for both datasets.

This test was setup to refute the null hypothesis that the two sets behave in a similar manner; in terms of their deterioration and failure due to collapse. For the purpose of validating the two datasets, an age band resolution of 10 years has been applied, Table 6-4.

Table 6-4. ANOVA test for public and private sewer deterioration rates

Ref	**Sewer Cohort**			**Sample Size (Nr.)**		**ANOVA**
	Installation Date	Material	Size (mm)	Public	S105A	P-value
1	1930-1939	Clay	≤165	154	12	0.301
2	1950-1959	Clay	≤165	709	25	2.24E-23
3	1960-1969	Clay	≤165	521	60	0.356
4	1960-1969	Pitch Fibre	≤165	36	13	0.323
5	1970-1979	Clay	≤165	1778	16	0.883
6	1970-1979	Pitch Fibre	≤165	110	45	0.123
7	1980-1989	Clay	≤165	451	35	0.437
8	1980-1989	Pitch Fibre	≤165	76	69	0.088
9	1990-1999	Clay	≤165	1884	11	0.607

Out of the nine sample cohorts tested which are representative of approximately 72% of the entire S105A network, eight of these had little or no evidence at the 99% confidence level to reject the assumption. Whilst only one cohort, 1950-59 Clay sewers less than 165mm diameter, which represents less than 8% of the network rejected the assumption. This result provides a sufficient degree of confidence in the use of the public sewer deterioration model for the analysis of the S105A network.

6.5 CONCLUSION

A series of innovative tools to help formulate a proactive asset management strategy for recently transferred private sewers has been presented. The methodology is founded on an enhanced bottom-up assessment of asset stock which is provided to the user within windows of uncertainty. The approach is structured to work with readily available datasets and is capable of applying innovative geospatial processes at individual property level to vastly enhance the level of information available. A sewer deterioration model is then applied against this improved asset stock to predict the underlying performance of the network, in-terms of its collapse rate now and into the future.

The model is calibrated using a 10 year window of Public sewer condition and collapse records, which has enabled it to effectively differentiate between the poorly performing cohorts of sewer and those that are more stable. For example, in 2017 vitrified clay sewers laid between 1950-59 have a predicted collapse rate of 32 (collapses per 1,000km per year), whereas pitch fibre sewers laid between 1980-89, are predicted to be more problematic with a collapse rate in excess of 164 (collapses per 1,000km per year). Following the application of the public sewer deterioration model to the S105A network, the location, extent, age, material and predicted condition of the entire S105A network is better understood. This provides the foundations to estimate the likely investment requirements in the network going forward, whilst also providing the basis for a proactive asset management strategy to be established by targeting survey investigations via CCTV towards poorly performing asset groups.

This methodology is mutually beneficial from both a business planning and proactive asset management perspective. For business planning, the model develops a comprehensive understanding of the transferred sewer network, which for most water utilities remains an area of uncertainty. It also provides an improved understanding of the likely future performance of the transferred sewer network, which has allowed South West Water to develop a more robust business planning submission to OFWAT, the economic regulator for England

and Wales. For proactive asset management, the methodology provides a mechanism for South West Water to effectively guide their proactive rehabilitation programme towards poorly performing sewers - thereby reducing time and survey costs for the business, whilst also ensuring that sewers with a high risk of failure are repaired first.

6.6 RESEARCH APPLICATION

The original objective of this research was to develop an improved understanding of the newly transferred private sewer network, as a mechanism for improving strategic business planning decision making. The original objective was achieved through the development of bespoke geospatial processes and statistical modelling tools which were used to automatically infer the most likely position and extent of the private sewer network across an entire Water Company.

However, it was recognised that an understanding of the extent and attribution of the transferred sewer network alone, was insufficient for the purposes of long-term business planning. Therefore to supplement the knowledge of these assets, research was conducted into sewer deterioration modelling techniques that could be applied to inform asset managers of the likely condition and expected number of yearly collapses over a 25 year planning horizon across this portfolio of assets.

An analytical framework was subsequently developed to enhance the understanding of the transferred sewer network alongside the deterioration and collapse modelling outputs, by simulating the impact of different investment strategies on the performance of these assets over-time; with the aim of predicting the long-term investment requirements to maintain stable sewer collapse rates.

Previously mapped private sewer locations were used to calibrate the modelling approach and have provided the mechanism to present the solutions within bands of uncertainty, which can be gradually reduced as the volume of mapped assets increases with time. Therefore, the methodology acts as an interim solution that Water Companies can use to improve their understanding of the newly transferred private sewer network without the need for extensive survey programmes to be embarked upon.

The modelling framework was implemented by the author and South West Water's wastewater planning manager to help South West Water justify and secure their annual investment programme across their transferred sewer network. The investment requirements were submitted to the economic regulator, Ofwat, during the 2014 Period Review (PR14) and defended during a regulatory audit. Due to confidentially, the outputs cannot be published within this thesis.

Since publication of the paper, a pilot study has been undertaken in South West Waters region to determine the effectiveness of this research when applied as a tactical modelling tool to help target inspections and the resulting sewer rehabilitation work towards poorly performing assets. A pilot study, involving 3.5km of CCTV investigations of the highest risk sewers within a catchment, has been completed to evaluate the ability for the deterioration model to identify poorly performing sewers. The outputs from the investigations have been tabulated as the percentage length of sewers in the each of the MSCC4 structural condition grades, 1 – 5.

Table 6-5. Pilot study CCTV inspection outputs

	Structural Condition Grades					Success
	CG1	*CG2*	*CG3*	*CG4*	*CG5*	*Rate*
Length (m)	952	348	830	1196	189	2,215
Length %	27%	10%	24%	34%	5%	63%

A survey is deemed to have been successful if a sewer that is predicted to be problematic is in fact in need of rehabilitation. By definition, this applies to sewers in condition grades greater than or equal to structural condition grade 3. Therefore, the tactical modelling approach is reported to have a 63% success rate in identifying sewers in need of rehabilitation.

To quantify the commercial benefits of this modelling approach, discussions were held with South West Waters operational teams to help understand the performance of the tactical modelling tool against other alternative methods. Previously, South West Water have used engineering and operational knowledge to target survey investigations towards sewers thought to be in poor in condition. It was estimated by South West Water's wastewater planning manager, that the success rate of this approach was somewhere between 15% - 20%.

Therefore, the modelling approach is up to three times more effective than traditional techniques for the identification of sewers in need of rehabilitation. On this basis, it is fair to conclude that a water companies CCTV budget could be reduced by up to two-thirds (2/3) by using this modelling technique instead of a traditional approach. To put this into context an illustrative example is provided to demonstrate a potential £2.33M saving that could be realised by Welsh Water against their commitment to Ofwat to renew and renovate 140km of sewerage infrastructure between 2015 – 2020 (Dŵr Cymru Welsh Water, 2015).

Table 6-6. Illustrative CCTV savings obtained from tactical modelling

	Traditional targeting	Tactical Modelling
Sewer length for renovation (m)	140,000	140,000
Success rate (%)*	20%	60%
Sewer surveys required (m)	**700,000**	**233,333**
Surveys prevented (m)		466,667
Survey cost (£/m)**		£5.0
Total saving (£)		**£2,333,333**

* This example assumes that all sewer renovations for Welsh Water need to be identified by targeted inspections. In reality a large proportion of the 140km will be pre-existing problematic sewers that are known about.

** Survey costs were provided by a local survey contract to help determine relative cost savings for indicative purposes only.

Although the potential savings illustrated in Table 6-6, assume that Welsh Water have not developed their own approach to inspection targeting, it remains a useful comparator to demonstrate the effectiveness of using predictive deterioration modelling outputs for targeting investigations. This research has also proven to the industry that the public sewer network can be taken as a good representation of the private sewer network until a better understanding of these assets can be formed.

7 DETERIORATION MODELLING OF SMALL-DIAMETER WATER PIPES UNDER LIMITED DATA AVAILABILITY

This chapter is being reviewed for the Urban Water Journal by Taylor & Francis.

Ward B, Selby A, Gee S and Savić D. A (2015). Deterioration modelling of small-diameter water pipes under limited data availability. Urban Water Journal. In Review.

7.1 BACKGROUND

Deterioration modelling for water distribution mains is a highly researched field due to the widely recognised benefits that an improved understanding of asset performance can bring to the management of the network; from both a performance and cost saving perspective. Despite these publicised benefits, such research has not been widely applied to other less critical assets in the distribution network. This is suspected to be a result of a previously perceived requirement for extensive asset data and failure observations requirements, which has been disproven (Le Gat and Eisenbeis, 2000; Mailhot et al., 2000).

Le Gat and Eisenbeis (2000) demonstrated that equally accurate deterioration and failure forecasting models could be established from 5 – 10 years of maintenance records and that extensive failure data sets offered limited improvement in modelling accuracy above a five year failure history window. However, despite their work, the application of deterioration modelling to less critical assets still remains under-utilised. It is thought this is because of the industries perception that these models still remain reliant on good quality asset data which is often not readily available for these assets, i.e., pipe age, diameter and material.

Consideration was also given to the fact that the potentially low maintenance costs associated with less critical infrastructure, specifically communication pipes, might be the reason for a deliberate oversight by the industry. However, more than 130,000 communication pipes failures were reported in 2010 across England and Wales, (Ofwat, 2010). Assuming an average replacement cost of £800 per asset would generate capital maintenance programmes in excess of £100M per year.

Therefore, in light of these investment levels and upon realisation that geospatial technology can be used to create a fairly accurate proxy data set for these types of assets, as demonstrated in Chapter 6. It was deemed beneficial to explore the suitability of developing a similar bottom up deterioration modelling methodology for small diameter water distribution assets which are already legally owned by the majority of water companies operating around the World and appear to lack the application of best practice asset management concepts.

Specifically this chapter seeks to develop equally successful deterioration modelling techniques for the communication pipe network, a high volume – low value asset group, as those used to predict the condition of the distribution main network.

Understanding and quantifying the accuracy of deterioration models developed under limited data availability was also recognised as an important factor in this research. It was deemed that if sufficient evidence supporting the effectiveness and benefits of this approach could be developed, then a stronger argument for the adoption of these technologies across low-value high-volume infrastructure would be presented. However, the underlying objective of the chapter is to improve the knowledge of low value – high volume water distribution assets and to subsequently develop a suitable deterioration modelling framework such that inspection and rehabilitation can be prioritised based on current and future performance.

7.2 INTRODUCTION

Until now, deterioration modelling for truly small diameter pipework (25-50mm diameter) has not been undertaken across the water industry. Although many authors describe various approaches to deterioration modelling of "small diameter" distribution assets, typically their work refers to better understood and well documented pipework, which have diameters between 100-200mm and are responsible for serving multiple properties (Atkinson, et al., 2002; Marlow, et al., 2015). As such, the methodology described within this paper is believed to be the first of its kind to offer a comprehensive modelling framework for truly small diameter assets.

Originally, it was thought that a comprehensive deterioration modelling process had not been previously developed for this group of asset due to their seemingly low value. However, an analysis of water company replacement figures between 2002 to 2010 has revealed that on average over 130,000 communications pipes are replaced each year across England and Wales alone (Ofwat, 2010). At an assumed replacement cost of £800 per communication pipe, a capital investment programme in excess of £100M is required to maintain this network of small diameter assets. Water utilities in England and Wales are not obligated to report operational expenditure against individual asset groups, but it is suspected that the operational expenditure associated with these assets is in the region of an additional 80-120% of the capital value; therefore generating a £200M total expenditure budget in England and Wales for communication pipes.

Assuming equivalent investment levels for communication pipes in other developed regions of the World, approximately 17.8% of the global population, would yield an annualised total expenditure in excess of £4.42bn ($6.95bn) in these regions alone (United Nations, 2011). Therefore, when considered as a collective asset stock, the global investment in the more developed regions of the World is significant enough to warrant the use of a deterioration model to better understand and manage the performance of these assets in the future. This could be achieved by using the outputs from the deterioration analysis to proactively target the replacement of poorly performing assets, or, via an awareness of upcoming investment requirements and future failure rates.

In the UK water distribution network, these small diameter assets that serve single properties are referred to as communication pipes, which can be defined as: the water carrying assets that lie between the water main and the boundary of the private property being supplied. If a stop-tap or water meter is fitted this usually represents the end of the communication pipe and beyond this point the pipework is referred to as the ‘supply pipe’, which, in the UK, is the responsibility of the property owner (Ofwat, 2014b). By their very nature communication pipes are considered high volume and low value assets. With typically one asset for each property, the pipework is of small diameter (25 - 50mm) and the length of the asset lies somewhere between 2-3m or 6-9m depending on the nature of the connection to the distribution main. Shorter connections, which typically occur when the property is located on the same side of the road as the distribution main are known as “short-side” communication pipes. Where-as communication pipes that required a road crossing, due to the location of the distribution main to property, are known as “long-side” connections.

In contrast, distribution mains can serve hundreds of customers usually range in size between 50 and 300mm in diameter. These assets are typically laid within the road and have significantly higher failure costs, not only due to the more vigorous and challenging repair techniques but as a result of the number of customers impacted. It is, therefore, understandable that past research effort has centred around the proactive management of these larger assets as the economic and social costs of pipe failures continue to rise (Engelhardt et al., 2000).

Research into pipe deterioration modelling has taken many forms. At the highest level, models are distinguished by their nature, either physical or statistical. Physical models, generally speaking, are built around the understanding of the underlying physical parameters that govern pipe failure. These require the acquisition of detailed information about the pipe(s) being modelled for accurate predictions to be established (Rajani and Kleiner, 2001). Currently, the collection of this data is costly and it is not widely available across the whole distribution network. Even when data is available, it is commonly limited to water mains of larger diameters which tend to be critical in nature. Therefore, the expenditure associated with the collection of this data is unjustifiable; particularly so for lower value assets like communication pipes.

An alternative solution is to use statistical based models which evaluate the relationship between water main condition and key pipe characteristics by the use of historical data, which is mined and statistically evaluated to find patterns that can then be used to formulate a deterioration modelling equation. The most cited and widely recognised publications at the forefront of statistical modelling in the water industry at the time were (Shamir and Howard, 1979; Clark et al., 1982; O’Day et al., 1986).

The early developments in these models took a linear form and a few fundamental draw backs have since been identified with linear based models. The main disadvantage is that these models were heavily reliant on the availability of sufficient data for each pipe class for the rate of deterioration to be established without the interference of third party influences that lead to failure. These third party causes are commonly referred to as ‘noise’ because of their undesired influence on the identification of failure rates. Another important and restricting factor is that these models did not include data from assets where failure had not yet occurred, even though in some instances failure was imminent.

In the early 1990’s semi-Markovian models were used to describe the deterioration process (Li and Haimes, 1992). The semi-Markovian model is a simplification of the deterioration process by modelling the current condition of an asset in one of a number of states. A probability is then applied to each asset to account for the likelihood of it moving into another state over a given time period. These types of model are the more commonly applied where condition information, obtained through inspections conducted over-time, is available. For this reason, semi-Markov deterioration models developed for sewerage assets, where condition inspection information is plentiful, have been found to provide an accurate representation of the assets deteriorating behaviour, (Ward et al., 2014).

Although less well published, Artificial Neural Networks (ANN) have also been applied to distribution main networks with the aim of learning the pipe breakage frequency rate through the use of historical incident data and to subsequently predict the future. Sacluti (1999) demonstrated their effectiveness rather early on in development of ANN's for civil engineering applications in a case study in Edmonton, Canada. Jafar et al. (2010) had similar success by coupling an ANN with Multiple-Linear Regression in a distribution network in Wattrelos, France. The authors also both acknowledged potential benefits in the use of ANN's for establishing rehabilitation strategies.

Evolutionary Polynomial Regression (EPR) is another machine learning technique used to predict deterioration and failure by discovering patterns in pipe failure data amongst homogenous groups (Giustolisi and Savić, 2006). The EPR model produces simple relationship equations between a number of variables and confirmed the importance of; pipe age, diameter and length; when considering pipe burst frequencies and occurrences. The benefit of EPR over more conventional data mining techniques is the simplicity of the relationship equations although it is reliant on the accuracy of the data modelling inputs (Berardi et al., 2008).

The application of whole life cost modelling for investment planning is a natural progression from statistical deterioration models which usually form the foundations of the approach (Lei and Sægrov, 1998). An aggregated statistical model was used in this study alongside a lifetime modelling tool to develop optimised planning regimes. Similar techniques have been used to try to determine the optimal time for pipe replacement by forecasting the service life of a water main under two intervention scenarios; replacement or rehabilitation, (Shamir and Howard, 1979). In advancement towards multi-objective optimisation, researchers have considered how to evaluate the problem of maximising network performance whilst minimising cost.

The benefits of presenting the problem in a multi-objective framework are that solutions take the form of a trade-off between cost vs. benefit. Thus, cheaper solutions with lower benefit and lower cost implications are not overlooked; there-by giving the decision maker a broader range of the potential solutions available to them. Halhal et al. (1997) is one of the first cited examples in this field and work continues, (Berardi et al., 2008; Engelhardt et al., 2002; Nafi and Kleiner, 2010).

The aforementioned literature reaffirms that the benefits of these technologies are already being realised for larger and more critical assets, e.g., distribution mains. Water companies are harnessing the power of these techniques to help them select optimal intervention timings and solutions, whilst also targeting maintenance towards poorly performing, high risk assets. In contrast, communication pipes form a typically unmapped and unattributed asset stock, which are often sub-optimally managed as a result of insufficient knowledge and un-optimised investment plans.

Although these assets are deemed low value infrastructure in comparison to distribution mains, the high asset volume means that substantial yearly capital investment is needed to maintain serviceability, thus justifying the development and application of a deterioration model to help utility managers better understand the performance of communications pipe. (Ward et al., 2015b) have progressed the deterioration model further via the development of an asset level decision support tool used to trade-off between whole life costs (totex) and the prevention of future asset failures (serviceability).

7.3 METHODOLOGY

7.3.1 Asset data quality improvements

The starting position for the study is to address the lack of data availability and quality for communication pipes, which are often two of the governing factors presenting a barrier to the successful deployment of effective asset management techniques for high volume-low value infrastructure, i.e., where information surrounding the extent, attribution and condition of the asset stock is limited (Vangdal and Reksten, 2011). To overcome this knowledge gap a set of notional assets, which are arbitrary straight line connections formed between customer property address points and the nearest most relevant distribution mains (or trunk main) are generated using a Geospatial Information System (GIS). This approach also allowed for an approximation of asset length. However, with all geospatial processes of this nature some un-realistic asset lengths are created due to the variability of specific individual locations, i.e., where a property actually connects directly to a near-by trunk main but it is digitised as a connection to a distribution main considerable distance away.

To account for these anomalies, all notional asset lengths are plotted on a frequency distribution by asset length graph, to help identify a threshold at which individual assets beyond a certain length become highly unlikely or unrealistic. Notional assets lengths exceeding this threshold are subsequently assigned the mean length for the group to avoid unrealistically long lengths biasing the model. For communication pipes, this approach is applied to two groups of asset; short and long side communication pipes. Where-by a long-side communication pipe is defined as a communication pipe connecting to the water main across a road, i.e., the water main is located in the opposite carriage way of the road to the property being supplied. Assets that do not cross a road centre line have been defined as short-side connections for the purpose of this study. The authors deemed this to be a reasonable approach and achieve the main aim of the analysis which is to distinguish between assets with higher associated failure costs, due to asset length and social distribution, e.g., road closures.

Determining and attributing pipe dates retrospectively cannot be precise. Therefore, a logical data hierarchical procedure is developed to take advantage of the most appropriate data sources available. Depending on data availability the process uses a mixture of: corporate communication pipe and distribution mains asset age data; property age estimates from the HM Revenue and Customs (HMRC) Valuation Office Agency (VOA); and historic mapping. Each of the data sets were used in the following manner: Distribution mains age was used as an approximation for communication pipe age by identifying which distribution main the communication pipe was connected to and using the installation date for this asset as a surrogate for its own age. This was only applied so long as the distribution main had not been rehabilitated which would have reset the age of the asset.

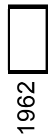
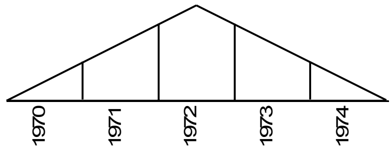
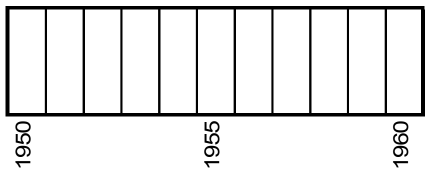
Property age estimates from HMRC Valuation Office Agency were provided at postcode level and despite not being applicable to an individual property, the methodology assumes that the data could be applied with reasonable accuracy where the majority of properties within a postcode were of the same age. Finally, an analysis of historic mapping created development regions, formed by observing the growth of a town over time, Figure 7-1. For example, housing estates shown on maps produced in 1950 that were previously not visible on a 1940’s map were attributed, via selections within polygons, as a 1940-1950’s development.

Figure 7-1. Development regions

7.3.2 Handling data uncertainty

To handle the uncertainty associated with this type of methodology, unique distributions are assigned to each asset depending on the level of confidence surrounding the data source and/or the range of dates it covers. Therefore, the characteristics of a single asset are spread across multiple years according to the distribution, where-by the distribution is selected according to the confidence levels assigned to the different data sources. Whilst it may seem obscure to further segregate individual assets over age ranges, when the asset stock is considered at regional level this approach provides an improved representation of the network by spreading potential uncertainties in the data. Table 7-1 is prepared to help visualize the different distributions.

Table 7-1. Age data uncertainty distributions

Data Source	Visual representation	Justification
Installed year		Uniform distribution for a single year, where the date is known to be accurate and correct.
Mains Age		The mains installation year is reasonably reliable therefore only a small distribution is applied, centered around the installation year, i.e., 1972.
VOA **& Historic mapping**		Uniform distribution from the earliest to the latest date spanned by the range for each individual year.

After establishing a commissioning distribution for each communication pipe, a further procedure is developed to determine the likely material for the asset. This assessment was based on industry research publications and engineering experience from operational management teams who worked to identify unique operating zones where different materials were installed over-time, (WRc and UKWIR, 2005). Within these zones unique material age usage profiles were assigned to help account for the subtle differences surrounding the materials installed over time, often dictated by a local council's preferences or availability of materials in the region. Rather than using traditional binary indicators which would assign a single material to an individual asset, the methodology adopts a type -1 fuzzy inference system (Mendel, 2000).

IF-THEN rule sets are used to define the fuzzy membership of an asset to different pipe materials, depending on its age. The use of this technique has helped to address the deficiencies that are inherent in the application of binary logic to imprecise systems by propagating uncertainties through the model (Kleiner et al., 2009). Membership functions are often applied to linguistic variables that describe a condition or state which is imprecise.

However, in this instance the installation date for the asset is used as the antecedent to which the fuzzy inference system is applied, in order to derive the consequent which is expressed as a fuzzy membership of the asset to specific materials .There-by addressing the uncertainty of the material used at each installation date and also accounting for the phasing in and out of different materials over time.

Figure 7-2 depicts a typical material usage profile showing the phasing in and out of materials overtime for a single operating zone that installed Lead (PB), Cooper (CU), Black Polyethene (BPE) and Medium Density Polyethylene (MDPE) pipework overtime. A five year phasing in out period was identified by both operational teams as the most likely representation of reality due to the fact that new pipe materials take time to establish themselves as the preferred technology and the stock of the material being replaced takes time to be depleted. As such, assets installed within a transition period are attributed with a percentage of both materials, e.g., 20% CU and 80% BPE for assets installed within this operating zone in 1965.

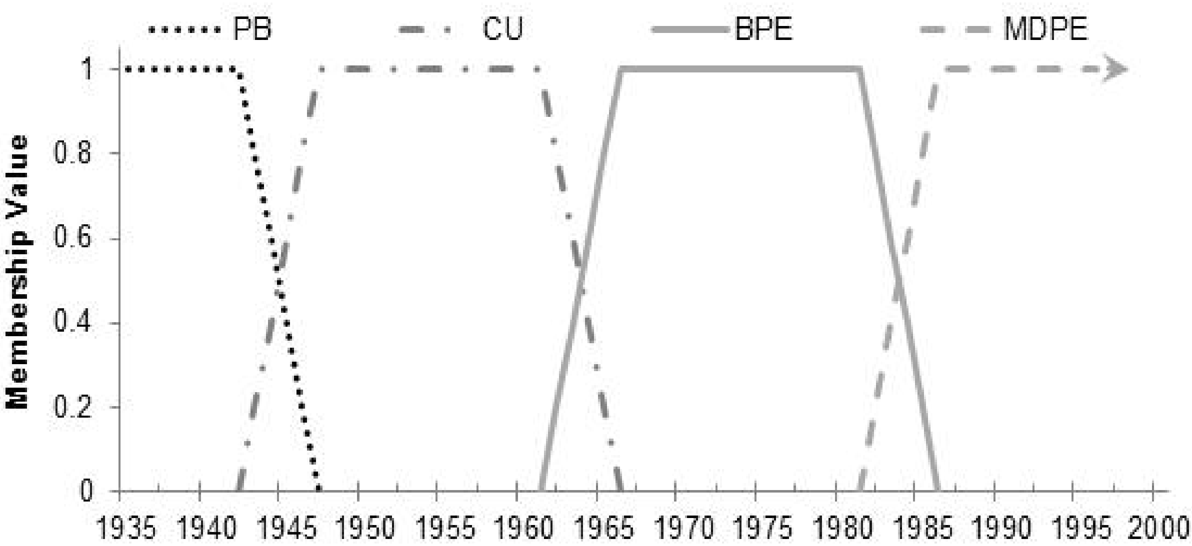


Figure 7-2. Material usage profile for an individual operating zone

7.3.3 Deterioration modelling

The key assumption underpinning the deterioration modelling process is that all assets in the same material peer group and of the same age have the same probability of failure. The process fully accounts for the assets having different commissioning years and different failure years, whilst applying this age assumption. Hence a PB pipe commissioned in 1930 and reported as failing in 2000 is equivalent in age and hence behaviour to a similar pipe commissioned in 1938 and reported as failing in 2008. A diagrammatic representation of the full modelling process is presented in Figure 7-3 which is interpreted as follows. Starting with a random estimation for Weibull parameters, the asset stock and associated failure counts are modelled on a yearly basis from 1837 to present day, taking into account new assets that are installed in each year and the predicted failures by material type. The mathematical form of the 3-parameter Weibull probability density function (pdf) is displayed in Equation 7-1, together with the corresponding cumulative Weibull distribution function in Equation 7-2.

$$f(T) = \frac{\beta}{\eta}\left(\frac{T-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}}$$ Equation 7-1

$$F(T) = 1 - e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}}$$ Equation 7-2

In each year the simulated failures are recorded for each pipe material to allow for a comparison against the observed failures during the observation window, 2001 and 2011. The individual errors for each material are then aggregated to provide an overall assessment of error which is used as the measurement of accuracy during the calibration process. An aggregated error is used to ensure that the interaction and transition between the different pipe materials are fully accounted for, i.e., as one asset fails in one of the material groups it can become re-born as a new asset in the same or a more modern material group depending on the fuzzy rule set applied.

This material transition is achieved in the model by the use of feedback, applied at each time step, to account for the effects of the historic repair and/or replacement activity. The repair and replacement rates are fixed over time but are variable by material type – this is necessary to reflect actual business policy whereby certain materials are replaced more than others. Upon replacement of the pipe, where this is by a different material, feedback is used to account for the reduction in the former material and the gain in the new material stock.

Future failures of the replacement material(s), known as secondary failures, are modelled under the same process. Conversely, whilst repairs do not alter the original pipes material, an adjustment is made in the model to allow for the fact that a pipe failed at particular age and is re-born in the same material group – effectively a “new” pipe, but with the same probability of failure as its peers. Two examples are provided to demonstrate this concept for an asset commissioned in 1920 and attributed as 100% PB material.

1) If failure year = 1963 And, intervention type = Replacement

Then, PB failure count for pipe age 43 years = +1

And, PB asset stock count for pipe age 43 years = - 1

And, BPE asset stock count for pipe age 1 years = + 0.8

And, CU asset stock count for pipe age 1 years = + 0.2

2) If failure year = 1963 And, intervention type = Repair

Then, PB failure count for pipe age 43 years = +1

And, PB asset stock count for pipe age 43 years = +/- 0

7.3.4 Calibration

The calibration process itself is an iterative procedure which seeks to minimise the aggregated error by solving for the Weibull parameters for each pipe material to give the most representative failure output. The overall process is visualised overleaf in Figure 7-3 and demonstrates the material migration process over time. The process aims to solve for three Weibull parameters using either: 1. The method of least squares, solved by using the non-linear generalized reduced gradient method (Lasdon et al., 1974); or, 2. Through the application of a multi-objective genetic algorithm considering the residual error in two dimensions, using the NSGAII algorithm in GANetXL (Bicik et al., 2008; Savić et al., 2011) . Whilst the genetic algorithm offered a minor improvement in the overall calibration of the parameters, the computational requirement did not warrant its use. Therefore, for the purposes of expediency, the Weibull parameters are calibrated using the method of least squares.

The output from the process is a calibrated set of Weibull parameters which describe probability of failure for each pipe material over its lifecycle. The probabilities of failure over time have been transformed into a more commonly used metric, reliability, for the comparison of asset performance in the case studies. Reliability values at yearly asset age time steps are calculated by subtracting the cumulative probability of failure from 1, to obtain a probability value between 0 and 1 which describes the percentage of asset stock likely to be in service at any asset age (T), Equation 7-3.

$$R(T) = \left(1 - F(T)\right) = 1 - \left(1 - e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}}\right) \quad \text{Equation 7-3}$$

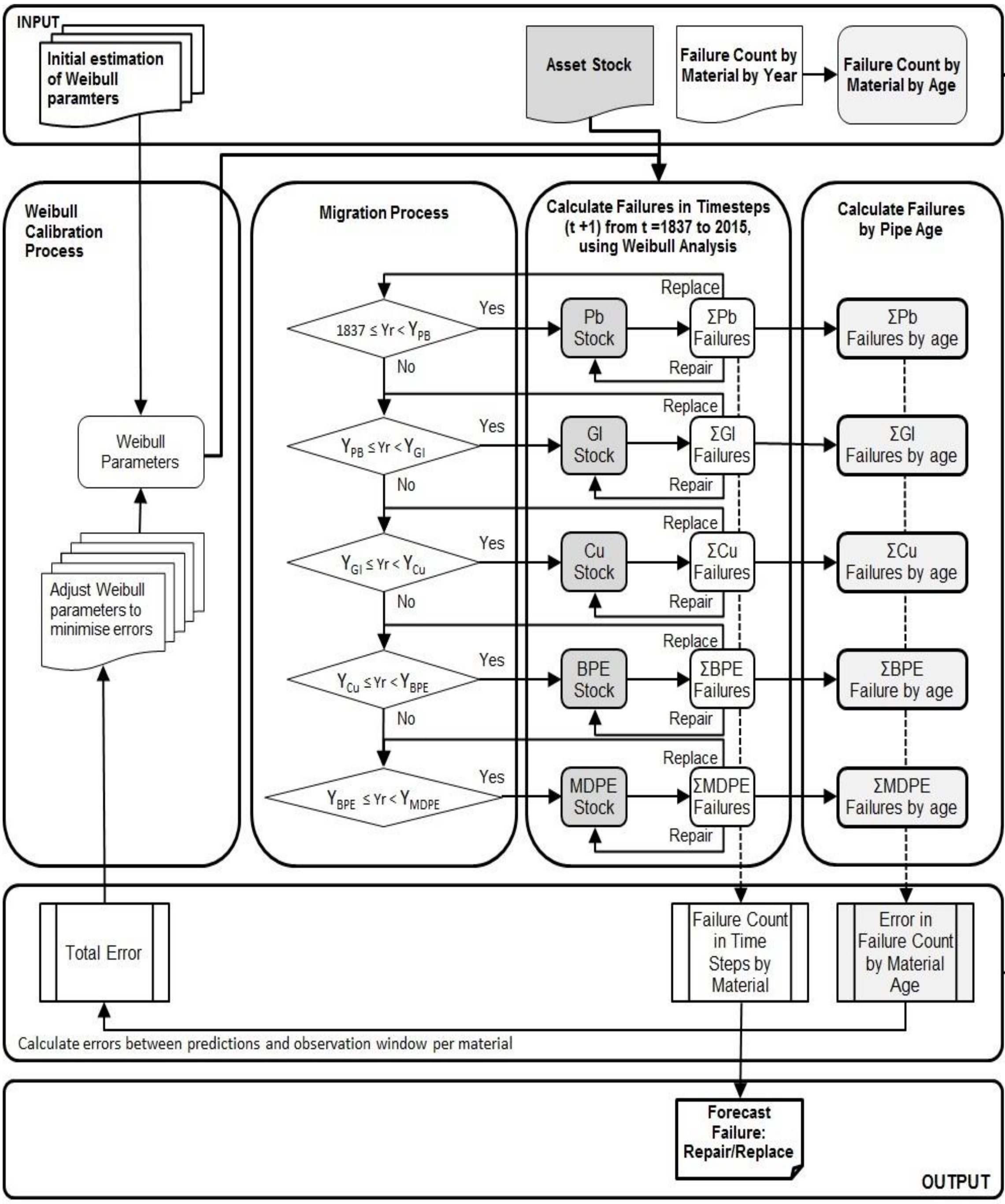


Figure 7-3. Material migration in a deterioration modelling framework

7.4 CASE STUDY

The modelling approach has been developed to model the deterioration and failure of communication pipes assets which have previously presented a challenge to utility managers due to the typically unmapped and unattributed nature of the asset stock. The methodology has been applied independently to two English water utility providers, allowing testing of the accuracy and robustness of the approach. Both companies in this study own and operate a similar sized asset portfolio of approximately 800,000 communication pipe per Water Company, of which c.85% are unmapped in both organisations.

The previously described notional communication pipe asset digitisation and attribution process, developed in GIS, was run for all unmapped and/or unattributed assets across both regions. A frequency distribution by asset length graph was then used to identify a threshold at which individual assets beyond a certain length become highly unlikely or unrealistic in each region to account for local geographic conditions and typical arrangements. The outputs for Water Company 1 provided a threshold of 18m and 46m for short-side and long-side communication pipes lengths respectively.

A mean length value of 2.5m and 7.3m for short and long-side connections was observed and these mean values were applied as corrections to all notional assets in excess of the threshold lengths. As expected, a greater standard deviation from the mean was witnessed for long side connections of 5.4m versus 2.7m for short-side connections. This is to be expected and reflects the non-standard property layouts for dwellings set back from the road, as opposed to those that follow more traditional construction arrangements that run parallel to the road alignment. The short and long side communication pipe length distributions, post correction, are shown in Figure 7-4 and Figure 7-5 for Water Company 1.

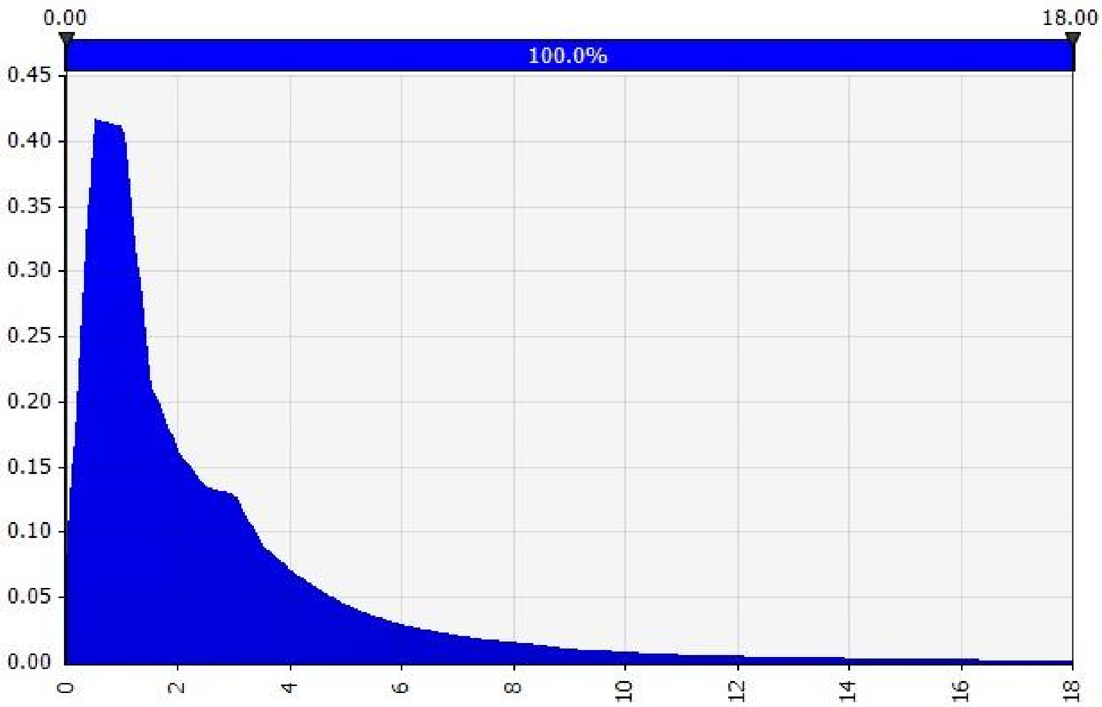


Figure 7-4. Short side communication pipe length distribution

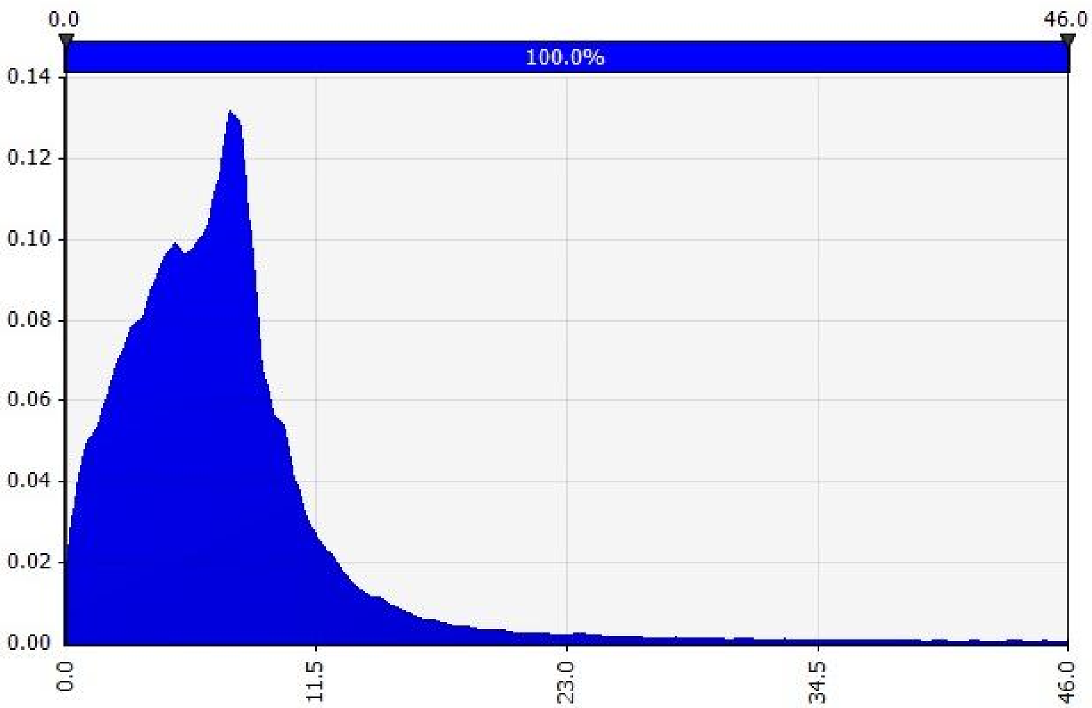


Figure 7-5. Long side communication pipe length distribution

Asset age and material were later inferred for the notional asset stock using the most appropriate available age data source for each asset and the associated fuzzy material rule sets according to the operating zone encompassing that asset. Eight and twelve distinctly different operating zones and accompanying fuzzy rules sets were identified by the two utilities companies, leading to the assignment of the assets within these zones to materials according to the fuzzy rule set for the zone, e.g., Figure 7-2. For the purposes of deterioration model calibration a combined 122,649 communication pipe failure observations were supplied over an eleven year period between 2001 to 2012 by Water Company 1 (60,827 records) and Water Company 2 (61,822 records). A normalised failure rate calculation for each material and each observation year is plotted using Equation 7-4, Figure 6, to provide a comparison of the failure data supplied by each Water Company.

$$Failure\ Rate\ (No.per\ year) = \frac{\sum Failures\ Count}{\sum Assets} \quad \text{Equation 7-4}$$

It is observed in Figure 7-6 that the failure rates witnessed by both companies are broadly in agreement and identify higher failure rates for PB and BPE pipe materials and lower rates for Galvanised Iron (GI). Whilst the observed failure rates for PB assets during this window are higher than other materials, it does not indicate that PB is a poorly performing material. In fact, given the estimated average age for PB pipes, which were no longer installed past the 1960’s, the failure rate is surprisingly comparable to the more modern pipe material, BPE.

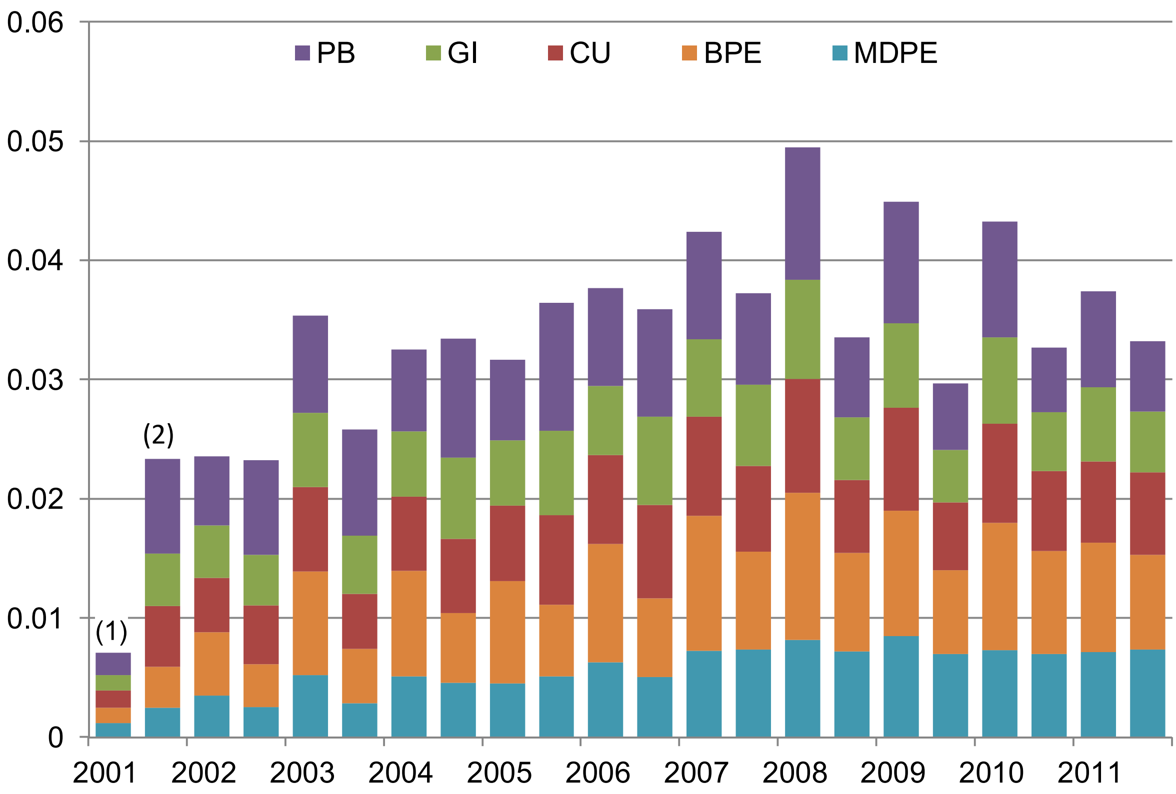


Figure 7-6. Comparison of failure rates by material type over-time between Water Company (1) and (2).

The failure observation records used for the calibration of deterioration curves for each pipe material are applied independently for each Water Company to account for any subtle differences in pipe material performance in each region, which could arise from differing ground conditions, climate variations and/or the quality of workmanship during installation. The observations used in the calibration of the deterioration curves were recorded over an eleven year period, 2001 to 2011 inclusive. The failure observations for Water Company 1 in 2001 were not used in the calibration process to prevent from biasing the model based on smaller than normal failure counts. The notably reduced failure counts in this year are thought to be due to missing records, captured on a previous work order management database as the company transitioned to a new system.

Although a failure observation window of ten years is deemed to be relatively low for assets installed as far back as the 1800's, statistical modelling techniques have been shown to be successful when applied to buried water distribution network assets with similar failure histories (Røstum, 2000; Le Gat and Eisenbeis, 2000; Mailhot et al., 2000; Pelletier et al., 2003). Given that communications pipes are smaller and less critical assets than those modelled in the aforementioned literature, the availability of failure data is surprising.

A Weibull based statistical modelling approach was selected due to the relatively low failure records in respect to the overall asset stock (8%) and for the usefulness of the graphical Weibull survival curve outputs in an engineering and decision making context (Weibull, 1951), Figure 7-7. It is observed that each pipe material tends to follow a typical S-Curve reliability distribution which can generally be described as follows: Failure at commissioning due to deterioration is generally low, with asset reliability values in excess of 90% for assets under 40 years of age. However, after the initial onset of failure the asset reliability decreases at its fastest rate for a period of time and until it reaches a more steady state of reducing reliability between approximately 75 to 125 years. After the steady state of reducing reliability, incremental change in probability of failure lowers as the asset progresses towards "old age", when the majority of assets in the same class have failed leaving a small residual remaining in a serviceable state for a notable time period.

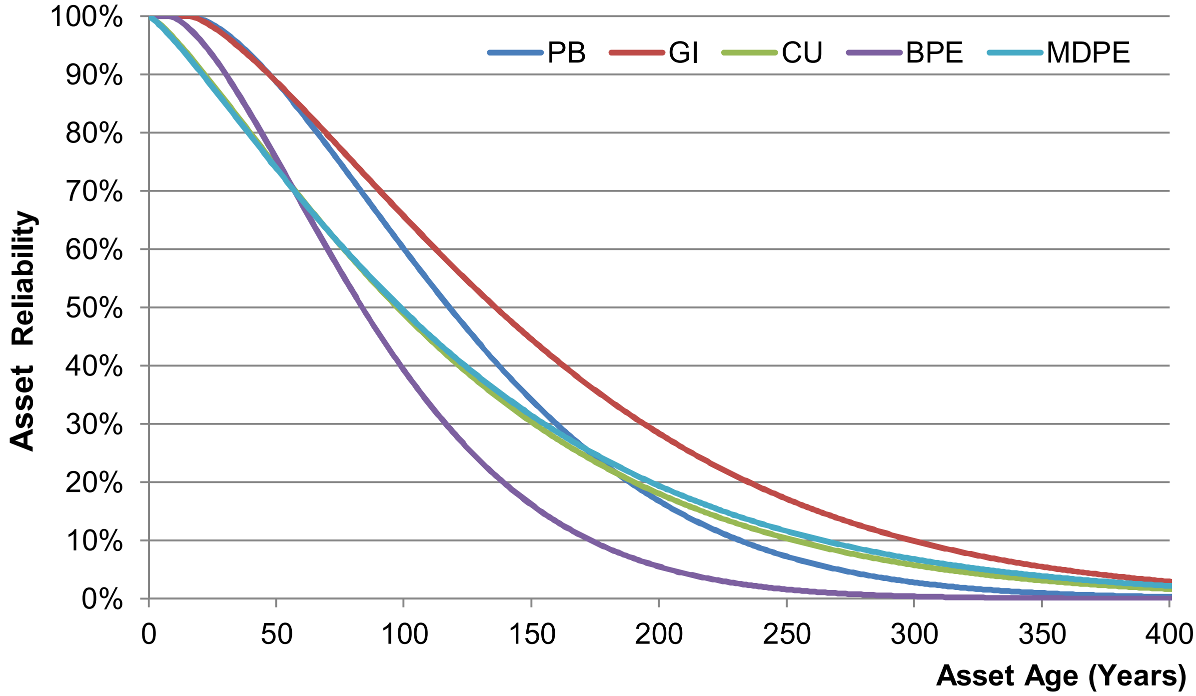


Figure 7-7. Deterioration profiles by material for Water Company 1

It can also be seen that whilst the reliability of GI assets is consistently higher than other materials over-time and conversely BPE is consistently lower, the reliability of the other materials is interchangeable over time. For instance, it is observed that PB assets outperform CU and MDPE pipework up until an asset age of approximately 115 years at which time PB continues to have a lower reliability. However, when considering an even more useful comparator for material performance, asset half-life, it shows little difference in performance: PB (101 years), MDPE (98 years), CU (97 years). Where-as it can be seen that 50% of GI assets are expected to be in service past 120 years of age in comparison to only 75 years for BPE.

The accuracy of all the deterioration modelling curves against the failure observations for Water Company 1 and Water Company 2 are shown by the coefficient of determination, R-Squared, in Table 7-2 and Table 7-3. In support of this analysis, Figure 7-8 is produced to demonstrate the accuracy of predicted total failure counts for PB pipes by asset age versus the actual failure observations.

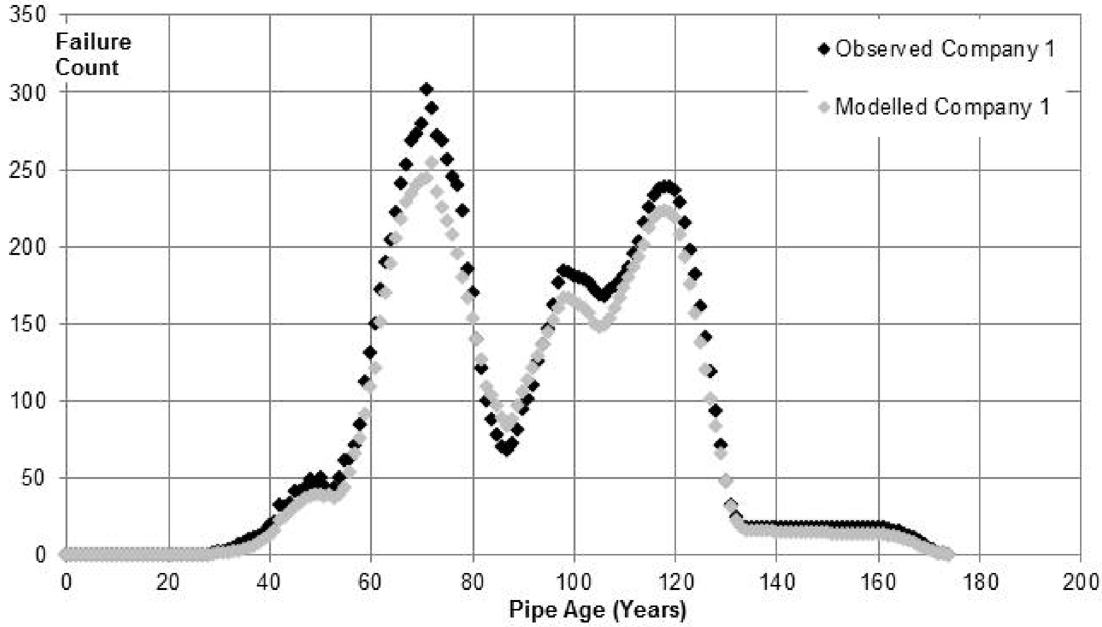


Figure 7-8. Modelled vs. Observed failure counts for Lead (PB) pipes by age

Figure 7-8 clearly demonstrates two distinct pipe ages where the failure count is highest; pipe age 70 years and 120 years. The 70 year peak coincides with steepest rate of failure for PB, Figure 7-7, and the highest asset stock attributed to post World War II construction. The accuracy of the data fit between the modelling outputs and the observed failure data is evaluated using a commonly accepted coefficient of determination, R-Squared (Gupta and Guttman, 2014).

The R-Squared is calculated by looking at the individual errors between predicted and observed failure counts for specific pipe ages and materials, e.g, 42 year old PB pipe. Therefore, each point on the graph represents a single pipe age and the associated predicted failure counts for this pipe is plotted against the observed failures, Figure 7-9. Whilst this is a fairly onerous assessment of model accuracy it helps to identify the individual age bands at which the deterioration model either over predicts, 81 – 100 years, or under-predicts, 61 – 80 years.

For PB pipes it is observed that the model fairly consistently under predicts, albeit only marginally but more notably around the peak failures. Reassuringly, this is not a common characteristic of the model. In fact, BPE is the only other material with a slight under prediction. Whereas the other pipe materials experience marginal over predictions at the peak failure rates.

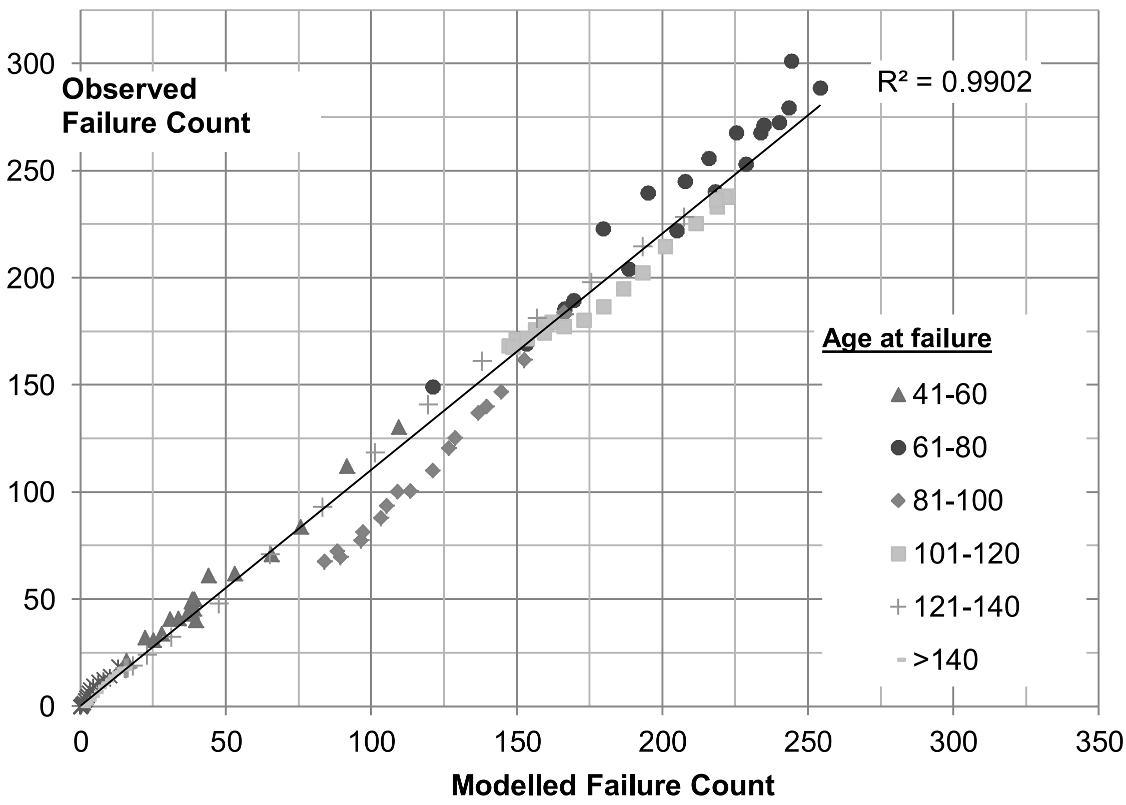


Figure 7-9. Data fit for Lead (PB) failures by pipe age

A full analysis of the accuracy of all pipe material deterioration models for Water Companies 1 and 2 is presented in Table 7-2 and Table 7-3, showing R-Squared values greater than 0.959 for all material types across both organisations. The failure observation counts used in the calibration of the Weibull parameters are also shown. It is observed that the Weibull parameters and associated deterioration curves are similar in nature between Water Company 1 and Water Company 2, despite the modelling framework being customised for each company to account for the different historic material usage profiles and failure observations. This is reassuring as it is expected that communication pipes of the same material and those installed in the same year, would deteriorate in a similar manner regardless of where they were installed. To the authors knowledge, the only condition whereby this assumption might not be valid is for pipework subjected to varying levels of water hardness (Sarin, et al., 2004).

The reason for the location parameter (γ) only being used for older pipe materials is because failure observations in the dataset were not observed in these materials for ages less than 16 and 29 years. This is due to the phasing out of the PB and GI pipework between the 1950's to 70's and our failure observation window starting in 2001. As a result, all failures occurring in the early ages of asset life, which is often referred to as infant mortality, are missed by this model. However, this will not hinder the accuracy of the model for future predictions because PB and GI assets are no longer installed and infant mortality failures counts are typically very low.

Table 7-2. Water Company 1 modelling data

Material	Failure Observations	β	η	γ	R^2
PB	13,972	1.599	127.968	16	0.990
GI	3,090	1.398	155.875	16	0.990
CU	14,074	1.259	130.434	0	0.988
BPE	15,609	1.536	90.005	0	0.988
MDPE	13,454	1.218	133.136	0	0.996

Table 7-3. Water Company 2 modelling data

Material	Failure Observations	β	η	γ	R^2
PB	26,094	1.458	103.479	29	0.973
GI	15,247	1.158	152.056	29	0.960
CU	5,161	1.149	130.707	29	0.996
BPE	8,210	1.804	110.162	0	0.988
MDPE	7,110	0.922	343.824	0	0.974

Weibull deterioration curves are particularly useful for predicting future failure rates over a given time horizon, whereby the time horizon for failure projections can be extended for more accurate models (Røstum, 2000). To test the accuracy of the calibrated model in this study the predicted future failures are tested against the observed failures for the three years immediately following calibration, 2012 to 2014.

A cumulative yearly failure count is produced to show the accuracy of the modelled output versus the observed failures during the calibration window (2002 to 2011) and the three year model verification period (2012 to 2014). A ten year failure rate projection is also plotted, Figure 7-10. The cumulatively failure count is a useful comparator for model accuracy because it is not influenced by yearly extremes which can be caused by unpredictable external conditions such as the weather.

The final cumulative failure count from 2002 to 2014 produced by the model is within 1% of the observed failures. It is also reassuring that on average the absolute error for the modelling predictions during the verification window are within 5% for each individual year. This is compared to 8% for the calibrated data when yearly outliers are removed. Where-by outliers are defined as those with values +/- 1 standard deviation from the mean. Without this exclusion the models performance against the validation and calibration data is 18% and 14% respectively.

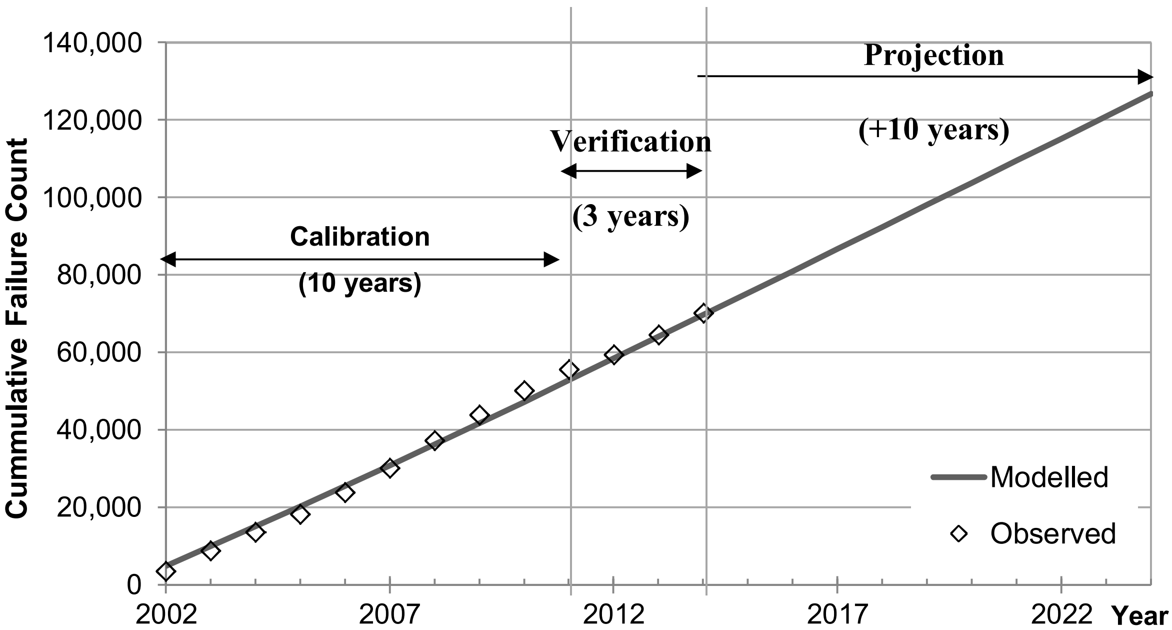


Figure 7-10. Model calibration, verification and projection

7.5 CONCLUSION

This paper demonstrates the effectiveness of a bottom up deterioration modelling framework for small diameter water distribution assets which connect individual customers to water distribution mains. The low asset value and low consequence of failure, for individual assets of this nature, is thought to be the main reason why previous literature has been focused on larger and more critical assets. However, when considered as a collective asset group, investment across the developed World is estimated to be in excess of £4.4bn per year, demonstrating the potential benefits of adopting more comprehensive asset management techniques founded on deterioration models of this nature.

The modelling approach developed by the authors uses a series of geospatial algorithms and fuzzy rule sets to infer the asset stock and assign basic attribution, prior to calibrating Weibull reliability curves for the five most commonly installed pipe materials; PB, GI, CU, BPE and MDPE. A three parameter Weibull function is used to simulate failures for each time step so that they can be compared against actual failure records within a ten year observation window for each material. Feedback processes that incorporate fuzzy rules sets have been introduced within the modelling framework to account for the fact that these assets are either repaired or replaced upon failure and that different materials were used when replacing these assets over time. The output is a calibrated set of Weibull parameters for each pipe material which can be used to calculate yearly reliability values that describe the probability of an asset remaining in service at any given age.

All five pipe materials were observed to behave differently over time and the modelled failure rates showed good correlation to the observed failures with R-Squared values exceeding 0.97. Similar reliability curves were observed for each of the materials between two UK based Water Companies that this modelling framework was applied to independently. Finally, the accuracy of the modelling approach was validated by comparing the predicted number of failures against three years of failure data not used in the calibration process. The yearly failure counts were predicted to within +/-5% accuracy and the overall cumulative modelled failure count at the end of 2014 was predicted within 1%.

The benefit of developing an accurate modelling framework to simulate future deterioration and failure of Communication pipe assets is that future maintenance expenditure can be modelled, which in turn provides Water Companies with a better understanding of their future capital and operational budgetary requirements. Additional benefits could be realised through the application of a whole life cycle cost optimisation model to identify the most cost effective maintenance strategy with respect to total expenditure. Similarly, maintenance strategies could also been developed with the objective of improving serviceability if a relationship between asset degradation and performance can be established. For example, by understanding the impact of GI pipework degradation on discolouration events and/or low pressure, a targeted proactive replacement programme could be implemented with the aim of improving customer satisfaction.

However, this is a complex phenomena to model due to the number of additional contributing factors that lead to reduced serviceability, some of which are associated with the water distribution network itself and not necessarily the communication pipe assets. Therefore, the delivery of an effective proactive communication pipe replacement programme should give consideration to the combined structural and serviceability performance of all components in the distribution network.

7.6 RESEARCH APPLICATION

This research has demonstrated an effective approach that can be used for modelling the deterioration and failure of less well understood assets in the water distribution system, namely; small diameter communication pipes. Infrastructure assets of this nature are notoriously poorly managed and often overlooked within literature due to the perceived requirements for extensive data which is scarcely available.

The outputs from the research are a set of calibrated deterioration curves which can be used to better understand the current and future condition of communication pipe assets; which is a primary component in the delivery of an effective asset management programme. Therefore, this research has provided the foundations for the industry to adopt a more comprehensive approach to the management of small diameter distribution assets. It is hoped that water infrastructure asset owners will adopt the principles outlined in this research to enable them to better understand the performance and investment requirements of the infrastructure for which they are responsible.

In conjunction with one of the UK water companies, the research concepts presented in this chapter have been explored further; with the aim of targeting proactive maintenance programmes towards poorly performing assets and problematic materials. From the analysis obtained in the research, it is suggested that areas with high Black Polyethylene (BPE) pipe concentrations should be the focus for proactive maintenance, due to their high failure rates. A simple mapping based exercise was performed against the modelled outputs to colour coded each individual postcode region with the primary communication pipe material. Postcode areas with mixed materials were excluded and therefore not coloured. Based on this approach, it can be seen in Figure 7-11, that large areas are identified for investigation.

Where-as when failure data is overlaid, the focus area for proactive investigations could be reduced to a much smaller area, which has the added benefit of focusing investigations towards those assets which are predicted to be in poor condition in addition to having a history of failures. Here-by ensuring that investments in proactive renewals are directed towards those assets that are most likely to fail.

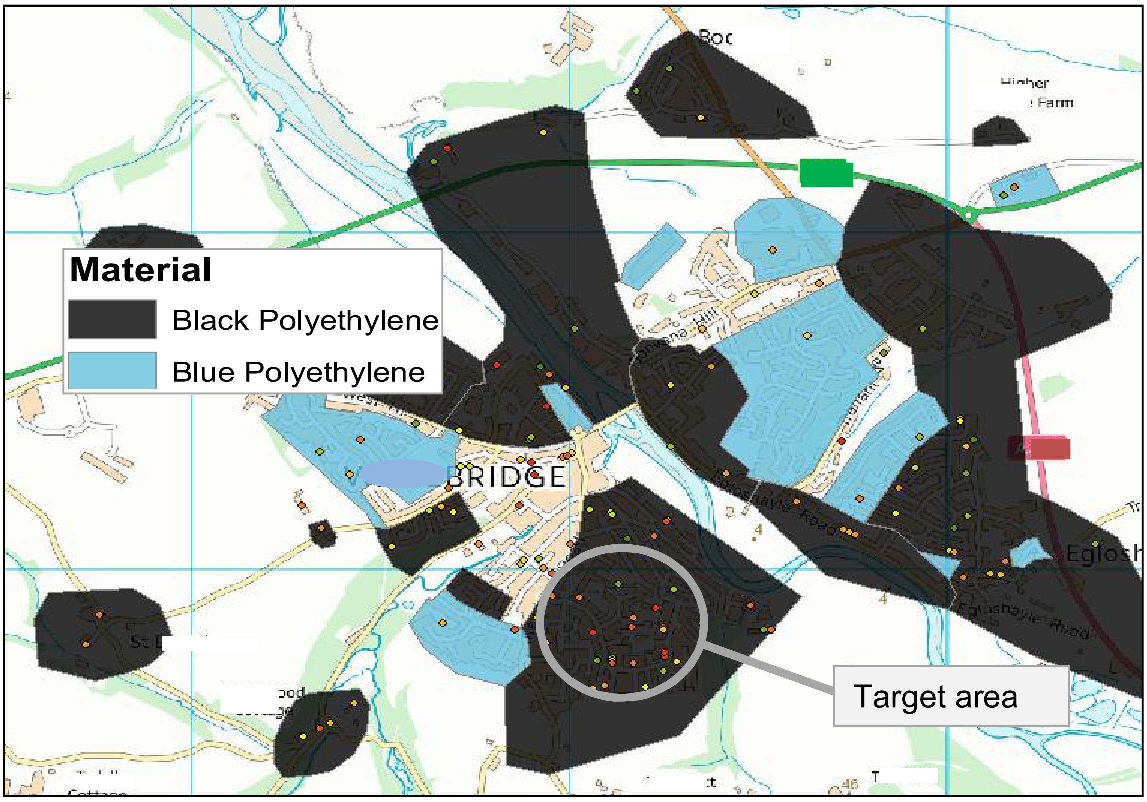


Figure 7-11. Problematic material targeting

The challenge therefore, is to develop an approach that automatically prioritises these areas across the entire network such that the target areas for proactive replacement is reduced, e.g., Figure 7-11. This is achieved by using 100m x 100m grid squares, within which the predicted condition of these assets are considered alongside the frequency and trend of the failure events, rather than just the primary pipe material.

Fenner et al. (2000) reviewed a number of different methodologies for ranking and predicting future performance of grid squares for sewerage related incidents, including; repeat events, cumulative counts and the number of occurrences of events in adjacent squares. It was found that an algorithm based simply on past events provided a consistently better output. As such a similar methodology was adopted but with the inclusion of a temporal component to provide focus towards grid squares with rapidly worsening performance, rather than those that have a history of poor performance which may no longer be causing an issue, i.e., those that might have already had the majority of their defective assets repaired or replaced.

The temporal component is uniquely considered by developing scoring ranges that are based on the yearly failure frequency across the network. These ranges are calculated in each yearly time step by considering the cumulative failure count in each grid square across the network and assigning it a performance score relative to the other grid squares. The performance score is assigned based on a data clustering methodology, known as the ‘natural breaks algorithm’, which seeks to minimise the squared deviations of the groups’ means and thus in-turn find the natural grouping of the data sets from 1 (good) to 5 (poor), (Jenk, 1967).

Accordingly, the individual grid squares are assigned a score based on the relationship between the cumulative failure count in the grid square and the scoring boundaries; which are re-calculated on an annualised basis and are dependent on the overall performance of the network. Figure 7-12 is produced to visualise the concept for a 5-point scoring system. Where-by the score for four postcodes are tracked through time and change depending on their relative performance. By way of explanation, it can be seen that postcode “Post 2” begins with a normalised failure score of approximately 0.8 in 2010, giving the postcode an overall score of 4. The normalised failure score remains unchanged until 2012, i.e., no new failures are observed, which when compared to the increasing failure observations in other postcodes, results in the overall postcode’s score reducing in 2011 to a score of 3. From 2012 onwards, failures continue to be observed in the postcode year-on-year which results in a rapid change in the postcodes score from 3 to 5.

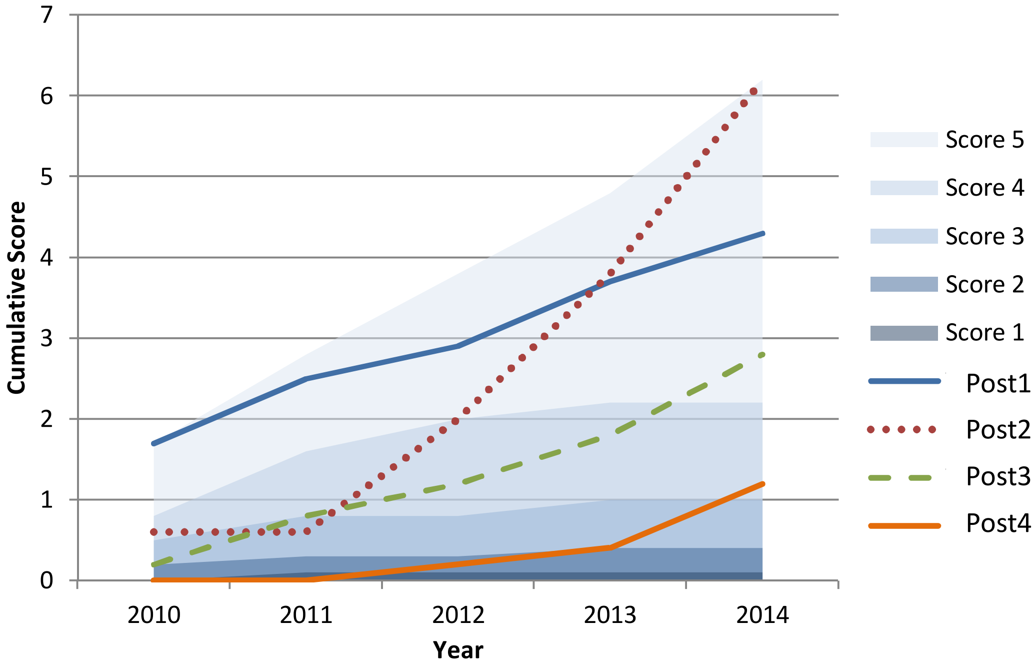


Figure 7-12. Data clustering with temporal consideration

The output from the model is a single performance score between 0 (best) to 5 (worst) for each grid square based on the historical serviceability performance of the assets in that grid. This result is then combined with a score for the overall grid squares predicted collapse rate. The predicted collapse rate scoring mechanism is calculated using the normalised collapse rate for each grid which is then ranked against the other grid squares across the network using the same natural breaks algorithm. Therefore, the combined output from both models is a single investigation priority score between 0 (lowest) to 10 (highest), as shown in Figure 7-13.

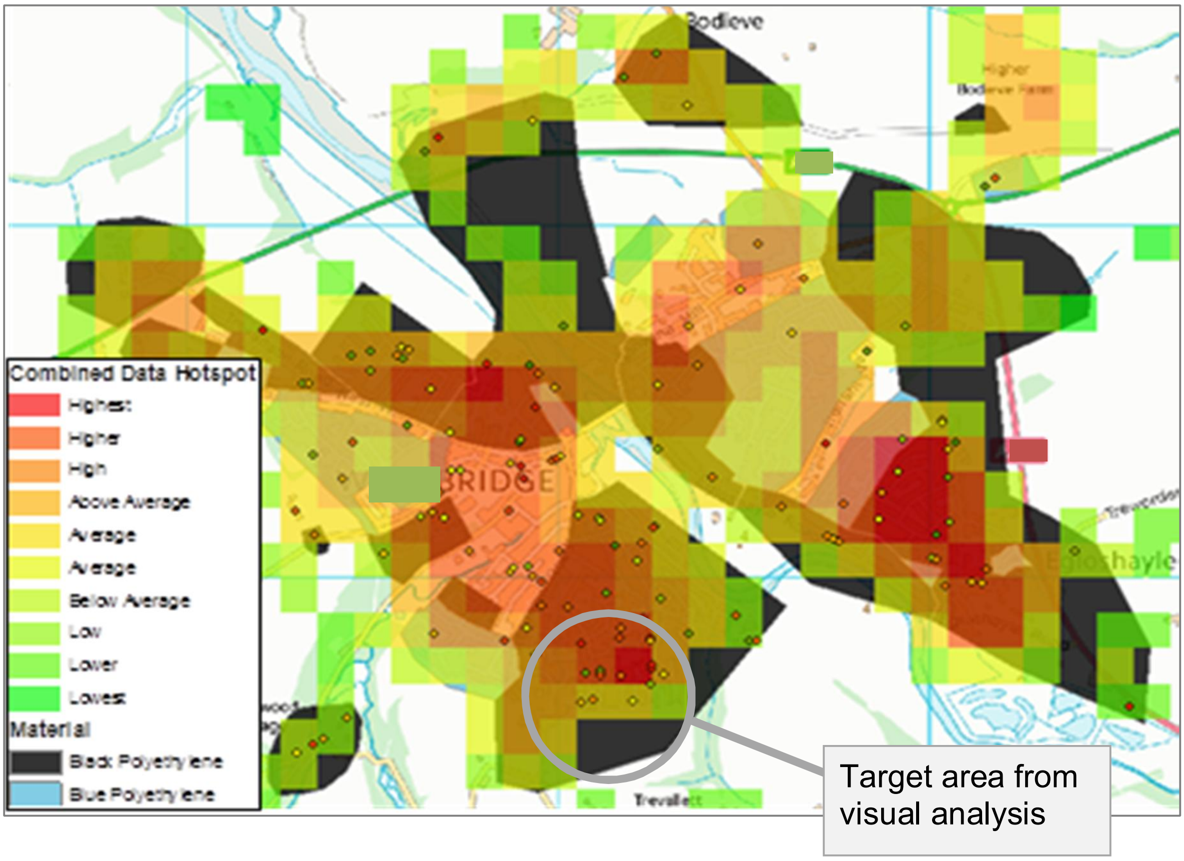


Figure 7-13. Proactive rehabilitation targeting model

It is thought that this approach is highly beneficial for prioritising locations based on observed and predicted performance because it uniquely considers the temporal element associated with failure events and the predicted deterioration, i.e., locations which have a high historic baseline failure rate but which are observed and predicted to be gradually improving, would slowly transition out of the top priority locations. Where-as those postcodes with a low historic failure rate which is increasing rapidly and agrees with the predicted deterioration, would transition more quickly into the top priority locations.

This aligns itself to the natural deterioration process where-by locations with the majority of their assets already in old age are likely to experience less failures in the near future due to the fact that the majority of failures have already occurred and/or the majority of assets have been replaced. Conversely, postcodes containing assets that are all approaching peak deterioration rates should be prioritised for proactive maintenance to avoid the potential high future failures associated with this stage in their lifecycle.

In addition to the benefits associated with the development of a proactive rehabilitation programme for communication pipes, the reliability curves developed from this research can be used by network managers to determine optimal business policy decisions regarding the nature of interventions upon failure. For example, by considering the likely future performance of the failed asset, an assessment can be made about the assets remaining service life. Thus informing the decision about whether to repair or replace the asset from a whole life cost perspective.

Quantifying the potential savings that can be realised through the adoption of different repair and replacement policies is a difficult and complex process to comprehend, particularly when decisions can be made based on pipe material and age. Therefore, performing this analysis accurately, to enable a truly optimised investment strategy to be developed, is the motivation behind Chapter 8.

However, prior to undertaking research into optimising investment strategies for these assets, it was recognised that the modelling work undertaken in this chapter could provide an improved insight into private supply pipes. As such, further work documented in Appendix A was undertaken to develop a methodology capable of establishing the condition of the private supply network across a given region.

Appendix A also documents a case study showing the application of the methodology and how this enhanced asset information, when coupled with a performance model, can be used to evaluate the financial impact of a transfer in ownership for the private water supply pipe network. The study concludes that a transfer in ownership would equate to a financial burden between £4.1 and £6.8 per household, depending on the nature of the maintenance policy selected by the water company.

8 OPTIMISED INVESTMENT PLANNING FOR HIGH VOLUME-LOW VALUE BURIED INFRASTRUCTURE ASSETS

This chapter is under revision for a secondary review by the Journal of Pipeline Systems, American Society of Civil Engineers.

Ward B, Smith D, Roebuck J, Savić D. A and Collingbourne J (2015). Journal of Pipeline Systems. In Review.

8.1 BACKGROUND

During the past few decades, the global water industry has evolved to become a much more mature industry that is capable of justifying its investment in its infrastructure based on historical performance analysis and forward-looking models. The UK water industry is a prime example of this evolution where-by a common framework was developed to support water companies in the adoption of a risk based approach to capital maintenance planning (UKWIR, 2002a).

This led to the formation of water companies business plans in 2009 (PR09) being largely based on some form of cost-benefit analysis and prioritisation, which helped the industry to understand the value of different maintenance programmes and to schedule their investments accordingly. During the following iteration of business plans in 2014 (PR14) more advanced decision support tools were used which allowed investment decisions to be optimised based on achieving long-term corporate goals.

Optimisation is a vast improvement upon prioritisation methods which are likely to adopt a simplistic ranking based approach to maintenance planning. Where-as optimisation techniques are capable of identifying different combinations of maintenance solutions and different intervention timings, to find the lowest whole life cost. Or alternatively, optimisation can be applied to identify the combination of interventions which deliver the best performance outcome given budgetary constraints.

Multi-objective optimisation has similar capabilities, but instead of converging towards a single solution, multi-objective optimisation algorithms are capable of providing the decision makers with a wide array of optimal solutions that trade-off between the competing objectives, i.e., cost vs. level of service. Optimisation is commonly applied across a whole portfolio of assets such that the best blend of investment scenarios can be identified which align to corporate objectives; these typically trade-off between minimising cost, maximising serviceability and minimising risk. Prior to portfolio level optimisation, asset level optimisation can be applied in conjunction with whole life-cost modelling techniques to help determine a short-list of optimal maintenance scenarios for each particular asset group.

Despite this realisation and a significant rise in published literature and case studies demonstrating the advantages of such techniques, their application has only been applied to the main asset groups that make up the buried water supply network, i.e., distribution mains. At the time of writing, 2015, literature to this affect could not be found for less critical assets, i.e., smaller diameter water mains which often only supply a single property. Chapter 7 had previously identified that the global maintenance expenditure in the developed World, for these small diameter communication pipes is in excess of £4.42 billion per annum, thus warranting further research to determine the suitability of applying whole life-cycle cost optimisation techniques for these assets.

In accordance, a case study is used to demonstrate the development and deployment of a whole life cost optimisation framework for communication pipes – this is thought to be the first instance of optimising communication pipe maintenance policies at asset level in the UK water industry, making it likely to be a first across the globe.

Specifically this chapter seeks to explore the benefits which could be achieved by using the previously improved deterioration modelling analysis within a whole-life cost optimisation environment for the purposes of long-term investment planning

8.2 INTRODUCTION

Communication pipes are defined as the water carrying assets that lie between the water mains and the boundary of the private property being supplied. If a stop-tap or water meter is fitted this usually represents the end of the communication pipe and beyond this point the pipework is referred to as the ‘supply pipe’ which is the responsibility of the property owner (Ofwat, 2014). By their very nature communication pipes are considered high volume and low value assets. With typically one asset for each property, the pipework is small diameter (25 - 50mm) and the length of the asset typically lies somewhere between 2-3m or 6-9m depending on the nature of the connection to the distribution main, i.e., shorter connections occur when the property is located on the same side of the road as the distribution main, thus avoiding a road crossing and vice versa. In contrast, distribution mains can serve hundreds of customers and usually range in size between 50 - 300mm in diameter. These assets are typically laid within the road and have significantly higher failure costs, not only due to the more vigorous and challenging repair techniques but also as a result of the number of customers impacted. It is therefore understandable that past research has focused on the proactive management of these assets as the economic and social costs of pipe failures continue to rise (Engelhardt et al., 2000).

In this research the authors have tailored best practise asset management techniques, developed primarily for use in the management of distribution mains and more critical infrastructure, so that they are applicable to communication pipes which are a smaller diameter and a less well attributed asset stock. The focus of the work centres on coupling the two key elements identified as being critical for effective investment planning decision making: 1. a pipe deterioration model or forecasting tool (Ward et al., 2015a); *and* 2. an optimisation programme to maximise investment (Engelhardt and Skipworth, 2005).

Pipe deterioration modelling can take many forms. At the highest level, models are distinguished by their nature, either physical or statistical. Physical models, generally speaking, are built around the understanding of the underlying physical parameters that govern pipe failure which require the acquisition of detailed information about the pipe(s) being modelled in-order for accurate predictions to be established. Currently, the collection of this data is costly and not widely available across the whole distribution network, and even when data is available, it is commonly limited to water mains or larger diameter pipework. Therefore, the expenditure associated with the collection of this data is unjustifiable; particularly so for lower value assets like communication pipes.

An alternative solution is to use statistical based models which evaluate the relationship between water main condition and key pipe characteristics by the use of historical data, which is mined and statistically evaluated to find patterns that can then be used to formulate a deterioration modelling equation. Although this is an extensively research field for distribution mains, the authors found that none of the more widely successful modelling techniques had been applied to Communication pipes, for instance: statistical modelling (Shamir and Howard, 1979;Clark et al., 1982); Semi-Markovian models (Li and Haimes, 1992); or more recent machine learning methods in the form of Artificial neural networks (Sacluti, 1999) and Evolutionary Polynomial Regression (Giustolisi and Savić, 2006). It was felt that this was a result of the typically unmapped and unattributed nature of the asset stock and so a comprehensive deterioration modelling framework for small diameter water distribution assets under limited data availability was developed (Ward et al., 2015a).

The application of whole life cost modelling for investment planning is a natural progression from statistical deterioration models which usually form the foundations of the approach. Similarly, this field has been well researched for distribution mains where-by Shamir and Howard (1979) were amongst the first authors to try to determine the optimal time for pipe replacement by forecasting the service life of a watermain under two intervention scenarios; replacement or rehabilitation. Lei and Sægrov (1998) and Giustolisi et al. (2006) were also successful in their use of deterioration models as the foundation for optimised investment planning through the adoption of a risk based modelling framework. Researchers have since considered how to evaluate the problem of maximising network performance and reliability whilst minimising cost by advancing multi-objective optimisation (Dandy and Engelhardt, 2006). The benefits of presenting the problem in a multi-objective framework is that solutions take the form of a trade-off between cost vs. benefit. Thus, cheaper solutions with lower benefit and lower cost implications are not overlooked which provides the decision maker with a broader knowledge of the potential solutions available. Halhal et al. (1997) is one of the first cited examples in this field and similar work has continued, (Engelhardt et al., 2002;,Berardi et al., 2008; Nafi and Kleiner, 2010).

The aforementioned literature shows how water companies are already harnessing the power of these techniques to help them select optimal intervention timings and maintenance regimes for larger and more critical infrastructure assets. In contrast, communication pipes form a typically unmapped and unattributed asset stock, which are often sub-optimally managed as a result of insufficient knowledge and un-optimised investment plans. Although these assets are deemed low value infrastructure in comparison to distribution mains, the high asset volume means that substantial yearly capital investment is needed to maintain serviceability. Ward et al., (2015a) estimated a globalised annual total expenditure across the developed World for communication pipes alone is in excess of £4.42bn ($6.95bn) of which £200M is spent in England and Wales (Ofwat, 2010).

Upon reflection of these levels of expenditure and the potential benefits that can be realised by deploying optimised whole life cost decision making frameworks, the authors have coupled a successful deterioration modelling framework for high volume-low value infrastructure with a whole life-cycle cost optimisation decision support tool to demonstrate and quantify potential investment savings.

8.3 METHODOLOGY

This methodology provides a review of all upfront modelling work undertaken to allow for the application of a whole life cost optimisation framework for communication pipes. This includes how the asset data quality improvements and deterioration modelling analysis from Ward et al., (2015a) are re-structured for use in the context of strategic long-term investment planning and optimisation.

Initially, an asset data quality enhancement process using a Geospatial Information System (GIS) is completed to infill unmapped assets by making a logical connection between the customers' property address location and the nearest most relevant distribution mains (or trunk main). Long-side communication pipes are then identified by assessing whether the logical connection crosses the road centre line, i.e., where the water main is located in the opposite carriage way of the highway to the property being supplied. Assets that do not cross a road centre line have been defined as short side connections for the purpose of this study. The authors deemed this to be a reasonable approach and achieve the main aim of the analysis which is to distinguish between assets with higher failure costs, due to asset length and social distribution, e.g., road closures.

A logical data hierarchical procedure is then used to attribute age to each asset utilising the most appropriate data sources available which are ordered in terms of accuracy and data quality: 1. Corporate communication pipe and distribution mains asset age data; 2. property age estimates from the HM Revenue and Customs (HMRC) Valuation Office Agency (VOA); *and* 3. Historic mapping which has been used to identify development periods through the comparison of maps produced in different eras. After establishing a commissioning date for each communication pipe, a fuzzy based rule-set is applied to determine the likely material for the asset (Mendel, 2000).Refer to "Handling data uncertainty" Section in the previous Chapter for further details.

The output from the process is a fully digitised communication pipe data set across the entire region, attributed with asset age, material and its nature, i.e., short or long-side connection. This dataset is can therefore be described as combined dataset drawing on a mix of corporate GIS and notional data to establish the most accurate representation of the communication pipe asset stock.

8.3.1 Deterioration modelling

The deterioration modelling process then seeks to develop a representative model that can be used to predict future performance of all communication pipe assets across the network. This is achieved by calibrating a set of Weibull parameters for each pipe material to give the most representative failure output when compared to the observed failure data. Initially, the three parameters of the Weibull deterioration curve are estimated and the model is solved iteratively in time steps from 1837 to 2015. The failures associated with each pipe material and the associated year/age of the asset at failure is compared to the failure observation window of the data set. This allows for the error between predicted and observed data to be calculated. The three parameters are then adjusted in the calibration process with the aim of minimising this error, using the method of least squares which is solved by using the non-linear generalized reduced gradient method (Lasdon et al., 1974).

The output from the process is a calibrated set of Weibull parameters which describe the behaviour of each pipe material with age, Figure 8 1. It is observed that each pipe material tends to follow a positively skewed normal distribution whereby failure at commissioning, due to deterioration, is generally zero. After the onset of failure, there tends to be a gradual increase in the trend and the rate of increase in probability of failure becomes approximately constant, until it peaks. Immediately after the peak, the probability of failure lowers as the asset progresses towards “old age” when the majority of assets in the same class have already failed.

The result is a small proportion of assets remaining in a serviceable state for a notable period of time. It can be seen that GI and PB pipe materials have a lower and more well spread distribution, indicating that a high volume of assets are likely to reach old age and continue to be in service. BPE is clearly a problematic material with a high probability of failure for assets less than 50 years old and a very low proportion of assets reaching old age. MDPE and CU also have high peaks at around 40-50 years but these probabilities of failure are substantial less than BPE and have a much wider spread distribution after the peak, which would indicate a prolonged asset life in comparison.

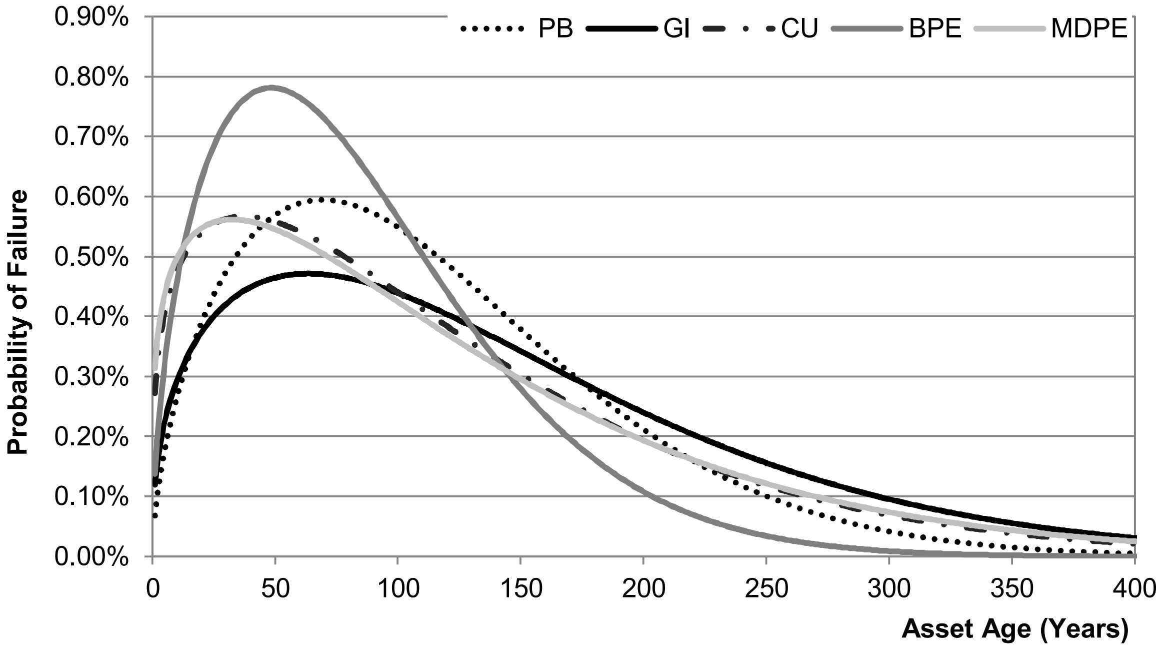


Figure 8-1. Pipe deterioration profiles by material

Engelhardt et al. (2000) acknowledged that the development of long-term investment planning strategies need to be based on a comprehensive understanding of the behaviour of the assets over an extended period of time, as well as suitable knowledge about the levels of service delivered by these assets across the network. This is to ensure that the comparison of different strategies is representative of the actual costs that will be incurred to deliver the desired levels of service.

The modelling projections used as the foundations of this decision support framework were found to be within +/-1% accuracy, when compared as a cumulative failure count against the latest three years of failure data which was unseen during the model calibration process (Ward et al., 2015a).

8.3.2 Cost of failure

The secondary component in the investment planning process, cost of failure, is evaluated in terms of Total Expenditure (Totex) which includes the costs incurred as a result of failure, or, the costs avoided via the prevention of failure which are quantified using Operational Performance Measure (OPM). These are considered one off benefits, realised through the prevention of communication pipe failure and are accounted for by considering the avoidance of two costs; Private (PR) and Social/Environmental (S/E) costs.

Private costs are expressed under the same cost model as the reactive repairs, which represent the absolute minimum expenditure that the utility provider will incur to restore service, i.e., a pipe repair. This cost is typically well understood and can be derived from an assessment of historic costs. Where-as the social and environmental costs refer to those costs that are incurred by society and/or the environment as a result of a collapse, i.e., disruption to traffic or customer inconvenience. These costs are typically more difficult to define and water utility providers often refer to customer willingness to pay information linked to Operational Performance Measures (OPM's),(Willis et al., 2005; Heather and Bridgeman, 2007).

In almost all instances of communication pipe failure, the customer is impacted directly and so the majority of OPMs are triggered at a 1:1 ratio, i.e., one customer contact is received per pipe failure. Therefore the costs shown in Table 8-1 are additive. Where-by any of the proceeding criteria are also valid for the failed asset. Thus, allowing for the total cost of failure to be calculated in accordance with Equation 8-1.

Table 8-1. Failure costs

Ref (i)	Operational Performance Measure (OPM)	Measure	Probability per collapse (P)	Criteria	Cost per event (£ 000)	
A	Failure	Repair	1	Short side pipes	*PR*	0.5
				Long side pipes	*PR*	0.6
B		Replace		Short side pipes	*PR*	0.8
				Long side pipes	*PR*	1
C	Customer Contact	Call	1	All pipes	*PR*	0.02
					S/E	0.01
D		Letter	0.05	All pipes - conditional probability per customer call	*PR*	0.05
					S/E	-
E	Traffic Disruption	Minor Road	1	All long-side pipes	*S/E*	0.1
F		B Road		All long-side pipes beneath B roads	*S/E*	0.2
G		A Road		All long-side pipes beneath A roads	*S/E*	1.5

**Costs shown for indicative purposes only*

$$Failure\ Cost\ (£) = \sum_{i=A}^{G} \mathrm{P}(i) * \left[\mathrm{PR}(i) + \frac{\mathrm{S}}{\mathrm{E}(i)}\right]$$ Equation 8-1

$$where\ i = A, B, \dots, G$$

Where;

(i) *is the OPM reference*
P(i) *is the probability of the OPM being triggered*
PR (i) *is the private cost associated with the OPM*
S/E (i) *is the social and economic cost associated with the OPM*

8.3.3 Whole-life cost modelling

Upon establishing the cost and likelihood of failure in a single year for each asset type, a whole life cost simulation can be run to model the future maintenance expenditure and likely failure rates based on different policy decisions. Where-by a policy decision describes the options available to the decision maker across the asset base at any point in time, i.e., should the asset be repaired or replaced upon failure or what level of proactive renewals should be implemented across the network.

Decisions surrounding reactive maintenance are typically rule based, i.e., if the pipework is of a certain material then repair or replace the asset. These important decisions, particularly for high-volume and low-value infrastructure, are often solely based on operational experience without any consideration to the true whole life cost associated with the different decisions. Similarly, whilst UK utilities are becoming well versed in the use of a risk based maintenance planning principles for high value infrastructure, in accordance with the common framework (UKWIR, 2002a), decisions surrounding proactive maintenance levels for small diameter water distribution pipes are often made based on a “what did we do last year” based approach. This approach, where-by investment decisions are made without fully understanding the complexity and the impact of the decision, causes inadvertent squander of economic, environmental and social resources (Lemer, 1998). It also directly conflicts with commonly accepted best practice asset management principals such as ISO 55000 (British Standards Institution, 2014).

The reason for neglecting best practise asset management principals is often due to the highly complex nature of the problem, making it unfeasible for decision makers to appropriately consider the costs and benefits associated with varying levels of repair, replacement and renewal activities across a network of assets. The complexity of the problem is demonstrated for communication pipe assets as follows: Ten distinct asset groups for which policy decisions can be applied are formed from the five primary communication pipe materials and two asset types, i.e., short or long side connections.

Given that the decision maker can select any combination of repair, replacement and renewal rates for each distinct asset group and in each annualised time step, then the decision space is infinitely large. Even when only whole numbers between 0% and 100% are considered for each of the interventions options, an infinitely large search space remains. As such, a number of practical simplifications are applied to simplify the decision space to 1×10^{66}.

1. Instead of evaluating all of the repair-to-replacement intervention ratios, only three options are put forward for consideration: i) 100% repair and 0% replacement; ii) 100% replacement and 0% repair; or iii) 50% repair and 50% replacement.
2. The level of proactive renewals across the network is limited to between 0% and 2% of the network in 0.5% increments.
3. It is assumed that each policy selected by the decision maker is implemented for a full financial investment cycle of five years, allowing for up to five different strategies to be deployed over the course of a 25 year planning horizon.

Whilst this is a realistic and simplified representation of the original decision space, it still remains incomprehensible to evaluate the full combination of decision options in-order to identify the optimal combination of business policies. To put the search space into perspective, it would take a standard computer 1×10^{50} decades to simply count to this number, assuming an average computer can count to ten million in 1.2 seconds. Therefore instead of exhaustively searching all of the decision space, an adaptive heuristic search algorithm, such as a genetic algorithm, is applied. Genetic algorithms are now a mature technology in the water and waste water industry because of their ability to solve complex network management and planning problems by mimicking natural evolution. They stem from the field of evolutionary computation and are used to converge upon optimal solutions in large search problems by mimicking behaviours found in biological evolution, namely, survival of the fittest, cross-over and mutation (Nicklow et al., 2010).

In this instance, the genetic algorithm is used to evaluate and converge upon the optimal business policy by solving for two conditions, known as the objective functions: 1. Expenditure minimisation, the optimiser searches for the least cost decisions with the objective of outperforming the expenditure of the base policy; and 2. Failure minimisation, the optimiser searches for the least cost decisions with the objective of outperforming the base case asset failure numbers.

Put simply, the optimisation routine is presented with the challenge of outperforming the existing business policy in two dimensions: Total Expenditure (Totex) and Serviceability. For clarity, Table 8-2 distinguishes between the different intervention types and associated maintenance activities that contribute to Totex Expenditure, i.e., Operational Expenditure (Opex) plus Capital Expenditure (Capex).

Table 8-2. Intervention activity and expenditure allocation

Intervention type	Maintenance classification	Cost model inclusions	Funding allocation
Repair	Reactive	Costs account for an isolated repair applied to a failed section of asset.	Opex
Replacement	Reactive	Costs include all activities required to replace a failed asset with new.	Capex*
Renewal	Proactive	Average costs per asset, including all work necessary to deliver the replacement of the listed assets as standalone project.	Capex

* *All replacements are allocated to Capex in this study. However, in reality a minimum £1,000 capitalisation value is applied meaning that replacement costs less than this value would be attributed to an Opex budget line.*

Rather than presenting the problem as a multi-objective trade-off, it was deemed more efficient to run two separate single objective optimisations routines where-by the secondary objective function is used as a constraint. The constraint is used to penalise undesirable solutions which are classified as solutions that fail to outperform the base scenario in both objectives. For example, when the Totex minimisation scenario is run, the model is constrained to find solutions that do not worsen the serviceability performance. Conversely, when the model is solved to maximise serviceability performance, it is constrained to match the base level Totex.

The result is a series of outputs that improve on the baseline policy in both dimensions, whilst seeking to identify the optimal solution according to the users preference, either Totex Minimisation or Serviceability Maximisation. The benefit of adopting this methodology is that the model seeks to identify the most beneficial solution(s) in each extreme, whilst outperforming the original solution. It is also able to reach a solution in a much more computationally efficient process, thus helping to ensuring the optimal solutions for each of the objectives are achieved, as opposed to a less efficient multi-objective trade-off.

The GA itself is steady state algorithm with a population of 400 individuals. Each individual solution is modelled to determine its whole life cost and serviceability performance such that the fitness of each solution can be evaluated in-terms of the objective functions being minimised or maximised by the algorithm. In each iteration, the worst performing solutions are eliminated according to the solutions ranking within the population, before a mutation process is applied to prevent convergence on local optima. A variable mutation was found to be advantageous because of its ability to encourage higher rates of mutation during the early iterations of the algorithm which helps to maintain a diverse population during the early phases (Srinivas and Patnaik, 1994). Subsequently, as the algorithm converges towards an optimal region of search space, the mutation rate is reduced which in effect helps to the algorithm to perform a more focused local search. This variable mutation was configured according to the parameters in Table 8-3.

Table 8-3. Variable mutation rate parameters

Parameter	Description	Value
Maximum mutation rate	The maximum possible (and initial) mutation rate.	0.02
Minimum mutation rate	The minimum possible mutation rate.	0.005
Decrease mutation rate	Mutation rate is multiplied by this value if no new individuals are accepted into the population for a given number of generations.	0.95
Increase mutation rate	The mutation rate is multiplied by this value every time a new individual is accepted into the population.	1.01
Decrease after generations	The number of generations without a new individual being accepted into the population after which the mutation rate is reduced.	10

Finally, the stopping criterion for the algorithm is selected manually by evaluating the convergence of the solutions. Where-by convergence is assessed by the rate at which improvements are generated, such that when the average fitness of the population is marginally less than the fitness of the best performing solution, the algorithm is assumed to have converged on the optimal solution(s) and it is terminated. In this model run, it was observed that no new solutions were being accepted into the population after approximately 50,000 generations and therefore it was assumed that the algorithm had converged. Due to the complexity and computationally demanding nature of the optimisation problem, Amazon’s cloud computing services were used in conjunction with the optimisation algorithm and whole life cost model, to identify a high benefit and low cost asset management policy, from a search space in excess of 1 x 10^{66} solutions. Despite the enormous search space, optimal asset management policies were converged upon in approximately 5 hours for each run.

8.4 CASE STUDY

South West Water are a UK water utility provider who supply water services across an operational area of 11,137km^2, encompassing 1.6 million residents (South West Water, 2013). This study was commissioned to understand and quantify the magnitude of potential benefits that can be realised by developing a comprehensive and optimiseable modelling framework for communication pipe investment planning in South West Water's region. For the purposes of comparison, South West Water's historic operating philosophy for communication pipes, referred to henceforth as the "base policy", Scenario 0, has been modelled within the whole life cost model to provide an un-optimised comparative position. Hereby allowing any optimised strategies to be compared for their relative financial and failure avoidance benefits.

The base policy decisions for communication pipe maintenance, upon failure, are displayed in Table 8-4. These figures refer to South West Waters typical replacement rates for each material and pipe classification. Therefore, the pipe repair rate is simply the inverse of these values. A yearly proactive renewal programme is also undertaken and is simulated within the model. This programme is largely opportunistic renewals which are independent of material and are therefore shown as a percentage renewal rate each year of the total asset stock in each classification. It should be noted that these policies act as guidelines for the operational teams to follow and deviations from the policy will occur due to unforeseen circumstances, such as repeat failures and/or the need to accommodate specific customer requests.

Table 8-4. Base policy material replacement rates upon asset failure

#	Scenario	Pipe Classification	Pipe Material Replacement Rate					Proactive renewal
			PB	GI	CU	BPE	MDPE	
0.	Base Policy	Short Side	0%	100%	0%	100%	0%	0.07%
		Long-side	0%	50%	0%	50%	0%	0.08%

Using the modelling techniques described in the body of this paper, South West Water's entire communication pipe asset stock was modelled over a forward looking 25 year planning horizon from 2015 to 2040. The model simulates the failure of each individual asset according to the deterioration curves presented in Figure 8-1. At the point of failure the asset is either repaired or replaced according to the business rule sets for each pipe material, Table 8-4. The repair and replacement costs and the associated cost of failure, Table 8-1, is recorded to provide a yearly total expenditure cost to the business. Against the base policy, the optimisation model is run to determine the most efficient repair and replacement rates, by pipe material and classification, subject to the constraints imposed on the model.

Two scenarios constraints have been presented. **Scenario 1 – Totex Minimisation**: Where-by the optimisation model penalises solutions that identify higher failure rates than the base policy but seeks to minimise the total expenditure over the 25 year planning horizon. **Scenario 2 – Failure Minimisation**: Where-by the optimisation model penalises solutions that identify higher total expenditure solutions than the base policy but seeks to minimise the overall failure rate. The optimised business policies for both scenarios identified by the model, in-terms of replacement rates for each pipe material and classification, are presented in Table 8-5 and compared for their Totex and Serviceability benefits in Figure 8-2 and Figure 8-3 respectively.

Table 8-5. Optimised strategy material replacement rates upon asset failure

#	Scenario	Pipe Type	Pipe Material Replacement Rate					Proactive renewal
			PB	GI	CU	BPE	MDPE	
1	Totex Minimisation	Short Side	100%	0%	0%	100%	0%	0.06%
		Long side	100%	0%	0%	100%	0%	0.05%
2	Failure Minimisation	Short Side	100%	100%	100%	100%	0%	0.07%
		Long side	100%	0%	100%	100%	0%	0.08%

It is observed that the total expenditure minimisation strategy, Scenario 1, has identified an investment scenario where-by a minimum saving of £1.74M per AMP (£345,080 per annum) can be achieved across the 25 year planning horizon; with a maximum single year saving of £504,690 realised in 2021 (£2.51M in AMP7). The strategy associated with this scenario places greater emphasis on the need for reactive replacements in all investment periods. In AMP6, the optimised scenario suggests that an equal level of service can be achieved by spending £2.07M less on reactive repairs and £3.44M less on proactive renewals, if investment is increased by £3.77M in reactive replacements. Under this scenario a net saving of £1.74M can be realised across the investment period (AMP6) without causing detriment to the level of service delivered to the customer. The failure counts are therefore omitted in Figure 8-2 because they remain equal for both policies which was an original constraint of the optimisation model under the totex minimisation strategy.

In general, reactive replacements have been identified as being more cost effective, in terms of whole life costs, for short-side PB and long-side BPE assets, as opposed to repairing these assets which is the current policy. It is also observed that based on structural performance alone, GI pipes should be repaired rather than replaced. However, the current business policy is to replace short-side GI pipes upon failure due to the potential for these assets to cause discoloration complaints and the practical difficulties associated with repairing these assets; which is not considered in this modelling environment.

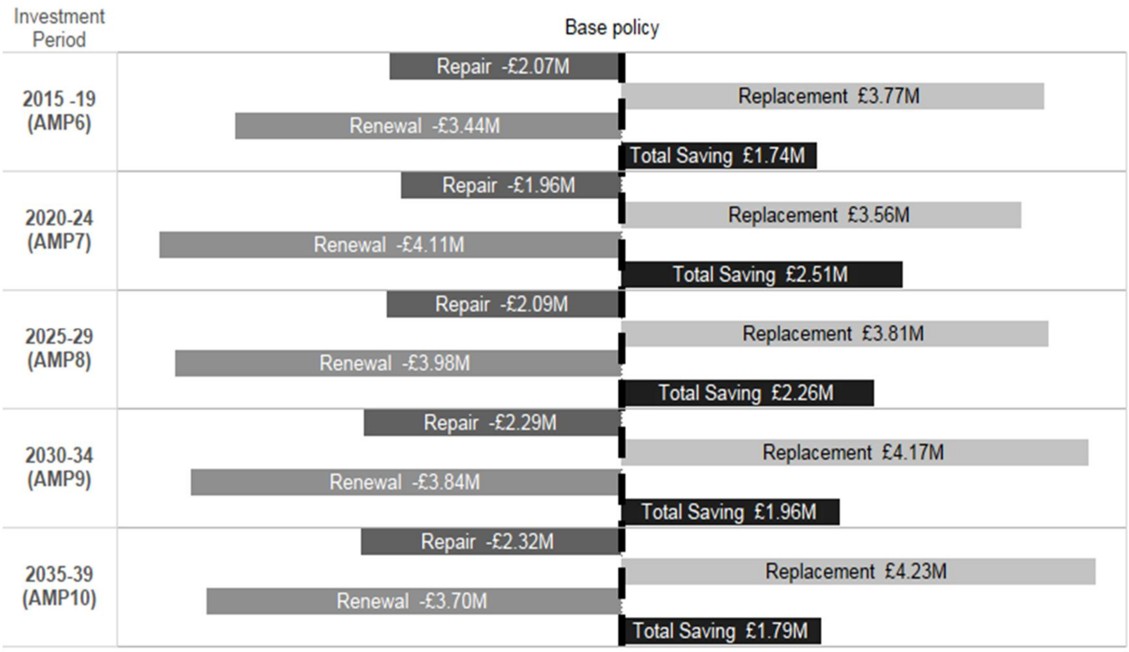


Figure 8-2. Totex minimisation scenario vs. base policy

Similarly, the optimisation model was run to identify a failure minimisation strategy under a constrained total expenditure which could not exceed the base policy expenditure. Therefore for the purposes of comparison the predicted asset failures rates within each AMP for the base policy and the failure minimisation strategy are plotted in Figure 8-3 in addition to the investment profiles. Whilst the overall total expenditure remains equal to the baseline policy, Figure 8-3, demonstrates how the optimised scenario re-balances the different levels of repair, replacement and renewals across each investment period to minimise overall failures.

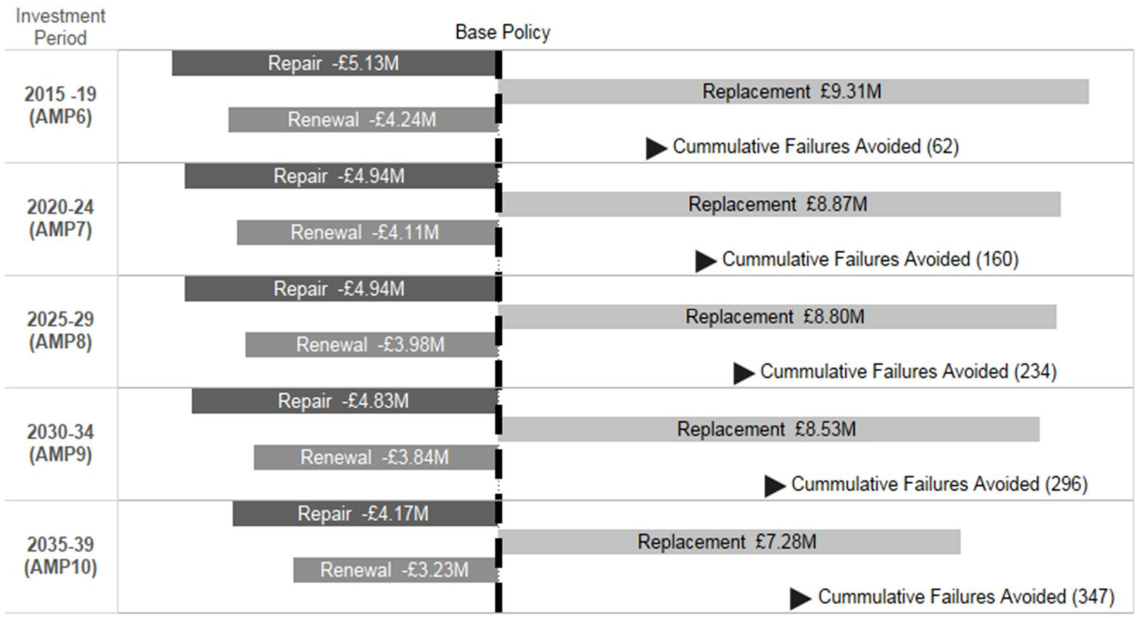


Figure 8-3. Failure minimisation strategy vs. base policy

The output from this optimisation identified an even greater shift in investment towards reactive replacement in all time periods which can be achieved with even greater reductions in reactive repairs and proactive renewals. In AMP6, the optimised failure reduction strategy increases investment in reactive replacements by +£9.3M and reduces investment in reactive repairs and proactive renewals by -£5.1M and -£4.2M respectively.

In-terms of a policy decision, this is achieved by replacing all PB assets upon failure, as well as long-side BPE and short-side GI assets, Table 8-5. By adopting this failure minimisation policy the yearly failure count could be reduced by 347 failures per five year investment period in 2035-30. This is a steady year-on-year reduction which reflects the fact that a change in policy will not have an immediately high effect, but rather a gradual improvement as the replaced assets outperform those that would have previously been repaired. Although a reduction of 70 failures per year may seem immaterial, it is an ongoing benefit and avoided series of customer contacts that can be realised at no additional cost.

The reduction in proactive renewals observed in both optimised scenarios has identified that the current methods for proactive replacement are not cost effective in comparison to the replacement or repair of these assets upon failure from a whole life cost perspective.

This is believed to be largely a result of the relatively low consequence of individual asset failure and the marginal cost savings associated with proactive renewals as compared to reactive replacements. To this effect, further work is being undertaken to explore the price point at which proactive renewals become cost effective and the different technologies that could help deliver efficiencies in communication pipe renewals, i.e., trenchless solutions. Research is also being conducted into the costs and benefits of integrating communication pipe renewals with mains replacements and and/or meter installations.

8.5 CONCLUSION

Modelling the 25 year forward looking impact of different investment scenarios is a huge benefit to asset managers and asset owners. It provides a platform to develop a series of “what-if” scenarios that can be benchmarked against the current business policy, as demonstrated by the use of the decision support tool in this case study. The additional functionality of applying an optimisation algorithm to identify the most effective business policy under basic constraints is a distinct advantage because the outputs can provide the decision maker within an informed view of what the optimal maintenance strategy should be across his/her portfolio of assets.

In reality other constraints such as political or regulatory drivers might prevent the business achieving the truly optimal position. Under these circumstances, the minimum proactive renewal rate should be constrained in the model to reflect the company’s regulatory or political commitments which would prevent the optimisation algorithm selecting infeasible scenarios. A relevant example would be the commitment from UK Water Companies to replace lead communications at the same time that their customers replace their own lead supply pipes. Therefore, the minimum proactive renewals in the model should be accounted for based on historic levels of proactive lead replacement.

Regardless of the regulatory or political drives that prevent Water Companies achieving true optimality with respect to infrastructure maintenance policies, improvements via the deployment of individual asset level optimisation techniques are fundamentally achievable. This is evidence in the modelling outputs which have provided suitable challenge to long-established business policies, by demonstrating total expenditure efficiencies in the region of £1.7M to £2.5M per five year investment cycle. All of which can be achieved by simply changing the level of repair vs. replacement maintenance for specific pipe materials.

Ultimately, this methodology provides a quantitative and auditable framework for strategic asset management decision making for high volume-low value infrastructure assets. This in turn empowers decision makers to challenge the optimality of their existing business policies. In this instance, the existing business policy wasn't far from either of the optimal policies identified by the model. Therefore, the main benefit provided by this approach has been through the development of a repeatable and mathematically sound process for optimising business policy decisions, rather than relying upon operational experience alone. The methodology also allows for the re-optimisation of policies in future years, which is necessary as the asset stock moves into different phases along their deterioration curves. The ability for these considerations to be undertaken manually is incomprehensible, particular for low-value high-volume infrastructure where knowledge of asset performance is lacking. As such, the authors believe they have developed a highly valuable decision making methodology for otherwise challenging infrastructure assets which have the potential to be sub-optimally managed.

8.6 RESEARCH APPLICATION

The optimisation of strategic asset management and maintenance decision making is moving to the forefront of the industry thanks to the recent advancements in data availability, unprecedented access to cheap computational power coupled with more intelligent algorithms that can make use of this processing capability.

This chapter demonstrates these principals by using Amazon's cloud computing services in conjunction with an intelligent optimisation algorithm to identify a high benefit and low cost asset management policy, from a search space in excess of 1×10^{66} solutions. Tackling a search space of this magnitude is incomprehensible through sheer computational power alone and requires the additional support of an intelligent algorithm to converge upon optimal solution(s). To put the search space into perspective, it would take a standard computer $1\text{x}10^{50}$ decades to simply count to this number - assuming an average computer can count to ten million in 1.2 seconds!

The improved communication pipe maintenance strategies, identified from this research, have been discussed with engineers who are responsible for the operation of water distribution networks. Although, it was acknowledged that the repair of all long-side GI communication pipes would not be achieved due to local conditions that often enforce the assets to be replaced, i.e., when a repair poses a risk to discoloration, or it is technical unfeasible. All other policy recommendations were deemed logical and achievable, which include; the replacement of PB and BPE pipes, as opposed to repairing these assets upon failure.

The effect of these policy changes will not be witnessed for some-time, but it is re-assuring that an experienced management team agree with the findings of the study and are willing to change historic business policies in the hope to achieve improved serviceability for customers.

9 CONCLUSIONS AND FURTHER WORK

The research presented within this thesis has successfully achieved the overall objective of **"developing a series of decision support tools and methodologies that can improve asset management decision making for water and waste water assets across all decision making levels, namely; Operational, Tactical and Strategic decision making"**.

Throughout this thesis, data quality has been recognised as a critical component in the overall asset management business process. Data availability, reliability and the usefulness of condition information have been specifically addressed. For low value – high volume infrastructure, improvements in data availability have been realised through the development of innovative geospatial processes capable of infilling missing asset data as well as assigning attribution. These developments were primarily aimed at permitting the application of strategic investment planning best practise across these assets, but secondary benefits have also been passed forward into the tactical levels of asset management decision making, i.e., the prioritisation of assets for inspection or rehabilitation.

The use of condition information for operational decision making was also approved upon in the early chapters of this thesis, Sections 3, 4 and 5. Firstly, for buried infrastructure (sewers) and secondly, for high value – low volume assets (service reservoirs). Whilst the approach differs for each type of asset, the underlying objective of improving the usefulness of condition information through the development of decision support tools has been achieved.

This was achieved in Sections 3 and 4 through the development of a new methodology that maximises the use and value of condition inspection information for buried sewerage infrastructure. The new methodology provides a decision support framework that allows rehabilitation decision making to be optimised across a region, such that individual asset rehabilitation investments can now be considered in the wider context of the benefits they deliver. Ultimately, the new methodology vastly improves upon the conventional process of rehabilitation decision making and in doing so provides a mechanism to better align operational decision making with an organisations strategic business objectives.

Section 5 provides an improved risk management framework for high value – low volume assets, specifically service reservoirs. The new methodology adopts best practise risk management from across a spectrum of engineering industries and applies them within an innovative framework that translates typical condition inspection survey observations into reliability scores which allow better risk management.

Sections 6 and 7 developed deterioration modelling methodologies for low value – high volume infrastructure assets, namely private sewers and communication pipes, respectively. Due to limited data availability and a lack of understanding surrounding the performance of these assets, it had meant that methodologies of this nature had not been previously developed. Despite these challenges, the approach adopted within this thesis demonstrates strong predictive capabilities in-terms of asset deterioration and collapse rates.

Finally, Section 8 developed an approach to capitalise on the improved understanding of low value – high volume infrastructure assets, by integrating this information into a whole life cost optimisation framework. This methodology allows asset managers to adopt a significantly improved investment planning process for these assets which is aligned with the Common Framework (UKWIR, 2002a) and International asset management standards (British Standards Institution, 2014). It is believed this is the first example of optimising investment planning and maintenance policy decision making for communication pipes across the industry. Significant financial and performance benefits were also demonstrated from both of the optimised maintenance policies that were produced.

9.1 SPECIFIC CONCLUSIONS

The process of operational asset management decision making can be improved using optimisation techniques to evaluate total expenditure

A unique methodology for the optimal specification of sewer rehabilitation investment is presented in this thesis, chapters 3 and 4. The methodology uses an advanced optimisation algorithm to evaluate the cost benefit trade-offs that exist between different rehabilitation solutions and the combination of these solutions that can be delivered across a catchment or drainage area.

It is evidenced to be a superior methodology than the conventional sewerage rehabilitation specification process which relies upon the expertise from engineers who manually evaluate CCTV inspection information when determining the nature and extent of different rehabilitation solutions. This process is not only tedious and subjective but it has no quantifiable means of identifying optimal solutions, or, possible combinations of optimal solutions in the delivery of catchment wide rehabilitation programmes. Therefore, the purely manual process of sewer rehabilitation design leaves a number of unanswered questions, such as: (1) Does the solution offer the greatest structural benefit to the network? (2) Is the solution the most cost effective solution available? And, (3) Does the solution most greatly reduce the risk of critical asset failure?

By framing the problem such that multi-objective optimisation techniques can be used, allows these questions to be answered. Furthermore, the versatility of the approach is also demonstrated through its ability to respond to the UK Water industries recent requirement to adopt a total expenditure approach to investment planning. Here-by allowing sewerage engineers to evaluate the operational and capital benefits of different schemes in a single platform.

Quantitative Risk Analysis delivers improved asset management for long-lived water infrastructure

It is widely recognised that best practise asset management planning should adopt a risk based process which seeks to define both the reliability and the consequence of asset failure. This is supported in the UK Water industry through the Capital Maintenance Planning Framework (UKWIR, 2002a). The framework sets the industry guidelines for risk based decision making, which has since become a requirement imposed by the UK Water industry regulatory to encourage water companies to consider the probability and consequence of failure when justifying capital investment.

Despite the successful application of the Capital Maintenance Planning Framework for assets with a robust history of failure, the principles present a number of challenges for assets with limited failure data, i.e., high value – low volume assets (UKWIR, 2011). Therefore, it is often the case that pre-emptive asset management techniques in the form of visual condition inspections are used to determine the current operational and structural condition of the asset as well as to help estimate the assets remaining service life and value. Whilst traditional condition inspection techniques are useful to help prioritise maintenance regimes, it remains difficult to benchmark the current performance of one asset against another, or, to evaluate how far along the deterioration process the structure may be. This is a common problem when the condition or performance of an asset is simply measured using a 1 (good) to 5 (poor) grading system.

In response to this challenge a methodology has been developed in this thesis for understanding and benchmarking the performance of high value – low volume water industry assets, chapter 5. The approach is founded on a severity and extent scoring system which is used to translate sub-component condition observations into reliability scores against a variety of failure modes, namely; structural integrity, water quality and health & safety performance.

The new methodology has been integrated within an innovative iPad and Data Cloud management system to provide an efficient and common framework complaint approach for prioritising maintenance and investment programmes with respect to structural reliability.

The advantage of being able to express condition in-terms of structural reliability is that it can be used to develop an understanding of risk – thereby aligning with the UK regulators requirement to justify capital investment in this way. Furthermore, by being able to express risk in a clear and quantitative manner, the job of decision making is made easier and more informed through an improved understanding of the true costs and benefits that are associated with different decisions. This ultimately helps progression towards the overall goal of developing a Quantitative Risk Analysis (QRA) framework for long-lived infrastructure; which has the overarching aim of identifying optimised maintenance regimes and pro-active intervention options which can then be systematically planned and implemented.

Tactical asset management decision making can be developed with accuracy for assets under limited data availability

This thesis has proven how geospatial technologies can be used to develop an enhanced understanding of unmapped buried infrastructure networks which in-turn can be used as the basis for the development of predictive deterioration models to help understand the likely future performance of these networks. Targeted renewal and inspections programmes can also be developed accordingly, using the outputs from this work.

Two different methodologies have been developed to demonstrate the improvements that can be achieved via the adoption of such methodologies for both clean and wastewater infrastructure, chapters 6 and 7. Initially, a methodology was developed to better evaluate the extent and likely condition of the newly transferred private sewer network. The recent transfer in ownership, 2013, meant that failure data for these specific assets was limited. Resulting in the development of a deterioration modelling approach using CCTV survey and asset failure datasets that were captured across the public sewer network. The model is unique in the way that it applies transitional matrices to condition profiles, rather than peak scores, which is deemed to be a more representative modelling process for sewer deterioration. Statistical modelling techniques were later used to prove that these deterioration relationships were valid for the private sewer network using a random condition sample taken from the private sewer network.

A similar geospatial data improvement methodology was developed for the communication pipe network, which despite being under the ownership of the UK water utility companies since privatisation in 1989, remains a poorly understood network. In addition to the basic improvements in asset understanding delivered via this methodology, a bespoke set of deterioration models were developed, calibrated and validated for the most commonly used pipe materials in the network.

Furthermore, bespoke deterioration models for small diameter communication pipes were able to be developed due to the more extensive failure datasets captured by UK utilities as a result of their ownership of these assets for a longer period of time. Until now, these failure datasets appeared to have been underutilised because of the poor data quality associated with these records which has been improved as a result of the earlier geospatial data improvements delivered across the communication pipe network. Whilst many authors describe various approaches to deterioration modelling of “small diameter” distribution assets, typically their work refers to assets having diameters between 100-200mm and which serve multiple properties. In contrast, small diameter is referred in this research as assets serving a single property with typical diameters of less than 50mm. As such, this research is thought to be amongst the first in the industry for truly small diameter pipework.

Asset level optimisation and strategic planning for low value – high volume buried infrastructure can deliver efficiencies

Investment planning and business policy optimisation is becoming a more common practise for buried infrastructure networks, thanks to the improvements in computational power, advances in optimisation search algorithms and the improved understanding of asset performance, now and into the future.

Prior to the advancements developed in this thesis, which have improved the understanding of asset performance for low value – high volume buried infrastructure, it was previously not possible to optimise long term investment planning or business policy decisions for these assets. Initial research suggests that most UK water companies were developing their long-term investment requirements based on historical expenditure, with little consideration given to materials of the asset stock in the ground, the likely future performance of these assets, or whether alternative maintenance policies would deliver improved business performance.

Therefore, research was conducted to take advantage of the previous modelling improvements by developing a methodology and modelling framework capable of optimising investment planning and policy decisions for communication pipe assets. The methodology demonstrates superior performance to traditional business planning approaches by optimising the maintenance policies for these assets under two scenarios: 1. Identification of the least whole life cost maintenance programme under constraints not to exceed existing failure rates across the network; 2. Identification of the maintenance regime leading to the lowest possible failure rates under constraints not to exceed the current levels of investment. Optimised regimes for both scenarios were delivered, offering either total expenditure savings of £1.74M or the prevention of 62 failures, between 2015 -20.

9.2 FURTHER WORK

Suggested additional work which would enhance the current practise of asset management decision making in the water industry is presented in the context of the decision making improvements delivered by this thesis, i.e., operational, tactical and strategic decision making.

9.2.1 Operational decision making

Chapter 3 provides a novel solution for how the strategic asset management objectives of an organisation can be reflected within its operational decision making. The new methodology applies a multi-objective optimisation model to help decision makers identify the location and extent of the optimal rehabilitation interventions, using trenchless rehabilitation techniques, across the network.

In reality, it will not always be possible to rehabilitate a sewer using trenchless rehabilitation techniques, i.e., where the defects are too severe or the pipework is already partially or completely collapsed. In these instances, it is likely that an open cut repair or replacement technique would be required, albeit sometimes in conjunction with, or to allow the trenchless techniques to be applied. Therefore, future improvements in this context of decision making would be improved by the development of an interactive expert system capable of working alongside the optimisation algorithm to over-rule the optimisation outputs where specific conditions would prevent the practical delivery of the optimised solution. The ability to manually over-rule the optimised solutions at individual asset level prior to catchment wide optimisation was delivered as a process improvement in chapter 4. However, achieving automation of this process would be a notable improvement.

Further operational decision making improvements were delivered in chapter 4 by providing a modelling framework capable of evaluating rehabilitation schemes for their true operational and capital benefits. The operational benefits delivered are assessed in this model based on the occurrence of historic events extrapolated forward over-time. Although there is no guarantee that these events will continue at the same frequency, this approach was deemed a fair representation in the absence of further information or analysis. To improve the accuracy of this assessment, other modelling techniques which have been developed to predict the frequencies of ongoing operational incidents could be incorporated, i.e., sewer blockages and flooding and pollution events.

Additional operational decision making benefits could also be realised by the development of a fourth objective function, or a standalone model, to consider alternative routine maintenance interventions as opposed to capital solutions that provide operational benefit. For serviceability to be evaluated in this way, alternative operational interventions would need to be accurately costed, as well as their benefits quantified and a rule-set developed around the frequency of the operational work. Therefore, the objective functions in the model would need to be re-established in a way that allows the optimisation algorithm to evaluate the costs vs. benefits of capital based solutions against operational alternatives.

9.2.2 Tactical asset management decision making

The Quantitative Risk Analysis framework developed in chapter 5 demonstrates a modelling framework which can be used to help move the industry away from a condition based assessment of asset performance and towards a more quantitative approach. The traditional condition grade scoring based approach is not granular enough to fit a reliability curve which is where this methodology offers a marked improvement because it provides a mechanism where-by a relationship between the input observations (severity, extent and weighting factor) and asset reliability can be established.

Currently, the relationship between the input observations and the reliability score for the component is established based on a notional reliability curve that is fitted using an engineers' assessment of the deterioration profile of the specific component. Further work to explore a more scientifically based process to define the relationship between the input observations and the reliability curves for each of the different structural components, would enhance the accuracy of the modelling outputs.

Tactical asset management decision making was also improved for the private sewer network which has previously not benefited from the adoption of proactive asset management. To allow a proactive methodology to be adopted, significant research was conducted in chapter 6 to provide an improved understanding of the extent, condition and the likely future performance of the asset stock which has been achieved with reasonable success. Due to the ability of the model to identify areas of poorly performing assets, from a structural condition perspective, it would be advantageous to develop this tactical modelling platform such that serviceability performance is also included in the investigation targeting process. A potential framework, where-by a simple cluster analysis is undertaken to assess the spatial distribution of serviceability events within a postcode polygon would fit well alongside the existing process.

It was realised that with appropriate modifications to account for differences in asset performance and deterioration, the principles developed in this paper would also be applicable to other less well understood infrastructure assets. In recognition of this, research was conducted within this thesis to develop a deterioration modelling process for small diameter water pipes under limited data availability. Reassuringly, significant benefits were also observed for this asset stock which demonstrates how other low value – high volume assets could also benefit from adopting these techniques, i.e., boundary boxes and stop-taps.

An attempt was made in Appendix A to use the secondary outputs from the GIS techniques developed for the communication pipe network analysis as a means of estimating the extent of the private supply pipe network. Although understanding the extent and performance of the private supply network was not the primary driver of the research, it was evident that an improved understanding could be delivered using fairly basic rule-sets and assumptions. Therefore, a review of these rules and assumptions from the perspective of private supply pipes could potentially lead to the development of a comprehensive and vastly improved process for estimating the extent and condition of the private supply network. Furthermore, the optimised investment planning methodology developed in chapter 8 should be considered as a potential mechanism to more accurately understand the costs vs. benefits of private supply pipe adoption. If legislative change in ownership of these assets is likely, then I would strongly advocate the use of these outputs for long-term investment planning and for the development of targeted asset renewal programmes.

9.2.3 Strategic asset management decision making

Strategic asset management modelling was the final area of research conducted in this thesis. It benefits from the previous data quality improvements and explores the potential savings that can be realised by applying whole life cost modelling and optimisation to low value - high volume buried infrastructure.

The modelling framework has been developed for communication pipes which are just one of the asset types where tactical modelling improvements have been developed in this thesis. An obvious and novel application of this new modelling framework lies in the application of this approach to the private water supply network (discussed previously) and the private sewer network; for which a comprehensive asset stock and set of deterioration models has been developed in chapter 6.

The strategic modelling process for all infrastructure assets could also benefit from an additional level of granularity. If distinct areas, or individual asset types, can be identified that make proactive renewals more cost effective, then these should be distinguished in the model and the renewal costs adjusted accordingly. For example, cul-de-sacs that would require less traffic management than terraced homes along a main road could be identified from Ordnance Survey mapping data and assigned a more representative renewal / replacement cost accordingly. This would present the model with a more cost effective renewal programme which would be considered for its long-term costs and benefits, against, the predominately reactive solutions currently being identified as the ‘optimal’ strategy.

In contrast, benefits would also be gained from identifying areas adjacent to critical infrastructure such as hospitals, fire stations or train stations, where unplanned maintenance or replacements would cause severe disruption. Therefore, by increasing the cost of failure for these assets within the model, it would ensure that the model prioritises proactive rehabilitation of these assets to prevent failure.

Reassuringly, the modelling framework has been developed in a comprehensive way that allows for regular updates of the key elements in the model, namely: the assets themselves; the unit costs for repairs, replacements and renewals; the deterioration curves that define the different assets behaviour; and the indirect costs associated with asset failure. Therefore, as new technologies are developed that allow for interventions to be delivered more cost effectively, i.e., through trenchless technologies, then it is recommended that the maintenance polices are re-optimised. This is on the basis that the cost benefit ratio of proactive renewals and reactive replacements would become more favourable. Similarly, the model should be re-optimised if further work is undertaken to more accurately capture the indirect costs associated with asset failure, which would be another contributing factor to the cost benefit ratio associated with proactive interventions.

9.3 FINAL REMARKS

This thesis contributes to knowledge across all of the three asset management decision making levels by providing novel solutions, developed within comprehensive modelling frameworks that offer improvements to a range of the different disciplines within the overall asset management practise, as depicted in Figure 9-1. The specific thesis chapters are referred to in brackets (#) in the figure below, alongside a short explanation of the improvements offered.

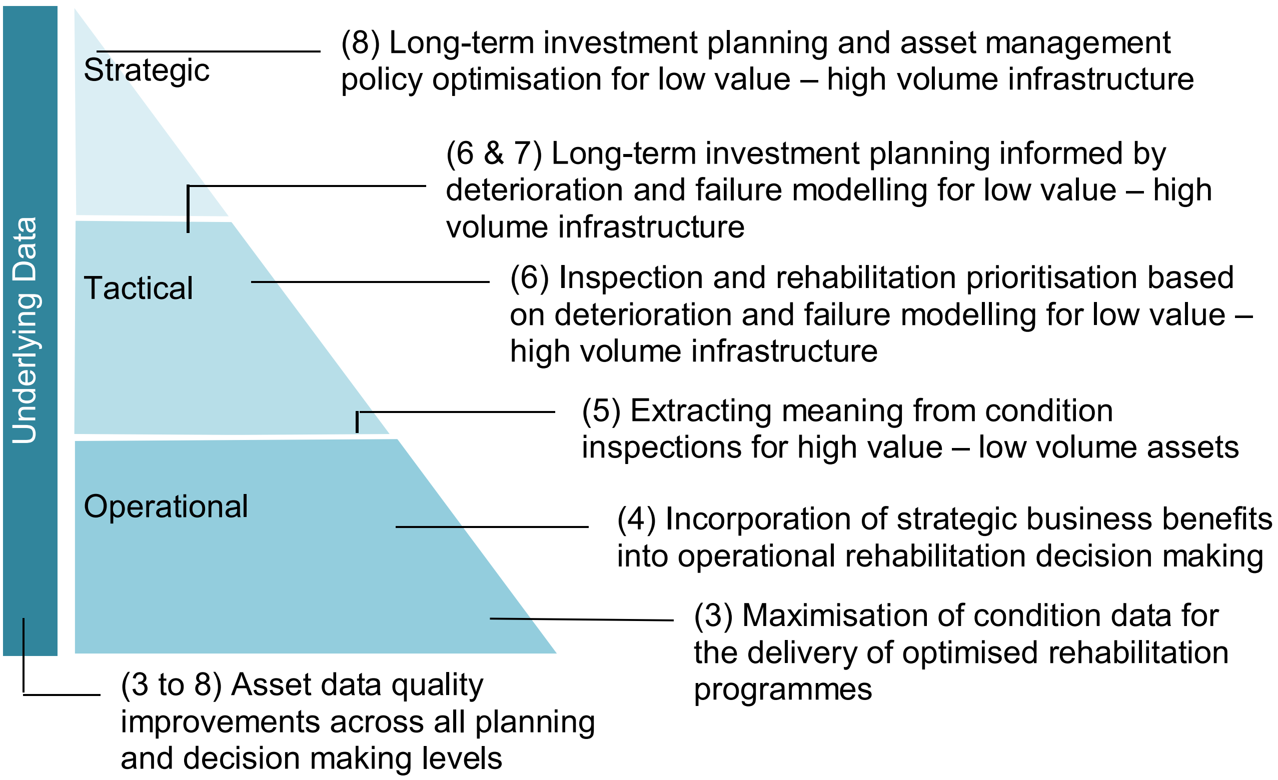


Figure 9-1. Asset management decision framework

Upon reflection it would appear that asset management practises for sewerage and potable water infrastructure assets has lagged behind other industries, e.g., rail, nuclear, and the oil and gas markets. This is thought to be a result of the high consequence of asset failure driving a need for improved asset management practise in other industries.

Despite lagging behind other markets, the water industry is well positioned to capitalise on the latest technological advancements and asset management maturity of other industries and in some cases, the advancements and maturity of its own industry. To this effect, the research in this thesis is best thought of as a re-invention of established ideas which have required the development of comprehensive modelling frameworks to support the application of these technologies across other infrastructure assets, which were previously deemed unable to benefit from these advancements.

What is achieved by this thesis is a notable progression in three of the five key asset management challenges as denoted by the Institution of Civil Engineers (Institution of Civil Engineers, 2013).

1. Whole-life asset management
2. Balancing competing priorities
3. Prioritising inspection and maintenance

Arguably, a contribution towards the ICE’s fifth challenge, “the development of young asset management professionals”, has also been made through my own professional development during the course of this research.

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APPENDIX A. METHODOLOGY TO PERMIT STRATEGIC PLANNING FOR PRIVATE SUPPLY PIPES

A short case study is written to demonstrate the applicability and benefits of the deterioration modelling principles developed in 7.

BACKGROUND & INTRODUCTION

The considerations, benefits and practical issues associated with the transfer in ownership of private supply pipes to UK utilities have been discussed by the industry for some time (Great Britain, 1991; UKWIR 2004; and UKWIR 2009). However, it is unlikely that business planning for customer supply pipes has not previously been undertaken by any UK Water Company. This is in-light of the current legislation which places the ownership and responsibility in-terms of maintenance on the property owner and not the water company (WRc and UKWIR, 2005).

Notwithstanding this legislation, the very recent private sewer transfer in 2011 has set a precedence for the transfer in ownership of assets to water companies, which in-turn is driving a heightened interest surrounding the potential costs and benefits of the transfer in ownership of private water supply pipes. Previous studies conducted in this field, have generally concluded that whilst the current information available would suggest it is not economically cost beneficial to adopt private supply pipes and invest in maintaining a stable asset stock, other intangible benefits may influence a legislative decision in favour of the adoption.

For example, if water companies are responsible for water supplies from the source to the tap:

- A holistic approach to leakage could be adopted;
- Discoloration quality improvements could be delivered through the replacement of galvanised iron pipes;
- Taste and odour issues could be reduced through the replacement of poorly performing pipes; *and*
- Customer service could be improved by addressing the negative impact on customers that the likely increasing failure rates will cause.

It was however acknowledged, that under the current ownership arrangements the level of investment directed towards private supply pipes is insufficient. It is believed this lack of investment is the primary reason for an increased rate of asset deterioration and failure which is in-turn increases levels of leakage and customer dis-satisfaction.

Given these findings from the aforementioned studies, in-conjunction with the precedence set by the transfer in ownership of private sewers, it is surprising that little guidance has been developed to help water companies better understand the financial implications of a transfer in the ownership of supply pipes. The 2009 UKWIR study also identified an industry knowledge gap and recognised weaknesses in its own study, as a result of limited data availability. This led to modelling work being conducted based on assumptions as opposed to observed asset behaviours and real asset data.

For these reasons, it was deemed that a more accurate methodology to improve the understanding of the potential economic costs associated with a transfer in supply pipe ownership would be highly beneficial for the water industry. Benefits were considered from three perspectives: Firstly, the outputs from the study could help empower utilities such that they are better positioned to influence, inform and shape any policy decisions that are made in advance of legislative change. Secondly, it would provide the foundations of any strategic asset management plans aimed at improving serviceability and performance of private supply pipes. Thirdly, it was thought that the outputs of this work could be used in subsequent studies aimed at exploring whether optimised asset maintenance strategies could be achieved, which make the adoption of supply pipes cost beneficial, i.e., by targeting materials or specific locations for proactive renewals, or, by realising economies of scale through the maintenance of both communication pipe and supply pipe as one asset.

To this effect, a case study is explored in this appendix which seeks to utilise the outputs from the previous research through the development of a more accurate methodology capable of assessing the potential cost of any new legislative changes in private water supply ownership.

CASE STUDY

This methodology follows the same logic which has been applied for communication pipe modelling, 7, where-by a number of geo-spatial models and processes have been used to infer a “notional” asset stock for areas where corporate GIS records are unavailable.

In summary, a notional asset is formed between the customer property address point and the nearest most relevant distribution mains (or trunk main). The address point is taken from the OS Master Map address layer and is reviewed for alignment with the water utilities customer database. Where digitised supply pipes for customer properties exist, the notional assets are removed and corporate GIS systems are used. The age and material of the supply pipe is inferred where unknown using the same rule set applied to communication pipes. This is achieved by firstly making an assessment of the assets age from the available data sources; mains age, property age or age mapping polygons (EPOCH maps). The material is then inferred from the age of asset using operational staff knowledge of local materials for different areas; see Table A 2.

Table A 1. Material rules by zone

Date range	*Zone 1*	*Zone 2*	*Zone 3*	*Zone 4*	*Zone 5*	*Zone 6*	*Zone 7*	*Zone 8*
<1945	GI	Pb	Pb	GI	Pb	Pb	Pb	GI
1945 – 49	Cu	Cu	Cu	Cu	Cu	GI	Pb	GI
1950 – 55	Cu	BPE*	Cu	Cu	Cu	GI	Pb	GI
1956 - 63	BPE*	BPE*	Cu	Cu	Cu	GI	Pb	Cu
1964 – 84	BPE*	BPE*	BPE*	BPE*	Cu	Cu	BPE*	BPE*
>1985	MDPE*	MDPE*	MDPE*	MDPE*	MDPE*	MDPE*	MDPE*	MDPE*

** BPE and MDPE installed at 95% to 5%Cu ratio*

The deterioration model developed for communication pipes, 7: Figure 7-7, is assumed to be representative of customer supply pipe behaviours, based on the understanding that supply pipes will behave in a similar manner to communication pipes over their lifecycle.

Therefore, a simplistic life-cycle process is assumed where-by the supply pipe asset stock is modelled over-time to simulate the expected number of failures in each year. Once the supply pipe asset stock is understood, which is an extract from the geospatial analysis undertaken for communication pipe assets, failure rates are applied to the asset stock to calculate the volume of failures in each year that are likely to be experienced. Against each failure, an assumed repair and replacement rate is applied based for three different maintenance strategies, Table A 2. Finally, the failure rates are then multiplied by the unit cost for the intervention scenario being modelled, Table A 3, to obtain the overall cost of supply pipe ownership.

Table A 2. Maintenance strategies

Maintenance Strategy		*Description*
1	Repair only.	All assets to be repaired upon failure. An allowance is made for the replacement of assets < 5m which is justified on economic grounds
2	Replacement of problematic materials	Lead, Galvanised Iron and Alkathen (BPE) pipework to be replaced upon failure. All other materials are remediated in-line with the strategy presented in Solution 1.
3	Replace all pipework	Complete replacement of all pipework, regardless of material, upon failure.

Table A 3. Supply pipe unit costs

Ref	Description	Avg. Unit Price (£)
Repair	Locating and repairing a leak on a service pipe greater than 5m in length.	500.0
Replacement	Renewal from the property boundary to the point of entry to the building.	1,000.0

Given that the extent of supply pipe ownership which could potentially transfer in ownership to the water utilities is unknown. An assumed *likely* ownership scenario has been developed, Figure A2. Under this ownership scenario the transfer of all buried pipework from the communication pipe to the boundary of the dwelling is assumed to transfer from the customer to the water company; including connected outbuildings to the dwelling being served i.e., garages or conservatories, but excluding disconnected outbuildings or garages.

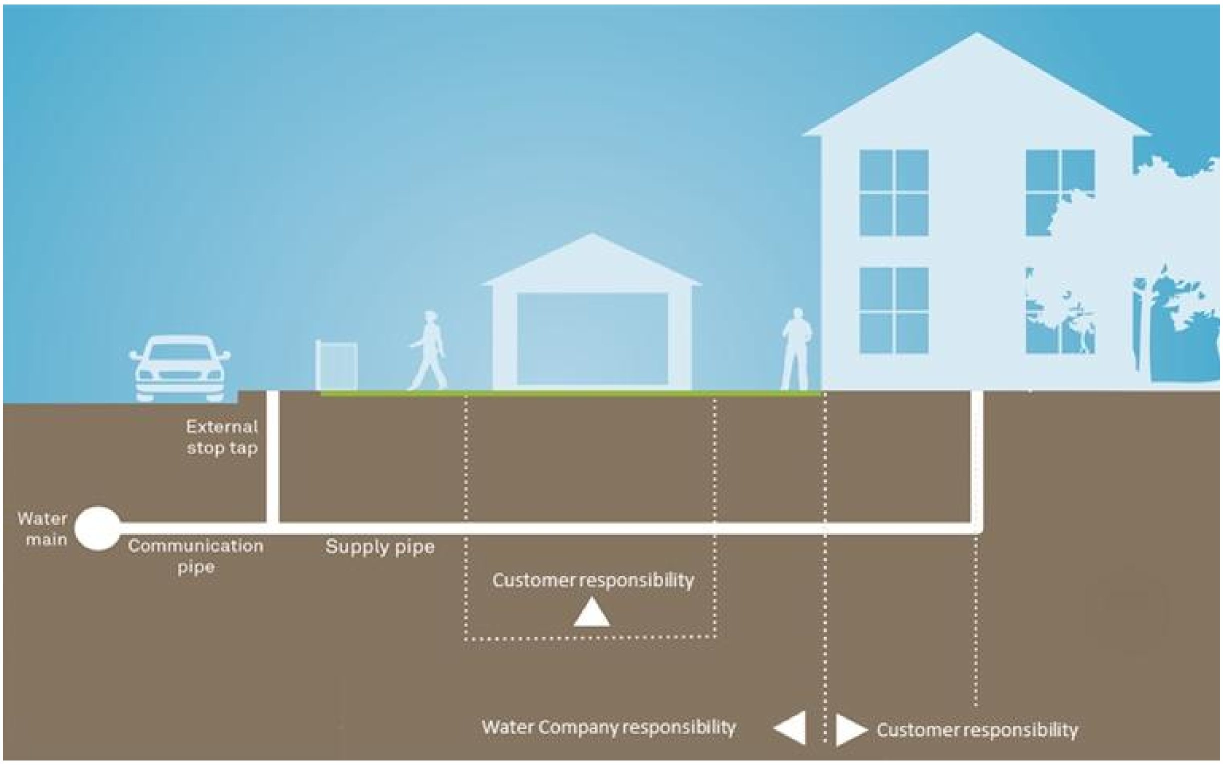

Figure A 1. Private supply pipe ownership scenarios

Following the life-cycle cost modelling process the following annualised costs associated with asset repairs and replacements are presented in Figure A 2. For the purposes of presentation, repairs are considered as operational expenditure (OPEX) and replacements are considered to be accounted for by capital budgets (CAPEX). It can be seen that customer supply pipes would represent an additional financial burden between £4.1 and £6.8 per household, depending on the maintenance strategy adopted.

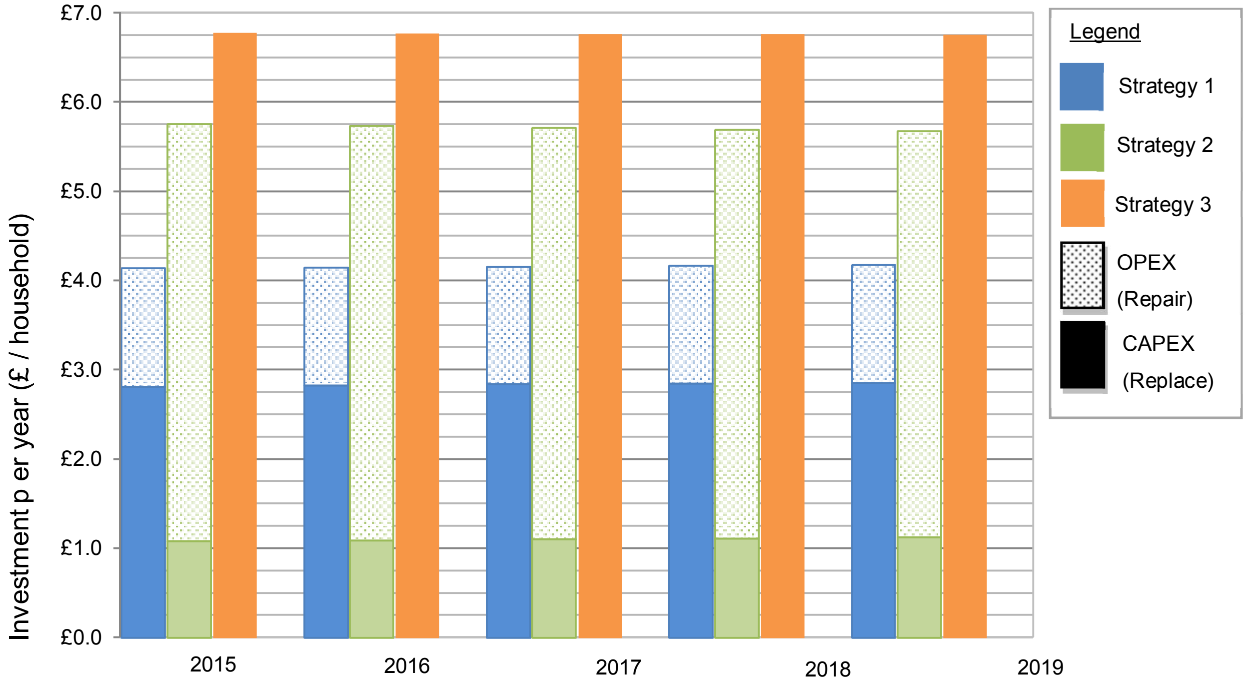

Figure A 2. Financial impact of private supply ownership under three investment strategies

CONCLUSION

This analysis was conducted for a UK water company and identifies an increased financial burden of between £4.1 and £6.8 per household. Reassuringly, this is in alignment with the 2009 UKWIR study which estimates annualised costs to the water company of approximately £6.17 per property, based on full adoption and managed replacement which seeks to maintain a stable burst rate (UKWIR, 2009). Although not modelled in the same way, the UKWIR scenario for stable service is most closely aligned to Scenario 2 which replaces problematic materials upon failure and would result in a cost of approximately £5.8 per property per year.

Given the close alignment to the UKWIR study, it cannot be argued that it is economically cost beneficial for the transfer for water supply pipes to the utility providers. However, the other intangible benefits such as improved leakage management, less discoloration events and less taste and odour complaints should not be forgotten.

As alluded to in the objectives of this sub-chapter, the outputs from this study could be used to inform further work aimed at exploring whether optimised asset management strategies could be achieved via the combined maintenance of private supply pipes and communications pipes. Which would help make the transfer in ownership of supply pipes a cost beneficial proposition.

APPENDIX B. OPTIMISATION RESULTS VS. ENGINEERING RESULTS, CHAPTER 3

SEWER INFORMATION					ENGEERING SOLUTION						OPTIMISATION SOLUTION					
ID	Dia	Criticality Code	Cw	S^0	S^1	ΔS	$Max\left[S_d^1(i)\right]$	C	Rc	Repair Description	S^1	ΔS	$Max\left[S_d^1(i)\right]$	C	Rc	Repair Description
1	150	AE	5	440	0	440	0	£13,899	0	Full Liner	0	440	0	£2,826	0	1No. Patch + 6m Part Liner
2	225	AE	5	642	642	0	180	£-	900	No Repairs	2	640	1	£2,393	5	8m Part Liner
3	150	AK	4	121	21	100	20	£1,557	80	1No. Patch Repair	21	100	20	£1,557	80	1No. Patch Repair
4	225	AE	5	241	0	241	0	£13,515	0	Full Liner	0	241	0	£2,630	0	9m Part Liner
5	225	AE	5	1082	0	1082	0	£12,096	0	Full Liner	230	852	40	£3,818	200	9m + 5m Part Liners
6	300	AE	5	1260	0	1260	0	£14,385	0	Full Liner	110	1150	20	£6,528	100	6m + 3m + 12m Part Liners
7	150	AE	5	50	10	40	10	£1,557	50	1No. Patch Repair	50	0	40	£-	200	No Repairs
8	150	BC	3	81	81	0	40	£-	120	No Repairs	81	0	40	£-	120	No Repairs
9	150	AK	4	181	1	180	1	£1,557	4	1No. Patch Repair	1	180	1	£1,557	4	1No. Patch Repair
10	150	AE	5	80	80	0	80	£-	400	No Repairs	0	80	0	£1,557	0	1No. Patch Repair
11	300	BC	3	160	0	160	0	£1,815	0	5m Part Liner	0	160	0	£1,815	0	3m Part Liner
12	150	AE	5	635	0	635	0	£3,247	0	Full Liner	0	635	0	£1,979	0	*7m Part Liner*
13	150	AE	5	350	0	350	0	£3,247	0	Full Liner	10	340	10	£1,562	50	*5m Part Liner*
14	150	AE	5	80	80	0	80	£-	400	No Repairs	0	80	0	£1,557	0	1No. Patch Repair

SEWER INFORMATION					ENGEERING SOLUTION						OPTIMISATION SOLUTION					
ID	Dia	Criticality Code	Cw	S^0	S^1	ΔS	$Max\left[S_d^1(i)\right]$	C	Rc	Repair Description	S^1	ΔS	$Max\left[S_d^1(i)\right]$	C	Rc	Repair Description
15	150	AE	5	670	670	0	160	£-	800	No Repairs	40	630	40	£4,304	200	*18m Part Liner*
16	100	AE	5	80	80	0	80	£-	400	No Repairs	0	80	0	£1,474	0	1No. Patch Repair
17	100	AK	4	201	0	201	0	£3,222	0	Full Liner	0	201	0	£1,477	0	*5m Part Liner*
18	150	AE	5	450	0	450	0	£3,458	0	Full Liner	450	0	80	£-	400	No Repairs
19	100	AE	5	80	0	80	0	£1,475	0	Full Liner	80	0	80	£-	400	No Repairs
20	225	AE	5	1230	0	1230	0	£9,492	0	Full Liner	250	980	40	£2,873	200	4m Part Liner + 1 Patch
21	225	AC	5	40	40	0	10	£-	50	No Repairs	40	0	10	£-	50	No Repairs
22	300	BC	3	200	40	160	40	£1,810	120	1No. Patch Repair	200	0	160	£-	480	No Repairs
23	300	CO	1	40	40	0	40	£-	40	No Repairs	40	0	40	£-	40	No Repairs
24	150	CO	1	171	171	0	80	£-	80	No Repairs	171	0	80	£-	80	No Repairs
25	100	CY	1	800	0	800	0	£2,444	0	Full Liner	40	760	40	£1,667	40	*6m Part Liner*
26	100	BK	2	741	0	741	0	£1,861	0	Full Liner	10	731	10	£1,477	20	*5m Part Liner*
27	100	BK	2	150	150	0	70	£-	140	No Repairs	150	0	70	£-	140	No Repairs
28	150	CO	1	162	0	162	0	£1,557	0	Full Liner	162	0	162	£-	162	No Repairs
29	150	CO	1	41	41	0	40	£-	40	No Repairs	41	0	40	£-	40	No Repairs
30	150	CO	1	140	0	140	0	£1,557	0	1No. Patch Repair	140	0	140	£-	140	No Repairs
31	150	CO	1	163	0	163	0	£1,979	0	Full Liner	163	0	81	£-	81	No Repairs
32	150	BK	2	43	43	0	40	£-	80	No Repairs	43	0	40	£-	80	No Repairs
33	150	BK	2	80	80	0	80	£-	160	No Repairs	80	0	80	£-	160	No Repairs
34	225	BC	3	80	0	80	0	£1,685	0	Full Liner	80	0	80	£-	240	No Repairs
35	225	BC	3	74	3	71	1	£1,683	3	1No. Patch Repair	74	0	71	£-	213	No Repairs
36	150	BC	3	10	10	0	10	£-	30	No Repairs	10	0	10	£-	30	No Repairs

SEWER INFORMATION					ENGEERING SOLUTION						OPTIMISATION SOLUTION					
ID	Dia	Criticality Code	Cw	S^0	S^1	ΔS	$Max\left[S_d^1(i)\right]$	C	Rc	Repair Description	S^1	ΔS	$Max\left[S_d^1(i)\right]$	C	Rc	Repair Description
37	225	BC	3	490	0	490	0	£9,019	0	Full Liner	490	0	130	£-	390	No Repairs
38	300	BC	3	350	0	350	0	£10,455	0	Full Liner	350	0	90	£-	270	No Repairs
39	300	AC	5	50	50	0	50	£-	250	No Repairs	50	0	50	£-	250	No Repairs
40	300	BC	3	120	0	120	0	£3,382	0	Full Liner	120	0	80	£-	240	No Repairs
41	150	BC	3	461	0	461	0	£4,726	0	Full Liner	40	421	30	£1,979	90	7m Part Liner
42	150	BC	3	684	392	292	160	£1,559	480	2No. Patch Repairs	0	684	0	£2,824	0	11m Part Liner
43	125	BC	3	309	0	309	0	£1,717	0	Full Liner	3	306	2	£1,517	6	*3m Part Liner*
44	150	AK	4	130	130	0	40	£-	160	No Repairs	130	0	40	£-	160	No Repairs
45	100	BC	3	339	0	339	0	£2,250	0	Full Liner	12	327	12	£1,477	36	*5m Part Liner*
46	225	BC	3	20	20	0	10	£-	30	No Repairs	20	0	10	£-	30	No Repairs
47	225	BC	3	100	100	0	50	£-	150	No Repairs	100	0	50	£-	150	No Repairs
48	150	BC	3	345	0	345	0	£2,191	0	Full Liner	0	345	0	£2,191	0	Full Liner
49	150	BC	3	21	0	21	0	£1,562	0	Full Liner	21	0	20	£-	60	No Repairs
50	150	BC	3	20	0	20	0	£1,562	0	Full Liner	20	0	20	£-	60	No Repairs
51	150	BC	3	460	0	460	0	£5,572	0	Full Liner	460	0	140	£-	420	No Repairs
52	300	BC	3	280	0	280	0	£12,027	0	Full Liner	280	0	140	£-	420	No Repairs
53	150	BK	2	176	54	122	52	£1,560	104	3m Part Liner	176	0	80	£-	160	No Repairs
54	150	AI	4	175	175	0	165	£-	660	No	0	175	0	£1,559	0	Full Liner
55	150	AI	4	495	62	433	40	£2,191	160	8m Part Liner	64	431	40	£1,768	160	6m Part Liner
56	100	BC	3	231	0	231	0	£4,000	0	No Repairs	81	150	80	£1,476	240	4m Part Liner
57	150	BC	3	420	200	220	120	£1,768	360	6m Part Liner	0	420	0	£2,824	0	1No. Patch + 6m Part Liner
58	150	BC	3	40	40	0	40	£-	120	No Repairs	40	0	40	£-	120	No Repairs
59	225	AI	4	380	380	0	220	£-	880	No Repairs	0	380	0	£1,686	0	3m Part Liner

SEWER INFORMATION					ENGEERING SOLUTION						OPTIMISATION SOLUTION					
ID	Dia	Criticality Code	Cw	S^0	S^1	ΔS	$Max\left[S_d^1(i)\right]$	C	Rc	Repair Description	S^1	ΔS	$Max\left[S_d^1(i)\right]$	C	Rc	Repair Description
60	225	CO	1	1575	0	1575	0	£9,729	0	Full Liner	0	1575	0	£4,760	0	*8m + 10m Part Liners*
61	225	CO	1	30	30	0	30	£-	30	No Repairs	30	0	30	£-	30	No Repairs
62	100	BC	3	125	2	123	2	£1,475	6	3m Part Liner	2	123	2	£1,475	6	3m Part Liner
63	150	CO	1	400	0	400	0	£3,458	0	Full Liner	0	400	0	£2,615	0	2No. Patch Repairs
64	225	BC	3	1039	251	788	130	£5,470	390	21m Part Liner	111	928	41	£4,528	123	12m + 5m Part Liners
65	225	BC	3	1252	1252	0	220	£-	660	No Repairs	2	1250	2	£3,103	6	11m Part Liner
66	150	AK	4	83	83	0	82	£-	328	No Repairs	83	0	82	£-	328	No Repairs
67	150	BC	3	415	0	415	0	£1,979	0	Full Liner	0	415	0	£1,560	0	*3m Part Liner*
Totals				**22,064**	**5,504**	**16,560**		**£186,747**	**8,665**		**5,454**	**16,610**		**£80,393**	**7,710**	

Red indicates identical solution

Blue italics indicates impractical solution

APPENDIX C. FEASIBLE ENGINEERING SOLUTIONS, CHAPTER 4

Solution 1 for each sewer is “No Repairs” which provides the following values for the three objective functions:

1. Structural condition score improvement (ΔS) = 0
2. Cost (C) = £0
3. Operational benefit cost (Op) = £0

	Solution 2				Solution 3				Solution 4				Solution 5			
ID	C	ΔS	Op	Desc	C	ΔS	Op	Desc	C	ΔS	Op	Desc	C	ΔS	Op	Desc
1	£13,899	440	£87,593	Full Liner	£2,826	440	£87,593	1No. Patch + 6m Part Liner	£1,559	180	£87,593	1Patch	£1,768	260	£87,593	6m Part liner
2	£8,546	642	£42,336	Full Liner	£2,393	640	£42,336	8m Part Liner								
3	£7,685	121	£137,143	Full Liner	£1,557	100	£137,143	1No. Patch Repair	£1,057	20	£137,143	1No. Patch Repair				
4	£13,515	241	£47,043	Full Liner	£2,630	241	£47,043	9m Part Liner								
5	£12,096	1082	£200,643	Full Liner	£3,818	852	£200,643	9m + 5m Part Liners	£2,630	752	£200,643	9m part liner	£1,686	490	£200,643	2No. Patch
6	£14,385	1260	£33,003	Full Liner	£6,528	1150	£33,003	6m + 3m + 12m Part Liners	£2,072	600	£33,003	6m Part liner	£1,813	440	£33,003	3m part liner
7	£3,247	50	£137,143	Full Liner	£1,557	40	£137,143	1No. Patch Repair								
8	£5,149	81	£21,503	Full Liner	£1,557	40	£21,503	1Patch	£1,561	80	£21,503	4m part line				
9	£3,036	181	£137,143	Full Liner	£1,557	180	£137,143	1No. Patch Repair								

	Solution 2				Solution 3				Solution 4				Solution 5			
ID	C	ΔS	Op	Desc	C	ΔS	Op	Desc	C	ΔS	Op	Desc	C	ΔS	Op	Desc
10	£8,530	80	£21,503	Full Liner	£1,557	80	£21,503	1No. Patch Repair								
11	£6,787	160	£86,093	Full Liner	£1,815	160	£86,093	3m Part Liner	£1,815	160	£86,093	5m Part Liner				
12	£3,247	635	£87,593	Full Liner	£1,559	325	£87,593	1No. Patch								
13	£3,247	350	£138,643	Full Liner												
14	£1,562	80	£21,503	Full Liner	£1,557	80	£21,503	1No. Patch Repair								
15	£5,994	670	£31,503	Full Liner	£2,613	320	£31,503	2No. Patch								
16	£1,476	80	£31,503	Full Liner	£1,474	80	£31,503	1No. Patch Repair								
17	£3,222	201	£148,093	Full Liner	£1,472	160	£148,093	1No. Patch								
18	£3,458	450	£137,143	Full Liner												
19	£1,475	80	£87,134	Full Liner												
20	£9,492	1230	£24,178	Full Liner	£2,873	980	£24,178	4m Part Liner + 1 Patch	£1,687	590	£24,178	4m part liner				
21	£8,783	40	£21,503	Full Liner			£-									
22	£8,097	200	£86,093	Full Liner	£1,810	160	£86,093	1No. Patch Repair								
23	£10,717	40	£21,503	Full Liner	£1,810	40	£21,503	1No. Patch Repair								
24	£3,881	171	£31,503	Full Liner	£1,557	80	£31,503	1No. Patch Repair	£2,615	170	£31,503	2No Patch Repairs				
25	£2,444	800	£35,543	Full Liner												

ID	Solution 2				Solution 3				Solution 4				Solution 5			
	C	ΔS	Op	Desc	C	ΔS	Op	Desc	C	ΔS	Op	Desc	C	ΔS	Op	Desc
26	£1,861	741	£90,718	Full Liner												
27	£5,944	150	£24,628	Full Liner	£1,475	150	£24,628	3m Part Liner								
28	£1,557	162	£86,543	Full Liner												
29	£3,036	41	£31,503	Full Liner	£1,557	40	£31,503	1No. Patch Repair								
30	£1,560	140	£47,543	Full Liner	£1,557	140	£47,543	1No. Patch Repair								
31	£1,979	163	£48,584	Full Liner	£1,557	80	£48,584	1No. Patch								
32	£2,402	43	£36,584	Full Liner												
33	£2,824	80	£35,543	Full Liner	£1,557	80	£35,543	1No. Patch Repair								
34	£1,685	80	£86,093	Full Liner												
35	£3,340	74	£86,093	Full Liner	£1,683	71	£86,093	1No. Patch Repair								
36	£2,402	10	£86,093	Full Liner	£1,557	10	£86,093	1No. Patch Repair								
37	£9,019	490	£86,093	Full Liner	£1,683	130	£86,093	1No. Patch	£2,866	250	£86,093	2No. patch				
38	£10,455	350	£87,593	Full Liner	£1,814	140	£87,593	4m Part Liner								
39	£2,072	50	£87,593	Full Liner	£1,810	50	£87,593	1No. Patch Repair								
40	£3,382	120	£86,093	Full Liner	£1,810	80	£86,093	1No. Patch								
41	£4,726	461	£148,093	Full Liner	£2,613	431	£148,093	10m Part Liner	£2,613	140	£148,093	1No. Patch				

ID	Solution 2				Solution 3				Solution 4				Solution 5			
	C	ΔS	Op	Desc	C	ΔS	Op	Desc	C	ΔS	Op	Desc	C	ΔS	Op	Desc
42	£4,515	684	£86,093	Full Liner	£1,559	292	£86,093	2No. Patch Repairs	£2,824	684	£86,093	11m Part Liner	£1,559	292	£86,093	1No. Patch
43	£1,717	309	£86,093	Full Liner												
44	£5,783	130	£45,543	Full Liner	£1,517	306	£45,543	3m Part Liner								
45	£2,250	339	£87,593	Full Liner												
46	£3,340	20	£45,543	Full Liner	£1,685	20	£45,543	1No. Patch Repair								
47	£5,233	100	£21,503	Full Liner	£1,683	50	£21,503	1No. Patch Repair								
48	£2,191	345	£87,593	Full Liner	£1,559	245	£87,593	1No. Patch								
49	£1,562	21	£86,093	Full Liner	£1,557	20	£86,093	1No. Patch Repair								
50	£1,562	20	£86,093	Full Liner	£1,557	20	£86,093	1No. Patch Repair								
51	£5,572	460	£88,634	Full Liner	£1,557	140	£88,634	1No. Patch								
52	£12,027	280	£87,134	Full Liner	£1,812	180	£87,134	1No. Patch								
53	£3,458	176	£86,093	Full Liner	£1,560	122	£86,093	3m Part Liner	£1,557	80	£86,093	1No. Patch				
54	£1,559	175	£138,643	Full Liner												
55	£3,036	495	£137,143	Full Liner	£2,191	433	£137,143	8m Part Liner	£1,768	431	£137,143	6m Part Liner	£1,557	346	£137,143	3m part liner
56	£4,000	231	£86,093	Full Liner	£1,476	150	£86,093	4m Part Liner								
57	£11,277	420	£87,593	Full Liner	£1,768	220	£87,593	6m Part Liner	£2,824	420	£87,593	1No. Patch + 6m Part Liner				

ID	Solution 2				Solution 3				Solution 4				Solution 5			
	C	ΔS	Op	Desc	C	ΔS	Op	Desc	C	ΔS	Op	Desc	C	ΔS	Op	Desc
58	£1,562	40	£87,593	Full Liner	£1,557	40	£87,593	1No. Patch Repair								
59	£1,688	380	£56,376	Full Liner	£1,686	380	£56,376	3m Part Liner								
60	£9,729	1575	£35,543	Full Liner	£2,393	590	£35,543	8m Part Liner	£2,866	985	£35,543	10m Part Liner				
61	£3,813	30	£31,503	Full Liner	£1,683	30	£31,503	1No. Patch Repair								
62	£2,444	125	£87,134	Full Liner	£1,472	123	£87,134	Patch	£1,475	123	£87,134	3m Part Liner				
63	£3,458	400	£35,543	Full Liner	£2,615	400	£35,543	2No. Patch Repairs								
64	£10,439	1039	£89,218	Full Liner	£5,470	788	£89,218	21m Part Liner	£4,528	928	£89,218	12m + 5m Part Liners	£1,683	501	£89,218	1No. Patch
65	£9,256	1252	£106,926	Full Liner	£2,157	1090	£106,926	7m Part Liner	£4,286	1250	£106,926	16m Part Liner				
66	£1,560	83	£21,503	Full Liner												
67	£1,979	415	£86,093	Full Liner												

APPENDIX D. OPTIMISATION RESULTS VS. ENGINEERING SOLUTION, CHAPTER 4

ID	Sewer Type	Incident Code	Incident Freq	25 yr Ops Benefit	OPM Refs	Avoided Cost	S1	Engineering Solution ΔS	Engineering Solution C	Engineering Solution Op	Engineering Solution Repair Description	Selected Optimised Solution ΔS	Selected Optimised Solution C	Selected Optimised Solution Op	Selected Optimised Solution Repair Description
1	Combined /Foul	0	0	£-	A,C,H,E,F,I ,K,O,P	£87,593	440	440	£13,899	£87,593	Full Liner	440	£2,826	£87,593	1No. Patch + 6m Part Liner
2	Surface	CPA	1	£20,833	A,O,P	£21,503	642	0	£-	£-	No Repairs	640	£2,393	£42,336	8m Part Liner
3	Combined /Foul	0	0	£-	A,B,G,I,K, O,P	£137,143	121	100	£1,557	£137,143	1No. Patch Repair	100	£1,557	£137,143	1No. Patch Repair
4	Combined /Foul	0	0	£-	A,D,E,F,I,K ,O,P	£47,043	241	241	£13,515	£47,043	Full Liner	241	£2,630	£47,043	9m Part Liner
5	Combined /Foul	0	0	£-	A,B,G,E,F,I ,K,L,O,P	£200,643	108 2	1082	£12,096	£200,643	Full Liner	752	£2,630	£200,643	9m + 5m Part Liners
6	Surface	0	0	£-	A,E,D,F,O, P	£33,003	126 0	1260	£14,385	£33,003	Full Liner	600	£2,072	£33,003	6m + 3m + 12m Part Liners
7	Combined /Foul	0	0	£-	A,C,H,I,K, O,P	£137,143	50	40	£1,557	£137,143	1No. Patch Repair	0	£-	£-	No Repairs
8	Surface	0	0	£-	A,O,P	£21,503	81	0	£-	£-	No Repairs	0	£-	£-	No Repairs
9	Combined /Foul	0	0	£-	A,C,H,I,K, O,P	£137,143	181	180	£1,557	£137,143	1No. Patch Repair	180	£1,557	£137,143	1No. Patch Repair
10	Surface	0	0	£-	A,O,P	£21,503	80	0	£-	£-	No Repairs	80	£1,557	£21,503	1No. Patch Repair
11	Combined /Foul	0	0	£-	A,C,H,I,K, O,P	£86,093	160	160	£1,815	£86,093	3m Part Liner	160	£1,815	£86,093	5m Part Liner
12	Combined /Foul	0	0	£-	A,C,H,E,F,I ,K,O,P	£87,593	635	635	£3,247	£87,593	Full Liner	325	£1,559	£87,593	1No. Patch Repair
13	Combined /Foul	0	0	£-	A,B,G,E,F,I ,K,O,P	£138,643	350	350	£3,247	£138,643	Full Liner	350	£3,247	£138,643	Full Liner

								Engineering Solution				Selected Optimised Solution			
ID	Sewer Type	Incident Code	Freq	25 yr Ops Benefit	OPM Refs	Avoided Cost	S1	ΔS	C	Op	Repair Description	ΔS	C	Op	Repair Description
14	Surface	0	0	£-	A,O,P	£21,503	80	0	£-	£-	No Repairs	0	£-	£-	No Repairs
15	Surface	0	0	£-	A,D,O,P	£31,503	670	0	£-	£-	No Repairs	320	£2,613	£31,503	2No. Patch
16	Surface	0	0	£-	A,D,O,P	£31,503	80	0	£-	£-	No Repairs	0	£-	£-	1No. Patch Repair
17	Combined /Foul	0	0	£-	A,C,H,I,K,L ,O,P	£148,093	201	201	£3,222	£148,093	Full Liner	160	£1,472	£148,093	1No. Patch
18	Combined /Foul	0	0	£-	A,B,G,I,K, O,P	£137,143	450	450	£3,458	£137,143	Full Liner	0	£-	£-	No Repairs
19	Combined /Foul	BPR	2	£1,042	A,C,H,I,K, O,P	£86,093	80	80	£1,475	£87,134	Full Liner	80	£1,475	£87,134	Full Liner
20	Surface	BRO	1	£3,125	A,E,FO,P	£21,053	123 0	1230	£9,492	£24,178	Full Liner	980	£2,873	£24,178	4m Part Liner + 1 Patch
21	Surface	0	0	£-	A,O,P	£21,503	40	0	£-	£-	No Repairs	0	£-	£-	No Repairs
22	Combined /Foul	0	0	£-	A,C,H,I,K, O,P	£86,093	200	160	£1,810	£86,093	1No. Patch Repair	160	£1,810	£86,093	1No. Patch Repair
23	Surface	0	0	£-	A,O,P	£21,503	40	0	£-	£-	No Repairs	0	£-	£-	No Repairs
24	Surface	0	0	£-	A,D,O,P	£31,503	171	0	£-	£-	No Repairs	0	£-	£-	No Repairs
25	Combined /Foul	0	0	£-	A,I,K,O,P	£35,543	800	800	£2,444	£35,543	Full Liner	800	£2,444	£35,543	Full Liner
26	Combined /Foul	BRO	1	£3,125	A,C,E,F,H,I ,K,O,P	£87,593	741	741	£1,861	£90,718	Full Liner	741	£1,861	£90,718	Full Liner
27	Surface	BRO	1	£3,125	A,O,P	£21,503	150	0	£-	£-	No Repairs	0	£-	£-	No Repairs
28	Combined /Foul	0	0	£-	A,D,I,K,N, O,P	£86,543	162	162	£1,557	£86,543	Full Liner	162	£1,557	£86,543	Full Liner
29	Surface	0	0	£-	A,D,O,P	£31,503	41	0	£-	£-	No Repairs	0	£-	£-	No Repairs
30	Combined /Foul	0	0	£-	A,I,K,M,O, P	£47,543	140	140	£1,557	£47,543	1No. Patch Repair	140	£1,557	£47,543	1No. Patch Repair
31	Combined	BPR	1	£1,042	A,I,K,M,O,	£47,543	163	163	£1,979	£48,584	Full Liner	0	£-	£-	No Repairs

ID	Sewer Type	Incident Code	Incident Freq	25 yr Ops Benefit	OPM Refs	Avoided Cost	S1	Engineering Solution ΔS	Engineering Solution C	Engineering Solution Op	Engineering Solution Repair Description	Selected Optimised Solution ΔS	Selected Optimised Solution C	Selected Optimised Solution Op	Selected Optimised Solution Repair Description
	/Foul				P										
32	Combined /Foul	BPR	3	£1,042	A,I,K,O,P	£35,543	43	0	£-	£-	No Repairs	0	£-	£-	No Repairs
33	Combined /Foul	0	0	£-	A,I,K,O,P	£35,543	80	0	£-	£-	No Repairs	0	£-	£-	No Repairs
34	Combined /Foul	0	0	£-	A,C,H,I,K, O,P	£86,093	80	80	£1,685	£86,093	Full Liner	80	£1,685	£86,093	Full Liner
35	Combined /Foul	0	0	£-	A,C,H,I,K, O,P	£86,093	74	71	£1,683	£86,093	1No. Patch Repair	71	£1,683	£86,093	1No. Patch Repair
36	Combined /Foul	0	0	£-	A,C,H,I,K, O,P	£86,093	10	0	£-	£-	No Repairs	0	£-	£-	No Repairs
37	Combined /Foul	0	0	£-	A,C,H,I,K, O,P	£86,093	490	490	£9,019	£86,093	Full Liner	0	£-	£-	No Repairs
38	Combined /Foul	0	0	£-	A,C,E,F,H,I ,K,O,P	£87,593	350	350	£10,455	£87,593	Full Liner	0	£-	£-	No Repairs
39	Combined /Foul	0	0	£-	A,C,E,F,H,I ,K,O,P	£87,593	50	0	£-	£-	No Repairs	0	£-	£-	No Repairs
40	Combined /Foul	0	0	£-	A,C,H,I,K, O,P	£86,093	120	120	£3,382	£86,093	Full Liner	120	£3,382	£86,093	Full Liner
41	Combined /Foul	0	0	£-	A,C,H,I,K,L ,O,P	£148,093	461	461	£4,726	£148,093	Full Liner	431	£2,613	£148,093	7m Part Liner
42	Combined /Foul	0	0	£-	A,C,H,I,K, O,P	£86,093	684	292	£1,559	£86,093	2No. Patch Repairs	684	£2,824	£86,093	11m Part Liner
43	Combined /Foul	0	0	£-	A,C,H,I,K, O,P	£86,093	309	309	£1,717	£86,093	Full Liner	309	£1,717	£86,093	Full Liner
44	Combined /Foul	0	0	£-	A,D,I,K,O, P	£45,543	130	0	£-	£-	No Repairs	306	£1,517	£45,543	5m Part Liner
45	Combined /Foul	0	0	£-	A,C,E,F,H,I ,K,O,P	£87,593	339	339	£2,250	£87,593	Full Liner	339	£2,250	£87,593	5m Part Liner
46	Combined /Foul	0	0	£-	A,D,I,K,O, P	£45,543	20	0	£-	£-	No Repairs	0	£-	£-	No Repairs

								Engineering Solution				Selected Optimised Solution			
ID	Sewer Type	Incident Code	Freq	25 yr Ops Benefit	OPM Refs	Avoided Cost	S1	ΔS	C	Op	Repair Description	ΔS	C	Op	Repair Description
47	Surface	0	0	£-	A,O,P	£21,503	100	0	£-	£-	No Repairs	0	£-	£-	No Repairs
48	Combined /Foul	0	0	£-	A,C,E,F,H,I ,K,O,P	£87,593	345	345	£2,191	£87,593	Full Liner	245	£1,559	£87,593	Full Liner
49	Combined /Foul	0	0	£-	A,C,H,I,K, O,P	£86,093	21	21	£1,562	£86,093	Full Liner	21	£1,562	£86,093	Full Liner
50	Combined /Foul	0	0	£-	A,C,H,I,K, O,P	£86,093	20	20	£1,562	£86,093	Full Liner	20	£1,557	£86,093	Full Liner
51	Combined /Foul	BPR	2	£1,042	A,C,E,F,H,I ,K,O,P	£87,593	460	460	£5,572	£88,634	Full Liner	460	£5,572	£88,634	Full Liner
52	Combined /Foul	BPR	4	£1,042	A,C,H,I,K, O,P	£86,093	280	280	£12,027	£87,134	Full Liner	180	£1,812	£87,134	1No. Patch
53	Combined /Foul	0	0	£-	A,C,H,I,K, O,P	£86,093	176	122	£1,560	£86,093	3m Part Liner	122	£1,560	£86,093	3m Part Liner
54	Combined /Foul	0	0	£-	A,B,G,E,F,I ,K,O,P	£138,643	175	0	£-	£-	Full Liner	175	£1,559	£138,643	Full Liner
55	Combined /Foul	0	0	£-	A,B,G,I,K, O,P	£137,143	495	433	£2,191	£137,143	8m Part Liner	346	£1,557	£137,143	6m Part Liner
56	Combined /Foul	0	0	£-	A,C,H,I,K, O,P	£86,093	231	231	£4,000	£86,093	Full Liner	150	£1,476	£86,093	4m Part Liner
57	Combined /Foul	0	0	£-	A,C,E,F,H,I ,K,O,P	£87,593	420	220	£1,768	£87,593	6m Part Liner	420	£2,824	£87,593	1No. Patch + 6m Part Liner
58	Combined /Foul	0	0	£-	A,C,E,F,H,I ,K,O,P	£87,593	40	0	£-	£-	No Repairs	40	£1,562	£87,593	1No. Patch Repair
59	Combined /Foul	CPA	1	£20,833	A,I,K,O,P	£35,543	380	0	£-	£-	No Repairs	380	£1,688	£56,376	3m Part Liner
60	Combined /Foul	0	0	£-	A,I,K,O,P	£35,543	157 5	1575	£9,729	£35,543	Full Liner	1575	£9,729	£35,543	Full Liner
61	Surface	0	0	£-	A,D,O,P	£31,503	30	0	£-	£-	No Repairs	0	£-	£-	No Repairs
62	Combined /Foul	BPR	1	£1,042	A,C,H,I,K, O,P	£86,093	125	123	£1,475	£87,134	3m Part Liner	123	£1,472	£87,134	3m Part Liner

ID	Sewer Type	Incident Code	Incident Freq	25 yr Ops Benefit	OPM Refs	Avoided Cost	S1	Engineering Solution ΔS	Engineering Solution C	Engineering Solution Op	Engineering Solution Repair Description	Selected Optimised Solution ΔS	Selected Optimised Solution C	Selected Optimised Solution Op	Selected Optimised Solution Repair Description
63	Combined /Foul	0	0	£-	A,I,K,O,P	£35,543	400	400	£3,458	£35,543	Full Liner	400	£2,615	£35,543	2No. Patch Repairs
64	Combined /Foul	BRO	1	£3,125	A,C,H,I,K, O,P	£86,093	103 9	788	£5,470	£89,218	21m Part Liner	501	£1,683	£89,218	12m + 5m Part Liners
65	Combined /Foul	CPA	1	£20,833	A,C,H,I,K, O,P	£86,093	125 2	0	£-	£-	No Repairs	1090	£2,157	£106,926	11m Part Liner
66	Surface	0	0	£-	A,O,P	£21,503	83	0	£-	£-	No Repairs	0	£-	£-	No Repairs
67	Combined /Foul	0	0	£-	A,C,H,I,K, O,P	£86,093	415	415	£1,979	£86,093	Full Liner	415	£1,979	£86,093	Full Liner
								16,560	**£186,747**	**£3.89M**		**16,414**	**£103,099**	**£3.92M**	

Red indicates identical solution

APPENDIX E. SERVICE RESERVOIR RELIABILITY ASSESSMENT, CHAPTER 5

Inspector: *B.Ward*	Inspection type: *General*	Compartment *1* of *1* for this Reservoir	**Failure Modes:** 1. Structural Collapse 2. Deficiency in Water Quality 3. Security/Safety
Reservoir Name: *ABC*	Form of construction: *Type D. Flat Perimeter bay with central column bases*	Reservoir Ref/No: *R001*	
Reservoir Capacity: *9.09ML*		Total no. of compartments: *1*	

Element	Defect Description	Severity (S) Extent (E), Condition Grade (CG)			Failure Mode Weighting			Weighted Condition Grade			Comments/Assumptions based on Inspection	Reliability for Failure Modes		
		S	Ex	CG	WF1	WF2	WF3	CG* WF1	CG* WF2	CG* WF3		R1	R2	R3
Column Reference														
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Roof Slab	Concrete spalls and/or corrosion of reinforcement	*3*	*E*	*4*	1	0.25	0	4	1	0	*Evidence of surface erosion and corrosion*	0.9972	0.9997	
	Structural cracking in concrete	*1*	*A*	*0.2*	1	0	0	0.2	0	0	*No evidence of cracking*	0.9998		
	Delamination	*1*	*A*	*0.2*	1	0.25	0	0.2	0.05	0	*The general condition of the structure appears reasonable*	0.9998	0.9998	
	Cracking due to freeze thaw attack	*1*	*A*	*0.2*	1	0	0	0.2	0	0	*No evidence of cracking*	0.9998		
	Water Ingress/Leakage through cracks	*3*	*E*	*4*	0.25	1	0	0	4	0	*Evidence of water ingress*		0.9972	
	Slime growth	*1*	*A*	*0.2*	0	0.5	0	0	0.1	0	*Not observed*		0.9998	
	Plant root intrusion	*1*	*A*	*0.2*	0.5	0.5	0	0.1	0.1	0	*No root ingress*	0.9998	0.9998	
	Deterioration/leakage of construction joint/seals	*2*	*E*	*2*	0.5	1	0	1	2	0	*Joint condition poor*	0.9997	0.9994	
	Deterioration/leakage of sliding joint (roof/wall)	*2*	*E*	*2*	0.5	1	0	1	2	0	*Joint condition poor*	0.9997	0.9994	
	Invertebrates	*2*	*E*	*2*	0	0.25	0	0	0.5	0	*Evidence inside*		0.9998	

Element	Defect Description	Severity (S) Extent (E), Condition Grade (CG)			Failure Mode Weighting			Weighted Condition Grade			Comments/Assumptions based on Inspection	Reliability for Failure Modes		
		S	Ex	CG	WF1	WF2	WF3	CG* WF1	CG* WF2	CG* WF3		R1	R2	R3
External Walls	Concrete spalls and/or corrosion of reinforcement	3	E	4	1	0.25	0	4	1	0	Evidence of surface erosion and corrosion	0.9972	0.9997	
	Structural cracking in concrete	1	A	0.2	1	0	0	0.2	0	0	No evidence of cracking	0.9998		
	Delamination	1	A	0.2	1	0.25	0	0.2	0.05	0	The general condition of the structure appears reasonable	0.9998	0.9998	
	Cracking due to freeze thaw attack	1	A	0.2	1	0	0	0.2	0	0	No evidence of cracking	0.9998		
	Water Ingress/Leakage through cracks	3	E	4	0	1	0	0	4	0	Evidence of water ingress		0.9972	
	Slime growth	1	A	0.2	0	0.5	0	0	0.1	0	Not observed		0.9998	
	Plant root intrusion	1	A	0.2	0.5	0.5	0	0.1	0.1	0	No root ingress	0.9998	0.9998	
	Sliding	1	A	0.2	1	0	0	0.2	0	0	The general condition of the structure appears reasonable	0.9998		
	Rotation	1	A	0.2	1	0	0	0.2	0	0	The general condition of the structure appears reasonable	0.9998		
	Overturning	1	A	0.2	1	0	0	0.2	0	0	The general condition of the structure appears reasonable	0.9998		
	Deterioration/leakage of construction joint/seals	3	E	4	0.5	1	0	2	4	0	Joint condition poor	0.9994	0.9972	
Columns	Concrete spalls and/or corrosion of reinforcement	3	E	4	1	0.25	0	4	1	0	Evidence of surface erosion and corrosion	0.9972	0.9997	
	Structural cracking in concrete	1	A	0.2	1	0	0	0.2	0	0	No evidence of cracking	0.9998		
	Delamination	1	A	0.2	1	0.25	0	0.2	0.05	0	The general condition of the structure appears reasonable	0.9998	0.9998	
	Cracking due to freeze thaw attack	1	A	0.2	1	0	0	0.2	0	0	No evidence of cracking	0.9998		
	Water Ingress/Leakage through cracks	3	E	4	0	0.25	0	0	1	0	Evidence of water ingress		0.9997	
	Slime growth	1	A	0.2	0	0.5	0	0	0.1	0	Not mentioned in report		0.9998	
	Deterioration/leakage of construction joint/seals	2	E	2	0.5	0.5	0	1	1	0	Joint condition poor	0.9997	0.9997	

Element	Defect Description	Severity (S) Extent (E), Condition Grade (CG)			Failure Mode Weighting			Weighted Condition Grade			Comments/Assumptions based on Inspection	Reliability for Failure Modes		
		S	Ex	CG	WF1	WF2	WF3	CG* WF1	CG* WF2	CG* WF3		R1	R2	R3
Column Bases	Concrete spalls and/or corrosion of reinforcement	3	E	4	1	0.25	0	4	1	0	*Evidence of surface erosion and corrosion*	0.9972	0.9997	
	Structural cracking in concrete	1	A	0.2	1	0	0	0.2	0	0	*No evidence of cracking*	0.9998		
	Delamination	1	A	0.2	1	0.25	0	0.2	0.05	0	*Not observed*	0.9998	0.9998	
	Cracking due to freeze thaw attack	1	A	0.2	1	0	0	0.2	0	0	*No evidence of cracking*	0.9998		
	Water Ingress/Leakage through cracks	2	E	2	0	1	0	0	2	0	*Evidence of water ingress*		0.9994	
	Slime growth	1	A	0.2	0	0.5	0	0	0.1	0	*Not observed*		0.9998	
	Deterioration/leakage of construction joint/seals	2	E	2	0.5	0.5	0	1	1	0	*Joint condition poor*	0.9997	0.9997	
Floor Slab	Concrete spalls and/or corrosion of reinforcement	3	E	4	1	0.25	0	4	1	0	*Evidence of surface erosion and corrosion*	0.9972	0.9997	
	Structural cracking in concrete	1	A	0.2	1	0	0	0.2	0	0	*No evidence of cracking*	0.9998		
	Cracking due to freeze thaw attack	1	A	0.2	1	0	0	0.2	0	0	*No evidence of cracking*	0.9998		
	Water Ingress/Leakage at cracks	2	E	2	0	1	0	0	2	0	*Evidence of water ingress*		0.9994	
	Slime growth	1	A	0.2	0	0.5	0	0	0.1	0	*Not observed*		0.9998	
	Plant root intrusion	1	A	0.2	0.5	0.5	0	0.1	0.1	0	*No root ingress*	0.9998	0.9998	
	Settlement	1	A	0.2	1	0	0	0.2	0	0	*The general condition of the structure appears reasonable*	0.9998		
	Differential Movement	1	A	0.2	1	0	0	0.2	0	0	*The general condition of the structure appears reasonable*	0.9998		
	Sliding	1	A	0.2	1	0	0	0.2	0	0	*The general condition of the structure appears reasonable*	0.9998		
	Rotation	1	A	0.2	1	0	0	0.2	0	0	*The general condition of the structure appears reasonable*	0.9998		
	Uplift/flotation	1	A	0.2	1	0	0	0.2	0	0	*The general condition of the structure appears reasonable*	0.9998		
	Deterioration/leakage of construction joint/seals	2	E	2	0.5	0.5	0	1	1	0	*Joint condition poor*	0.9997	0.9997	
	Invertebrates	2	E	2	0	0.25	0	0	0.5	0	*Evidence inside*		0.9998	
	Deposits due to animal ingress	1	A	0.2	0	0.75	0	0	0.15	0	*No animal ingress*		0.9998	

Element	Defect Description	Severity (S) Extent (E), Condition Grade (CG)			Failure Mode Weighting			Weighted Condition Grade			Comments/Assumptions based on Inspection	Reliability for Failure Modes		
		S	Ex	CG	WF1	WF2	WF3	CG* WF1	CG* WF2	CG* WF3		R1	R2	R3
Roof slab & membrane	Tears in membrane	-	-					0	0	0	*N/A - No roof slab membrane*			
	Deterioration of mesh/membrane	-	-					0	0	0	*N/A - No roof slab membrane*			
	Not present	5	E	16	0	0.5	0	0	8	0	*No membrane present*		0.9500	
	Plant root intrusion	1	A	0.2	0.25	0.25	0	0.05	0.05	0	*No root ingress*	0.9998	0.9998	
	Weathering of surfacing material	1	A	0.2	0	0	0	0	0	0	*Good condition*			
Embankments	Subsidence/deformation / settlement	2	C	1.2	1	1	0	1.2	1.2	0	*The condition of the reservoir banks appear to be well maintained and free from slippage apart from in a few minor locations*	0.9996	0.9996	
	Leakage	1	A	0.2	0	1	0	0	0.2	0	*The condition of the reservoir banks appear to be well maintained and free from slippage*		0.9998	
Reservoir roof cover (access)	Rusting/damage	1	A	0.2	0	0.75	0	0	0.15	0	*The covers appear adequate*		0.9998	
	Loss of section thickness	1	A	0.2	0	1	0	0	0.2	0	*The covers appear adequate*		0.9998	
	Rusting/damage to bolts, nuts and rivets	1	A	0.2	0	0.5	0	0	0.1	0	*The covers appear adequate*		0.9998	
	Corrosion/damage to weld runs	1	A	0.2	0	0.5	0	0	0.1	0	*The covers appear adequate*		0.9998	
	Weathering of finishing coat	1	A	0.2	0	0.25	0	0	0.05	0	*The covers appear adequate*		0.9998	
	Deterioration/leakage of sealant strip	1	A	0.2	0	1	0	0	0.2	0	*The covers appear adequate*		0.9998	
	Deterioration of flashing	1	A	0.2	0.25	0	0	0.05	0	0	*Not deterioration observed*	0.9998		
Safety Grid	Rusting/damage	1	A	0.2	0	0.75	0.5	0	0.15	0	*The covers appear adequate*		0.9998	
	Loss of section thickness	1	A	0.2	0	1	1	0	0.2	0	*The covers appear adequate*		0.9998	
	Rusting/damage to bolts, nuts and rivets	1	A	0.2	0	0.5	0.75	0	0.1	0	*The covers appear adequate*		0.9998	
	Corrosion/damage to weld runs	1	A	0.2	0	0.5	0.75	0	0.1	0	*The covers appear adequate*		0.9998	
	Weathering of finishing coat	1	A	0.2	0	0.25	0.25	0	0.05	0	*The covers appear adequate*		0.9998	
	Blockage	1	A	0.2	1	1	0.25	0.2	0.2	0	*The covers appear adequate*	0.9998	0.9998	

Element	Defect Description	Severity (S) Extent (E), Condition Grade (CG)			Failure Mode Weighting			Weighted Condition Grade			Comments/Assumptions based on Inspection	Reliability for Failure Modes		
		S	Ex	CG	WF1	WF2	WF3	CG* WF1	CG* WF2	CG* WF3		R1	R2	R3
Reservoir roof cover Handrail	Rusting/damage	-	-					0	0	0	NA - No handrail			
	Loss of section thickness	-	-					0	0	0	NA - No handrail			
	Rusting/damage to bolts, nuts and rivets	-	-					0	0	0	NA - No handrail			
	Corrosion/damage to weld runs	-	-					0	0	0	NA - No handrail			
	Weathering of finishing coat	-	-					0	0	0	NA - No handrail			
	Not present	5	E	16	0	0	0.5	0	0	0	No handrail			
Ventilation inlets (mesh screens)	Rusting/damage	-	-					0	0	0	N/A as air vent on access cover			
	Loss of section thickness	-	-					0	0	0	N/A as air vent on access cover			
	Rusting/damage to bolts, nuts and rivets	-	-					0	0	0	N/A as air vent on access cover			
	Corrosion/damage to weld runs	-	-					0	0	0	N/A as air vent on access cover			
	Weathering of finishing coat	-	-					0	0	0	N/A as air vent on access cover			
	Deterioration/leakage of sealant strip	-	-					0	0	0	N/A as air vent on access cover			
	Blockage	1	A	0.2	1	1	0.75	0.2	0.2	0	Air vents and gauzes are fitted and intact	0.9998	0.9998	
	Tears in membrane	1	A	0.2	0	1	0	0	0.2	0	Air vents and gauzes are fitted and intact		0.9998	
Ladder Access Steelwork	Rusting/damage	4	E	8	0	0.75	0.25	0	6	0	Both ladders are badly corroded		0.9881	
	Loss of section thickness	2	E	2	0	1	0.75	0	2	0	Both ladders are badly corroded		0.9994	
	Rusting/damage to bolts, nuts and rivets	4	E	8	0	0.5	0.25	0	4	0	Both ladders are badly corroded		0.9972	
	Corrosion/damage to weld runs	4	E	8	0	0.5	0.25	0	4	0	Both ladders are badly corroded		0.9972	
	Weathering of finishing coat	5	E	16	0	0.25	0.25	0	4	0	Both ladders are badly corroded		0.9972	

Element	Defect Description	Severity (S) Extent (E), Condition Grade (CG)			Failure Mode Weighting			Weighted Condition Grade			Comments/Assumptions based on Inspection	Reliability for Failure Modes		
		S	Ex	CG	WF1	WF2	WF3	CG* WF1	CG* WF2	CG* WF3		R1	R2	R3
Roof drainage Edge gullies and pipes	Blockage of cross section	-	-					0	0	0	*N/A - No roof drainage provisions*			
	Deterioration of pipe	-	-					0	0	0	*N/A - No roof drainage provisions*			
	Not present	5	E	16	0	0.25	0	0	4	0	*No roof drainage provisions*		0.9972	
Drainage Channels	Blockage of cross section	-	-					0	0	0	*N/A - No roof drainage provisions*			
	Not present	5	E	16	0	0.25	0	0	4	0	*No roof drainage provisions*		0.9972	
Guttering and downpipes	Blockage of cross section	-	-					0	0	0	*N/A - No roof drainage provisions*			
	Deterioration of pipe	-	-					0	0	0	*N/A - No roof drainage provisions*			
	Not present	5	E	16	0	0.25	0	0	4	0	*No roof drainage provisions*		0.9972	
Inlet Pipe	Rusting/damage	3	E	4	0	0.75	0	0	3	0	*All pipework within the reservoir is significantly corroded but in satisfactory working order*		0.9987	0.9999
	Loss of section thickness	1	A	0.2	0	1	0	0	0.2	0	*All pipework within the reservoir is significantly corroded but in satisfactory working order. Assume no loss of section*		0.9998	0.9999
	Weathering of finishing coat	5	E	16				16	16	16	*NA - No finishing coat*			
	Submersion	1	A	0.2	0	0	0	0	0	0	*All pipework within the reservoir is significantly corroded but in satisfactory working order*			0.9999
	Blockage	1	A	0.2	0	0	0	0	0	0	*All pipework within the reservoir is significantly corroded but in satisfactory working order*			0.9999
	Leakage	1	A	0.2	0	1	0	0	0.2	0	*All pipework within the reservoir is significantly corroded but in satisfactory working order*		0.9998	

Element	Defect Description	Severity (S) Extent (E), Condition Grade (CG)			Failure Mode Weighting			Weighted Condition Grade			Comments/Assumptions based on Inspection	Reliability for Failure Modes		
		S	Ex	CG	WF1	WF2	WF3	CG* WF1	CG* WF2	CG* WF3		R1	R2	R3
Outlet Pipe	Rusting/damage	3	E	4	0	0.75	0	0	3	0	All pipework within the reservoir is significantly corroded but in satisfactory working order		0.9987	0.9999
	Loss of section thickness	1	A	0.2	0	1	0	0	0.2	0	All pipework within the reservoir is significantly corroded but in satisfactory working order.		0.9998	0.9999
	Weathering of finishing coat	5	E	16				16	16	16	NA - No finishing coat			
	Submersion	1	A	0.2	0	0	0	0	0	0	All pipework within the reservoir is significantly corroded but in satisfactory working order			0.9999
	Blockage	1	A	0.2	0	0	0	0	0	0	All pipework within the reservoir is significantly corroded but in satisfactory working order			0.9999
	Leakage	1	A	0.2	0	1	0	0	0.2	0	All pipework within the reservoir is significantly corroded but in satisfactory working order		0.9998	
Overflow pipe	Rusting/damage	3	E	4	0	0.75	0	0	3	0	All pipework within the reservoir is significantly corroded but in satisfactory working order		0.9987	0.9999
	Loss of section thickness	1	A	0.2	0	1	0	0	0.2	0	All pipework within the reservoir is significantly corroded but in satisfactory working order.		0.9998	0.9999
	Weathering of finishing coat	5	E	16				16	16	16	NA - No finishing coat			
	Submersion	1	A	0.2	1	0	0	0.2	0	0	All pipework within the reservoir is significantly corroded but in satisfactory working order	0.9998		0.9999
	Overflow	1	A	0.2	1	0	0	0.2	0	0	All pipework within the reservoir is significantly corroded but in satisfactory working order	0.9998		0.9999
	Blockage	1	A	0.2	0	0	0	0	0	0	All pipework within the reservoir is significantly corroded but in satisfactory working order			0.9999
	Leakage	1	A	0.2	0	1	0	0	0.2	0	All pipework within the reservoir is significantly corroded but in satisfactory working order		0.9998	
	Deterioration	3	E	4	0	0	0	0	0	0	All pipework within the reservoir is significantly corroded but satisfactory			0.9999

Element	Defect Description	Severity (S) Extent (E), Condition Grade (CG)			Failure Mode Weighting			Weighted Condition Grade			Comments/Assumptions based on Inspection	Reliability for Failure Modes		
		S	Ex	CG	WF1	WF2	WF3	CG* WF1	CG* WF2	CG* WF3		R1	R2	R3
Washout Valve	Rusting/damage	*3*	*E*	*4*	0	0.25	0	0	1	0	*All pipework within the reservoir is significantly corroded but in satisfactory working order*		0.9997	0.9999
	Loss of section thickness	*1*	*A*	*0.2*	0	0.25	0	0	0.05	0	*All pipework within the reservoir is significantly corroded but in satisfactory working order. Assume no loss of section*		0.9998	0.9999
Other Control valves	Rusting/damage	*3*	*E*	*4*	0	0.25	0	0	1	0	*All pipework within the reservoir is significantly corroded but in satisfactory working order*		0.9997	0.9999
	Loss of section thickness	*1*	*A*	*0.2*	0	0.25	0	0	0.05	0	*All pipework within the reservoir is significantly corroded but in satisfactory working order. Assume no loss of section*		0.9998	0.9999
Perimeter Fence	Rusting/damage	*1*	*A*	*0.2*	0	0	0.25	0	0	0.05	*Fence condition Okay*			0.9998
	Loss of section thickness	*1*	*A*	*0.2*	0	0	0.5	0	0	0.1	*Fence condition Okay*			0.9998
	Rusting/damage to bolts, nuts and rivets	*1*	*A*	*0.2*	0	0	0.25	0	0	0.05	*Fence condition Okay*			0.9998
	Corrosion/damage to weld runs	*1*	*A*	*0.2*	0	0	0.25	0	0	0.05	*Fence condition Okay*			0.9998
	Weathering of finishing coat	*1*	*A*	*0.2*	0	0	0.25	0	0	0.05	*Fence condition Okay*			0.9998
	Adjacent vegetation growth	*3*	*E*	*4*	0	0	0.25	0	0	1	*Hedgerows need to be maintained to prevent damage to fencing*			0.9997
	Stock proof	*1*	*A*	*0.2*	0	0	0.5	0	0	0.1	*Fence condition Okay*			0.9998
	Damage	*1*	*A*	*0.2*	0	0	0.5	0	0	0.1	*Fence condition Okay*			0.9998
Paths	Weathering of surfacing material	*1*	*A*	*0.2*	0	0	0.125	0	0	0.025	*No significant defects observed*			1.0000
	Crazing, tracking and/or fretting	*1*	*A*	*0.2*	0	0	0.25	0	0	0.05	*No significant defects observed*			0.9998
	Deterioration of texture	*1*	*A*	*0.2*	0	0	0.125	0	0	0.025	*No significant defects observed*			1.0000
	Cracking and potholes	*1*	*A*	*0.2*	0	0	0.25	0	0	0.05	*No significant defects observed*			0.9998
	Slippery	*1*	*A*	*0.2*	0	0	0.25	0	0	0.05	*No significant defects observed*			0.9998
	Vegetation growth	*1*	*A*	*0.2*	0	0	0.125	0	0	0.025	*No significant defects observed*			1.0000

Element	Defect Description	Severity (S) Extent (E), Condition Grade (CG)			Failure Mode Weighting			Weighted Condition Grade			Comments/Assumptions based on Inspection	Reliability for Failure Modes		
		S	Ex	CG	WF1	WF2	WF3	CG* WF1	CG* WF2	CG* WF3		R1	R2	R3
Gates	Rusting/damage	1	A	0.2	0	0	0.25	0	0	0.05	Gates in good working order			0.9998
	Loss of section thickness	1	A	0.2	0	0	0.5	0	0	0.1	Gates in good working order			0.9998
	Rusting/damage to bolts, nuts and rivets	1	A	0.2	0	0	0.25	0	0	0.05	Gates in good working order			0.9998
	Corrosion/damage to weld runs	1	A	0.2	0	0	0.25	0	0	0.05	Gates in good working order			0.9998
	Weathering of finishing coat	1	A	0.2	0	0	0.25	0	0	0.05	Gates in good working order			0.9998
	Adjacent vegetation growth	3	E	4	0	0	0.25	0	0	1	Hedgerows need to be maintained to prevent damage to fencing			0.9997
	Stock proof	1	A	0.2	0	0	0.25	0	0	0.05	Gates in good working order			0.9998
	Damage	1	A	0.2	0	0	0.5	0	0	0.1	Gates in good working order			0.9998
	Lockable	-	-					0	0	1	Not mentioned in report			0.9999
Access road	Weathering of surfacing material	1	A	0.2	0	0	0.125	0	0	0.025	No significant defects observed			1.0000
	Crazing, tracking and/or fretting	1	A	0.2	0	0	0.25	0	0	0.05	No significant defects observed			0.9998
	Deterioration of texture	1	A	0.2	0	0	0.125	0	0	0.025	No significant defects observed			1.0000
	Cracking and potholes	1	A	0.2	0	0	0.25	0	0	0.05	No significant defects observed			0.9998
	Slippery	1	A	0.2	0	0	0.25	0	0	0.05	No significant defects observed			0.9998
	Vegetation growth	1	A	0.2	0	0	0.125	0	0	0.025	No significant defects observed			1.0000
Hardstanding	Weathering of surfacing material	1	A	0.2	0	0	0.125	0	0	0.025	No significant defects observed			1.0000
	Crazing, tracking and/or fretting	1	A	0.2	0	0	0.25	0	0	0.05	No significant defects observed			0.9998
	Deterioration of texture	1	A	0.2	0	0	0.125	0	0	0.025	No significant defects observed			1.0000
	Cracking and potholes	1	A	0.2	0	0	0.25	0	0	0.05	No significant defects observed			0.9998
	Slippery	1	A	0.2	0	0	0.25	0	0	0.05	No significant defects observed			0.9998
	Vegetation growth	1	A	0.2	0	0	0.125	0	0	0.025	No significant defects observed			1.0000

Element	Defect Description	Severity (S) Extent (E), Condition Grade (CG)			Failure Mode Weighting			Weighted Condition Grade			Comments/Assumptions based on Inspection	Reliability for Failure Modes		
		S	Ex	CG	WF1	WF2	WF3	CG* WF1	CG* WF2	CG* WF3		R1	R2	R3
											Total Reliabilities by Failure Mode	0.9787	0.90	0.9931